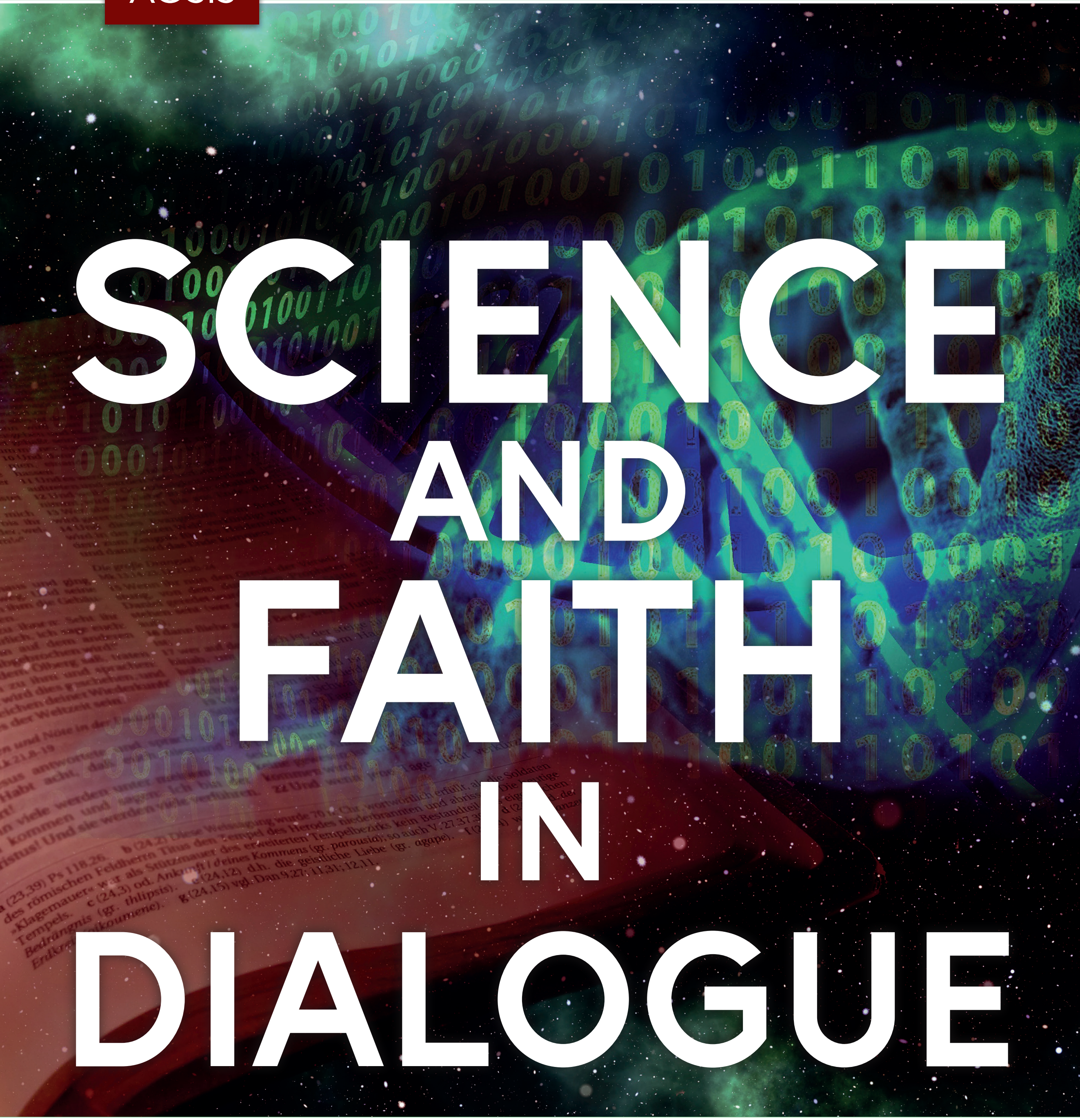
AOSIS

Reformed Theology in Africa Series

Volume 10



SCIENCE AND FAITH IN DIALOGUE

Edited by

Frederik van Niekerk
& Nico Vorster

Reformed Theology in Africa Series
Volume 10

SCIENCE AND FAITH IN DIALOGUE

AOSIS

Published by AOSIS Books, an imprint of AOSIS Publishing.

AOSIS Publishing
15 Oxford Street, Durbanville, 7550, Cape Town, South Africa
Postnet Suite 110, Private Bag X19, Durbanville, 7551, Cape Town, South Africa
Tel: +27 21 975 2602
Website: https://www.aosis.co.za

Copyright © Frederik van Niekerk and Nico Vorster (eds.). Licensee: AOSIS (Pty) Ltd
The moral right of the authors has been asserted.

Cover image: Original design created with a provided image. The image is https://pixabay.com/photos/biblespace-universe-starry-sky-5320415/, released under the appropriate Pixabay License.

Published in 2022
Impression: 1

ISBN: 978-1-77995-206-6 (print)
ISBN: 978-1-77995-207-3 (epub)
ISBN: 978-1-77995-208-0 (pdf)

DOI: https://doi.org/10.4102/aosis.2022.BK334
How to cite this work: Van Niekerk, F & Vorster, N (eds.) 2022, *Science and Faith in Dialogue,* in Reformed Theology in Africa Series, Vol. 10, AOSIS Books, Cape Town.

Reformed Theology in Africa Series
ISSN: 2706-6665
Series Editor: J.M. Vorster

Printed and bound in South Africa.

Listed in OAPEN (http://www.oapen.org), DOAB (http://www.doabooks.org/) and indexed by Google Scholar.

Some rights reserved.

This is an open-access publication. Except where otherwise noted, this work is distributed under the terms of a Creative Commons Attribution-NonCommercial-NoDerivatives 4.0 International License (CC BY-NC-ND 4.0). A copy of which is available at https://creativecommons.org/licenses/by-nc-nd/4.0/. Enquiries outside the terms of the Creative Commons license should be directed to the AOSIS Rights Department at the above address or to publishing@aosis.co.za.

(cc) BY-NC-ND

The publisher accepts no responsibility for any statement made or opinion expressed in this publication. Consequently, the publisher and copyright holders will not be liable for any loss or damage sustained by any reader as a result of their action upon any statement or opinion in this work. Links by third-party websites are provided by AOSIS in good faith and for information only. AOSIS disclaims any responsibility for the materials contained in any third-party website referenced in this work.

Every effort has been made to protect the interest of copyright holders. Should any infringement have occurred inadvertently, the publisher apologises and undertakes to amend the omission in the event of a reprint.

Reformed Theology in Africa Series
Volume 10

SCIENCE AND FAITH IN DIALOGUE

Editors
Frederik van Niekerk
Nico Vorster

AOSIS

Religious Studies Domain Editorial Board at AOSIS

Commissioning Editor: Scholarly Books

Andries G. van Aarde, MA, DD, PhD, D Litt, South Africa

Board members

Warren Carter, LaDonna Kramer Meinders Professor of the New Testament, Phillips Theological Seminary, United States of America

Evangelia G. Dafni, Faculty of Theology, Aristotle University of Thessaloniki, Greece

Lisanne D'Andrea-Winslow, Professor of Department of Biology and Biochemistry and Department of Biblical and Theological Studies, University of Northwestern, United States of America

Christian Danz, Dekan der Evangelisch-Theologischen Fakultät der Universität Wien and Ordentlicher Universitätsprofessor für Systematische Theologie und Religionswissenschaft, University of Vienna, Austria

David D. Grafton, Professor of Islamic Studies and Christian-Muslim Relations, Duncan Black Macdonald Center for the Study of Islam and Christian-Muslim Relations, Hartford International University for Religion and Peace, United States of America

Sigríður Guðmarsdóttir, Professor of Department of Theology and Religion, School of Humanities, University of Iceland, Iceland; Centre for Mission and Global Studies, Faculty of Theology, Diakonia and Leadership Studies, VID Specialised University, Norway

Jeanne Hoeft, Dean of Students and Associate Professor of Pastoral Theology and Pastoral Care, Saint Paul School of Theology, United States of America

Nancy Howell, Professor of Department of Philosophy of Religion, Faculty of Theology and Religion, Saint Paul School of Theology, Kansas City, United States of America

Llewellyn Howes, Professor of Department of Greek and Latin Studies, University of Johannesburg, South Africa

Fundiswa A. Kobo, Professor of Department of Christian Spirituality, Church History and Missiology, University of South Africa, South Africa

William R.G. Loader, Emeritus Professor, Murdoch University, Australia

Jean-Claude Loba-Mkole, Department of Hebrew, Faculty of Humanities, University of the Free State, South Africa

Piotr Roszak, Professor of Department of Christian Philosophy, Faculty of Theology, Nicolaus Copernicus University, Poland

Marcel Sarot, Emeritus Professor of Fundamental Theology, Tilburg School of Catholic Theology, Tilburg University, the Netherlands

David Sim, Department Biblical and Early Christian Studies, Catholic University of Australia, Australia

Corneliu C. Simut, Professor of Biblical Theology (New Testament), Faculty of Humanities and Social Sciences, Aurel Vlaicu University, Romania

Peer review declaration

The publisher (AOSIS) endorses the South African 'National Scholarly Book Publishers Forum Best Practice for Peer Review of Scholarly Books'. The manuscript underwent an evaluation to compare the level of originality with other published works and was subjected to rigorous two-step peer review before publication, with the identities of the reviewers not revealed to the editor(s) or author(s). The reviewers were independent of the publisher, editor(s), and author(s). The publisher shared feedback on the similarity report and the reviewers' inputs with the manuscript's editor(s) or author(s) to improve the manuscript. Where the reviewers recommended revision and improvements, the editor(s) or author(s) responded adequately to such recommendations. The reviewers commented positively on the scholarly merits of the manuscript and recommended that the book be published.

Research justification

Science and Faith in Dialogue presents a cogent, compelling case for concordance between science and theism. The term *theism* used in this book refers to the belief in God's existence. Within theology, the term theism is often used to convey a range of presuppositions about the nature and attributes of God. The topic of God's attributes does not fall within the scope of this study. Based on scientific and natural theological perspectives, two pillars of natural theology are revisited: the Cosmological Argument and the Argument from Design. The book argues that modern science provides undeniable evidence and a scientific basis for these classical arguments to infer a rationally justifiable endorsement of theism as being concordant with reason and science – nature is seen as operating orderly on comprehensible, rational, consistent laws, in line with the conviction that God is Creator. The expression 'undeniable evidence and scientific basis' is not understood as scientific proof but rather as inference, footprint, signature, deductive reasoning and rational justification for theism in world view. The premise that theism asserts a more causally adequate explanation of recent developments in modern natural science (than naturalism) is based upon: (1) Strong *epistemological support:* explanatory power and confirmation of hypothesis (rather than just deductive entailment); and (2) the *contemporary cosmological consensus*, building upon the rigour of the physical sciences and *illuminating biological discoveries*. The discovery that the universe had a beginning and the abundant scientific evidence for *fine-tuning* is best explained by theism. The phrase 'global fine-tuning' refers to fine-tuning of initial conditions, fundamental forces and other physical laws and constants for an expanding universe and the formation of galaxies, stars and planets. The phrase 'local fine-tuning' refers to the protection of the earth by the planetary giants, Earth's life-sustaining capabilities, water and its miraculous properties for life, Earth's rare habitability fine-tuned for life and scientific discovery. The phrase 'biological fine-tuning' is linked to the 'Argument from Irreducible Complexity and the Argument from Biological Information'.

Naturalistic explanations for the existence of the universe and sentient life are contested by showing that philosophical arguments against the cosmological argument and the argument based on design are weak and that naturalistic theories purported to provide explanations lack explanatory power. Claims that theistic design arguments have been refuted by some philosophers are disputed. Divergent philosophical assumptions, scientific overreach and logical fallacies and (for Christian scholars) different views of scripture and hermeneutic tradition arouse discordant dialogue and false dichotomies between science and faith. Alternative theories to avoid or explain the beginning of the universe (the eternal universe, multiverse, self-contained universe, cyclical universe and a universe out of nothing) overreach and lack credibility. Functions for life demonstrate clear evidence of foresight, coordination and goal-direction, which are all unmistakable signatures of intelligent design. Explanations based on prebiotic abiogenesis are futile. Origin-of-life research points to a Creator. Macroevolution (albeit not incompatible with theism) fails to provide a consistent theoretical framework to explain, for example, a viable mechanism to generate a primordial mechanism for abiogenesis, the origin of the genetic code, the genetic information required for life, the abrupt appearance of species in the fossil record. In conclusion, six myths, which have ostensibly contributed to the conflict thesis between science and religion and are seemingly ingrained in present-day scholarship, are debunked.

The target audience of the book comprises theological scholars, natural scientists and science philosophers. This book contains no plagiarism, and any work re-used by authors or published elsewhere has been clearly indicated, with permission from publishers as required.

Frederik van Niekerk, Unit for Energy and Technology Systems, Faculty of Engineering, North-West University, Potchefstroom, South Africa.

Contents

Abbreviations and acronyms, figures and tables appearing in the text and notes

List of abbreviations and acronyms

3D	Three-dimensional
AG	Andromeda Galaxy
AGN	Active Galactic Nucleus
AHI	Animal Habitability Index
AUs	Astronomical Units
BGV	Borde–Guth–Vilenkin
BHI	Basic Habitability Index
CAA	Canonical Amino Acid
CHA	Cosmic Habitable Age
CHZ	Circumstellar Habitable Zone
COBE	Cosmic Background Explorer
DNA	Deoxyribonucleic Acid
EEA	Environment of Evolutionary Adaptedness
ELSI	Earth-Life Science Institute
ENCODE	Encyclopedia of DNA Elements
GAMA	Galaxy and Mass Assembly
GCR	Galactic Cosmic Ray
GHZ	Galactic Habitable Zone
GMCs	Giant Molecular Clouds
GPS	Global Positioning System
GRBs	Gamma Ray Bursts
GRN	Gene Regulatory Network
HARs	Human Accelerated Regions
HPE	Hawking–Penrose–Ellis
IBE	Inference to the Best Explanation
ID	Intelligent Design
JIT	Just-in-Time
LGT	Lateral Gene Transfer
LIGO	Laser Interferometer Gravitational-Wave Observatory

LMCs	Large Magellanic Clouds
LUCA	Last Universal Common Ancestor
MIT	Massachusetts Institute of Technology
MS	Mass Spectrometry
MWG	Milky Way Galaxy
NBA	National Basketball Association
NCBI	National Center for Biotechnology Information
NGE	Natural Genetic Engineering
NOMA	Non-overlapping Magisteria
NWU	North-West University
OPEs	Oligo(phenylene ethynylene)s
PBS	Public Broadcasting Service
PCA	Principal Component Analysis
PISA	Polymerization-Induced Self-Assembly
RCIs	Rescaled Consistency Indexes
RNA	Ribonucleic Acid
RPA	Robust Perfect Adaptation
SETI	Search for Extraterrestrial Intelligence
SMBH	Supermassive Black Hole
SMC	Small Magellanic Clouds
SMCB	System Modeling in Cellular Biology
SMFM	Single-molecule Fluorescence Microscopy
SNRs	Supernova Remnants
STM	Scanning Tunnelling Microscopy
TEs	Transposable Elements
TOL	Tree of Life
UETSs	Unit for Energy and Technology Systems
UNICAMP	University of Campinas
US	United States
UV	Ultraviolet
VOCs	Volatile Organic Compounds
WMAP	Wilkinson Microwave Anisotropy Probe
YECs	Young-Earth Creationists

List of figures

Table list

Notes on contributors

Marcos Eberlin
Discovery-Mackenzie Research Centre for Science, Faith and Society,
Mackenzie University,
São Paulo, Brazil
Email: mneberlin@gmail.com
ORCID: https://orcid.org/0000-0003-4868-0618

Marcos Eberlin is the director of the Discovery-Mackenzie Research Centre for Science, Faith and Society at Mackenzie University in São Paulo, Brazil. He is a member of the Brazilian Academy of Sciences, received his PhD in Chemistry from the University of Campinas (UNICAMP) and served as a postdoctoral fellow at Purdue University. At UNICAMP, he founded and for 25 years coordinated the ThoMSon Mass Spectrometry (MS) Laboratory, making it an internationally recognised research centre, one of the best-equipped and innovative MS laboratories worldwide. Eberlin has published nearly 1000 scientific articles and is a recipient of many awards and honours, including the title of Commander of the National Order of Scientific Merit (2005) from Brazil's President, the Zeferino Vaz Award (2002) for excellence in teaching and research. He is the founder and current president of the Brazilian Society for Mass Spectrometry (BrMASS) – one of the largest MS societies. Eberlin is also President of the Brazilian Society for Intelligent Design (TDI Brasil). Before writing *Foresight*, he published the best-selling book *Fomos Planejados*, the first book in Portuguese presenting scientific evidence for intelligent design in nature.

Guillermo Gonzalez
Center for Applied Optics,
University of Alabama,
Huntsville, Alabama, United States of America
Email: ggonzo@mac.com
ORCID: not available

Guillermo Gonzalez received his PhD in Astronomy in 1993 from the University of Washington, Seattle, Washington. He has conducted postdoctoral work at the University of Texas, Austin and the University of Washington, and has extensive experience observing and analysing data from ground-based observatories. He has discovered two extrasolar planets and helped develop the concept of the 'Galactic Habitable Zone', which captured the October 2001 cover story of *Scientific American*. Gonzalez has also published over 70 articles in refereed astronomy and astrophysical journals. He is a senior fellow at Discovery Institute's Center for Science and Culture and is has co-authored *The Privileged Planet: How Our Place in the Cosmos is Designed for Discovery* with Jay W. Richards.

Michael N. Keas

Talbot School of Theology,
Biola University,
La Mirada, California, United States of America
Email: mkeas@discovery.org
ORCID: https://orcid.org/0000-0002-5604-4585

Michael N. Keas is a lecturer in History and Philosophy of Science, Talbot School of Theology, in the MA programme in Science and Religion, Biola University, La Mirada, California. After earning a PhD in the History of Science from the University of Oklahoma, Michael N. Keas won research grants from organisations such as the National Science Foundation and the American Council of Learned Societies. He experienced some of the last historic moments behind the Berlin Wall as a Fulbright scholar in East Germany. Keas serves as a lecturer in the history and philosophy of science at Biola University and is on the board of directors of Ratio Christi, an alliance of apologetics clubs on college campuses. He is also a senior fellow of the Discovery Institute. He has numerous publications, including the book *Unbelievable: 7 Myths about the History and Future of Science and Religion* and the essay 'Systematizing the Theoretical Virtues' (downloaded over 11 000 times) in the top-tier philosophy journal *Synthese*. This essay demonstrates that there are at least 12 major virtues of good scientific theories: evidential accuracy, causal adequacy, explanatory depth, internal consistency, internal coherence, universal coherence, beauty, simplicity, unification, durability, fruitfulness and applicability. This has been widely cited in fields such as philosophy, medicine, technology, cognitive science, biology, physics and cosmology.

Casey Luskin

Center for Science and Culture,
Discovery Institute,
Seattle, Washington, United States of America
Email: cluskin@discovery.org
ORCID: https://orcid.org/0000-0002-7329-3321

Casey Luskin holds a PhD in Geology from the University of Johannesburg and a Law degree (Juris Doctor) from the University of San Diego, having served as a California-licensed attorney since 2005. He works as associate director of the Center for Science and Culture at Discovery Institute, helping direct the ID 3.0 Research Program and assisting and defending scientists, educators and students who seek to investigate the scientific debate over Darwinian evolution and intelligent design. He has published in the *South African Journal of Geology* and contributed to or co-authored multiple books, including *Science and Human Origins*; *The Archaean Geology of the Kaapvaal Craton, Southern Africa* (Springer Nature); *Discovering Intelligent Design*; *Theistic Evolution: A Scientific, Theological, and Philosophical Critique*; and *The Comprehensive Guide to Science and Faith*.

Stephen C. Meyer
Center for Science and Culture,
Discovery Institute,
Seattle, Washington, United States of America
Email: stevemeyer@discovery.org
ORCID: https://orcid.org/0000-0003-2912-3971

Stephen C. Meyer received his PhD in the Philosophy of Science from the University of Cambridge. A former geophysicist and college professor, he now directs Discovery Institute's Center for Science and Culture. Meyer has authored the New York Times best-seller *Darwin's Doubt: The Explosive Origin of Animal Life and the Case for Intelligent Design*; *Signature in the Cell*, a (*London*) *Times Literary Supplement* Book of the Year and *Return of the God Hypothesis*, a *USA Today* national best-seller and *World Magazine* Book of the Year. Meyer's other publications include contributions to, and or the editing of, *Debating Design* (Cambridge University Press), *Darwinism, Design and Public Education* (Michigan State University Press) and *Theistic Evolution: A Scientific, Philosophical and Theological Critique* (Crossway). In addition to scientific articles in journals such as Trends in Evolution and Ecology and *The Proceedings of the Biological Society of Washington*, Meyer has published editorials in national newspapers such as *The Wall Street Journal*, *USA Today*, *The Jerusalem Post*, *The Boston Globe*, *The New York Post*, *The National Post* (of Canada), *The Los Angeles Times* and *The Daily Telegraph.*

Brian Miller
Center for Science and Culture,
Discovery Institute,
Seattle, Washington, United States of America
Email: bmiller@discovery.org
ORCID: https://orcid.org/0000-0003-1944-1810

Brian Miller is research coordinator at the Center for Science and Culture, Discovery Institute, Seattle, Washington. He received his BS in Physics from Massachusetts Institute of Technology (MIT) with a minor in Engineering and his PhD in Complex Systems Physics from Duke University. He has conducted pioneering research related to the thermodynamic challenges to the origin of life and into the evidence for design inherent in the minimal requirements for self-replication. He has also conducted key research related to the extreme rarity of amino acid sequences that correspond to functional proteins based on the thermodynamics of protein structures. He is also supervising an engineering research group studying how principles of engineering best explain the organisation and operations of living systems. He has also consulted on organisational development and strategic planning, and he is a technical consultant for The Startup, a virtual incubator dedicated to bringing innovation to the marketplace. He has contributed to multiple books and journals covering the debate over intelligent design, including *The Mystery of Life's Origin: The Continuing Controversy*, *The Comprehensive Guide to Science and Faith* and *Inference Review*.

Fazale R. Rana
Research and Apologetics Scholar Department,
Reasons to Believe,
Covina, California, United States of America
Email: frana@reasons.org
ORCID: https://orcid.org/0000-0002-9827-918X

Fazale R. Rana is the vice president of the Research and Apologetics Scholar Department at Reasons to Believe, Covina, California. He earned a PhD in Chemistry (with an emphasis in Biochemistry) from Ohio University. He received the Clippinger Research award at Ohio University twice. Rana completed two postdoctoral fellowships in the Chemistry Departments of the Universities of Virginia and Georgia. He spent over seven years working in R&D for a Fortune 500 company before joining Reasons to Believe in 1999. While at Procter and Gamble, he was awarded two patents. He has authored or co-authored numerous books that explore the intersection of science and the Christian faith, including *Origins of Life*, *The Cell's Design*, *Creating Life in the Lab*, *Fit for a Purpose*, *Dinosaur Blood and the Age of the Earth*, *Thinking about Evolution*, *Building Bridges*, *Who Was Adam?* and *Humans 2.0.*

Hugh Ross
Reasons to Believe,
Covina, California, United States of America
Email: hross@reasons.org
ORCID: https://orcid.org/0000-0002-0465-3629

Hugh Ross is the founder and president of Reasons to Believe (Covina, California, USA), science professor in residence, Regent University (Virginia Beach, Virginia, USA), adjunct professor in science apologetics, Southern Evangelical Seminary (Charlotte, North Carolina, USA) and minister of apologetics, Christ Church Sierra Madre (Sierra Madre, California, USA). Ross is the founder and president of Reasons to Believe, an organisation that researches and communicates regarding how ongoing scientific discoveries provide increasing evidence for the reliability and trustworthiness of the Bible. After obtaining a PhD in Astronomy from the University of Toronto, Hugh continued his research on quasars and galaxies as a research fellow in radio astronomy at the California Institute of Technology. He has published seven papers in peer-reviewed science journals, authored 21 books on a variety of science-faith topics, contributed chapters to more than a dozen other books and written several hundred articles for magazines and blog sites on scientific evidence for the Christian faith. He has delivered lectures in over 300 university and college campuses and spoken at numerous conferences. At Reasons to Believe, he helps provide leadership to a community of 150 scholars in universities and laboratories around the world.

James M. Tour
Carbon Nanotechnology Laboratory,
Rice University,
Houston, Texas, United States of America
Email: tour@rice.edu
ORCID: https://orcid.org/0000-0002-8479-9328

James M. Tour is the director of the Carbon Nanotechnology Laboratory, T.T. and W.F. Chao professor of Chemistry, professor of Computer Science and professor of Materials Science and Nanoengineering at Rice University, Houston, Texas. James M. Tour, a synthetic organic chemist, has over 600 research publications and over 120 patents with total citations of over 69 000. He was inducted into the National Academy of Inventors in 2015, named among 'The 50 Most Influential Scientists in the World Today' by TheBestSchools.org in 2014, listed in 'The World's Most Influential Scientific Minds' by Thomson Reuters ScienceWatch.com in 2014 and named 'Scientist of the Year' by *R&D Magazine* in 2013.

Frederik (Frik) van Niekerk
Unit for Energy and Technology Systems (UETS),
Faculty of Engineering, North-West University,
Potchefstroom, South Africa
Email: frik.vanniekerk@nwu.ac.za
ORCID: https://orcid.org/0000-0002-3425-8507

Frederik van Niekerk is a professor in the Unit for Energy and Technology Systems (UETS), Faculty of Engineering, North-West University (NWU), Potchefstroom, South Africa. He received his DSc in Nuclear Reactor Science from the former Potchefstroom University for Christian Higher Education (now NWU). He also holds post-graduate qualifications in Physics and Applied Mathematics. He is a member of the Academy of Science of South Africa. He is a former vice-rector and deputy vice-chancellor of the NWU (2001–2017) for research, innovation, information technology and internationalisation. He also serves as contracts director of the Hydrogen South Africa Centre of Competency at the NWU. His previous appointments include an appointment as a scientific collaborator at the Gesellschaft für Reactorsicherheit in München, Germany and senior positions in South Africa at the Nuclear Energy Corporation of SA, Denel Aviation on the Rooivalk Mission Helicopter programme and the Pebble Bed Modular Reactor company as the main power systems engineering manager.

Synopsis

Frederik van Niekerk,
Unit for Energy and Technology Systems (UETS),
Faculty of Engineering, North-West University,
Potchefstroom, South Africa

Science and Faith in Dialogue presents a cogent, compelling case for concordance between science and theism. Based on scientific and natural theological perspectives, two pillars of natural theology are revisited: the cosmological argument and the argument from design. Modern science provides undeniable evidence and a scientific basis for these classical arguments to infer a rationally justifiable endorsement of theism as being concordant with reason and science – nature is seen as operating orderly on comprehensible, rational, consistent laws, in line with the conviction that God is Creator. The contemporary cosmological consensus, building upon the rigour of the physical sciences, provides overwhelming evidence in support of theism. Similarly, illuminating discoveries in the biological sciences provide powerful evidence in support of theism.

Broad outline: Chapters support this central theme and provide complementary perspectives to support the premise of the research. The first two chapters (Stephen C. Meyer and Frederik van Niekerk) provide mutually supportive philosophical and natural theological views of various aspects of the dialogue. Hugh Ross and Guillermo Gonzalez describe global and local fine-tuning, ranging from the macro-cosmos to the local galaxy, the solar system and a habitable planet Earth. Fazale R. Rana, James M. Tour, Brian Miller and Marcos Eberlin elucidate various aspects of the origin of life and of foresight and design in nature, including the implausibility of naturalistic explanations. Casey Luskin provides a review of the failure of contemporary evolutionary models of palaeoanthropology, archaeology, genetics and psychology to account for human origins. Historian Michael N. Keas presents an overview of myths that have ostensibly contributed to the conflict thesis between science and religion, seemingly ingrained in present-day scholarship.

Logical fallacies and false dichotomies in the science and faith debate: impact on world view and public opinion contrasts ontological naturalistic arguments against theistic arguments, based on divergent assumptions regarding reliable sources of knowledge and truth, rationality, justification for claims such as falsifiability, tacit extrapolation of scientific findings beyond their proven validity range, logical fallacies (such as incorrect use of infinite regress arguments) and (for Christian scholars) different views of scripture and hermeneutic tradition. These divergent points of departure influence

How to cite: Van Niekerk, F 2022, 'Synopsis', in F van Niekerk & N Vorster (eds.), *Science and Faith in Dialogue*, in Reformed Theology in Africa Series, Vol. 10, AOSIS Books, Cape Town, pp. xxvii–xxxix . https://doi.org/10.4102/aosis.2022.BK334.00

worldview and public opinion and often lead to discordant dialogue, unscientific conjecture and false dichotomies between science and faith.

Classical and contemporary versions of the cosmological argument are discussed from philosophical natural theological perspectives. It is contended that theism provides a cogent and compelling explanation for the universe and sentient life in harmony with the findings of modern science. A deeper concordance is found between science and theism through proper science and philosophical reasoning, even in cases of superficial or apparent conflict. Enlightenment-spawned ideas and many of the contemporary philosophical objections to the cosmological argument or the argument from design are shown to be weak, overstated and that alternative naturalistic theories purported to provide explanations lack explanatory power.

Alternative explanations for the beginning or existence of the universe (eternal universe, multiverse, self-contained universe, cyclical universe, a universe from 'nothing') are not considered legitimate topics of scientific inquiry, are based on philosophical speculation and some rest on fallacies. Classical versions of the argument from design culminate in powerful contemporary versions, by considering biological fine-tuning and the intrinsically linked arguments from biological information and the argument from irreducible complexity.

The science-faith dialogue invariably influences worldview and public opinion. The chapter concludes by critiquing scientism, overreach and lack of rigour in ontological naturalistic reasoning. With the scientific method as a yardstick, the rigour in the physical sciences is contrasted against the hypocritical science underpinning macroevolution (notwithstanding its compatibility with theism), which lacks consistency, explanatory power and the rigour associated with the scientific method. The impact of unabated ontological naturalism in public opinion and worldview is illustrated.

Stephen C. Meyer argues in *Qualified agreement: How scientific discoveries support theistic belief* that the demise of theistic arguments from nature and the corresponding rise of a scientifically based materialistic worldview, fostered a profound shift in the way many scientists and scholars conceptualised the relationship between science and Christian faith or theistic belief. With the rise of scientific materialism or naturalism, during the 20th century many scientists, philosophers and even theologians began to perceive science and theistic belief as standing in conflict with one another. Scientific origins theories in particular seemed to support the materialistic vision of an autonomous and self-creating natural world. Darwin's evolutionary theory sought to show that the blind process of natural selection acting on random variations could and did account for the origin of new forms of life without any discernible guidance or design.

Meyer contends that the testimony of nature (i.e. science) actually supports important tenets of a theistic or Christian world view and reasserts the view that scientific evidence does provide epistemological support, (though not proof), for the theistic world view affirmed by biblical Christianity. He develops a model of the relationship between science and theistic belief termed 'qualified agreement' or 'mutual epistemic support' according to which scientific evidence and biblical teaching can and do support each other. In spite of superficial disagreement because of the limits of human knowledge, advocates of this model affirm a broad agreement between the testimony of the natural world and the propositional content of Judeo-Christian theism – between science and religion so defined.

Unlike the conflict model, qualified agreement denies that the best or most truthful theories ultimately contradict a theistic or Christian worldview. Instead, it views theological and scientific truth as issuing from the same transcendent and rational source, namely, God. Advocates of qualified agreement anticipate, therefore, that these two domains of knowledge, when rightly understood and interpreted, will come increasingly into agreement as advances in science and theology eliminate real points of conflict that have sometimes existed.

The chapter supports the *Return of the God Hypothesis*. Meyer updates the case for this view by giving examples of contemporary scientific evidence from cosmology, physics and biology in support of a theistic worldview and provides a more refined notion of epistemological support for Christianity or theism. His elucidating explanation of anthropic fine-tuning and of general relativity and the Big Bang Theory, which provide a scientific description of the origin of the universe not dissimilar to what Christian theologians have long described in doctrinal terms as *creatio ex nihilo* – creation out of nothing (or nothing physical), shows that these theories place a heavy demand on any proposed materialistic explanation of the universe as they imply that any proposed cause of the universe must transcend space, time, matter and energy. Meyer refutes alternative explanations of fine-tuning (such as the multiverse) that rest on speculative cosmologies (string theory and inflationary multiverse) by showing that these theories require prior fine-tuning.

The chapter presents evidence of intelligent design (ID) in biology by detailing the intricate information and information-processing systems in DNA (deoxyribonucleic acid) and contends that ID rests on recent scientific discoveries and upon standard methods of scientific reasoning in which our uniform experience of cause and effect guides our inferences about what happened in the past. Meyer presents a *mutual epistemic support model* of the relationship between science and theistic belief based on confirmation of hypothesis and explanatory power, rather than just deductive entailment, to demonstrate how recent developments in modern science provide such support for theism, by inference to the best explanation.

The spectrum of arguments presented to support the cosmological argument and the argument from design range from the macro-cosmos and the beginning of the universe to 'local' cosmological considerations, to the intricacies of biological life and the basic chemistry of life:

Hugh Ross' *Cosmological fine-tuning* of the large-scale structure of the universe, the Laniakea Supercluster, the Virgo Cluster the Local Group of galaxies, the Milky Way Galaxy (MWG) and the local galactic neighbourhood illustrate the ubiquitous nature of exquisite cosmic fine-tuning (at *all* scales) and the steady growth of evidence for this fine-tuning suggests that every component of the universe and every event in the history of the universe co-determine human life and global civilisation on Earth.

The range of fine-tuning parameters includes more than 140 specific features of the universe as a whole and of the laws of physics governing the universe that must be carefully fixed within an exquisitely narrow range of variance to make advanced life possible – the entire universe must be precisely the way it is to give rise to the possibility of even one planet on which advanced physical life can potentially exist.

The cosmic history had to be fine-tuned, and evidence reveals fine-tuning on the large-scale universe and even more so on smaller scales. Exquisite fine-tuning is revealed for the total quantity of matter, the ratio of baryonic to dark matter quantities, the cosmic expansion rate, the strength of intergalactic magnetic fields, the moving apart of galaxy clusters and galaxies within them, by the just-right distances at the just-right times in the universe's history to allow for the possible future existence of advanced physical life.

Low-mass dwarf galaxies in the Local Group of galaxies are the oldest, least chemically enriched, most gas-rich and most dark-matter-dominated stellar systems known as yet. The Local Group's precise gas content, the relative abundance of elements in the Group's dwarf galaxies, the unique population, demographics and spatial distribution of the larger and smaller dwarf galaxies, as well as remnant gas streams and clouds, *all* factor into the MWG's capacity to host advanced life. The MWG is exceptional among spiral galaxies in that very little of its total mass is in the form of ordinary matter. Its supermassive black hole (SMBH) is 35 times less massive than SMBHs in other similarly sized spiral galaxies. The activity level just outside the event horizon of the MWG's SMBH has been exceptionally low throughout the past 12 000 years, the same era during which human civilisation has evolved and sustained.

The MWG is unique in multiple respects, all of which bear on its capacity to host advanced life. The long list of extraordinary advanced-life-essential features includes its ratio of stellar mass to total mass; its dark matter halo and gas disk; its bar-bulge structure; its star distribution; its astonishingly small, extremely quiescent SMBH; its inventory of elements; the relative dimensions of its thin disk and thick disk; its number of spiral arms and their precise pitch angle; the symmetry of its spiral arms; its few spurs and feathers between spiral arms and its green hue from a balance of old, middle-aged and young stars.

Localised Fine-Tuning (by Guillermo Gonzalez) considers how sensitive the habitability of a planet is to changes in its properties and those of its environment and illustrates that Earth's rare habitability is not only fine-tuned for life but also for scientific discovery. The chapter rules out probabilistic explanations for local fine-tuning and Earth's habitability from the observed number and diversity of other planetary systems in the cosmos.

Local fine-tuning considers planets, stars and galaxies and their properties that vary over a broad range. Life's dependency on local parameters can be studied while keeping the global parameters fixed – the aim is to accurately quantify the available probabilistic resources and to estimate how much of our local circumstances can be explained by observer self-selection.

Gonzalez explains the Circumstellar Habitable Zone (CHZ), with its focus on habitability within planetary systems, the Galactic Habitable Zone (GHZ), which describes habitability on the scale of the MWG and the Cosmic Habitable Age (CHA), which describes the evolution of the habitability of the universe over time) and elucidates the awe-inspiring intricate fine-tuning in conditions needed for life.

The CHZ (i.e. the range of distances from the Sun that an earth-like planet must be within to maintain liquid water on its surface) has been an important unifying concept in astrobiology, combining knowledge of stellar evolution, planetary dynamics, climatology, biology and geophysics. The GHZ is based on a very different set of physical processes, including the radial gradients of the supernova rate, gas metallicity, density of gas and density of stars in the galactic disk.

In studying the habitability of a planet, the basic needs of life and the conditions to sustain life are defined. These conditions are constrained most fundamentally by limits on the planet's mean surface temperature, the presence of liquid water and the composition of its atmosphere. In addition, constraints on the temporal and spatial variations of a planet's surface temperature play a vital role – a slowly rotating earth-like planet, for example, will experience greater temperature variations than a similar but faster-rotating planet with the same mean temperature. Gonzalez rules out the idea of observer bias, based on evidence from chemistry, which lends support to the view that liquid water and carbon are essential for life. In addition, single-celled life requires some 16 elements, and mammals require an additional 10 for essential biological processes, all of which must be cycled in the environment.

While photosynthesis is not the most basic form of habitability, it is one that has existed on Earth since very early times and has proven critical for the oxygenation of the atmosphere. Following others, Gonzalez proposes that a Basic Habitability Index (BHI) be adopted as a measure of habitability. In addition, a habitability index for earthly animal life, the Animal Habitability

Index (AHI, describing large, oxygen-breathing, mobile metazoans), can be defined. An earth-*like* planet is defined as a terrestrial planet with surface water, dry land and geophysics similar to the earth.

Gonzalez contends that the definition of the CHZ depends on much more than just the flux of radiation a terrestrial planet receives from its host star. A terrestrial planet's habitability also depends on its orbital eccentricity, presence of a large moon, size, initial volatile inventory, initial rotation period and its evolution, the locations and properties of any giant planets, the distributions of small bodies and the host star's modulation of the cosmic ray flux.

The evolution of the GHZ is determined by factors including interstellar gas metallicity (which should reach a value close to solar metallicity), the distribution of radiation hazards, interstellar clouds and comets. Threats to life increase towards the centre of the Galaxy and decrease with time. The greatest uncertainty about the GHZ concerns stellar dynamics and how a given star's orbit interacts with the spiral arms.

Gonzalez illustrates the intricate fine-tuning of the CHA, which makes it unlikely that another 'island of habitability' will be found in parameter space. If, for example, Earth had formed 20% farther from the Sun, it would still be within the traditional CHZ, but it would be subjected to a different asteroid and comet impact rate, different gravitational perturbations to its orbit and rotation and different exposure to interstellar clouds and cosmic ray flux, and it would have needed more carbon dioxide in its atmosphere to maintain liquid surface water. Similar arguments apply to the type of host star, the location within the Milky Way and to the type of galaxy. Processes that affect planetary habitability are intertwined in a complex web that sets severe constraints.

The implications for global fine-tuning are severe. Upon establishing the kinds of habitable environments, the effect of changes in the global parameters on habitability at the local scale can be studied. As an example: the carbon/oxygen (C/O) ratio in condensed solids varied with the location in the early protoplanetary disk and correlates with metallicity, which is linked to the strong nuclear force. If the C/O ratio at a given location and time differs from the Solar System value, other aspects of the environment are also likely to differ. Metallicity is a critical parameter in determining whether a system is habitable. A region with a C/O ratio different from the Sun will likely also have a different metallicity.

Changing the strong force has other local effects, such as nuclear reactions in stars and the stability of nuclei and thus the length of the periodic table. The other forces also display multiple sensitivities. Changing the weak force strength affects the relative amounts of hydrogen and helium produced in the first few minutes after the Big Bang, the fusion reactions inside stars, the explosion of massive stars as supernovae and the decay of radioactive isotopes. Changing the electromagnetic force changes of the entire chemistry and all processes involving the interaction of light with matter. If gravity is changed, planets, stars, galaxies and the large-scale dynamics of the universe will change.

Gonzalez asserts that 'multiple global tuning', that is local and global fine-tuning, combined with the complex web of interdependent habitability factors, makes it even less likely that changes in global parameters will result in another island of habitability. High specificity and interdependence of the local parameters required for a habitable environment make it unlikely that environments significantly different from ours will be as habitable.

In *Material and theistic perspectives on the origin of life*, Fazale R. Rana posits that, despite the expansive range of ideas encompassed by chemical evolution (more than 150 years of exploration of chemical evolutionary explanations of Darwin's 'warm little pond' and extensive contemporary origin-of-life research), a materialistic approach to the problem has yielded little true insight into the process of abiogenesis. A growing minority of scientists and philosophers now support the possibility that a teleological approach, which appeals to the work of an intelligent agent, may lead to a solution to the origin-of-life problem.

Most scientists strongly resist any suggestion that life's origin stems from the work of God and regard an appeal to agency as a violation of the key tenet of methodological naturalism. In response, Rana advances two theistic approaches to the origin-of-life question that make it possible to entertain a role for the divine agency while providing the means to investigate the origin-of-life question scientifically.

One of these approaches arises out of the recently acknowledged problem of unwarranted researcher involvement in prebiotic chemistry and the other stems from some provocative work that suggests the anthropic principle may manifest in prebiotic chemistry.

Rana presents a brief of history of the origin-of-life research, in which he identifies an unwavering commitment to methodological naturalism and the pursuit of an exclusively materialistic explanation to life's origin since Darwin. In his illuminating exposition of contemporary origin-of-life research, he contends that the role of the researcher in prebiotic chemistry mimics that of an intelligent *agent*, a designer and actor in intricate procedures and protocols to achieve outcomes that are only a *fraction* in terms of what is needed to render first life. The implication is that a purely naturalistic explanation of life fails dismally and that even in such rudimentary demonstrations, intelligence is needed. Rana builds upon the concept of hypernaturalism, which he believes removes the dichotomy between the natural process of chemical evolution and the reliance on the divine agency.

There appear to be constraints on prebiotic chemistry that inevitably lead to the production of key biotic molecules with the just-right properties that make them unusually stable and ideally suited for life. This remarkable coincidence suggests a fitness for purpose to prebiotic chemistry, that is there appears to be a teleology to prebiotic chemistry, suggesting that the laws of physics and chemistry may well have been predetermined at the onset to ensure that life's building blocks naturally emerge under the conditions of early Earth.

These two approaches build upon his and others' previous work of ID, while opening up new research vistas that encourage genuine dialogue between origin-of-life investigators steeped in materialism and Christian theists who see agency as an integral aspect for the explanation of life's genesis on Earth.

Rana argues that growing evidence and insight into the origin-of-life question points to the necessity of a Creator, whether the Creator chose to intervene directly to create the first life forms or whether he rigged the universe in such a way that life would inevitably emerge because of the design and constraints imposed by the laws of nature.

In *Are Present Proposals on Chemical Evolutionary Mechanisms Accurately Pointing toward First Life*, James M. Tour contends that much of the current proposals for abiogenesis (the prebiotic process wherein life, such as a cell, arises from non-living materials such as simple organic compounds) seem to be directed down paths of futility despite hyperbolic claims to the contrary. The implication of a naturalistic view is that the origin of first life, that first cell, would have to come from some simpler non-living molecules (carbohydrates, nucleic acids, lipids and proteins) long before evolution could even begin. Tour describes the process by which organic synthesis is performed and the considerations required to synthesise a complex system where many molecular parts come together to operate concertedly, by reference to the synthesis of nanomachines. He considers some proposals that some researchers espoused for the synthesis of carbohydrates and carbohydrate-bearing nucleotide bases, from a prebiotic milieu. He expounds the obstacles to the much more difficult task of having the molecular building blocks assemble into a functional system and presents the researchers' own data as the strongest evidence against the proposals of current prebiotic research. Tour asserts that from the data, the synthetic chemist can easily deduce the fact that under prebiotic conditions the reaction in question is not likely to yield anything useful. With each added step, difficulties are compounded by improbabilities that are so overwhelming that no other field of science would depend on such levels of faith. In his opinion, abiogenesis research would never be accepted in any other area of chemistry.

The next level of complexity is building a cell and self-assembling protocells. Tour contends that origin-of-life research has failed dismally and that we cannot explain the mass transfer of starting materials to the molecules needed for life; the origin of life's code; the combinatorial complexities present in any living system and the precise nonregular assembly of cellular components. He concludes by proposing that students be exposed to the massive gap in our current understanding, which may lead them to consider alternative explanations.

In his chapter, *Engineering principles better explain biological systems than evolutionary theory*, Brian Miller elucidates the increasing trend of recent discoveries that have forced biologists to replace evolutionary assumptions with design-based assumptions, language and methods of investigation. This trend is to a large extent driven by the observation that the same engineering motifs and patterns employed in human creations are pervasive in living systems. What is becoming increasingly clear is that engineering principles explain nearly every aspect of life far better than evolutionary theory. This conclusion perfectly coincides with the central Christian doctrine that life was designed by God and was not an unintended accident of nature.

In spite of the explanatory deficits of neo-Darwinism (also known as Modern Synthesis), most materialist biologists display a reticence to admit the predicament, as evolution operates not only as a scientific theory but as a sacrosanct creation narrative for a secular society. Despite the hesitancy to question the official scientific orthodoxy, a scientific revolution, systems biology (the study of higher-level organisation of living systems by biologists and engineers), has emerged. Their discoveries have forced them to replace historic evolutionary assumptions with design-based assumptions, language and methods of investigation.

The traditional approaches implemented in biological research were founded on reductionism, a notion that systems biologists reject because of its lack of explanatory power of complex organisation of living systems. Life must be viewed as a collection of integrated systems composed of integrated components where the whole is greater than the sum of the parts (also known as holism). Michael Behe's concept of irreducible complexity has implicitly become a central tenet of the field. Science is proving that teleology is central to life.

The underlying logic of evolutionary models predicts that suboptimal design and non-functional remnants of organisms' evolutionary past should litter the biosphere and has an expectation of poor design, such as the notion of 'junk' DNA. In stark contrast to evolutionary predictions, mounting evidence demonstrates that life consistently demonstrates optimal design. Systems biologists increasingly recognise that assuming optimal design leads to the most productive research. DNA replication and translation, embryological development and sensory processes operate at efficiencies close to the limits of what is physically possible. Human engineering pales in comparison to such achievements.

Evolutionary theory predicts that biology should resemble human engineering only marginally at best. The underlying logic dictates that the components of complex biological structures and traits came together haphazardly without the benefit of foresight or goal-direction by an intelligent agent. In contrast, systems biologists now recognise that biology demonstrates top-down design where an overarching goal and corresponding design constraints dictate the engineering of a complex trait. Each component of a structure or system perfectly integrates with other members to achieve a predetermined goal with astonishing efficiency.

Biology does not simply resemble human engineering generically, but it contains the very same design frameworks. Design motifs employed in life are known to represent the most effective strategies for achieving target goals. Not only does engineering embody ID, but engineers have developed a deep intuition of what incremental processes can and cannot achieve. And they recognise that the design patterns pervasive in life could not possibly have emerged through any gradual, undirected process.

In response, biologists wedded to scientific materialism have argued that life is so different from human artifacts that they can dismiss engineers' conclusions about organisms' limited evolvability. The central fallacy in this argument is that nearly every difference between human creations and life makes the latter ever more challenging to design. And the challenges translate into more daunting obstacles for any evolutionary scenario.

An engineering or design inference is reinforced by the fossil record. Where the evidence is most abundant and clear, species are only observed to change during their tenure on Earth within the constraints of the predefined adjustable operational parameters. As mentioned, anytime a new species appears with a new logic or architecture, it always appears abruptly without transitional forms leading back to a fundamentally different ancestor.

Over the past few decades, every facet of the engineering model has been increasingly affirmed. One engineering model for adaptation assumes that organisms adapt to the environment using the same engineering principles seen in human tracking systems. The strongest supportive evidence comes from studies of what have been termed natural genetic engineering (NGE) and phenotypic plasticity (which refers to an organism's ability to transform its anatomy and physiology in response to environmental stimuli).

Observed variation in all the most iconic model organisms (e.g. fruit flies, cichlids, stickleback fish, cavefish) purported to support evolutionary theory is now known to support engineering-based model predictions.

Engineering models' explanatory and predictive power is particularly well illustrated by the minimally complex cell and the bacterial flagellum. The two chapters by Tour and Rana detail the implausibility of a cell ever originating through undirected natural processes. Miller, a recognised authority on the implications of the second law of thermodynamics on ID, sees insurmountable thermodynamic challenges to a chemical system spontaneously coalescing into an autonomous cell. In contrast, engineering analyses elucidate the underlying architecture and design logic of all cells with remarkable accuracy.

In *Evidence of Foresight in Nature*, Marcos Eberlin asserts that nature demonstrates foresight where ingenious solutions were devised to confront problems and challenges related to sustaining and propagating life. This is exemplified by the cell membrane, the genetic code, bacteria acting as ecosystem engineers, bird navigation, water and our planet. Eberlin contends that this evidence points to life not resulting from blind, undirected processes but to every aspect of nature being designed by God.

Eberlin observes that life is full of solutions whose needs have to be predicted to avoid various dead-ends; that is, many biological functions and systems require planning to work. Anticipation of problems before they arose, the ingenuity evident in those solutions and the need for the orchestrated, simultaneous delivery of multiple, fully functioning components right from the beginning of a given system pose a significant challenge to blind evolution. And not just blind evolution but the materialism that undergirds it, for foresight requires something more than matter in motion. Foresight is a hallmark of the mind.

Eberlin elucidates several examples that illustrate the undeniable evidence of foresight in nature. The multi-tasking cell membrane with its phospholipids and aquaporins and intriguing proton wires are irreducibly complex structures for life, required foresight, purpose and design. Incremental natural selection offers no plausible explanation for such foresight and complex designs.

He provides an enlightening description of foresight in DNA. If it is to be viable, life's long-term storehouse of genetic information should not break down in the presence of water. The hydrolysis problem, in other words, has to be solved in advance or life's information storehouse would dissolve. How DNA meets this challenge is a wonder of engineering finesse. Polymeric DNA, with its multiple phosphate–sugar bonds and very slow kinetics, and the proper enzymes (large, exquisitely designed biomolecules) to accelerate the formation of the DNA phosphate–sugar bonds have to be in place at the same time. Enzymes would have been needed from the very beginning to make DNA. Yet enzymes have to be made using the DNA sequence they participate in making. Ribose has to be both stable and capable of carrying the genetic code. It is also ideal for forming a three-dimensional (3D) molecular structure. The genetic redundancy in DNA, its unique bases, regulation of protein synthesis tempo, sensitivity to environmental stimuli, safeguards against single-point mutations are all examples of foresight without which life would not have been possible. With its double-helix structure, DNA is the most efficient, most protected, best calibrated in terms of chemical stability and most compact form of information-storage known on the planet.

The marvellous examples of foresight include microbes (with its cause-effect paradox), anammox (producing high-energy content fuel), quantum entanglement in birds' 'GPS'-like navigation capability, the remarkable characteristics of water, our atmospheric composition and the ozone layer, elegantly elucidated.

These examples far exceed in sophistication any examples of engineering foresight that we could point to in human culture. Eberlin asserts that whether the evidence points to primary causation, secondary causation or a combination, it still follows that a mind was required to foresee the many potential dead-ends and escape them. Life and the universe are full of these clever escapes and ingenious solutions that speak strongly in favour of ID.

In Chapter 9, *Evolutionary Models of Palaeoanthropology, Archaeology, Genetics, and Psychology Fail to Account for Human Origins: A Review*, Casey Luskin reviews and questions the modern consensus of palaeoanthropology. He illustrates the extremely rich history of paleoanthropological research in South Africa (which he hails as the birthplace of the field of palaeoanthropology) by referring to the premiere palaeoanthropology Maropeng Museum located at the Cradle of Humankind World Heritage Site just north of Johannesburg. As estimated, 48% of all hominid fossil finds worldwide come from South Africa.

Luskin contends that the 'evidence' for many of the claims made by materialist evolutionists rests on dubious findings, such as the claim that *Homo sapiens* evolved from ape-like species through apparently unguided processes driven by natural selection acting upon random mutations.

In particular, Luskin elucidates the failure of evolutionary models to account, for example, the large unbridged morphological and temporal gaps between human-like members of the genus *Homo* and their supposed australopithecine ancestors. In spite of significant South African fossil finds (adding to the fragmented hominin fossil record) over the past two decades (e.g. *Australopithecus sediba* and *Homo naledi*), this long-recognised conundrum is left unresolved. He also notes the abrupt 'explosion' of human creativity about 30–40 thousand years ago in the archaeological record is unanticipated by previous evolutionary trends.

Based on the numerous genetic and morphological differences between humans and chimpanzees, the roughly 6 to 8 million years allowed for human evolution from our most recent common ancestor with chimpanzees is insufficient time for necessary genetic mutations to arise blindly and become fixed into our lineage. Traditional 'junk DNA' models of evolutionary genetics have failed to predict the mass functionality in non-coding portions of the human genome.

Luskin questions the imprint of materialistic reasoning by illustrating the approach in a prominent South African museum, hailed as one of the best displays in the world, which claims that human beings are mere 'survival machines'. He contends that multiple converging lines of evidence contradict evolutionary psychology models and suggest humans were designed for purposes higher than simply passing on our genes. Given the ensemble of evidence pointing towards the design of the human species, and South Africa's prominence as a world centre of excellence in palaeoanthropology research, Luskin suggests that South Africa may wish to consider its paleoanthropological roots that in the past have affirmed ID.

In conclusion, historian Michael N. Keas debunks six myths in *Rumors of War and Evidence for Peace between Science & Christianity* – myths that have ostensibly contributed to the conflict thesis between science and religion, seemingly ingrained in present-day scholarship. Powerful evidence for peace between science and Christianity is provided in cogent and novel historiographic perspectives. The historical misrepresentations include myths such as that Christianity produced years of anti-science; ignorance (taken from incorrect literalistic reading of Scripture) regarding the shape and size of the earth; our status in the cosmic centre and hence confidence in a divine plan for humanity; the Galileo affair and misrepresentations regarding the religious convictions of famous scientists. He illustrates that the vast majority of scientists who laid the foundations of modern science were theists or had theistic convictions. Keas contends that the evidence for peace between Christianity and science is substantial.

Chapter 1

Logical fallacies and false dichotomies in the science and faith debate: Impact on worldview and public opinion

Frederik van Niekerk
Unit for Energy and Technology Systems (UETS),
Faculty of Engineering, North-West University,
Potchefstroom, South Africa

> 'In so many ways, the same impulse to know the world and our place in it is at the roots of both science and spirituality. Both are attempts to illuminate the mysteries of our world and expand our vision of the greater whole [...] Throughout history, scientific discovery has brought us closer to the wonders of life and the universe – and immeasurably deepened our appreciation for creation. It engages the world and inspires the best in us. But the pursuit of truth should not be driven by zealous agenda. Nor should it overreach and speak with righteous authority where it's on unsolid ground. That's not science – and let's not allow those who falsely invoke its name to diminish us.' (Aczel 2014, p. 175)

How to cite: Van Niekerk, F 2022, 'Logical fallacies and false dichotomies in the science and faith debate: Impact on worldview and public opinion', in F van Niekerk & N Vorster (eds.), *Science and Faith in Dialogue*, in Reformed Theology in Africa Series, Vol. 10, AOSIS Books, Cape Town, pp. 1–31. https://doi.org/10.4102/aosis.2022.BK334.01

Introduction

This chapter explores some of the underlying epistemological assumptions and points of departure underpinning much of the recent science-faith dialogue, which ranges from coherent, enriching, concordant views on the relation between faith and science to disharmonious debate and conflict. Discordant dialogue and unscientific conjecture, often misrepresented as scholarly in the media, sustain false dichotomies between science and faith and inevitably influence worldview and public opinion.

The science-faith dialogue is characterised by varying underlying philosophical frameworks and traditions, assumptions regarding what constitutes reliable sources of knowledge and truth, rationality and justification for claims such as falsifiability, tacit extrapolation of scientific findings beyond their proven validity range, logical fallacies (such as incorrect use of infinite regress arguments) and (for Christian scholars) different views of scripture and hermeneutic tradition.

The success and standing of naturalism are largely attributable to the successes of methodological natural science – the scientific method and empirical verification – which originated during the Scientific Revolution, with significant contributions by many prominent Christian scholars. Naturalism claims to preclude sources of knowledge and truth other than the natural world and hence precludes time-honoured ontological arguments for the conclusion that God exists. Yet, attempts are made in ontological naturalism to incorporate arguments for questions previously not asked by methodological naturalism. Two examples are used to illustrate overreach and lack of rigour in ontological naturalistic reasoning: biological evolutionism and atheistic arguments involving the origin and unfolding of the universe. The pseudo-religious add-ons of ontological naturalism are highlighted. When the distinction between rigorous logic and overreaching conjecture is lost, the integrity of science is compromised.

This chapter contrasts ontological naturalistic arguments against theistic ontological arguments by referring to recent scientific advances and discoveries in the natural world. It is argued that undeniable and compelling evidence for the cosmological argument and the argument from design is revealed in nature. The discovery that the universe had a beginning, the abundant scientific evidence for global and local fine-tuning expressible in physical, chemical, geological and biological fundamentals and the irreducible complexity of life on Earth are used to contrast a naturalistic and a theistic worldview.

Philosophical traditions and worldview

The classical conception of philosophy

In *The Rediscovery of Wisdom*, philosopher David Conway (2000) restates the value of the *classical conception of philosophy as* literally the 'love' (*philo* in Greek) of 'wisdom' [*sophia*], the attainment of *sophia* or theoretical wisdom, that is, a knowledge of the world and why it exists. The cogency of the philosophical arguments undergirding this view can be defended (even) without relying on any claims of revelational theology (which is often met with intellectual scepticism, inter alia because of the disparate claims of religions). The *classical conception of philosophy*, with its core theistic doctrine, formed the anchor of Western civilisation for several centuries, notably since the adoption of Christianity by the later Roman Empire as its official religion. It agrees with Christianity in the assumption that the explanation for the natural world is divine.

How did the philosophic framework of the (Western) world digress to lose its once formidable truth and wisdom-seeking *philosophia*? This *philosophia* was once in harmony with theism and science, inspiring the greatest minds of all times, who stood in awe of both the *Book of God's words* (Scripture) and the *Book of God's works* (nature), a metaphor attributed to Sir Francis Bacon (Bacon, Spedding & Ellis 1884). Stephen C. Meyer elucidates the demise of theistic arguments in his chapter in this book.

During the ages, there was overwhelming concordance between philosophers, scientists and theologians in their quest for understanding nature and the value and meaning of life. The greatest scientists were often mathematicians, philosophers and theologians. Augustine asserted a close affinity between Platonism and Christianity. In his *Concerning the City of God against the Pagans*, he observed (Augustine n.d.):

> [*W*]e rate the Platonists above the rest of the [*pagan*] philosophers […] [*because*] the Platonists, coming to a knowledge of God, have found the cause of the organised universe, […] and the spring which offers the drink of felicity. All philosophers who have this conception of God are in agreement with our idea of him. (n.p.)

Aristotle equates wisdom with his description of science or knowledge as 'the most divine science' and states as rationale that 'God is thought to be among the causes of all things and to be a first principle' (Aristotle 1928, p. 980).

Science, philosophy and theology remained in relative harmony throughout the medieval period. Although basic religious tenets were challenged during the Scientific Revolution, science posed no immediate challenge to God's existence. Natural theology blossomed – apologists for Christianity (e.g. Bacon, Copernicus, Galileo, Kepler, Newton, Leibnitz, Boyle, Pascal, Faraday, Euler, Dalton, Ampere, Riemann, Maxwell, Joule, Stokes, Kelvin, Röntgen to name but a few) found a new rational basis for their religious convictions, a rational basis that at the same time led them to challenge those religious convictions based purely on doctrine. In a sense, a seminal idea of the Enlightenment took root – the breaking away from doctrine as a primary carrier of truth. The apologists for Christianity found harmony between their spiritual convictions and the 'new science' by looking at the Bible as God's specific revelation and nature as God's general revelation. For these apologists, any discrepancy between science and faith could only be apparent; whenever Scripture was in disagreement with empirical fact, biblical narratives were reinterpreted in non-literal reading to be reconciled with the new science. At the same time, religious convictions obtained a rationally unimpeachable endorsement as being concordant with reason – nature was seen as operating orderly on comprehensible, rational, consistent laws, in line with the conviction that God is Creator.

Enlightenment-spawned ideas

During the period prior to and during the Enlightenment, scientific discoveries and philosophical development spawned new philosophical ideas and growing secularisation ensued. Many aspects of what was traditionally the domain of the Church (and classical philosophy) were increasingly subjected to challenge when scientific perspectives emerged, with implications for worldview. The epitome of the process was reached during the Enlightenment. During the early period of the Enlightenment, scepticism towards institutionalised authority was directed at the institutionalised church – it was not a reaction against religion per se. During the period, doctrinal strife and drawn-out (religious) wars of the past were ostensibly substituted by philosophical intellectual controversy.

With the newly awakened and highly self-confident reason associated with the Enlightenment, mounting the successes of scientific advances, it became commonplace to frown upon past superstition and myths (which for some included organised Christianity). Enlightenment scepticism towards organised Christianity subsequently intensified among philosophers, culminating in many cases in militant atheism, which questions the importance of truth and worldview.

Conway (2000) contends that the present-day philosophical landscape in the developed Western world seems to be dominated by naturalism and anti-realism, all of which constitute philosophical paradigms that share in unabated secularisation of thought and a common antipathy towards Christianity and any other form of religion. Since the onset of naturalism, atheism has been on the rise. The persistent critique of religion, by Karl Marx (in sociology), Sigmund Freud (in psychology) and Friedrich Nietzsche (in philosophy) was largely responsible for the rise of modern atheism. Immanuel Kant attempted to create a universal ethics based on reason alone but was not hostile towards religion. These philosophers, together with many latter-day philosophers, attempted to erode the basis of natural philosophy by formulating objections to what had hitherto been arguments of natural theology, of which the cosmological argument and the argument from design have been two main pillars.

In the naturalistic viewpoint (Masterson 1973):

> [*T*]here is neither any basis nor any need to go beyond the world of experience and scientific explanation for an ultimate account of the meaning and value of reality in general and of human existence in particular. (p. 99)

According to Christian philosopher Alvin Plantinga (1992), this viewpoint holds that:

> [*T*]here is no God, nor anything else beyond nature; and we human beings are insignificant parts of a vast cosmic machine that proceeds in majestic indifference to us, our hopes and aspirations, our needs and desires, our sense of fairness and fittingness. (p. 296)

Putting man rather than God as central, atheist humanism relates the dignity of the individual to rational capacities and accentuates the human's individual and social potential and agency rather than looking at spiritual arguments based on religion for moral and philosophical inquiry. Naturalism proposes that problems can be resolved solely through science and reason. Many contemporary philosophers mistakenly find only these approaches acceptable, which, since the Enlightenment, seemingly overshadow the classical and Christian viewpoint.

Another idea is anti-realism, which asserts that only the natural world exists, but it differs from naturalism by asserting that nature is ontologically dependent on humans. Anti-reality maintains that reality is established by one's own mental activity – it does not really exist. One variety of anti-realism is moral anti-realism, denying the existence of normative facts or objective moral values. Anti-realism has also spawned post-modernism, with its relativistic nihilistic outlook on truth and value. Logical positivism views scientific knowledge as the only kind of factual knowledge and holds that metaphysical doctrines are futile.

These jaundiced intellectual (in)sensibilities seem to have lost the love of wisdom and are (in my opinion) in need of serious rehabilitation. Nevertheless, the prevalence of the ideas and their inflammatory impact on science and worldview warrants careful consideration.

In contrast, the classical conception of philosophy, like Christianity (Conway 2000):

> [*E*]quates wisdom with a knowledge of God, construing such knowledge to be an indispensable condition of the supreme human good, which, again like Christianity, it equates with the loving contemplation of God. (p. 9).

While the classical conception leaves no room for revelational theology, Christian thinkers relied to a great extent on the classical conception of philosophy. A new group of theistic philosophers, such as Alvin Plantinga, William Lane Craig, Richard Swinburne, Dave Conway, Alister McGrath, Peter Van Inwagen, John Haldane, John Lennox, Stephen C. Meyer and many more, successfully restates and defends the case for theism and sets out to dispose of historically influential arguments and objections raised against theism by present-day philosophers who deny its cogency. These arguments imply the untenability of the case for atheism.

Science and faith in harmony?

In *Three Landmark Debates*, Alister E. McGrath (2010) explores the essentialist fallacy about science and religion. His perspective entails the assumption that the interrelationship between faith and science is determined by something mutually essential to each of the disciplines, discounting the contingencies of history or culture. This assumption gives rise to the 'warfare' model that became popular during the 19th century. The tone of this model was set by John William Draper's *History of the Conflict Between Religion and Science* (Draper 1875) and Andrew Dickson White's *The Warfare of Science with Theology in Christendom* (White 1895). The essentialist fallacy portrays historical and contemporary intellectual science-faith engagements as essentially adversarial. It casts the relationship between science and faith as a war between rationalism and superstition that leads to a (fallacy of) false dichotomy between science (one form of rationalism) and faith (alleged by some to be the most common form of superstition). A fallacy of hasty generalisation follows when the Christian church as an institution is not distinguished from the ideas of Christian theology, especially during the late medieval period. Many contemporary scientists and philosophers seem to adhere to (or even actively advocate) the essentialist narrative.

The rise of the 'new science' during the Scientific Revolution spurred opposition to the authority of the church and by implication to the social standing of the clergy. The rise of the 'conflict' model of science and religion can therefore be attributed to changing patterns in academic culture, which necessitated some professional scientists to demonstrate their independence from the church and other bastions of the establishment. McGrath dispels myths about science and religion and stereotypes that prevailed because of historical and cultural misreading and misunderstanding of three landmark events: the astronomical disputations of the 16th and early 17th centuries (often referred to as the Galileo affair); the advance of the Newtonian worldview in the late 17th and 18th centuries (which led to a mechanistic worldview, possibly spawning deism); and the controversies of Darwinist of the 19th century, a controversy that is still prevalent.

Views of Scripture and Hermeneutic tradition

Theists maintain that the 'Book of God's works' and the 'Book of God's words' are in harmony and that any inconsistencies between Scripture and science hinge on either a misreading of Scripture or invalid scientific interpretation. Rigid adherence to our evolving scientific theories and interpretations of Scripture without continued analysis will scupper any attempt to resolve apparent inconsistencies. Stenmark (2018) proposes a reconciliation model of the relationship between science and religion. His proposal entails a peaceful co-existence of science and religion; it enriches and enlightens the human experience. Accordingly, inconsistencies would be approached either from a science-priority or from a religion-priority reformative view. In our discussion, Dr Chris Berg (with degrees in science and theology) noted the reconciliatory aspiration of *Science and Faith in Dialogue*:

> 'The data from the "Book of God's works" can be studied by all people and, when interpreted rightly, will implicitly bear witness to "the eternal power and divine nature" of God regardless of the beliefs of the scientific investigator.' (C. Berg, pers. comm., July 2021)

Three approaches

The literal approach in reading and interpreting the Bible is based on taking Scripture at its face value, with the greatest concern for authorial intent, and utilises both concrete and symbolic language. The allegorical approach detaches the meaning of the text from authorial intent, broadening the spectrum of viable interpretation. This view suggests that, for example, the opening chapters of Genesis should be read as poetic or allegorical accounts, from which theological and ethical principles can be derived.

The theological principle of divine accommodation (or condescension) refers to the manner in which God communicates with humanity, to accommodate the language and general level of understanding of the original audience (McGrath 1998). Protestant Reformer John Calvin contributed significantly to the development of this concept, based on the contributions of the church fathers, and dated back to ancient Jewish biblical interpretation. Luther's and Calvin's influence on scriptural interpretation encouraged scientific activity since the Reformation and Scientific Revolution.

More than 500 years ago, Galileo Galilei wrote to Mary Christine of Lorraine, expounding the relationship between biblical exegesis and scientific knowledge. He stated the principle of accommodation as 'avoiding confusion in the minds of the common people' and denied that 'the Bible has confined itself rigorously to the bare and restricted sense of its words'. Galilei (1957) thought that when discussing physical problems:

> [*W*]e ought to begin not from the authority of scriptural passages, but from sense-experiences and necessary demonstrations; for the holy Bible and the phenomena of nature proceed alike from the divine Word. (p. 2)

As theistic scientist and philosopher, Galilei (1957) saw the harmony in the general revelation of nature and specific revelation in Scripture:

> [*H*]aving arrived at any certainties in physics, we ought to utilize these as the most appropriate aids in the true exposition of the Bible [...] for these must be concordant with demonstrated truths. (p. 3)

It follows that the worldviews of the biblical authors must be considered in interpreting the Bible. Nowadays, the principle of divine accommodation refers to ancient conceptions of the world and the cosmos in Scripture and the findings of modern science. Many discoveries and developments in science (e.g. fossils, geological time, the rotation of the earth, etc.) show that the Scriptural interpretation should be more nuanced.

The general view today is that biblical books must be read in terms of their genre. Parables and wisdom literature, prophetic literature and apocalyptic literature cannot be read in the same way. Moreover, the theological intentions of biblical authors must always be taken into account. It is thus not purely a question of symbolic or literal reading. The genre of the text itself dictates the kind of reading. The prosaic poem of Genesis 1, for instance, cannot be read as a natural scientific explanation of the origins of things. The genre of Genesis 1 itself tells us not to do so.[1] Conversely, the historical approach of Luke and Acts dictates that the book must be read as real history (N. Vorster, pers. comm., August 2021).

Atheists (old and new) seem to read the Bible a-historically and literally and often contrast passages from authors with ancient worldviews with modern science – hence the blistering attacks on religion that atheists allege to be the most common form of superstition. In this regard, atheists are masters of straw man arguments.

Straw man

Straw man arguments are informal fallacies. The fallacy consists of the impression that the argument(s) of an opponent is refuted, whereas the kernel of the opponent's argument is neither addressed nor refuted. Instead, the opponent's argument is cunningly replaced by a false (weaker) argument. Straw man arguments are more effective when subtly concealed in a verbal sleight of hand. Talisse and Aikin (2006) identify, analyse and explore the implications of two forms of the straw man fallacy, often used in arguments to conjure up support for a standpoint. The two forms identified are *representation* (i.e. opportunistic misrepresentation in a dialectic exchange underemphasising the opponent's primary premises and focusing instead on weaker arguments) and *selection* (which underplays the diversity and quality of the opponent's arguments).

---

[1] Only after the discovery of the Dead Sea Scroll did theologians start to understand the theo-poetic genre.

The relative success of straw man tactics depends not only on the capabilities of the opposition but often also on an audience's ignorance or inexperience. Straw man tactics in polemics undermine discourse, dialogue and argumentation and perpetuate ignorance unless properly refuted at the level of the participants in the debate, as well as at the level of the audience (if different).

In a lecture given at Oxford University, James Wood (2011a, 2011b) exposed some of the basic flaws of atheism. In referring to the strict literalism children are often 'stuck' in, which they eventually outgrow, he noted:

> The New Atheism is locked into a similar kind of literalism. It parasitically lives off its enemy. Just as evangelical Christianity is characterized by scriptural literalism and an uncomplicated belief in a personal God, so the New Atheism often seems engaged only in doing battle with scriptural literalism. The God of the New Atheism and the God of religious fundamentalism turn out to be remarkably similar entities. (n.p.)

Wood aptly identifies the straw man tactic of the atheist, but he inadvertently invokes another straw man by aiming his generalised criticism of 'literalism' at 'evangelical Christianity'. The latter is also a fallacy of generalisation. Scripture is not read literally by the majority of Christians. The text of the Bible is often elegantly poetic, sometimes historically factual or mysteriously apocalyptic, with prophesy and examples of fulfilment thereof. Yet, in all literary genres, Scripture is generally infused with (moral) teaching. These texts warrant scholarly exegesis from different hermeneutic perspectives. Reading these texts without understanding the historical (often ancient) contexts leads to the philosophical conjecture so characteristic of the atheist materialistic worldview and specifically to that of the (aggressive) new atheists.

Influence on the dialogue

A similar literalism dominated some Christian traditions in the past and prevails today in some groups, which stifles dialogue between science and faith and exacerbates the false dichotomy between faith and science. The Galileo affair is a classic example of unwarranted overreach in following a literalistic approach in reading and interpreting Scripture: to preserve a literal interpretation of Scripture, the Catholic Church promoted the ideas of Aristotle, whose philosophy relied on reason more than experimentation. His geocentrism and insistence on the immutability and constancy of nature stood in stark contrast to scientific developments during and after the Scientific Revolution (Harrison 2010; St. Augustine n.d.).

The differences in opinion among theists also emanate primarily from a difference in reading and interpreting Scripture. Denis Lamoureaux (2015), with adaptations by Van Niekerk (2020), presents a simplified synopsis contrasting three major theistic groups with deism and atheism in terms of themes and attributes relevant to the science-faith dialogue. The major theistic groups are discussed further.

Young-earth creationists (YEC) read Scripture utilising a literal hermeneutic and interpret the word 'day' as a 24-h period. They tend to link the doctrine of inerrancy to their specific interpretation of the Genesis account. To them, God's actions in creating the universe and life are direct and occurred in six creation Earth days. They accept a literal Adam and Eve and a global flood and leave little room for the allegorical reading of Scripture or the idea of accommodation. They commonly reject the interpretations of scientific data made by established scientists and are in favour of putting forth alternative scientific theories that agree with their scriptural convictions.

Evolutionary creationists seem to prefer the term evolutionary theists (possibly to escape the criticism and straw man tactics of opponents). They fully embrace (even defend) macroevolution and interpret Scripture using an allegorical approach. They accept contemporary estimations of the age of the universe and that God created the universe through ordained and sustained processes, and that humanity evolved. The BioLogos organisation represents theists with this position.

Progressive 'old earth' creationists have a literalistic approach in their interpretation of Scripture but argue that the author of Genesis 1–2 intended the word 'day' to be symbolic of a longer period. They believe that scientific data do point towards contemporary estimates of the age of the universe but that there is a growing body of scientific evidence against macroevolution. Proponents of ideas common to this group are undeterred in criticising macroevolution from a strictly scientific point of view, in spite of opponents invoking straw man tactics by alleging ulterior motives. Most leading scholars associated with the Discovery Institute and ID are representative of this group.

■ The cosmological argument

Within the multitude of philosophical traditions and the offshoots they spawned over time, one central question underpins all science-faith questions, namely that of the origin of the cosmos, of (sentient) life and of human beings who are conscious and intelligent. In the science-faith dialogue, a major point of difference between theists and atheists is that of the first cause.

In natural theology, the a posteriori cosmological argument claims that God's existence can be derived from observations and facts in the universe that pertain to cause, explanation, change and movement, contingency, dependency or boundedness (Craig 2001; Oderberg 2007)). The reason-based a posteriori cosmological argument flows from a consideration of the existence and order of the physical universe.

Theists and atheists agree: for anything to exist, something that always existed needs to precede it. The atheist believes there is no God, no transcendent, benevolent, omnipotent, omniscient Creator. Prior to the scientific discovery that the universe had a beginning, atheists believed that the universe was eternal – that was their *proper basic belief* and they placed the burden of proof (that God exists) on the theist. In the words of Russell, '[...] The universe is just there, and that's all' (Russell & Copleston 1964, p. 1). Theists take the existence of God as their *proper basic belief*. The theist believes God, the first cause, is transcendent and created all that exists.

The philosophies of the theist and the atheist diverge from these fundamentally different points of departure. This divergence culminates in different worldviews and explanations of everything. It is intended (for both) to render a coherent and consistent picture of all human experience.

Charles Darwin (1958) is less well known for his (initial) support of the cosmological argument:

> [*Reason tells me of the*] extreme difficulty or rather impossibility of conceiving this immense and wonderful universe, including man with his capability of looking far backwards and far into futurity, as the result of blind chance or necessity. When thus reflecting I feel compelled to look to a First Cause having an intelligent mind in some degree analogous to that of man; and I deserve to be called a Theist. (n.p.)

The greatest scientists of the classical as well as the modern era saw a link between natural laws and God's immanent creative act. All but a few saw the link: scientists of the Scientific Revolution to the Enlightenment, and later on Albert Einstein (the discoverer of relativity), Max Planck, Werner Heisenberg, Erwin Schrödinger and Paul Dirac (who discovered and developed different aspects of quantum mechanics) (Varghese 2010).

Antony Flew is regarded by some as one of the most prolific antitheological philosophers of the past century. His systematic, comprehensive writings promoted atheism with originality – until '[...] the world's most notorious atheist changed his mind. He now believes in God more or less based on scientific evidence [...]' (Flew 2007, p. 7). In *There is a God*, Flew shares his quest from atheism to theism and elaborates how he shifted to believe in a Creator God through contemplating philosophical argument and scientific evidence. *Time Magazine*'s cover story in April 1980 highlighted Flew's turn toward theism:

> In a quiet revolution in thought and argument that hardly anyone would have foreseen only two decades ago, God is making a comeback. Most intriguingly this is happening [...] in the crisp intellectual circles of academic philosophers. (n.p.)

In his erstwhile atheist writings, such as *The Presumption of Atheism*, Flew contended that atheism must assume the universe and its natural laws as 'properly basic', as ultimate, as every explanatory framework cannot itself be explained by the system. Flew, then as an atheist, in debates with theists, showed that theists are faced by the same inevitability: theists cannot avoid taking the existence and nature of their God as ultimate and beyond explanation. Since the early 1980s, Flew seemingly gradually changed his mind, until '[he] confessed that atheists have to be embarrassed by the contemporary cosmological consensus', which provides solid scientific proof of the fact that the universe had a beginning. Modern science was 'providing a scientific proof of what St. Thomas Aquinas contended could not be proved philosophically' (Anthony Flew 2007).

Terry Mithe's version of the cosmological argument is based on the concept of existential causality, rather than sufficient reason as a concept (Flew 2007):

> There cannot be an infinite regress of causes of being, because an infinite regress of finite beings would not cause the existence of anything. Therefore, there is a first Cause of the present existence of these beings. The first Cause must be infinite, necessary, eternal, and one. The first uncaused Cause is identical with the God of the Judeo-Christian tradition (p. 71).

Philosopher and Theologian William Lane Craig expounds on the medieval Muslim Kalam cosmological argument, according to which the beginning of the universe is a demonstration that the world is not self-explanatory with respect to its existence – it is not a necessary being. He uses two scientific confirmations (the Big Bang Theory and an inference from the second law of thermodynamics) and two philosophical arguments to support his thesis that anything that comes into existence has a cause, implying that a transcendent cause of the universe must exist (Craig 2001).

Richard Swinburne (2004) proposed an explanation of the universe based on his inductive cosmological argument:

> There is quite a chance that, if there is a God, he will make something of the finitude and complexity of a universe. It is very unlikely that a universe would exist uncaused, but rather more likely that God would exist uncaused (p. 152).

My view is that, through sound philosophical reasoning and the evidence revealed by modern science, we have all the evidence we need to argue a cogent, compelling case for God (not to mention the convictions from revelational theology, which has a personal nature). Only a deliberate, blind adherence to a naturalistic worldview is responsible for any variety of atheism.

Attacks on the cosmological argument

Atheists deny any evidence for God's existence; some even argue that any such evidence, if ever found, would need to be noncoercive, lest free will be sacrificed.

When Dawkins and other atheists (new and old) ask, 'Who created God?', they ignore the theist's view of God as the transcendent, uncaused, eternal, omnipotent and omniscient loving, personal God. They think their point of departure (an uncaused universe) is the 'natural position', thereby escaping the burden of proof. Manufactured gods are idols, lifeless objects, (self-) glorified mortals or made-up deities. They are the sort of god Michael Shermer disingenuously equated to God when in a public debate at Oxford in 2013 he invited the audience, having rejected multiple (non-Christian) gods, to '[...] just go one god further [...]' and, by implication, become atheists as well (Lennox & Shermer 2013).

☐ The eternal universe

Atheists and materialists previously assumed, as their proper basic belief, that the universe was unchanged and constant, itself being the first uncaused cause. During the early 20th century, many great scientists assumed the universe was 'always there'. Until 1932, Einstein was among them.

The writers of Genesis understood that the cosmos had to have had a beginning.

The cosmological argument stood unabated for more than 2000 years. In spite of naturalists' view that the argument is moot, contemporary science has revealed a picture of the universe that ostensibly strengthens the argument that the universe had a beginning. It is therefore no wonder that naturalists and atheists would want to devise escape routes to preserve their non-theist status quo.

In an interview with Amir Axel in 2010, Steven Weinberg, the Nobel laureate physicist, was asked how the Big Bang was caused and what preceded it. He responded with a simple: 'This we do not know, and have no way of knowing' (Aczel 2014, p. 75). This answer, by one of the world's leading physicists and thinkers, convinced Axel that science cannot disprove a 'creator': science cannot take us to the actual moment of creation and before it. It seems logical to conclude that science also cannot prove a 'creator'. The choice to believe in a Creator God would hence not be coercive – humans are not 'programmed' to always make the right choice, but are *given* or *allowed* the freedom to choose.

With the discovery that the universe had a beginning, a new 'story line' had to be devised. There is no way to know what happened prior to the Big Bang – physics breaks down in the so-called singularity of the Big Bang. Since the scientific discovery that the universe had a beginning, many naturalistic scientists have engaged in sheer speculation about the origins of the universe, ostensibly to circumvent the idea of a first cause. The irony is that nature (through science) has revealed something that sits uncomfortably with them. In the postmodern world, where apparently 'anything goes', speculation and conjecture are often not distinguished from 'pure' science; with these speculations and generalisations, those scientists seem to have embraced ontological naturalism (or anti-realism, for thinking that laws and ideas can have agency).

☐ Multiverse

The idea of a multiverse (a hypothetical group of multiple universes comprising everything that exists) has been postulated to have been generated by endless quantum vacuum fluctuation events. These ideas are speculative as they cannot be verified or falsified. There is no general support among physicists and cosmologists for the idea, and many scientists do not regard the multiverse idea as a legitimate topic of scientific inquiry (Ellis & Silk 2014). Multiverse proposals are scientifically based philosophical speculations (Ellis 2011). Stephen C. Meyer details multiverse theories in his chapter.

The problem with the infinite multiverse models lies in a misunderstanding of the mathematical idea of infinity. If infinity is allowed to enter any argument, almost anything can be 'proved': simply by the immense power of the concept of infinity, a universe with all the required parameters for life to exist can be 'found' (Aczel 2014):

> And this isn't science, since it's not based on any reality, any experimentation, or even any viable theory. It is simply a 'forcing argument' that allows you to prove anything you like. (p. 117)

Multiverse proponents inadvertently invoke the (in?)famous 'monkey theorem' (i.e. enough monkeys typing on enough typewriters will ultimately render, e.g. a Shakespearian play). Nevertheless, probability experts have identified explanations of the apparent fine-tuning of the universe, inferred from a multiverse, as an example of inverse gambler's fallacy (Goff 2021). Multiverse theories are often also invoked to try to refute the cosmological argument.

Paul Steinhardt has argued that if a theory provides for all possible outcomes, it cannot be ruled out by any experiment (Steinhardt 2014). The type of reasoning invoked in multiverse theory 'is better described as an audacious exercise in superstition, anything we desire should exist somewhere if we just invoke the magic of large numbers' (Flew 2007, p. 173).

Multiverse ideas are untested speculative conjecture, often motivated by an ontological naturalistic desire to deny the role of a divine Creator. These ideas do not provide a viable refutation of the cosmological argument, for at least two reasons. Firstly, we cannot know whether a multitude of universes exist. Secondly, even if we had some means of establishing their existence, the cosmological argument would still apply to all universes, as it applies to the one we live in – such arguments are as unsuccessful in refuting the cosmological argument as is panspermia; it only moves the argument a step further.

☐ Hawking's self-contained universe

Stephen Hawking (1988) realised the implications of a beginning of the universe:

> So long as the universe had a beginning, we could suppose it had a creator. But if the universe is really completely self-contained, having no boundary or edge, it would have neither beginning nor end: it would simply be. What place, then, for a creator? (p. 134)

In *The Grand Design*, Hawking and Mlodinow (2010) claim to have found new and stronger arguments to knock God out of the picture once and for all. Hawking's arguments hinge on untested ideas. Relativity and quantum mechanics are integrated and used as a basis to explain the emergence of the universe from 'nothing'. Hawking applies M-Theory, a string-inspired theory of everything, for which there is no empirical evidence. He claims confirmation for the theory from NASA's Cosmic Background Explorer (COBE) and Wilkinson Microwave Anisotropy Probe (WMAP) satellites and maintains it can help to answer those 'deep questions'. He believes that M-Theory was the theory Albert Einstein had hitherto been looking for, implying that it was the ultimate Grand Unification Theory that would lead us to 'know the mind of God'.[2] He then reverts to a more tentative position, stating that '*if* the theory is confirmed by observation, it will be the successful conclusion of a search going back more than 3000 years. We will have found The Grand Design' (Hawking 1988, pp. 138–139; [*emphasis added*]).

The concept *design* used in *The Grand Design* seems to indicate *apparent design* (Hawking 1988):

> But just as Darwin and Wallace explained how the apparently miraculous design of living forms could appear without intervention by a supreme being, the multiverse concept can explain the fine-tuning of physical law without the need for a benevolent creator who made the universe for our benefit (p. 126).

This naturalistic worldview possibly includes a degree of anti-realism: After decades of work on the integration of quantum mechanics and relativity, Hawking (cited in Hawking & Mlodinow 2010) claims:

> Because there is a law such as gravity, the universe can and will create itself from nothing. Spontaneous creation is the reason there is something rather than nothing, why the universe exists, why we exist [...] It is not necessary to invoke God to [...] set the universe going. (p. 138)

Besides the illogical category mistakes contained in the statement, statements like these, from scientists with celebrity status, are misleading scientific hype and bring physics into disrepute. If left unchallenged, such statements have implications for the worldview of people without the scientific background to see the statements for what they are. Add to that the fear of the *God-of-the-Gaps* fallacy (a variant of the Argument from Ignorance fallacy) or fear of

---

[2] Theorists now realise that there are a vast number of M-theory versions, which 'predict' a vast number of possible universes – reminiscent of the 'monkey'-theorem.

straw man tactics, and the fallacy *argumentum ad captandum* (an improper argument intended to captivate the populace) rears its head.

Even if the category mistake is forgiven for argument's sake and it is assumed that the universe was created by the laws of nature, it is implied that these laws must have existed prior to time – our conception of time is linked to the creation of the universe. Logically, the laws of nature would be outside the universe but only came into existence in this universe. Quantum mechanics and general relatively only work on 'something, rather than nothing' (Schroeder 2021):

> What we have then is totally non-physical laws, outside of time, creating a universe. Now that description might sound somewhat familiar. Very much like the biblical concept of God: not physical, outside of time, able to create a universe [...] The wonder is that the seemingly inert, lifeless energy of the Big Bang creation metamorphosed and became alive and sentient. (n.p.)

Neither the vain certitude of science nor the blind dogmatism of religion will help us to reconcile (and know where to apply) totally different (concordant or conflicting) frameworks for comprehending the universe and our place in it. Science is about studying the 'how?' – questions about *regularities* in nature in order to find the existing underlying laws and principles that govern the universe. Origins (of the physical universe and life) is about a first cause and invariably involve questions of teleology, which science cannot provide.

Cyclic models of the universe

Since the advent of relativistic cosmology, the ideas around cyclic universes could be formulated precisely using mathematics. Steven Weinberg (1977, p. 148), Nobel Physics laureate, said, 'some cosmologists are philosophically attracted to the oscillating model, especially because, like the steady-state model, it nicely avoids the problem of Genesis'. The implication is clear: an eternal cyclic model avoids a beginning. The theist's conceptualisation is, however, that God is eternal, 'outside time', that God created time as we know it 'in the beginning'.

These speculative models are popular among a minority of physicists and have remained contentious, not only because of previous associations with antireligious worldviews but primarily because of its speculative nature and inconsistencies with some aspects of basic physical laws (in ch. 2 Stephen C. Meyer discusses these matters in more detail). No wonder these ideas have recently been revived by proponents of string theory.

Cyclic models might face another inconsistency. In *The Grand Design*, Hawking described time as becoming endless in a black hole, and the same argument would apply for the singularity of a Big Bang. Presumably, in a cyclical universe, time would become 'endless' in the series of 'episodes' of big crunches, which would imply a series of 'endless time' episodes? How would one 'big crunch' ever reach the next, if the time in between is endless?

A universe out of nothing?

Almost 400 years ago, German polymath Gottfried Wilhelm Leibnitz, mathematician, philosopher and scientist asked: 'Why is there something rather than nothing?' (Leibniz 1951, p. 527). For ages, philosophers, scientists and theologians have pondered this question in awe and wonder of the universe and its order. To these intellectuals, it was logically impossible that a necessary being (God) could not exist.

Stephen Hawking acknowledged (at first, in *A Brief History of Time*) that his cosmological model did not imply the (non)existence of God. He explained that, in saying that the beginning of the universe was determined by physical laws, it is only implied that God did not 'set the universe going in some arbitrary way that we could not understand. It says nothing about whether or not God exists – just that He is not arbitrary' (Hawking 1993, p. 158). He admits that 'Even if there is only one possible unified theory, it is just a set of rules and equations', a statement that seems to be well aligned with the scientific method or methodological naturalism.

Hawking poses this question in his earlier writings: 'What is it that breathes fire into the equations and makes a universe for them to describe?' (Hawking 1988, p. 170). Does this question imply an intuitive admission that an explanation outside the laws of physics, outside the universe, is needed? The cosmological model that he subsequently considered avoided a cosmic beginning. In his model, Hawking employed 'imaginary' time, which was a non-starter. It rendered a model unlike our universe. Hawking (1988) admitted:

> When one goes back to the real time in which we live, however, there will still appear to be singularities [...] Only if [*we*] lived in imaginary time would [*we*] encounter no singularities [...] In real time, the universe has a beginning and an end at singularities that form a boundary to space-time and at which the laws of science break down. (p. 131)

Physicist Lawrence Krauss, known for disparaging philosophy, knows the answer to the origin of the universe: 'nothing!' In *A Universe from Nothing: Why There is Something Rather Than Nothing* Krauss (2012) expounds and redefines 'nothing' in a manner that does not stand up to scientific rigour or philosophical scrutiny. As can be expected, atheist Sam Harris, in his appraisal of the book, writes: 'As it turns out, everything has a lot to do with nothing – and nothing to do with God' and calls the book 'disarming'. Dawkins' opinion is that the book is a 'knockout blow' for the cosmological argument, the 'deadliest blow to supernaturalism', and the book's foreword calls it a 'fascinating antidote against outmoded philosophical and religious thinking'.

Krauss (2012, p. 136) claims that something can come from nothing – 'even the laws of physics may not be necessary or required'. In this approach, it seems that Krauss is making a category mistake and adheres to an unscientific and incomplete philosophical conception of what 'nothing' entails. Energy fields or quantum fields are not 'nothing', and if, for example, a particle and an antiparticle annihilate, 'nothing' remains of the particles, but energy is released. Conversely, particles created from an energy field emerge from 'nothing'. This seems to be the implication, inferred from Krauss' explanation. However, the particles were 'created' in the energy field, according to the laws of the known existing universe. The laws of physics cannot be conjured up from nothing. Krauss does not succeed in refuting the cosmological argument – even by misunderstanding or misrepresenting the work of Russian physicist Vilenkin, which he popularised in his book *A Universe from Nothing* (Meyer 2021).

None of the current widely accepted cosmological models excludes a cosmic beginning of the universe. These models depend on *a priori* assumptions and or specified conditions. Two major, widely accepted theoretical models prove that the universe had a beginning: the Hawking–Penrose–Ellis (HPE) singularity theorems (which depend on different energy conditions and the validity of general relativity) and the Borde–Guth–Vilenkin (BGV) theorem, which does not require specific energy conditions, but assumes that the universe is expanding on average. The HPE theorems did not account for the possibility of indeterministic quantum fluctuations in the early universe. Concerns about the standard Big Bang model and the applicability of singularity theorems to the early universe led many theoretical physicists and cosmologists, to seek alternative models, such as the alternative version of the Big Bang model, which is generally known as the inflation model (Guth 1981). In investigating whether the inflation model was 'past eternal', Borde, Guth and Vilenkin subsequently proved (the BGV proof) that the universe must have had a beginning, even if inflationary cosmology is correct (Borde, Guth & Vilenkin 2003; Meyer 2021) (Guth 2007):

> [*Inflation*] is not eternal into the past: it can be proven under reasonable assumptions that the inflating region must be incomplete in past directions, so some physics other than inflation is needed to describe the past boundary of the inflating region. (p. 6811)

In *The Return of the God Hypothesis*, Stephen C. Meyer (2021) highlighted the error Krauss made in *A Universe from Nothing*, in which Krauss used the work of Alexander Vilenkin to refute the cosmological argument for the existence of God. Vilenkin's work implied the need for a pre-existing mind. The BGV theorem applies to any universe that meets very general conditions (including those implied by inflationary cosmological models), irrespective of the material content of the universe or whether general relativity applies. The only assumption of the BGV proof is that the expansion rate of the universe remains positive, irrespective of how small the value is. '[C]osmologists [...] have to face the problem of a cosmic beginning' (Vilenkin 2006, p. 176). Hence the quantum-tunnelling scenario presupposes the origin of the universe.

A philosophical argument to support, inter alia, the BGV theorem:

- if the universe is past infinite

- if the universe is always expanding (irrespective of how fast)
- then the universe should have reached the ultimate heat death cosmology predicts, based on all current relevant data.

We are, however, here to ponder the question. Hence, the universe is not past infinite.

John Leslie (2001), the philosopher of science, has argued convincingly that none of the contemporary cosmological speculations rules out the possibility of a Creator:

> No matter how you describe the universe – as having existed for ever, or as having originated from a point outside space-time or else in space but not in time, or as starting off so quantum-fuzzily that there was no definite point at which it started, or as having a total energy that is zero – the people who see a problem in the sheer existence of Something Rather Than Nothing will be little inclined to agree that the problem has been solved. (pp. 194–195)

The argument from design

Over the ages, people have had an intuitive, even compelling, conviction that the exquisiteness, law-like regularity and order found in natural phenomena (amidst its embeddedness in irregular or even random natural events) are reminiscent of structure, function, interconnectedness and purpose. Reminiscent of the creative output of human agency, of *mind* and an intuitive ability to distinguish such activity from chaotic variability, people have been led over the ages to assume a deliberative and directive mind behind natural phenomena, to be natural. The argument from design, or the teleological argument, has been known and assumed to be valid for more or less as long as the cosmological argument.

Over the years, many classical adaptations of the argument from design and, recently, modern-day design argument versions were formulated (Himma 2021).

Classical versions of the design argument

Philosophers, theologians and scientists have toiled to shape this intuition into a more formal, logically rigorous inference. The ensuant philosophical and theistic arguments invoke logic and the prevailing body of (scientific) knowledge of the natural world and focus on plan, purpose, intention, foresight and design.

The ancients' intuition and the inference that led to a firm belief in the truthfulness of the argument from design hinged on reason and observation within a logical framework. Throughout the ages, the capacity to reason and to observe more precisely grew as more in-depth knowledge about the world was discovered and with the onset of more rigorous scientific methodologies.

Scientific advances, especially since the Scientific Revolution, have revealed a more complete and consistent picture of our world. As with the cosmological argument, the ‘new science’, since the science revolution, and even more so in modern times, has revealed compelling and cogent support for the argument from design, in spite of numerous unsuccessful refutation attempts by materialists and the like.

Proponents of the classic argument from design infer the action of a supernatural designer, God, from the vast complexity in structure and function in nature. Classical versions of the design argument were originally encountered in Greek natural philosophy and science. During the Roman era, the stoics ‘developed the battery of creationist arguments broadly known under the label “The Argument from Design”’ (Sedley 2007, p. xvii). Medieval philosophers and theologians argued, based on revelation, that God exists and is the Creator of all things, for example (Rm 1):

> For since the creation of the world His invisible attributes are clearly seen, being understood by the things that are made, even His eternal power and Godhead, so that they are without excuse. (v. 20; New King James Version)

In *Summa Theologica*, Thomas Aquinas describes five ways in his endeavours to prove God’s existence. In his second way, he argues, ‘therefore it is necessary to admit a first efficient cause, to which everyone gives the name of God’ and in his fifth way, he states: ‘Therefore some intelligent being exists by whom all natural things are directed to their end; and this being we call God’ (St. Thomas Aquinas 1947, p. 16).

The argument from design is usually associated with William Paley (well known for his Watchmaker’s analogy) and his 1802 treatise *Natural Theology*, *or Evidence of the Existence and Attributes of the Deity*, *Collected from the Appearances of Nature* (Gregory 2009). Less well-known is contemporary Charles Darwin’s (1872) (initial?) implicit acceptance of the argument from design:

> There is grandeur in this view of life, with its several powers, having been originally breathed by the Creator into a few forms or into one; and that, while this planet has gone circling on according to the fixed law of gravity, from so simple a beginning endless forms most beautiful and most wonderful have been, and are being evolved. (p. 465)

Contemporary versions of the design argument

Present-day adaptations of the design argument hinge on sophisticated strategies and the most recent advances in modern science for discovering evidence of design in the world. Design arguments include the *argument from irreducible complexity*, the *argument from biological information* and several *fine-tuning arguments* (for cosmological fine-tuning, planetary fine-tuning, geological fine-tuning, chemical fine-tuning and fine-tuning of mechanisms for biological life). The arguments are elucidated in other chapters of this book – in this chapter, only a cursory overview of the arguments is presented.

The chapters by Fazale R. Rana, James M. Tour, Brian Miller and Marcos Eberlin provide complementary expositions of various aspects of contemporary renditions of the argument from design.

The intuition, insight and logic of contemporary design arguments are similar to the classical versions, except that arguments have gained in sophistication and cogency, relying on the latest scientific advances and insights and present even more compelling arguments (much as is the case with the cosmological argument, which gained dramatically from the developments in modern cosmology). These arguments typically infer God's existence as the best explanation for the world and its observed features. Classical arguments, such as William Paley's Divine Watchmaker metaphor, relied on an intuitive insight derived from the experience of designed objects and from human experience and understanding of causality. But contemporary design arguments are more rigorous and go into more scientific detail and calculations; they indicate the absurdity of 'accidental natural' explanations of the world that invoke the monkey theorem or the magic of large numbers. The observed order, design, sentient life and intelligence the material universe exhibits point to an intelligent designer, who intentionally created the material universe and the overwhelming evidence of design that exists, as the best or most probable explanation.

☐ Irreducible complexity

Charles Darwin stated in *The Origin of Species* (1872, p. 154): 'If it could be demonstrated that any complex organ existed which could not possibly have been formed by numerous, successive, slight modifications, my theory would absolutely break down'. This admission reminds of Karl Popper's *falsification* principle (the principle Popper proposed for replacing induction and as a way of demarking science from non-science).

Michael J. Behe (1996, p. 39) defines an irreducibly complex system as a system 'composed of several well-matched, interacting parts that contribute to the basic function, and where the removal of any one of the parts causes the system to effectively cease functioning'. He convincingly demonstrates that Darwinian evolution is insufficient to explain life as we know it: the likelihood of irreducibly complex systems to have evolved along Darwinian lines is negligibly small and cannot explain irreducible biochemical complexity. The logic behind the idea is exactly what Darwin indicated would break down his theory of evolution. Slight, successive modifications of a precursor system cannot produce irreducibly complex systems – any missing part would render the system non-functional. Integral biological systems are needed for natural selection to act on (Behe 1996, p. 39):

> The simplicity that was once expected to be the foundation of life has proven to be a phantom; instead, systems of horrendous, irreducible complexity inhabit the cell. The resulting realization that life was designed by an intelligence is a shock to us in the twentieth century who have gotten used to thinking of life as the result of simple natural laws. (p. 266)

In *The Design Inference*, William Dembski (1998) presents a mathematical or statistical appraisal of the extreme improbability of structured design requiring complex information of complex systems coming about randomly.

Proponents of macroevolution seem unwavering in their belief in what they term as 'the scientific consensus' about macroevolution and are apparently willing to invoke the magic of large numbers as justification for their belief.

☐ The argument from biological information

Two arguments are intricately and intrinsically linked. They are, firstly, the argument from biological information (the information in the cell needed for the intricate and sophisticated designs observed in living organisms) and secondly, the argument from irreducible biochemical complexity (implying a design for purpose, foresight and function). Both arguments point to the need for design, which is the product of an intelligent mind. Invoking the magic of large numbers and chance to explain away the remarkable level of purposeful design contained in the genetic code of living organisms seems a deliberate absurdity.

In (inter alia) *Return of the God Hypothesis*, Stephen C. Meyer (2021) gives an elaborate appraisal in a scientifically and philosophically astute, cogent manner, of the grounds for supporting the argument from biological information (as well as the argument from design and fine-tuning arguments). Even though Darwinian theories typically do not propose to explain the origin of living organisms, some proponents of naturalistic explanations have tried to propose conditions that may have generated the first life forms 'accidentally'. All such attempts have failed dismally, even when experimenters (using their *minds* to *design* such experiments) carefully chose ideal laboratory conditions and ingredients for typical experimental setups. No plausible naturalistic explanation has been offered to explain either the formation of amino acids from non-organic elements or the origin of information in genetic code.

Absurd statements such as the following seem like an enthusiastic category error (Dawkins 1995):

> The universe we observe has precisely the properties we should expect if there is, at bottom, no design, no purpose, no evil, no good, nothing but blind, pitiless indifference. DNA neither cares nor knows. DNA just is. (p. 133)

If materialists are willing to *believe* the idea of the emergence of ‘a universe from nothing’, then *believing* the emergence of ‘information from nothing’ seems consistent with an ontological naturalistic worldview – it is, however, inconsistent with methodological naturalism, which claims to rely on the scientific method. Hume’s reference to *whimsical imagination* seems apt in his weak refutation of Lucretius (Hume 1999):

> Not only the will of the Supreme Being may create matter; [...] but, for aught we know *a priori*, the will of any other being might create it, or any other cause, that the most *whimsical imagination* can assign. (p. 164; [*emphasis added*])

☐ Fine-tuning arguments

By all accounts of modern science, the universe appears ‘fine-tuned’ for sentient life, to an astonishing degree of fine-tuning. The fine-tuning events carry a sequential interdependence reminiscent of irreducible complexity – all steps in the chain of fine-tuning events are necessary in the specific sequence observed, to render conscious life as we know it. The chain of fine-tuning events used in fine-tuning arguments focuses on:

1. global fine-tuning (e.g. the fine-tuning of initial conditions, fundamental forces and other physical laws and constants for an expanding universe and the formation of galaxies, stars and planets [Ross, 2008, 2016])
2. local fine-tuning (e.g. Earth’s life-sustaining capabilities, water and its miraculous properties for life and the protection by the planetary giants [Gonzalez & Richards 2004; Ross, 2016])
3. biological fine-tuning, which is linked to the argument from irreducible complexity and the Argument from Design (Behe 1996; Meyer 2013, 2021; William A. Dembski 2004).

Whimsical imagination aside, chance or ID seems to be the reasonable explanations for the astounding degree of fine-tuning. If the sequential dependence of fine-tuning (groups of) events is taken into account, a vastly higher improbability of random change as an explanation for fine-tuning for sentient life is implied.

Attacks on the argument from design

While some writers believe that David Hume refuted the argument from design long before Darwin, he only questioned whether the existence of a God can be logically inferred from apparent design in nature, without offering alternative explanations for such apparent design. Some philosophers argue that Hume’s position can be neither described as ‘atheism’ (a too restrictive position) nor as ‘scepticism’ or ‘agnosticism’ (not strong enough to properly describe his completely hostile, critical attitude towards orthodox religion) and suggest that the term *irreligion* more aptly describes Hume’s position (Hume on Religion 2005).

Some philosophers go further (than Hume) to propose the possibility for the development of life in all its variety without the need for design. This position is augmented by another speculation that, early in the history of Earth's development and cooling, original living matter came forth quite fortuitously, emerging without the benefit of any design – an assumption that many life scientists are ostensibly quite comfortable with (Fletcher 1974). The apparent plausibility, to some, of such a narrative is seemingly enough to convince many atheists today to concur with Richard Dawkins in asserting that the plausibility of theism has effectively been destroyed by Darwin's theory. Many seem to agree with Dawkins' (2015) persuasion:

> [*A*]lthough atheism might have been logically tenable before Darwin, Darwin made it possible to be an intellectually fulfilled atheist. Natural selection, the blind, unconscious, automatic process which Darwin discovered [...] we now know is the explanation for the existence and apparently purposeful form of all life. (p. 19)

This ontological naturalist explanation of life is premised on a generalised hypothesis, which is neither falsifiable nor scientifically rigorous and lacks the characteristic of what would be deemed (in the physical sciences) as theory. In spite of the hypothesis having been made more than a century and a half ago, and notwithstanding the advances in many other branches of life sciences available to corroborate any of its claims, Darwinism remains flawed, even in terms of the attributes for success posed by Darwin himself.

Many theistic philosophers have asserted that the objections to the argument from design raised by Hume have not been successful in bringing into question its cogency, even when supplemented with Darwin's theory of evolution (which was formulated after Hume's time) and concomitant considerations. Conway (2000) asserted:

> [*T*]he classical conception of philosophy is no more vulnerable to Nietzsche's genealogical subversion of religious belief than it is to Hume's or Kant's strictures against the speculative theology on which it is ultimately grounded. The conclusion of this discussion of Hume, Kant and Nietzsche must be that the present-day repudiation of theism in philosophy is ill-founded. There is no reason for rejecting the classical conception. (p. 133)

Objections against the cosmological argument and the argument from design, by Hume and Kant are not nearly as persuasive as some assume.

Even in the absence of the latest scientific discoveries and the powerful, compelling support for theistic arguments, it seems as though any atheistic standpoint well exceeds anything that Hume or Kant ever achieved. The atheistic standpoint is ostensibly prevalent among many contemporary philosophers and other intellectuals and goes well beyond Hume's irreligion, for regarding belief in God as philosophically exorbitant, irrational or illogical.

Swinburne (2004) concludes that it is more reasonable to assume the creation of our universe, with its multitudinous life forms, by a benevolent supreme intelligent being (whom we call God), rather than to emerge accidentally.

Three sets of biological phenomena cast doubt on the possibility of accounting for the existence of biological life in purely naturalistic terms without considering design (Haldane 1996):

1. Living matter emerging from non-living matter, which possesses a teleological functioning and composition not present in non-living constituents.
2. The emergence of life forms with reproducing capacity, without which different species could not emerge through random mutation and natural selection. In the absence of providing an explanation for the emergence of such mechanisms, they cannot be invoked to explain how life forms lacking this capacity first 'evolved' into life forms with reproducing capacity.
3. No naturalistic explanation can explain sentient life. If human beings can only acquire conceptual and symbolic thought from beings previously in possession of them, the emergence of symbolic thought in humans is inexplicable by the evolution of symbolic thought from any other natural preceding species.

■ Critique of overreach and lack of rigour in ontological naturalistic reasoning

Developments in the physical sciences and the biological sciences have far-reaching implications for a worldview. Worldview is (Hiebert 2008):

> [*T*]he fundamental cognitive, affective, and evaluative presuppositions, inferences and conclusions a group of people or individuals make about the nature and interaction of everything, and which they use to seek meaning and to order their lives. (n.p.)

In gaining these insights, the rigorous scientific method is successful in applications to nature, to understand and to describe regularities or patterns in nature by fitting theory to data. However, 'Successful as it is, and universally encompassing as its subject is, a scientific view of the world is hopelessly incomplete. Matters of value and meaning are outside science's scope' (Ayala 2007, p. 102).

When the theist and atheist enter the laboratory, they should not expect different outcomes if they strictly adhere to the scientific method. If 'pure science' espouses universal, timeless, self-correcting, repeatable, objective, evidence-based, falsifiable, rational, logical and dispassionate observation in order to make predictions, it follows that the scientific method would leave no room for revelation, dogma, appeals to tradition, common sense or commonly held beliefs. Some definitions of methodological naturalism refer to naturalism without its ontological add-ons (Stanford Encyclopedia of Philosophy 2021).

The scientific method is widely accepted and should be common ground between the theist and the atheist. But is it? It seems that ontological ‘feedback’ into the ‘science’ of the beholder is rendering different outcomes. In applying science beyond its reach, the atheist either ends up with unfalsifiable conjecture or in the metaphysical realm. To annex the scientific method (by equating it to methodological naturalism and integrating naturalistic ontological add-ons) is a common fallacy many atheists seem untroubled to make.

Scientism

An excessive belief in the power of scientific knowledge and techniques, the belief that scientific knowledge (such as physics or biology) has a higher value than other expressions of knowledge (e.g. philosophy or ethic) is termed scientism (Stenmark 2018, p. 19). Sire (1998) states:

> Scientism […] is a speculative worldview about the ultimate reality of the universe and its meaning […] Rather than working within carefully constructed boundaries and methodologies established by researchers, it broadly generalizes entire fields of academic expertise and dismisses many of them as inferior […] Scientism restricts human inquiry. (p. 15)

Scientism has grown slowly by gaining authority and standing over many domains of life until it became pervasive and entrenched in the worldview of many individuals and groups.

Science should not be driven by zealous agenda or speak with confidence and authority where it is on shaky ground. It is the duty of scientists, philosophers and theologians to engage robustly in scholarly intellectual discourse – the ‘big questions’ have implications for worldview and the general public need to rely on the highest level of integrity and ethics by those who engage in and communicate these matters.

The scientific method

A brief appraisal of the scientific methodology employed in this paragraph with reference to two relevant fields having an impact on worldview highlights the importance of rigour in scientific reasoning and a realisation of its limits. In particular, the process of hypothesis verification of gravity and quantum physics are contrasted against the process of hypothesis verification of biological evolutionism. Quantum mechanics and general relativity are contrasted against macroevolution, in terms of the attributes of the scientific method.

☐ Quantum physics and general relativity

Quantum physics and general relativity are exact scientific sub-disciplines of physics; they rely heavily on precise mathematical descriptions of theory and laws of nature. The mathematical rigour employed in physics leaves no room for conjecture. Both fields are governed by precise formulas and verified to a stunning level of accuracy. The extension of Newtonian physics to special relativity and later to general relativity is a classic example of the rigorous process of hypothesis verification: extend the validity range of a theory systematically, until validity breaks down, then revise or refine the theory within a consistent framework to extend the validity range. If this cannot be done, the theory is rejected and replaced by a more general theory.

The intellectual Platonic ideal, *follow the evidence wherever it leads*, is followed without compromise. The validity range of a theory is openly and cautiously proclaimed and rigorously applied. Such rigour allows for the co-existence and application of general relativity and quantum mechanics (amidst the ongoing quest for a grand unifying theory) within known boundaries and is pervasive in everyday use and application. Predictions are made and theories are falsifiable. This rigour underpins the findings of modern physics and cosmology: the Big Bang and a richness of findings elucidating global and local fine-tuning – in support of the philosophical arguments of the cosmological argument and the argument from design. Consensus on the validity and reach of these theories prevails in the physics community. Physics is on a continual quest to search deeper and further to understand its natural underpinnings, which are based on complex principles, often going significantly beyond intuition.

A cautionary note: in spite of the relative maturity of the field of cosmology, a physical science having gained tremendously from established theories in physics, ‘cosmology necessarily involves pushing the nature of scientific investigation to the limits, where philosophical assumptions rather than experiments and data start to shape theories’. Cosmology (and astronomy) are observational sciences, with limited opportunities for experimentation. There are still some major open scientific questions in cosmology in spite of successes where model predictions could be verified, for example, galaxy red-shift, cosmic background radiation, matter compositions in galaxies and primordial element abundancy measurements. Open questions include so-called dark energy, dark matter, the applicability of general relativity on large scales, the cause and nature of cosmic inflation, the matter or anti-matter asymmetry found ‘locally’, the question whether space is open, closed or flat, and other cosmological questions – questions with deep philosophical implications (Ellis 2021).

☐ Hypo-critical science

The hyphen in 'hypo-critical' is intended: science betraying the scientific method. Any scientific discipline easily generates pseudoscience or conjecture when:

1. it loses or compromises critical appraisal of the distinction between hypothesis and theory
2. it generalises and overreaches beyond validity domain.

This has been demonstrated in some ontological naturalistic arguments regarding the reach of macroevolution, the idea of 'survival of the fittest', which rests on the heritable variability of individuals within populations to survive and reproduce, which is non-random if subjected to non-random external influences.

Can any criticism be levelled against macroevolution without suspicion of ulterior motives? Proponents of Darwinism see criticism of macroevolution as motivated by fundamentalist creationist ideas. However, evolution and belief in God are not necessarily contradictory. Early in the 20th century, the prominent French Jesuit priest (also philosopher, palaeontologist and geologist), Pierre Teilhard de Chardin, argued convincingly that evolution does not replace God, as God could well work through evolution by creating the laws or conditions of evolution. Teilhard said. 'I see no contradiction between evolution and my faith in God'. (Teilhard De Chardin 2008, p. 200). In Teilhard's view, evolutionary processes 'do not replace an original creator who has set evolution in motion and created the germ of life' (Aczel 2014, p. 140). This view resonates with the views of most theistic evolutionists.

In *Where the Conflict Really Lies*, philosopher Alvin Plantinga (2011, p. 9) argues convincingly that 'there is superficial conflict but deep concord between science and theistic religion, but superficial concord and deep conflict between science and naturalism'.

A question emerging from the notion that the human mind 'emerged' from an unguided random evolutionary process has to be whether the beholder can trust the outcomes of a mind that came into existence purely 'bottom-up' from constituent parts and unguided processes supposedly geared towards survival. The notion that mind can emerge from lifeless matter through random processes is deeply flawed, inconsistent with reason, logic or common sense.

Evolutionary theists view macroevolution as part of the 'evolutionary consensus' and generally avoid criticism of macroevolution – some even defend macroevolution in spite of its many scientific controversies. These viewpoints are, in the opinion of Casey Luskin (2014a), scientifically flawed, theologically hostile and apologetically weak. Hence the discussion among theists is often dominated by divergent opinions about the validity and reach of macroevolution and its implications for education and worldview.

Darwin's hypothesis contained many difficulties, although his ideas hinged on the well-understood and demonstrated artificial selection observed in (uncontroversial and generally accepted) microevolution and could explain observed inconsistencies (adaptation of species, extinct species, uneven species distribution, vestigial biological structures). In *The Origin of Species*, Darwin (1872) recorded his doubt; he was nevertheless confident that his explanation was the best available:

> Long before the reader has arrived at this part of my work, a crowd of difficulties will have occurred to him. Some of them are so serious that to this day I can hardly reflect on them without being in some degree staggered; but, to the best of my judgment, the greater number are only apparent, and those that are real are not, I think, fatal to the theory. (p 162)

In spite of his confidence, Darwin (1872) recognised the difficulties of his ideas:

> [*W*]hy, if species have descended from other species by fine gradations, do we not everywhere see innumerable transitional forms? [...] Why [*are*] species [...] well defined? [...] Can we believe that natural selection could produce, on the one hand, an organ of trifling importance, such as the tail of a giraffe, which serves as a fly-flapper, and, on the other hand, an organ so wonderful as the eye? [...] [*C*]an instincts be acquired and modified through natural selection? What shall we say to the instinct which leads the bee to make cells, and which has practically anticipated the discoveries of profound mathematicians? (p. 162)

The evidence that new distinct biological species should evolve was conspicuously absent to Darwin and is still absent, more than 150 years after his hypothesis. The emergence in all advanced life forms of sophisticated eukaryotic cells, containing irreducibly complex structures such as mitochondria, membrane protection and genetic material in a nucleus, are not fully understood or explained through evolutionary mechanisms. Darwinism cannot explain the information in DNA – no random process has ever explained the emergence of sentient life or intelligence (Aczel 2014):

> Consciousness, symbolic thinking, self-awareness, a sense of beauty, art, and music, and the ability to invent language and pursue science and mathematics – these are all qualities that transcend simple evolution: they may not be absolutely necessary for survival. (p. 153)

The qualities surpass survival instincts akin to evolution and may well be described as divine gifts.

To claim that evolution explains everything by natural selection is a hasty generalisation and glaring overreach. In spite of macroevolution being reconcilable with theism and in spite of the advances in many fields that could provide support for macroevolution, within the scientific method, it remains controversial. The generalisations from microevolution to macroevolution are descriptive, do not follow logically within a consistent framework and lack explanatory power. New terminology is often invented in what appears to be a lack of a rigorous scientific approach. Macroevolution lacks the advantages of rigorous mathematical expression and the power of mathematical effectiveness. There seems to be little use of formulas and accuracy is unknown. It seems to describe nature directly and has many attributes of historical science. Theories are somewhat general and invoke simple-looking principles in a rather *ad hoc* manner. The relationship between punctuated equilibria, species selection, major transitions, historical contingency and the relationship between micro- and macroevolution are not unambiguously elucidated to form an integrated theory of evolution at large scales. The question arises as to whether these ideas represent something like 'a heterogeneous grab bag of scientific ideas that are more or less useful in different contexts?' (Turner & Havstad 2019).

Macroevolution fails to provide a consistent theoretical framework to explain, for example, a feasible mechanism to generate the prebiotic process of abiogenesis, origin of the genetic code, the genetic information required for life, the sudden appearance of species in the fossil record. Neo-Darwinism has consistently rendered inaccurate Darwinian predictions about rudimentary organs and 'junk DNA'. Darwinism struggles to explain behavioural and cognitive abilities in humans, ostensibly lacking survival advantage (Luskin 2014b). Casey Luskin presents a review of the failure of evolutionary models of palaeoanthropology, archaeology, genetics and psychology to account for human origins in Chapter 9 of this book.

When the attributes of 'pure science' and the scientific method are used as a yardstick, macroevolution does not live up to expectations, given it being touted by some as an explanation for the emergence of sentient life or, more, to 'replace God' as it were. The issue here is that macroevolution seems hypocritical, in the methodological naturalistic sense, and even more so with its ontological baggage, it appears hypocritical for failing to recognise its ontological component.

■ Conclusion

The science-faith dialogue attracts many because of its contemporary scientific and philosophical relevance and deep connectedness with worldview, which concerns the very essence of existence, origin, purpose and destiny of nature and sentient life. Making sense of the world involves our deepest intuitions and all our senses and cognitive abilities, to estimate the nature, value, quality, ability, extent and significance of those premises we adopt, which we believe are best to make sense of the world we live in, to understand our place in the vast cosmos.

From a natural theological perspective, the view expressed by Conway (2000) resonated throughout history and is still resonating in the age we live in, with increasing beauty and crisp clarity:

> [*T*]he explanation of the world and its broad form is that it is the creation of a supreme omnipotent and omniscient intelligence, more commonly referred to as God, who created it in order to bring into existence and sustain rational beings such as ourselves who, by exercising their intellects, can become aware of the existence of God and thereby join their Creator in the activity of contemplating God in which activity God is perpetually and blissfully engaged. (p. 13)

The vastness of our world in all its dimensions, the richness of humanity's total experience, our consciousness compels us to ask those deep questions about our existence with cognition and affection. This richness of information and depth of intuition and insights are continuously changing, inferred from dynamically changing stimuli and often leave us with unanswered questions, even inconsistencies or (false) dichotomies.

If the pursuit of truth is driven by naturalistic zeal, any form of inquiry:

1. speaks with righteous authority where it is on shaky ground
2. tends to overreach and conjecture
3. invokes and builds on fallacies
4. disparages domains of legitimate inquiry
5. generates disharmony.

Such distorted pictures of our world are not conducive to concordant dialogue, where elucidation of scientific discovery and philosophical insights and theological revelation can attract us to the marvels of life and the universe and can incalculably intensify our appreciation and admiration for creation.

The words of Tertullian (*c*. 155 AD–*c*. 220 AD), the prolific early Christian author: 'We conclude that God is known first through Nature, and then again, more particularly, by doctrine; by Nature in His works, and by doctrine in His revealed word' (Galilei 1957, p. 3) still ring invitingly as a model for reconciling science and faith.

While the Christian scientist's religious convictions obtained from natural theological arguments may have obtained a rational cogency as being concordant with reason, the divine gifts and revelation from God through his Word and his Spirit bring immeasurable joy and meaning to life and remind us to (1 Pt 3):

> [*I*]n your hearts revere Christ as Lord. Always be prepared to give an answer to everyone who asks you to give the reason for the hope that you have. But do this with gentleness and respect [...]. (v. 15; New International Version)

Chapter 2

Qualified agreement: How scientific discoveries support theistic belief

Stephen C. Meyer
Center for Science and Culture,
Discovery Institute,
Seattle, Washington, United States of America

Introduction[3]

Alfred North Whitehead (1926) said that:

> [*W*]hen we consider what religion is for mankind and what science is, it is no exaggeration to say that the future course of history depends upon the decision of this generation as to the relations between them. (n.p.)

Whitehead spoke early in the 20th century at a time when most elite intellectuals believed that science contradicted classical theism with its traditional belief in a divine creator, the uniqueness of humanity and the immortality of the soul.

---

[3] Sections of this chapter represent a substantial reworking and amalgamation of the following four publications: (1) Meyer (1999b, pp. 1–38), with gratitude to the Editor-in-Chief Oskar Gruenwald who grant permission for the reworking of the original published article; (2) Meyer (2000a, pp. 127–194); (3) Meyer (2008) and (4) Meyer (2021). Readers are encouraged to examine Meyer 2021, a book-length treatment of some of the ideas of this chapter. Special thanks to HarperOne for their kind permission.

How to cite: Meyer, SC 2022, 'Qualified agreement: How scientific discoveries support theistic belief', in F van Niekerk & N Vorster (eds.), *Science and Faith in Dialogue*, in Reformed Theology in Africa Series, Vol. 10, AOSIS Books, Cape Town, pp. 33–63. https://doi.org/10.4102/aosis.2022.BK334.02

For many intellectuals, a scientifically informed worldview was a materialistic worldview in which entities such as God, free will, mind, soul or purpose could play no objective role. Scientific materialism denied evidence of any ID in nature and any ultimate purpose to human existence. As Whitehead's contemporary Bertrand Russell put it, 'man is the product of causes which had no prevision of the end they were achieving' and which predestine him 'to extinction in the vast death of the solar system' (Conant 1953).

It is not hard to see why many intellectuals held this opinion. Over the previous 200 years, Western science and philosophy had witnessed a profound shift away from its earlier Judeo-Christian orientation. Starting in the Enlightenment, many philosophers began to deny the validity of the classical proofs for God's existence from nature. Philosophers such as David Hume and Immanuel Kant raised powerful objections to the design argument and the cosmological argument, the two most formidable theistic arguments of this kind.

Furthermore, despite the now well-documented influence of Judeo-Christian thinking on the rise of modern science from the time of Robert Grosseteste and William of Ockham to Robert Boyle and Sir Isaac Newton (see Butterfield 1967, pp. 16–17, 19; Eisley 1961, p. 62; Foster 1934; Hodgson 1974; Hooykaas 1972; Pearcy & Thaxton 1994, pp. 17–42, 43–56; Von Weizsacker 1964, p. 163; Whitehead 1926, pp. 3–4, 12–13), much of 19th century science took a decidedly materialistic turn. Scientific origins theories in particular seemed to support the materialistic vision of an autonomous and self-creating natural world. In astronomy, the French mathematician Laplace offered an ingenious theory known as the nebular hypothesis to account for the origin of the solar system as the outcome of purely natural gravitational forces (Hetherington 1997).[4] In geology, Charles Lyell explained the origin of the earth's most dramatic topographical features – mountain ranges and canyons – as the result of slow, gradual and completely naturalistic processes of change (Lyell 1830–1833). In astronomy and physics, a belief in the infinity of space and time obviated any need to consider the question of the ultimate origin of matter (Luminet 2016). Perhaps most significantly, Darwin's evolutionary theory sought to show that the blind process of natural selection acting on random variations could and did account for the origin of new forms of life without any discernible guidance or design. According to Darwin, living organisms only *appeared* to be designed by an intelligent creator; nature itself was the real creator (Darwin 1985; see Meyer 2008).[5] As Francisco Ayala (1994) has explained:

> The functional design of organisms and their features would [...] seem to argue for the existence of a designer. It was Darwin's greatest accomplishment to show that the directive organization of living beings can be explained as the result of a natural process, natural selection, without any need to resort to a Creator or other external agent. (p. 4)

---

[4] The nebular hypothesis was also developed independently by Emanuel Swedenborg and Immanuel Kant.

[5] See a detailed discussion in Meyer (2008).

These theories, taken jointly, suggested that the whole history of the universe could be told as a seamless, or nearly seamless, unfolding of the potentiality of *matter and energy.* Thus, science seemed to support, if it could be said to support anything, a materialistic or naturalistic worldview, not a theistic one. Science no longer needed to invoke a pre-existent mind to shape matter in order to explain the evidence of nature. Matter had always existed and could – in effect – arrange itself without a pre-existent designer or creator. Thus, by the close of the 19th century, both the logical and evidential basis of theistic arguments from nature had seemingly evaporated.

The demise of theistic arguments from nature and the corresponding rise of a scientifically based materialistic worldview fostered a profound shift in the way many scientists and scholars conceptualised the relationship between science and Christian faith or theistic belief. With the rise of scientific materialism or naturalism, many scientists, philosophers and even theologians during the 20th century began to perceive science and theistic belief as standing in conflict with one another.[6] Others, however, denied that science contradicts theistic or Christian beliefs. Nevertheless, they have typically done so by portraying science and religion as such totally distinct enterprises that their teachings do not intersect in significant ways. Some subscribed to a model of science and faith integration called 'compartmentalism' or what Stephen J. Gould would later call NOMA ('non-overlapping *magisteria*') (Gould 1999). Compartmentalism holds that science and religion describe completely different realities. In support of this view, proponents often quote an aphorism attributed to Galileo, 'the Bible tells us how to go to heaven, not how the heavens go' (Galilei 1615). Others subscribed to a closely related idea called 'complementarity' (Peterson 1989).[7] Proponents of this view acknowledge that science and religion may sometimes describe the same realities, but they do so in complementary but ultimately incompatible or 'non-commensurable' language (MacKay 1974; Van Till 1986; Van Till, Young and Menninga 1988).[8] Both these models assumed the religious and metaphysical neutrality of scientific knowledge (MacKay 1974; Van Till 1986; Van Till et al. 1988).[9]

---

[6] A classic book promoting the warfare model is Andrew D. White's 1896 book *History of the Warfare of Science with Theology in Christendom*.

[7] Michael Peterson provides a helpful threefold typology of perceived relationships between science and religion (Peterson 1989). Peterson discusses the conflict, compartmentalism and complementarity models of science and religion interaction. He does not, however, consider the possibility that scientific evidence might support theistic belief although that remains a logical possibility. I have, therefore, proposed (and am defending here) a fourth model called 'qualified agreement' or 'epistemic support' (see Meyer 2000b; Dembski & Meyer 1998, p. 415–430).

[8] See also Gruenwald (1994) for a different interpretation of complementarity, which affirms methodological autonomy of science and religion but conjoins their findings.

[9] See also Gruenwald (1994) for a different interpretation of complementarity, which affirms methodological autonomy of science and religion but conjoins their findings.

Thus, some have seen the witness of science as hostile to theistic and Christian faith, while others have attempted to cast it as entirely neutral. Few, however, have thought – in contrast to the founders of early modern science such Kepler, Boyle and Newton[10] – that the testimony of nature (i.e. science) actually supports important tenets of a theistic or Christian worldview.

This chapter reasserts this classical view and argues that scientific evidence does provide epistemological support (though not proof) for the theistic worldview affirmed by biblical Christianity (see e.g. Ac 17, Col 1, Rm 1). It will develop a model of the relationship between science and theistic belief that I call ‘qualified agreement’ or ‘mutual epistemic support’. This model maintains that, when correctly interpreted, scientific evidence and biblical teaching can and do support each other. While accepting some disagreement about details as inevitable given the limits of human knowledge, advocates of this model affirm a broad agreement between the testimony of the natural world and the propositional content of Judeo-Christian theism – between science and religion so defined. Although advocates of qualified agreement acknowledge (with compartmentalism and complementarity advocates) that much scientific research and theorising does address metaphysically and religiously neutral topics, we do not agree that *all* scientific theories have this character.

Instead, the qualified agreement model, like the conflict model, asserts that some scientific theories do have a larger worldview or metaphysical implications. Nevertheless, unlike the conflict model, qualified agreement denies that the best or most truthful theories ultimately contradict a theistic or Christian worldview. Instead, it views theological and scientific truth as issuing from the same transcendent and rational source, namely God. Advocates of qualified agreement anticipate, therefore, that these two domains of knowledge, when rightly understood and interpreted, will come increasingly into the agreement as advances in science and theology eliminate real points of conflict that have sometimes existed.

Because many of the founders of early modern science held this view (although with a less nuanced justification, perhaps), I will also refer to this model as the ‘classical’ formulation of the relationship between science and religion. Indeed, from the late-Middle Ages through the Scientific Revolution (roughly 1250–1750), scientists often affirmed the agreement between ‘the book of nature’ and ‘the book of scripture’, both of which were understood to be mutually reinforcing revelations of the same God.

This chapter will update the case for this view by giving examples of contemporary scientific evidence from three fields: (1) cosmology, (2) physics and (3) biology that now supports a theistic worldview. It will also provide a

---

[10] For a discussion on how the Christian faith helped establish the foundation for modern science, see Pearcy and Thaxton (1994).

more refined notion of epistemological support. Many thinkers, both theistic and naturalistic, have assumed that science supports a Christian or theistic worldview only if it can provide the basis for a deductively certain proof of God's existence. I will argue that this demand expresses an unrealistically high epistemological standard for any empirically based enterprise, including the natural sciences. Even so, I will show how evidence from the natural sciences can and does provide epistemological support for Christianity or theism without having to underwrite such proofs.

The rise and fall of theistic arguments[11]

Two types of arguments for God's existence from nature have proven especially effective in the history of Western thought: the design (Manson 2003) and cosmological (Craig 2001) arguments. The classical design argument begins by noting certain highly ordered or complex features within nature, such as the configuration of planets or the architecture of the vertebrate eye. It then proceeds to argue that such features could not have arisen without the activity of a pre-existent intelligence (typically identified as the mind of God).

The cosmological argument starts from the existence and causal regularity of the universe and seeks to deduce a necessary being – that is, God – as the first cause or sufficient reason for the universe's existence (Craig 1994). One version of the cosmological argument, known as the Kalam cosmological argument, asserts that 'anything that begins to exist' must have a cause and that the universe had a temporal beginning. (Medieval philosophers typically sought to justify that latter proposition by showing the logical or mathematical absurdity of an actual infinite regress of cause and effect.) The argument then concluded by affirming that the beginning of the physical universe must have resulted from an uncaused first cause – namely, God – who exists independently of the universe (Craig 1994, 2000; Swinburne 1979).

Because of the popularity of these arguments throughout much of Western history, many philosophers and scientists viewed science (and philosophy) and theistic belief as mutually reinforcing. Yet, the most important versions of these arguments came into disrepute by the end of the 19th century because of developments within both philosophy and science.

The demise of the design argument

With the advent of the Enlightenment, both Judeo-Christian belief and the design argument came under attack. For example, the sceptical empiricist philosopher David Hume (1711–1776) rejected the existence of God and the validity of the design argument (Hume 1989). Hume maintained in his *Dialogues Concerning*

---

[11] The following section is predominantly based on a reworking of Meyer (1999b, pp. 1–38).

Natural Religion (1779) that the design argument depended on a flawed analogy with human artifacts. He admitted that artifacts derive from intelligent artificers, and that biological organisms have certain similarities to complex human artifacts. Eyes and pocket watches both depend on the functional integration of many separate and specifically configured parts. Nevertheless, he argued, biological organisms also differ from human artifacts – they reproduce themselves, for example – and the advocates of the design argument fail to take these dissimilarities into account. Since experience teaches that organisms always come from other organisms, Hume argued that analogical argument really ought to suggest that organisms ultimately come from some primeval organism (perhaps a giant spider or vegetable), not a transcendent mind or spirit.

Despite his objections, Hume's categorical rejection of the design argument did not prove decisive with either theistic or secular philosophers. Thinkers as diverse as the Scottish Presbyterian Thomas Reid (1710–1796) (Lehrer 1987) and the Enlightenment deist Thomas Paine (1925) continued to affirm the validity of the design argument because of the order they perceived in nature. Even Immanuel Kant (1724–1804), who rejected the design argument as proof of the transcendent and omnipotent God of Judeo-Christian theology, accepted that it could establish the reality of a powerful and intelligent author of the world.[12] Kant sought to limit the scope of the design argument but did not reject it entirely.[13]

In any case, science-based design arguments continued into the early 19th century, especially in biology. William Paley's (1743–1805) *Natural Theology* (Paley 1802), published in 1803 (several years after Hume's criticism of the design argument), catalogued a host of biological systems that suggested the work of a superintending intelligence. He argued that the astonishing complexity and superb adaptation of means to ends in such systems could not originate strictly through the blind forces of nature, any more than could a complex pocket watch. Indeed, despite the widespread currency of Hume's objections, many scientists continued to find Paley's watch-to-watchmaker reasoning to be compelling well into the 19th century.

Thus, it was not ultimately the arguments of the philosophers that undermined the popularity of the design argument, but the emergence of increasingly powerful materialistic explanations of apparent design, particularly Charles Darwin's theory of evolution by natural selection. In 1859, Darwin proposed a completely naturalistic mechanism, natural selection acting on random variations, to explain the origin of new forms of life as well as the adaptation of organisms to their environment. Thus, in his view, living organisms – which had always been seen as the most obvious example of

---

[12] In Immanuel Kant's (1963) words, 'physical-theological argument can indeed lead us to the point of admiring the greatness, wisdom, power, etc., of the Author of the world, but can take us no further'.

[13] See detail discussion in Meyer (2006).

God's creative power – only 'appeared' to be designed. Indeed, as Francisco Ayala (1994), William Provine (1988), Douglas Futuyma (1986), Richard Dawkins (1986) and G.G. Simpson (1967) have all affirmed, Darwinism and modern neo-Darwinism deny (*contra* biblical theism) any discernible evidence of divine purpose, guidance, direction or design in living systems. Neo-Darwinism teaches, as G.G. Simpson once put it, 'that man is the result of a purposeless and natural process that did not have him in mind' (Simpson 1967, pp. 344–345). Or as Miller and Levine (1993, p. 63) argue, 'evolution works without either plan or purpose'. And, clearly, if the origin of biological organisms can be explained completely naturalistically, then design arguments invoking the need for an intelligence to explain the origin of living systems seem unnecessary and even vacuous (Darwin 1985, p. 453).

The demise of the cosmological argument

The demise of the cosmological argument also began with Enlightenment philosophers. Kant, for example, challenged the arguments of medieval Christian, Islamic and Jewish thinkers related to the need for a first cause of the universe. He argued that there could be an unbroken line of material effects and causes going back infinitely in time, thus eliminating the need for a transcendent or immaterial First Cause. Instead, Kant accepted the possibility that the material universe itself might be eternal and self-existent (Kant 1963, pp. 511–512).

Kant's scepticism about the cosmological argument and, in particular, the Kalam version of it found reinforcement in the scientific world picture of the 18th and 19th centuries. Though Newton supported the design argument, one aspect of his physics – the postulation of infinite space – helped to indirectly undermine the Kalam cosmological argument.[14] According to Newton's theory of universal gravitation, all material bodies attract one another. Yet this created a puzzle. According to Newton's theory, every star should gravitate towards the centre of the universe until the whole universe collapses in on itself.

To offset the tendency of the universe 'to convene into one mass' as a result of the gravitational attraction of the bodies within it, Newton proposed

---

[14] The Kalam cosmological argument attempts to argue for the existence of God as a necessary first cause for the origin of a finite universe. The Kalam argument is not the only version of the cosmological argument, however. St. Thomas Aquinas argued for God as a necessary first cause of the universe, not in a temporal sense, but in an ontological sense (Craig 1994, pp. 80–83). Gottfried Leibniz championed another version of the cosmological argument in which he postulated God as the only 'sufficient reason' for the contingent causal structure of the universe as a whole. These versions of the argument were not predicated upon a finite universe. Though they remained in philosophical currency well after the repudiation of the Kalam argument during the enlightenment, they had less popular appeal due in part to their philosophical complexity. In any case, the demise of the Kalam argument had a tremendously negative effect on both popular and scholarly perceptions of the relationship between science and religion in part perhaps because Newtonian physics helped to undermine it. Moreover, its resuscitation as the result of scientific discoveries in the 20th century has provided considerable epistemic support for a theistic world view, whatever the status of the Thomistic and Leibnizian versions of the argument then and now. For Newton's own version of the design argument (in physics), see Newton (1713).

that ‘the matter was eavenly diffused through an infinite space’ (Newton 1959–1977, vol. 3, p. 234). He thought that if there were an infinite number of stars scattered evenly throughout a universe of infinite space, then every star would attract every other star with equal forces in all directions simultaneously. Thus, the stars would remain forever suspended in a tension of balanced gravitational attraction (Hawking 1988, p. 9). Newton also found the infinite universe appealing for theological reasons. He thought of space as a ‘Divine Sensorium’, a medium in which God perceived His creation.[15] Since God was infinite, space had to be as well.

Physicists with a more materialistic outlook later found Newton’s infinite and static universe concept philosophically agreeable. Some extended the infinite-static universe model by assuming that if space must be infinite, then time must also be infinite in both the forward and reverse directions.[16] Even so, few physicists and astronomers explicitly articulated this view during the 19th century. Rather, with the rise of scientific materialism, many scientists and philosophers simply seemed to assume that the universe must be eternal and self-existence (Hawking 1988, p. 6). By the end of the 19th century, this view had become deeply entrenched in the scientific community and provided a powerful reason for rejecting the Kalam cosmological argument that depended on the premise of a temporally finite universe.

Failed theistic arguments and the rise of scientific materialism

The demise of these two theistic arguments and the emergence of a fully materialistic account of the origin of the natural world – from the infinite past to the dawn of human life on Earth – had a profound effect on the perception of the relationship between science and theistic belief.[17]

Philosophical materialists regarded the emergence a comprehensive materialistic account of natural history as epistemic support for their worldview. Consequently, they perceived science and theism as standing in opposition. If theism asserts the reality of a purposive creation, and if science could

---

[15] As Thayer (ed. 2012) writes, ‘Newton speaks, in the *Optics*, of space as the *divine sensorium*; space is that in which the power and will of God directs and controls the physical world. Space is not to be identified with God [...] Newton says in this scholium that God ‘governs all things, and knows all that are or can be done. He is not eternity or infinity, but eternal and infinite; He is not duration or space, but he endures and is present. He endures forever, and is everywhere present; and by existing always and everywhere, he constitutes duration and space’. God constitutes duration and space since ‘by the same necessity [as he exists] he exists *always* and *everywhere*’ (cf. ed. Thayer 2012, pp. 185–186).

[16] Newton believed that the material contents of the universe were created a finite time ago, but that time had existed infinitely far back (Newton 1728).

[17] Again, see detail in Meyer (2008, 2021).

account for the origin of living organisms, for example, by reference to wholly undirected material processes, then one of these two views must be incorrect. For this reason, the demise of the design and cosmological arguments during the 18th and 19th centuries contributed to the rise of the 'conflict' model of the relationship between science and religion.

Oddly, the demise of these arguments contributed to the rise of the compartmentalist (NOMA) and complementarity models as well. Advocates of these models developed them to defend theistic belief against the aggressive philosophical materialism of many conflict theorists. But to counter the claims of scientific materialists advocates of NOMA and complementarity had to insist upon the strict metaphysical and religious neutrality of even the most apparently materialistic origins theories (MacKay 1974; Van Till 1986; Van Till et al. 1988). That inclined them to concede the validity of those theories. Proponents of these models have thus argued that materialistic origins theories do not necessarily contradict theological accounts of creation as God may have used Darwinian mechanisms, or other similarly materialistic processes, to create the world. On this view, statements about the *purposelessness* of evolution do not represent scientific statements *per se*, but 'Evolutionism' – an 'extra-scientific' apologetic for philosophical materialism. Thus, advocates of NOMA and complementarity generally have not only conceded the scientific legitimacy of materialistic theories of origin they typically also reject science-based design and cosmological arguments.

In any case, the demise of theist arguments during the 18th and late 19th centuries led scientists to assert that either (1) science contradicts Christian or theistic belief or (2) to deny that science has any religious or metaphysical implications whatsoever. Either way, scientists and philosophers have for the most part denied that the testimony of nature affirmatively *supports* to theistic belief.

The Return of the God Hypothesis

Nevertheless, during the 20th and 21st centuries, a quiet but remarkable scientific shift has occurred. The evidence from cosmology, physics and biology now tells a different story than did the science theories of the late 19th century. Evidence from cosmology now supports a finite, not an infinite universe, while evidence from physics and biology has reopened the question of design.

General relativity and the Big Bang Theory

During 1915–1917, Albert Einstein shocked the scientific world with his theory of general relativity (Chaisson & McMillan 1993; Einstein 1915, 1916; Lorentz et al. 1923). Though Einstein's theory challenged Newton's theory of gravity in many important respects, it also implied (as did Newton's) that the universe would collapse in on itself unless a contravening force were at work. According to general relativity, massive bodies alter the curvature of space (or more precisely 'space-time') so as to draw nearby objects to them. To illustrate, imagine placing a bowling ball on a trampoline covered with tennis balls. Einstein's conception of gravity implied that all material bodies would congeal and space would contract in on itself unless the effects of gravitation were continually counteracted by the expansion of space itself (Eddington 1930). Yet, as such a contraction has not happened (at least not yet) and as, further, the universe we observe today contains matter surrounded by empty space, Einstein thought something – some outward pushing force of expansion – must be counteracting the effect of gravitation to account for the empty space between massive bodies in the universe.

Thus, in his famous 1917 paper, 'Cosmological Considerations in the General Theory of Relativity', Einstein (1917) posited a 'cosmological constant' to describe a constantly acting repulsive force countering the effects of gravitational contraction.[18] He further assigned *a precise value* to the cosmological constant to ensure that the strength of gravity and the repulsive force described by this constant exactly balanced so as to sustain the universe in a kind of equipoised, static state – one neither expanding outward from a beginning nor collapsing inward toward an end.[19]

Einstein's choice of the value for the cosmological constant had no physical justification apart from his assumption of a static universe – an assumption he favoured for philosophical reasons.[20] In particular, his assumption of a static

---

[18] In this paper, Einstein argued that his equations allowed for a static universe if two assumptions held: (1) that the curvature of space was negative (like the surface of a sphere) and (2) that the field equations included an additional term known as the cosmological constant (with a precisely calibrated value). For a historical overview, see https://blogs.scientificamerican.com/guest-blog/einsteins-greatest-blunder/

[19] Einstein's field equations represent the radius and curvature of the space in the universe at a given time as a function of the mass-energy density within space. Einstein's field equations included a term called the stress-energy tensor that depicts how mass-energy functions to curve space inward based upon different parameters, most importantly the density of mass-energy and the radiation pressure within space. This tensor can have a positive value that corresponds to mass curving space more tightly. It can have a zero value in the absence of matter in a given volume of space. But it cannot have a negative value corresponding to an 'uncurving' or the expansion of space, because according to Einstein's theory, the mass-energy in the universe always curves space towards itself. Consequently, to account for the origin of space in the first place, Einstein needed to invoke something else that could plausibly explain (or describe) how space itself expands. To do this, Einstein proposed his cosmological constant to represent the energy *inherent in space itself* – energy that causes space itself to expand. In order to depict a static – neither expanding nor contracting universe – he further assigned an extremely precise value to this negative vacuum energy so as to balance its repulsive force precisely against the gravitational attraction produced by the mass energy contained in space (as opposed to the energy inherent in space).

[20] Though the *value* for the cosmological constant that he chose was arbitrary in the sense of being unmotivated by any physical consideration other than his assumption that the universe must be static, the constant itself did appear naturally in the derivation of the field equations as a constant of integration.

universe allowed him to conceive of the universe as eternal and self-existent (Singh 2005, pp. 116–143).

Immediately after Einstein published his cosmology paper, a series of mathematical results challenged his static universe in various ways (Nussbaumer 2014). In 1922, the Russian physicist Alexander Friedmann solved Einstein's gravitational field equations. Friedmann's solutions and resulting equations included terms that allowed the density and radius of the universe to change or vary with time – a possibility that Einstein's arbitrary choice of the cosmological constant and initial conditions foreclosed.

Friedmann's solutions to Einstein's field equations describing how matter bends space implied a dynamic universe for *almost all* values of the cosmological constant and almost all choices of initial conditions. Consequently, though Friedmann did not disprove Einstein's static universe concept, his solutions to the field equations implied the need for an implausible degree of fine-tuning in both the value of the cosmological constant and the initial conditions of the universe in order to maintain a balance between the pressure of cosmic expansion and gravitational attraction.

Other discoveries and theoretical developments only highlighted this implausibility. In 1927, the Belgian priest and physicist Georges Lemaître independently produced the same solutions to the field equations. Lemaître, however, not only showed that the field equations most naturally implied a dynamic universe; he also used observational data about distant nebulae to formulate a definite cosmological model of the origin of the universe (Luminet 2007).

Specifically, he incorporated observations of the light from distant galaxies into his model of the origin of the universe. In 1912, a young astronomer named Vesto Slipher had shown that the light from what were then called 'nebulae' typically exhibited spectral lines that were shifted as a group *en masse* towards the red (longer wavelength) end of the electromagnetic spectrum.[21] This evidence of 'red-shift' suggested recessional movement, for the same reason – the so-called Doppler effect – that a train whistle drops in pitch (and sound waves lengthen) as a train moves away from a stationary observer.

Then in 1924 another astronomer, Edwin Hubble working with the 100-inch Hooker Telescope at Mount Wilson in California showed that Slipher's nebulae were in fact distant galaxies beyond our Milky Way. By correlating Slipher's red-shift data with Hubble's 1924 measurements of the distances to other galaxies, Lemaître realised that the galaxies beyond our Milky Way were receding from Earth in all directions. He also determined that the galaxies that

---

[21] In other words, the spectral lines corresponded to longer wavelengths than those of laboratory spectra for any given element, although the characteristic pattern of the spectral lines (the specific spacing between the lines) was roughly the same for each element.

were further away were receding faster than those close at hand, a relationship that Hubble would later formulate more precisely. In any case, this 'farther the faster' relationship, later called 'Hubble's law', suggested a spherical expansion of the universe in all directions of space, as if the universe were expanding in all directions from a singular explosive beginning – from a 'Big Bang' (Hubble 1929).

Einstein first learned about the red-shift evidence from Lemaître in a taxicab ride during a conference in Solvang, Belgium in 1927. To his credit, Einstein then later publicly acknowledged the evidence for an expanding universe after visiting Hubble in Pasadena in 1931. He also later said that his postulation of an arbitrary value for the cosmological constant was 'the greatest blunder of my life'.[22]

During the remainder of the 20th century, physicists and cosmologists formulated many alternatives to the new Big Bang cosmology, most of which attempted to restore the idea of an infinite universe. For example, in the late 1940s, Fred Hoyle, Thomas Gold and Hermann Bondi proposed the 'steady state' model to specifically explain galactic recession without invoking the objectionable notion of a beginning. According to the steady-state theory, as the universe expands new matter is generated spontaneously in the space between expanding galaxies. The matter of which our galaxy is made spontaneously popped into existence in between other galaxies that had in turn emerged from the empty space between other galaxies and so on. Hoyle, Gold and Bondi further envisioned a universe of infinite extent in time and space without beginning or end – one that had *always been expanding* in the past and that would also always be expanding in the future (Bondi & Gold 1948).

By the mid-1960s, the steady-state theory ran afoul of a decisive, if unintended, discovery made by two scientists at the Bell Telephone Laboratories in New Jersey. According to the steady-state model, the density of the universe must always remain constant; hence they affirmed the creation of new matter as the universe expands. Yet in 1965, two Bell Lab researchers, Arno Penzias and Robert Wilson, found what physicists believed to be the radiation left over from the universe's initial hot, extremely high-density state. Though physicist George Gamow had predicted the existence of this 'cosmic background radiation' as a consequence of the Big Bang model, advocates of the steady state theory acknowledged that, given their model, such radiation should not exist (Gamow 1946). Thus, the discovery of this radiation with almost the exact predicted wavelength (and a corresponding 'blackbody temperature') proved decisive (Penzias & Wilson 1965). By the 1970s, even Bondi, Gold (though not Hoyle) had abandoned their own theory (Kragh 1993, p. 403).

---

[22] Quoted in the autobiography of George Gamow (1970).

Following the demise of the steady-state model in the mid-1960s, some physicists proposed an oscillating-universe model as an alternative to the finite universe. But as Massachusetts Institute of Technology (MIT) physicist Alan Guth showed in 1984, our knowledge of thermodynamics suggests the impossibility of an indefinitely bouncing universe (Guth & Sher 1983). According to the second law of thermodynamics, the entropy (or disorder) of the matter and energy in the universe would increase over time in each cycle. But Guth showed that such increases in entropy (or the disorderly distribution of mass-energy) would result in less energy *available to do work* in each cycle. That would result in progressively longer and longer cycles of expansion and contraction as increasing inhomogeneities in mass-energy density throughout space would decrease the efficiency of gravitational contraction. Yet, if the duration of each cycle necessary increases as we move forward in time, then it follows that each cycle in the past would have been progressively shorter.[23] Since the periods of each cycle cannot decrease indefinitely, the universe – even on an oscillating model – would have had to have had a beginning.[24]

Prior to the formulation of the oscillating-universe theory, three physicists, Stephen Hawking, George Ellis and Roger Penrose, published a series of papers between 1966 and 1970 that explicated the implications of Einstein's theory of general relativity for the origin of space and time as well as matter and energy (Hawking & Penrose 1970). Hawking and his colleagues showed that as one extrapolated back in time the curvature of space-time would approach infinity. But an infinitely curved space corresponds to a radius (within a sphere for example) of zero units and thus to no spatial volume. Furthermore, as in general relativity space and time are inextricably linked, the absence of space implies the absence of time. Moreover, neither matter nor energy can exist in the absence of space. Thus, the resulting 'Singularity Theorem' based on general relativity implied that the universe sprang into existence a finite time ago from literally nothing, at least nothing physical.

---

[23] Similarly, if in every cycle mass and energy grow progressively more randomised, eventually – given infinite time – the universe would reach heat death in which *no* energy will be available to do work, rather like a rubber ball that bounces to smaller and smaller heights until finally it can bounce no more. Indeed, if the oscillating universe were infinitely old, it should have reached such a state an infinitely long time ago. But since we do not find ourselves in such a cold universe with maximally inhomogeneous distributions of matter and energy, it follows – even assuming an oscillating universe – that the universe has not existed for an infinite amount of time. Indeed, the universe would have reached a nullifying equilibrium long ago if it had indeed existed eternally (see WMAP Science Team 2011).

[24] In any case, recent astronomical measurements suggest that the universe has a mass density slightly less than the so-called 'critical density' necessary to stop the expansion of the universe, thus ensuring that the universe will never re-collapse. Also, the expansion of the universe actually seems to be accelerating, perhaps as the result of what astrophysicists call dark energy. Dark energy is a postulated but unidentified form of energy that putatively permeates all of space and exerts an outward pressure on space, contributing to its expansion – see WMAP Science Team 2011.

British physicist Paul Davies (1978) describes the implications with great clarity:

> If we extrapolate this prediction to its extreme, we reach a point when all distances in the universe have shrunk to zero. An initial cosmological singularity therefore forms a past temporal extremity to the universe. For this reason, most cosmologists think of the initial singularity as the beginning of the universe. On this view the Big Bang represents the creation event; the creation not only of all the matter and energy in the universe, but also of space-time itself. (pp. 78–79)

Taken together, general relativity and the Big Bang Theory provide a scientific description of the origin of the universe not dissimilar to what Christian theologians have long described in doctrinal terms as *creatio ex nihilo* – creation out of nothing (or nothing physical). These theories place a heavy demand on any proposed materialistic explanation of the universe as they imply that any proposed cause of the universe must transcend space, time, matter and energy.

Anthropic 'fine-tuning'

While evidence from cosmology now point to a transcendent cause for the origin of the universe, new evidence from physics suggests an intelligent cause for the origin of its fundamental architecture. Since the 1950s and 1960s, physicists have discovered that life in the universe depends on a highly improbable set of physical forces and features as well as an extremely improbable balance among many of them. The precise strengths of the fundamental forces of physics, the masses of elementary particles, the initial arrangement of matter and energy at the beginning of the universe and many other specific features of the cosmos, such as the exact strength of the cosmological constant that drives the expansion of the universe, appear delicately balanced to allow for the possibility of life. If any of these properties were altered ever so slightly, complex life simply would not be possible. If several of them were altered even slightly, basic chemistry would not be possible.

Physicists now refer to the fortuitous values of these factors as 'anthropic coincidences' (from the Greek *anthropos* for man) and to the fortunate convergence of all these coincidences as the 'anthropic fine-tuning' of the universe (Barrow, Tipler & Wheeler 1988). The term 'fine-tuning' in physics refers to properties of the universe that fall within extremely narrow and improbable ranges that, again, turn out to be necessary for life.[25]

---

[25] Other parameters require so-called 'one-way' fine-tuning. One-way fine-tuning parameters impose a single condition on the existence of life by ensuring that life can only exist if the parameter in question has a value either greater than or less than some particular threshold. Often in these cases of one-sided fine-tuning the value of the parameter in question falls just near the edge of the life-permitting region.

The fine-tuning of these properties has puzzled physicists not only because of their extreme improbability but also because there does not seem to be any necessary physical or logical reason why they have to be as they are. Consequently, philosophers of science call such fine-tuning features ‘contingent’ properties as they could conceivably have been different without violating either fundamental laws of physics or necessary principles of logic or mathematics. Instead, we live in a kind of ‘Goldilocks universe’ where dozens of these contingent properties have just the right strengths or values or characteristics to make life possible.

Many physicists have noted that this fine-tuning strongly suggests design by a pre-existent intelligence. As physicist Paul Davies has put it, ‘the impression of design is overwhelming’ (Davies 1988, p. 203). Consider the following illustration: imagine a cosmic explorer has just stumbled into the control room for the whole universe (Meyer 2021, pp. 143–144). There she discovers an elaborate ‘universe-creating machine’, with rows of dials each with many possible settings. As she investigates, she learns that each dial represents some particular parameter that has to be calibrated with a precise value in order to create a universe in which life can survive. One dial represents the possible settings for the strong nuclear force, one for the gravitational constant, one for Planck’s constant, one for the ratio of the neutron mass to the proton mass, one for the strength of electromagnetic attraction and so on. As our cosmic explorer examines the dials, she finds that the dials can be easily spun to different settings – that they could have been set otherwise. Moreover, she determines by careful calculation that even slight alterations in any of the dial settings would alter the architecture of the universe, causing life to cease to exist.

Yet for some reason, each dial sits with just the exact value necessary to keep a life-sustaining universe running – almost like a bank vault with its door found wide open, its contents missing and every dial set just right. What should someone infer about how such a propitious combination of dial settings came to be set?

Not surprisingly, many physicists have been asking the same question about the anthropic fine-tuning of the universe. As George Greenstein muses, ‘the thought insistently arises that some supernatural agency, or rather Agency, must be involved. Was it God who stepped in and so providentially crafted the cosmos for our benefit?’ (Greenstein 1988, pp. 26–27);[26] or as Fred Hoyle (1982) commented:

---

[26] Greenstein himself does not favour the design hypothesis. Instead, he favours the so-called ‘participatory universe principle’ or ‘PAP’. PAP attributes the apparent design of the fine tuning of the physical constants to the universe’s (alleged) need to be observed in order to exist. As he says, the universe ‘brought forth life in order to exist […] that the very Cosmos does not exist unless observed’ (see Greenstein 1988, p. 223).

> [*A*] common sense interpretation of the facts suggests that a superintellect has monkeyed with physics, as well as chemistry and biology, and that there are no blind forces worth speaking about in nature. (p. 16)

Indeed, for many physicists, the design hypothesis seems an obvious and intuitively plausible explanation for the fine-tuning. They argue that – in effect – the dials in the cosmic control room appear finely tuned because someone carefully set them that way.

☐ Alternative explanations for the fine-tuning

Nevertheless, several alternative naturalistic explanations have been proposed: (1) the so-called weak anthropic principle, which denies the fact that the fine-tuning needs explanation, (2) explanations based upon natural law and (3) explanations based on chance, in particular, the idea that our universe represents the lucky outcome of a vast cosmic lottery that also produced a multiplicity of other universes.

I have critiqued all three of these alternative explanations at length in my recent book *The Return of the God Hypothesis* and elsewhere (Meyer 2021). Nevertheless, it may help readers see why the design hypothesis provides such a compelling explanation of the fine-tuning to summarise some of the problems of the most popular of these naturalistic explanations – the multiverse hypothesis.

☐ The multiverse

To explain the vast improbabilities associated with the various fine-tuning parameters, some physicists have postulated – not a 'fine-tuner' or intelligent designer – but the existence of a vast number of other universes, parallel to our own. The multiverse concept also posits various mechanisms for producing these universes. Having a mechanism for generating new universes would, according to proponents of this idea, increase the number of opportunities for generating a universe capable of sustaining life. Thus, they portray our universe as something like the lucky winner of a cosmic lottery, and the universe-generating mechanism as something like a roulette wheel or a slot machine turning out either winners or losers with each spin or pull on the handle. The universe-generating mechanism spits out billions and billions of universes and ours just happens to be one of the few that can sustain life.[27]

It is important to understand why proponents of the multiverse need some universe-generating mechanism to explain the origin of the fine-tuning.

---

[27] Science writer Clifford Longley (1989, n.p.) explains the multiverse this way: 'There could have been millions and millions of different universes created each with different dial settings of the fundamental ratios and constants, so many in fact that the right set was bound to turn up by sheer chance'.

Most proponents do not think of the different universes that they postulate as interacting with each other. Nor do they expect to have any observational evidence of universes other than our own.[28] Consequently, nothing that happens in one universe would have any effect on things that happen in another universe. Nor would events in one universe affect *the probability* of events in another, including whatever events were responsible for setting the values of the fine-tuning parameters in another universe – or in ours.

Yet if all the different universes were produced by the same underlying causal mechanism, then it would be possible to conceive of our universe as the winner of a kind of cosmic lottery, one in which some winner had to eventually emerge. For this reason, postulating a universe-generating mechanism could conceivably render the probability of generating a universe with life-conducive conditions quite high and in the process explain the origin of the fine-tuning in our universe as the result of an underlying causal process with a randomising element.

Assessing the multiverse

So, does the multiverse concept provide a better explanation of the fine-tuning compared to an intelligent or theistic designer? As I explain in much more detail in my recent book, it does not – and for several reasons. Here are two.

Firstly, as the Oxford philosopher Richard Swinburne has argued, the theistic design hypothesis constitutes a simpler (i.e. more parsimonious) and less *ad hoc* hypothesis than the multiverse hypothesis (Swinburne 2004, p. 185). In saying this, Swinburne affirms the principle of Ockham's razor. Ockham's razor asserts that when attempting to explain events or phenomena we should, as much as possible, avoid 'multiplying theoretic entities'. In other words, we should prefer the simpler hypothesis with fewer such entities, all other things being equal. Swinburne notes that the God hypothesis requires the postulation of only one explanatory or theoretical entity, an intelligent and powerful transcendent agent, rather than the many purely hypothetical entities – including a quasi-infinite number of causally separate universes and separate universe-generating mechanisms – posited by multiverse advocates.

Philosopher of physics Bruce Gordon amplified this argument. He points out that multiverse advocates must not only postulate many universes, but two distinct types of universe-generating mechanisms in order to explain two distinct types of fine-tuning: initial condition fine-tuning and fine-tuning of laws and constants of physics (Gordon 2010, pp. 75–103, 2014, pp. 558–601). Yet, each of these universe-generating mechanisms themselves presuppose

---

[28] One recent exception to the assumption of noninteraction is the proposal by Feeney et al. (2011).

multiple hypothetical entities or processes. For example, string-theoretic cosmology presupposes the existence of 'strings' of vibrating energy and extra dimensions of space. Inflationary cosmology postulates an 'inflaton field' and a hypothetical process by which finely-tuned inflaton 'shut off energies' would generate new universes. To explain both types of fine-tuning, multiverse advocates must postulate two types of universe-generating mechanisms, the entities they presuppose and a quasi-infinite number of universes. Clearly, theistic design provides a more parsimonious explanation.

Secondly, multiverse proposals – whether based on string theory or inflationary cosmology – must postulate universe-generating mechanisms that *themselves require prior fine-tuning*. For example, in the inflationary multiverse, the mechanism that generates new universes is called 'an inflaton field'. Nevertheless, according to proponents of inflationary cosmology, the inflaton field and its 'shut off energy' needs to decay in a precisely finely-tuned way and amount to produce new bubble universes.

In fact, physicists calculate that the inflaton field requires fine-tuning of between one part in 10^{53} and one part in 10^{123} (depending on the inflationary model) in order to produce a life-compatible universe (Spitzer 2010, p. 88). Additionally, the shut-off *interval* of the inflaton field also requires precise fine-tuning. In current models, an inflationary epoch of rapid expansion of the universe begins at around 10^{-37} seconds after the Big Bang and lasts until 10^{-35} seconds, during which space itself expands by a factor of 10^{60} or so (in one model) (Guth 2002). For the inflaton field to produce a life-sustaining universe, inflation must occur within just such a narrow window of time.[29] Thus, the inflationary multiverse presupposes the very thing it seeks to explain, namely exquisite fine-tuning – as does the string-theoretic multiverse (Linde 2002).

Yet, as the philosopher of physics Robin Collins argues (Collins 2017, pp. 48–50), we have no experience of anything like a 'universe generator' (that is not itself designed) producing either finely-tuned functionally significant outcomes or infinite and exhaustively random ensembles of possibilities. Yet we do have extensive experience of intelligent agents producing finely-tuned devices to produce random distributions of events (e.g. roulette wheels) and plenty of experience of finely-tuned systems (circuits, software and machines) that produce specific functional outcomes. Thus, Collins

---

29. In order to explain the homogeneity of the universe using inflaton fields, physicists also have to make gratuitous assumptions about the singularity from which everything came. As Roger Penrose has pointed out, if the singularity were perfectly generic, expansion from it could yield many different kinds of irregular (inhomogeneous) universes, even *if* inflation had occurred. Thus, inflation alone, without additional assumptions, does not solve the homogeneity problem. Getting workable results requires imposing the right metric (distance measure) on space–time (Penrose 2004 *et passim*). The energy associated with the inflaton field – in particular, something called the 'inflaton-preheating coupling parameters' required to convert inflationary energy to normal mass energy – also has to be fine-tuned to produce a universe similar to ours in which life would be possible.

concludes, the postulation of ‘a supermind’ (God) to explain the fine-tuning of the universe constitutes a natural extrapolation from our experience-based knowledge of the causal powers of intelligent agency, whereas the postulation of multiple universes lacks a similar basis. Moreover, he argues that we know from experience that some machines (or factories) can produce other machines. But our experience also suggests that such machine-producing machines themselves require ID. Thus, he concludes that theistic design provides a better ultimate explanation for the origin of the fine-tuning than does the multiverse idea.

Evidence of intelligent design in biology

Even more compelling evidence of design can now be found in biology. In 1953, when Watson and Crick elucidated the structure of the DNA molecule, they made a startling discovery. The structure of DNA allows it to store information in the form of a four-character digital code. Strings of precisely sequenced chemicals called nucleotide bases store and transmit the assembly instructions – the information – for building the crucial protein molecules that cell needs to survive.

In 1958, Francis Crick developed this idea with his famous ‘sequence hypothesis’ (Crick 1958) according to which chemical bases in DNA function like letters in a written language or digital symbols in a computer code. Chemists represent these four nucleotide bases with the letters A, T, G and C (for adenine, thymine, guanine and cytosine). Just as English letters may convey a particular message depending on their arrangement, so too do certain sequences of chemical bases along the spine of a DNA molecule convey precise instructions for building proteins and protein machines. Indeed, the *specific* arrangement of the chemical characters in accord with an independent symbol convention known as ‘the genetic code’ determines the function of the sequence as a whole.

Moreover, DNA sequences do not just possess ‘information’ in the strictly mathematical sense of the theory of information developed by the famed MIT scientist Claude Shannon in the late 1940s. Shannon’s theory equated information with the reduction of uncertainty and stipulated that the amount of information in a sequence was inversely proportional to the probability of the occurrence of the sequence in question (Shannon 1948). However, the arrangements of the bases in functional stretches of DNA are not just highly improbable. Instead, DNA contains information in the richer and more ordinary dictionary sense of ‘alternative sequences or arrangements of characters that *produce a specific effect*’. DNA base sequences convey instructions. They perform functions and produce specific effects. Thus, they do not possess mere ‘Shannon information’, but instead what has been called ‘specified’ or ‘functional information’ (Hazen et al. 2007). Indeed, like the precisely arranged zeros and ones in a computer program, the chemical bases in DNA convey instructions in virtue of their 'specificity' of arrangement. Thus, Richard Dawkins notes that, 'the machine code of the genes is uncannily computerlike' (Dawkins 1996, p. 17), and software developer Bill Gates observes that 'Human DNA is like a computer program but far, far more advanced than any software we've ever created' (Gates 1998, p. 228). Similarly, biotechnology specialist Leroy Hood describes the information stored in DNA as 'digital code' (Hood & Galas 2003).

After the early 1960s, further discoveries made clear that the digital information in DNA and RNA (ribonucleic acid) is only part of a complex information-storage, transmission and processing system in the cell – an advanced form of nanotechnology that both mirrors and exceeds our own in its complexity, design logic and information-storage density.

Where did the digital information – a striking appearance of design – in the cell come from? And how does the information necessary to build new forms of life arise during the history of life? In my books *Signature in the Cell* (Meyer 2010) and *Darwin's Doubt* (Meyer 2014), I address these questions and show that materialistic theories of evolution (both biological and chemical evolutionary theories) have failed to explain the origin of the information necessary to build both the first living cells and forms of animal life.

The problem of the origin of the genetic information necessary to build the first living cell has proven particularly intractable for chemical evolutionary theories. During the late 19th century, many biologists thought of the cell as an extremely simple 'little lump of mucus or slime' (Haeckel 1883, p. 184). They thought that such an entity could have formed readily from a few simple, undirected chemical reactions without any designing hand involved.

As biologists gradually learned more about the complexity of the cell, evolutionary theorists devised increasingly more sophisticated theories of chemical evolution (Lazcano 2010) – theories that attempt to explain the origin of the first life from simpler pre-existing *chemicals*. Nevertheless, all such theories have failed to explain the information stored in DNA (and other crucial biomacromolecules such as RNA) at the very foundation of life.

Chance-based models of chemical evolution have failed to account for this information because the amount of specified information present in even a single protein or gene typically exceeds the probabilistic resources of the entire universe (Bowie & Sauer 1989; Cairns-Smith 1971, pp. 92–96; Dembski 1998, pp. 203–217; Meyer 2010, pp. 173–228; Morowitz 1968, pp. 5–12; Shapiro 1986, pp. 117–131; Yockey 1992, pp. 246–258). Models based on 'pre-biotic natural selection' (including popular RNA world scenarios) have failed as they presuppose the existence of a self-replicating system (Bertalanffy 1967, p. 82; Dobzhansky 1965, p. 310; Meyer 2010, pp. 271–323; Mora 1965, pp. 311–312; Pattee 1970, p. 123). Yet the replication systems in living organisms require *information-rich* biomolecules (either DNA and proteins or RNA replicators) – the very entities that required explanation in the first place. Finally, self-organisational models have failed as the information content of DNA defies explanation by reference to the physical and chemical properties of its constituent parts (Kok, Taylor & Bradley 1988; Kuppers 1987, p. 364; Meyer 2010, pp. 229–252; Polanyi 1968, p. 1309; Thaxton, Bradley & Olson et al. 1984, pp. 113–166; Yockey 1981). Just as the chemistry of ink does not explain the specific sequencing of letters in a newspaper headline, so too the properties of the chemical constituents of DNA text – the four nucleotide bases – do not explain the specific sequencing of the genetic text.[30]

Yet, the scientists arguing for ID do not do so merely because materialistic evolutionary theories have failed to explain the origin of the information necessary to build new forms of life. Instead, we argue for design because we know from our uniform and repeated experience – the basis of all scientific reasoning about the causes of events in the past – that systems possessing functional information invariably arise from intelligent causes. The information on a computer screen can be traced back to a user or programmer. The information in a newspaper ultimately came from a writer – from a mental, rather than a strictly material, cause. As the pioneering information theorist Henry Quastler observed, 'information habitually arises from conscious activity' (Quastler 1964, p. 16).

The causal connection between information and prior intelligence enables us to detect or infer intelligent activity from effects of unobservable causes in the distant past. Archaeologists infer ancient scribes from hieroglyphic inscriptions. The Search for Extraterrestrial Intelligence (SETI) Institute's search for extra-terrestrial intelligence presupposes that information embedded in electromagnetic signals from space would indicate an intelligent source. Yet, radio astronomers have not found information-bearing signals from distant star systems. But closer to home, molecular biologists have discovered information in the cell, suggesting – by the same logic that underwrites the SETI program and ordinary scientific reasoning about other informational artifacts – an intelligent source for the information in DNA.

DNA functions like a software program. We know from experience that software comes from programmers. We know generally that information – whether inscribed in hieroglyphics, written in a book or encoded in a radio signal – always arises from an intelligent source. So, the discovery of information in the DNA molecule provides strong grounds for inferring that a designing intelligence played a role in the origin of life, even if we were not there to observe it coming into existence.

---

[30] As Michael Polanyi (1968, p. 1309) put it: 'As the arrangement of a printed page is extraneous to the chemistry of the printed page, so is the base sequence in a DNA molecule extraneous to the chemical forces at work in the DNA molecule'.

Thus, contrary to media reports, the theory of ID is not based upon ignorance or 'gaps' in our knowledge, but instead upon recent scientific discoveries and upon standard methods of scientific reasoning in which our uniform experience of cause and effect guides our inferences about what happened in the past (Meyer 2010, pp. 396–415).

Reconceptualising epistemic support

Despite the rather dramatic developments in cosmology, physics and biology during the last century, many scientists and theologians remain reluctant to revise their understanding of the relationship between science and theistic belief. True, there are perhaps fewer scientists today than in the late 19th century who would assert that science and theistic religion stand in overt conflict. Yet many scientists and theologians still deny that science can provide evidential or epistemic support for a Judeo-Christian or theistic worldview. Instead, they express scepticism about what they see as a return to the failed 'natural theology' of the 19th century or to rationalistic attempts to prove the existence of God. They point out, perhaps rightly, evidence from the natural world cannot 'prove' God's existence.

Consider the view of Ernan McMullin, until his death in 2011, a prominent philosopher of science and theologian at the University of Notre Dame. McMullin explicitly denied that the Big Bang Theory provides any evidential support for Christian theism although he admits that if one assumed the Christian doctrine of Creation one might expect to find evidence for a beginning to time. As he explains (McMullin 1981):

> What one could say [...] is that if the universe began in time through the act of a Creator, from our vantage point it would look something like the Big Bang that cosmologists are talking about. What one cannot say is [...] that the Big Bang model 'supports' the Christian doctrine of Creation (pp. 17–57, esp. 39).

Deduction and the logic of entailment

Many philosophers, scientists and theologians assume that scientific evidence (represented here as A) can provide epistemological support for, or grounds for believing, a theological proposition (B) only if the theological proposition (B) follows from evidence (A) with deductive certainty. They assume that to succeed in providing epistemic support for God's existence, or other propositional commitments of theism, arguments must necessarily take a deductive logical form such as:

If *A*, then *B*

*A*_________

Therefore *B*

Of course, many arguments for God's existence have been framed in precisely such a deductive manner. Recall, for example, the classic statement of the Kalam cosmological argument (Craig 1994) for God's existence:

> Whatever begins to exist has a cause
>
> The universe began to exist________
>
> Therefore, the universe has a cause (separate from itself) of its existence. (p. 92)

Such deductive arguments utilise the standard *modus ponens* form.[31] Thus, they are logically valid. If the premises of such arguments are true and can be known to be true with certainty, then the conclusion follows with certainty as well. In such arguments, logicians say the premises 'entail' the conclusions. Of course, finding premises that can be known to be true with certainty can be very difficult, especially for an empirically based inquiry such as natural science. Many deductive arguments for God's existence failed for exactly this reason. Nevertheless, deductive entailment from true premises does constitute a perfectly legitimate, if infrequently attained, form of epistemic support. If A logically compels B, then it is irrational to deny B if one affirms A. In such cases, A clearly provides support for B (Dembski & Meyer 1998). Even so, deductive entailment involves a far stronger notion of support than empirical science requires. Scientists rarely prove their theories deductively from empirical evidence. Indeed, no field of inquiry apart from mathematics could progress if it limited itself to the logic of entailment. Rather, most fields employ alternate forms of inference known variously as the method of hypothesis, abduction, hypothetico-deductive method or inference to the best explanation.

Abduction and the logic of confirmation of hypothesis

During the 19th century, a logician named C.S. Peirce (1931, vol 2, p. 375) described the modes of inference that we use to derive conclusions from data. Peirce noted that in addition to deductive arguments, we often employ a mode

---

[31] The standard statement of the Kalam argument is actually an example of what logicians call an enthymeme. Enthymemes are arguments that omit a step often by leaving a deductive entailment relationship unstated. In this case, the full argument should be stated as follows:

> For all X, if X begins to exist then X has a cause
> If the universe begins exist, then the universe has a cause
> The universe began to exist
> Therefore, the universe had a cause.

The first premise in this argument involves a move that logicians call 'universal instantiation'. The second and third statements form a standard *modus ponens* argument with a deductively valid conclusion. This more complete formulation of the argument also provides an excellent example of an entailment relationship. Thus, the points made about the shorter version of the Kalam argument apply equally to this more complete version.

of logic he called ‘abduction’ or ‘the method of hypothesis’. To see the difference between these two types of inference, consider the following argument schemata (Meyer 1990):

DEDUCTIVE SCHEMA:

DATA: A is given and plainly true.

LOGIC: But if A is true, then B is a matter of course.

CONCLUSION: Hence, B must be true as well.

ABDUCTIVE SCHEMA:

DATA: The surprising fact B is observed.

LOGIC: But if A were true, then B would be a matter of course.

CONCLUSION: Hence, there is reason to suspect that A is true. (p. 25)

In the logic of the deductive schema, if the premises are true, the conclusion follows with certainty. The logic of the abductive schema, however, does not produce certainty, but instead plausibility or possibility. Unlike deduction, in which the minor premise affirms the antecedent variable (A), abductive logic affirms the consequent variable (B). In deductive logic, affirming the consequent variable (with certainty) constitutes a fallacy – a fallacy that derives from the failure to acknowledge that more than one antecedent might explain the same evidence. To see why, consider the following argument:

If it rains the streets will get wet,
the streets are wet_____________
therefore it rained.

or symbolically:

If R, then W
*W*_________
therefore R.

Obviously, this argument has a problem as it stands. It does not follow that because the streets are wet, it necessarily rained. The streets may have gotten wet in some other way. A fire hydrant may have burst, a snowbank may have melted or a street sweeper may have doused the street before beginning his cleaning operation. Nevertheless, that the streets are wet *might* indicate that it has rained. Thus, amending the argument as follows does not commit the fallacy:

If it rains, then we would expect the streets to get wet.
The streets are wet.
Therefore *perhaps* it rained.

or symbolically:

If R, then W
W________
perhaps R.

Even if one may not affirm the consequent with certainty, one may affirm it as a possibility. And this is precisely what abductive logic does. It provides a reason for considering that a hypothesis might be true even if one cannot affirm the hypothesis (or conclusion) with certainty.

The natural and historical sciences employ such logic routinely. In the natural sciences, if we have reason to expect that some state of affairs will ensue given some hypothesis, and we find that such a state of affairs has ensued, then we say that our hypothesis has been confirmed. This method of 'confirmation of hypothesis' functions to provide evidential support for many scientific hypotheses. Given Copernicus' heliocentric theory of the solar system, astronomers in the 17th century had reason to expect that the planet Venus should exhibit phases. Galileo's discovery that Venus does exhibit phases, therefore, supported the heliocentric view (Drake 1957, p. 74). The discovery did not prove the heliocentric theory, however, as other theories might – and in fact could – explain the same fact (Gingerich 1982, 1992, p. 110).

Peirce (1931) acknowledged that abductive inferences on their own may constitute a rather weak form of epistemic support. He noted:

> As a general rule [*abduction*] is a weak kind of argument. It often inclines our judgment so slightly toward its conclusion that we cannot say that we believe the latter to be true; we only surmise that it may be so. (p. 375)

Yet as a practical matter Peirce acknowledged that abduction often yields conclusions that are difficult to doubt even if they lack the airtight certainty that accompanies deductive proofs. For instance, Peirce argued that scepticism about the existence of Napoleon Bonaparte was unjustified even though Napoleon's existence could be known only by abduction. As Peirce (1931) put it:

> Numberless documents refer to a conqueror called Napoleon Bonaparte. Though we have not seen the man, yet we cannot explain what we have seen, namely, all these documents and monuments, without supposing that he really existed. (p. 375)

Thus, Peirce suggested that by considering the explanatory power of a hypothesis, the logic of abduction might underwrite more robust relations of epistemic support.

Inference to the best explanation

Since Peirce's time, philosophers of science have shown how abductive inferences (or confirmation of hypothesis) can provide a stronger form of epistemic support. Philosophers of science have recognised that the inconclusive character of abductive inferences often forces scientists who use them to evaluate the explanatory power of competing possible hypotheses. This method, alternatively called 'the method of multiple competing hypotheses' (Chamberlin 1965) or 'inference to the best explanation' (Lipton 1991, pp. 1–8, 56–74, 92–96; Meyer 1990, pp. 90–97; Sober 1993, pp. 27–46), often reduces, at least for practical purposes, the uncertainty or 'underdetermination' associated with abductive inference. In this method of reasoning, the explanatory or predictive[32] virtues of a potential hypothesis helps determine from among a competing set of possible explanations which one would be the best. Scientists infer that hypothesis among a competing group that would, if true, provide the best explanation of some set of relevant evidence. True, both an earthquake and a bomb could explain the destruction of the building but only the bomb can explain the presence of charring and shrapnel at the scene of the rubble. Earthquakes do not produce shrapnel, nor do they cause charring, at least not on their own.

This example suggests that considerations of causal adequacy often help determine from among a set of possible explanations that which will constitute the best. Indeed, recent work on the method of 'inference to the best explanation' (Lipton 1991, pp. 32–88; Meyer 1994, pp. 67–112, 300–12, esp. 88–94) suggests that determining which among a set of competing possible explanations constitutes the best depends on assessments of the causal powers of competing explanatory entities. Entities or events that have the capability to produce the evidence in question constitute better explanations of that evidence than those that do not. It follows that the process of determining the best explanation often involves generating a list of possible hypotheses, comparison of their known (or theoretically plausible) causal powers with respect to the relevant data and the progressive elimination of potential but inadequate explanations. Of course, in some situations, more than one hypothesis may serve as an adequate explanation for a given fact. Typically, in such situations, scientists expand their evaluation to include an ensemble of relevant data to discriminate between the explanatory power of various abductive hypotheses (Meyer 1990, pp. 99–108, esp. 102).

Inference to the best explanation (IBE) as a method of reasoning has a number of advantages over either deduction or simple abduction. Firstly, IBE can provide a strong form of epistemic support without having to achieve the

---

[32] Recent work in the philosophy of science suggests that predictive success constitutes a special case of explanatory power in which a theory's ability to predict an event stands as evidence of its ability to explain it (Lipton 1991). Other work has shown, however, that scientists can often explain events after the fact that they could not have predicted before the fact (see Scriven 1959). Still other work in the history of science has shown that the explanation of previously known facts often accounts more for the success of theory than does a theory's ability to predict previously unknown events (see Brush 1989). All these results have suggested the primacy of explanation as an indicator of theory success.

often-unrealistic standard of deductive certainty. If the logic of confirmation provides a weak form of epistemic support by suggesting a reason for believing that a hypothesis might be true, then the logic of comparative explanatory power – the method of IBE – can provide a stronger form of support by giving a reason for preferring a possibly true hypothesis over all competitors.

Secondly, in discussions of the relationship between science and faith, IBE provides a way of avoiding fideism – belief without justification, or faith in faith alone – on the one hand, or a return to strict rationalism on the other. If, as both rationalists and fideists assume, deductive proofs provide the only way to support a theistic worldview, then if such proofs fail, fideism or scepticism stands as the only alternative. If, however, scientific or other evidence suggest theism as a better explanation than competing metaphysical systems or worldviews, then one can affirm an evidential basis for theistic belief without embracing the failed rationalism of the past.

Theism as an inference to the best explanation

With confirmation of hypothesis and explanatory power, rather than just deductive entailment, included in our understanding of epistemic support, we can now see how recent developments in modern science provide such support for theism. Curiously, in the very passage in which he denies that the Big Bang model supports the Christian doctrine of Creation, McMullin suggests this very possibility: 'If the universe began in time through the act of a Creator […] it would look something like the Big Bang that cosmologists are talking about' (McMullin 1981, p. 39). But does this not simply mean that if we assume theism or the Christian doctrine of creation as a kind of metaphysical hypothesis, then the Big Bang is the kind of cosmological theory we have reason to expect? As Nobel laureate Arno Penzias (cited in Browne 1978) has said:

> [*T*]he best data we have (concerning the Big Bang) are exactly what I would have predicted had I nothing to go on but the first five books of Moses, the Psalms and the Bible as a whole. (p. 54)

But again, does not this statement, and McMullin's, imply that the Big Bang Theory provides a kind of confirmation of the Judeo-Christian understanding of creation and with it a theistic worldview? The previous discussion of confirmation would certainly seem to suggest as much. Explicating the earlier statements as an abductive syllogism helps to explain why:

> If theism and the Judeo-Christian view of creation are true, then we have reason to expect evidence of a finite universe.
>
> We have evidence of a finite universe,
>
> therefore, we have reason to suspect that theism and or the Judeo-Christian view of creation may be true.

This syllogism suggests that the evidence for a beginning of the universe functions to confirm the metaphysical hypothesis of theism in much the same way that empirical observations confirm scientific theories. It follows that such evidence provides epistemic support for theism at least in this limited way.

Yet scientific evidence may provide an even stronger form of epistemic support for theism if we compare theism's explanatory power to that of other major worldviews such as naturalism and pantheism.

Let us initially compare the explanatory power of theism and naturalism, perhaps the two most influential worldviews in the West. Let us specifically compare their ability to explain the three main classes of evidence examined concerning cosmological and biological origins.

Firstly, theism, with its notion of a transcendent creator provides a more causally adequate explanation of the evidence for the beginning of the universe than fully naturalistic explanations can offer. Since naturalism assumes, in astronomer Carl Sagan's formulation, that 'the Cosmos is all that is, or ever was or ever will be' (Sagan 1980, p. 4), naturalism denies the existence of any entity with the causal powers capable of explaining the origin of the universe as a whole. Since the evidence for the Big Bang, in conjunction with general relativity, implies a singular beginning for matter, space, time and energy (Hawking & Penrose 1970), it follows that any entity capable of explaining this singularity must transcend these four dimensions or domains. In so far as God, as conceived by Judeo-Christian theists, possesses precisely such transcendent causal powers, theism provides a better explanation than naturalism for the cosmological singularity and the evidence for the universe having a beginning. Theism also provides a better explanation for the origin of the universe than does pantheism, for much the same reason. Although a pantheistic worldview affirms the existence of an impersonal god, the god of pantheistic religions and philosophy exists within and is co-extensive with the physical universe. God as conceived by pantheists cannot act to bring the physical universe into being from nothing (physical) as such a god does not exist independently of the physical universe. If initially the physical universe did not exist, the pantheistic god would not have existed either. If it did not exist, it could not cause the universe to come into existence.

Many naturalists have in effect admitted the dissonance created by the Big Bang Theory for their worldview. Einstein, at a time when he was still a strict philosophical materialist, tacitly acknowledged this dissonance when he introduced his cosmological constant to maintain a static and infinite universe (Luminet 2007, p. 10). Fred Hoyle admitted the challenge posed by a finite universe to naturalism when, for explicitly philosophical reasons, he proposed his steady-state theory to retain the concept of an infinite universe (Kragh 1996, pp. 179–187) – despite its flagrant violation of the law of conservation of energy. The English astronomer and physicist Sir Arthur Eddington (Eddington 1956)[33] acknowledged the dissonance when he confessed that he found the idea of a beginning of the universe philosophically 'repugnant'.[34]

In any case, if the universe is finite, as the Big Bang Theory and general relativity affirm, then the evidence in support of those theories provide confirmation of, and epistemic support for, the metaphysical hypothesis of theism. Furthermore, theism provides a better, more causally adequate explanation for the evidence of a finite universe than its main metaphysical competitors. Hence, if we credit confirmation of hypothesis and explanatory power, rather than just deductive entailment, as legitimate forms of epistemic support, then the evidence for the beginning of the universe provides support for theism (including Judeo-Christian theism) and the idea of a specifically *transcendent* creator.[35]

Other classes of scientific evidence provide support for other attributes of a theistic God. As noted, ID provides a highly plausible, and arguably the best, explanation for the exquisite fine-tuning of the laws and constants of physics, and the configuration of mass-energy at the beginning of the universe. Since the fine-tuning dates from the origin of the universe itself, this evidence suggests the need for a transcendent and intelligent cause for the origin of the universe. Since God as conceived by Judeo-Christian and other theists possesses precisely these attributes, God's creative action can adequately explain the origin of the cosmological singularity and the anthropic fine-tuning. Since naturalism denies a transcendent and pre-existent intelligent cause, it follows that theism provides a better explanation than naturalism for these two evidences taken jointly.

Since pantheism, with its belief in an immanent and impersonal god, also denies the existence of a transcendent and pre-existent intelligence, it too

---

[33] Eddington was raised a Quaker and may have retained some religious sensibilities or even theistic belief into his adult life. Nevertheless, in his work as an astronomer, he was functional materialist, accepting methodological materialism as a normative canon of method. Thus, he would have found a picture of the universe that was effectively impossible to explain materialistically 'repugnant'.

[34] Many claim to have resolved the dissonance between naturalism and Big Bang cosmology by positing various quantum cosmological models. I critique these models extensively in my book *The Return of the God Hypothesis*. I show that, ironically, to the extent that these cosmological models may have validity; they themselves have latent theistic implications. For example, on the standard Copenhagen interpretation of the so-called 'collapse of the wave function', a wave function only acquires discrete values upon observation. Thus, if the universe initially could be represented as quantum wave function describing different possible spatial geometries and configurations of matter as quantum cosmologies suggest, the universe could not have acquired discreet characteristics until some 'cosmic observer' had actualised one of its potential combination of states by observing it (see Meyer 2021: Chapters 17–19; also see Hartle & Hawking 1983; Plantinga 1974, pp. 213–217; Craig 1988).

[35] Some have argued on philosophical grounds, however, that personal agency constitutes the best explanation of the abrupt beginning of time attested to by the Big Bang (see Moreland 1987, pp. 42–43; Craig 1994, p. 117).

lacks causal adequacy as an explanation for these evidences. Indeed, a completely impersonal intelligence is almost a contradiction in terms. Thus, theism stands as the best explanation of the three major worldviews – theism, pantheism and naturalism – for the evidence of the beginning of the universe and its fine-tuning.

Admittedly, theism, naturalism and pantheism are not the only worldviews that can be offered as metaphysical explanations for the three classes of evidence discussed. Deism, like theism, for example, can explain the cosmological singularity and the anthropic fine-tuning. Like theism, deism conceives of God as both a transcendent and intelligent creator. Nevertheless, deism denies that God continues to participate within the creation, either as a sustaining presence or as an actor within it after the origin of the universe. Thus, deism has difficulty explaining evidence of discrete acts of design or creation during the history of the cosmos (i.e. after the Big Bang). Yet, as noted, precisely such evidence now exists in the living world.

Current fossil evidence puts the origin of life on Earth at 3.5–3.8 billion years ago (Schopf et al. 2018), roughly 10 billion years *after* the origin of the universe. If the origin of the specified information necessary to produce the first cell provides compelling evidence of ID (as argued earlier), then that suggests the need for an act of creative intelligence, or a period of creative activity, well after the origin of the universe.[36] On the other hand, theism conceives God as an agent who may periodically act within the natural order that He otherwise sustains and upholds and that such a theistic God may act in such a discrete manner at points in time long after His initial act of creation. The existence and activity of such a God can, therefore, explain functional biological information arising long after the beginning of the universe. Deism, on the other hand, cannot account for evidence of creation or design after the origin of the universe, as deism stipulates that God (the ‘absentee landlord’) chose not to involve himself in the events or workings of the universe after He first created it.

Interestingly, some philosophical naturalists have postulated an immanent intelligence as an explanation for the origin of the first life on Earth. Francis Crick (1981, pp. 95–166) and Richard Dawkins,[37] for example, have each either proposed (or in Dawkins’ case) considered the possibility of ‘directed panspermia’. This idea holds that life was intelligently designed (or seeded) by an intelligence within the cosmos – a space alien or extra-terrestrial agent that

---

[36] One could argue against this by asserting that the functional information necessary to build life was present in the initial configuration of matter at the Big Bang. Yet the implausibility of a such a view can be clearly demonstrated empirically (see Meyer 2017, 1999a, pp. 89–100, esp. 92).

[37] See interview between Richard Dawkins and Ben Stein in the 2008 documentary *Expelled: No Intelligence Allowed.*

evolved by purely naturalistic processes somewhere else in the universe – rather than by a transcendent intelligent God.

Nevertheless, positing that life arose somewhere else in the cosmos does not explain how the information necessary to build the first life, let alone the first intelligent life, could have arisen. Instead, positing another form of pre-existing life only presupposes the existence of the very thing that all theories of the origin of life must explain – the origin of functional biological information.

Beyond that, panspermia certainly does not explain the origin of the fine-tuning. Since the anthropic fine-tuning dates from the very origin of the universe itself, if ID best explains the fine-tuning, then the designing intelligence responsible for the fine-tuning must have had the capability of setting the fine-tuning parameters and initial conditions from the moment of creation. Yet, clearly, no intelligent being *within* the cosmos could be responsible for the fine-tuning of the laws and constants of *physics* that made its existence and evolution possible. Similarly, no intelligent being arising after the beginning of the universe could have set the initial conditions of the universe upon which its later evolution and existence would depend – to say nothing of causing the origin of the universe itself.

■ Conclusion

In 1992, the historian of science Frederic Burnham stated that the God hypothesis 'is now a more respectable hypothesis than at any time in the last one hundred years' (Briggs 1992). Burnham's comment came in response to the discovery of the so-called 'COBE background radiation', which provided yet another dramatic confirmation of the Big Bang cosmology. Yet it is not only cosmology that has rendered the 'God hypothesis' respectable again. As one surveys several classes of evidence from the natural sciences – from cosmology, physics, biochemistry and molecular biology – theism emerges as a worldview with extraordinary explanatory scope and power. Theism explains a wide ensemble of metaphysically significant scientific evidence and theoretical results more simply, adequately and comprehensively than other major competing worldviews or metaphysical systems. This does not, of course, *prove* God's existence, as superior explanatory power does not constitute deductive certainty. It does suggest, however, that scientific evidence concerning cosmological and biological origins now provides strong *epistemological support* for the existence of God as affirmed by both a theistic and Judeo-Christian worldview.

Chapter 3

Cosmological fine-tuning

Hugh Ross
Reasons to Believe,
Covina, California, United States of America

Introduction[38]

The cosmological anthropic principle is the observation that the fundamental features of the universe, including the laws and constants of physics, must be exquisitely narrowly specified, or 'fine-tuned', to make possible the existence of human beings. This chapter describes some of the more spectacular examples of this fine-tuning and shows how the evidence for it has dramatically increased as astronomers have continued to learn more about the universe. Most of the chapter will focus on the most recently recognised features of cosmological fine-tuning, that of (1) the large-scale structure of the universe; (2) the Laniakea Supercluster of galaxies; (3) the Virgo Cluster of galaxies; (4) the Local Group of galaxies; (5) the MWG and (6) the local galactic neighbourhood, all of which favour the existence of human beings on

---

[38] This chapter represents a substantial reworking of evidence published in several of my books (Ross 2008, 2016, 2018, in press). Ross (2008, 2016) refers to *Why the Universe Is the Way It Is; Improbable Planet*. Only a tiny percentage of the intellectual content in my chapter appears in Ross (2008, 2016), and what does appear from Ross (2008, 2016) also appears in Ross (2018, in press) and in the third edition of *The Creator and the Cosmos*. Therefore, I can truthfully state that 100% of the intellectual content of my chapter comes from Reasons to Believe (RTB) sources where RTB owns all rights and that I am granting you permission for this content to appear in the chapter within *Science and Faith in Dialogue*.

How to cite: Ross, H 2022, 'Cosmological fine-tuning', in F van Niekerk & N Vorster (eds.), *Science and Faith in Dialogue*, in Reformed Theology in Africa Series, Vol. 10, AOSIS Books, Cape Town, pp. 65–91. https://doi.org/10.4102/aosis.2022.BK334.03

planet Earth. Evidence for anthropic fine-tuning has been observed at all six of these cosmic size scales and continues to increase as astronomical knowledge and understanding advances. The ubiquitous nature of exquisite cosmic fine-tuning and the steady accumulation of evidence for it suggests that every component of the universe and every event in the history of the universe plays some role in making possible human life and global civilisation on Earth.

Evidence for a designer's fine-tuning in the natural realm has long been used as an argument for God. Various passages in the Old Testament affirm that God's existence and character can be seen in nature (Gn 1; Job 37–39; Ps 19, vv. 1–4; Ps 104; Pr 8, vv. 22–31). Socrates and Plato argued that true explanations for any given physical phenomenon must be teleological, its purposes and functions best explained by God's design (Ahbel-Rappe & Kamtekar 2009, p. 45; Plato 1952, pp. 200–212, 221–248).

Some philosophers and scientists have argued that the fine-tuning argument for God is some kind of fallacy. For example, some claim that cosmic fine-tuning is akin to a puddle observing that the hole in which it exists is perfectly fit for it. The puddle, then, concludes that someone perfectly designed the hole just for it. In a previous article, I explained why the puddle analogy for humans being able to exist in the universe is fatally flawed (Ross 2021).

Other scholars appeal to a dice analogy. They assert that demonstrating how extremely improbable it is for everything in the universe to be exactly the way astronomers observe it is akin to noting that the outcome of a thousand throws of dice is extremely unlikely regardless of what that outcome is. This dice analogy overlooks the purposes of the outcome. The outcome of a thousand throws of dice serves no significant ontological purpose other than perhaps to win a bet. As I explained in *Why the Universe Is the Way It Is* (Ross 2008, pp. 154–163), the cosmic fine-tuning observed by astronomers serves at least 11 distinct ontologically important and highly specified purposes.

Many scientists acknowledge the fact that the universe is highly fine-tuned to make the existence of humans possible but argue that the fine-tuning is better explained by the multiverse (an infinite number of universe where every universe is different from the infinite number of other universes) rather than God. In *The Creator and the Cosmos* (Ross 2018, pp. 148–153), I show that the appeal to a multiverse to eliminate God as the cosmic designer simultaneously eliminates all humans as having achieved any designs, writings or constructions. Such an appeal to a multiverse inevitably leads to philosophical inconsistencies and contradictions.

In spite of attempted claims that it lacks rigour and thoroughness, the argument from design, or fine-tuning, has consistently remained among the most compelling scientific arguments for God. It is clear, concrete and measurable. Showing that the design evidence is pervasive, increasing at an exponential rate and fulfils multiple independent purposes, I have found, helps remove remaining scepticism about the case for intentional design. This chapter offers a summary of that evidence, presented in several of my books (Ross 2008, 2016, 2018, in press).

■ Fine-tuned fundamentals

More than 140 specific features of the universe as a whole and of the laws of physics governing the universe must fit within an exquisitely narrow range of variance to make advanced life possible. These features reveal that the entire universe must be precisely the way it is to make possible even one planet on which advanced physical life can potentially exist. Before examining the most significant of these features, it may be valuable to acknowledge how carefully the laws of physics must be fixed.

Life molecules require a delicate balance among the constants of physics governing the strong and weak nuclear forces, gravity, electromagnetism and the nuclear ground state energies (quantum energy levels important for the forming of certain elements from protons and neutrons).

If the strong nuclear force – the force governing the degree to which protons and neutrons stick together in atomic nuclei – were too weak, multi-proton nuclei would not hold together, and, thus, hydrogen would be the only element in the universe. If the strong nuclear force were slightly stronger, protons and neutrons would have such a strong affinity for one another that none would remain alone. They would all attach to other protons and neutrons, and thus, no hydrogen would exist. Life chemistry is impossible without hydrogen and also impossible if hydrogen is the only element.

How delicately balanced is the strong nuclear force? If it were just 4% stronger, diprotons (atoms with two protons and no neutrons) would form. Diprotons would cause stars to exhaust their nuclear fuel so rapidly as to make any kind of physical life impossible. On the other hand, if the strong nuclear force were just 10% weaker, carbon, oxygen and nitrogen would be unstable. Again, any conceivable kind of physical life would be impossible (Barrow 2002, pp. 165–167).

The strong nuclear force is both the strongest attractive force in nature and the strongest repulsive force. Over lengths no less than 0.7 fermis (one fermi = a quadrillionth of a meter), and no greater than 2.0 fermis, it is attractive and maximally attractive at about 0.9 fermis (Wilczek 2007, pp. 156–157). At lengths shorter than 0.7 fermis, the strong nuclear force is strongly repulsive for this reason: Protons and neutrons are packages of more fundamental particles called quarks and gluons. If the strong nuclear force were not strongly repulsive on length scales below 0.7 fermis, the proton and neutron packages of quarks and gluons would merge. Such mergers would mean no atoms, no molecules and no chemistry would ever be possible anywhere or any time in the universe.

Both the attractive effect of the strong nuclear force and the repulsive effect must be extremely precise, both in length range and strength. The fact that it is attractive on one length scale and repulsive on another length scale makes it highly unusual, but without these weird properties, life would be impossible.

In the case of the weak nuclear force – the force that governs, among other things, radioactive decay rates – if it were much stronger than we observe, all ordinary matter (matter composed of protons, neutrons and electrons) in the universe would be converted rapidly into heavy elements. If it were much weaker, the only remaining ordinary matter in the universe would be hydrogen, helium and lithium. Either way, the elements essential for life chemistry (carbon, oxygen, nitrogen, phosphorus, etc.) would be non-existent or would exist in amounts far too small for the assembly and operation of life chemistry. What is more, unless the weak nuclear force were delicately fine-tuned to better than 1 part in 10 000, those life-essential elements produced only in supergiant stellar cores would never escape those cores because supernova explosions would not occur (Rees 1983, p. 317).

The gravitational force strength determines how hot the nuclear furnace in a star's core burns. If the gravitational force were any stronger, stars would be so hot as to burn up relatively quickly – too quickly and too erratically to provide what life on any planet orbiting them would require. A planet capable of sustaining life must be orbiting a star that is both stable and long burning. If the gravitational force were any weaker, stars would never become hot enough to ignite nuclear fusion. In such a universe, no elements heavier than hydrogen, helium and lithium would ever be produced.

Decades ago, Sir Fred Hoyle discovered that the nuclear ground state energies for helium, beryllium, carbon and oxygen require exquisite fine-tuning for any kind of physical life to exist. If the ground state energies for these elements were higher or lower with respect to each other by more than 4%, the universe would yield either no carbon and oxygen or insufficient quantities of carbon and or oxygen for life (Hoyle 1965, pp. 147–150, 1982, p. 16). Hoyle, who expressed his opposition to theism (1952, p. 109, 1975, pp. 522, 684–685, 1982, p. 3) and to Christianity in particular (1952, p. 111), nevertheless concluded on the basis of this quadruple fine-tuning that 'a superintellect has monkeyed with physics, as well as with chemistry and biology' (1982, p. 16).

In 2000, astrophysicists from Austria, Germany and Hungary demonstrated that the design level for electromagnetism and the strong nuclear force actually exceeds, by far, what physicists had previously determined (Oberhummer, Csótó & Schlattl 2000, pp. 88–90). The team noted that for any conceivable physical life to be possible in the universe, certain minimum abundances of both carbon and oxygen must be present. Next, they pointed out that the only astrophysical sources of adequate quantities of carbon and oxygen are red giant stars (large stars that, through nuclear fusion, have consumed all their hydrogen fuel and subsequently fuse helium into heavier elements).

The team mathematically constructed models of red giant stars using slightly different values for the strong nuclear force and electromagnetic force constants. They discovered that tiny changes in the value of either constant lead to insufficient carbon, or oxygen or both. Specifically, they determined that if the value of the electromagnetic coupling constant were 4% smaller or 4% larger, the carbon and oxygen essential for life would not exist. In the case of the strong nuclear force coupling constant, if it were 0.5% lesser or greater, life would be impossible.

These new limits on the strength of the electromagnetic and strong nuclear forces provide much tighter constraints on the quark mass and on the value of the Higgs vacuum expectation (Oberhummer et al. 2000, p. 90). Without getting into the technical details of the Higgs vacuum expectation value and quarks, the new limits demonstrate even greater degrees of fine-tuning not only in the physics of stars and planets but also in fundamental particle physics.

Gravity causes stars to shrink. Electromagnetic radiation causes stars to expand. For the range of star masses needed for advanced life to exist and for these stars to manifest stable sizes, the ratio of the electromagnetic force constant to the gravitational force constant must be fine-tuned to within 1 part in 10^{40}! This degree of fine-tuning exceeds that found in the best designs achieved by humans.

Fine-tuned cosmic history

The universe is massive and beyond our capability to comprehend. This fact leads many people to question whether it really needs to be so massive for physical life to be possible. As explained in some detail in *Why the Universe Is the Way It Is* (Ross 2008, pp. 27–41) and in *The Creator and the Cosmos* (Ross 2018, pp. 45–63), if the universe were ever so slightly less massive (its mass density ever so slightly lower), then the periodic table would forever possess only hydrogen, helium and lithium. In such a universe, chemistry courses would be easy to pass but physical life would be impossible. On the other hand, if the universe were ever so slightly more massive (its mass density ever so slightly greater), then soon after the formation of the first stars the periodic table would contain no elements lighter than iron.

The universe's mass also plays a role in determining whether or not stars and planets form. The mass of the universe determines how effectively gravity slows down the cosmic expansion rate. In a less massive universe, gravity would be unable to compress any of the expanding primordial cosmic gas into stars and planets. Such a universe would remain dispersed gas. In a more massive universe, gravity would quickly compress all the primordial cosmic gas into neutron stars and black holes. In such a universe, atoms and molecules would not exist. The entire universe, as massive as it is, must exist at precisely its mass level for even one planet like Earth (and the elements needed for physical life) to exist.

The universe must be fine-tuned to provide not only a just-right quantity of nucleons (protons and neutrons), but also a precise number of electrons. Unless the number of electrons was equivalent to the number of protons to an accuracy of one part in 10^{37} or better, electromagnetic forces in the universe would have so overcome gravitational forces that galaxies, stars and planets would never have formed.

At present, the average distance between stars is about 400 light-years. If the universe's stars were jammed more tightly together, planets orbiting them would suffer life-threatening gravitational disturbances and stellar radiation. On the other hand, if the universe were to expand more rapidly, stars would be farther apart from each other, and planets would be insufficiently enriched with the heavy elements that advanced life requires (these heavy elements come solely from the ejected debris from massive stars). Therefore, the universe must be the spatial size it is now for advanced life to exist.

Cosmic mass, by itself, however, cannot generate the exacting cosmic expansion rates that produce, with just-right timing, all the galaxies, stars, planets, asteroids and comets with the appropriate spatial distribution advanced life's possible existence requires. Dark energy must come to the rescue.

For dark energy to play its part, it must be fine-tuned with vastly greater precision than the cosmic mass – and not just once, but twice in cosmic history! Its initial value must be extremely high, and then, within a split second after the origin event, it must drop to an extremely low value. By any accounting, the initial dark energy density must have been at least 122 orders of magnitude greater than its detectable density today. Its original density must be this large to explain the cosmic inflation event that occurred between 10^{-35} and 10^{-32} s after the cosmic origin, the moment when the universe expanded at millions of times the velocity of light.[39] This difference between the initial and current dark energy density implies that during the first tiny fraction of a second of cosmic existence, all but just one minuscule part (one in 10^{122}) was somehow cancelled out. (This cancellation event is roughly analogous to the

---

[39] Cosmic inflation results from the symmetry breaking that occurs when, because of cosmic cooling, the strong-electroweak force of physics separates into the strong nuclear force and the electroweak force. If this symmetry breaking had not occurred with its accompanying cosmic inflation, life would be non-existent (Ross 2018, pp. 68–69).

annihilation of nucleons by anti-nucleons, a cancellation effect that left a just-right quantity of nucleons in the universe.)

The precision represented by one part in 10^{-122} ranks as the most spectacular fine-tuning measurement to date. If one were to compare the fine-tuning of dark energy density with the greatest fine-tuning yet achieved by humans, that in the Laser Interferometer Gravitational-Wave Observatory (LIGO), the fine-tuning of dark energy would rank 10^{99} times superior – a factor of 1000 trillion trillion trillion trillion trillion trillion trillion trillion times superior. (Invented and designed by physicists at the California Institute of Technology and the MIT, LIGO is able to identify and measure a disturbance equivalent to one-tenth the diameter of a proton over a 4-km baseline.)

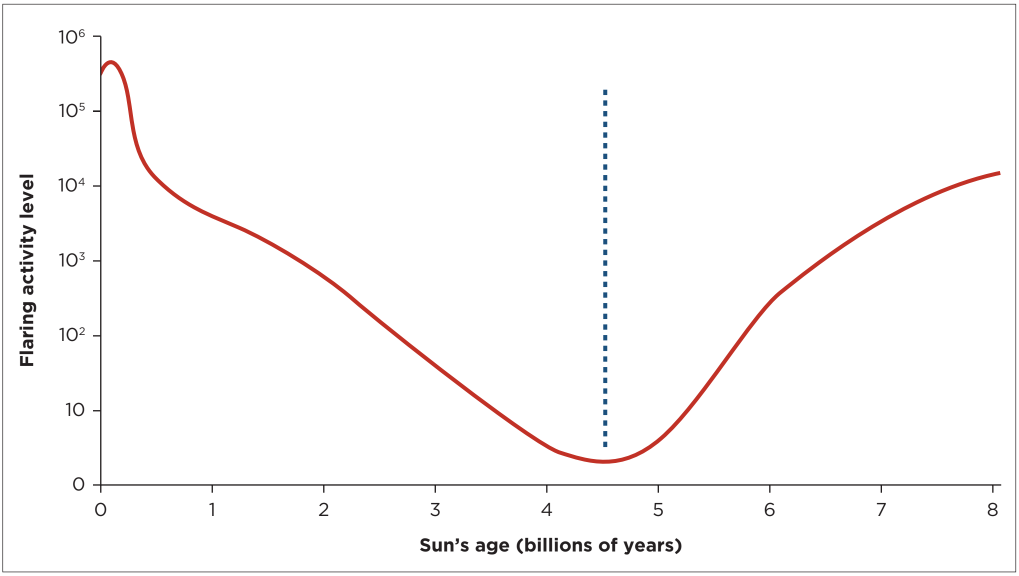
What does this capacity for the precision of design and implementation tell us about the Source of our universe? Clearly, design and implementation require intellect, knowledge, intention and capacity (power and resources), all of which are attributes of a personal being, not of a nebulous force or forces. Secondly, this person must be, at a minimum, some 10^{99} times more brilliant, knowledgeable and capable, not to mention intentional, than any human or collaboration of humans. The fine-tuning observed and measured in dark energy, as well as the fine-tuning of well over a hundred other cosmic features and the laws of physics, leads to the reasonable conclusion that an omniscient, omnipotent, personal Being *caused* the universe for purposes that include the existence of humans.

The universe's age is 13.791 ± 0.021 billion years (Aiola et al. 2020). As the universe ages, stellar characteristics change and the relative abundance of elements changes. The universe begins with just one element: hydrogen. Within the first few minutes after the Big Bang origin event, nuclear fusion occurs on a cosmic scale. The universe's hydrogen becomes transformed, yielding 76% hydrogen, 24% helium and a trace amount of lithium.

About 200 million years after the cosmic creation event, the first stars form. The nuclear furnaces inside these stars begin to fuse some of their primordial hydrogen, helium and lithium into elements heavier than lithium. With each successive generation of star formation, the abundance of elements heavier than lithium increases.

Individual stars also change as they age. Figure 3.1 shows how the flaring activity and deadly radiation emission of sun-like stars vary throughout their burning history. Stars with masses less than or greater than the Sun's will change at rates much less conducive to life support on any of their planets. Advanced life requires a star equal to the Sun's mass and possessing an age of 4.57 billion years (Ross 2016, pp. 143–159, 2020, pp. 117–127).

Advanced life also requires a planet with an enormous abundance of thorium and uranium. It is these radioactive elements that provide the



Source: Author's own work.
Note: Dotted line indicates the present epoch.

FIGURE 3.1: Sun's level of flaring activity and deadly radiation emission throughout its nuclear burning history.

necessary internal planetary heat to establish a long-lasting, strong planetary magnetic field (needed to shield advanced life from deadly stellar and cosmic radiation) and equally long-lasting and powerful plate tectonic activity (needed for surface oceans and continents to coexist so that nutrients crucial for advanced life can be efficiently recycled).

Thorium and uranium arise from only two sources: supernova eruptions and neutron star mergers. The rates of supernova eruptions and neutron star mergers change throughout the universe's history. Thorium and uranium, being radioactive, become progressively less abundant after they are formed. The abundance of uranium and thorium in the universe attains a peak when the universe is slightly more than 9 billion-years-old (Ross 2008, pp. 45–47). That the solar system formed when the universe was slightly more than 9 billion-years-old is one reason why the earth is extremely rich in uranium and thorium. The slightly more than 9 billion years + 4.57 billion years is one of many reasons why the universe must be no younger and no older for advanced physical life to possibly exist.

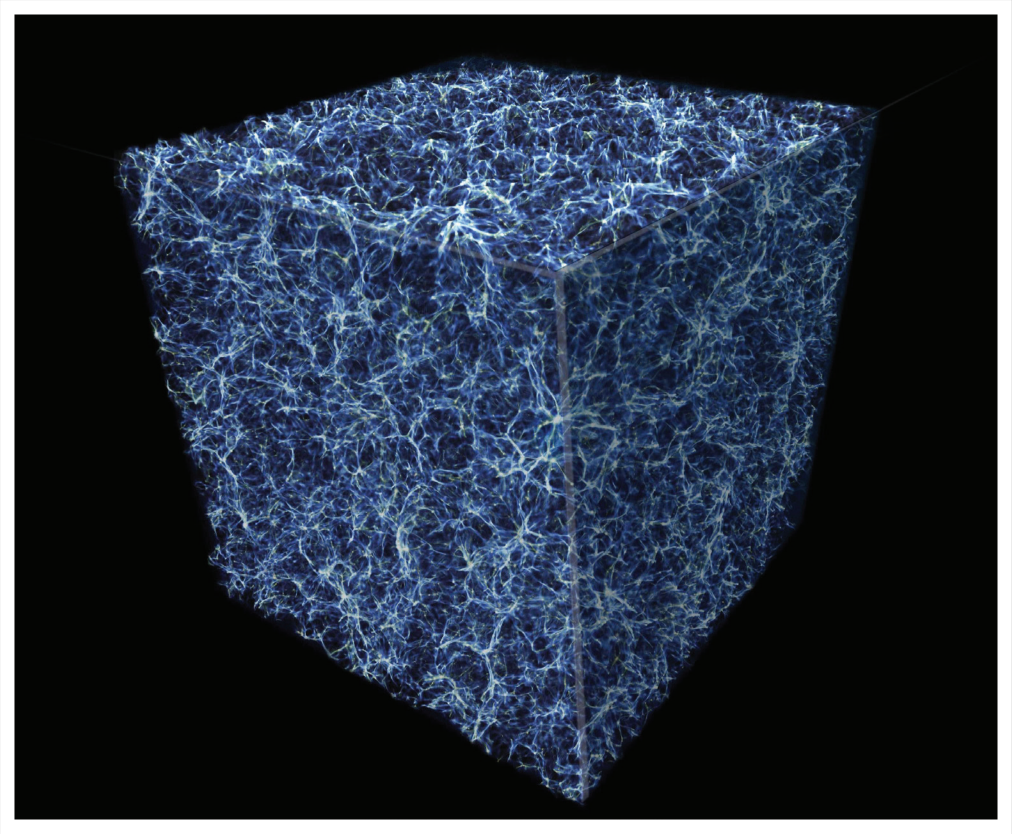
As much evidence as science has noted for fine-tuning on the scale of the entire universe, far more evidence for fine-tuning has been observed on smaller size scales. In fact, fine-tuning is abundant on all cosmic size scales, from the cosmic web to our super galaxy cluster, to our galaxy cluster, to our galaxy and to our galactic neighbourhood. Space permits the presentation of just a few highlights.

Fine-tuned cosmic web

By looking at cosmic space regions smaller than 840 million light-years in diameter, the seemingly random, homogeneous, uniform jumble of galaxy superclusters gives way to ordered structures. This ordered arrangement of gas, galaxies, galaxy clusters and galaxy superclusters together constitute the cosmic web.

The cosmic web appears as soap foam – filaments and sheets of gas, galaxy clusters and galaxy superclusters distributed on the surfaces of gigantic bubbles (see Figure 3.2). Nearly all the universe's baryonic matter (matter comprising protons and neutrons) and much of the dark matter (matter comprising particles that do not, or very weakly, interact with light) in the universe are distributed along the bubbles' surfaces. The bubbles' interiors are largely void of matter.

Membranes comprising ordinary matter encapsulate voids of such matter (credit: NASA/ESA/E. Hallman, University of Colorado, Boulder)



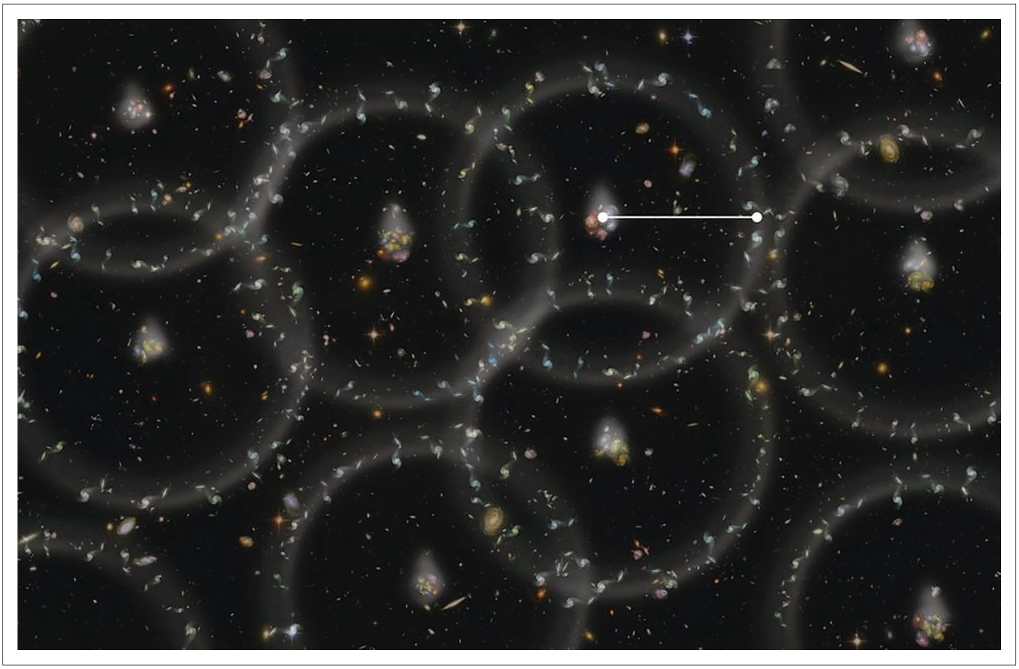
Source: Credit: NASA/ESA/E. Hallman (University of Colorado, Boulder), published with the appropriate permissions.

FIGURE 3.2: Graphic portrayal of cosmic webs.

The bubbles formed when baryonic matter clumped together in the early history of the universe. The clumping aggressively formed stars. The newborn stars radiated huge numbers of photons. The photons generated pressure that counteracted gravity, creating ripples that radiated throughout the universe's space-time surface.

Since dark matter interacts so very weakly with photons, the photon pressure that gave rise to the ripples did not affect dark matter. Hence, most of the universe's dark matter remained at the centres, or cores, of the ripples. Meanwhile, the baryonic matter got pushed outward to form bubbles around the cores (see Figure 3.3). A small amount of baryonic matter did fall into the bubble cores because of the gravitational tugs of dark matter there.

The total quantity of matter, the ratio of baryonic to dark matter quantities, the cosmic expansion rate and, to a much lesser degree, the strength of intergalactic magnetic fields determined the sizes of cosmic web bubbles. The bubble sizes meant that galaxy clusters and the galaxies within them moved apart from each other by the just-right distances at the just-right times in the universe's history to allow for the possible future existence of advanced physical life.



Source: Zosia Rostomian, Lawrence Berkeley National Laboratory, published with the appropriate permissions.

FIGURE 3.3: Artist's depiction of bubbles of ordinary matter surrounding cores of predominantly dark matter.

Fine-tuned galaxy supercluster

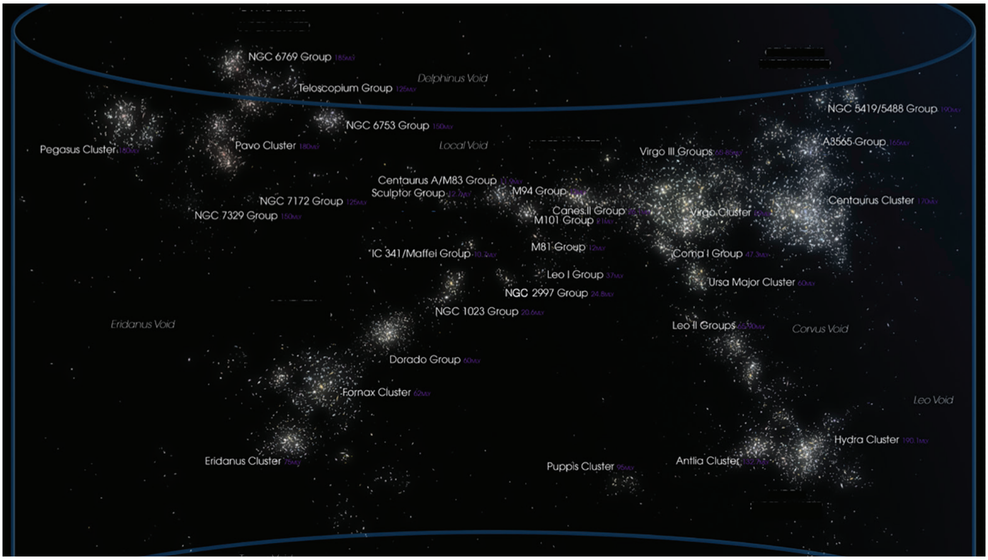
A galaxy supercluster is a cluster of galaxy clusters, where galaxy clusters contain (on average) several thousand galaxies. The observable universe contains millions of galaxy superclusters.

We live in the Laniakea Supercluster. It is a galaxy supercluster like no other. Its shape and interior structure are apparently unique. All other galaxy superclusters that astronomers observe have spheroidal or ellipsoidal shapes. The Laniakea Supercluster is shaped like a stick insect (see Figure 3.4).

Other galaxy superclusters are densely packed with galaxy clusters and galaxies. The galaxy clusters and galaxies in the Laniakea Supercluster are strung out along well-separated long filaments.

The Laniakea's long, thin, spindly filaments prove crucial for hosting advanced life. The filaments provide just enough density of matter to fuel and sustain the structure of a galaxy-type advanced life needs – a large, symmetrical, unwarped spiral galaxy. Because the Laniakea Supercluster's filaments are long and well-spaced, it is possible for such a galaxy within one of its filaments to avoid the gravitational distortions and deadly radiation from the massive Virgo, Centaurus and Hydra clusters.

Unlike other galaxy superclusters, the Laniakea has a low population of supergiant galaxies. Supergiant galaxies possess black holes in their cores with masses ranging from 0.5 to 50 billion solar masses. Fortunately for



Source: Andrew Z. Colvin, published with the appropriate Creative Commons Attribution permissions.

FIGURE 3.4: Map of the galaxy clusters comprising the Laniakea Supercluster.

advanced life, for nearly all the few supergiant galaxies in the Laniakea Supercluster, their SMBHs are presently accreting very little matter. Therefore, they are not emitting radiation that would rule out advanced life in the Laniakea Supercluster.

Fine-tuned galaxy cluster

Just as the Laniakea Supercluster manifests a unique structure, so does the Virgo Cluster of galaxies. Most large galaxy clusters are dominated by a spheroidal core densely populated by thousands of galaxies (giant, large and medium-sized) and surrounded by a less dense halo of medium-sized and small galaxies. While the Virgo Cluster's core possesses a similar conglomeration, its core is disk-shaped and much less densely populated.

The Virgo Cluster's shape as a whole is likewise distinct. Large galaxy clusters typically manifest a spheroidal shape. The Virgo Cluster's shape resembles a flattened ellipsoid.

The most striking difference between the Virgo Cluster and other large galaxy clusters is twofold: the extent to which long filaments of small galaxy groups radiate from the core and the asymmetry with which these long filaments are dispersed.

The longest and most complex of the Virgo Cluster filaments radiates far outward from its core and then branches into four sub-filaments. The Local Group of galaxies – home to our MWG – resides near the nexus of three of these sub-filaments. This region hosts an exceptionally low density of galaxies, especially of large galaxies. This zone of low galaxy density along a little sub-sub-filament branching off from the Virgo Cluster's main filament provides an ideal (for the possibility of advanced life) locale for the Local Group.

Fine-tuned galaxy group

The Local Group is an isolated galaxy group within the Virgo Cluster. The Virgo Cluster's other galaxy groups are much closer to neighbouring groups. They are also much more densely populated by large- and medium-sized galaxies.

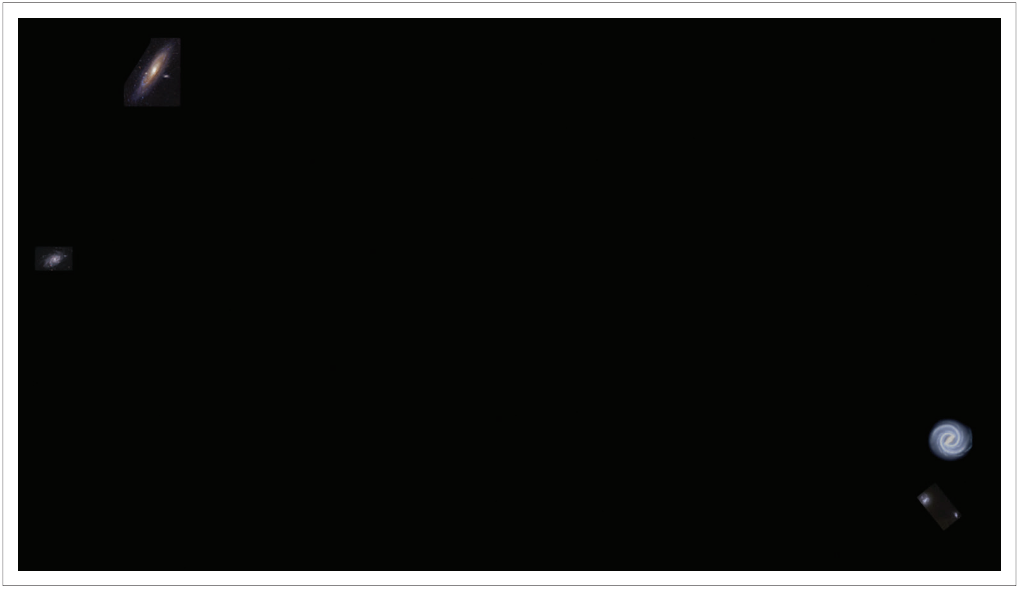
The Local Group is large in terms of spatial extent. Its diameter is as large as, or larger than, other galaxy groups in the Virgo Cluster and about the same size as the Virgo Cluster core. However, in contrast with the Virgo Cluster core, it is lightweight. It contains 50 times fewer galaxies and, while the Virgo Cluster core contains several giant galaxies, the Local Group contains none. While the Virgo Cluster core contains dozens of large galaxies, the Local Group contains only two. While the Virgo Cluster's core population of large galaxies includes elliptical, spheroidal and barred and unbarred spiral galaxies, the Local Group includes just two large galaxies, both barred spirals. While the Virgo Cluster core contains hundreds of medium-sized galaxies, the Local Group hosts just one, the Triangulum Galaxy and this galaxy is medium-sized only in its spatial extent. Its mass places it in the large dwarf category.

Among nearby galaxy groups the Local Group has the lowest total mass (although Sculptor may be nearly as low) (Karachentsev 2005). But its most striking feature is its centre. Unique to the Local Group is its *empty* dynamical core. Unlike the cores of all other known galaxy groups, it has no giant, large, medium-sized or large dwarf galaxies in or near its centre.

What especially sets the Local Group apart from other galaxy groups is the position of its large galaxies and large dwarf galaxies. Its two large galaxies reside relatively far apart from one another. Its large dwarf galaxies number only five and all five are located close to the two large galaxies (see Figure 3.5).

The vast majority of galaxies in the Local Group are low-mass dwarf galaxies. Over a hundred have been discovered so far (Drlica-Wagner et al. 2020; McConnachie 2012; McConnachie et al. 2018, 2021). Low-mass dwarf galaxies in the Local Group are the oldest, least chemically enriched, most gas-rich and most dark-matter-dominated stellar systems yet known.

The sizes and separations of the galaxies are to scale. The Andromeda Galaxy (AG) with its two nearby dwarf galaxies, M32 (left) and NGC 205 (right), is at the upper left. The Triangulum Galaxy is to the extreme left



Source: Image provided by Hugh Ross, published with the appropriate permissions provided by Hugh Ross.

FIGURE 3.5: Map of the largest galaxies in the Local Group.

just above centre. The MWG and the Large Magellanic Clouds (LMCs) and Small Magellanic Clouds (SMCs) are at the lower right. Galaxy image credits: NASA/ESA/ESO/JPL-Caltech (R. Hurt).

The Local Group's precise gas content, the relative abundance of elements in the Group's dwarf galaxies, the unique population, demographics and spatial distribution of the larger and smaller dwarf galaxies, as well as remnant gas streams and clouds, *all* factor into the MWG's capacity to host advanced life. A major determining factor is the manner in which two of the Local Group's larger dwarf galaxies funnel essential ingredients into the MWG.

The (LMC and SMC) serve as the MWG's feeders. The configuration of the MWG and the LMC and SMC (see Figure 3.6) is rare and possibly unique in the universe.

The mass distribution and configuration of the LMC and SMC relative to the MWG explain the MWG's just-right diet that sustains its symmetrical spiral arm structure to a large extent. Low-mass dwarf galaxies that have escaped tidal stripping, unlike their larger cousins, are extremely gas-rich. Thus, if the gravitational pull of a spiral galaxy is strong enough to draw such dwarf galaxies into its bulge (its central core), it will receive the gas it needs to sustain its spiral structure. However, if the spiral galaxy draws in one of the larger of these dwarf galaxies, or several smaller dwarf galaxies all at once, it will receive that much gas so as to produce a 'burp'.

Source: Image credits for the individual galaxies: NASA/ESO/JPL-Caltech (R. Hurt) , published with the appropriate permissions.
Note: The visual sizes and separations of the galaxies are to scale.

FIGURE 3.6: Map of the Milky Way and the Large and Small Magellanic Clouds.

The consumption of a large dwarf galaxy or several smaller galaxies all at once would have gravitationally distorted the structure of the MWG's spiral arms to an intolerable degree for the sake of advanced life. What is more, the infusion of so much gas would have generated such an aggressive burst of star formation so as to shower advanced-life-conceivable sites with deadly radiation and caused additional gravitational disturbances.

Computer simulations show that as long as the MWG consumes a dwarf galaxy no larger than one-seventieth its mass at a just-right rate, its bar structure remains a stable feature of its central bulge (Zinchenko et al. 2015). The simulations also demonstrate that if the MWG had consumed dwarf galaxies significantly larger than one-seventieth its mass at any time throughout the past 10 billion years, its spiral arm structure and disk shape would have suffered one or more severe distortions (Zinchenko et al. 2015).

The unusual characteristics and history of our Local Group have allowed the MWG to maintain its central bar and highly symmetrical spiral arms, with only a few spurs and feathers between them, throughout the past 10 billion years (Dobbs & Bonnell 2006; Filistov 2012; Hammer et al. 2007; Kim & Ostriker 2006; Shetty & Ostriker 2006). The new study shows that the stability and symmetry of this spiral structure have been maintained for many billions of years primarily because our galaxy has maintained a strict diet. It has consumed dwarf galaxies of the just-right elemental composition and just-right mass at a just-right rate. Unlike all other known spiral galaxies, the MWG continuously 'sips' rather than intermittently 'gulps' available matter.

The dieticians responsible for the MWG's 10-billion-year-long strict diet are the LMC and SMC. The proximity of the LMC and SMC, as well as their large mass and high gas content, allows the tidal forces of the MWG to draw from them a nearly steady stream of gas (Crnojević et al. 2012, p. 321; Indu & Subramaniam 2015; Lucchini et al. 2020; Pardy, D'Onghia & Fox 2018; Robotham et al. 2012). The Magellanic Clouds are massive enough, sufficiently close together and positioned at the just-right distance from the MWG as to funnel a steady supply of the Local Group's gas-rich, low-mass dwarf galaxies into the MWG's core (Deason et al. 2015; Lucchini et al. 2020; Zhang, Luo & Kang 2019). The Magellanic Stream and its Leading Arm exemplify a shepherding role – provisional and protective (Vasilev, Belokurov & Erkal 2021). This steady, gradual supply of gas has sustained our galaxy's spiral structure throughout the past several billion years without disturbing its overall symmetry and morphology.

Astronomers have found no other example of the mass distribution and spatial configuration of the MWG, LMC and SMC within a group of galaxies that lacks both a core and a much larger galaxy. Our Local Group is amazing and elegant in ways that make advanced life possible within the MWG.

■ Local Group's extraordinary supermassive black holes

Astronomers define a SMBH as a black hole with a mass greater than 1 million solar masses. All known medium, large and giant galaxies possess an SMBH in their central core region, with one remarkable exception: the LMC.

With a mass now determined to be at least 200 billion solar masses and likely 250 billion solar masses (Deason et al. 2015; Laporte et al. 2018; Peñarrubia et al. 2016), the LMC is firmly in the medium-sized galaxy category. Although it does have a black hole in its core, it is not a supermassive one.

The kick velocity of the star HE 0437-5439 (aka HVS3) as it is being ejected from the centre or very near the centre of the LMC requires the presence of a black hole with a minimum mass = 4 000 solar masses (Erkal et al. 2019; Gualandris & Portegies Zwart 2007). Astronomers' inability to detect any radiation emission from the region just outside the event horizon of the LMC's central black hole implies one of two possibilities: either this black hole's mass is close to the measured lower limit of 4 000 solar masses, or this black hole is presently accreting little or no gas and no objects more massive than one of the smaller moons (diameter ~1km) in our solar system. Whatever the case, the LMC's central black hole currently poses no radiation risk to life in the MWG.

Astronomers have been unsuccessful in their attempts to detect a central black hole in the SMC. Neither have they observed any significant x-ray radiation from the SMC's central region. Thus, neither the LMC nor SMC emits radiation deadly enough to pose a risk to advanced life in the MWG.

The AG is home to the Local Group's largest SMBH. An analysis performed by 15 astronomers on the dynamics of three distinct stellar nuclei in the AG's core showed that the AG's SMBH's mass = 140 million solar masses (Bender et al. 2005).

With the AG residing only 2.5 million light-years away from the MWG, its SMBH mass would appear to pose a deadly threat to any potential advanced life in the MWG. If it were to accrete anything as massive as a planet, let alone a star, the region just outside the AG's SMBH's event horizon would emit intense, highly energetic radiation throughout the Local Group. As it is, astronomers have been surprised by how little deadly radiation output in the Local Group, they can attribute to the AG's SMBH.

In a paper entitled ‘The Murmur of the Hidden Monster’, eight astronomers reported on their Chandra X-Ray Observatory measurements of the x-ray radiation attributable to the AG’s SMBH (Li et al. 2011). From 1999 to 2005, such radiation measured less than or equal to 10^{36} ergs/second – less than a 10-billionth of its maximum possible output. In the six years after that study, astronomers observed an average x-ray flux of only 4.8×10^{36} ergs/second. This very low x-ray flux resulting from the AG’s SMBH led the astronomers to describe the SMBH as ‘remarkable’ for its ‘extreme radiative quiescence’ (Li et al. 2011, p. 1).

As surprisingly tiny LMC’s central black hole apparently is, given LMC’s high mass, astronomers have been equally astonished at how massive M32’s central black hole is, given M32’s low mass. (M32 is the dwarf galaxy just to the left of the AG’s central bulge Figure 3.5. Its mass is only 0.25% of the MWG’s mass.) A combination of Hubble Space Telescope and ground-based telescope measurements of the velocities of stars in M32’s core reveal that M32’s SMBH = 3.4 million solar masses (Van der Marel et al. 1998).

The very weak x-ray radiation from M32’s core indicates that M32’s SMBH must be fuel starved. Its accretion rate must be less than a 10-billionth of a solar mass per year (less than the mass of the asteroid Vesta per year) (Loewenstein et al. 1998). The known history of M32 tells us that the accretion rate of its SMBH has remained low throughout the past 200 million years (Block et al. 2006). Thus, during the past 200 million years M32’s SMBH has posed no threat to life in the MWG.

The other large dwarf galaxies in the AG’s vicinity, M33 and NGC 205, both lack an SMBH. Observations made with the Hubble Space Telescope Imaging Spectrograph establish that M33’s central black hole is no more massive than 1500 solar masses (Gebhardt et al. 2001; Merritt, Ferrarese & Joseph 2001). Likewise, Hubble Space Telescope images and spectra show that NGC 205’s central black hole must be less massive than 38 000 solar masses (Valluri et al. 2005). Hence, the central black holes in M33 and NGC 205 pose no threat to life in the MWG.

All the remaining dwarf galaxies in the Local Group possess central black holes less massive than 10 000 solar masses. At about double the distance from the Local Group’s outer boundary, the dwarf galaxy NGC 404 has a central black hole roughly 100,000 times as massive as the Sun (Seth et al. 2010). It is sufficiently distant to pose no threat.

■ Fine-tuned galaxy

Galaxies without spiral arms are noncandidates for possible support of advanced life because of the high density of stars in such galaxies. High star density leads to erratic planetary orbits and frequent bombardment by planetesimals, comets, asteroids, molecular clouds and dust. Large armless galaxies grow especially large SMBHs, the kind that generates deadly radiation. Given that the existence of advanced life requires a long, continuous history of less advanced life (Ross 2016, pp. 94–197), a galaxy that can possibly host advanced life must maintain its stable spiral structure for at least several billion years.

Dwarf galaxies, on the other hand, lack mass. The smaller the total mass of a galaxy, the higher the probability it will suffer frequent and substantial gravitational disturbances because of the influence of other nearby galaxies. As it is, the MWG is barely massive enough to have avoided such disturbances over the past four billion years.

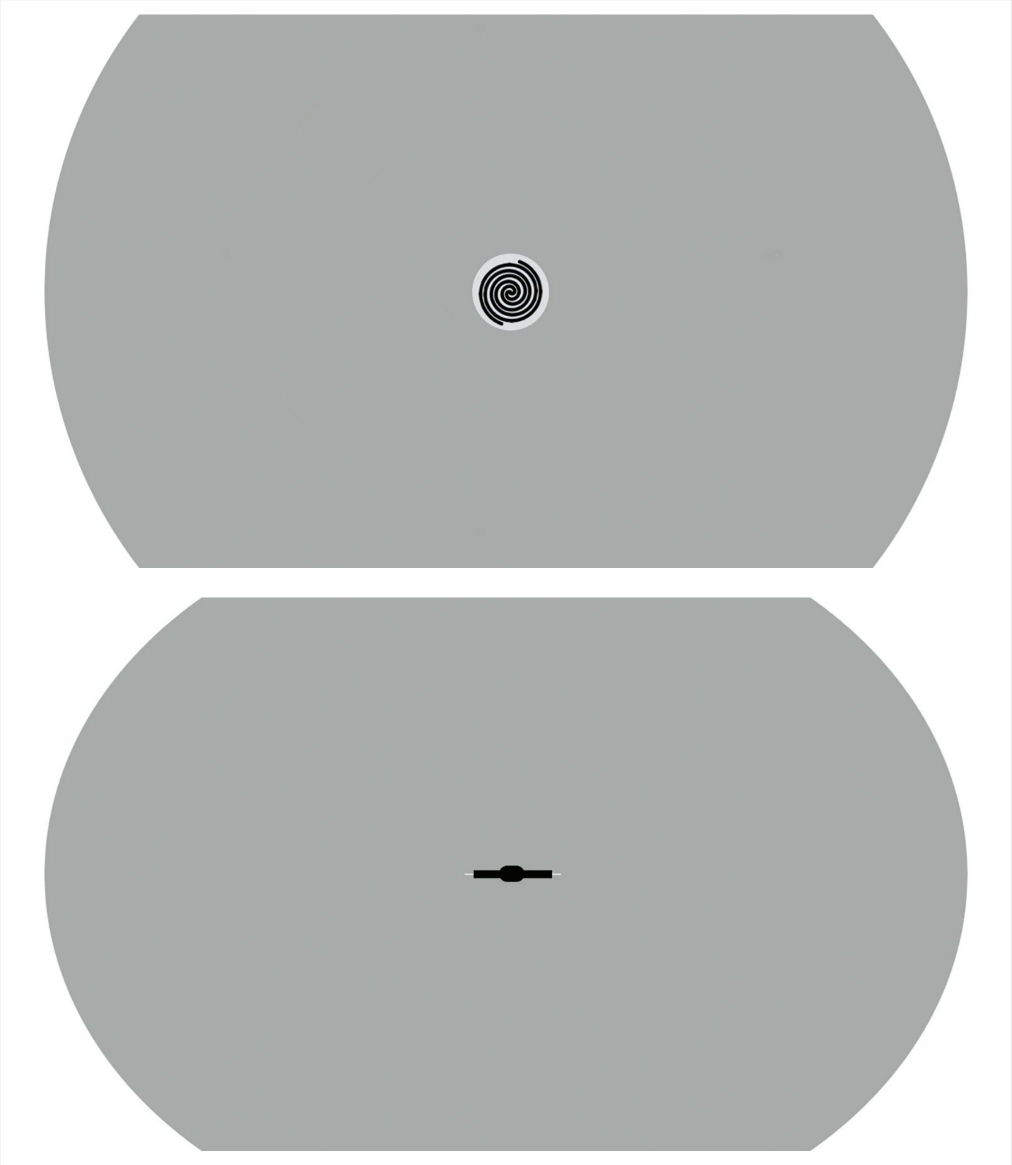
At the same time, the mass of the MWG is barely small enough to avoid attracting, within too brief a period, other galaxies of sufficient mass to substantially disturb its structure. Currently, the MWG is on a collision course with both the Large Magellanic Cloud and the AG. However, neither of these collisions will occur within the next four billion years, and the MWG's structure appears stable enough for life's existence for at least the next billion years.

Less than 1% of the present-day non-dwarf galaxy population are spiral galaxies within the mass range necessary for the possible existence of advanced life (Dressler et al. 1994). Both the MWG and the AG fall within the needed mass range. However, the MWG's mass distribution is unique.

By nature, spiral galaxies possess a low ratio of stellar mass to the total mass. In the case of the MWG, that ratio is exceptionally low. Its mass in the form of stars is only 54.3 billion ± 5.7 billion solar masses (McMillan 2017). The MWG's sister galaxy, the Andromeda, has double the stellar mass of the MWG (Sick et al. 2014).

Figure 3.7 shows the three major parts of the MWG's structure. The most familiar part is the smallest component, the stellar disk. This pancake-shaped disk has a diameter of about 130,000 light-years (Skowron et al. 2019), but its star density falls off rapidly at distances beyond 50 000 light-years from the galactic centre. Only a few disk stars have been detected at distances as far as 85 000 light-years from the galactic centre (López-Corredoira et al. 2018).

The MWG's stellar disk is embedded in a larger but thinner disk of gas, measuring at least 165,000 light-years across (Levine, Blitz & Heiles 2006). Much of the gas in this disk results from ongoing interactions of the MWG with the nearest low-mass dwarf galaxies. Both these disks are embedded within a much larger halo of dark matter (matter comprising particles that either do not interact with photons or very weakly interact with photons). This dark matter halo has the shape of a mildly oblate



Source: López-Corredoira et al. (2018); Skowron et al. (2019).

FIGURE 3.7: Major components of the Milky Way Galaxy. Top: Plan view of the Milky Way Galaxy components. Bottom: Side view of the Milky Way Galaxy components.

spheroid (Piffl et al. 2014), similar to a slightly flattened beach ball. In other words, the MWG contains a nearly flat disk inside a much larger, nearly (but not quite) round ball.

The central stellar bulge and the stellar disk are shown in black. The thin disk of gas appears in light grey. The much larger dark grey area depicts the dark matter halo, not all of which shows up in the plan view. The dark matter halo in this view would be circular.

Computer simulations show that just beyond the edge of a large spiral galaxy's dark matter halo, the velocities of nearby low-mass dwarf galaxies will drop sharply. A team of astronomers led by Alis Deason detected such a sudden drop of about 950,000 light-years from the MWG's centre (Deason et al. 2020). That is, the diameter of MWG's dark matter halo in the plane of its disk is a staggering 1.9 million light-years.

The MWG is exceptional among spiral galaxies in that so little of its total mass is in the form of ordinary matter, matter made up of protons and neutrons – also known as baryons. These baryons comprise only 4.2% of the MWG's total mass (Piffl et al. 2014). The cosmic average for galaxies is 15.7% (Planck Collaboration 2020). The predominance of the MWG's dark matter halo, with its size, shape and distribution, plays a major role in maintaining the exceptional symmetry and stability of the MWG's spiral arm structure. This structure, in turn, plays a major role in the galaxy's possible role as a home for advanced life.

Supermassive black hole like no other

The MWG's SMBH weighs in at only 4.152 million ± 0.014 million solar masses (GRAVITY Collaboration 2019). This low mass limits the quantity of deadly radiation it can possibly generate. Astronomers have determined that the MWG's SMBH's low mass is truly extraordinary and unexpected. It deviates, by far, from the otherwise strong and consistent correlations among multiple galaxy characteristics and the mass of those galaxies' SMBHs. Based on the following seven features, astronomers would expect the MWG's SMBH to be much more massive than it is:

1. number of globular clusters orbiting the galaxy (González-Lópezlira et al. 2017; Harris, Poole & Harris 2014; Rhode 2012)
2. mass of the galaxy's central bulge (De Nicola, Marconi & Longo 2019; Kormendy & Ho 2013; Miki et al. 2014; Yang et al. 2019)
3. luminosity of the galaxy's central bulge (Marconi & Hunt 2003)
4. luminosity of the galaxy (Do et al. 2014; Gültekin et al. 2009)
5. the pitch angle of the spiral arms (Berrier et al. 2013; Seigar et al. 2008)
6. velocity dispersion (range of velocities) of stars in the central bulge (Ateş, Kilinç & İbanoğlu 2013; Marsden et al. 2020)
7. total stellar mass (Shankar et al. 2020).

The total mass of the AG is equal to the MWG's mass and both galaxies are barred spirals (Beaton et al. 2007). The mass of the AG's SMBH aligns with all seven galaxy features to SMBH mass correlations. The mass of the MWG's SMBH does not. The MWG's SMBH is 35 times less massive than the AG's SMBH.

This mass difference means that our galaxy's SMBH holds 35 times less potential to emit deadly radiation from regions just outside its event horizon. This much lower potential – by a factor of 35 – makes a huge difference in the possibility of advanced life's survival in the MWG.

Just as importantly, the MWG's SMBH has, for at least the past 100,000 years, remained extraordinarily quiet. It emits a relatively low level of radiation. This implies that it is currently drawing a low quantity of gas, dust, comets, asteroids, planets and or stars towards its event horizon.

Supermassive black holes in nearby galaxies consume a star of the Sun's mass or greater on average about once every 100,000 years (Zubovas, Nayakshin & Markoff 2012). When this happens, a bright flare lasting several months or longer blasts deadly radiation throughout the galaxy. Stars smaller than the Sun are consumed about once every 10 000 years. When they are, deadly radiation is emitted for several days to weeks. Molecular gas clouds are consumed at a rate anywhere from one per century to one every few millennia. These events likewise pour out deadly radiation lasting days to weeks.

The MWG's SMBH has entered a phase of minimal consumption, comparable to light snacking. Its intake produces tiny flares on an almost daily basis that last only hours (Zubovas et al. 2012). As a team of astronomers led by Lia Corrales wrote, 'The supermassive black hole at the centre of our galaxy, Sgr A*, is surprisingly under-luminous' (Corrales et al. 2017). The activity level just outside the event horizon of the MWG's SMBH has been exceptionally low throughout the past 12 000 years, the same era during which human civilisation has been launched and sustained.

The MWG is unique in multiple respects, all of which bear on its capacity to host advanced life. The long list of extraordinary advanced-life-essential features includes its ratio of stellar mass to total mass; its dark matter halo and gas disk; its bar-bulge structure; its star distribution; its astonishingly small, extremely quiescent SMBH; its inventory of elements; the relative dimensions of its thin disk and thick disk; its number of spiral arms and their precise pitch angle; the symmetry of its spiral arms; its few spurs and feathers between spiral arms and its green hue from a balance of old, middle-aged and young stars. This list grows as research continues and new instruments become available.

Figure 3.8 captures the images of 11 spiral galaxies plus a detailed map of our MWG. The 11, among all the galaxies astronomers, have been able to image in structural detail, come closest to matching the MWG's morphology. A comparison of these 11 images with the detailed map of the MWG helps illustrate at least some of the MWG's uniqueness, most clearly its arms' beautiful symmetry and freedom from spurs, feathers, large nebulae, large star clusters and gravitational disturbances.

Source: Shulman Foundation, NASA/ESA/Hubble Space Telescope, ESA/NASA, NASA/ESA/Hubble Heritage (STScI/AURA), ESO, respectively. Published with the appropriate permissions provided by Adam Evans. Map credit for the Milky Way Galaxy: NASA/JPL-Caltech (R. Hurt), published with the appropriate permissions.

FIGURE 3.8: Spiral galaxies that most closely match the Milky Way Galaxy's structure.[40]

---

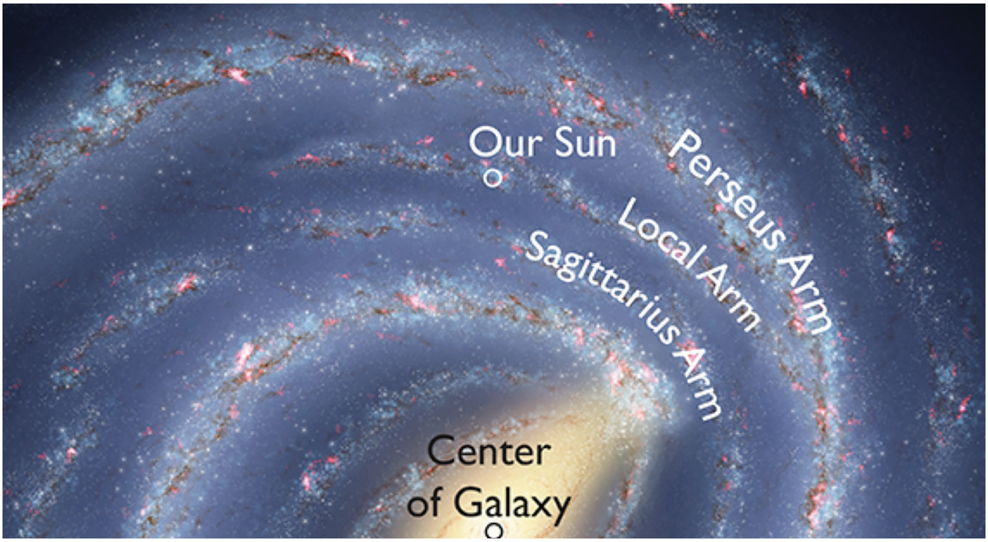
[40] Top panel: upper row, left to right: Andromeda Galaxy, NGC 4526, NGC 908; lower row, left to right: NGC 6384, NGC 3344, NGC 4921.
Bottom panel: top row, left to right: M100, UGC 6903, Pinwheel Galaxy; bottom row, left to right: NGC 3370, NGC 1232, Milky Way Galaxy

Fine-tuned local galactic arm

Due to the very long baseline array – a chain of ten 25-m (82-foot) diameter radio telescopes distributed across the earth from Hawaii to St. Croix, creating a baseline of 8611 km (5351 miles) – astronomers have made accurate trigonometric distance measurements to specific radio sources (called masers) in our solar system's nearby spiral arms. These measurements and others made by the European Very Long Baseline Interferometer and the Japanese Very Long Baseline Interferometer, provide astronomers with a detailed map of the MWG's arms in the vicinity of our solar system (Reid et al. 2014, 2019; Sakai et al. 2019; Wu et al. 2014). Figure 3.9 shows that map.

The map reveals that the Sun is located roughly halfway between the MWG's two major arms, the Sagittarius and Perseus. It resides in the Local Arm, an appendage that split off from the Perseus Arm about 75° back from the Sun's current position.

The part of the Sagittarius Arm nearest the Sun contains only small- to medium-sized star-forming nebulae and star clusters, no large ones. The portion of the slightly more distant Perseus Arm that comes closest to the Sun likewise contains smaller-sized star-forming nebulae and star clusters. The absence of large nebulae and clusters means that the Sun and its planetary system are protected, at least for the time being, from any major gravitational disturbances or life-threatening radiation coming from either the Sagittarius or Perseus Arm.



Source: IPAC, Robert Hurt; NRAO/AUI/NSF, Bill Saxton, published with the appropriate permissions.

FIGURE 3.9: Milky Way Galaxy spiral arms near the sun.

Meanwhile, the Local Arm (where the Sun resides) carries still smaller star-forming nebulae and star clusters than either the Sagittarius Arm or the Perseus Arm, especially in the region nearest the Sun. The closest nebula to the Sun with significant star formation shows up as a pink spot (in the online colour version of Figure 3.9) slightly above and left of the Sun. That pink spot shows the Orion Nebula, with a total mass about 2000 times that of the Sun.

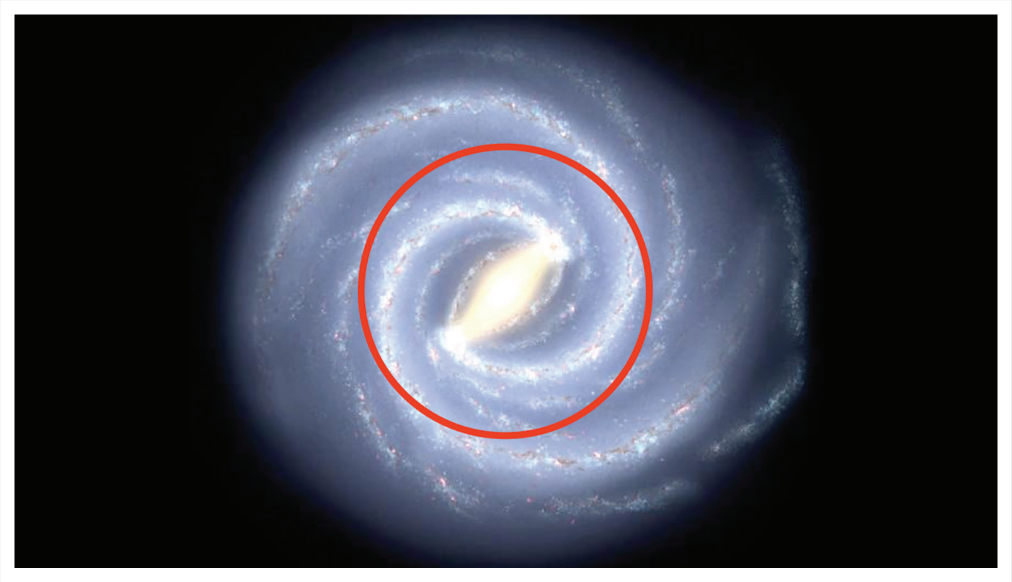
Because Figure 3.9 is a two-dimensional map, the proximity of the Orion Nebula to the Sun is deceptive. The actual distance between Orion and the solar system = 1345 ± 19 light-years (Reid et al. 2009, p. 138). On the distance scale of Figure 3.9, the Orion Nebula is 4.5 times farther from the Sun than that pink spot makes it appear. The point, here, is that the Orion Nebula is sufficiently distant and therefore poses no risk to the habitability of the Sun's planets.

Newton's laws of motion determine the rate at which stars revolve around the galactic centre. The greater a star's distance from the centre, the longer it takes to make a revolution around it. Density waves determine the rotation rate of the spiral arm structure.

The farther a star is from the galaxy's corotation radius (the distance from the galactic centre where stars revolve at the same rate as the spiral structure rotates), the more frequently that star crosses a spiral arm. Spiral arm crossings are hazardous to advanced life. Spiral arms are the sites for young supergiant stars, giant molecular clouds and star-forming nebulae that shower their vicinity with deadly radiation. These stars, clouds and nebulae also gravitationally disturb any nearby planetary system's asteroid-comet belts, unleashing an enhanced bombardment on those planets. Only stars near the corotation radius avoid frequent spiral arm crossings.

The corotation radius is different, of course, for each spiral galaxy, depending on the galaxy's total mass, stellar mass, gas mass, bulge mass, magnetic field and stellar disk dimensions. For the MWG, the corotation radius (see Figure 3.10) is far enough from the galactic centre and hence planetary systems near the corotation radius will not be exposed to deadly radiation coming from the galactic nucleus. However, any planetary system forming much farther out from the corotation radius would be unable to accrete life-essential quantities of heavy elements. (The density of matter in the galactic disk decreases with distance from the galactic centre, and the ratio of heavy-to-light elements varies in a complex way with respect to distance from the galactic centre.)

The safest place for life would not be *exactly* at the corotation distance. A planetary system in that precise place would experience the chaos of destructive mean-motion resonances (Voglis, Stavropoulos & Kalapotharakos 2006). The safest orbital distance would be just inside the corotation radius.



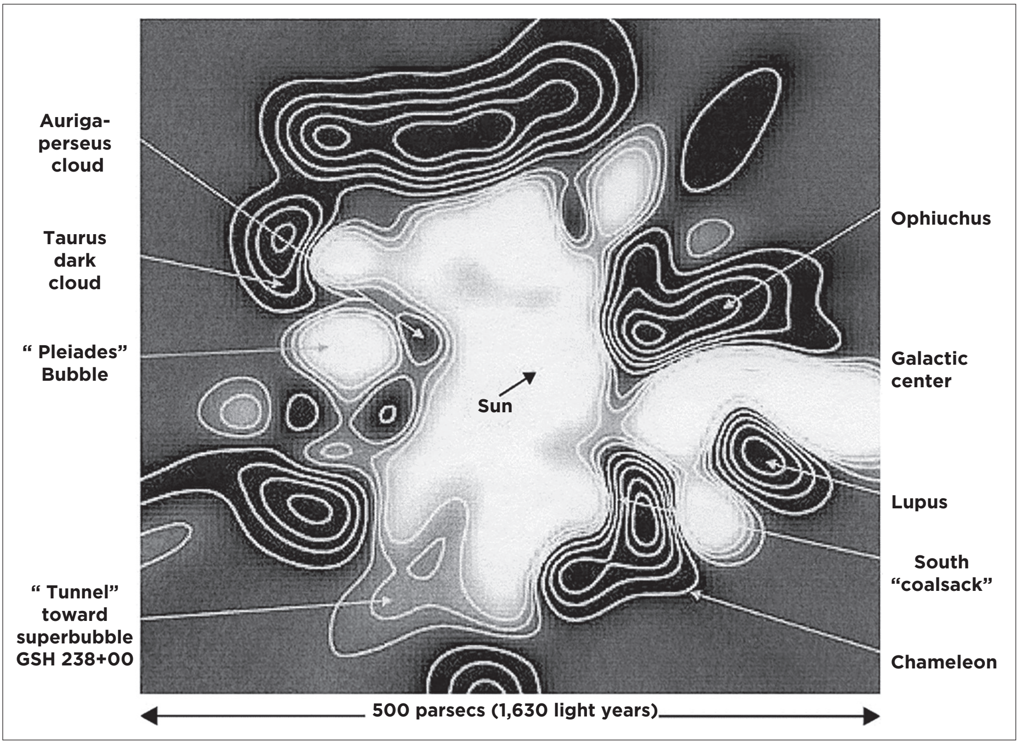
Source: NASA/JPL-Caltech (R. Hurt), Skowron et al. (2019), published with the appropriate permissions.
FIGURE 3.10: Corotation radius of the Milky Way Galaxy.

The Sun orbits the centre of the MWG at 98% of the corotation radius (Dias et al. 2019).

Just inside the corotation radius, galaxy arm fraying is minimised. A move in either direction away from just inside the corotation radius would result in increased formation of an arm's spurs and feathers. In this location near the corotation radius, the density of stars is at a minimum (Barros & Lépine 2014). For the possibility of advanced life, no better location for our star, the Sun, can be imagined.

Fine-tuned Local Bubble

The Sun resides amid a rare and temporary feature referred to as the Local Bubble (see Figure 3.11), a magnetised cavity, or void, of exceptionally low-density gas extending 160–640 light-years in all directions from the Sun (Slavin 2017). Research indicates that beginning between 10 and 15 million years ago, some 14–20 supernova eruptions within a co-moving group (surviving members comprise the Scorpius-Centaurus star association) passed by the Sun's vicinity and excavated the region now called the Local Bubble (Breitschwerdt et al. 2016; Fuchs et al. 2006). Winds from the supernova eruptions blew dust outward, forming the Bubble's shell of cold, dusty, relatively high-density gas (Pelgrims et al. 2020).



Source: Abt (2011, p. 165), published with the appropriate permissions.

FIGURE 3.11: The Local Bubble.

The solar system's location near the centre of a largely vacuous, relatively dust-free magnetised region encased in a dense wall of molecular clouds, comprised cold neutral gas and dust (Alves et al. 2018), means extraordinary protection for advanced life. This protection has been enhanced by the recent million-year time window of the Bubble's quiescence (Slavin 2017). Furthermore, by impacting the directionality of cosmic rays and producing cosmic ray diffusion (Gebauer et al. 2015), the Local Bubble has mitigated, to some degree, the potential damage to advanced life caused by cosmic radiation.

Conclusion

Fine-tuning has implications.

Evidence for the exquisite fine-tuning observed at all astronomical levels, from the farthest reaches of the cosmos to our solar system's neighbourhood, arouses a profound sense of awe and wonder. Such awe and wonder may lead one to ponder the deep questions raised by the several close-up glimpses of nature's unfolding story, as described in this chapter.

Here are six of the more obvious questions, among many others:

1. How firmly has the anthropic principle been established, to date?
2. How useful is the anthropic principle as a guide for future scientific research?
3. How ‘anthropic’ does the principle seem, in light of increasing evidence?
4. What can we deduce from fine-tuning about the fine-tuner’s attributes?
5. Can we discern the fine-tuner’s purpose(s) for crafting the universe as it is?
6. Can we discern anything from the fine-tuning evidence about our purpose and ultimate destiny?

Chapter 4

Local fine-tuning and habitable zones

Guillermo Gonzalez
Center for Applied Optics,
University of Alabama,
Huntsville, Alabama, United States of America

Introduction[41]

In the second half of the 20th century, physicists discovered that the values of the physical constants and cosmological initial conditions must not differ greatly from their observed values for life to be possible in the universe (Barrow & Tipler 1986; Collins 2003; Rees 2000, 2003). Small changes to the values of some constants, for example, would result in universes far too short-lived or too simple (e.g. only hydrogen or black holes) or too chaotic for life. The conclusion from these theoretical considerations is that the universe must be 'fine-tuned' for life.

In considering fine-tuning, physicists assume that the constants and initial conditions (and possibly the physical laws) could have been different. In other words, our universe is not logically necessary. Thus, the question arises as to whether the properties of our particular universe were designed and selected

---

[41] This chapter represents a 50% reworking of sections originally published in *The Nature of Nature: Examining the Role of Naturalism in Science* (Gordon & Dembski 2014). Reworking and republication with permission.

How to cite: Gonzalez, G 2022, 'Local fine-tuning and habitable zones', in F van Niekerk & N Vorster (eds.), *Science and Faith in Dialogue,* in Reformed Theology in Africa Series, Vol. 10, AOSIS Books, Cape Town, pp. 93–124. https://doi.org/10.4102/aosis.2022.BK334.04

for us. Alternately, how much of what we observe was selected *by* us? The latter question falls under the category of one of the species of the *anthropic principle.* The observer self-selection 'explanation' for the properties of the universe we inhabit (the *weak anthropic principle*), however, suffers from a lack of independent observational evidence for other universes or domains, and theoretical motivation for them is controversial.

It is helpful to split fine-tuning into two distinct types, which we will call 'global' and 'local'. Global tuning deals with the global properties of the observable universe. These include the masses of the fundamental particles, the strengths of the four fundamental forces, the initial cosmological conditions and the cosmological constant.

In contrast, local tuning includes things that are not universal in their properties: planets, stars and galaxies. Not only do we know that planets, stars and galaxies do not have fixed properties, we actually observe them to vary in their properties over a broad range. We can study how life depends on the local parameters while keeping the global parameters fixed. We can also tally their numbers. For local tuning, then, we have the hope of accurately quantifying the available probabilistic resources and estimating how much of our local circumstances can be explained by observer self-selection.

Although it is helpful to examine fine-tuning in this way, eventually we must re-join local and global tuning if we are to determine how finely tuned our universe is for life. Discussions of global tuning do not get us very far unless we understand how the global parameter values are instantiated locally in planets, stars and galaxies.

Historically, local tuning has been explored within the context of exobiology or astrobiology. Motivated by the desire to find other inhabited planets, astrobiologists have sought to determine the full range of environments compatible with life (i.e. habitable environments). Over the past 20 years, considerable progress has been made towards this end. In the following section, I review the state of our knowledge about habitable environments (Gonzalez 2005). In the section 'Implications for global tuning', I return to the topic of global tuning and describe how local and global tuning are linked.

Habitable zones

Introduction

Since its introduction over four decades ago, the CHZ concept has served to focus scientific discussions about habitability within planetary systems. Early studies simply defined the CHZ as that range of distances from the Sun that an earth-like planet must be within to maintain liquid water on its surface. Too close, and too much water enters the atmosphere, leading to a runaway greenhouse effect. Too far, and too much water freezes, leading to runaway glaciation. Since these modest beginnings, CHZ models have become more complex and realistic, mostly because of improvements in the treatment of energy transport in planetary atmospheres and the inclusion of the carbon-silicate cycle. Along the way, Mars and Venus have served as 'real-world' test cases of the CHZ boundaries.

The CHZ has been an important unifying concept in astrobiology. Research on the CHZ requires knowledge of stellar evolution, planetary dynamics, climatology, biology and geophysics. Yet even modern CHZ models are far from complete. Many factors relating to planet formation processes and subsequent gravitational dynamics have yet to be incorporated in a formal way.

While they were not the first to discuss habitability beyond the Solar System, Gonzalez, Brownlee and Ward (2001a, 2001b) were the first to introduce a unifying concept called the GHZ. The GHZ describes habitability on the scale of the MWG. While the GHZ appears superficially similar to the CHZ, it is based on a very different set of physical processes, including the radial gradients of the supernova rate, gas metallicity, density of gas and density of stars in the galactic disk. It should also be possible to define habitable zones for other galaxies and to even extend the concept to the whole universe (Lineweaver 2001). The largest of all habitable zones can be termed the CHA, which describes the evolution of the habitability of the universe over time.

In the following text, published studies relevant to the CHZ, GHZ and CHA will be reviewed, but first life's basic needs will be reviewed.

The needs of life

Published studies of the CHZ focus on the maintenance of minimal habitable conditions on the surface of a terrestrial planet. These conditions are constrained most fundamentally by limits on the planet's mean surface temperature, the presence of liquid water and the composition of its atmosphere. To these, we can add constraints on the temporal and spatial variations of a planet's surface temperature; a slowly rotating earth-like planet, for example, will experience greater temperature variations than a similar but faster-rotating planet with the same mean temperature.

It may seem that the requirement of liquid water is merely an assumption of convenience for defining the CHZ based on our knowledge of 'life as we know it'. The evidence from chemistry, however, lends support to the view that liquid water (Ball 2008; Brack 2002; Chaplin 2006) and carbon (Pace 2001) are essential for life. In addition, single-celled life requires some 16 elements and mammals require an additional 10 for essential biological processes (Davies & Koch 1991), all of which must be cycled in the environment (Wilkinson 2003).

Astrobiologists sometimes treat habitability as a binary, either-or quantity. A planet is either sterile or it is teeming with life; it either has liquid water on its surface or it does not. Franck et al. (2001) advanced beyond this simplistic approach, quantifying the habitability of a planet in terms of its photosynthetic productivity. While photosynthesis is not the most basic form of habitability, it is one that has existed on Earth since very early times and has proven critical for the oxygenation of the atmosphere. Following Franck et al., we propose that a BHI be adopted as a measure of habitability. We can additionally define a habitability index for earthly animal life (i.e. large, oxygen-breathing, mobile metazoans); we can call it the AHI. According to the *Rare Earth* hypothesis (Ward & Brownlee 2000), the AHI would be more restrictive on the environment than the BHI. The limits on the mean surface temperature and the surface temperature variations would both be narrower for the AHI. An upper limit on the carbon dioxide partial pressure also needs to be added, as well as a lower limit on the oxygen partial pressure for the AHI. These limits can be estimated from the physiology of extant animals, the reconstructed evolution of the partial pressures of carbon dioxide and oxygen in Earth's atmosphere (Berner et al. 2000) and the history of life. While such limits will be necessarily parochial, certain general physiological principles we have learned from earthly life will apply universally; for example, large metazoans (e.g. you and me) require an oxygen-rich atmosphere (Catling et al. 2005).

Particularly helpful in quantifying the AHI and BHI is knowledge of the global ecological patterns of the present Earth. Ecologists have noted that a few large-scale spatial patterns account for the distribution of biodiversity (Gaston 2000). The most prominent among these are a decrease in biodiversity (quantified as species richness) with increasing latitude and altitude. More fundamentally, Allen, Brown and Gillooly (2002) argue that biodiversity increases with increasing temperature and nutrient availability; they explain the temperature dependence in terms of basic biochemical kinetics. Biodiversity also correlates positively with primary ecosystem productivity (Waide et al. 1999); for example, Schneider and Rey-Benayas show how the diversity of vascular plants correlates with productivity (Schneider & Rey-Benayas 1994). Other factors that influence biodiversity and ecosystem productivity include temperature variability and mean insolation, both of which are more important at high latitudes. Finally, productivity is sensitive to essential nutrient availability. An interesting example concerns the molybdenum (Mo) concentration in the oceans. Molybdenum is necessary for fixing nitrogen (N) in living things. Most Mo in the oceans comes from the continents, but its concentration is sensitive to the oxygen content of the atmosphere (Scott et al. 2008).

Another possibly fruitful approach towards generalising habitability would be to construct an 'equation of state of life'. For example, Méndez

(2001, 2002) compiled a database of the physiological properties of several hundred genera of prokaryotes and studied statistical trends in it. Prokaryotes are an important element of the primary producers and, thus, of biodiversity. He found that about 85% of prokaryotes have an optimum growth temperature between 295 K and 315 K. This is interesting because it implies that the biophysical limitations of prokaryotes have been more important to their distribution on Earth than adaptations. A complete equation of state for prokaryotes would include at least temperature, pressure and water concentration as parameters.

The history of life on Earth is another important source of information on factors relevant to habitability (Nisbet & Sleep 2001). The fossil record reveals that single-celled life appeared on Earth at least 3.5 billion years ago (Schopf et al. 2002), shortly after the end of the 'late heavy bombardment'. The 'Cambrian explosion' occurred about 540 million years ago. Since then, there have been many extinction events with global footprints (Sepkoski 1995). Only the K/T extinction (65 million years ago) has been securely linked to a well-dated extra-terrestrial event – the Chicxulub impact structure. Once additional extinction events can be linked to individual impacts, it will be possible to produce a 'kill curve', which relates the magnitude of extinction and the size of the impact crater (Rampino 1998). It will probably be necessary to include some threshold impactor energy required to trigger global extinctions, given that other large impacts, such as the two that occurred 35.5 million years ago (Chesapeake & Popigai; about 100 km each), had relatively little global effect on the biosphere.

The habitability of a terrestrial planet depends sensitively on its total water content. Planets with scarce surface water, like Mars, experience larger temporal and spatial temperature variations. On the other hand, planets with much more surface water than the earth are not necessarily more habitable. On the first consideration, we should expect such planets to have less variable surface temperature and therefore to be more habitable. However, the reduced dry land area also means less opportunity for land-based life and less surface area for chemical weathering, an important part of the carbon-silicate cycle (Kump et al. 1999). Marine organisms depend on nutrients and minerals washed off the continents and on the regulation of the oceanic salt content by the continents (Knauth 2005). With enough water, dry land can be completely absent on a terrestrial planet. Such a 'waterworld' is unlikely to be habitable. Models of planet formation, though still in their infancy, predict that terrestrial planets can vary widely in their water content (Raymond 2008).

Therefore, we should define an earth-*like* planet as a terrestrial planet with surface water, dry land and geophysics similar to the earth. This should be contrasted with a merely earth-*mass* terrestrial planet.

The Circumstellar Habitable Zone

All published studies of the CHZ start with an earth-like planet. The planet is assumed to be habitable as long as liquid water can be maintained on its surface. It is embedded in a planetary system identical to ours, except possibly a different host star. It has the same orbital eccentricity, Moon and planetary neighbours. Thus, all the difficult questions about the formation of a planetary system are avoided. This is the traditional definition of the CHZ.

Kasting, Whitmire and Reynolds (1993) defined the boundaries of the CHZ in multiple ways (Kasting et al. 1993). One definition of the inner boundary is based on the 'moist greenhouse'. In this process, water gets into the stratosphere, where it is dissociated by solar ultraviolet (UV) radiation and the hydrogen atoms are lost from the top of the atmosphere. A second definition for the inner boundary is based on the runaway greenhouse. They calculated the outer boundary according to the maximum possible CO_2 greenhouse or the increase of planetary albedo because of the formation of CO_2 clouds. The inner and outer boundaries were also estimated from the states of Venus and Mars, respectively. Their most restrictive case has inner and outer boundaries of 0.95 and 1.37 Astronomical Units (AUs), respectively.

Franck et al. (2001) presented a new set of CHZ models based on a more realistic treatment of geophysical processes. Previous studies had assumed constant continental area, metamorphic outgassing of CO_2 and weathering rate over geologic timescales. Building on the climate models of Kasting et al. and Caldeira and Kasting and relaxing these assumptions, Franck et al. thus modelled Earth's coupled climate-geologic systems as dynamical processes (Caldeira & Kasting 1992; Kasting et al. 1993). Their CHZ is defined by surface temperature bounds of 0 °C and 100 °C and CO_2 partial pressure above 10^{-5} bar. They added the CO_2 partial pressure requirement to ensure that conditions are suitable for biological productivity via photosynthesis. It sets the inner boundary of their CHZ, while the minimum temperature requirement sets the outer boundary; their CHZ inner and outer bounds for the present Solar System are 0.95 and 1.2 AUs, respectively. Franck et al. also determined that the maximum lifespan for an earth-like planet around a star between 0.6 M_{sun} and 1.1 M_{sun} (6.5 billion years) is limited by planetary geodynamics.

While CHZ models have improved steadily over the past few decades, they are still at an immature stage of development. They lack many deterministic and stochastic processes relevant to habitability, and the modellers have yet to describe how the formative processes of a planetary system set the initial conditions for their CHZ calculations. The relevant initial conditions include the locations, masses, compositions, initial volatile inventories, initial rotation periods, initial obliquities, initial orbital inclinations, presence of moons, initial eccentricities of the terrestrial planets and the orbits and masses of the giant planets; they also include the properties of the asteroid and comet reservoirs.

These have significant stochastic components, and they cannot properly be treated in isolation, as there are many complex interdependencies among them. Proper treatment of the initial conditions requires simulations that begin with a protoplanetary nebula of a given mass, composition and environment and follow its evolution through the final stages of star and planet formation.

Lissauer (1993) identified four dynamical stages of planet formation in a protoplanetary disk: (1) condensation and growth of grains, (2) grains grow to km size either by pairwise accretion or gravitational instability of the solid disk, (3) oligarchic growth to Mars-size terrestrial bodies and giant planet runaway accretion and (4) development of crossing orbits leading to giant impacts. Numerical simulations have shown that, while stochastic processes are important, the final distributions of orbital periods, eccentricities and masses of the terrestrial planets are significantly constrained by the initial and boundary conditions (Raymond, Quinn & Lunine 2004).

The origin of planetary rotation is still a matter of some controversy. Simulations indicate that large impacts near the terminal stage of terrestrial planet formation may dominate any systematic preference for one spin direction over the other (Kokubo & Ida 2007; Lissauer, Dones & Ohtsuki 2000). For example, the formation of the Moon via an impact by a Mars-sized body probably imparted more angular momentum to the earth than it had prior to that event (Canup 2004). Following the early formative phase, the rotation periods of terrestrial planets continue to evolve via tidal torques from the host star and from any orbiting moons. Whether the rotation periods increase or decrease and how fast they change depends on the details of a planet's interior, the presence of oceans and atmosphere, as well as the direction of its rotation and the rotation period in comparison to its moon's orbital period.

Planetary rotation is highly relevant to habitability. A planet's rotation period affects its day-night temperature variation, obliquity stability and magnetic field generation (Griebmeier et al. 2005). Unless a terrestrial planet has a thick carbon dioxide atmosphere, the slower rotation will result in larger day-night temperature differences. In addition, the prolonged absence of light will be a factor for photosynthetic life on any slowly rotating terrestrial planet. For the extreme case of synchronous rotation, the complete freeze-out of water on the dark hemisphere is very likely.

The details of the origin of the atmospheres of the terrestrial planets are also uncertain. The two general classes of sources of volatiles are accretion from local material in the protoplanetary nebula and collisions with comets and bodies from the asteroid belt. Among the volatiles, most research has focused on water, given its importance in defining the CHZ. According to protoplanetary disk models, Earth could not have received its water from material formed near 1 AU, as the protoplanetary disk temperature would have been too high for it to condense. Water must have been delivered from beyond about 2.5 AU. Apparently, nearly all of Earth's water came from large bodies in the region of the outer asteroid belt (Morbidelli et al. 2000). Contrary to previous expectations, isotopic and dynamical data indicate that comets contributed no more than about 10% of Earth's crustal water (Morbidelli et al. 2000).

The net quantity of water and other volatiles delivered to and retained by a terrestrial planet also depends on its size and location. Smaller planets, like Mars, are subject to a much greater degree of atmospheric impact erosion (Lunine et al. 2003). Earth's gravity, however, is sufficiently large that impacts added much more to its atmosphere than they removed. Even the giant impact proposed to have formed the Moon probably removed only a modest portion of Earth's atmosphere (Genda & Abe 2003, 2004; Melosh 2003). The impact velocity depends, in part, on the impactor's original orbit and on the orbit of the target body. Comets, which originate far from the Sun, impact at a higher velocity than objects from the asteroid belt. Likewise, terrestrial planets closer to their host star will encounter objects at greater velocities. Higher velocity impacts tend to erode planetary atmospheres more effectively.

Lunine (2001) argued that the delivery of volatiles to the terrestrial planets in the Solar System should be very sensitive to the location and eccentricity of Jupiter's orbit. One of the critical quantities is the location of the innermost giant planet in relation to the so-called snowline. The presence of Jupiter near the snowline in the Solar System allowed it to transfer water-rich embryos efficiently from the asteroid belt into the terrestrial planet region. Recent N-body simulations of the formation of the terrestrial planets have generally confirmed this. Raymond et al. (2004) showed that increasing the eccentricity of Jupiter produces drier terrestrial planets, and moving it farther from the Sun produces more massive, water-rich planets; they also find that the volatile delivery has considerable stochastic variability. In addition, terrestrial planets in the CHZ of a lower-mass star tend to be drier (Raymond, Scalo & Meadows 2007).

Today, the radial distributions of asteroid and comet perihelia peak just outside the orbit of Mars (Gonzalez 2005). As the outermost terrestrial planet, Mars takes the brunt of asteroid and comet impacts (except that, because it is smaller than Earth, it has a smaller cross-section for collision). In fact, any planet that is the outermost terrestrial planet in a system similar to the Solar System will take the brunt of the asteroid and comet impacts.

With the discovery of the first extrasolar giant planet around a nearby Sun-like star in 1995, it became immediately obvious that other planetary systems can be very different from ours. About 10% of the detected systems have a giant planet within about 0.1 AU of their host stars. The remaining systems have giant planets with eccentricities that scatter nearly uniformly between 0.0 and 0.80. Several processes were proposed to account for the great variety of orbits observed. These include inward planet migration (Lin, Bodenheimer and Richardson 1996) and strong disk–planet and planet-planet interactions (Chiang, Fischer & Thommes 2002; Goldreich & Sari 2003; Marzari & Weidenschilling 2002). Some of these processes also result in non-coplanar orbits, which tend to produce less stable systems (Thommes & Lissauer 2003). Veras and Armitage (2005), assuming that the observed eccentricities are because of planet-planet scattering, determined that terrestrial planets are unlikely to form in a star's habitable zone if an eccentric giant planet has a semi-major axis between 2 AU and 3 AU.

Giant planet migration is also important for the habitability of the terrestrial planets. For example, the migration of a giant planet towards its host star will remove any terrestrial proto-planets in the CHZ and reduces the probability that more planets will form there afterward (Armitage 2003). Raymond, Mandell and Sigurdsson (2006), however, find that the terrestrial planets that do form in the wake of a migrating giant planet are very water-rich (and thus not earth-like).

Similarly, Kuchner (2003) and Léger et al. (2004) note that an icy planet like Uranus or Neptune or something smaller, if it migrates into the CHZ, can become an 'ocean planet'. Such a planet would have a very deep ocean of water surrounding a thick ice mantle, which would separate the deeper silicate mantle from the ocean. The pressure at the bottom of its ocean would be too high for any known life. Such a planet would also be more sensitive to tidal torques from its host star and any large moons, causing more rapid spin-down. A small influx of life-essential elements at the surface could be provided by micrometeorites, but the quantities could support at most a feeble biosphere. Finally, an ocean planet would not be able to regulate the concentration of salt dissolved in its oceans (Knauth 2005).

Migrating giant planets would probably bring along at least some of their moons. How habitable would an earth-size moon in the CHZ be? Williams, Kasting and Wade (1997) explored this possibility. Even if such a moon could be as large as Earth (Canup & Ward 2006), it is unlikely to be as habitable for several reasons (Gonzalez et al. 2001a). For example, a moon formed far beyond the CHZ would contain a great deal of water (a possible exception would be a large moon intermediate in composition between Io and Europa). Other relevant factors include rotational synchronisation (causing longer days and nights and a weakened magnetic field), tidal-induced migration, immersion in the host planet's radiation belts and higher frequency and energy of small-body impacts.

The giant planets also have significant influences on the obliquity variations of the terrestrial planets. Laskar, Joutel and Robutel (1993) showed that a terrestrial planet can exhibit large and chaotic obliquity variations, which are caused by resonances between its precession frequency and combinations of secular orbital frequencies of the giant planets in the system. The chaotic zones are broad, and they depend on several parameters, including the orbital period, rotation period and mass of the terrestrial planet, the presence of a large moon and the orbital periods and masses of the giant planets. Certain combinations of these parameters result in very small obliquity variations. Today, Earth exhibits tiny obliquity variations of ±1.3° around an average value of 23.4°. The lunar gravitational torque increases Earth's precession frequency by a factor of about three compared with what it would be without the Moon, taking it far from a spin-orbit resonance (Laskar & Robutel 1993). The Moon has a similar effect to reducing Earth's rotation period by the same factor.

Ward, Agnor and Canup (2002) demonstrated that the region of chaotic obliquity variation is very broad in the Solar System. They calculated the amplitude of obliquity variations for Mars over a broad range of locations and rotation periods. They found stability comparable to Earth's only for distances less than 0.7 AU from the Sun and with faster rotation (but solar-induced tides would slow the rotation over a few billion years). Interestingly, if Mars had a large moon (keeping all else the same), it would still exhibit large obliquity variations because it would be brought closer to a resonance (Ward et al. 2002).

Atobe, Ida and Ito (2004) and Atobe and Ida (2007) have conducted more general simulations of obliquity variations of terrestrial planets. They include an analysis of hypothetical terrestrial planets in known extrasolar planetary systems and an exploration of the varieties of dynamical histories possible for collision-formed moons.

A moonless Earth would have exhibited a stable obliquity if its rotation period were less than about 10 h. The likelihood of such a state depends primarily on the last few large collisions it experienced near the end of its formation. Earth's initial rotation period was indeed less than 10 h, but it has since slowed to 24 h, mostly by the action of the lunar tides. Ironically, Earth likely received its fast initial rotation from the impact that resulted in the Moon's formation.

Mercury is presently locked into a 3:2 spin-orbit resonance with a stable low obliquity value, but it was very likely born with a much faster rotation. Its precession frequency gradually declined via core-mantle interactions and tidal dissipation from the Sun that gradually slowed its rotation. Before reaching its present state, however, Mercury must have passed through a large chaotic zone in obliquity.

The case of Venus offers additional insights on obliquity variations. Correia, Laskar and Neron De Surgy (2003) and Correia and Laskar (2003) showed that most initial conditions drive Venus to its present state and that this is generally true of terrestrial planets with very thick atmospheres.

Touma and Wisdom (2001) studied the core-mantle, spin-orbit interactions for Earth and Venus and concluded that both planets have passed through major heat-generating core-mantle resonances. They speculate that Earth's passage through such a resonance about 250 million years ago may have been responsible for generating the Siberian traps and causing the Permo-Triassic extinction and that Venus's passage through a similar resonance caused the planet to resurface itself about 700 million years ago and generate its thick atmosphere. They find that terrestrial planets with retrograde rotation generate much more heat from such resonance passages. In addition, the Moon's tidal torque on Earth allowed it to pass quickly through its resonance, avoiding the fate of Venus. They also speculate that Venus's high surface temperature caused by its thick atmosphere maintained a magma ocean, which led to a rapid slowdown of its rotation through tidal dissipation. As a result, Touma and Wisdom (2001) argue that Venus was born with retrograde rotation; otherwise, it would have generated less heat through its core-mantle resonance passage. The case of Venus shows us how intimately are geology, rotation, obliquity, orbit and atmosphere of a terrestrial planet linked.

Both the value of the obliquity and the amplitude of its variation affect the habitability of a planet. Seasonal variations would be absent on a planet with a stable obliquity near zero degrees. While it would have constant surface temperatures, this benefit to life would be offset by two problems. Firstly, weather systems would be more constant, some areas receiving steady precipitation, others receiving very little. More seriously, the polar regions would experience smaller maximum surface temperatures. Analogous to the water 'cold traps' on synchronously rotating planets, polar ice would extend to lower latitudes, and it is possible that all the water would eventually freeze out at high latitudes. A thick atmosphere would be a possible way out of such a state, as would a deep ocean, but they would have other consequences for life that would have to be examined in detail.

At the other extreme, a stable obliquity near 90° would result in very large surface temperature variations over most of the surface of a terrestrial planet. Most planets will have unstable obliquities over at least a few billion years, varying between small and large angles. Each case will have to be treated in detail to determine overall habitability. Williams and Pollard (2003) have explored seasonal surface temperature variations for a wide range of obliquities using general circulation climate models of earth-like planets, confirming that high obliquity angles produce more extreme variations in surface temperatures.

Low eccentricities characterise the orbits of the planets in the Solar System. The present eccentricity of Earth's orbit is 0.016, smaller than most of the other planets. While exhibiting chaos, the planets have maintained low eccentricity orbits since they formed (Laskar 1994).

Numerical orbital simulations demonstrate the sensitivity of the earth's orbit to changes in the orbit of Jupiter (Gonzalez 2005). Earth's eccentricity increases significantly as Jupiter's orbit is made more eccentric. What is more, its orbit becomes unstable if Jupiter's eccentricity is greater than about 0.15. Increasing the mass of Jupiter reduces the eccentricity of Earth's orbit while reducing its mass increases it. Decreasing Jupiter's semi-major axis has a significant effect on Earth's orbit only near resonances. Interestingly, Earth's orbit becomes significantly more eccentric if its mass is less than about half its present value.

Once it is known how the eccentricity of a terrestrial planet evolves, it is possible to calculate how its climate responds. There are two ways to do this for Earth. Williams and Pollard (2002) approached the problem with simulations of the climates of Earth-like planets under the assumptions of different eccentricities. Not surprisingly, they found that larger eccentricities produce larger annual temperature variations; larger eccentricity can also reduce the amount of time a planet spends in the CHZ. One of the most important factors describing the response of surface temperature to insolation variation is the radiative time constant of the atmosphere. It depends on, among other quantities, the surface pressure and heat capacity of the atmosphere. Earth's atmosphere has a time constant of about 1 month; planets with thicker atmospheres will have longer time constants. If the radiative time constant is much smaller than the orbital period, then a planet's surface temperature will be more sensitive to eccentricity-induced insolation variations.

The study of Earth's ancient climate via proxies stored in sediments and polar ice is another way to elucidate the relationships between orbital variations and climate change. The Milankovitch cycles (obliquity, precession and eccentricity) have been detected in several such records (Berger & Loutre 1994; EPICA 2004; Petit et al. 1999). Even the small ranges of variation in the obliquity and eccentricity of 23.4 ± 1.3 degrees and 0.00–0.04, respectively, have been sufficient to leave their marks in the paleoclimate records. Earth's climate has been fluctuating dramatically in response to these small forcings for the past 3 million years.

The size of a terrestrial planet affects its habitability in diverse ways. Hart (1982) and Kasting et al. (1993) considered the effects of changing the size of a terrestrial planet on the evolution of its atmosphere. Hart described how outgassing, atmospheric escape and surface chemical processes depend on the size of a terrestrial planet. Kasting et al. (1993) noted that a change in a planet's size has substantial effects on the greenhouse effect, albedo, atmospheric loss and internal heat flow. Also, Lissauer (1999) noted that a larger terrestrial planet, all else being equal, should have a deeper ocean and higher surface pressure due in part to the increasing importance of self-compression for terrestrial planets larger than Earth.

A planet's geophysics is also sensitive to its size. A smaller planet will lose its interior heat more quickly, primarily because of its larger surface area to volume ratio. A smaller planet also has smaller pressure throughout its interior, which affects core formation (Agee 2004). O'Neill and Lenardic (2007) argue that terrestrial planets more massive than the earth are unlikely to exhibit earth-like plate tectonics, but Valencia, O'Connell and Sasselov (2007) reach a different conclusion.

Mars is an important comparison case; it is half the size of Earth and lacks plate tectonics and a global magnetic field. Evidence from space missions and Martian meteorites indicates that it did once possess a global magnetic field and was volcanically active for about the first billion years (Zuber 2001), confirming that its interior cooled more quickly than Earth's interior. The generation of a global magnetic field is closely linked to the operation of plate tectonics (Nimmo & Stevenson 2000). Plate tectonics produces a larger surface heat flux than a one-plate mode of tectonics, which, in turn, produces a larger temperature gradient in the deep interior and convection in the liquid portion of the core. A convecting outer core and fast planetary rotation are considered to be necessary requirements for generating a global magnetic field.

The generation of a global magnetic field also depends on the composition of the core. The presence of alloying light elements affects the melting temperature of iron (the most abundant element in the core) and can cause chemical convection. In the case of Mars, the volatile element sulphur is speculated to be the most abundant light element in the core (Spohn et al. 2001). In the early stages of its growth, a terrestrial planet's 'feeding zone' spans a relatively narrow range in the protoplanetary nebula (Lissauer 1995). It is only during the later stages of its growth that a terrestrial planet accretes embryos from more distant regions. Thus, because of the negative radial temperature gradient in the protoplanetary disk, terrestrial planets farther from the Sun should have relatively more sulphur in their cores. For this reason, even if Mars were as massive as Earth, it would not have the same core chemistry, structure and magnetic field evolution as Earth.

Relatively little research has been conducted on the biological consequences of a weak or absent magnetic field. Mars does provide some clues, however. The absence of a strong magnetic field over most of Mars's history has been implicated in the loss of a substantial fraction of its atmosphere through solar wind stripping (Jakosky & Phillips 2001). Additional consequences include increased secondary cosmic ray particle radiation at the surface (Griebmeier et al. 2005).

The exchange of water between a planet's interior and its surface also depends on its geophysics (Franck et al. 2001; Hauck & Phillips 2002). Over billions of years, water on the surface of a terrestrial planet is lost to space and sequestered into its mantle (Bounama, Franck & Von Bloh 2001). Water itself is intimately linked to the operation of plate tectonics (Regenauer-Lieb, Yuen & Branlund 2001). For this reason, it is likely that the present mode of Venus's geophysics depends, in part, on the loss of its water.

A planet's host star plays a very important role in the evolution of the CHZ. The host star affects the planets with its gravity and radiation. Assuming the core-accretion model for giant planet formation (Pollack et al. 1996), Laughlin, Bodenheimer and Adams (2004) and Ida and Lin (2005) find that giant planets are less likely to form around stars less massive than the Sun. This theoretical result is consistent with observations (Johnson et al. 2007; Laws et al. 2003). Simulations also indicate that terrestrial planets forming around low-mass stars in their CHZs are less massive (Raymond et al. 2007). Clearly, then, planetary systems forming around stars different than the Sun should be very different from the Solar System.

The Sun's radiation allows Earth to maintain liquid water on its surface and allows plants to produce chemical energy from photosynthesis, but it also has negative effects on life. There is evidence that small variations in the Sun's energy output on timescales from decades to millennia affect Earth's climate. They are caused by changes in the Sun's atmosphere and are not related to what goes on in its core. However, we know from stellar evolution models that the Sun has brightened by about 30% since its formation 4.6 gigayears (Gyrs) ago. Unlike the short-term variations, this one is taken into account in modern CHZ models.

We can infer the evolution of the Sun's chromospheric activity from observations of nearby Sun-like stars spanning a broad range in age. Such a research programme, called 'The Sun in Time', began about 20 years ago (Ribas et al. 2005). Young Sun-like stars are observed to have shorter rotation periods, higher UV and X-ray luminosities and more frequent flares (which produce temporary high fluxes of ionising radiation). From satellite observations of such stars, the Sun's X-ray luminosity is inferred to have decreased by about three orders of magnitude, while its UV declined by about a factor of 20 (Güdel 2003; Ribas et al. 2005). Observations also imply that the Sun's optical variability has declined by a factor of about 50 over the same period (Radick et al. 2004). Interestingly, Radick et al. also confirmed that the Sun's optical variability on decadal timescales is anomalously small compared with otherwise similar stars. The early higher activity is very relevant to habitability in part because the higher flux of ionising radiation stripped a significant fraction of the terrestrial planets' early atmospheres (Pepin 1997).

Chromospheric activity also correlates with the rate of flares. Flares produce X-ray and proton radiation. X-rays entering the top of the atmosphere are downgraded to UV line emission at the bottom of the atmosphere (Smith, Scalo & Wheeler 2004). Protons can alter the chemistry in the middle atmosphere and stratosphere. In particular, the two strongest solar proton events of the past four decades (1972 and 1989) were calculated to have temporarily reduced the total ozone by 1%–2% (Jackman, Fleming & Vitt 2000). Even stronger flares should occur over longer timescales, and they should have been more frequent in the Sun's past (Smith et al. 2004).

Stellar activity also varies along the main sequence. Many red dwarf stars exhibit extremely powerful and frequent flares. West et al. studied a large sample of nearby M dwarfs and found that activity peaks near spectral type M8 at about 80%incidence (West et al. 2004). The UV flux can increase by a factor of 100 during a flare (Gershberg et al. 1999). Active M dwarfs have a soft X-ray to bolometric flux ratio several orders of magnitude greater than the Sun; during flares, this flux ratio can be 10^6 times the Sun's. Since the size of the CHZ is set by the bolometric flux, a planet in the CHZ of an M dwarf will be subjected to a much greater flux of ionising radiation. Smith et al. found that the UV flux in the lower atmosphere of a planet around an M dwarf is completely dominated by redistributed energy from flare X-rays and reaches biologically significant levels.

The red colour of an M dwarf star means that relatively less blue light will reach the surface of its orbiting planets compared with the Sun. Although photosynthesis does not require blue light, it generally becomes less effective without abundant light blueward of 6 800 Å. Wolstencroft and Raven (2002) showed that earth-like planets in the CHZ of cooler stars should be less effective at producing oxygen from photosynthesis. Some bacteria can still use infrared light, but not to produce oxygen. Any marine photosynthetic organisms would have difficulty using red light as an energy source as ocean water transmits blue-green light much better than violet-blue or red light. The precise wavelength of peak transmission will depend on the minerals dissolved in the oceans. The transmittance of pure water peaks at 4 300 Å, while that of Earth's oceans peaks a few hundred Å to the red.

Planets around M dwarfs should be less habitable than Earth also because they achieve rotational synchronisation quickly (Kasting et al. 1993). If a rotationally synchronised planet has a circular orbit, then one side will continuously face its host star while the other remains in darkness. In other words, the length of the year equals the length of the day. This will lead to large temperature differences between the day and night sides and to the freeze-out of its water. Slower rotation would also result in a weaker magnetic field (Griebmeier et al. 2005). Rotational synchronisation can be avoided in two ways. Firstly, a planet can have a sufficiently eccentric orbit so that, like Mercury, it has a 3:2 spin-orbit resonance. Such a planet would avoid water freeze-out, but it would still exhibit large temperature variations over the course of its orbit and have a weak magnetic field. The second way is to have a planet-sized moon orbiting around a giant planet in the habitable zone. Such a planet, if it could exist in such a configuration (which is doubtful), would suffer from many of the same difficulties already noted.

Finally, the recent discovery of a possible link between the cloud fraction and the galactic cosmic ray (GCR) flux in Earth's atmosphere has a direct bearing on models of the CHZ. Higher GCR flux leads to enhanced production of low-altitude clouds, which leads to a cooling of the earth (Marsh & Svensmark 2005). Svensmark et al. (2006) presented the first experimental evidence for what had been a missing part of this link – demonstration that the ionisation induced by cosmic rays enhances the formation of cloud condensation nuclei (and therefore clouds). The GCR flux is modulated by the solar interplanetary magnetic fields. Therefore, Earth's albedo is determined partly by the state of the magnetic fields of the Sun and the GCR flux arriving at the Solar System (Svensmark 2006). More generally, it is determined by the location of a terrestrial planet in the Solar System. At a greater distance from the Sun, the influence of the solar magnetic field is weaker, and therefore variations in the GCR flux entering the Solar System are relatively more important. This existence of the GCR–cloud link also implies that the carbon-silicate cycle is not as important for climate regulation as it is currently believed to be (Shaviv 2005).

In summary, the definition of the CHZ depends on much more than just the flux of radiation a terrestrial planet receives from its host star. A terrestrial planet's habitability also depends on its orbital eccentricity, presence of a large moon, size, initial volatile inventory, initial rotation period and its evolution, the locations and properties of any giant planets, the distributions of small bodies and the host star's modulation of the cosmic ray flux. Much progress is being made on each of these factors, but eventually they will have to be treated together, given their sometimes strong interdependencies.

The Galactic Habitable Zone

Habitability on the scale of the MWG has been discussed at least since Shklovsky and Sagan (1966) considered the perturbations to the biosphere by nearby supernovae (SNe). Since then, several studies have re-examined this question. Some have considered the effects of ionising radiation from a nearby SN on Earth's ozone layer (Gehrels et al. 2003). Others have searched the paleobiological and geological records for signatures of nearby SNe. For example, Benitez, Maiz-Apellaniz and Canelles (2002) present evidence linking the Pliocene–Pleistocene boundary marine extinction event about 2 million years ago to a nearby SN, and Knie et al. (2004) and Wallner et al. (2004) discovered spikes in the ^{60}Fe and ^{244}Pu concentrations, respectively, in marine sediments from about the same time, consistent with an SN explosion about 40 parsecs from Earth (Basu et al. 2007).

The Galactic environment also affects the orbits of comets in our Solar System and (presumably) others. The weakly bound Oort cloud comets are sensitive to large-scale gravitational perturbations, including the Galactic vertical (disk) (Heisler & Tremaine 1986; Matese et al. 1995) and radial

(Heisler & Tremaine 1986; Matese, Whitman & Whitmire 1999) tides, giant molecular clouds (GMCs) (Hut & Tremaine 1985) and nearby star encounters (Matese & Lissauer 2002). Of these, the Galactic disk tide is the dominant perturber of the present outer Oort cloud comets; the disk tide is about 15 times greater than the radial tide (Heisler & Tremaine 1986). Such perturbations can cause ‘comet showers’ in the inner Solar System and thus increase the comet impact rate on Earth. Matese et al. (1999) argued that the imprint of the radial Galactic tide is present in the observed distribution of long-period comet aphelia on the sky. Stars closer to the Galactic centre will experience more intense comet showers because of the increased radial Galactic tide and more frequent nearby star encounters (Masi, Secco & Vanzani 2003).

Gonzalez et al. (2001a, 2001b) unified the various Galactic factors by introducing the GHZ concept (Lineweaver 2001 introduced a similar idea). The inner boundary of the GHZ is set by the various threats to the biosphere (e.g. nearby SNe and comet impacts), and its outer boundary is set by the minimum metallicity required to form an earth-*like* planet, not merely an earth-*mass* planet. If the metallicity is too low, then it will not be possible to form an earth-like planet, which is composed mostly of O, Mg, Si and Fe. These elements are produced primarily by massive star SNe, which enrich the originally pure H and He interstellar gas with their processed ejecta. The incidence of giant planets is much higher among metal-rich stars, but the planets detected to date tend to have highly eccentric or very-short-period orbits (Marcy et al. 2005). Such orbits are less likely to be compatible with the presence of habitable terrestrial planets. The temporal evolution of the GHZ is determined primarily by the evolution of the metallicity of the interstellar gas, the interstellar abundances of the geologically important radioisotopes (^{40}K, ^{235}U, ^{238}U and ^{232}Th) and the rate of transient radiation events.

Lineweaver, Fenner and Gibson (2004) further quantified the GHZ by applying Galactic chemical evolution models. They only included the effects of the evolving interstellar gas metallicity and SN rate and estimated that 10% of all the stars that have ever existed in the Milky Way have been in the GHZ. While this is a helpful study, as we show, several other factors need to be included to provide a more complete picture of the GHZ.

There is strong evidence for an extra-terrestrial influence on Earth’s climate (Kirkby 2007). Bond et al. (2001), for example, employed ^{14}C and ^{10}Be as proxies for solar variations and marine sediments in the North Atlantic as proxies for polar ice extent. They found a strong correlation between the polar climate and variations of solar activity on centennial to millennial timescales. This and many other recent studies present evidence that Earth’s climate has varied in response to solar variations over the entire Holocene. Several mechanisms for solar-induced climate change have been proposed, of which the leading contender is the GCF–cloud link noted earlier.

The GCR flux from Galactic sources also varies over long timescales. Thus, the importance of GCR-induced low cloud formation will depend on the Galactic star formation rate and the location of the Solar System in the galaxy, as well as the location of a planet in the Solar System.

Transient radiation events important on the Galactic scale include SNe, gamma ray bursts (GRBs) and active galactic nucleus (AGN) outbursts. Less powerful events, such as novae and magnetar outbursts, while more frequent, are less important on average and will not be considered here. I will provide a brief review of the rates, distributions and energetics of these three classes of Galactic transient radiation events along with their possible effects on the biosphere.

The possible threats posed by SNe to life on a planet over the history of the MWG depend on their spatial distribution, temporal frequency and typical total radiant energy. Galactic chemical evolution models are required to estimate the temporal evolution of SNe, but observations can give us helpful constraints. A simplifying starting assumption is that the average SN rate in galaxies similar to the Milky Way (Hubble type Sbc) is representative of the rate in the Milky Way (Dragicevich, Blair & Burman 1999). This is probably a good assumption, but over relatively short time intervals the Milky Way's SN rate will sometimes deviate from the average significantly. Extragalactic SN surveys also yield reliable estimates of the average rates (Cappellaro 2004) of the various types of SNe (the main types are Type Ia [SN Ia] and Type II+Ib/c [SN II]) and their luminosity distributions (Richardson et al. 2002). Supernova rates are usually given in units of number per century per 10^{10} solar luminosities of blue light (SNu). For example, the total SN rate for elliptical galaxies is 0.18 ± 0.06 SNu, increasing to 1.21 ± 0.37 SNu for Scd-Sd Hubble types (Cappellaro 2004); SNIa are the only type of supernovae observed in elliptical galaxies. The total SN rate in the Milky Way is 2–3 SN per century (Ferrière 2001).

It is helpful to know the rates for the SN Ia and SN II separately, given their different distributions in the Milky Way. SN II, which result from massive stars, are observed in the thin disk and in the spiral arms. SN Ia result from older stars and occur throughout the Milky Way. Surveys of supernova remnants in the Milky Way (Case & Bhattacharya 1998), pulsars in the Milky Way (Yusifov & Küçük 2004) and SNe in nearby galaxies (Van den Bergh 1997) show that SNe peak at about 5 kiloparsec (kpc) from the Galactic centre.

Gehrels et al. explored the effects on Earth's atmosphere of the gamma ray and cosmic ray radiation from a nearby SN II (Gehrels et al. 2003). The gamma ray radiation resulting from the decay of ^{56}Co lasts a few 100 days, while the elevated cosmic ray flux can last thousands of years. They simulated 20 years of atmospheric evolution and found that an SN would have to occur within 8 pc for the UV radiation at Earth's surface to be at least doubled. They estimate a rate of about 1.5 dangerous SNe per billion years. They did not explore the biological effects of the secondary particle radiation produced in the atmosphere nor the effects of the cosmic ray flux on the cloud fraction. Thus, their calculations should underestimate the important biological effects of a nearby SN II.

Gamma ray bursts are rare, very short-duration (~10s), very luminous (~10^{51} ergs s^{-1}) explosions that produce most of their luminous energy in gamma rays with energies between 100 keV and at least 1 MeV. Scalo and Wheeler (2002), assuming GRBs are produced by massive star supernovae (SN Ib/c), calculated that the GRB rate in the Milky Way is about one per ≥ 30 000 SN Ib/c. This rate depends on the assumed degree of collimation of the GRB radiation, GRB evolution with red-shift and the properties of the GRB progenitor (e.g. minimum mass star to explode as an SN Ib/c).

Still, the number of GRBs that affect Earth is not dependent on the degree of collimation, only on the observed rate (only those GRBs which we can see will affect us). The gamma-ray photons from a GRB cannot reach the ground for planets with thick atmospheres like Earth. The incoming photons are first downgraded to X-rays via Compton scattering, and then the X-rays are absorbed and generate photoelectrons. The energetic electrons then collide with oxygen and nitrogen atoms, exciting them and causing ultraviolet emission, which makes it to the surface. Scalo and Wheeler (2003) estimate that GRBs aimed at a planet with a thin atmosphere can do significant damage to the DNA of eukaryotes from as far away as 14 kpc (nearly twice the distance to the Galactic centre); the corresponding distance for prokaryotes is 1.4 kpc. The critical distance for significant UV production at the surface of Earth is about 11 kpc. They estimate that this occurs once every 2–4 million years. The very short duration of the photon radiation burst on the surface of a planet resulting from a GRB implies that only life on one hemisphere of the planet will suffer its direct effects.

Melott et al. (2004), Thomas et al. (2005) and Thomas and Melott (2006) also consider the possible long-term damaging effects of a GRB's energetic photons on a planet's atmosphere, including ozone destruction, global cooling and acid rain. They estimated that a GRB within 3 kpc of Earth can cause significant damage to its ozone layer, and that such an event should occur every 170 million years. They also suggested that a GRB might have caused the late Ordovician mass extinction.

Gamma Ray Bursts should also generate collimated jets of energetic particles (Dermer & Holmes 2005; Waxman 2004). Dar, Laor and Shaviv (1998) and Dar and De Rújula (2002) consider the effects on the biosphere of particle jets from GRBs impinging on Earth's atmosphere. These include atmospheric muons, radioactive spallation products and ozone destruction. The muons can penetrate deep underwater and underground. The duration of the cosmic ray irradiation is expected to be a few days, long enough to cover all longitudes (but not necessarily all latitudes). Dar and De Rújula estimate that cosmic rays from a GRB at the Galactic centre aimed at Earth would produce a lethal dose of atmospheric muons to eukaryotes.

The Milky Way's nucleus is presently in a relatively inactive state, but there is strong evidence that a 2.6 million solar mass black hole resides there (Morris et al. 1999). It is among the smaller black holes detected in the nuclei of nearby large galaxies. The Milky Way's nuclear black hole has grown over time by accreting gas and disrupted stars. While it is accreting, the black hole's disk emits electromagnetic and particle radiation.

High-resolution optical observations indicate that all large galaxies have a supermassive nuclear black hole (Marconi et al. 2004; Miller et al. 2003). When active, such black holes are observed in the bulges of galaxies as AGNs (called Seyfert galaxies). The fraction of galaxies observed in the nearby universe with AGNs is related to the duty cycles of their black holes. Assuming the AGN–nuclear black hole paradigm is correct, then the larger the observed fraction of AGNs, the larger the average duty cycle. Large duty cycles are possible if AGNs are long-lived and or frequent. Miller et al. (2003) studied the distribution of AGNs in the nearby universe and concluded that about 40% of massive galaxies have an AGN. They concluded from this that the typical AGN lifetime is about 2×10^8 years, or that the typical AGN has burst 40 times over the 5.7×10^8 years covered by their survey. Marconi et al. (2004) modelled the growth of nuclear black holes during AGN phases and found that duty cycles have declined over the history of the universe and that they are larger for smaller black holes.

If these numbers can be applied to the recent history of the MWG's nuclear black hole, then it should have been in an active state during about 40% of the past half-billion years. The luminosity of its nucleus in an active state would be about 10^{44} ergs s^{-1} in 2^{-10} keV X-rays (Gursky & Schwartz 1977). Emission in this range alone would generate the energy of a typical supernova in less than a year. Above about 5 keV, there is relatively little attenuation by the interstellar medium towards the Galactic centre. The total interstellar extinction towards the Galactic centre is also a sensitive function of the distance from the Galactic midplane; planets located near the midplane will be the most protected from ionising photons produced by an AGN. At Earth, the X-ray flux would be 130 erg m^{-2} s^{-1}, assuming no intervening absorption. This is about 20 times the typical flux from the Sun in the same energy band and is comparable to the peak flux of an M-class X-ray solar flare. Including absorption would make the Galactic centre X-ray flux comparable to that of the Sun's average X-ray output. Thus, the X-ray emission from an AGN outburst would probably not be very important for life on Earth, but it probably would be damaging for planets within ~ 2 kpc of the Galactic centre. BL Lacertae objects and flat-spectrum radio quasars are observed to have gamma ray luminosities up to 10^{49} erg s^{-1} and 10^{50} erg s^{-1}, respectively (Hartman et al. 1999). Whether the Milky Way was ever in such a state, however, is an open question.

Clarke (1981) argued that the particle radiation from an AGN outburst would be much more important to life than its ionising photons. He calculated, assuming no propagation energy losses, that particle radiation fluxes at Earth would increase by a factor of ~100, causing significant damage to the ozone layer and increased radiation at the surface.

In order to model the GHZ, it is also important to understand the spatial gradients and temporal evolution of the disk gas metallicity in the Milky Way. The disk radial metallicity gradient is determined from a variety of objects, including open clusters, H II regions, planetary nebulae and Cepheid variables. Recent abundance measurements of cepheids (arguably the best type of indicator of the gradient) give a gradient value of –0.07 dex kpc^{-1} (Lemasle et al. 2007; Luck, Kovtyukh & Andrievsky 2006). Maciel, Lago and Costa (2005) determined that the gradient has been flattening over the past 8 billion years and is in the range of 0.005–0.010 dex kpc^{-1} Gyr^{-1}. Observations of thin disk G dwarfs in the solar neighbourhood show that the disk gas metallicity is increasing at a rate of about 0.035 dex Gyr^{-1} (Gonzalez 1999).

Knowledge of the metallicity gradient is critical to understanding the GHZ, as the initial gas metallicity of a cloud strongly constrains the properties of the terrestrial and giant planets that form from it. Firstly, the incidence of Doppler-detected giant planets around nearby Sun-like stars is now known to be very sensitive to the host star's metallicity. It rises steeply from about 3% at solar metallicity to 25% for stars with twice the solar metallicity (Fischer & Valenti 2005; Santos et al. 2004, 2005).

The best explanation for the correlation between metallicity and the presence of giant planets is that giant planets are more likely to form around metal-rich stars (Gonzalez 2006). How the Solar System fits into this picture is still unsettled, but it is beginning to appear that it is not typical (Beer et al. 2004).

Ida and Lin (2004) have explored the metallicity dependence of giant planet formation with simulations based on the core-accretion theory. They succeed in reproducing qualitatively the observed metallicity dependence on the incidence of giant planets. Since the processes in the early phases of giant planet formation also apply to terrestrial planet formation (prior to the gas accretion phase), studies like Ida and Lin's should help us understand the metallicity dependence of terrestrial planet formation as well. Gonzalez et al. (2001a) suggested that the mass of a typical terrestrial planet formed in the CHZ should depend on the initial metallicity raised to the 1.5 power, while Lineweaver (2001) assumed that the dependence should be linear. Gonzalez (2008) explored this question but concludes that we are not yet ready to decide between these two assumptions.

The major comet reservoirs in the Solar System reside beyond the orbits of Neptune and Pluto (Stern 2003). Three reservoirs are typically recognised (listed with heliocentric distances): the Kuiper belt (30–1000 AU), the inner

Oort cloud (1000–20 000 AU) and the outer Oort cloud (20 000–50 000 AU). There is direct observational support for the existence of the Kuiper belt and indirect evidence for the Oort cloud (Levison, Dones & Duncan 2001). The Kuiper belt has about 7 × 10^9 comets, while the Oort cloud has about 10^{12} comets (Stern 2003); the inner Oort cloud has about five times as many comets as the outer Oort cloud.

The properties of the Oort comet cloud around a given planetary system depend in part on the properties of its giant planets and the initial metallicity of its birth cloud. Presumably, a planetary system forming from an initially more metal-rich cloud will form a more populated Oort cloud, but this needs to be confirmed with self-consistent simulations that include the metallicity dependence of the properties of the giant planets. Given the high sensitivity of the incidence of giant planets to metallicity, it seems likely that this is a reasonable assumption. Granting this and the known Galactic metallicity disk gradient, planetary systems born in the inner Galaxy should start with more populous Oort clouds. The subsequent history of interaction between an Oort cloud and its Galactic environment is also critical to understanding the threats from comets.

Interstellar gas metallicity, stellar velocity dispersion, stellar density, GMC density and Galactic tides all vary with location and all affect the orbits of the Oort cloud comets. To the first order, the initial number of comets in the Oort cloud can be approximated as being proportional to the initial metallicity. The stellar density, GMC density and tides are all greater in the inner Galaxy, relative to the Sun's location. Moving the Solar System halfway to the Galactic centre would increase the comet flux by a factor of about seven.

In addition to the threat from comets residing in the Sun's gravitational domain, there is also the threat from interstellar comets. They can be grouped into two distinct types: (1) free-floating comets lost from Oort clouds around other stars (IS1) and (2) comets gravitationally bound to other stars (IS2).

The probability that an interstellar comet collides with Earth is much greater than just the geometrical cross-section of Earth amplified by the Sun's gravity; it depends on the cross-section of the orbits of the giant planets, which can capture an interstellar comet into an orbit that brings it close to the inner planets repeatedly. Taking this factor into account and assuming a local density of IS1 comets of 10^{12} pc^{-3}, Zheng and Valtonen (1999) calculated that Earth should have collided with about 100 such comets over its history or one every 40 million years.

Presently, there are no stars sufficiently close to the Sun for their bound comets to pass near enough to the Sun for us to see them. A type IS2 comet only poses a threat to us when its host star passes within about one-third of an AU of the Sun. Thus, a nearby star passage will threaten Earth both from its comets and from the perturbed comets in the Sun's domain. Taking an average heliocentric distance in the Sun's inner Oort cloud (10 000 AUs) and the present number of comets there (~10^{12}), the average number density is 2×10^{15} pc^{-3} (or, about one comet per five cubic AUs). This is at least three orders of magnitude greater than the number density of IS1 comets in the solar neighbourhood.

The probability of impact from interstellar comets should vary with Galactic location. The three key factors are the initial metallicity, stellar density and stellar velocity dispersion. The higher gas metallicity in the inner Galaxy should result in the formation of more interstellar comets. The inner Galaxy should be populated by a higher density of IS1 comets resulting from more frequent star–star and star–GMC encounters and stronger Galactic tides. On the other hand, the larger stellar velocity dispersion in the inner Galaxy will reduce the cross-section for comet captures. The more efficient stripping of comets from their Oort clouds in the inner Galaxy will reduce the importance of type IS2 comet collisions relative to those of type IS1; the accelerated stripping of comets from a star's Oort cloud in the inner Galaxy is at least partly compensated by the increased number of interstellar comets.

While a planetary system is traversing interstellar space, it will occasionally encounter a GMC (and more often, lower-density clouds), and the probability of encounter is increased when it is crossing a spiral arm. Talbot and Newman (1977) calculated that the Solar System should encounter an average density GMC (~330 H atoms cm^{-3}) every 100 million years and a dense GMC (~2×10^3 H atoms cm^{-3}) every billion years. The biologically significant effects of such an encounter are varied. These could include comet showers, exposure to a greater flux of cosmic ray particles, glaciations and more nearby SN.

Begelman and Rees (1976) first noted that passage of the Sun through interstellar clouds with densities of at least 10^2 to 10^3 H atoms cm^{-3} is sufficient to push the heliopause inside Earth's orbit. This would leave Earth exposed to interstellar matter. Scherer, Fichtner and Stawicki (2002) noted that the shrinking of the heliopause during the passage of the Solar System through an interstellar cloud will also eliminate the solar modulation of the cosmic rays at Earth and expose it to a higher cosmic ray flux, possibly leading to more clouds because of the GCR–cloud link noted previously. Florinski, Zank and Axford (2003) determine that the GCR flux at Earth would be enhanced by a factor of 1.5–3 by a cloud with a hydrogen density of 8.5 cm^{-3}, which is only about 30 times the present local interstellar gas density. In addition, the cosmic ray flux within a GMC would be much greater due both to recent SNe within it and to the longer cosmic ray diffusion time within it.

Yeghikyan and Fahr (2004a, 2004b) modelled the passage of the Solar System through a dense interstellar cloud (10^3 cm^{-3}), confirming that the heliopause is pushed into the region of the terrestrial planets. In such a situation, the interstellar matter interacts directly with Earth's atmosphere. They found that the ozone in the upper atmosphere is depleted, and Earth is cooled by about 1 °C, possibly causing an ice age.

Pavlov et al. (2005a) noted two effects neglected in previous studies that should significantly increase the effects to the biosphere of a cloud passage. Firstly, the flux of anomalous cosmic rays (generated from interstellar neutrals) would increase much more than the GCR flux. Secondly, during passage through a typical cloud (lasting about 1 million years) there would be one or two magnetic field reversals, during which time Earth's atmosphere would remain unprotected from cosmic rays at all latitudes. Pavlov et al. calculated that passage through a cloud with a density of 150 H atoms cm^{-3} would decrease the ozone column by 40% globally and up to 80% near the poles. Pavlov et al. (2005b) studied the possible effects of dust accumulation in Earth's atmosphere during passage through a GMC. They concluded that such an event could produce global snowball glaciations and that less dense clouds could still produce moderate ice ages.

Of course, a planet closer to the outer edge of the CHZ would feel the effects of cloud passages more intensely and more often, as would a planet with a weak or absent magnetic field. Thus, among the terrestrial planets in the Solar System, Mars should have been subjected to the most severe interactions with interstellar clouds. This is another reason that the CHZ definition should be expanded beyond merely the maintenance of liquid surface water.

How would the effects from passages through GMCs vary with location in the Galaxy? Firstly, GMC encounters should be more frequent in the inner Galaxy because of the higher density of GMCs there. Secondly, the encounter velocities should be greater in the inner Galaxy, making it more likely that the heliopause will be pushed back to the vicinity of the terrestrial planets, even for relatively low-density interstellar clouds. In addition, at high encounter velocity, the energy deposited by interstellar dust impacting a planet's atmosphere might become an important factor in atmospheric loss, but this needs to be explored quantitatively.

Galactic dynamics is arguably the most complex aspect of the GHZ. While the Sun's original birth orbit in the Galactic disk cannot be determined, there is little doubt that it has changed significantly. Older stars in the disk have larger velocity dispersions. Stars form in relatively circular orbits, and over time they experience gravitational perturbations that make their orbits more eccentric and send them farther from the disk midplane. Thus, older stars tend to pass through the midplane at a higher velocity and traverse a greater range of radial distances from the Galactic nucleus.

Given that stars migrate in the disk over billions of years, the present metallicity of interstellar gas in a star's vicinity, corrected for the time of its formation, will not be representative of the star's metallicity. The disk radial metallicity gradient allows us to calculate the metallicity of a star at the time of its formation, but the star will later wander to a region with a higher or lower gas metallicity. As a result, the GHZ has fuzzy boundaries.

The spiral arms are important structures for determining the boundaries of the GHZ. They contain most of the GMCs and SNe II in the Milky Way. The interarm regions have less star-formation activity, but the star density there is only modestly less than that in the arms at the same Galactocentric radius. Within the framework of the density wave hypothesis, the spiral arms rotate about the nucleus of the Milky Way like a solid body, with a constant angular frequency (Lin, Bodenheimer & Richardson 1996). Assuming the Milky Way's spiral arm pattern can be maintained for at least several billion years (Lépine et al. 2001), surveys of the spiral arms can be used to conduct long-term simulations of stars' motions with respect to them.

Stars at the corotation circle will orbit the Galactic centre with the same period as the spiral arm pattern. Thus, the interval between spiral arm crossings is the longest for a star in a circular orbit at the corotation circle. However, Lépine et al. (2003) show that a star near the corotation circle experiences resonant perturbations with the spiral density waves that cause it to wander in the radial direction by 2 kpc–3 kpc in less than a Gyr. This would imply that, over Gyr timescales, spiral arm crossings are minimised, instead, at a moderate distance from the corotation circle. If the Sun is indeed very close to the corotation circle, as some recent studies indicate (Dias & Lépine 2005), then it is a surprise that its orbit has such a small eccentricity.

Additional benefits for life at the corotation circle include reduced gas density and reduced star formation. It is interesting to note that on this basis alone, Marochnik (1983) concluded that there must be a habitable zone in the Milky Way not unlike the GHZ.

The interarm spacing at the Sun's location is 2.8 kpc ± 0.3 kpc (Vallée 2008). The Sun is presently located 0.20 kpc inside its mean Galactic orbital radius and about 0.14 kpc from its perigalactic radius (Sellwood & Binney 2002). It is 0.9 kpc from the Sagittarius arm (Vallée 2008). Thus, the Sun is presently safe from radial excursions into either the inner or outer arms, assuming it is near the corotation circle.

Shaviv (2003) reported having found a link between spiral arm crossings and long-term variations in Earth's climate, especially glaciations. At the core of his thesis is the GCR–cloud link. He reconstructed the historical GCR flux from meteorite exposure ages and the concurrent temperature variations from ancient calcite shells. He compared these data to the calculated cosmic ray flux fluctuations resulting from spiral arm crossings (varying from about 35% to 140% of the present value). The strength of the correlation, however, depends sensitively on the still-controversial value of the Sun's position relative to the corotation circle. His data could also be interpreted in terms of a varying star-formation rate combined with close encounters with (as opposed to crossings of) spiral arms.

In summary, the evolution of the GHZ is determined by a number of astrophysical processes. In a given region of the Milky Way, Earth-like planets are unlikely to form within the CHZ until the interstellar gas metallicity reaches a value close to solar metallicity. Survival of life depends on the distribution of radiation hazards, interstellar clouds and comets. Threats to life increase towards the centre of the Galaxy and decrease with time. The greatest uncertainty about the GHZ concerns stellar dynamics and how a given star's orbit interacts with the spiral arms.

The Cosmic Habitable Age

The steady-state theory held that the universe has always appeared as it does today (Hoyle 1948). The replacement of the steady-state theory by the Big Bang Theory in the 1960s, however, made it clear that this is not the case. Analysis of the WMAP data indicated that the universe began in a hot dense state 13.7 billion years ago (Komatsu et al. 2008). Analyses of distant galaxies showed that the global star-formation rate has been declining for the past 5 billion years (Heavens et al. 2004). Old stars in the Milky Way are observed to be systematically deficient in metals compared with young stars, mirroring the evolution of metals in the broader universe. The universe has changed drastically since its formation, and these changes bear on the question of habitability.

Discussions of the CHA have usually been framed in terms of the anthropic principle (Dicke 1961; Garriga, Livio & Vilenkin 2000; Rees 2000, 2003). Given that the universe has changed so dramatically since its origin, the question naturally arises why we observe ourselves to be living during this particular time as opposed to some other time. Clearly, chemically based life is not possible in the very early universe before atoms formed or in the distant future after all the stars burn out. Other considerations indicate that the boundaries of the CHA are much narrower than these extreme limits.

Lineweaver (2001) estimated the probability of forming Earth-like planets over the history of the universe based on the evolution of the global metallicity. He assumed that habitable terrestrial planets are most probable over a narrow range of metallicity centred on the solar value. Von Bloh et al. (2003) used the results from Lineweaver to calculate the peak time of the incidence of Earth-like planets in the Milky Way; they found it to be at about the time of the formation of the earth.

Progress in refining the CHA will come primarily from improvements in our understanding of the evolution of the cosmic star-formation rate. Star formation, in turn, determines the evolution of the average supernova rate, AGN activity and gas-phase metallicity in galaxies. Many of the same studies relevant to the GHZ can also be applied in a broader sense to the CHA.

If all galaxies were just like the Milky Way, then the GHZ could just be applied to other galaxies. But they are not; there is great variation in their properties. Galaxies differ in their Hubble types (elliptical, spiral or irregular), metallicities, luminosities, masses and environments. Some of these properties correlate with each other. For example, mass correlates with luminosity. Metallicity also correlates with luminosity, in the sense that more luminous galaxies are more metal-rich (Lee et al. 2006).

Calura and Matteucci (2004) calculated the evolution of the production of metals over the history of the universe. They determined that the present mean metallicity of galaxies is close to the solar value. This is consistent with the fact that the MWG is among the 1%–2% most luminous galaxies in the local universe. The inner Galaxy experienced more metal enrichment over its history and has a higher mass density than the solar neighbourhood. Thus, the mass-weighted average of the Galaxy's metallicity is larger than the solar value. An additional consideration is that luminosity-weighted metallicity averages for galaxies tend to be smaller than mass-weighted ones because the bright red giants in a galaxy tend to be more metal-poor.

Even though the average metallicity of local Galactic matter is now close to solar, there were many metal-rich stars formed within the first 2–3 billion years after the Big Bang. The metals first built up quickly in the inner regions of (now) massive galaxies. Presumably, these metal-rich stars have been accompanied by planets. However, like the juvenile MWG, these were also the regions with the most dangerous radiation hazards, including supernovae, GRBs and intense AGN activity.

Galaxy evolution is not the same everywhere. Ellipticals are much more common in dense galaxy clusters than in small groups, like our Local Group. Spiral galaxy disks tend to be stripped of gas more efficiently in dense cluster environments, and star formation is suppressed as a result (Vogt et al. 2004). Galaxy collisions are also less frequent in sparse groups.

Galaxy collisions shape galaxies and alter their star-formation rates. Major collisions can temporarily increase the star-formation rates throughout each of the involved galaxies (becoming starburst galaxies) and possibly consume most of the gas. Most often, colliding galaxies become ellipticals following exhaustion of their gas, with a greatly reduced star-formation rate (and thus a reduced planet-formation rate). Mergers can also feed fresh gas into any SMBHs in their nuclei, causing AGN outbursts. Mergers were frequent in early times, but even today they continue. For example, Hammer et al. (2005) argue that about three-quarters of intermediate-size spirals have experienced major collisions within the last 8 billion years.

Surveys of supernovae and their remnants tell us not only about the present supernovae distribution and rate in the Milky Way; they also reveal how these quantities vary among the various types of galaxies. Surveys of supernova remnants (SNRs) in large nearby galaxies show that their radial scale lengths are generally similar (about 30% their disk radii), and many have peaks at

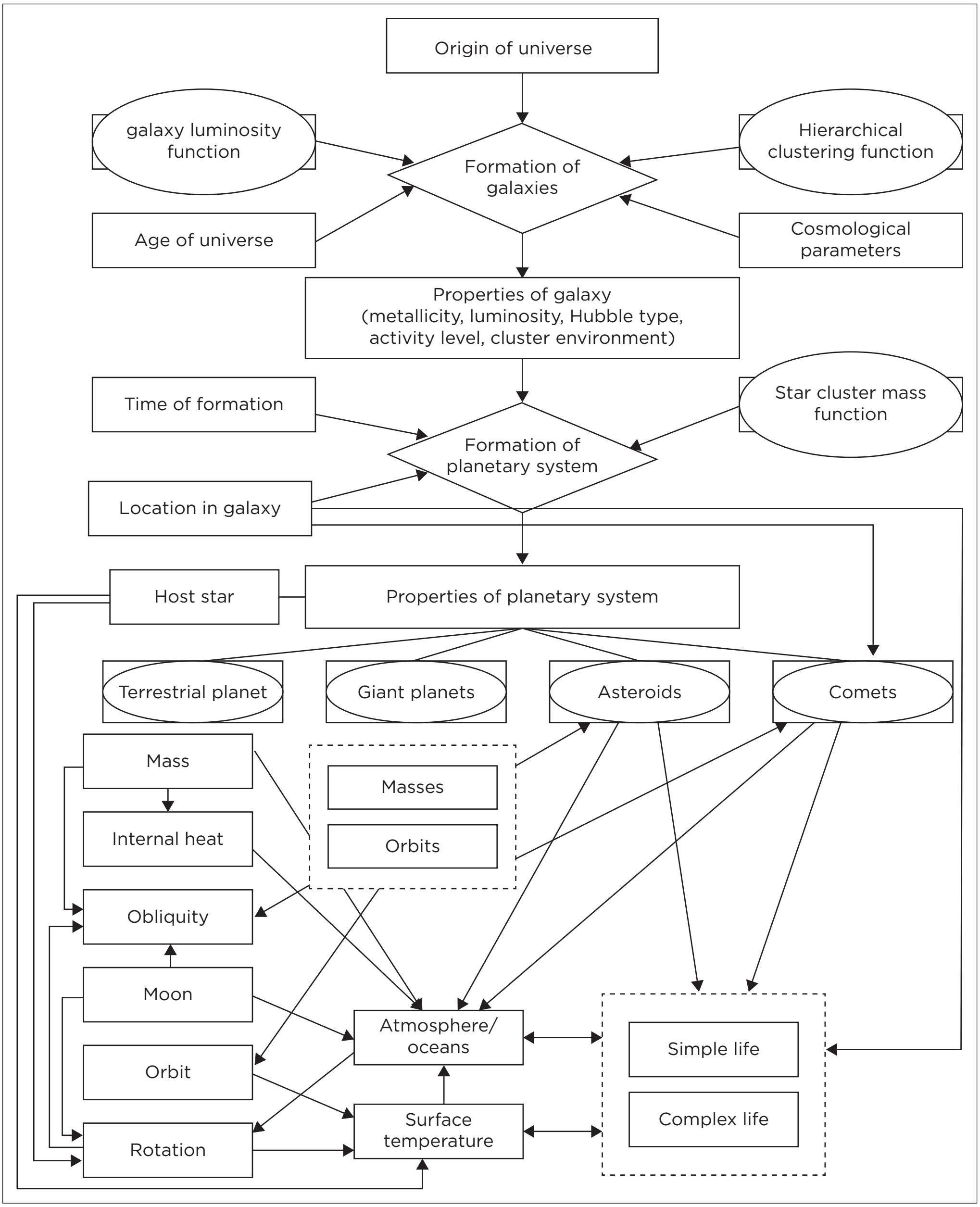
20%–40% of their disk radii (the Milky Way being such a case) (Matonick & Fesen 1997; Sasaki, Breitschwerdt & Supper 2004). The starburst spiral galaxy NGC 6946, however, has a sharp peak of the SNR density at its nucleus. Particularly helpful are studies like Capellaro's, which catalogues the observed rates of all SN types for all types of galaxies (Cappellaro 2004). Such studies reveal that SNe II do not occur in ellipticals, while they predominate in late-type spirals, where the overall SN rate is greater.

With the star-formation rate continuing to slow, the mean metallicity will increase ever more slowly. Many galaxies presently below solar metallicity will eventually build up enough metals to form Earth-size terrestrial planets. The time in the history of the universe when a particular region in a given galaxy reaches this critical stage is important – too early, and the radiation environment may be too harsh for life to flourish. There is also a limit at late times. As the star-formation rate declines, the production of the long-lived geologically important radioisotopes cannot keep up with their decay in the interstellar medium. Earth-size terrestrial planets forming in the future will have less radiogenic heating (Gonzalez et al. 2001a). Of course, increasing the size of a planet can compensate for this deficit, but then all the processes dependent on planet size discussed earlier will need to be taken into account.

In the future, massive stars will become rarer, which means that the SN rate will continue to decline. AGN activity will also decline. Galaxies will continue to recede from each other. Thus, the universe should become safer from powerful transient radiation events. On the other hand, G dwarfs will also become rarer, and stellar galactic orbits will become hotter. Adams and Laughlin (1997) speculated on the fate of the universe in the far distant future, after nucleons decay and black holes evaporate. While these are very great extrapolations from the present, there is no question that the future history of the universe will differ drastically from its present state. The changes will take it ever further from the conditions we know are compatible with life (especially complex life).

Based on the evolution of the global star-formation rate, the CHA probably encompasses the last few billion years and the next 10 billion years. This is brief compared with the possible future history of the universe. Interestingly, there appears to be a convergence of several time scales that permits life to flourish on a planet within this brief window. These include the nuclear evolutionary timescale of the Sun; the rate of decline of the Sun's activity; the mean half-life of the geologically important radioisotopes; the loss rate of Earth's volatiles; the recession rate of the Moon and the related slowdown of Earth's rotation; the evolution of the star formation rate in the Galaxy and the expansion rate of the universe. Is this just a coincidence, or is this telling us that these timescales must match for life to be possible now?

By way of summary, some of the complexity of the many habitability factors is presented in a highly schematic form in Figure 4.1. The many interrelationships



Source: Gordon and Dembski (2014), published with the appropriate permissions.
Note: The factors with the ellipses have significant stochastic components. The factors for terrestrial planets continue along the bottom of the figure, as they did not all fit along the left column.

FIGURE 4.1: A highly schematic diagram showing the many interrelationships among the important habitability factors.

are represented by the links between the boxes. The overall problem of habitable zones is highly nonlinear. It will require considerable computational power to perform the required Monte Carlo simulations and long temporal integrations. Its solution will require continued advancements in astrophysics, geophysics, climatology and biology.

The multitude of interactions shown in Figure 4.1, both positive and negative for life, makes it unlikely that another 'island of habitability' will be found in parameter space. For example, if Earth had formed 20% farther from the Sun, it would still be within the traditional CHZ, but it would be subjected to a different asteroid and comet impact rate, different gravitational perturbations to its orbit and rotation and different exposure to interstellar clouds and cosmic ray flux and it would have needed more carbon dioxide in its atmosphere to maintain liquid surface water. Similar arguments apply to the type of host star, the location within the Milky Way and to the type of galaxy. If we change one parameter, it is not often the case that we can change another parameter to compensate for any deleterious effects to life. As astrobiologists continue to learn about the formation and long-term evolution of planetary systems, they are discovering that processes that affect planetary habitability are intertwined in a complex web that sets severe constraints.

Implications for global tuning

Once we have established what kinds of environments are habitable, we can use this information to examine how changes in the global parameters affect habitability at the local scale. For example, if it turns out to be the case that an environment very similar to ours is necessary for complex life, as now seems likely, even relatively small changes to the global parameters will result in a lifeless universe. On the other hand, if environments significantly different from ours can be just as habitable, then relatively large changes in the global parameters are likely to find other local islands of habitability in parameter space. When adjusting a global parameter, it is necessary to follow its effects all the way down to the local scale. The physicist and cosmologist must partner with the astrobiologist. We will briefly explore one example of changes to global parameters to illustrate how the global parameters are linked to local parameters.

Probably the most famous example of fine-tuning is Fred Hoyle's discovery of the critical placement of a resonant energy level in the carbon-12 nucleus within the context of nuclear reactions inside stars. Changes in the strong nuclear force by about 0.5% or in the electromagnetic force by about 4% would significantly change the relative yields of carbon and oxygen (Oberhummer, Csótó & Schlattl 2000). Carbon and oxygen are needed by living things in comparable amounts, and stars are the only sources of these key elements.

The key steps in getting from the universal physical constants to the needed mix of carbon and oxygen for life are as follows. Given a set of global parameters including the cosmological initial conditions, the masses of the fundamental particles and the strengths of the four forces (or higher-level forces), how does changing one of these – say, the strength of the strong force – alter the abundances of carbon and oxygen at the local scale? The first step is to calculate the sensitivity of the production of carbon and oxygen in stars to changes in the strong force (Schlattl et al. 2004). The next step is to calculate how carbon and oxygen, thus produced, are distributed in galaxies over the history of the universe.

Following the mixing of the ejected carbon and oxygen atoms into the interstellar medium, we must next consider their incorporation into star-forming clouds. As a planetary system forms out of a denser clump of gas and dust in a giant molecular cloud, carbon and oxygen react with other elements, mostly hydrogen, to generate several molecular species. The gas chemistry is highly sensitive to the carbon-to-oxygen (C/O) ratio (Watt 1985). If the ratio is greater than one, then molecules containing carbon and hydrogen dominate, while water dominates for ratios less than one. The final critical step is the formation of the solid planetary building material from the cooling gas.

The C/O ratio in condensed solids varied with the location in the early protoplanetary disk. Solids formed close to the Sun were more strongly fractionated and contained less C. Solids formed farther from the Sun were more volatile-rich and had a C/O ratio closer to the initial value of the birth cloud. As a result, the C/O ratio of the bulk Earth is much smaller than the solar ratio. This follows from the low abundance of C in the earth’s core and mantle. The C/O ratio of the crust, however, is closer to the solar value. Earth’s crust is believed to have formed from a late accretion of material rich in volatiles from the outer asteroid belt. Of course, it is in the crust where the ratio needs to be close to unity for life.

The C/O ratio varies over time and location in the Milky Way in a systematic way (Carigi et al. 2005). Its value at a given location depends on the star-formation history there. The C/O ratio in matter returned to the interstellar medium depends on the mix of low- and high-mass stars. If the C/O ratio at a given location and time differs from the Solar System value, other aspects of the environment are also likely to differ. For example, the C/O ratio correlates with metallicity in the Milky Way. As I noted, metallicity is a critical parameter in determining whether a system is habitable. A region with a different C/O ratio from the Sun will likely also have a different metallicity.

Multiple global tuning

The example discussed shows how a change in the strong force can alter the C/O ratio locally. However, changing the strong force has other local effects, such as nuclear reactions in stars and the stability of nuclei and thus the length of the periodic table. The other forces also display multiple sensitivities. Changing the weak force strength affects the relative amounts of hydrogen and helium produced in the first few minutes after the Big Bang, the fusion reactions inside stars, the explosion of massive stars as supernovae and the decay of radioactive isotopes (Clavelli & White 2006; Harnik, Kribs & Perez 2006). Changing the electromagnetic force changes all of chemistry and all processes involving the interaction of light with matter. If we change gravity, we change planets, stars, galaxies and the large-scale dynamics of the universe.

When combined with the complex web of interdependent habitability factors illustrated in Figure 4.1, this phenomenon of 'multiple global tuning' makes it even less likely that changes in global parameters will result in another island of habitability.

■ Conclusion

Astrobiology research (Gonzalez 2014, p. 625) is revealing the high specificity and interdependence of the local parameters required for a habitable environment. These two features of the universe make it unlikely that environments significantly different from ours will be as habitable. At the same time, physicists and cosmologists have discovered that a change in a global parameter can have multiple local effects. Therefore, the high specificity and interdependence of local tuning and the multiple effects of global tuning together make it unlikely that our tiny island of habitability is part of an archipelago. Our universe is a small target indeed.

Chapter 5

Materialistic and theistic perspectives on the origin of life

Fazale R. Rana
Research and Apologetics Scholar Department,
Reasons to Believe,
Covina, California, United States of America

Introduction[42]

Today the origin-of-life problem is one of the most challenging and fascinating issues confronting science. Most investigators who seek answers to the myriad questions surrounding life's origin carry out their pursuit from within a materialistic framework. The exploration of chemical evolutionary explanations for life's origin began over 150 years ago with the idea of Darwin's 'warm little pond'. Today, a diversity of chemical evolutionary models and scenarios

---

[42] This chapter represents, with appropriate permissions, a substantial reworking of sections of and amalgamation of articles published by *Reasons to Believe*, viewed 04 May 2022, from https://reasons.org/about (see e.g. 'Perspectives on Theistic Evolution', https://reasons.org/explore/publications/articles/perspectives-on-theistic-evolution).

How to cite: Rana, FR 2022, 'Materialistic and theistic perspectives on the origin of life', in F van Niekerk & N Vorster (eds.), *Science and Faith in Dialogue*, in Reformed Theology in Africa Series, Vol. 10, AOSIS Books, Cape Town, pp. 125–148. https://doi.org/10.4102/aosis.2022.BK334.05

populates contemporary origin-of-life research. Despite the expansive range of ideas encompassed by chemical evolution, a materialistic approach to the problem has yielded little true insight into the process of abiogenesis. This frustrating lack of progress has emboldened a growing minority of scientists and philosophers to entertain the possibility that a teleological approach, which appeals to the work of an intelligent agent, may offer key insight into the origin-of-life problem.

Yet most scientists oppose any model that would rely on teleological considerations, namely, life's origin arises from the work of God. They regard an appeal to agency as a violation of the principle of methodological naturalism. With this concern at the forefront, I present two theistic approaches to the origin-of-life question that make it possible to entertain a role for the divine agency, while providing the means to investigate the origin-of-life question in a way that conforms to the spirit of the scientific method. These two approaches hold the possibility of establishing reproachment between the origin-of-life research community and ID proponents.

The origin-of-life question serves as one of the most captivating and enduring questions of our time. Most people view the origin of life as a scientific problem to be solved. Towards this end, most scientists who seek to understand life's genesis approach the problem from a materialistic perspective, exploring and evaluating plausible chemical evolutionary pathways that could yield the first cellular entities. Despite the impressive body of work generated over the last seven decades by origin-of-life investigators from a wide range of disciplines, the scientific community has, at best, only been able to produce a set of disparate scientific clues about how chemical evolutionary processes might have led to the genesis of life.

Clearly these clues are important, but even so, it could be argued that origin-of-life researchers have no genuine understanding about abiogenesis. In his book *The Fifth Miracle* (which presents a knowledgeable outsider's perspective on the origin-of-life problem), physicist and astrobiologist Paul Davies (1999) writes:

> When I set out to write this book, I was convinced that science was close to wrapping up the mystery of life's origin. […] Having spent a year or two researching the field, I am now of the opinion that there remains a huge gulf in our understanding. […] This gulf in understanding is not merely ignorance about certain technical details; it is a major conceptual lacuna. (p. 17)

Davies's words are as true today as they were in 1999. In the contravening years, a growing number of origin-of-life investigators have started to fear that this 'major conceptual lacuna' may render the origin-of-life problem an intractable and impenetrable scientific mystery.

The inability of the scientific community to explain abiogenesis within a materialistic framework has opened the door for a growing minority of scientists and philosophers to consider the radical idea that an intelligent agent played a role in the emergence of life on Earth. This conviction extends beyond ‘god-of-the-gaps’ reasoning in which God is inserted as the explanation where gaps in scientific knowledge exist. Instead, scientists, mathematicians and philosophers working in this arena have advanced several distinct lines of scientific and philosophical arguments that collectively constitute the case for ID (Axe 2016; Behe 2006; Dembski 2001; Eberlin 2019; Meyer 2010; Rana 2008).

In other words, both materialistic and teleological approaches to the origin-of-life question have yielded a rich and diverse collection of ideas and models. One of the goals of this chapter is to explore some of these ideas. Given space constraints, it is impossible to present an exhaustive survey, so I will present a sampling of the most prominent chemical evolutionary scenarios.

As James M. Tour demonstrates in his contribution to this book, materialistic approaches to the origin of life inevitably fail. Nevertheless, most scientists stand in strong opposition to any proposal that appeals to the work of God to explain life’s origin. They regard any appeal to teleology and the supernatural as an egregious violation of the principle of methodological naturalism – the philosophical framework that serves as the foundation for modern-day science. In part, their hesitation stems from the concern that explanations involving divine agency reside outside the bounds of science, rendering these types of proposals as untestable and, hence, unscientific – though they may be philosophically or theologically tenable. Considering this concern, I propose two theistic approaches to the origin-of-life question that make it possible to entertain a role for the divine agency while also conforming to the spirit of the scientific method (though they depart from methodological naturalism). These two approaches build upon previous work of ID proponents (including my own), while opening up new research vistas that encourage genuine dialogue between origin-of-life investigators steeped in materialism and Christian theists who see agency as an integral aspect for the explanation of life’s genesis on Earth.

Methodological naturalism and the origin of life

Most origin-of-life researchers are convinced that, eventually, some form of chemical evolution will explain life’s start. Part of this confidence stems from the impressive achievements of modern-day science. Based on these past successes, these investigators express certainty that with enough time, effort and funding the mystery of abiogenesis will be solved. At the same time, it is not uncommon to hear origin-of-life researchers acknowledge the fact that finding an explanation for the origin of life has turned out much more challenging than was originally thought.

Another source of this widespread confidence derives, in large measure, from an *a priori* commitment to methodological naturalism, which demands that all scientific explanations rely exclusively on physicochemical processes. Astrobiologist Paul Davies (1999, pp. 81–82) makes this very point when he says, 'Although biogenesis strikes many as virtually miraculous, the starting point of any scientific investigation must be the assumption that life emerged naturally, via a sequence of normal physical processes'.

This unwavering commitment to methodological naturalism and the pursuit of an exclusively materialistic explanation to life's origin extends back to the mid-1800s and the publication of *On the Origins of Species*, the book that brought about the Darwinian revolution. Charles Darwin's ideas transformed the life sciences and have shaped the scientific community's approach to biological origins to this day.

■ A brief history of origin-of-life research

To this day, Iris Fry's *The Emergence of Life on Earth* stands as one of the best scholarly treatments on the history and philosophy of origin-of-life research. Fry traces the beginnings of the modern-day origin-of-life research programme back about 170 years ago to the ideas of Charles Darwin. His theory of evolution revolutionised biology, stripping it of all the teleological considerations that were at play in the early 1800s (Fry 2000, pp. 54–57). With Darwin's push, biology moved full force into the materialistic arena. Darwin and those who embraced his ideas of materialistic evolution no longer viewed species as the fixed product of God's creative activity. Rather, biologists came to view species as 'fluid' entities, continually evolving through natural mechanisms – inheritable variation operated on by natural and sexual selection. Darwin argued that, when extrapolated over vast periods, the same mechanism that generated new species could account for the origin of major biological groups and, hence, could explain the entirety of life's history, diversity and biogeographical distribution. Darwin believed that natural selection could even account for the exquisite adaptations possessed by organisms that make them ideally suited for their environment and for the impressive appearance of design displayed by the biological system. With his proposal, Darwin supplanted William Paley's divine Watchmaker with natural selection. Evolutionary biologist Richard Dawkins (1987) masterfully captures the significance of this change of perspective in *The Blind Watchmaker*:

> Natural selection, the blind, unconscious, automatic process which we now know is the explanation for the existence and apparently purposeful form of all life, has no purpose in mind. It has no mind and no mind's eye. It does not plan for the future. It has no vision, no foresight, no sight at all. If it can be said to play the role of watchmaker in nature, it is the blind watchmaker. (p. 9)

Ultimately, this revolution in biology extended to the origin-of-life question.

A warm little pond[43]

Darwin avoided the topic of life's genesis in *On the Origin of Species*. In fact, he never *formally* addressed the idea at all. However, in an 1871 letter to Joseph Hooker, Darwin *informally* advanced the radical idea that life could originate on an early, lifeless Earth through chemical evolution from ammonia, phosphates and other inorganic materials (see Rana & Ross 2004). Scientific contemporaries who embraced Darwin's ideas, such as Thomas Huxley and Ernst Haeckel, proposed similar abiogenic or nonbiological processes to account for the origin of the first life form. Ernst Haeckel, perhaps Darwin's leading supporter in Germany, speculated on the existence of ancient creature-like entities that occupied the space between life and inanimate matter. Haeckel called these entities 'monera' and imagined them to be formless lumps of gel that could 'reproduce'. Huxley seemingly provided observational evidence for the existence of monera when he detected gelatinous lumps in ocean-floor mud. Huxley interpreted the gelatinous material as 'moneran' remnants (Gould 1980, pp. 236–244).

The protoplasmic theory of the cell – which regarded the cell as a wall surrounding a nucleus and a homogeneous, jelly-like protoplasm – made the initial attempts to provide materialistic explanations of abiogenesis seem reasonable (Fry 2000, pp. 57–59). In the 1830s, Matthias Schleiden and Theodor Schwann independently advanced cell theory – the idea that all life is composed of units called cells. Observational limits at that time-constrained biologists' view to three cellular features: the cell wall, the nucleus and the protoplasm. In retrospect, it is understandable why life scientists would think that chemical routes could readily produce the single ingredient believed to form the cell's protoplasm. German chemist Edward Pflüger suggested that simple carbon- and nitrogen-containing compounds on early Earth experienced a sequence of chemical transformations to yield a single, molecular entity that forms the cell's protoplasm.

Towards the latter part of the 19th century, the protoplasmic view of the cell waned with the rise of biochemistry. Scientists discovered that the cell's protoplasm was not composed of a single molecular component but, instead, is a chemically complex, heterogeneous system. The discovery of enzymes in the protoplasm that catalysed a diverse array of chemical reactions served to highlight the cell's complexity. These insights undermined the earliest ideas about abiogenesis. Chemical studies revealed that Huxley's 'moneran' remains were calcium sulphate salts precipitated from mud samples by the addition of alcohol.

---

[43] This section of the chapter represents a reworking of Rana and Ross (2004).

Panspermia

In the late 19th and early 20th centuries, a new approach to the origin-of-life question gained popularity in the scientific community. Scientists regarded life to be eternal just like matter. They circumvented the question of life's origin by assuming that life was endemic and present everywhere in the universe. Scientists called this idea 'panspermia' (meaning 'everywhere life's seeds') (Fry 2000, pp. 59–62). Proponents of panspermia viewed life as an inherent part of the universe. The prevailing view of the universe at that time, which held the cosmos as eternal and infinite, lent credibility to panspermia. Part of the appeal of panspermia was the discovery of the complexity of biological organisation. Because of this complexity, many scientists at that time questioned if life could have emerged by the random chemical processes that were central to the earliest explanations for abiogenesis.

Prominent scientists of the time, such as Lord Kelvin, Hermann von Helmholtz and Nobel laureate Svante Arrhenius, accepted panspermia. Those seeking to advance panspermia focused attention on identifying mechanisms that could transport life throughout the universe. Life's origin on Earth was the result of life's transport and arrival on early Earth.

Lord Kelvin and von Helmholtz suggested that meteorites transported life forms to Earth. Arrhenius proposed that naked bacterial spores or those associated with dust particles were rampant throughout the universe. Arrhenius proposed that radiation pressure from stars would have driven these spores through interstellar space.

Panspermia was dealt a blow in the early 20th century when cosmologists recognised that the universe was temporal and finite. Equally problematic was the discovery that ultraviolet radiation killed bacterial spores. Because ultraviolet radiation permeates interstellar space, bacteria cannot survive interstellar journeys.

Neovitalism

Because of the newly recognised complexity of the cell and the challenging problems that confronted the earliest versions of abiogenesis and panspermia, most scientists gave up on the origin-of-life question altogether (Fry 2000, pp. 62–64). The origin of life was viewed as a profound mystery. Other scientists proposed the existence of a special 'life force'. Embracing this idea, a scientific minority advocated for a type of neovitalism. Hans Driesch, a leading proponent of neovitalism, argued that the life force mysteriously propagated from generation to generation and that the origin-of-life question stood beyond reach.

Revisiting the warm little pond: Chemical evolution

As a reaction to neovitalism, Russian biochemist Alexander I. Oparin and British geneticist J.B.S. Haldane independently proposed detailed models for abiogenesis in the 1920s. Together, their ideas are referred to as the Oparin–Haldane hypothesis. This hypothesis became the chief organising framework in origin-of-life research from its inception in the 1950s (with the famous Miller Urey experiment) through the 1970s. In many ways, the Oparin–Haldane hypothesis still influences thinking in origin-of-life studies (Miller, Schopf & Lazcano 1997).

For the first time, the mechanism for life's origin was cast in the form of a detailed scientific model. Oparin and Haldane each proposed explicit stepwise pathways that began with inorganic systems on early Earth and ended with the first living entities. Both Oparin and Haldane postulated a primordial atmosphere that lacked O_2 and was made up of reducing gases – hydrogen, ammonia, methane and water vapour. Energy discharges propagating through the primordial atmosphere formed prebiotic molecules that accumulated in the earth's oceans (or some other more confined location on Earth), establishing a primordial soup of prebiotic molecules. Within the primordial soup, chemical reactions led stepwise to the first life forms. Oparin and Haldane had different ideas about the intermediate chemical systems that led to the first cells. Oparin viewed the transitional molecular system as protein aggregates, whereas Haldane regarded life's intermediate as a large self-replicating molecule.

In the 1950s, Stanley Miller, a student of Nobel laureate Harold Urey at the University of Chicago, carried out experiments that became the first experimental verification of the Oparin–Haldane hypothesis and launched the origin-of-life research programme as a formal scientific discipline (Miller 1953, 1955). Miller's famous spark-discharge experiments involved passing an electrical discharge through a reducing gas mix devoid of oxygen, presumably simulating early Earth conditions. To his delight, this experiment yielded amino acids and other organics.

Miller's successful experiment inspired countless experiments by other scientists (Fry 2000, pp. 79–83). The results from these studies seemingly provided added validation of the Oparin–Haldane hypothesis. Bolstered by these early accomplishments, many scientists assumed the origin-of-life problem would be solved in short order in the decades to come (Horgan 1997, pp. 38–42).

Optimism characterised the next few decades of origin-of-life research. The excitement in the research community grew when, in the 1970s, American biochemist Sidney Fox and his group coaxed amino acids to condense to form 'proteinoids' compounds that closely resembled proteins. These compounds could catalyse chemical reactions. In fact, Fox and his co-workers discovered that under certain conditions, 'proteinoids' aggregated to form microspherical structures that resembled cells superficially (Fry 2000, pp. 83–88).

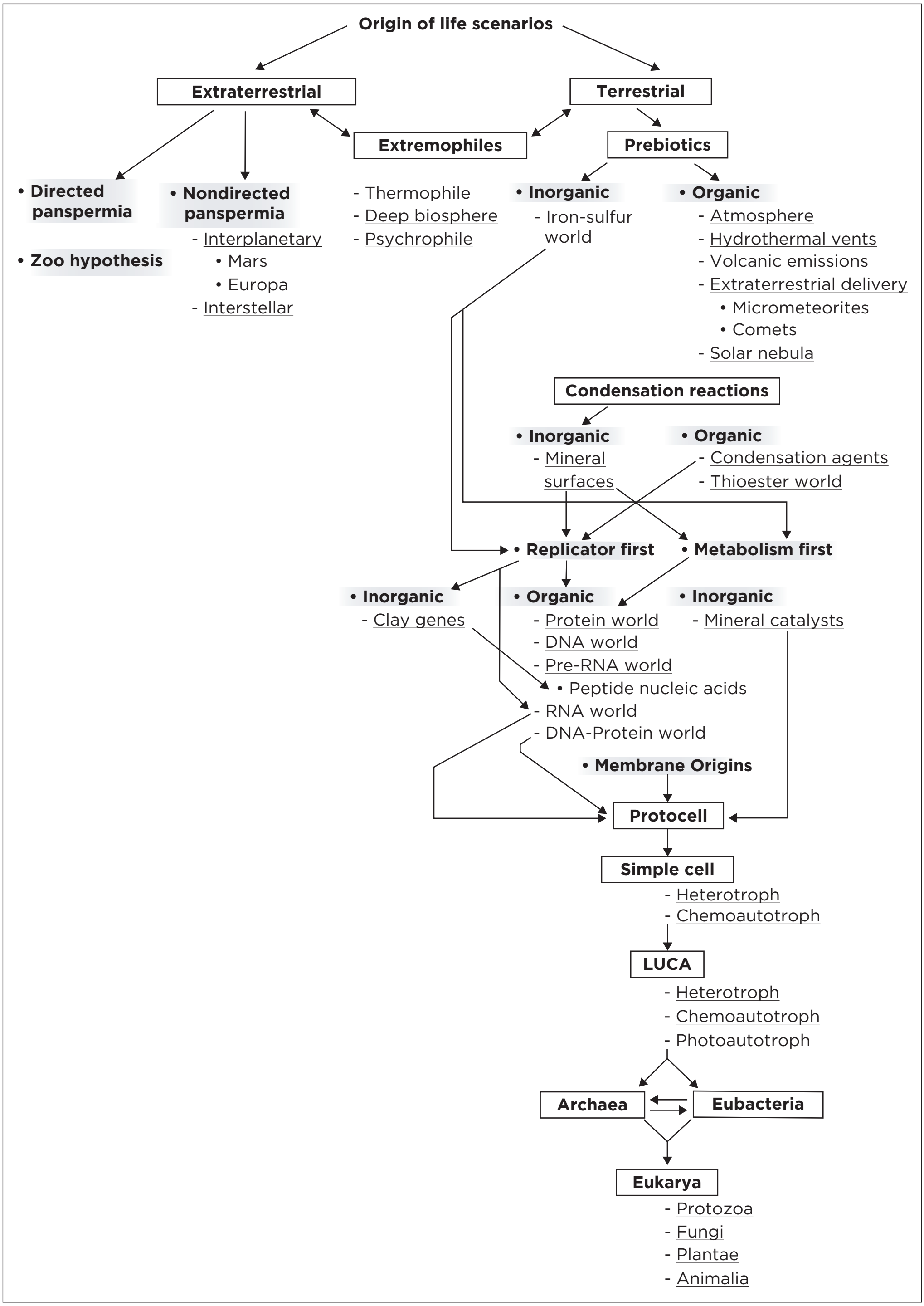
■ Contemporary work in the origin-of-life research

Beginning in the 1980s and continuing today, work on the origin-of-life problem has become a multidisciplinary scientific effort that extends beyond laboratory studies in prebiotic chemistry. As a result, origin-of-life investigators now propose a wide range of chemical evolutionary scenarios for the emergence of life on Earth (Figure 5.1). For an introduction to contemporary origin-of-life research, see *Life's Origin* (Schopf 2002), *The Emergence of Life* (Luisi 2006), *Chemical Evolution and the Origin of Life* (Rauchfuss 2008) and *First Life* (Deamer 2011).

All evolutionary origin-of-life scenarios require a source of prebiotic compounds. Some researchers explore atmospheric chemistry as their source (Kasting & Brown 1998). Some origin-of-life investigators speculate that early Earth's volcanoes served as the site of prebiotic synthesis (Navarro-Gonzalez, Molina & Molina 1999). Presumably reducing gases made up the volcanic emissions on early Earth and energy sources like volcanic lightning was the spark that catalysed reactions within the volcanic gases to produce prebiotic materials. Deep-sea hydrothermal vents are perhaps the most popular location for prebiotic synthesis in current origin-of-life thought (Orgel 1998). Presumably, metal ions and sulphide catalysed reactions within the gases released at these vents to produce prebiotic compounds. This line of thought is further fuelled by the discovery of microbes believed to be some of the oldest on Earth that inhabit these environments (Stetter 1998).

In a different vein, some origin-of-life investigators propose an extra-terrestrial source for prebiotic compounds. Extra-terrestrial delivery rivals the deep-sea hydrothermal vent models in importance among today's origin-of-life investigators. These researchers look to comets, micrometeorites and interplanetary dust particles as the delivery vehicles that carried prebiotic compounds to Earth (Chyba & Sagan 1997; Oró & Lazcano 1997). Those that advocate extra-terrestrial delivery find support for this hypothesis in the recovery of a diversity of organic compounds from meteorites.

The next stage in all origin-of-life scenarios begins once prebiotic compounds accumulate either globally or locally on primordial Earth. In this step, these materials react to generate complex molecules that eventually result in important biomolecules like lipids, proteins and nucleic acids. Often, this complexification involves condensation reactions. Water forms as a by-product of these condensation reactions. For this reason, condensation



Note: This chapter is adapted with permission from articles published by Reasons to Believe, published with the appropriate permissions by Reasons to Believe.

FIGURE 5.1: Origin-of-life scenarios.

reactions are thermodynamically problematic in an aqueous environment. To sidestep this problem, most origin-of-life scenarios appeal to localised evaporation of the prebiotic soup or the deposition of prebiotic compounds through tidal actions on the shore of the volcanic islands. Condensation reactions become energetically favourable under dehydrating conditions. These condensation reactions may gain assistance from condensing agents (Ferris & Usher 1984). In effect, these materials remove a water molecule from the reactants and then add it to its own structural make-up. Through this chemical process, condensing agents drive condensation reactions. Origin-of-life investigators maintain that if condensing agents co-deposited with other prebiotic compounds in locations where the prebiotic soup evaporated, then, in principle, these compounds could help generate more complex biomolecules. Laboratory studies have demonstrated that, under simulated early Earth conditions, condensing agents such as cyanamide, cyanogen, cyanoformamide, cyanate, diaminomaleonitrite, trimetaphosphate and pyrophosphates readily form.

Alternatively, origin-of-life researchers turn to mineral surfaces as the catalysts for condensation reactions (Hazen 2005). The chemical characteristics of mineral surfaces make them ideally suited to bind organic molecules and catalyse chemical reactions. Origin-of-life researchers think that mineral-assisted formation of biomolecules from prebiotic precursors could occur either at locations where the prebiotic soup evaporates or within the aqueous environment of the prebiotic soup. Because prebiotic compounds can adsorb to mineral surfaces, minerals found on early Earth could bind and sequester prebiotic compounds in an aqueous setting and promote iterative condensation reactions before the complex biomolecules desorbed from the mineral surface. This idea finds support from studies that have demonstrated that clays (Kaolinite, montmorillonite) will facilitate the condensation of amino acids into protein precursors (peptides) and short RNA chains from activated nucleotides, respectively (Ferris 1998).

A debate exists within the origin-of-life community as to the order and primacy of events that kick-started the process of abiogenesis. One group argues that self-organisation started with metabolism (the metabolism-first model), another other camp insists that life stemmed from self-replicators (the replicator-first model) and a third camp posits that life began with membrane compartments (the membrane-first model).

Metabolism-first proponents maintain that mineral surfaces catalysed the formation of a diverse collection of small molecules that evolved to form an interconnected series of chemical reactions. Once in place these interrelated chemical reactions formed the basis for the cell’s metabolic systems (Morowitz 1992). Over time, these chemical networks became encapsulated to form protocells replete with a form of protometabolism. Some metabolism-first scenarios, like the iron–sulphur world, even suggest that minerals, such as pyrite, became encapsulated along with the protometabolic networks and, thereby, served as life's first catalysts. Once established, protometabolic systems spawned self-replicating molecules.

Replicator-first advocates argue that information-rich molecules, including a naked replicator, emerged first and later became encapsulated along with the precursor molecules needed to sustain its activity. Metabolism emerged subsequently to support the production and turnover of the replicator's building blocks and, ultimately, its self-replicating activity. The leading replicator-first model is the RNA world hypothesis (Bernhardt 2012; Joyce & Szostak 2018; Orgel 2004; Robertson & Joyce 2012).

Those who hold to membrane-first models argue that self-organisation began with the emergence of membrane vesicles, formed from lipidic materials that either formed on Earth or were delivered to early Earth via extra-terrestrial means (Deamer 1998, 2011).

The limited success of chemical evolutionary scenarios

Despite the diversity of ideas and impressive body of work generated by these investigators, the scientific community has amassed only a handful of pieces to the origin-of-life puzzle – and few of those pieces fit well together. It would be wrong to conflate the discovery of these clues with *bona fide* scientific advance. For a detailed scientific discussion of the problems confronting chemical evolutionary models for the origin of life, see *Origins of Life* (Rana & Ross 2004), *Creating Life in the Lab* (Rana 2011) and *The Mystery of Life's Origin* (Thaxton, Bradley & Olsen 2020).

Currently, origin-of-life researchers are very far from truly understanding life's beginning, perhaps no closer than they were almost 70 years ago when Stanley Miller conducted his initial experiments. This lack of progress is not because the origin-of-life research programme is in its infancy as scientists sometimes assert. Substantial resources have brought to bear on the origin-of-life question over the last 30 years.

A fair assessment of the work done to date in origin-of-life research leads to the recognition that each major approach to account for the origin of life faces intractable problems for a single reason: though origin-of-life researchers have identified potential prebiotic routes that could contribute to chemical evolution, they have consistently failed to establish the geochemical relevance of the prebiotic processes that work in a laboratory setting.

Prebiotic chemistry

Today, origin-of-life research finds contributions from a cadre of scientists with expertise in a wide range of scientific disciplines (Rana 2019). Due to this multidisciplinary effort, origin-of-life scientists have gained important clues into abiogenesis from the fossil and geochemical records of Earth's oldest rock formations – yet this evidence only offers a glimpse 'through the glass darkly'. For this reason, prebiotic chemistry remains preeminent when it comes to studying how life began. Origin-of-life researchers have little choice but to perform studies in the laboratory, where they try to replicate the myriad steps they think contributed to chemical evolution.

Investigators working in prebiotic chemistry have three main objectives:

1. **Proof of principle:** The focus of these experiments is to establish – in principle – if chemical or physical processes exist that could conceivably contribute to the stages thought to constitute the pathway to life's beginning.
2. **Mechanistic studies:** Once researchers have identified processes that could contribute to the emergence of life, they need to investigate these processes in detail to learn about the mechanisms that produce the physicochemical transformations.
3. **Geochemical relevance:** The ultimate objective of prebiotic simulations is to determine the geochemical relevance of the plausible physicochemical processes that could have, in principle, contributed to life's start. In other words, how well do the chemical and physical processes identified and studied in the laboratory translate to primordial conditions on early Earth?

Origin-of-life investigators have enjoyed much success with respect to the first two objectives. For example, working in a laboratory setting, origin-of-life investigators have:

1. synthesised most 'building block' molecules (Miller & Lazcano 2003)
2. produced an array of biopolymers from these building blocks (Ferris 2003)
3. evolved functional RNA molecules (Robertson & Joyce 2012)
4. generated self-replicating systems (Horning & Joyce 2013)
5. manufactured protocells that can grow and divide (Joyce & Szostak 2018)

Without question, origin-of-life investigators have shown that – *in principle* – many of the physicochemical processes required for chemical evolution to successfully generate life do exist. But are the pathways identified and studied by origin-of-life investigators in the laboratory relevant geochemically? In other words, would these laboratory processes be productive under the conditions of early Earth?

I have argued elsewhere that when it comes to the third objective, origin-of-life researchers have had limited success, if any. Their frustration stems from a phenomenon called unwarranted researcher intervention (Rana 2011). This phenomenon, now acknowledged by a growing number of origin-of-life scientists, provides empirical evidence that life's origin arises from the work of an intelligent agent, pointing the way to one theistic approach to the origin-of-life question that allows the scientific community to entertain a role for the divine agency, while providing the means to scientifically investigate the origin-of-life question.

Researcher intervention and prebiotic chemistry

Under the best circumstances, humans would not need to intervene at all in prebiotic simulation studies. But this ideal is not realistic. Researchers have no choice but to involve themselves in the experimental design out of necessity. How else would the experiment be performed? Yet, when scientists do this, they assume the risk of no longer remaining passive observers. If not careful, these researchers can unwittingly become active participants in the prebiotic processes they seek to probe. This involvement can take place in each stage of the experiment:

1. design of the protocol
2. assembly of the experimental apparatus
3. supplying of the solvent and reagents for the experiment
4. adjustment of the initial conditions and their regulation throughout the study
5. monitoring of the course of chemical and physical changes, which usually requires withdrawing material from the apparatus.

Researchers involve themselves in these types of experiments to ensure that their results are reproducible and interpretable. If researchers do not set up the experimental apparatus, adjust the starting conditions, add the appropriate reactants and analyse the product, then obviously the experiment would never happen. Utilising controlled conditions and chemically pure reagents is necessary for reproducibility and to make sense of the results. In fact, this level of control is essential for *proof-of-principle* and *mechanistic* prebiotic studies – and perfectly acceptable.

In other words, the extent of researcher intervention in the design and execution of proof-of-principle experiments is irrelevant because the goal of this work is simply to determine whether certain physical and chemical outcomes are even possible – *in principle*. Researchers engaged in proof-of-principle studies are not immediately concerned with how realistic the experimental conditions are with respect to early Earth. They are merely trying to understand what is physically and chemically permissible. At the outset, researchers are often uncertain if a physical or chemical process is possible. They must try different experimental protocols, controlling and manipulating variables to make this determination. If an experiment fails, it does not necessarily mean the process in question is impossible from an evolutionary standpoint; it may mean that the researchers have not discovered the specific conditions required to support the process. On the other hand, if the experiment is successful, it does not necessarily *explain* a stage in the origin of life; it only shows that the physicochemical process to achieve that stage is possible.

When it comes to mechanistic studies, researchers' influence on the outcome cannot be avoided. In fact, the more the researchers are involved, the better, even though it may seem counterintuitive at first. The goal of origin-of-life research is to explain how life could have emerged via unguided processes. And, typically, the more researchers involve themselves in the design and execution of an experiment, the more artificial and unrealistic results become. However, only by the elaborate design and deliberate manipulation of experimental conditions can scientists tease out the critical mechanistic features of the process under investigation. As with proof-of-principle experiments, researcher intervention is irrelevant in mechanistic studies. When researchers perform these types of investigations, they are not immediately concerned with the likely conditions and available resources on early Earth and how they relate to the process. Instead, researchers are seeking detailed insights into the physics and chemistry of the processes. Ironically, these efforts are critical for assessing whether the proposed physicochemical pathway to the origin of life is relevant to early Earth's conditions and supports the notion of chemical evolution.

Again, researchers must be careful to avoid conflating success in *proof-of-principle* experiments and *mechanistic* studies with gaining support for abiogenesis. This support can only come after evaluating the geochemical relevance of these physicochemical processes.

When it comes to the final objective of prebiotic chemistry, *geochemical relevance*, the controlled laboratory conditions become a liability. The necessary researcher intervention can easily become unwarranted. Of course, the conditions on early Earth were uncontrolled and complex. Chemically pristine and physically constrained conditions did not exist. And, of course, scientists were not present to oversee the processes and guide them to the desired end. It is rare for prebiotic simulation studies to fully take the actual primordial conditions into account in the experiment design. It is seldom that origin-of-life investigators acknowledge this limitation. This complication means that many prebiotic studies designed to simulate processes on early Earth seldom accomplish anything of the sort because of excessive researcher intervention.

When origin-of-life scientists explore the implications of their experimental results for chemical evolution scenarios, researcher involvement is seldom acknowledged, let alone properly assessed. Chemists Charles Thaxton, Walter Bradley and Roger Olsen expressed concern about unwarranted researcher involvement as early as the 1980s (Thaxton, Bradley & Olsen 1984). I echoed this concern in 2011 (Rana 2011). Remarkably, these issues have been largely ignored in print – until recently.

Almost a decade after I expressed unease about unwarranted researcher involvement in prebiotic simulations studies, Clemens Richert, an origin-of-life researcher from the University of Stuttgart in Germany, raised this same concern in a commentary article (2018). He agrees that origin-of-life investigators rarely offer a clear and proper assessment of geochemical relevance when they report the results of their prebiotic simulation studies (Richert 2018). Richert's concern serves as an important first step towards more realistic prebiotic simulation studies and points the way for caution when interpreting the results of these studies. Hopefully, it will also lead to a more circumspect assessment about the relevance of these kinds of studies when it comes to accounting for the various steps in the origin-of-life process.

Unwarranted researcher involvement renders prebiotic studies artificial to the extent that this work no longer reflects actual evolutionary events that could have conceivably transpired on early Earth. Instead, these efforts reflect what is possible only when a researcher – an intelligent Agent – manipulates physicochemical processes towards a prescribed end.

Two theistic models for the origin of life

Unwarranted researcher intervention does not bode well for chemical evolutionary models. Yet, if we are willing to set aside the demands of methodological naturalism, it appears that unwarranted researcher involvement may point us towards an unexpected solution to the origin-of-life problem. In other words, when the constraints of methodological naturalism are relaxed, one could reasonably conclude that the last seven decades of work in prebiotic chemistry provides experimental evidence that agency played a significant role in the emergence of life on Earth.

Researcher intervention and the hand of God

One issue Richert fails to address in his commentary is the consequence that results because of the fastidiousness of many of the physicochemical transformations deemed central to chemical evolution. This fastidiousness has been discovered through mechanistic studies. In other words, these putative prebiotic processes are only possible – even under the most optimal laboratory conditions – because of human intervention. The researcher creates the just-right set of conditions in the laboratory for the reaction to proceed successfully. As a corollary, these processes would be unproductive on early Earth. They often require chemically pristine conditions, unrealistically high concentrations of reactants; controlled order of additions; regulated temperature, pH, salinity levels, etc.

As Richert (2018) states:

> It's not easy to see what replaced the flasks, pipettes, and stir bars of a chemistry lab during prebiotic evolution, let alone the hands of the chemist who performed the manipulations (and yes, most of us are not comfortable with the idea of divine intervention). (p. 2)

Even though origin-of-life scientists do all they can to eschew a Creator's role in the origin-of-life, could it be that abiogenesis required the hand of God – divine intervention?

This proposal follows from laboratory studies in prebiotic chemistry and the consistent demonstration that researchers play an indispensable part in the success of prebiotic simulation studies. It is becoming increasingly evident that the hand of the researcher serves as the analogue for the hand of God. Or as evolutionary biologist Simon Conway Morris (2003) so aptly states:

> Many of the experiments designed to explain one or other step in the origin of life are either of tenuous relevance to any believable prebiotic setting or involve an experimental rig in which the hand of the researcher becomes for all intents and purposes the hand of God. (p. 41)

In other words, intelligent agency is an indispensable feature of prebiotic simulation experiments in the lab, whether origin-of-life researchers like it or not and, by extension, we should expect this reality to be in effect on early Earth. This recognition provides empirical evidence that a Creator must have intervened to bring about the origin of life (and biochemistry). Ironically, the experiments designed to bolster a purely materialistic evolutionary explanation for the origin of life provide empirical evidence that intelligent agency played a role in the genesis of life. Clearly, this conclusion paves the way to introduce teleology into origin-of-life research and can have metaphysical implications. It is where the data take us.

Hypernaturalism and prebiotic chemistry

It is safe to say that a growing number of scientists would agree with the concerns about the relevancy of prebiotic chemistry – yet they reject any suggestion that life's origin reflects the work of a divine agent (Archer 2001). They regard an appeal to agency as a strict violation of the tenets of methodological naturalism. To address these concerns, the concept of hypernaturalism, proposed by Old Testament scholar Daniel J. Dyke and physicist Hugh Henry is helpful (Henry & Dyke 2018). Like most scientists, Henry and Dyke eschew the concept of supernaturalism, which they argue has the Creator operating outside the laws of nature. In contradistinction, they advance the concept of hypernaturalism. This is the idea that God operates *within* the laws and phenomena of nature in an extraordinary manner with respect to timing, location and magnitude.

Using the concept of hypernaturalism, the opposition between natural process chemical evolution and divine agency largely dissipates. Instead, in this framework, the origin of life can be viewed as a hypernatural processes in which God made use of physicochemical mechanisms to affect the origin of life. In this schema, life's origin does not occur via the *suspension* of the laws and processes of nature but *through* them. The origin of life is a miracle, but one by which God *intervenes* within the laws of nature he created. Applying hypernaturalism to the origin-of-life scenario makes it possible to find common ground with research scientists holding to methodological naturalism.

Hypernaturalism engages another concern expressed by the scientific community, namely, that the appeal to agency (conceived as supernatural interference) obstructs the scientific process. If God created life 'supernaturally', then scientists have nothing to investigate. On the other hand, viewing the origin of life as the product of God's hypernatural action makes it possible for scientists to study the origin-of-life question within the context of modern-day science, even if life's emergence is a 'miracle'.

In essence, when origin-of-life researchers carry out prebiotic simulation experiments, they are behaving hypernaturally. By exerting control over the experimental setup and laboratory environment, they bring about extraordinary circumstances – within the constraints of nature's laws and natural processes – that make it possible for key steps in the origin-of-life pathway to transpire. Could it be that God worked as a divine organic chemist to originate life? It is provocative that the Judeo-Christian scriptures describe humans as made in God's image (Gn 1, vv. 26–27). If such is the case, then when we create – or when humans step into the laboratory to run a chemical reaction – are we mimicking, though imperfectly, the Creator?

Anthropic coincidences and prebiotic chemistry

More recent results in prebiotic chemistry make possible another theistic approach to abiogenesis that allows the scientific community to both entertain a role for the divine agency and continue scientific investigation (Rana 2019). These studies seem to indicate that plausible prebiotic reactions may be constrained by the laws of nature in the just-right (fine-tuned) way as to produce materials with the just-right chemical and physical properties needed for life. In other words, the cosmological anthropic principle, which defines the structure and design of the universe, may well manifest in the prebiotic reactions that conceivably took place on early Earth.

While investigating the origin of the Krebs cycle, the late origin-of-life researcher Harold Morowitz stumbled upon one of the first indications that anthropic coincidences manifest in prebiotic chemistry. The Krebs cycle (also known as the tricarboxylic acid cycle and the citric acid cycle) oxidises pyruvate from the glycolytic pathway producing carbon dioxide and water. This combustion of pyruvate releases chemical energy that is captured and used to drive the formation of NADH and $FADH_2$. Once formed, these two molecules transfer high-energy electrons into the electron transport chain. This chemical pathway uses these electrons to establish a proton gradient across the mitochondrial inner membrane. Through a process called oxidative phosphorylation, the proton gradient powers the formation of ATP molecules by the enzyme complex ATP synthase. This process requires molecular oxygen and generates over 90% of the ATP used by aerobic organisms.

The Krebs cycle is also a major component of central carbon metabolism. Many of the Krebs cycle's intermediates are used to produce compounds such as glucose, fatty acids, amino acids and nucleobases. The Krebs cycle is positioned as the key metabolic hub for intermediary metabolism, integrating many of the metabolic pathways in the cell.

Because Krebs cycle assumes a central role in intermediary metabolism and because of its nearly universal occurrence throughout the living realm, many origin-of-life researchers postulate that this metabolic pathway may have been one of the first to originate, predating the emergence of last universal common ancestor (LUCA). In fact, some origin-of-life researchers think that a primitive version of Krebs cycle appeared before the primitive genetic material and primitive cell boundaries. In other words, Krebs cycle functioned as an autocatalytic cycle that initiated abiogenesis. In other words, for some origin-of-life researchers, understanding the evolutionary pathway that led to Krebs cycle provides them with an important clue for solving the origin-of-life mystery.

As part of their work on the origin-of-life problem, Morowitz and a team of collaborators sought to identify the prebiotic compounds that could plausibly emerge under prebiotic conditions. They speculated that this list of compounds would yield insight that could help them determine whether the Krebs cycle could emerge spontaneously on early Earth (Morowitz et al. 2000). Morowitz' collaborators screened 3.5 million entries in Beilstein's compendium of organic compounds, eliminating compounds through a set of rules that reflect realistic physical and chemical constraints relevant to early Earth's prebiotic conditions. They identified relatively low molecular weight compounds that (1) consist of carbon, hydrogen and oxygen, (2) are water soluble and (3) possess either aldehyde or ketone functional groups. The team excluded compounds with high heats of combustion, compounds that were chemically unstable and compounds that contained functional groups that would be difficult to generate under plausible prebiotic conditions. Applying this filter, they winnowed the 3.5 million Beilstein entries to 153 compounds, which included all 11 of the Krebs cycle intermediates. Morowitz and his team concluded that the compounds that constitute the Krebs cycle are emergent features that arise naturally out of the properties of carbon chemistry and prebiotic conditions. They speculated that Krebs cycle intermediates may well be a unique set of molecules.

Extending the work of Morowitz and his colleagues, a team of French researchers discovered that they could generate 9 of the 11 Krebs cycle intermediates from pyruvate or glyoxylate in water held under an inert atmosphere at 70 °C in the presence of the ferrous ion (Muchowska, Varma & Moran 2019; Pascal 2019). This set of conditions simulates mild hydrothermal vent conditions on early Earth. Hydrothermal vents could have plausibly produced pyruvate and glyoxylate. Both compounds are stable in water with a propensity to form carbon-carbon bonds.

Remarkably, a team of investigators from Furman University and the Scripps Institute demonstrated that all the ingredients for a precursor to the Krebs cycle are generated from glyoxylate and pyruvate in a single reaction vessel under mild temperatures and pH conditions without the need for metal catalysts (Stubbs et al. 2020). They discovered that the reaction sequence proceeded in the same order as the reverse Krebs cycle. They also discovered that the components of the sequence could be converted into amino acids via a transamination reaction.

Collectively, these results suggest that the Krebs cycle is not necessarily the product of a contingent evolutionary history but arises out of the dictates of carbon chemistry and the geochemical conditions of early Earth. As origin-of-life researchers Eric Smith and Harold Morowitz argue:

The chart of intermediary metabolism has a universal anabolic core, which should not be understood as merely a result of common ancestry but rather as a solution imposed on early life within the energetically structured environment of the early earth by details of carbon chemistry and carbon transportation functions performed only by biomass (Smith & Morowitz 2004).

It is highly suspicious to note that (1) the constraints that arise out of the geochemical and geophysical settings of the early Earth, (2) the physicochemical constraints that arise out of carbon chemistry and (3) the interplay between organic compounds and water conspire to spontaneously generate the Krebs cycle intermediates. These physicochemical constraints produce a set of just-right metabolic intermediates that organise into highly optimal metabolic routes. There appears to be a set of anthropic coincidences associated with the origin of Krebs cycle. It is eerie.

A study from Tokyo's Earth-Life Science Institute (ELSI) further builds the case that anthropic coincidences define prebiotic chemistry. The ELSI investigators hoped to gain a better understanding of the optimality of the canonical set of protein amino acids and the evolutionary origin of the canonical set (Ilardo et al. 2019).

Towards this end, the researchers constructed random sets of amino acids from a library of 1913 amino acids (including the 20 that make up the canonical set). They varied the set sizes from 3 to 20 amino acids and evaluated the capacity of the random sets to support (1) the folding of protein chains into three-dimensional structures, (2) protein catalytic activity and (3) protein solubility. They learned that if a random set included even one canonical amino acid (CAA), it dramatically outperformed random sets of the same size without any CAA. The researchers concluded that each of the 20 amino acids used to build proteins displays highly unusual properties that make each one perfectly suited for their biochemical role. From an evolutionary standpoint, the ELSI researchers believe that these results shed light onto how CAAs emerged. Because of the unique functional properties of the CAAs, the researchers speculate that (Ilardo et al. 2019):

> [*E*]ach time a CAA was discovered and embedded during evolution, it provided an adaptive value unusual among many alternatives, and each selective step may have helped bootstrap the developing set to include still more CAAs. (n.p.)

In other words, whenever evolutionary processes stumbled upon a CAA and incorporated it into nascent biochemical systems, the addition offered such a significant adaptive advantage that the CAA became instantiated into the biochemistry of the emerging cellular systems. Over time, members of the canonical set would become incorporated, one by one, into the evolving amino acid set, eventually culminating in the canonical set.

Further support for this scenario comes from their observation that some of the CAAs seem to play a more important role optimising smaller sets of amino acids, some play a more substantial role optimising intermediate-size sets of amino acids and others play a more prominent role optimising larger sets. They speculate that this difference may point to the evolutionary sequence by which amino acids were added to the expanding canonical set of amino acids as life emerged.

The ELSI researchers argue that no matter the evolutionary starting point, the pathways will all converge at the canonical set of amino acids because of the amino acids' unusual adaptive properties. That is to say, CAAs are not the outworking of historically contingent evolutionary process but seem to be prescribed fundamentally by the laws of nature. For this reason, the constraints imposed by the laws of nature that imbue the canonical set with the just-right properties for life would force the same evolutionary outcome time and time again. One of the study's authors, Rudrarup Bose, suggests, 'Life may not be just a set of accidental events. Rather, there may be some universal laws governing the evolution of life' (Tokyo Institute of Technology 2019).

This study raises the prospect that at least some of the endpoints of chemical evolution have been preordained by the very design of the universe itself – and, by extension, the Mind behind the universe.

Even if one adopts an evolutionary perspective on life's origin, for scientific reasons alone it becomes increasingly reasonable to think that an Agent is responsible for jimmy-rigging the process to a predetermined endpoint. It looks as if this Agent purposed for life to be present in the universe and structured the laws of nature so that, in this case, the uniquely optimal canonical set of amino acids would inevitably emerge. This jimmy-rigging is scientifically detectable, bringing agency into the scientific arena.

Along these lines, it is provocative to also consider other types of prebiotic chemistry that could have transpired on early Earth. Origin-of-life investigators have discovered chemical processes that could have – in principle – generated amino acids (the Strecker reaction), sugars (the formose reaction), fatty acids (the Fischer-Tropsch reaction) and nucleobases and nucleotides (the Sunderland reaction). It is remarkable that these processes produce all the necessary building blocks for life. Could these physicochemical processes also reflect a type of prebiotic anthropic principle? The work of origin-of-life researchers from the Polish National Academy of Sciences supports this possibility.

These investigators developed and deployed a computer algorithm (called Allchemy) to perform computer-assisted organic chemistry designed to mimic the earliest stages of chemical evolution. In effect, they performed an *in silico* Beilstein reaction with some rather intriguing results (Wolos et al. 2020).

Using Allchemy, the researchers identified reactions and products that formed under plausible prebiotic conditions. They initiated the computer-assisted reactions, beginning with an original set of reactants that included hydrogen sulphide, water, ammonia, nitrogen, methane and hydrogen cyanide, assuming that these small molecules would have been present on early Earth. After the reactions reached completion, the researchers eliminated any products with an 'invalid' chemical structure. They then incorporated the remaining products into the original set of starting compounds and repeated the computer-assisted reactions. They reiterated this process a total of seven times.

For each generation of reactions, the researchers relied on a set of 614 rules to 'compute' reaction pathways and products. They developed these rules by encoding into the algorithm all the known prebiotic reactions published in the scientific literature. They also encoded plausible conditions of early Earth into the algorithm. The researchers also took into account incompatible chemical functional groups. They discovered that it was possible to group these 614 rules into 72 chemical reaction classes. The algorithm began each generation of reactions by identifying suitable reactants for each class of reactions and then ‘reacting’ them to discover the types of products that would form.

Through the course of seven generations of reactions, Allchemy produced almost 37 000 chemical compounds. Yet, of these compounds, only 82 were biotic. And, of this collection, 41 were peptides (formed when amino acids react together to form an adduct).

The biotic compounds had some unusual properties that set them apart from the vast collection of abiotic molecules. They learned that the biotic compounds tend to:

1. be more thermodynamically stable
2. display less hydrophobicity
3. harbour fewer distinct functional groups
4. possess fewer reactive functional groups
5. have a balanced number of functional groups distributed between hydrogen-bond donors and acceptors.

The researchers also discovered that many of the biotic compounds could be produced through several distinct pathways. In other words, they observed synthetic redundancy for the biotic compounds. They learned that they could eliminate nearly half of the 72 reaction classes from the algorithm and still generate all 82 biotic compounds. In contrast, the abiotic compounds lacked synthetic redundancy. For the abiotic molecules, the research team discovered that they could eliminate only eight of the reaction classes and still generate the same suite of abiotic molecules.

The researchers also discovered that some of the compounds generated by the *in silico* reactions – such as formic acid, cyanoacetylene and isocyanic acid – served as synthetic hubs that give rise to a large number of additional products. It is quite possible that the existence of these reaction hubs contributes to the synthetic redundancy of the biotic compounds.

The researchers discovered that through the course of seven generations of chemical synthesis, the Allchemy algorithm produced all the prebiotic reactions reported in the scientific literature, to date. The algorithm also yielded prebiotic reactions that have yet to be discovered by origin-of-life researchers. The research team demonstrated the validity of these pathways, discovered *in silico*, by successfully executing these same reactions in the laboratory.

The team from the Polish National Academy of Sciences also discovered emergent properties that manifested after seven generations of *in silico* prebiotic reactions. Surprisingly, some of the reaction products themselves, in turn, had the capacity to catalyse additional chemical reactions.

This unexpected catalytic activity substantially expanded the range of prebiotic reactions. Reaction cycles and reaction cascades also emerged. Remarkably, the reaction cycles displayed the property of self-regeneration. In fact, after seven generations, the chemical space of the prebiotic reactions became densely populated with reaction cycles. Surfactants, such as fatty acids, also emerged. They also discovered peptides with surfactant properties. Both of these types of compounds can form vesicles that can encapsulate materials to yield protocellular structures.

The implications of this work are intriguing. Even if one concedes that life did have an evolutionary origin, once again, it is impossible to escape the necessary role an agent must have played in the appearance of the first life on Earth. It is provocative that the 82 biotic compounds that formed – a small fraction of the nearly 37 000 compounds generated by the *in silico* reactions – all share a suite of physicochemical properties that make these compounds unusually stable and relatively unreactive. These qualities cause these materials to persist in the prebiotic setting. It is also intriguing that the generation of these 82 compounds is characterised by synthetic redundancy. It is quite fortuitous that these compounds possess the just-right set of properties – many of which overlap with the set of properties that distinguish them from the vast number of abiotic compounds – that make them ideally suited to survive on early Earth and also make them useful as building block materials for life.

In other words, there appear to be constraints on prebiotic chemistry that inevitably lead to the production of key biotic molecules with the just-right properties that make them unusually stable and ideally suited for life. This remarkable coincidence suggests a fitness for purpose to prebiotic chemistry. To put it another way, there appears to be a teleology to prebiotic chemistry, suggesting that the laws of physics and chemistry may well have been rigged at the onset to ensure that life's building blocks naturally emerge under the conditions of early Earth. Could it be that this coincidence reflects the fact that a Creator is behind it all?

■ Conclusion

Origin-of-life investigators have proposed a rich array of ideas and models based on chemical evolution scenarios. Yet, this materialistic approach has yielded little true insight into the process of abiogenesis. A growing minority of scientists and philosophers now entertain the possibility that a teleological approach, which appeals to the work of an intelligent agent, may lead to a solution to the origin-of-life problem.

Most scientists strongly resist any suggestion that life's origin stems from the work of God. They regard an appeal to agency as a violation of the key tenet of methodological naturalism. With this concern at the forefront, I advanced two theistic approaches to the origin-of-life question that make it possible to entertain a role for divine agency while providing the means to investigate the origin-of-life question scientifically. One of these approaches arises out of the recently acknowledged problem of unwarranted researcher involvement in prebiotic chemistry and the other stems from some provocative work that suggests the anthropic principle may manifest in prebiotic chemistry.

It is remarkable to me as a biochemist and a Christian that the more we gain insight into the origin-of-life question the more the evidence points to the necessity of a Creator, whether the Creator chose to intervene directly to create the first life forms or whether he rigged the universe in such a way that life would inevitably emerge because of the design and constraints imposed by the laws of nature (Rana 2020).

Chapter 6

Are present proposals on chemical evolutionary mechanisms accurately pointing towards the first life?

James M. Tour
Carbon Nanotechnology Laboratory,
Rice University,
Houston, Texas, United States of America

Introduction[44]

Abiogenesis is the prebiotic process wherein life, such as a cell, arises from non-living materials such as simple organic compounds. Long before evolution could even begin, the origin of the first life, that first cell, would have arisen from some simpler non-living molecules. On Earth, the essential molecules for life as we know it are carbohydrates (also called sugars or saccharides),

---

[44] This chapter represents a substantial reworking (adapted and abridged), by permission of the editor, from Tour (2016, 2019). Images are adapted with permission from the American Chemical Society. The author thanks Paul Nelson for helpful insights. Walt Shaw and Steve Burgess of Avanti Polar Lipids kindly provided information on lipid bilayer assemblies. See also Tour (2017).

How to cite: Tour, JM 2022, ‘Are present proposals on chemical evolutionary mechanisms accurately pointing towards the first life?’, in F van Niekerk & N Vorster (eds.), *Science and Faith in Dialogue,* in Reformed Theology in Africa Series, Vol. 10, AOSIS Books, Cape Town, pp. 149–174. https://doi.org/10.4102/aosis.2022.BK334.06

nucleic acids, lipids and proteins (polymers of amino acids). Described in this chapter is the process by which organic synthesis is performed and the considerations that are generally required to synthesise a complex system where many molecular parts come together to operate concertedly. This will be demonstrated in the synthesis of nanomachines. Then some proposals that others have espoused for the synthesis of carbohydrates and carbohydrate-bearing nucleotide bases will be considered, from a prebiotic milieu. The obstacles to the much more difficult task of having the molecular building blocks assemble into a functional system will be briefly mentioned. The scientifically unknown entities that have been proposed to have seeded life on Earth, such as a design agent or panspermia are not considered. An opinion showing that the strongest evidence against the proposals of current prebiotic research is the researchers' own data will be rendered. The current proposals can prevent the discovery of scientific solutions in the field as they seem to be directing researchers down paths of futility despite hyperbolic claims to the contrary.

Any account of the origin of the first form of life must include a mechanism for the generation of the chemicals needed for life and then for how life arose from those pre-existing non-living chemicals. Abiogenesis proposals attempt to explain how chemical processes transformed pre-existing non-living chemicals into more complex information-bearing molecules such as DNA, RNA and proteins. For an account of the origin of life to be realistic, there must be chemical processes that can successfully arrange simple organic compounds into complex biologically relevant macromolecules and living cells. Life requires carbohydrates, nucleic acids, lipids and proteins. But what is the chemistry behind their origin? What is the origin of metabolism, or of the information-storage and processing systems that depend on these complex biochemical compounds?

Working in synthetic chemistry, building relatively simple nanomachines, has led to being sceptical of proposals for the origin of the requisite chemical building blocks necessary for life.[45] Some biologists seem to think that there are well-understood prebiotic molecular mechanisms for the synthesis of carbohydrates, proteins, lipids or nucleic acids. They have been grossly misinformed.[46] Others think that, if not yet known, such chemical pathways will soon be identified. To me, these biologists are naively optimistic. What they hope for will not happen anytime soon.

---

[45] Synthetic chemistry involves the design and making of molecules in a laboratory. Nanotechnology is the study, design and fabrication of matter wherein at least one of the matter's axes is in the 1–100 nanometer size region.

[46] Prebiotic chemistry relates to the chemistry that occurred on Earth prior to life or in a pre-biological world. The conditions of such a world are not known but are supposed to be rich in an atmosphere of dinitrogen and ammonia, water and simple organic compounds such as carbon dioxide, formaldehyde and methanol. Inorganic compounds such as metal oxides and metal salts are also presumed to have been abundant. In the context here, 'prebiotic' has nothing to do with the recent use of the term prebiotics, which is taken to mean a nondigestible food or food ingredient that promotes the growth of beneficial microorganisms in the intestines.

And no wonder: few biologists have ever synthesised a complex molecule *ab initio*. Experience with organic synthesis leads to suggesting that chemistry acting on its own simply does not do what it would need to do to generate the biologically relevant macromolecules, let alone the complex nanosystems in a living cell. The reasons for this scepticism are further explained in more detail.

Lessons from synthetic chemistry

Designing molecules

The process of molecular design and synthesis in general, what it takes to successfully build a molecule to perform a particular function is discussed at the start.

The initial design is important. Sometimes molecular designs are computer-assisted, but more often than not, the initial steps are noted on paper. A target must first be drawn or otherwise designated. This is no trivial task. In some cases, chemists have seen the target in a related system; in other cases, they guess the target's properties on the basis of its molecular weight, its shape, the moieties appended to the main backbone and its functional capacities.

Once a target is selected, retrosynthesis is next, whether on paper or on a computer screen. Placing the target at the top, the chemist draws an inverted tree (or graph), one step down at a time, into multiple branch points, until a level where starting materials are at hand is reached.

The inverted tree is then pruned. Certain branches lead to dead-ends. They are lopped off. Further refinement of various routes leads to a set of desired paths; these are the routes that can be attempted in the laboratory.

Given a target and a path to get there, the synthetic chemist must now try a number of chemical permutations. Each step may need to be optimised, and each step must be considered with respect to specific reaction site modifications and different reaction rates.

What is desired is often ever so slightly different in structure from what is not. If Product A is a mirror image of Product B, one left-handed and the other right-handed, separation becomes a time-consuming and challenging task, one requiring complementary mirror-image structures. Many molecules in natural biological systems are homochiral, meaning only left-handed or right-handed molecules are used, not both. Their mirror images cannot do their work.

In addition, few reactions ever afford a 100% yield; few reactions are free of deleterious by-products. Purification is essential. If by-products are left in the reaction, they result in complex mixtures that render further reactions impossible to execute correctly.

After purification, a number of different spectroscopic and spectrometric methods must be used to confirm the resulting molecular structures. In case the wrong molecular intermediate is made, the synthetic chemist quickly learns, and all subsequent steps are compromised.

Finally, intermediate products are often unstable in air, sunlight or room light or water. Synthetic chemists must work in seconds or minutes to prevent destructive natural processes or chemical reactions from taking over.

Building nanovehicles

As an example of what it takes to synthesise organic compounds, consider the synthesis of a molecular machine, a nanovehicle, a simple unimolecular structure that can translate itself along a surface when supplied with thermal or photonic energy. The author and his colleagues make these relatively simple machines in the laboratory, and what has been learned about synthesising nanovehicles has been published in numerous peer-reviewed papers (Chiang et al*.* 2012; Morin, Shirai & Tour 2006; Shirai et al*.* 2006).

The authors aimed to design 'nanotrucks' and 'nanocars' that can move across gold surfaces. They consist of three basic molecular mechanical parts: fullerene wheels,[47] a chassis made of fused aromatic rings or oligo(phenylene ethynylene)s (OPEs) and alkynyl axles (see Figure 6.1 [a & b] for trucks and [d & e] cars).

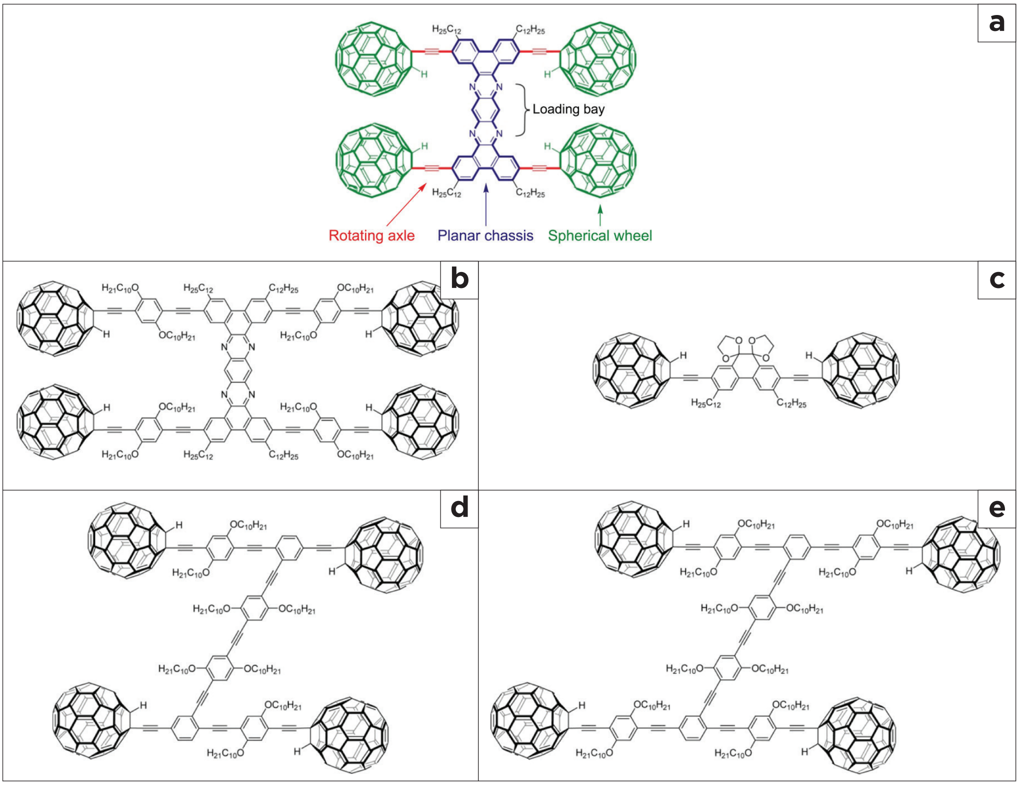
The first molecular-sized machine that incorporated mechanical components, such as wheels and axles, with movement at the single molecular level was developed.[48] The rolling motion of these nanocars resembled the rolling motion of macroscopic cars.

Two different kinds of nanovehicles were built: a rigid structure in nanotrucks (Figure 6.1 [a & b]), the precursors along the synthetic route to these compounds such as 1c and a semi-rigid structure in nanocars (Figure 6.1 [d & e]). All these designs were necessary because it was discovered along the process that better flexibility of the chassis structure combined with the increased number of alkyl units dramatically increased the solubility of the fullerene-wheeled structures, in the organic solvents in which they were synthesised.

---

[47] The name 'fullerene' was coined by Richard Smalley when he co-discovered the geodesic dome–shaped molecule, which looked like architectural structures designed by the architect Buckminster Fuller.

[48] Single-molecule-sized nanoscale machines with controlled mechanical motion had already yielded a variety of molecular machines resembling macroscopic motors, switches, shuttles, turnstiles, gears, bearings and elevators; but these nanomachines were operated and observed spectroscopically as ensembles of molecules in solution or solid state. Some examples where a molecule has a mechanical design and the mechanism of movement can be probed at the single molecular level are cyclodextrin necklaces, altitudinal molecular rotors, molecular barrows, molecular landers and nanowalkers. The nanocars have taken this research field to a more complex level in the study of motion at the single molecule level.



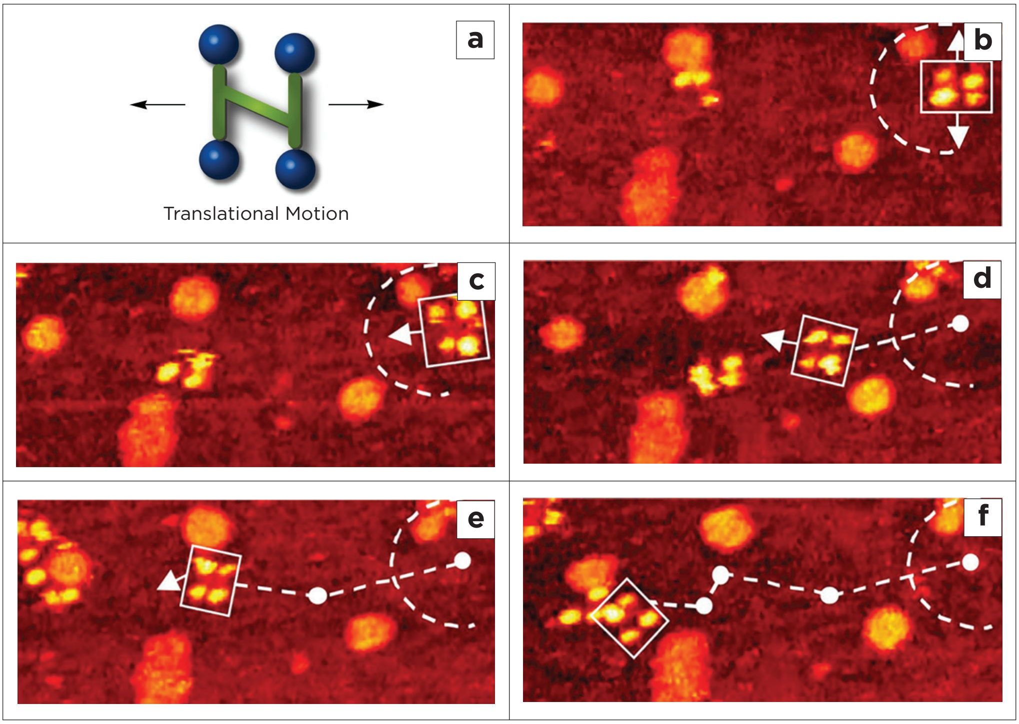
Source: adapted from Tour (2016), published with the appropriate permissions by the American Chemical Society.

FIGURE 6.1: Nanotrucks and nanocars.

The process was not straightforward. Firstly, a way to attach fullerene wheels (a 60-carbon sphere) to the alkynyl axles, then a way to build a chassis of the appropriate structure and attach the axles to the chassis had to be worked out. New reactions under new conditions had to be worked out in each case. For the nanotrucks, the first and second structures proved unworkable because of the stiffness of the chassis and insolubility. The chassis design was then modified: a semi-rigid Z-shaped chassis for nanocars remedied the difficulties. The first nanocar structure was still too insoluble to properly purify, but the nanocar 1e (the fourth overall design) could finally be adequately purified and characterised (i.e. its molecular structure could be determined) for further study. Notice that all this design and experimentation required considerable knowledge and skill. Yet even with all these efforts, the properties of each design could not be predicted *a priori*, and as problems were encountered, things had to be restarted and redesigned repeatedly.

In addition, many reagents were purchased to use in this protocol – otherwise the protocol would need to include steps for their synthesis and purification as well. Pre-treatment of solvents was needed so that the system would not be contaminated by impurities such as oxygen, which retard or mitigate the desired reactions. Purification was required at each step as the chemistry rarely affords the chemist materials that are of sufficient purity for use in subsequent steps. Each product needed a different purification protocol. Nature would not have this luxury as it moves towards the molecules needed for the first life or that the first living cell.

With nanocar 1e, it was possible to demonstrate the action of the fullerene-wheel architecture at the single-molecular level. Evidence for thermally induced wheel-assisted rolling motion in the nanocar 1e on gold was obtained by scanning tunnelling microscopy (Figure 6.2).



Source: Morin et al. (2006), published with the appropriate permissions.

FIGURE 6.2: Thermally induced motion of four-wheeled nanocar 1e (a) as imaged by scanning tunnelling microscopy (b–f).[49]

---

[49] Note: Consider this point when thinking about the origin of life: The molecular machines and the information processing system that cells use to synthesise macromolecules are far more complicated than anything illustrated here. Designing nanocars is child's play in comparison to the complex molecular machinery and information-processing systems at work in the synthesis of proteins, enzymes, DNA, RNA and polysaccharides, let alone their assembly into complex functional macroscopic systems – a point that has become increasingly apparent to me as we have learned more about how difficult it is to build and improve our relatively simple nanocars.

The work just described is merely a brief sketch of the processes used to synthesise the nanocars. The details are far richer (Shirai et al. 2006).

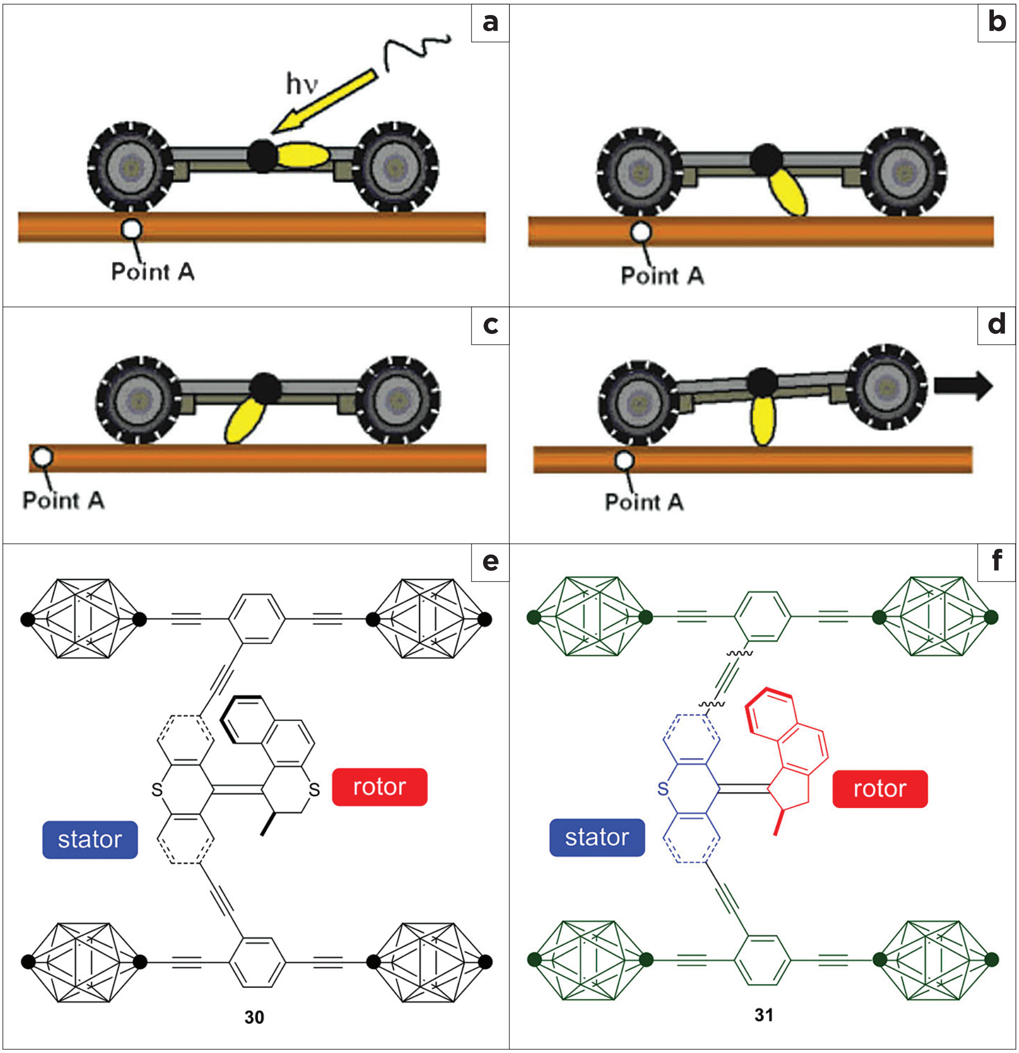
Cars with motors

The first-generation vehicles operated without motors (Abendroth et al. 2015; Astumian 2001; Balzani, Credi & Venturi 2008; Browne & Feringa 2006; Chiang et al. 2012; Morin et al. 2006; Kay & Leigh 2015; Vives & Tour 2009). Later, motorised versions that were more complex to design and synthesise were made (Chiang et al. 2012). The motors are ultraviolet-light-active; they rotate unidirectionally. The first motorised versions that were made rotated at 1.8 revolutions per hour. Too slow. But with a redesign, which took us back to step one in the synthesis, a light-activated nanocar whose motor spins at 3 MHz was achieved (3 million rotations per second) (Figure 6.3; Morin et al. 2006). Fast enough.

The plan to synthesise the fast nanocar (Figure 6.3f) involved a modular approach in which the coupling of the axles and the stator represented the last step. In the following indented paragraph, the description of the motor's synthesis is presented in its more technical form so as to highlight the many steps and specialised conditions: According to *Scheme 1*, heating ketone 32 to reflux in an ethanol and hydrazine solution produced the rotor, hydrazone 33. The conversion of ketone 34 into thione 35 was improved by decreasing both the concentration and the reaction time from those in the published procedure. The generation of the sterically hindered double bond between the rotor and the stator utilised Barton–Kellogg coupling. Hydrazone 33 was oxidised to the unstable diazo intermediate 36 using manganese dioxide by careful temperature control. The inorganic residue was removed by filtration in a setup that enforced the strict exclusion of air, oxygen and moisture. Thione 35 was added to the deep purple filtrate. A [33+34] cycloaddition occurred and evolution of nitrogen gas indicated the formation of episulfide 37. The white solid episulfide 37 was then treated with trimethyl phosphite in a screw-capped tube at 130°C to yield the molecular motor 38 as a mixture of isomers. Isomers are chemical structures that have the same order of attachment of atoms, but different three-dimensional structures.

Slow to fast

Consider the differences between motorised slow and fast nanocars (Figure 6.3). A small change in the rotors had an enormous impact on the rate of their unidirectional rotation, 1.8 revolutions per hour for the slow nanocar and 3 million rotations per second for the fast nanocar. The rotor portion in the slow nanocar has a six-membered ring bearing a sulphur atom, and the fast motor nanocar has a five-membered ring bearing all carbons. What was involved in going from the slow to the fast nanocar?



Source: Chiang et al. (2012) and Morin et al. (2006), published with the appropriate permissions.

FIGURE 6.3: (a–d) show the scheme of light actuation of the motor so that it acts as a paddlewheel to propel the nanocar along a surface. (e and f) show the structures of the slow (nanocar 30) and fast (nanocar 31) motorised nanocars. These nanocars have para-carborane wheels, for reasons that will become apparent.[50]

---

[50] Notice all the places where the chemist was actively involved in carefully controlling reaction conditions. Scheme 1 illustrates the compounds and steps involved.

The final assembly of the fast nanocar (*Scheme 2*) was attempted, but coupling between TMSA and motor 38 did not afford the desired bis-coupled product. A more reactive catalyst was used, but the result was disappointing because of a high degree of decomposition. By changing reagents and solvents again, a TIPS-protected bis-acetylene motor 39 was produced. The yield was excellent. Motor 39 had its TIPS groups removed, producing dialkyne 40 in quantitative yield. Dialkyne 40 and previously synthesised axle 41 were then coupled to produce the fast nanocar in moderate yield (*Scheme 2*, *Route I*). Next, a more convergent synthetic

Ketone 43 (see Figure 6.4) was used as the staring material for the slow motor and then ketone 32 (see Figure 6.4) was used for the fast motor.

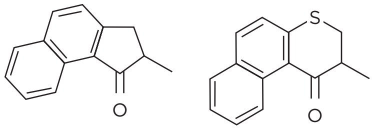
But ketones 43 and 32 are derived from entirely different starting materials. There is no known method to simply expunge the sulphur atom in motor 43 and obtain ketone 32.

It is all very easy on the blackboard, of course; one can simply erase atoms at will and show ketone 43 transforming ketone 32 (Figure 6.4). But chemistry does not happen that way. Even the oxidative expulsion of SO_2 from ketone 43 by the Ramberg–Bäcklund method would not work, as the sulphur is bound aromatically.

Ketone 43 can be left in a flask for millions of years and it would still not form ketone 32 by any known or rational thermal, reductive, photochemical or enzymatic method. This is not unusual when related compounds have clearly different starting points in organic chemistry. It is typical.

Wheel changes

Why were the fullerene wheels from nanocars in Figure 6.4 changed to the carborane-wheeled motorised nanocars in Figure 6.3 (e & f)? Because this had to be done. There is no way to achieve motor functionality in motorised nanocars using fullerene wheels. This was not know that until the motorised nanocars with fullerene wheels had already been built. This was learned later. It was disappointing to note that when the motors are photo-excited, they immediately transfer their energy to the fullerene wheels so that the motors do not rotate.



32 **43**

Source: Adapted from Tour (2016), published with appropriate permissions provided by the American Chemical Society.

FIGURE 6.4: Removal of the sulphur atom in ketone 43 can, in theory, directly result in ketone 32. Though it appears to be a simple process on paper using an eraser, there is no simple chemical methodology to effect that transformation.

(footnote 50 continues...)
pathway (*Scheme 2*, *Route II*) was tried using coupling between motor 38 and alkynylated axle 42 and applying conditions analogous to those for the synthesis of motor 39. The fast nanocar was thus obtained but in lower overall yield than that obtained from *Route I*.

This underscores a common occurrence in organic synthesis. Even with modular approaches, small changes in the structure of the reactants make for enormous differences in reactivity. There is no simple work around.

Thus, the wheels on the motorised cars had to be changed to carboranes as carboranes do not accept energy from the photo-excited motors.

The carborane wheels were not suitable for use on metal because of their low adhesion. But the carborane wheels worked well on glass; they have been extensively used to study nanocar motion on glass surfaces (Claytor et al*.* 2009; Chu et al*.* 2013; Khatua et al*.* 2010; Vives et al*.* 2010).[51]

Here is a summary of the process that led to functional nanocars, including further details about difficulties encountered:

1. Determine a target? Done. Molecular machines.
2. Insurmountable problems? Yes. The first generation of nanotrucks had insurmountable solubility problems. Although organic chemists have at least 50 widely differing solvents and solvent polarities from which to choose, no satisfactory solution could be found.
3. Start over? Yes, of course.
4. Redesign? Done. Molecular flexibility, specifically a less rigid chassis, was needed (nanocars *1b* to *1d*). When a motor was added to the nanocars, the former chassis proved insufficient. The intermediates had to be redesigned in order to affix the motors. Conveniently, all new intermediates could be stored in the freezer to prevent their decomposition while the motors were built and the published work of the Fer-inga group from the Netherlands could be accessed in order to build upon their initial designs. But even then, starting at step one for the motors, functional handles that would let them be accepted into the chassis and wheel assemblies had to be built. Only after constructing the new motors could it be learned that they were incompatible with the well-developed fullerene wheels because of energy-transfer problems.
5. Redo redesign? Yes. When it was desired to go from a slow motor to a fast motor, though the stator was reusable, the rotor was not. The rotor had to be redesigned, from step one, so as to become a faster unidirectional rotator.
6. And again? Of course. Once the wheels were changed to make them suitable to work with the motors, it was learned that the new wheels were not compatible with a gold surface. So, the glass surface had to be changed. The glass surface was not compatible with the imaging technique by scanning tunnelling microscopy (STM), which requires a conductive surface. Glass is an insulator.
7. Start from scratch? To image the nanocars on glass, a technique called single-molecule fluorescence microscopy (SMFM) had to be used, but another problem arose: the nanocars were not fluorescent. This meant

---

[51] A key point: parts are not always easily interchangeable without severe and unexpected consequences. When working environments change, drastic changes in molecular structure are often required to retain the system’s functions.

appending a fluorophore to the chassis. But first a new chassis to which the fluorophore appendage could be attached had to be re-synthesised. A pre-synthesised fluorophore could have been purchased from a chemical company. These bulky fluorophores slowed the nanocars. So, starting from scratch again, a chassis with fluorescent axles was built. These had to be built using an entirely different chemistry than we had used in the past cases. Sadly, motor energy transfer to the now fluorescent axles decreased the efficiency of the motors. Newer versions have motor excitation frequencies optically far-separated from the fluorophore excitation frequencies. What frequencies are to be targeted is known because we can record the optical spectra using UV-visible absorbance and emission spectroscopies.

8. Yes, but even the optimised yields were not quantitative (~100%). The first-time reaction yields were usually very low, sometimes as low as 0%. Only after repeated trials under different conditions could a yield range of 50%–60% be attained and sometimes not even that.

Most organic chemists would agree that even with extensive planning, 90% of reactions are failures. Substrates and conditions must be repeatedly modified to secure respectable and usable yields. At each step, a massive amount of time is spent on separations and optimisations. If by-products are permitted to accumulate, they can consume the new steps' reagents and alter the course of the reaction. After every one or two steps, there must be purification.

If all reactions had a near 100% yield, it would ease the separation problems. But this can take years to achieve if it is possible at all. And even then, sufficient atom efficiency is very rare. By-products from the other reagents fill the system. High atom-efficient reactions are even harder to achieve.

The loss of materials is expensive. In most cases, these by-products cannot be converted back to usable compounds in an efficient way. Developing a scrubber system for degrading these products back to usable starting materials would, in most cases, take more time and money than developing the original target synthetic routes themselves. The separated by-products are put into waste disposal containers and sent for destruction through combustion.

Unlike what would have been present in prebiotic times, resources available presently are plenty. Petrochemicals are used as our major feedstocks, and these come in enormous amounts from fine-chemical producers. Large amounts of energy come from power grids. There is also the convenience of ordering many of the requisite reagents to start our syntheses. The just-in-time (JIT) procurement system permits the availability of most chemicals at our doorstep within 18–24 h. Even so, detailed planning and logistics go into making sure all reagents and solvents and gases and glassware are ready for a day's lab work.

Solvents need to be pre-distilled before use as small impurities can promote or catalyse undesired side reactions. Intermediate molecules need to be premade and properly stored in a freezer away from light and oxygen to prevent their decomposition while the other segments of the synthesis are being done.

A rich chemical literature provides guidance on reaction types and conditions that are usable on similar molecular constructs although modifications are almost always needed as the substrates in a new synthesis are different. None of this would have been possible on the prebiotic earth.

As a further difficulty, reagent addition order is critical. A needs to be added before B and then C, and each at its own specific temperature to effect a proper reaction and coupling yield. The parameters of temperature, pressure, solvent, light, pH, oxygen and moisture have to be carefully controlled. Unless one can devise sophisticated promoters or catalysts that are stable in air and moisture and can work at common atmospheric conditions, precise control must be maintained. But making such ambient stable promoters or catalysts is more complex than just varying the temperature for the specific reagent or just putting the reaction in a carefully maintained atmospheric control box (dry-box) equipped with oxygen and moisture sensors, all maintained under a positive pressure of inert nitrogen gas.

It is not cheap. Once the desired product is synthesised, it can take much longer to properly characterise the product than it did to make it. Many tools, costing millions of dollars, are used to facilitate rapid molecular structure identification.

As teacher's is the great Scotch, water is the great solvent. But it is very difficult for for organic synthesis to be conducted in water. Highly oxygenated organic compounds are needed. The synthetic chemist must project the oxygenated groups out towards the water domain and project the non-oxygenated groups in towards each other, thus generating a hydrophobic domain. It is very hard to do.

By conducting the nanocar organic synthesis in organic solvents rather than in water, the difficulty is markedly lessened; it is a luxury that nature did not (and does not) enjoy. Starting from scratch, she would have had to design and redesign her structures, discarding the inevitable false starts and dead-ends as they occurred. Any prebiotic system is destined, at least some of the time, to crash and burn. How would nature know where to stop, or how to start over, with no goal in mind?

But whatever else she may have been doing in the prebiotic era, nature was not consulting the modern chemical literature.

Origin of life's building blocks

Life lessons for the prebiotic chemist

To illustrate that the problems described are not limited to exotic structures such as nanocars, the synthesis of foundational organic molecules needs to be examined: carbohydrates. Carbohydrates are the backbones of nucleotides, which in turn make up DNA and RNA. Carbohydrates also serve as 'recognition sites' for cells to communicate with each other and as food sources for living systems. The difficulties involved in conducting carbohydrate synthesis in a prebiotic environment parallel those found in making nanovehicles.

Consider the pentose sugars, carbohydrates with five-carbon atoms (Figure 6.5). These sugars have three stereogenic centres, so there are eight possible isomers. Some substructures are enantiomers (mirror images), others diastereomers (not mirror images); all are chiral. When chemical reactions are conducted, the reactions are designed to minimise diastereomeric mixtures that can be nearly impossible to separate. It is best to avoid the undesired diastereomers because their separation is too time-consuming and expensive.

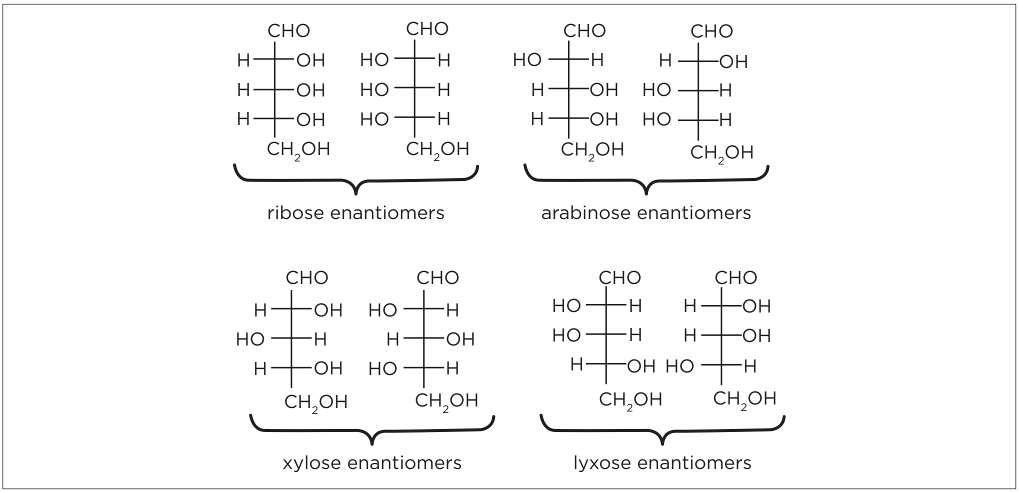
They waste a huge amount of starting material; they generate unwanted products. Enantiomeric separations are all the more difficult. Nature has apparently chosen a far harder route, using predominantly one enantiomer (homochiral), d-ribose, in a system with multiple stereogenic centres.

So how difficult would the synthesis of d-ribose be under prebiotic conditions?

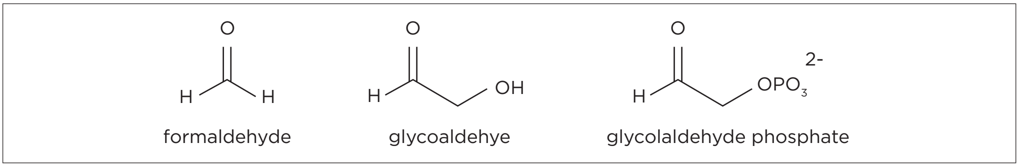
Albert Eschenmoser is a great synthetic chemist. He has spent years suggesting prebiotic routes to the five-carbon pentoses. Direct synthesis of ribose, he discovered, was not successful when starting with glycoaldehyde (Decker, Schweer & Pohlamnn 1982) using an old-fashioned formose reaction in which a base is catalysed with formaldehyde in the presence of a divalent cation such as calcium (Eschenmoser 2011; Eschenmoser & Loewenthal 1992).

To synthesise ribose, Eschenmoser had to make phosphorylated glycolaldehyde (glycoladehyde phosphate) (Figure 6.6) (Eschenmoser 2011).

Since glycolaldehyde is the dimeric form of formaldehyde, he first had to make the dimer of formaldehyde. Only then could there be further aldol chemistry in the formose reaction. A good organic chemist can design conditions that will isolate the product, purify it and then proceed. A very good organic chemist, this is what Eschenmoser did (Eschenmoser 2011).



Source: Adapted from Tour (2016), published with appropriate permissions provided by the American Chemical Society.
FIGURE 6.5: The eight pentose sugars showing the four sets of enantiomers depicted in Fischer projections.



Source: Adapted from (Tour) 2016, published with appropriate permissions provided by the American Chemical Society.
FIGURE 6.6: Three common starting materials in prebiotic chemistry research.

Can phosphorylation then occur? Yes, but only given a high concentration of a phosphorylating agent. It does not happen in the presence of the strong base required for the formation of the glycoaldehyde itself.

The glycoaldehyde needs a strong base to pump up the reaction, and then, to stop it dead, it needs to be separated from that strong base.

While in a near-neutral aqueous solution, and in the presence of magnesium ions, Eschenmoser phosphorylated glycoaldehyde with four molar equivalents of amidotriphosphate. Once phosphorylation was complete, and the glycolaldehyde phosphate isolated and purified, Eschenmoser then exposed glycolaldehyde phosphate to the very basic, 2N sodium hydroxide at a concentration of 0.08 moles per litre.

In other words, the formaldehyde started life in a strong base; its product was isolated and freed from the strong base and exposed to a neutral aqueous solution of amidotriphosphate (which the researchers made separately). That product, glycoladehyde phosphate, was then isolated and conveniently re-exposed to a strong base.

Even with this masterful design, the result was mostly undesired racemic hexose triphosphates. Using a stroke of superb synthetic insight, Eschenmoser placed the glycolaldehyde phosphate in the strong base and then added 0.04 moles per litre of formaldehyde to obtain a 40%–50% yield of mostly racemic pentose diphosphates (the mixture shown, but with two phosphates at C2 and C4 of each of the structures).

In that 40%–50% yield mixture, there were then eight possible isomers (four diastereomers): the desired racemic ribose-2,4-diphosphate (~15% of the total from the reaction), racemic arabinose-2,4-diphosphate, racemic lycose-2,4-diphosphate and racemic xylose-2,4-diphosphate (where racemic signifies a 1:1 mixture of the two enantiomers) along with 11 other identified carbohydrate species, all bearing their enantiomer partners. That meant 22 other identified species from the 40%–50%, with the remaining 50%–60% being unidentified nonvolatile compounds such as higher oligomers and polymers.

Even Eschenmoser did not attempt to separate out the desired, albeit still racemic, ribose-2,4-diphosphate. And for very good reason: it would have been nearly impossible.[52,53]

Also, time works against life. Over a mere 23 weeks, the desired diastereomer – the racemic ribose-2,4-diphosphates – was reduced from a 17% yield to a 7% yield. After a year, there would be very little left. In the laboratory, as anywhere else, it is essential to stop a reaction before the desired product degrades.

Of all the isomers, the one desired was not the most stable, even given the cleverly designed experiment that started with glycolaldehyde, and that was further intelligently and conveniently phosphorylated to the glycolaldehyde phosphate.

Racemic ribose-2,4-diphosphates degraded under the very controlled conditions under which they formed.

Eschenmoser writes that ‘the total amount of the four diastereomers is largely unchanged’, but his own data show that the combined yield of the four diastereomers dropped from 34% to 30% over the course of the additional 22 weeks, a relative 12% loss of the pentoses over 22 weeks (Eschenmoser 2011). After a few years, a brief moment in time in prebiotic terms, there would be few if any of the pentoses left, let alone the desired ribose-2,4-diphosphate.

---

[52] Biologists can easily imagine nature selecting the correct isomer because they work in a world that enjoys the specificity of biological systems. Not so synthetic chemists, who are bound to prebiotic molecules. Selected by what? No enzymes were yet available. The data more readily suggests that no prebiotic process is likely to yield the requisite carbohydrates.

[53] The most masterful synthetic chemists could produce only gross mixtures.

Where does the material go? It likely degrades to extended oligomers and polymers, a process common in organic reactions and especially common in extended aldol-based reactions.

Wish fulfilment

From a paper on prebiotic chemistry (Eschenmoser & Loewenthal 2011):

> Moreover, there was the well-known – but still no less remarkable – fact that in cellular biochemical processes, monosaccharides apparently never operate in the free state, but always in phosphorylated form. It is a short step from such considerations to the notion of a primordial scenario in which, again, phosphorylated and not simply neutral forms of carbohydrates would have been operative. In a self-organisation process in a primordial environment, it may have been of primary importance for carbohydrate molecules to escape chemical chaos, finding themselves instead at concentrations suitable for chemical reactions, and in reaction spaces that would facilitate efficient chemical transformation. With respect to both requirements, phosphorylated sugar molecules would, through their electrical charges, have offered advantages over neutral, water soluble carbohydrates in environments containing mineral surfaces or minerals with expandable layer structures. (p. 12424)

That short step is not short at all. Biochemical routes are far downstream and occur in far more complex scenarios. In the laboratory, phosphorylation requires precise control of phosphorylating agents. These hopeful but unlikely suggestions pain the synthetic chemist under any circumstance, but for some remarkable reason, they are tolerated in prebiotic chemistry.

Despite claims to the contrary, research on mineral surfaces has done little to solve the problem of overall yields or that of diastereo- and enantioselectivities (Pitsch et al. 1995). Reagent addition order is critical. An abiogenetic pathway would require several lines of intermediates forming in proximity and then coming together in the proper order at the precise moment and location needed for synthesis. It is possible to modify many parameters during synthesis: temperature, pressure, solvent type, light, pH, oxygen and moisture. No such controls figure in a prebiotic environment.

Characterisation is critical. Without it, impurities accumulate. What prebiotic characterisation might mean is anyone’s guess.

Given poor prebiotic reaction yields, it is impossible to envision a process in which the starting materials generate all of the desired products. In synthesising nanocars, one had to go back over and over again to generate molecular intermediates, a process known familiarly as ‘bringing up material from the rear’.

How would prebiotic chemistry bring up its own rear over and over again? It has kept no laboratory notebook to record the previous paths. In the present synthesis, a great deal of time was spent on separation and optimisation. If by-products are permitted to accumulate, they will often consume the new steps' reagents and alter the course of the reaction. This problem would plague abiogenesis, too.

It stands to reason[54]

There must have been a chemical means, once upon a time, to generate an information-bearing molecule such as DNA or RNA. Since the 1960s, a number of biologists have suggested that the polymer is RNA rather than DNA. Such is the RNA World Hypothesis (Robertson & Joyce 2012). And chemically activated ribonucleotides can polymerise to form RNA. So far so good.

But RNA is far less stable than DNA, and whatever the polymerisation, it yields generic RNA, a molecule lacking sequence specificity. Had RNA researchers succeeded in producing a volume of random sentences – for example, *subtends flack lachrymose esurient* – none of them would have imagined that they had succeeded in composing King Lear. The coupling of a ribose with a nucleotide is the first step and even those engrossed in prebiotic research have difficulty envisioning that process, especially for purines and pyrimidines (Fuller, Sanchez & Orgel 1972). John Sutherland and his co-workers have proposed that pyrimidine ribonucleotides can form short sequences using arabinose amino-oxazoline and anhydronucleoside intermediates, all from simple compounds such as cyanamide, cyanoacetylene, glycolaldehyde, glyceraldehyde and inorganic phosphate. The use of inorganic phosphate changes the experiment's basic conditions to a pH-buffered solution, thereby slowing decomposition pathways. But the work itself shows the intricacies required to generate the desired reactions.

The conditions they used were cleverly selected (Powner, Gerland & Sutherland 2009):

> Although the issue of temporally separated supplies of glycolaldehyde [*JIT scenario 1*] and glyceraldehyde [*JIT scenario 2*] remains a problem, a number of situations could have arisen [*prebiotically, what and where?*] that would result in the conditions of heating [*careful control of step 1 at 60°C*] and progressive dehydration [*careful control of step 2 by lyophilization, which is water removal by ice sublimation under reduced pressure of <0.001 atmospheres*] followed by cooling [*careful control of step 3 from 60°C to 23°C*], rehydration [*careful control of step 4 with precise adjustments of pH*] and ultraviolet irradiation [*careful control of step 5 with a selected 254nm light*]. (p. 242)

There were also multiple purification steps (careful control of step 6) and ion exchanges using commercial resins (careful control of step 7). All this for the synthesis of just one set of a mixture of adducts and in racemic form.

It remains clear that the controlled conditions required to generate even a mixed set of select structures are painfully improbable.

---

[54] See again Tour (2016, 2017b).

Routes to each one of the requisite carbohydrates, lipids, nucleic acids and proteins (polymers of amino acids) have been proposed in prebiotic studies. The attempted syntheses almost always create mixtures beset with the same difficulties.

From the data, the synthetic chemist can easily deduce that under prebiotic conditions the reaction in question is not likely to yield anything useful. With each added step, difficulties are compounded by improbabilities so overwhelming that no other field of science would depend upon such levels of faith.

Abiogenesis research would never be accepted in any other area of chemistry.

Building a cell

But this is not the end. Making carbohydrates, lipids, amino acids and nucleic acids still has not built a cell. Researchers have also made no progress in explaining the subsequent stages to life's origin such as the development of a metabolism inside of a cell membrane. Some researchers have reported progress towards these goals, but their claims are highly exaggerated.

Extrapolation on steroids

Sutherland and co-workers pointed out in 2015 that '[a] minimal cell can be thought of as comprising informational, compartment-forming and metabolic subsystems' (Patel et al*.* 2015). They also acknowledged that, to date, prebiotic chemistry has made ambitious extrapolations: 'To imagine the abiotic assembly of such an overall [cellular] system [or subsystem], however, places great demands on hypothetical prebiotic chemistry'. Yet this revealing comment by Sutherland and his co-workers is coupled with their disclosure of a new experimental finding showing (Patel et al. 2015):

> [*T*]hat precursors of ribonucleotides, amino acids and lipids can all be derived by the reductive homologation of hydrogen cyanide and some of its derivatives […] The key reaction steps are driven by ultraviolet light, use hydrogen sulfide as the reductant and can be accelerated by Cu(I)-Cu(II) photoredox cycling. (p. 301)

They assert boldly that 'all the cellular subsystems could have arisen simultaneously through common chemistry'. This has now raised the level of suppositions from mere molecule types to complex subsystems where molecules are working in concert towards a common functional goal. But compositions of a few molecule types, or even all of them, do not constitute a cellular subsystem. It is essential to emphasise that the authors only prepared precursors to the ribonucleotides, amino acids and lipids, not the actual molecules, so the gross extrapolation is all the more disconcerting.

When reading the protocols for the suggested prebiotic-like precursors, one is struck by the high-level sophistication, expert synthetic prowess and remarkable ingenuity of the researchers. Some reactions were run at room temperature, some at 60 °C, others at 100 °C and then washed with ice-cold water. Often the molecules prepared by these supposed prebiotic routes were not used but had to be made more cleanly and in larger scale using purely synthetic methods and organic solvents, such as Lawesson's reagent and tetrahydrofuran, respectively, 'to simplify the handling procedures'.

Just-in-time and precise order of addition protocols were used over and over again. One sees precise pH adjustments through the syntheses, use of ion exchange resins and separations from the reaction mixtures because proceeding without separations would have destroyed the carefully prepared products. The preparation of cyanoacetylene on Cu(I) was suggested as a way to prepare it conveniently and store it for use when needed. CuCl was mixed with KCl to generate the Nieuwland catalyst, K[CuCl2], at 70 °C. Then a separately generated source of acetylene gas was prepared from CaC_2 and water. This gas was bubbled through the Nieuwland catalyst to prepare acrylonitrile (an unstable molecule that needs proper isolation and storage to inhibit its polymerisation), which was then treated with KCN for 1 h, then 5 equivalents of NH_3 as a 13 molar NH_3/NH_4^+ solution adjusted to pH 9.2 with NaOH to generate the desired aminopropionitrile.

All of the reactions were executed in separate clean vessels and properly isolated before proceeding to the next reaction.

This is just a sampling of preparations that are difficult even for the skilled synthetic chemist to execute. The routes afford very simple precursors to just a few of the many molecules within the building block classes of molecules, carbohydrates, lipids, amino acids and nucleic acids. Finally, all the precursors were racemic if they even bore any possible stereoisomerism.

Self-assembling protocells

Consider the class of experiments that deals with the assembly of chemicals into what are referred to as protocells – 'a self-organised, endogenously ordered, spherical collection of lipids proposed as a stepping-stone to the origin of life' (*Protocell* 2021). In 2017, a team from the Origins of Life Initiative at Harvard University performed a type of polymerisation reaction in water known as the reversible addition-fragmentation chain transfer (Albertsen, Szymaski & Pérez-Mercader 2017). This reaction type is not seen in nature, and neither are the monomers that figure in the experiment. Still, this is standard chemistry. Polymers are made by a controlled radical polymerisation reaction, where two different monomer types are sequentially added to a chain bearing both a hydrophobic and a hydrophilic block. Researchers observed polymeric vesicles forming during polymerisation – interesting, but not extraordinary. The vesicles grew to bursting as researchers kept the radical chain growing through ultraviolet light activation. There is, in this, nothing surprising: the forces between the growing vesicle and the surrounding water dictate a critical growth volume before the vesicle ruptures.

The claims should have ended there.

Here is how the work was portrayed in the published article (Albertsen, Szymaski & Pérez-Mercader 2017):

> The observed net oscillatory vesicle population grows in a manner that reminds one of some elementary modes of sustainable (while there is available 'food'!) population growth seen among living systems. The data supports an interpretation in terms of a micron scale self-assembled molecular system capable of embodying and mimicking some aspects of 'simple' extant life, including self-assembly from a homogenous but active chemical medium, membrane formation, metabolism, a primitive form of self-replication, and hints of elementary system selection due to a spontaneous light triggered Marangoni instability [*provoked by surface tension gradients*]. (p. 6)

These claims were then rephrased and presented to the public by the Harvard Gazette (Powell 2017):

> A Harvard researcher seeking a model for the earliest cells has created a system that self-assembles from a chemical soup into *cell-like structures that grow*, move in response to light, replicate, and exhibit signs of *rudimentary evolutionary selection*. (n.p.; [*emphasis added*])

This degree of hyperbole is excessive as has been previously stated (Tour 2017b). Nothing in this experiment had growing cell-like structures with replication or that exhibited aspects of evolutionary selection.

Lipid bilayers with nucleotides

Teams from the University of California and the University of New South Wales recently conducted lipid bilayer assembly experiments, publishing a summary of their work in 2017 (Kranendonk, Deamer & Djokic 2017; see also Tour 2017b). They combined nucleotides and lipids in water to form lamellae, with the nucleotides sandwiched between the layers. Nucleotides are trimers of nucleobase–carbohydrate–phosphate, and, in this case, both nucleotides and lipids were purchased in pure homochiral form. Both teams then demonstrated that a condensation polymerisation of the nucleotides can take place within the lamella upon dehydration. Polymerisation takes place by means of a reaction between preloaded phosphate and the purchased stereo-defined alcohol moiety found on a neighbouring nucleotide. Similar reactions, they conjectured, may have occurred at the edge of hydrothermal fields, volcanic landmasses providing the necessary heat for reactions.

The chemistry that figures in these experiments is unremarkable. Bear in mind that derivatives were all preloaded. To provide the essential concentrations for the reactions, researchers removed the water, thus driving the intermolecular reactions to form oligomers that resembled nucleic acids. The problem with condensation polymerisation is obvious: any alcohol can compete for the reactive electrophilic site. In the case under consideration, researchers added no other alcohols. They were scrupulous, but the system was stacked. Condensation polymerisation reactions need to be very pure, free from competing nucleophilic and electrophilic components. Witness the Carothers equation, which defines degrees of polymerisation based on monomer purity (*Carothers equation* n.d.). If there happened to be amino acids or carbohydrates mixed with the nucleotides, they would terminate or interrupt the growth of the oligonucleotides.

What is more, the researchers did not confirm the integrity of the structures they claimed to have derived. If carefully analysed, these structures would likely have shown attacks from unintended hydroxyl sites. Since their sequences are essentially random, short oligonucleotides are not realistic precursors to RNA. An alphabet soup is not a precursor to a poem. The authors go on to suggest that the lamella sandwiching oligonucleotides eventually break off to form lipid bilayer vesicles. These contain the oligonucleotide-within-vesicle constructs, which they call protocells. The conversion of planar lamella into multilamellar vesicles as they hydrate is well-established, but shearing forces are generally required to form the requisite lipid bilayer vesicle. For this reason, yields were likely to be low (Gerbelli et al. 2018). It is hard to imagine finding highly purified homochiral nucleotides trapped in a pure lipid lamella on the prebiotic earth.

But set all that aside. These vesicles bear almost no resemblance to cellular lipid bilayers. Lipid bilayer balls are not cellular lipid bilayers. One would never know this from reading the authors' account (Kranendonk et al. 2017). 'Then, in the gel phase', they write, 'protocells pack together in a system called a progenote and exchange sets of polymers, selecting those that enhance survival during many cycles'.

Chemicals, of course, are indifferent to their survival. No mechanism is described to demonstrate how protocells would bear different sets of polymers or exchange polymers among them. Terms from biology have generally been misappropriated in a way that makes no chemical sense. This is not an isolated or incidental defect. It reappears when the authors write that '[t]he best-adapted protocells spread to other pools or streams, moving by wind and water' Best-adapted? Microbial communities apparently 'evolve into a primitive metabolism required by the earliest forms of life'. Molecules do not evolve, and nothing is being metabolised. Condensation polymerisation is a simple chemical reaction based on the addition of nucleophiles to electrophiles with loss of water. Such a reaction is never referred to as a form of metabolism within synthetic chemistry.

Terminology is one thing, nonsequiturs quite another. ‘After much trial and error’, the authors write, ‘one protocell assembles the complicated molecular machinery that enables it to divide into daughter cells. This paves the way for the first living microbial community’. How is the molecular machinery made? They do not say. The mechanisms needed for cellular division are complex, requiring cascades of precisely functioning enzymes. There is nothing between what the authors demonstrate and what they claim to have established, and nothing they propose ‘paves the way for the first living microbial community’.

The emerging cell

A functioning cell contains a complex noncovalent interactive system. Nobody knows how a cell emerges from its molecular components. An interactome is the set of molecular interactions in a given cell. Interactions may be between proteins, genes or molecules. Information is transferred within the cell through these molecular interactions. Electrostatic potentials permit information to flow through noncovalent molecular arrays, but these arrays require specific orientation (Tour, Kozaki & Seminario 1998). The interactome defines these intermolecular orientations, alignments that are unattainable through random mixing.

Peter Tompa and George Rose have calculated that if one considered only protein combinations in a single yeast cell, the result would be an estimated $10^{79,000,000,000}$ combinations (1 with 79 billion zeros behind it). The authors understand that this is a very large number, one that precludes ‘formation of a functional interactome by trial-and-error complex formation within any meaningful span of time’ (Tompa and Rose, 2011). What Tompa and Rose (2011) call ‘a complicated cellular sorting/trafficking and assembly system’, is required. Sophisticated scaffolding notwithstanding:

> [*I*]n the absence of energy even this well-developed infrastructure would be insufficient to account for the generation of the interactome, which requires a continuous expenditure of energy to maintain steady state. (p. 2076)

In their concluding paragraph, Tompa and Rose (2011) remark that:

> [*T*]he inability of the interactome to self-assemble de novo imposes limits on efforts to create artificial cells and organisms, that is, synthetic biology. In particular, the stunning experiment of ‘creating’ a viable bacterial cell by transplanting a synthetic chromosome into a host stripped of its own genetic material has been heralded as the generation of a synthetic cell (although not by the paper’s authors). Such an interpretation is a misnomer, rather like stuffing a foreign engine into a Ford and declaring it to be a novel design. The success of the synthetic biology experiment relies on having a recipient interactome […] that has high compatibility with donor genetic material. The ability to synthesize an actual artificial cell using designed components that can self-assemble spontaneously still remains a distant challenge. (p. 2078)

The fact is that interactomes add a massive layer of complexity to all cellular structures. It is one that underscores the difference between a real cell and the protocells or extant cells made by origin-of-life researchers.

In 2010, a team led by Craig Venter made a copy of a known bacterial genome and transplanted it into another cell (Gibson et al. 2010). In 2016, they did something better, removing all but 473 genes from a natural genome and transplanting it into another cell (Hutchison et al. 2016). Venter and his team were circumspect; the press was enthusiastic.

More recently, Henrike Niederholtmeyer, Cynthia Chaggan and Neal Devaraj have made what they term, ‘mimics of eukaryotic cells’ (Niederholtmeyer, Chaggan & Devaraj 2018). Science declared them ‘the most lifelike artificial cells yet’ (Leslie 2018). Microcapsules made of plastic and containing clay were prepared using microfluidic techniques. Clay has a high affinity for binding DNA. Thus, when DNA was added to the solution, it diffused through the semiporous plastic microcapsules and bound to the clay. The requisite RNA polymerases, together with the ribosomes, tRNA, amino acids, enzymatic cofactors and energy sources, were either purchased or extracted from living systems. The expected chemical reactions did result in protein synthesis. Newly formed proteins diffused from their microcapsules of origin to other microcapsules. The nearer the neighbouring microcapsule, the greater the exchange of reagents between them. Diffusion between microcapsules the authors dubbed quorum sensing. The chemistry would work no matter the container, whether a test tube or a large-scale industrial production tank. If the experimental design is clever, the synthesis is unremarkable.

Phys.org reported these modest results in markedly flamboyant terms, referring to ‘gene expression and communication rivaling that of living cells’ (University of California – San Diego 2018). There is no rivalry here. All of the active chemical components were extracted from living systems. If these are ‘the most lifelike artificial cells yet’, this serves only to underscore the point that no one has ever come close to the real thing.

Life as a lucky fluke

In an article entitled ‘How Did Life Begin?’, Jack Szostak asks whether the appearance of life on Earth is ‘a lucky fluke or an inevitable consequence of the laws of nature’ (Szostak 2018). It is a good but premature question, a point obvious from his own appreciation of current research. Having vetted the usual suspects of asteroids, dust clouds, volcanoes, lightning and time, Szostak appeals to ‘a concentrated stew of reactive chemicals’:

> Life as we know it requires RNA. Some scientists believe that RNA emerged directly from these reactive chemicals, nudged along by dynamic forces in the environment. Nucleotides, the building blocks of RNA, eventually formed, then joined together to make strands of RNA. Some stages in this process are still not

> well understood. […] Once RNA was made, some strands of it became enclosed within tiny vesicles formed by the spontaneous assembly of fatty acids (lipids) into membranes, creating the first protocells. […] As the membranes incorporated more fatty acids, they grew and divided; at the same time, internal chemical reactions drove replication of the encapsulated RNA. (p. 15)

The thesis that 'RNA emerged directly [emphasis added] from these reactive chemicals, nudged along by dynamic forces' is painful to a synthetic chemist. A complex pathway of reactions would have been needed, incorporating purification, assembly, polymerisation and sequencing. Nothing emerged directly in Szostak's scenario, let alone something as complex as RNA. Phrases such as 'nudged along by dynamic forces' have no meaning in terms of synthetic chemistry. Nucleotides never form and join together to make strands of RNA without complex protecting and deprotecting steps. It is perfectly true that '[s]ome stages in this process are still not well understood', if only because we are clueless about the chemistry needed on a prebiotic earth.

In the diagram to which Szostak appeals, the compounds listed as simple sugars are, in fact, glycerol and ethylene glycol. There are known routes to convert them to simple sugars, but only in gross relative and absolute stereochemically mixed states and as a mixture of several different polyols (Ritson & Sutherland 2012). Carbohydrate synthesis is a difficult prebiotic problem (Tour 2016). Szostak's carbohydrates would be useless in their mixed states, and separations are hard. The diagram's cyanide derivatives are unrecognisable as cyanide derivatives.

In an act of grace, let us attribute these chemical structural errors to the faulty renderings of a staff artist. The chemical errors are Szostak's own. There is simply no way that heat and light can directly make a nucleotide from simple sugars and cyanide derivatives. Such glossy presentations have become the standard of the Origins-of-Life community when it tries to build upon the careful work of exacting synthetic chemistry.

I have discussed these issues with Origins-of-Life researchers, and I am amazed that they fail to appreciate the magnitude of the problem in building molecules. They see little difficulty in accepting a chemical synthesis where a desired product is mixed with a large array of closely related yet undesired compounds. They seem unaware that separations would be enormously complex and subsequent reactions unavailing. In a 2018 article for *Progress in Biophysics and Molecular Biology*, Edward Steele et al. (2018) concede the following:

> The transformation of an ensemble of appropriately chosen biological monomers (e.g. amino acids, nucleotides) into a primitive living cell capable of further evolution appears to require overcoming an information hurdle of superastronomical proportions, an event that could not have happened within the time frame of the Earth except, we believe, as a miracle. All laboratory experiments attempting to simulate such an event have so far led to dismal failure. (p. 7)

'At this stage of our scientific understanding', they write, 'we need to place on hold the issue of life's actual biochemical origins – where, when and how may be too difficult to solve on the current evidence'. All is not lost. If life on Earth did not arise on Earth, '[i]t would thus seem reasonable', Steele et al. remark, 'to go to the biggest available "venue" in relation to space and time. A cosmological origin of life thus appears plausible and overwhelmingly likely'. Why chemical reactions that are unlikely on the earth should prove likely somewhere else, Steele et al. do not say.

Facing facts[55]

John Sutherland, one of Origins-of-Life's giants and the most skilled synthetic chemist to engage in Origins-of-Life research, has recently proposed that 'chemical determinism can no longer be relied on as a source of innovation, and further improvements have to be chanced upon instead' (Sutherland 2017). Chanced upon? It appears that Sutherland has come to appreciate the depths of the problems facing Origins-of-Life researchers.

In 2017, Ramanarayanan Krishnamurthy et al. showed that diamidophosphate can phosphorylate nucleosides, nucleotides and stereo-scrambled lipid precursors. These can further result in the formation of random oligonucleotides and oligopeptides. The fundamental challenges with respect to synthesis and assembly remain unaddressed. Krishnamurthy was rightly measured in writing about 'the pitfalls of extrapolating extant biochemical pathways backwards all the way to prebiotic chemistry and vice versa' (Gibard et al. 2017). In 2018, Clemens Richert argued that 'the ideal experiment does not involve any human intervention' (Richert 2018). This is a step in the right direction. So, too, is the fact that he scrupled at the pure chemicals used by the Origins-of-Life community.

It is time for a temporary time-out. Why not admit that it is not yet possible to explain: the mass transfer of starting materials to the molecules needed for life, the origin of life's code, the combinatorial complexities present in any living system and the precise nonregular assembly of cellular components?

Conclusion

To better appreciate the current state of the field, one only needs to imagine the following scenario.

The world's best synthetic chemists, biochemists and evolutionary biologists have combined forces to form a team – a dream team in two quite distinct senses of the word. Money is no object. They have at their disposal the

---

[55] This section in the chapter represents a substantial reworking of excerpts from Tour (2017b).

most advanced analytical facilities, the complete scientific literature, synthetic and natural coupling agents and all the reagents their hearts might desire. Carbohydrates, lipids, amino acids and nucleic acids are stored in their laboratories in a state of 100% enantiomeric purity.

Those who think scientists understand how prebiotic chemical mechanisms produced the first life are wholly misinformed. Nobody understands how this happened. Maybe one day we will. But that day is far from today. It would be far more helpful (and hopeful) to expose students to the massive gaps in our understanding. Then they may find a firmer – and possibly a radically different – scientific theory.

Chapter 7

Engineering principles explain biological systems better than evolutionary theory

Brian Miller
Center for Science and Culture,
Discovery Institute,
Seattle, Washington, United States of America

Introduction

Since antiquity, scholars have debated whether the appearance of design in life was the product of a transcendent mind or undirected natural processes. The latter view rose to dominance after the scientific community largely embraced Darwin's theory of natural selection. In the last few decades, the hegemony of the standard model for evolution has started to wane. Recent discoveries have forced biologists to replace evolutionary assumptions with design-based assumptions, language and methods of investigation. This trend is to a large extent driven by the observation that the same engineering motifs and patterns employed in human creations are pervasive in living systems. What is becoming increasingly clear is that engineering principles far better explain nearly every aspect of life than evolutionary theory. This conclusion

How to cite: Miller, B 2022, 'Engineering principles explain biological systems better than evolutionary theory', in F van Niekerk & N Vorster (eds.), *Science and Faith in Dialogue*, in Reformed Theology in Africa Series, Vol. 10, AOSIS Books, Cape Town, pp. 175–211. https://doi.org/10.4102/aosis.2022.BK334.07

perfectly coincides with the central Christian doctrine that life was designed by God and not an unintended accident of nature.

Since ancient times, scholars have debated whether everything in the world was simply the product of natural processes or derived from the plans of a supreme intellect (Lloyd 1970). The ancient form of the former philosophy is termed atomism. Its adherents believed that matter was composed of indivisible 'atoms' that interact according to various rules. The interactions of the atoms, chance and time resulted in everything observed in our world. The modern form of this philosophical tradition is termed scientific materialism.

The atomists developed evolutionary theories to explain the appearance of design in life. These theories seem eerily familiar to modern ears. The Greek physician Hippocrates proposed in the late 5th or early 4th century BC a model for heredity and adaptation that Charles Darwin described as nearly identical to his own (Tsiompanou & Marketos 2013). And the poet Lucretius developed in the 1st century BC an evolutionary framework based on a primitive form of natural selection (Campbell 2004). Lucretius' agenda was to remove teleology (aka design) and by extension the influence of any deity from the world.

In stark contrast, philosophers such as Plato and Aristotle rejected the claim that matter had in itself the capacity to self-organise into living creatures. Instead, they believed that a transcendent mind envisioned the architectural plan or design logic of every distinct creature. And the design plan detailed how the matter would be arranged in a creature's final form. That form would never have occurred without external direction.

Some scholars have argued that Aristotle's views are more compatible with scientific materialism than ID (Feser 2019). But such claims result from a misreading of Aristotle's writings (Bos 2003, 2018; Gerson 2005; Henry 2019). He, like Plato, would have aligned himself with modern design proponents far more than with scientific materialists.

The arguments the ancient philosophers employed to defend their conclusion of design in life (Archer-Hind 1888; Aristotle 2010) resemble those promoted by proponents of design today. And the atomists' justification for ignoring the evidence for design resembles arguments by modern scientific materialists (Sedley 2008). This conflict was reflected in the opening chapter of the Apostle Paul's letter to the Romans where he described how the clear evidence for God's 'eternal power' is 'understood by the things that are made' (Keener 2009). The apostle would have seen the design-evolution debate today as a continuation of the same conflict that raged in the 1st century.

Darwin developed the modern version of the evolutionary theory, and he, like his ancient predecessors, argued that evolutionary processes could mimic the creative power of an intelligent agent in generating biological features of any level of complexity and ingenuity. More specifically, natural selection could act as a designer substitute empowering the environment to act as a creative agent, thus removing the need for a creator. Such reasoning allowed evolutionists to simply dismiss any evidence for design, no matter how conclusive, as merely an artifact of a blind, undirected process that did not have any end goal in mind.

Francisco Ayala, a former president of the American Association for the Advancement of Science, described Darwin's achievement of returning the atomist philosophical tradition to dominance (Ayala 2007) in the clearest of possible terms:

> Darwin's greatest contribution to science is that he completed the Copernican Revolution by drawing out for biology the notion of nature as a system of matter in motion governed by natural laws. With Darwin's discovery of natural selection, the origin and adaptations of organisms were brought into the realm of science. The adaptive features of organisms could now be explained, like the phenomena of the inanimate world, as the result of natural processes, without recourse to an intelligent designer. (p. 8567)

Over the next century, biologists combined Darwin's theory with genetics and population genetics to form neo-Darwinism, also known as the Modern Synthesis. In the following decades, the theory was widely accepted to explain away all the evidence for design in life as mere illusion. This belief, however, is becoming increasingly untenable in light of developments in the biological sciences over the past several decades.

■ The demise of neo-Darwinism

To name but a few lines of evidence, the fossil record demonstrates that novel organisms consistently appear suddenly. Approximate ancestor-descendent series of intermediate forms that connect any organism to a common ancestor with a distinctly different species have never been identified (Meyer 2013). And no species has ever been observed to substantially change during its tenure on Earth.

Palaeontologists often point to 'transitional fossils' to argue that the record supports evolutionary narratives. An iconic example is the purported whale series that includes a sequence of fossils 'transitioning' from a terrestrial animal to one that is fully aquatic. What is often omitted is that such sequences do not correspond to anything close to an ancestor-descendent series. The creatures are at best cousins that reside at the ends of their own separate branches in the hypothetic tree of life (TOL) (Wells 2017). None has conclusively been demonstrated to be ancestral to or a descendent of the others. They each appear suddenly, and they do not appreciably change after their appearance.

The species share some common features with each other, but equally striking similarities exist between organisms that are not believed to be closely related. Given the millions of species that have existed, some set will inevitably appear to line up in a sequence purely by chance. One can find numerous comparable sequences in human creations such as the following: unicycle → bicycle → motorcycle → convertible car → station wagon → bus. A motorcycle could be described as a transition between a bicycle and a car, but that descriptor does not mean that the three share a common ancestor that incrementally evolved into the modern transportation vehicles. The same holds true with so-called transitional fossils.

Leading evolutionary theorist Eugene Koonin acknowledges the fact that the evolutionary processes seen today cannot explain the sudden appearances of new body plans – a body plan is the distinctive design architecture or blueprint shared by a group of organisms such as fish. He compares the sudden appearance of a new body plan to the cosmological Big Bang (Koonin 2007). He proposes that large-scale transformations (e.g. fish to amphibians) could have been driven by 'various processes of genetic information exchange, such as horizontal gene transfer, recombination, fusion, fission and spread of mobile elements'. But this assertion contradicts all observational and experimental evidence of what such processes could accomplish.

Major transformations require alterations to an organism's underlying architecture, and such changes must result from modifying the early stages of a fertilised egg developing into an embryo and an embryo developing into an offspring (or the equivalent). The challenge is that all alterations early in development that generate significant modifications are harmful. Leading developmental biologist Eric Davidson described how alterations to the developmental gene regulatory networks[56] underlying the embryological construction of body plans are always 'catastrophically bad' (Davidson 2011), implying that complex organisms can never significantly change because of any undirected process.

A related challenge is the implausibility of many novel proteins evolving by chance. Proteins are chains consisting of primarily 20 possible amino acids. The proper sequences will result in the chain folding into a complex three-dimensional structure that can serve as a structural component of a cell or act as an enzyme that drives a specific chemical reaction. The barrier for evolving novel proteins is the fact that the percentage of sequences that fold into functional enzymes is infinitesimally small. Protein evolution expert Doug Axe estimated the proportion of sequences that folded into one portion of the β-lactamase enzyme at 1 in 10^{77} – a 1 followed by 77 zeros (Axe 2004).

---

[56] A developmental gene regulatory network is a set of genes that coordinate to direct the development of an egg into an embryo and then into an offspring or the equivalent process.

Later research showed that the actual rarity is far more extreme for that protein and for many others.[57] Such small targets in sequence space (graph of all possible amino acid sequences) could never be located by an undirected search, so many proteins could not have originated through an evolutionary process.

Leading expert Dan Tawfik acknowledged that the origin of novel proteins is a complete mystery (Mukhopadhyay 2013):

> Once you have identified an enzyme that has some weak, promiscuous activity for your target reaction, it's fairly clear that, if you have mutations at random, you can select and improve this activity by several orders of magnitude [...] What we lack is a hypothesis for the earlier stages, where you do not have this spectrum of enzymatic activities, active sites and folds from which selection can identify starting points. Evolution has this catch-22: Nothing evolves unless it already exists. (n.p.)

He even described it as 'something like close to a miracle'.

Compounding the problem, the maximum possible time for major transitions (e.g. a few million years for the appearance of a new phylum) is sufficient for only the tiniest fraction of the required new genetic information to appear and spread throughout a population. For instance, the entire purported evolutionary history between an ape-like ancestor of humans to modern humans is insufficient for even two coordinated mutations to appear in any individual (Durrett & Schmidt 2008). Yet even simple evolutionary steps require far more specific mutations, such as the origin of a targeted mid-range neural connection. And time scales grow exponentially with the required number of specific mutations (Hössjer, Bechly & Gauger 2021). The disparity between the time available for major transitions and the minimal required time to generate the new genetic information is comparable to the difference between the world-record pole vault height and the distance to Alpha Centauri.

Such problems compelled leading evolutionary theorists to organise the Royal Society meeting titled New Trends in Evolutionary Theory in 2016. Speakers acknowledged the fact that the standard evolutionary model cannot adequately address the aforementioned challenges or related issues. In particular, natural selection was recognised as having no true creative power.

---

[57] Researchers determined for β-lactamase (Bershtein et al. 2006) and HisA (Lundin et al. 2018) the equations for the percentage of operational proteins as a function of the number of alterations to their amino acid sequences. The function declines hyper-exponentially with increasing numbers of alterations. The total number of functional sequences can be estimated by multiplying the fitness function by the number of sequences with n alterations away from the original sequence and then summing for all n. The percentage of functional sequences (aka rarity) equates to the number of functional sequences divided by the total number of sequences of length L, the protein's sequence length. The resulting percentage of functional sequences is much smaller than Axe's estimate. Axe looked at the rarity in a region of sequence space close to a functional sequence. The actual rarity is much more extreme when all of sequence space is considered. Moreover, β-lactamase is an enzyme that performs a relatively simple function, so a significant percentage of proteins almost certainly correspond to more extreme rarity.

Yet not one presentation offered concrete evidence that any of the proposed extensions to evolutionary theory could fill the standard model's explanatory deficits (Why the Royal Society Meeting Mattered, in a Nutshell 2016).

With natural selection off the table as a designer substitute, materialist biologists are left in a situation comparable to the crisis astronomy would face if physicists discovered that gravity stopped operating beyond 10 000 kilometres past a celestial body. The loss of the only feasible mechanism that could explain the motion of planets, stars and galaxies would result in absolute pandemonium and despair. Most biologists will not come to terms with their true predicament so easily as evolution operates not only as a scientific theory but as a sacrosanct creation narrative for a secular society.

■ The erosion of scientific materialism

Despite the reticence of many to question the official scientific orthodoxy, a scientific revolution has begun in a biological subdiscipline known as systems biology (Miller 2021a). Biologists and engineers have come together to better understand the higher-level organisation of living systems. Their discoveries have forced them to replace historic evolutionary assumptions with design-based assumptions, language and methods of investigation.

This transformation in thinking reflects how the philosophical foundation of scientific materialism, which has defined science for the past two centuries, is eroding in the face of the most recent biological data. The traditional approaches implemented in biological research were founded on reductionism – the belief that studying the physical and chemical interactions between biological molecules should eventually lead to an understanding of life's higher-level operations and organisation.

This assumption was central to evolutionary thinking as evolutionary processes can differentiate the results only from individual changes to DNA or other inherited information-bearing structures (Wells 2014). Such changes modify the lowest-level chemical interactions or structural details. Nearly every change must immediately benefit the organism, or it would not typically persist in the population. Consequently, the function of a biological system should represent the sum of the functions of each part. An analogy would be a team of cleaners whose net benefit is simply the sum of the activities of each individual cleaner.

Based on this framework, biologists expected that studying the actions of individual reactions and structural molecules would allow them to discern the operations of larger systems and structures. The role of the larger system should represent a summation of the roles of each individual part. Removing one part should simply reduce the function of the system by the minor role the removed part played.

More commonly today, systems biologists reject this reductionist approach as it has failed to yield any significant understanding of the organisation of living systems. Instead, they now recognise that they must look at life as a collection of integrated systems composed of integrated components where the whole is greater than the sum of the parts (also known as holism). In other words, Michael Behe's concept of irreducible complexity (Behe 2020) has implicitly become a central tenet of the field. Researchers would rarely use Behe's exact language or recognise the implications, but they are tacitly acknowledging the ubiquity of this feature in life.

Philosopher of science Michel Morange (2008) describes critiques of the traditional approach to biology in his provocatively titled article 'The Death of Molecular Biology?':

> [*D*]oes it mean that molecular biology is dead, and has been displaced by new emerging disciplines such as systems biology and synthetic biology? Maybe its reductionist approach to living phenomena has been substituted by one that is more holistic […] Some even consider the age of molecular biology as having been a period of extreme misorientation of biological research, an error that it is high time to repair. (p. 31)

Similarly, Virologist Derek Gatherer (2010) comments:

> The epistemological antireductionist is a holist because complete reductionism is technically impossible. For a systems biologist, sheer complexity, one might say irreducible complexity, can prevent the exhaustive analysis of a network of any interesting size […] The broadening of molecular biology into systems biology has created a situation where researchers have a vague inkling that their underlying philosophy is in need of refurbishment, and holism appears to offer much of what is wanted. (p. 4)

It is worth noting that if a system is too 'irreducibly complex' to even describe, it is certainly too specified and complex to originate through any undirected process (Ewert, Marks & Dembski 2013).

■ The return of teleology

Part and parcel with the erosion of the reductionist assumption has been the implicit acceptance of the assumption that teleology is central to life (Miller 2021g). Teleology is the philosophical term for design or purpose. This change is cataclysmic as the gatekeepers at most mainstream scientific institutions have historically forbidden researchers from explicitly appealing to teleology as an explanation.

Despite this prohibition, biologists have intuitively recognised that identifying the purpose of a structure or system was essential in understanding it. Yet they would not explicitly acknowledge their reliance on design-based reasoning. The German physician and physiologist Ernst Wilhelm Ritter von Brücke best described this tension (Krebs 1954, p. 45) 'teleology is a lady without whom no biologist can live. Yet he is ashamed to show himself with her in public'. The difference now is that the appeal to teleology is ubiquitous and explicit.

The scientific elite has attempted to explain the appearance of teleology as a by-product of evolutionary mechanisms. But the most philosophically minded biologists have come to recognise that appealing to such undirected processes as a designer agent is logically incoherent. Biologist David Hanke emphasises this point in his essay, 'Teleology: the explanation that bedevils biology' (Hanke 2004):

> Biology is sick. Fundamentally unscientific modes of thought are increasingly accepted, and dominate the way the subject is explained to the next generation. The heart of the problem is that we persist in making (literal) sense of the world that we now know to be senseless by attributing subjective values to the objects in it, values that have no basis in reality. (p. 143)

Hanke (2004) lists several statements by none other than atheist Richard Dawkins that embody this philosophical transgression:

> Somatic cell divisions are used to make mortal tissues, organs and instruments whose 'purpose' is the promoting of germ line divisions.
>
> The replicators that exist tend to be the ones that are good at manipulating the world to their own advantage. (pp. 143–144)

Hanke (2004) acknowledges the fact that life might display clear signatures of design to those uninitiated into scientific materialism, but he insists that reality must be the opposite of where the evidence naturally leads:

> The bits of living things at all levels of scale from molecules to the whale's tail also happen to have symmetry, precision, and complexity, clues that simply shout 'purpose' in the inquiring mind. This has to be wrong. Because they are not manufactured they cannot have been designed, and so no one ever had a purpose for them. They make themselves and so just exist, without purpose or intended use. (pp. 145–146)

He dedicates the rest of his essay to arguing that attempts to identify the intent of a biological structure or trait lead biologists astray. Investigators should instead assume that their objects of study simply exist without any higher purpose to meet some biological goal.

Zoologist John Reiss (2009) presents similar denunciations in his book *Not by Design: Retiring Darwin's Watchmaker*. He aims to convince biologists to purge all teleological language from their writing and thinking:

> Life is not designed, or at least it shows no evidence of design for anything other than continued existence, which needs no design [...] To truly retire the watchmaker, [...] We must admit that there is not only not design but indeed not even 'apparent design' in the biological world, in the sense of entities doing any more than they need to do to continue to exist. (p. 356)

He proposes that biologists instead appeal to palaeontologist Georges Cuvier's concept of the 'conditions of existence' in a manner that appears to be the biological equivalent of the weak anthropic principle in cosmology (Meyer 2021).

Hanke and Reiss's attempts to expel teleological language from biology in the face of the torrent of opposing data have proven as effective as attempting to use a toy sand bucket to hold back a striking tsunami. The most astute biologists now recognise that the only feasible approach to understanding biological systems is to understand their purpose. This realisation appears explicitly in the book *System modeling in cellular biology* (SMCB) (Szallasi, Stelling & Periwal 2007):

> A hope for understanding complexity in biology then is to uncover operational principles through a 'calculus of purpose' (Lander 2004) – by asking teleological questions such as why cellular networks are organized as observed, given their known or assumed function. (p. 24)

Other philosophers of science have also expressed the need to apply 'design explanations' to biology (Braillard 2010). Philosophers and complexity theorists Mantri and Thomas explained both the need for and the resistance against this change (Mantri and Thomas 2019):

> Unfortunately, research in the world of modern biology is currently divorced from that of design-theory. Yet each discipline could benefit from studying the other. From a design perspective (and subject to environment/precedent constraints), form seems to be following function (e.g. the elbow joint of the fore-arm for bringing food to the mouth). The fundamental problem associated with design in biology, is that of agency. […] In this paper, we try to bridge the seemingly insurmountable gap between design-theory and biological 'designs',' without getting derailed by 'intelligent design' polemics. (p 1)

Mantri and Thomas desperately attempt to reframe 'design-theory' within the confines of evolutionary assumptions, but their efforts amount to little more than invoking phrases such as 'stigmergic teleology' and 'emergence' without providing any substantive details of what such concepts would look like in an actual evolutionary scenario. They simply maintain that life looks like a duck, swims like a duck and quacks like a duck, but it is actually a cat.

■ The assumption of optimality

A second changing assumption in systems biology relates to the optimality of biological systems (Miller 2021h). The underlying logic of evolutionary models predicts that suboptimal design and non-functional remnants of organisms' evolutionary past should litter the biosphere. Philosopher Philip Kitcher emphasised this point in his book *Living with Darwin: Evolution, Design, and the Future of Faith*. He appealed to examples of what he believed were clumsy, incompetent designs and non-functional DNA regions as his primary argument for dismissing ID and accepting evolution (Kitcher 2007):

> If you were a talented engineer designing a whale from scratch, you probably wouldn't think of equipping it with a rudimentary pelvis [...] If you were designing a human body, you could surely improve on the knee. And if you were designing the genomes of organisms, you would certainly not fill them up with junk. (p. 57)

In a similar vein, biologist Nathan Lents argued in his book *Human Errors: A Panorama of Our Glitches, from Pointless Bones to Broken Genes* that the 'bungling' design seen throughout the human body demonstrates that we are not the product of an intelligent designer but an undirected evolutionary process (Lents 2018):

> The third category features those human defects that are due to nothing more than the limits of evolution. All species are stuck with the bodies that they have and they can advance only through the tiniest changes, which occur randomly and rarely. We inherited structures that are horrendously inefficient but impossible to change [...]
>
> This is why our throats convey both food and air through the same tiny space and why our ankles have seven pointless bones sloshing around. Fixing either of those poor designs would require much more than one-at-a-time mutations could ever accomplish. To suppose that these living things were separately created is to view the creative agent as whimsical, bungling, a mediocre engineer, an unintelligent designer. (pp. xi–xii)

The expectation of poor design is not simply a subjective conclusion based on intuition, but it has been rigorously demonstrated in computational models. One such model created by Snoke, Cox and Petcher (2015) elucidated why evolutionary processes that allow for increases in complexity must generate large quantities of junk DNA and non-functional elements. The details of their model are complex, but the underlying logic is straightforward.

For complex innovations to emerge, organisms must allow non-functional DNA to appear and persist in the population until a functional sequence arises. Such additions to the genome could occur through a gene duplicating and then repeatedly mutating. Junk DNA would inevitably accumulate to encompass a significant percentage of the genome. This requirement is why biologists once assumed that junk DNA comprised as much as 97% of the human genome (Hall 2012). Similarly, the origin of complex structures (e.g. molecular machines) requires countless trial-and-error arrangements of molecules or tissues until something advantageous appears. Most of the trials would be either non-functional or inefficient. Consequently, only a minority of biological structures and systems should appear highly optimised.

In stark contrast to evolutionary predictions, mounting evidence demonstrates that life consistently demonstrates optimal design. Most of the examples of allegedly poor design cited by Kitcher, Lents and other sceptics have been overturned such as the human appendix (Dunn 2012), wisdom teeth

(Lieberman 2013), eyes (Wells 2017) and spine (Nordin 2021). The remaining ones typically represent degradations of once optimal designs or appeal to the imperfection-of-the-gaps fallacy.

Purported examples of poor design usually represent opinions resulting from armchair critics' limited understanding of the technical literature and their lack of training in engineering. For instance, in direct contradiction to Kitcher's and Lents's assertions, engineers commonly reuse design motifs in new ways, just as is seen with the whale pelvis. Medical professionals and engineers have demonstrated how the human knee and ankle are optimally and exquisitely designed (Günther et al. 2004; Seo & Yi 2009). Engineers have even looked to these structures for inspiration in designing artificial limbs (Burgess & Etoundi 2014; Etoundi, Burgess & Vaidyanathan 2013).

Moreover, most of the human genome is now known to be functional because of the Encyclopedia of DNA Elements (ENCODE) project (Abascal et al. 2020). The devastating ramifications of this revelation for evolutionary theory have not gone entirely unnoticed. Biochemist Dan Graur bluntly stated (Graur 2013):

> If the human genome is indeed devoid of junk DNA as implied by the ENCODE project, then a long, undirected evolutionary process cannot explain the human genome. If, on the other hand, organisms are designed, then all DNA, or as much as possible, is expected to exhibit function. If ENCODE is right, then evolution is wrong. (slide 16)

Of equal significance, systems biologists increasingly recognise that assuming optimal design leads to the most productive research. For instance, Nikolaos Tsiantis, Eva Balsa-Canto and Julio R. Banga developed in their 2018 Bioinformatics article (Tsiantis, Balsa-Canto & Banga 2018) a model for studying biological systems based on identifying 'underlying optimality principles'. Tsiantis, Balsa-Canto and Banga (2018) also surveyed leading researchers who also demonstrated the predictive power of assuming optimality:

> Sutherland (2005) claims that these optimality principles allow biology to move from merely explaining patterns or mechanisms to being able to make predictions from first principles. Bialek (2017) makes the important point that optimality hypotheses should not be adopted because of esthetic reasons, but as an approach that can be directly tested through quantitative experiments. Mathematical optimization could therefore be regarded as a fundamental research tool in bioinformatics and computational systems biology. (pp. 2433–2434)

Other investigators have even shown that many biological systems operate at efficiencies close to the limits of what is physically possible. Examples include DNA replication and translation (Piñeros & Tlusty 2019), embryological development (Petkova et al. 2019) and sensory processes (Field & Sampath 2017). Human engineering pales in comparison to such achievements.

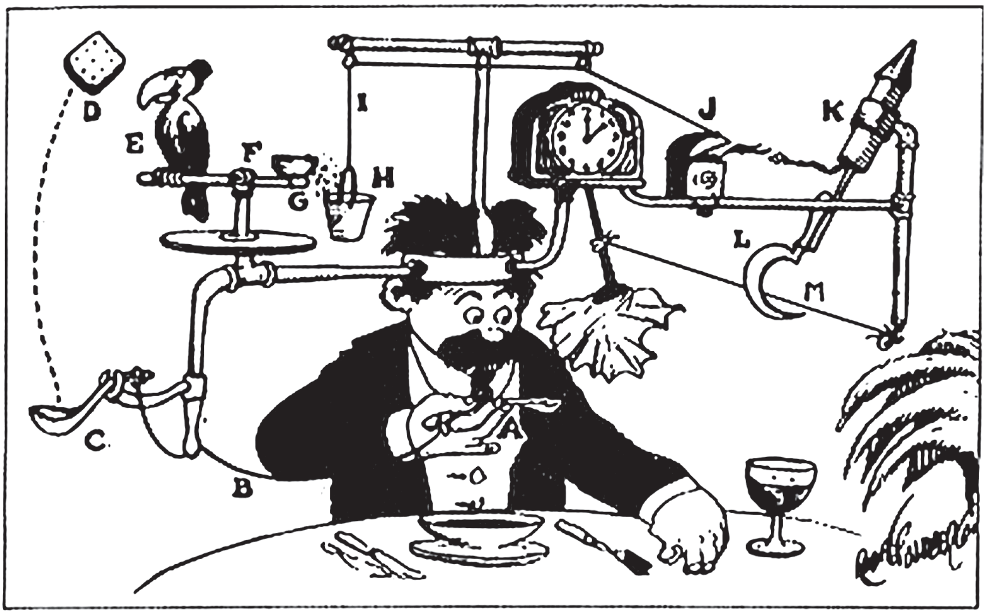
Human engineering and biology

A third changing assumption relates to the connection between human engineering and biological designs (Miller 2021c). Evolutionary theory predicts that biology should resemble human engineering only marginally at best. The underlying logic dictates that the components of complex biological structures and traits came together haphazardly without the benefit of foresight or goal-direction by an intelligent agent. Entities (e.g. proteins) that served one purpose linked with other entities serendipitously to achieve a different collective outcome (e.g. ATP synthase recharging ADP). The lowest-level pieces at the bottom or the organisational hierarchy originated first, so the final product represents a 'bottom-up' design.

In reality, any successful bottom-up design still requires designing the components and properly linking them together, but I will overlook this inconvenience for evolutionary theory for the sake of discussion.

Such composite systems should resemble Rube Goldberg machines (Figure 7.1). Rube Goldberg was an American inventor and cartoonist who drew contraptions that performed a simple task through a series of awkwardly interconnected unrelated devices. The action of one device would trigger the next, which would trigger the next and so on, to achieve some goal not directly

Self-Operating Napkin



Source: Rube Goldberg, https://en.wikipedia.org/wiki/Rube_Goldberg_machine, published under public domain permissions as allowed by Wikimedia Commons.

FIGURE 7.1: 'Professor Butts and the Self-Operating Napkin' (1931).

connected to any of the individual components. The entire mechanism was comically inefficient and cumbersome.

Evolutionist Jerry Coyne has repeatedly emphasised how life should display a similar bottom-up design (Coyne 2019):

> Indeed, the uniform experience of scientists who work on these systems is that they embody an absurd, Rube Goldberg-like complexity that makes no sense as the handiwork of an engineer but makes perfect sense as a product of a long and unguided historical process. (n.p.)

His insight into what evolution should produce is entirely correct. But he has yet to identify a single example of Rube Goldberg-like complexity in life because none exists.

In direct opposition to Coyne, systems biologists now recognise the fact that biology demonstrates a top-down design where an overarching goal and corresponding design constraints dictate the engineering of a complex trait. Each component of a structure or system perfectly integrates with other members to achieve a predetermined goal with astonishing efficiency. Thus, life does not resemble Rube Goldberg-type machines but human engineering. This stark contrast between evolutionary expectations and the actual high-level organisation of life has created tension within the biological community. The authors of SMCB commented (Szallasi, Stelling & Periwal 2007):

> An often noted reservation against the type of analogies between biological and engineered systems we brought forward states that these two types of complex systems arise in fundamentally different ways, namely through evolution versus purpose-driven, top-down design (see e.g. Bosl & Li 2005). (p. 32)

Biology does not simply resemble human engineering generically, but it contains the very same design frameworks. Szallasi, Stelling and Periwal (2007) explain:

> At a more abstract level, we see highly organized and structured networks that facilitate global and coordinated responses to variations in the environment on all time scales, using local and decentralized mechanisms [...] The basic framework is employed in many advanced technological systems [...] Clearly, from an engineering point of view, biology is a marvel of technological 'design'. We argue that analogies with engineered systems, in particular regarding how to generate appropriate responses to variations, are one major requirement on all highly integrated systems that can help us grasp biological complexity. (pp. 26–27)

The authors further argue that design motifs employed in life are known to represent the most effective strategies for achieving target goals (Szallasi, Stelling & Periwal 2007):

> From engineering, it is known that feedback control (plus feedforward control) enabled by fast and if possible remote advanced-warning sensing is the most powerful mechanism for providing robustness to fluctuations in the environment and the component parts. The heat-shock response in E. coli appears to employ exactly the same principles as shown by detailed modeling and subsequent model reduction to the core elements (El-Samad et al. 2005). (p. 39)

Equally striking, Gregory Reeves and Curtis Hrischuk identify a cell as an embedded computing system (Reeves & Hrischuk 2016) as human and biological computing systems share numerous components. Examples include processing engine, information code, primary memory, secondary memory, memory addressing, low-level memory layout, memory management, cache, timer, randomly accessed persistent storage, high-level data formatting and the list goes on. These components also share many of the same functional interrelationships. Computer engineers would attest that such systems can only operate if all essential elements exist and are properly interconnected.

The most philosophically astute materialist scientists recognise the hazard of comparing biology to engineering too closely. Not only does engineering embody ID, but engineers have developed a deep intuition of what incremental processes can and cannot achieve. And they recognise that the design patterns pervasive in life could not possibly have emerged through any gradual, undirected process.

In response, biologists wedded to scientific materialism have argued that life is so different from human artifacts that they can dismiss engineers' conclusions about organisms' limited evolvability. A central fallacy in this argument is that they underestimate the fundamental similarities. Design motifs such as four-bar linkages and control systems must meet exacting requirements whether implemented in a space shuttle or a fish. Many of these requirements operate largely independently of the constituent materials that compose them or the exact methods they employ in their operation.

Moreover, the distinctive nature of living systems entails many additional requirements and even stricter constraints. For instance, the vertebrate eye must conform to many of the same or comparable requirements seen in digital cameras (Keum et al. 2018). And its construction requires a highly coordinated manufacturing process in embryology directed by a meticulously engineered genetic control system (Ogino et al. 2012). Not only must a biological element function properly, but an organism must also manufacture, maintain and operate it. These additional requirements translate into insurmountable barriers for any evolutionary scenario (Miller 2017a, 2017b).

In addition, the fundamental differences between human and biological engineering reflect the superiority of the latter. For instance, an international team of biologists and chemists detailed the extraordinary ingenuity associated with the materials that organisms manufacture (Frølich et al. 2017). And nanotechnology engineer Michael Simpson and his team identified how the cells' complexity and capabilities far exceed those of human technology (Simpson et al. 2004):

> The genetic and biochemical processes that generate the complex and versatile behavior of cells operate as highly functional, densely packed, information-processing systems. […] At the heart of this functionality are complex genetic

> regulatory circuits and networks that process information in a manner similar to engineered circuits and systems, but with density, complexity, and capabilities that far exceed those found in manmade systems. […] Obviously, silicon technology will not approach bacterial-scale integration within the foreseeable future. (pp. 848–849)

Engineering models for biological design

The debate over design in life is quickly coming to an end at a practical level. Evolutionists have long stated that the key difference in predictions between evolutionary and design-based models is the extent to which biological systems demonstrate suboptimal (or non-functional) bottom-up design that resembles Rube-Goldberg machines verses optimal, top-down design that resembles human engineering. The latest research has continuously affirmed the design-based predictions.

The purported examples of poor design in biology have consistently been overturned. Supposed 'junk DNA' is increasingly recognised as serving functions such as regulating genes, localising proteins and supporting placental development (Chuong 2018; McGrath 2021; Quinodoz et al. 2021). Biologists increasingly recognise that they need to assume life is designed to properly understand it. Biological systems are now recognised to incorporate the most advanced and effective design patterns seen in human engineering.

Before continuing, two important caveats must be mentioned. Firstly, unlike human engineering, biological design is dynamic. An organism's design plan changes throughout its life cycle. During the development of an embryo into adulthood, different organs and systems appear, modify and disappear to sustain and direct each developmental stage to the next, and many of the features are unique to specific taxa (Ballard 1976; Kalinka & Tomancak 2012). Even after birth, the anatomy and physiology are constantly adjusting to optimise the performance of such activities as eating. For instance, fish are constantly readjusting their skull structure during growth from a juvenile into an adult to maximise their ability to ingest food and respirate (Von Herbing et al. 1996).

Secondly, life represents creations far more advanced than our own. Consequently, scientists may never come close to grasping some of the underlying design concepts. Nevertheless, those aspects of life that can potentially be understood will far more closely align with engineering principles than with what any undirected process could generate.

Despite the described shifts in biological research, the philosophical resistance to openly acknowledging the fact that life is designed will likely continue for several more decades. To help accelerate biological research and mitigate materialist assumptions from retarding scientific progress, proponents of ID have initiated research projects to demonstrate the explanatory and predictive power of design-based biological models. The developing models are founded on the principles and patterns central to human engineering, so they will be referenced as engineering models.

One set of projects addresses biological variation and adaptation. Evolutionary models predict that the total variation in a species during its and its ancestors' tenure on Earth should encompass every facet of the design plan from minor details of nonessential appendages to the underlying design logic. Such limitless variation is required to explain a species' purported history of evolving from something entirely different. Evolutionary models also predict that adaptation is driven by the environment externally. In contrast, design-based models predict that variation is always limited, and adaptation is largely driven by internal mechanisms.

An organism at any given point in its life cycle is organised according to a specific design logic or architecture or body plan founded on engineering principles and motifs. The design plan includes central features that are constant and unalterable (e.g. the basic architecture of an adult fruit fly), and it includes parameters that can vary. The adjustable parameters are defined by the design logic and established during construction, and they correspond to variables (e.g. insect wing length and width) whose values are tightly bounded. The variation allows the fine-tuning of structures and systems to best function in the immediate environmental conditions.

Unlike evolutionary models, environmental happenstance plays a minimal role in setting the extreme range of survivable conditions. Whether the organism can survive within a given environment is ultimately determined by the organism's pre-set operational parameters. For instance, a lack of available food would require muscles to be maintained at a reduced size, but the muscles can only shrink by so much before a functional tolerance is exceeded. After that point, an animal could no longer move quickly enough to capture food or flee predators. It would then soon perish.

The variation in values is determined in part by the internal capacities of an individual to alter variables. For instance, an animal forced to place high stress on its limbs can often increase the strength of bones through internal adaptive mechanisms. Variation also encompasses the genetic diversity in the population, whether originating or expanding through random mutations or through NGE.

The empirical data consistently affirm engineering models. The observed variation in any species is confined to a limited set of variables such as a finch beak's thickness. No genetic variation has been identified which would allow for the basic design logic and operational parameters to change. The average thickness of beaks may increase or decrease, but such changes always remain within a fixed range. And, more fundamentally, beaks always remain beaks. No evidence has been identified that any trait has started to transform into something fundamentally different. And no nonharmful mutation has ever been observed that would expand the genetic variation to allow such a change to occur in the future.

Tracking model for adaptation

One engineering model for adaptation assumes that organisms adapt to the environment using the same engineering principles seen in human tracking systems (Miller 2021d, 2021e, 2021f). More specifically, they continuously monitor the environment and track pre-specified environmental conditions. When the right conditions occur, internal mechanisms induce predetermined responses such as targeted genetic changes, physiological adjustments and or anatomical alterations.

These adaptive processes are directed by irreducibly complex systems that consistently include three components:

1. Sensors to detect pre-specified environmental conditions such as temperature.
2. Logic-based analysers that determine whether specific criteria are met such as the temperature exceeding a set point. When criteria are met, the analysers send signals to trigger the appropriate responses.
3. Effector systems and processes that generate predetermined output responses, such as growing thinner hair.

The resulting changes are targeted, rapid and often reversible. They are also predictable and repeatable. And their magnitude can range from minor alterations to dramatic transformations, but in all known cases these changes are bounded and predefined. The complexity and specificity requirements of tracking systems preclude any possibility of their having arisen through an undirected incremental process.

Over the past few decades, every facet of the tracking model has been increasingly affirmed. The strongest supportive evidence comes from studies of what has been termed NGE and phenotypic plasticity. The leading figure in NGE research has been University of Chicago geneticist James Shapiro. Notable researchers in phenotypic plasticity are developmental biologist Ralf Sommer (2020), extended synthesis proponent Sonia Sultan (Herman & Sultan 2016) and evolutionary biologist David Pfennig (2021). And the leading proponent of tracking models for adaptation in Christian circles has been Randy Guliuzza who has documented the employment of tracking systems in diverse species (Guliuzza & Gaskill 2018).

Natural genetic engineering

Natural genetic engineering refers to genetic alterations that are not random. Instead, they result from cells employing highly complex machinery to direct targeted DNA modifications. Shapiro summarises the processes in a 2016 review article (Shapiro 2016):

> Combinatorial coding, plus the biochemical abilities cells possess to rearrange DNA molecules, constitute a powerful toolbox for adaptive genome rewriting. That is, cells possess 'Read-Write Genomes' they alter by numerous biochemical processes capable of rapidly restructuring cellular DNA molecules. Rather than viewing genome evolution as a series of accidental modifications, we can now study it as a complex biological process of active self-modification. (p. 1)

He further elaborates on the editing systems in a 2017 review article (Shapiro 2017):

> Like all classes of cellular biochemistry, NGE DNA transport and restructuring functions are subject to control by regulatory circuits and respond to changing conditions [...] NGE activities typically affect multiple characters of the variant cell and organism. Consequently, major phenotypic transformations can occur in a single evolutionary episode and are not restricted to a gradual accumulation of 'numerous, successive, slight modifications.' (p. 2)

One could contest Shapiro's claims about what NGE accomplished in the past, but his general description clearly matches the engineering model's central features. The regulatory circuits that respond to environmental conditions correspond to sensors integrated with logic mechanisms. And the transport and restructuring functions correspond to specified output responses. In addition, the DNA modifications are targeted, rapid and bounded as the engineering model expects.

Natural genetic engineering has been identified in all domains of life from the simplest to the most complex. Yeast cells respond to nutrient starvation by increasing the mutation rates at specific locations referred to as mutational hot spots (Jacka et al. 2015). And the remarkable diversity in dog breeds is not the result of completely random mutations. Rather, it largely results from mutational hot spots that allow for increases in targeted genetic variation that can drive rapid adaptation. Biophysicists John Fondon and Harold Garner (2004) noted:

> The high frequency and incremental effects of repeat length mutations provide molecular explanations for swift, yet topologically conservative morphological evolution [...] We hypothesize that gene-associated tandem repeats function as facilitators of evolution, providing abundant, robust variation and thus enabling extremely rapid evolution of new forms. (p. 18058)

The phrase 'topologically conservative' means that the changes are tightly bounded, just as predicted by engineering models.

Equally striking, the genomes of diverse organisms contain DNA segments known as transposable elements (TEs) that can move to new locations, allowing them to alter the activity of local genes. Specific environmental stimuli can initiate relocation to target locations (Bucher, Reinders & Mirouze 2012; Dietrich et al. 2002), and stimuli can activate the TEs, resulting in adaptive benefits. For instance, TEs modify gene regulation in maize to confer drought tolerance, alter flowering time and enable plants to grow in toxic aluminium soils (Filmer 2017; Makarevitch et al. 2015).

Investigators' philosophical bias has led them to describe TEs using terms such as selfish, parasitic or 'invasive genetic elements' (Wells & Feschotte 2020). These depictions contrast sharply with the extent to which they are often regulated (Capy et al. 2000) and targeted (Sultana et al. 2017) and with the benefits they can confer to host organisms. Such observations are forcing the use of increasingly design-based language. Miller Enguita & Leitão (2021) in a recent review article about TEs and other NGE processes commented:

> [*B*]iological variation is the product of collective differential assessment of ambiguous environmental cues by networking intelligent cells. Such concerted action is enabled by non-random natural genomic editing in response to epigenetic impacts and environmental stresses. Random genetic activity can be either constrained or deployed as a 'harnessing of stochasticity.' Therefore, genes are cellular tools. (p. 1)

The phrase 'harnessing of stochasticity' refers to cells initiating mutations or other semi-random genetic changes in specific DNA regions to create targeted genetic variation. This increase in diversity allows a population to fine-tune specific traits to best perform in different environmental conditions.

Phenotypic plasticity

Phenotypic plasticity refers to an organism's ability to transform its anatomy and physiology in response to environmental stimuli. The changes do not result from genetic alterations but from internal adaptive mechanisms. Ralf Sommer enumerated these mechanisms' essential components in a 2020 review article (Sommer 2020):

> [*P*]lasticity requires developmental reprogramming in the form of developmental switches that can incorporate environmental information. However, the associated molecular mechanisms are complicated, involving complex loci, such as *eud-1*, that function as switches and GRNs. While still early, it is likely that switch genes point to a general principle of plasticity because other examples of plasticity also involve complex switch mechanisms. (p. 7)

The 'incorporation of environmental information' tacitly implies the presence of sensors and signal transmission pathways. The switch incorporating the sensory output equates to a logic-based analyser, and the gene regulatory network (GRN) activity corresponds to the output response. The core components perfectly match those of the engineering model for adaptation.

Phenotypic plasticity has been observed in numerous species in diverse taxa. Mice exposed to cold weather will produce offspring with shorter and fewer vertebrae (Ballinger & Nachman 2022). In a more astonishing example, gulls of the family Laridae track the sodium level in their blood with sensors in heart vessels (Sarras et al. 1985). When the level reaches a certain threshold, gulls generate a specialised gland that extracts excess sodium from the blood and excretes it through the beak. If the gull migrates to a freshwater environment, the gland disappears.

Anolis lizards raised on broad surfaces develop long legs allowing for greater sprint speeds, and lizards raised on narrow surfaces develop short legs allowing for more careful movements (Losos et al. 2000). Rove beetles respond to the presence of army ants by transforming their bodies, smell and movements to mimic the ants (Maruyama & Parker 2017). Many other examples have been identified in recent literature.

Model organisms confirm engineering-based models

Many model organisms have dramatically changed their anatomy and physiology as they adapted to new environments. The term model organism refers to a species that is widely studied because it is easy to breed and maintain in a laboratory setting. Key traits of interest are also accessible to the investigation such as how body shape adapts to changing environments.

The standard evolutionary story has been that traits modified gradually because of random mutations and natural selection. Such changes could potentially accumulate over extended periods resulting in large-scale evolutionary transformations. But experiments and observational studies over the past few decades are changing the narrative. Observed variation in all the most iconic model organisms originally purported to support evolutionary theory is now known to support engineering-based models.

Insect wings

Research on *Drosophila* fruit flies demonstrate tight constraints on wing variation. Mathematical biologist Vasyl Alba and his team analysed fruit fly wing diversity (Alba et al. 2021). The researchers employed a sophisticated analytical method to map the differences in wing structure between individual flies in a single population and between different populations. They found that the basic architecture of the wings never altered. They explained the permanence of the underlying structure as resulting from ‘global constraints within the developmental program’ that ensure similar outcomes.

In other words, developmental processes prevent wings from fundamentally altering when perturbed by mutations and environmental fluctuations. Complex mechanisms continuously compensate for such perturbations to keep the embryo's development on course. Previous research identified such corrective mechanisms as a central feature of development in complex organisms (Pezzulo & Levin 2016).

Some mutations sufficiently impact development that corrective mechanisms cannot maintain the core design architecture. Such 'macromutations' are invariably debilitating if not fatal. The negative consequences further confirm the engineering principle that any alteration of parameters beyond the predefined design constraints results in system failure. This conclusion is confirmed by the fact that no genetic variation exists in any species that would allow it to fundamentally change. Geneticist John F. McDonald called this observation a 'great Darwinian paradox' (McDonald 1983).

In addition, the researchers linked the minor variation that did exist to 'very weak mutations' and to phenotypic plasticity. Examples of the latter include a fly developing modified wings in response to changing temperature and diet. Remarkably, the team was able to map the variation from both sources to differences in the value of a single composite variable that primarily corresponds to the precise locations where wing veins intersect. Alba et al. (2021) summarise their work as follows:

> Remarkably, we find that the outcomes of wing development can be statistically described by a one-dimensional (1D) linear manifold in morphological space that corresponds to a non-intuitive combination of structural variations across the wing. This dominant mode is systematically excited by variants generated by very weak mutations in signaling pathway genes as well as by thermal and dietary environmental perturbations. As such, our work provides direct empirical evidence for the presence of global constraints within the developmental program of the wing, funneling environmental inputs and genetic variation into phenotypes stretched along a single axis in morphological space. (p. 2)

These observations perfectly match the engineering-based predictions that variation only exists for predefined adjustable parameters, and the values of related variables (e.g. locations of wing vein intersections) are tightly bounded.

Other research validates the tracking model for adaptation for fruit flies by demonstrating that even the variation in the adjustable parameters did not originate from random mutations but from engineered adaptive mechanisms. The genetic variation appears to have largely resulted from NGE. Up to 80% of 'spontaneous' mutations in fruit flies are initiated by TEs (Mérel et al. 2020). Weber et al. (2005) identified several TE insertions that affect wing structure.

Multiple studies have identified other examples of phenotypic plasticity in insect wings. For instance, Bitner-Mathé and Klaczko demonstrated that fruit flies respond to changing temperature and population density by altering their wing size, shape and vein pattern (Bitner-Mathé & Klaczko 1999).

Fraimout et al. (2018) described how fruit flies respond to lower temperatures by increasing the ratio of wing size to body size. The reduction in load on the wings compensates for cold-induced lower muscle efficiency. They also described how flies alter the shape of their wings to increase the stroke force to compensate for lower beat frequency.

Gao et al. detailed an even more dramatic example in planthoppers (Gao et al. 2019). These insects track environmental cues such as temperature, food quality and population density. Depending on the conditions, they can generate two different versions (aka phenotypes or morphs). In nutrient-rich environments, nymphs develop into the 'short-winged' phenotype with reduced or missing wings, decreased flight muscle tissue and lower energy metabolism. This form is more efficient in a local environment with abundant food. More importantly, this phenotype reproduces earlier and produces more eggs, which benefit the population in such favourable conditions.

The 'long-winged' phenotype is generated if the environmental conditions deteriorate because of reduced food supply or overpopulation. This version has a well-developed flight apparatus with longer wings, larger flight muscles and an enhanced energy metabolism. It can escape the unfavourable environment and colonise new locales.

The switching mechanism between the phenotypes is exceedingly intricate. Environmental sensors feed readings to the IIS signaling pathways that are commonly employed in complex organisms to control tissue growth and body size. The IIS signaling component triggers a host of other mechanisms that direct hundreds of genes including the production of alternative versions of proteins. The ingenuity and complexity behind switching mechanisms in even the simplest of animals (Sieriebriennikov et al. 2018), and the other referenced mechanisms not only highlight the extraordinary design behind biological adaptation, but they also reinforce the need for engineering models, tools and language to broaden and expand our understanding of living systems.

Cichlids

The dramatic variation in cichlid fish has become a poster child for the creative power of evolutionary processes, but research over the past 15 years has shown the opposite. Cooper et al. demonstrated that variation in cichlid feeding is tightly constrained (Cooper et al. 2010). The investigators used a principal component analysis (PCA) to quantify differences in feeding structures for cichlid populations in Lakes Tanganyka, Malawi and Victoria. This technique creates composite variables that capture how the value of one variable (e.g. head width) correlates with another variable (e.g. jaw length) or variables for each fish. The analysis revealed that variation in all populations largely resided along the same two composite variables (also known as principal component axes).

Kara Feilich performed a PCA on cichlid body and fin structures, and she also found that the same variation occurred repeatedly in separate populations (Feilich 2016):

> Body shape disparity among the cichlid fishes has been studied extensively, repeatedly demonstrating common axes of diversification across many lineages, including the tropheines (Wanek and Sturmbauer 2015), geophagines (Astudillo-Clavijo et al. 2015), and others (Clabaut et al. 2007; Muschick et al. 2012). (p. 2260)

Feilich noted that changes in traits were highly correlated to optimise hydrodynamics and manoeuvring. Of key importance, the underlying design architecture never changed. Only the flexible parameters were adjusted to fine-tuned individuals in a population to best perform in its immediate environmental conditions.

Other studies identified phenotypic plasticity in multiple traits. Mazzarella et al. raised cichlids in water with different salinity levels. Greater salinity resulted in adult fish displaying shallower bodies and longer jaws (Mazzarella et al. 2015). Härer et al. (2019) exposed Midas cichlids to light of different frequencies. In response to a change in frequency, the cichlids switched the expression of cone opsin genes crucial for colour vision in only a few days.

Parsons et al. fed two separate groups of young juvenile fish different diets (Parsons et al. 2016). The two groups developed into adults with distinctly different head-jaw structures that were tailored to forage for the available food most effectively. Navon et al. reported on a similar experiment that confirmed the Parsons et al. results (Navon et al. 2021). The investigators also demonstrated diet-induced adaptive changes to body shape and fin-ray number. The observed dissimilarity between the two diet groups mimicked the differences between distinct cichlid species in the wild.

Researchers increasingly recognise that the most significant variation in cichlid fish results not from random mutations but from internal adaptive mechanisms. Parsons et al. (2016) noted:

> [*T*]here is an emerging view that additive genetic variation accounts for a relatively small percentage of phenotypic variation and rather it's the context in which traits develop that determines their final form (Hallgrimsson et al. 2014; Hendrikse et al. 2007; Jamniczky et al. 2010; Pfennig et al. 2010). (p. 6021)

Other investigators discovered that some of the key genetic variation that did exist resulted from genetic alterations that point to NGE. Carleton et al. demonstrated that some of the most important variation resulted from TEs that were targeted to the genes underlying vision (Carleton et al. 2020).

Sticklebacks

As with cichlids, all studies on stickleback fish diversity demonstrate that variation is tightly constrained. Hohenlohe et al. documented how the same variation in traits and genetics appears repeatedly in separate populations (Hohenlohe et al. 2010):

> Genomic regions exhibiting signatures of both balancing and divergent selection were remarkably consistent across multiple, independently derived populations, indicating that replicate parallel phenotypic evolution in stickleback may be occurring through extensive, parallel genetic evolution at a genome-wide scale. (p. 1)

Miller et al. came to the same conclusion after analysing the genetic differences between populations that inhabited lakes in the presence and absence of prickly sculpin, a fish that is a stickleback predator (Miller, Roesti & Schluter 2019). Sticklebacks that interacted with prickly sculpin rapidly acquired similar alterations to hundreds of the same genes. The two studies demonstrate that sticklebacks adapt genetically to environmental changes predictably and rapidly.

These observations suggest that NGE might be driving targeted genetic alterations. Another study has identified NGE more explicitly. Ishikawa et al. discovered that multiple stickleback species duplicated the Fads2 enzyme allowing the species to better synthesise the essential fatty acid DHA (Ishikawa et al. 2019). This enhanced ability allowed them to colonise DHA-deficient freshwater environments. The authors suggest that the duplications were facilitated by NGE, possibly the relocation of TEs.

Other investigators identified examples of phenotypic plasticity. McCairns and Bernatchez discovered that sticklebacks inhabiting freshwater and saltwater zones of a large estuary measure the salinity of the water (McCairns & Bernatchez 2010). They use this information to optimally regulate the expression of genes controlling the transport of salt ions, so the fish can quickly adapt to salinity changes.

Baker et al. demonstrated that stickleback females track internal physiological information such as lipid supply and liver glycogen level and environmental cues such as availability of food and population density (Baker et al. 2015). Different cues initiate adjustments to such reproductive parameters as a time of breeding, egg size and clutch or brood size. The alterations improve the likelihood for the population’s continued survival. The researchers also discovered that individual fish coordinate the fine-tuning of multiple traits to ensure optimal reproductive success.

As a final example, Tibblin et al. (2020) raised sticklebacks in an aquarium with different colour backgrounds. The investigators also mimicked the presence of predators by chasing fish with a dip-net and introducing chemical cues mimicking the presence of Pike, which is a natural predator. Both colour and predatorial stimuli triggered changes in the dorsal colouration that assisted the fish in avoiding detection.

Cavefish

Cavefish also demonstrate phenotypic plasticity for multiple traits. Rohner et al. raised *A. mexicanus* embryos in water with low conductivity mimicking cave conditions (Rohner et al. 2013). The embryos developed into adults with significantly smaller eyes. Corral and Aguirre raised *A. mexicanus* in different temperatures and different levels of water turbulence (Corral & Aguirre 2019). The variant conditions resulted in adult fish differing in vertebral number and body shape. For instance, fish raised in more turbulent water displayed more streamlined bodies and extended dorsal and anal fin bases that improved their mobility in that environmental condition. Bilandžija et al. raised the same species in darkness, and the fish developed many cave-related traits such as resistance to starvation and altered metabolism and hormone levels (Bilandžija et al. 2020). Future studies will likely demonstrate more examples of phenotypic plasticity and NGE.

The collapse of evolutionary icons

Cichlid, stickleback and cavefish represent three of the most iconic examples of adaptation that biologists present as evidence for the plausibility of evolutionary processes driving large-scale transformations. Yet research over recent decades demonstrates that evolutionary and adaptive processes are constrained in these fish, as in all complex organisms, to only minor alterations to existing traits or to the loss or duplication of an existing structure.

Some random mutations do occur that confer benefits, but nearly all of them either degrade genes or cause modifications so trivial that they could never accumulate to fundamentally alter any trait. This conclusion was confirmed by an extensive survey of the technical literature conducted by Michael Behe in his book *Darwin Devolves: The New Science About DNA That Challenges Evolution* (Behe 2019).

Behe specifically addresses studies of the variation in cichlid genes. One investigation identified amino acid changes in a gene affecting colour patterning. The mutant genes appeared to lose certain abilities, so the mutations degraded the original gene. Another study identified a mutation in a gene that conferred slightly improved light sensitivity at certain depths (Nagai et al. 2011). In this case, only a single amino acid in one protein changed. In contrast, nearly all the most significant adaptation results from carefully controlled processes that leave little to blind chance.

Engineering models and the pattern of life

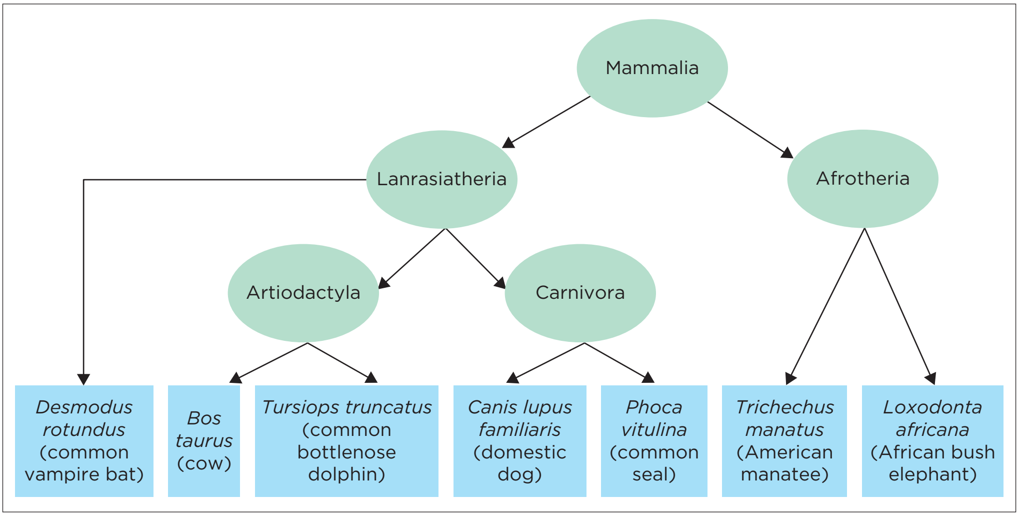
Engineering-based models also better explain the pattern of similarities and differences between species in the higher taxonomic groups (e.g. phyla, classes and orders) than the theory of common ancestry (Miller 2018, 2021b).

Computer scientist Winston Ewert demonstrated that the distribution of the same gene families in diverse species far better fits what he refers to as a dependency graph model than the common ancestry model (Ewert 2018). His central conclusion is that similarities in life represent modules that were implemented in diverse species to achieve similar goals. This general conclusion has been validated by multiple lines of research over the past few decades.

The collapse of the tree of life[58]

One of the central pillars of the standard evolutionary model is the belief that all living species evolved from a common ancestor through a gradually unfolding TOL. As a result, the theory predicts that the pattern of similarities and differences in species today should fit into a tree-like pattern or nested hierarchy where branching points correspond to the appearance of new traits. For instance, all mammals share certain features, such as producing milk, since their most recent common ancestor first evolved them. Those traits carried through each evolving branch of the mammal tree (Figure 7.2). The claim that all species fit into the TOL has been presented to the public as one of the strongest pieces of evidence for the belief that all of life evolved through undirected processes.

What the public is rarely told is that the pattern of physical traits and molecular sequences in species does not fit into a consistent evolutionary



Source: Ewert (2018).

FIGURE 7.2: A subset of the mammalian tree of life. Rectangles are extant species, and ellipses are postulated ancestral species, the most recent common ancestor of each taxonomic category.

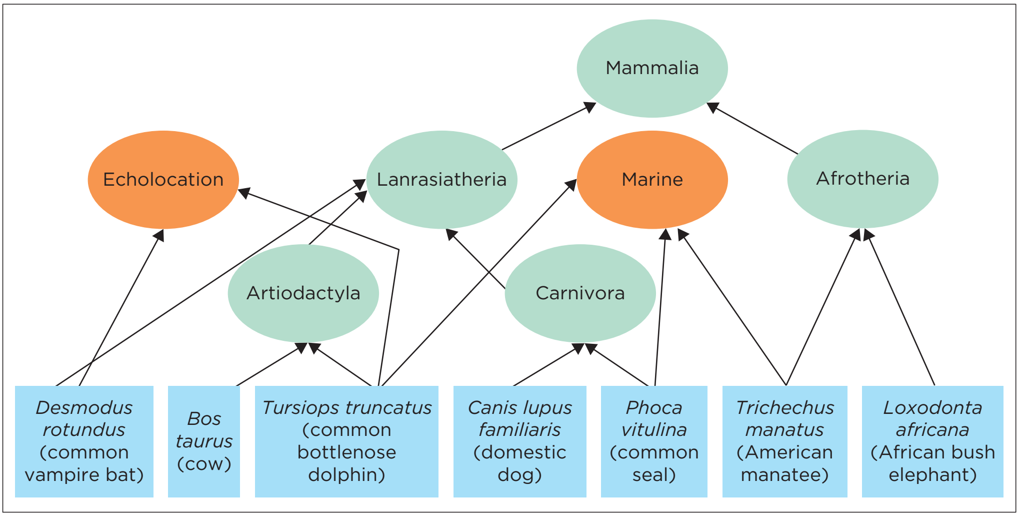
---

[58] This section represents a reworking of excerpts from Miller (2018).

tree (Figure 7.3). As an iconic example, bats and dolphins both possess echolocation, which is undergirded by the same modifications at nearly 200 locations in their genomes (Parker et al. 2013). The species are not believed to be closely related, so the similarities must have originated independently in direct conflict with the prediction of common ancestry. Such conflicts are frequent and widespread in nearly all taxa.

Zoologists Klassen, Mooi and Locke (1991) summarised across numerous studies the percentages of traits that fit consistently with the best-constructed evolutionary trees. The researchers plotted the percentages (also known as consistency indexes) on the same graph as those derived from randomly generated data, and the values were then adjusted to remove the effect of random noise. The results indicate that most of the data do not fit the prediction of common ancestry.

More recent research on the rescaled consistency indexes (RCI) of numerous animal groups confirms this conclusion. An RCI of 1 indicates that all the data fit consistently with an evolutionary tree. An RCI of 0 indicates that the appearance of similarities is completely random. Data of the traits in arthropods yielded an RCI of 0.39 (Wolfe 2017). The RCI for therapsids (purported ancestors to mammals) was 0.42 (Huttenlocker 2009). The RCI for primates and their purported closest relatives was 0.29 (Bloch et al. 2007). And the RCI for Cetaceans (e.g. whales and dolphins) and their purported closest relatives was 0.24 (Thewissen et al. 2001). Evolutionists cite these groups as representing some of the strongest evidence for common ancestry, but their low RCI values demonstrate the opposite.



Source: Ewert (2018).

FIGURE 7.3: A possible subset of the mammalian dependency graph of life. Rectangles are species, and ellipses are postulated modules. The orange ellipses are modules postulated in addition to the standard taxonomic modules.

Evolutionists historically predicted that RCI values would fall far closer to 1 than to 0, which they clearly do not. The low values demonstrate that the assumption that similarities in traits reliably imply common ancestry is false. The problem has become so acute for microorganisms that microbiologists Merhej and Raoult described attempts to identify the TOL in the most disparaging of terms (Merhej & Raoult 2012):

> None of the seven points laid out in the introduction to this manuscript can be permanently retained, as established by Darwin's theory, which was at the time a fight against the creationists. This theory cannot be upheld in its entirety. Recent advances from genomics refute the ideas of gradualism, exclusive vertical inheritance, evolution selecting the fittest, a common ancestor and the TOL. Indeed, there may not be any two genes that have the same evolutionary tree. (p. 36)

These disappointing results have forced evolutionists to propose several mechanisms to explain the recurrent inconsistencies. Examples include lateral gene transfer (LGT), differential gene loss, incomplete lineage sorting and convergent evolution. Lateral gene transfer refers to genes passing from one organism to another. This process could theoretically explain how the same genes appear in unrelated species, but the plausibility of widespread LGT in complex organisms has been seriously questioned (Martin 2017). Incomplete lineage sorting and gene loss cannot explain complex traits appearing in distantly related organisms. The claim that complex adaptations can evolve independently multiple times (i.e. convergent evolution) collapses on close examination because of the implausibility of their appearing through undirected processes even once.

For instance, eyes with lenses are believed to have evolved independently multiple times, but all evolutionary scenarios face insurmountable barriers. The first mutations in the origin of a lens would allocate tissue in front of the photoreceptors. The problem is that undifferentiated tissue would degrade light reception, so the first mutations would quickly disappear. The lens would not become beneficial until a complex developmental process coupled to a new GRN emerged (Ogino et al. 2012). Yet the available time based on the fossil record is insufficient for even the tiniest fraction of required new genetic information to arise (Hössjer et al. 2021).

Engineering modules

In contrast, engineering-based models satisfactorily explain the pattern of similarities throughout life. Design architectures often fall into a hierarchical pattern. All transportation vehicles have certain common features such as allocated space for cargo and or passengers, propulsion system and steering. Cars possess all these features plus such components as wheels, breaks, coolants, lubricants and axles. Toyota Camry models possess all these features plus additional specialised components. The similarities in transportation vehicles would likely fit into a constructed tree at least as well as different groups of species.

While many features in human products fit into a hierarchical tree-like pattern, many break that pattern. A police car and an airplane both have two-way radios while two-way radios are absent in most other cars. In addition, the same circuitry is implemented in a wide variety of vehicles to meet similar goals. This pattern reflects how engineers often create modules that can be used in diverse contexts. The modules must be designed with the explicit intent of operating in different products, and the products that use the modules must be designed to properly incorporate them into their operations. The same pattern and constraints are observed in life.

Many of the same traits are implemented in diverse creatures to perform similar functions. Different versions of eyes (e.g. compound and camera-like) appear independently multiple times to allow optimal vision in each species' particular environment. And very similar neural and developmental modules appear independently in unrelated species. Neuroscientists Sanes and Zipursky identified in both fly and human visual systems remarkably similar design motifs in the retinas, neural circuits in the brains and genetic control mechanisms in development (Sanes & Zipursky 2010) even though the different eyes are believed to have evolved independently (Piatigorsky 2008).

Similarly, mathematical biologists Robyn Araujo and Lance Liotta (2018) demonstrated that all biological networks that perform 'robust perfect adaptation' (RPA) can be broken down into two distinct classes of modules. The researchers define RPA as (Araujo & Liotta 2018):

> [*T*]he ability of a system to generate an output that returns to a fixed reference level (its 'set point') following a persistent change in input stimulus, with no need for tuning of system parameters. (p. 2)

The same modules appear in systems as diverse as signal transmission, gene regulation, protein interaction networks, sensory systems and developmental regulation. They are often combined hierarchically to perform more complex functions.

Of key importance, the base modules operate within exacting constraints:

1. Their constituent components must interconnect according to specific blueprints.
2. They cannot be subdivided, so they comprise a set of components that are irreducibly complex.
3. Their operations must solve a local adaptation equation, so reactions or other processes must operate within tight bounds.
4. The integration of the modules into larger systems must also meet rigid mathematical criteria.

These constraints imply that the modules' origin and implementation could not have occurred incrementally through an undirected process as their construction and integration requires coordination, foresight and goal-direction. Szallasi, Stelling & Periwal (2007) assume evolution must be true as a faith commitment, but they still comment:

> [*T*]he concept of 'modular design' is borrowed from human engineering and therefore has an essentially forward looking, goal-oriented nature. Complex engines and networks are constructed from modules while the final overall behavior of the system is kept in mind. (p. 44)

The pattern of nature also corresponds to engineering principles in the distribution of species diversity. In human engineering, many versions of a particular design are often created. Each year, Toyota manufactures the same car model with different sets of modules such as cameras and tracking systems. But few products would fall outside of the larger categories. Vehicles have rarely been designed that would fall part-way between a submarine and an airplane.

Similarly, many different species exist that represent different versions of the same theme. Several ape-like and human-like creatures have been identified that share various similarities. But the similarities do not fit within a consistent evolutionary tree (Collard & Wood 2000). And clearly intermediate creatures between primates and other orders of mammals have never been identified (Gingerich 2006). In summary, the pattern of nature does not point to an undirected evolutionary process but ID.

Case studies on engineering models

Two case studies will further illustrate engineering models' explanatory and predictive power. The first focuses on minimally complex cells and the origin of life. The second describes an engineering-based analysis of the bacterial flagellum.

Minimally complex cell

The two chapters by James M. Tour and Fazale Rana detail the implausibility of a cell ever originating through undirected natural processes. I have previously explained the insurmountable thermodynamic challenges to a chemical system spontaneously coalescing into an autonomous cell (Miller 2020a, 2020b). These analyses are critical to the design argument. The only explanations for life, or any artifact, are natural processes, chance, chance and natural processes or design (Dembski 2006). The fact that natural processes and or chance cannot explain life's origin in itself supports the design inference. The addition of the following positive evidence makes the identification of the design conclusive.

Engineering analyses elucidate in even the simplest of cells much of the underlying architecture and the clear top-down design logic. Top-down logic requires levels of foresight, coordination and goal-direction that only intelligent agents can implement. Such evidence has forced even scientists who philosophically reject design to unconsciously recognise in life's origin its necessity.

Systems engineers have analysed the minimal requirements for self-replication in such systems as lunar factories (Freitas 1980) and robots (Moses & Chirikjian 2020). The research was guided by the theoretical work of mathematician John Von Neumann (1966). In parallel, several studies have attempted to identify the minimal components of an autonomous cell (Xavier, Patil & Rocha 2014). The confluence of these two streams of research demonstrates that a minimally complex autonomous cell must possess at least the following components:

1. Machinery for energy production and delivery.
2. Information repositories and processors.
3. Selective gateways with active transport.
4. Sensors coupled to signal transduction pathways and signal processing.
5. Actuators that implement instructions.
6. Manufacturing and auto-assembly processes.
7. Automated repair machinery.
8. Error-correction systems.
9. Waste disposal and recycling mechanisms.
10. Control systems capable of global coordination.

The theoretical engineering analyses match not only many of the components of minimally complex cells but also their interrelationships and underlying design logic.

This correspondence demonstrates that cells display top-down design where an overarching design architecture determines the higher-level systems and their interdependencies. Each system also operates according to its own design pattern (e.g. control feedback loop) that determines the lowest-level processes. The design patterns are disassociated from and transcend the physics and chemistry of the underlying molecules, so little that occurs in a cell would happen without external management.

Leading origin-of-life researchers Elbert Branscomb and Michael Russell explain how cells must employ molecular machines to manage such processes as chemical reactions (Branscomb & Russell 2018a):

> But even those of life's molecular transformations that do run downhill have to be taken out of chemistry's hands and 'managed' by a dedicated macromolecular machine – in order to impose conditionally manipulable control over reaction rates and to exclude undesirable reactions, both as to reactants and products. On its own, chemistry is far too indiscriminate and uncontrollable [...]. (p. 1)

They even acknowledge that everything must conform to an 'elaborate organisational design'.

The researchers state that molecular machines are not only required in life today, but they were also essential at its emergence (Branscomb & Russell 2018b). Remarkably, they also acknowledge that even the most basic elements of life could never have arisen through natural chemical processes:

> We claim in particular that it is untenable to hold that life-relevant biochemistry could have emerged in the chemical chaos produced by mass-action chemistry and chemically nonspecific 'energy' inputs, and only later have evolved its dauntingly specific mechanisms (as a part of evolving all the rest of life's features). (p. 4)

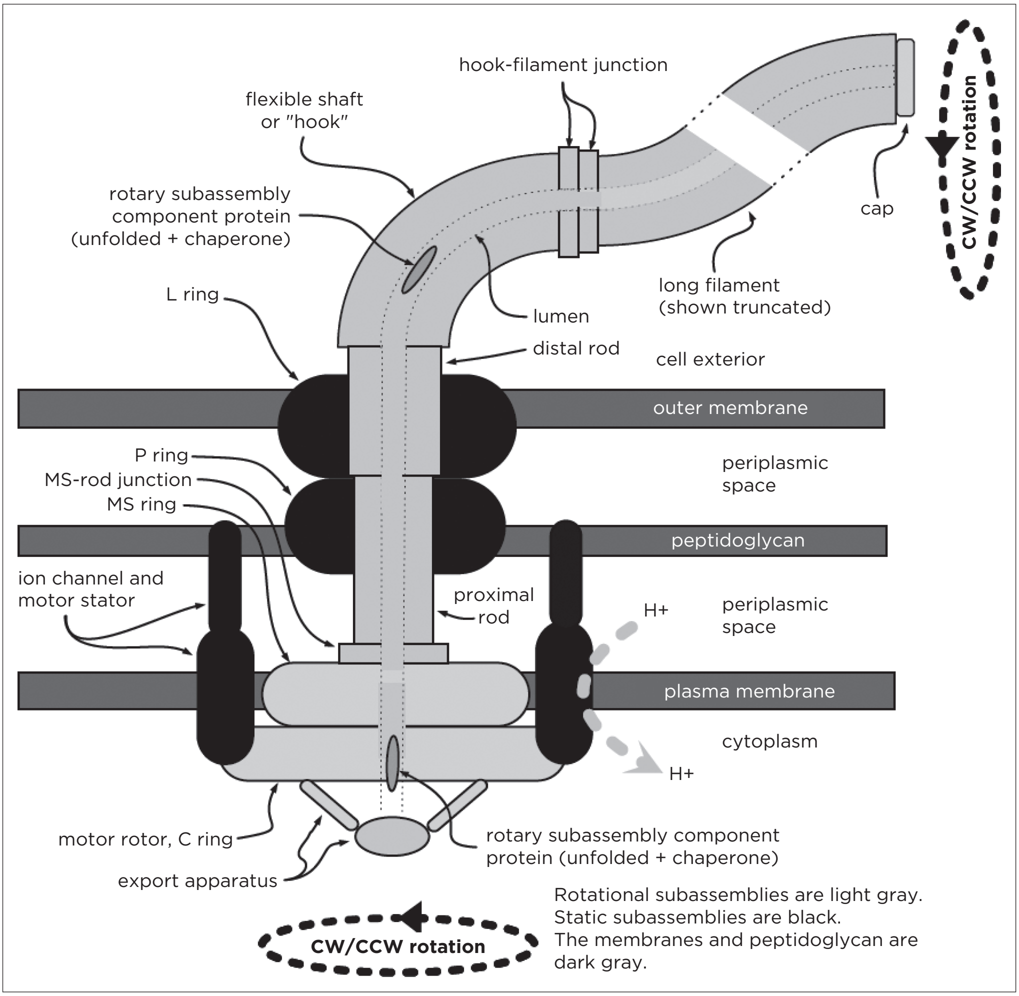
They respond to this seemingly insurmountable barrier by appealing to natural selection as a guiding hand to bring every system into being and properly interconnect them. The obvious problem is that natural selection could not have commenced before an autonomous self-replicating entity appeared. The authors in effect tacitly acknowledge that life is the product of ID, but they use the language of natural selection to smuggle intelligent agency into their theory without giving due credit to the designer.

Bacterial flagellum

The bacterial flagellum functions as a rotary propulsion system in bacteria (Figure 7.4) and showcases the predictive power of engineering models (Miller 2022). The system employs many stunningly complex subsystems. The assembly operation is directed by a genetic network (Fitzgerald, Bonocora & Wade 2014) that ensures the manufacture of the right proteins in the right quantities at just the right time. The proteins that compose the propeller are transported across the cell membrane through a transport gate that only allows the correct ones through at the correct time by employing protein signal sequences (Evans, Hughes & Fraser 2014).

Other proteins assemble the hook and propeller (Kim et al. 2017; Ohnishi et al. 1994). Another protein acts as a ruler that coordinates with the gate to ensure that the flagellar hook extends to the correct length (Waters, O'Toole & Ryan 2007). A navigational control system controls the rotation of the rotary motor (Hamadeh et al. 2011).

Computer scientist and engineer Waldean Schulz approached the design of the flagellum with a method that could be described as ground-breaking. He first outlined what he expected would be the most efficient architecture for a nanotechnology rotary propulsion system (Schulz 2021a). He started with the highest level in the organisational hierarchy and mapped the overarching design of the core processes, including manufacturing, assembly, energy production, torque generation, environmental tracking and directional control. He graphed the expected minimal components and their functional relationships. He also anticipated design requirements and constraints.



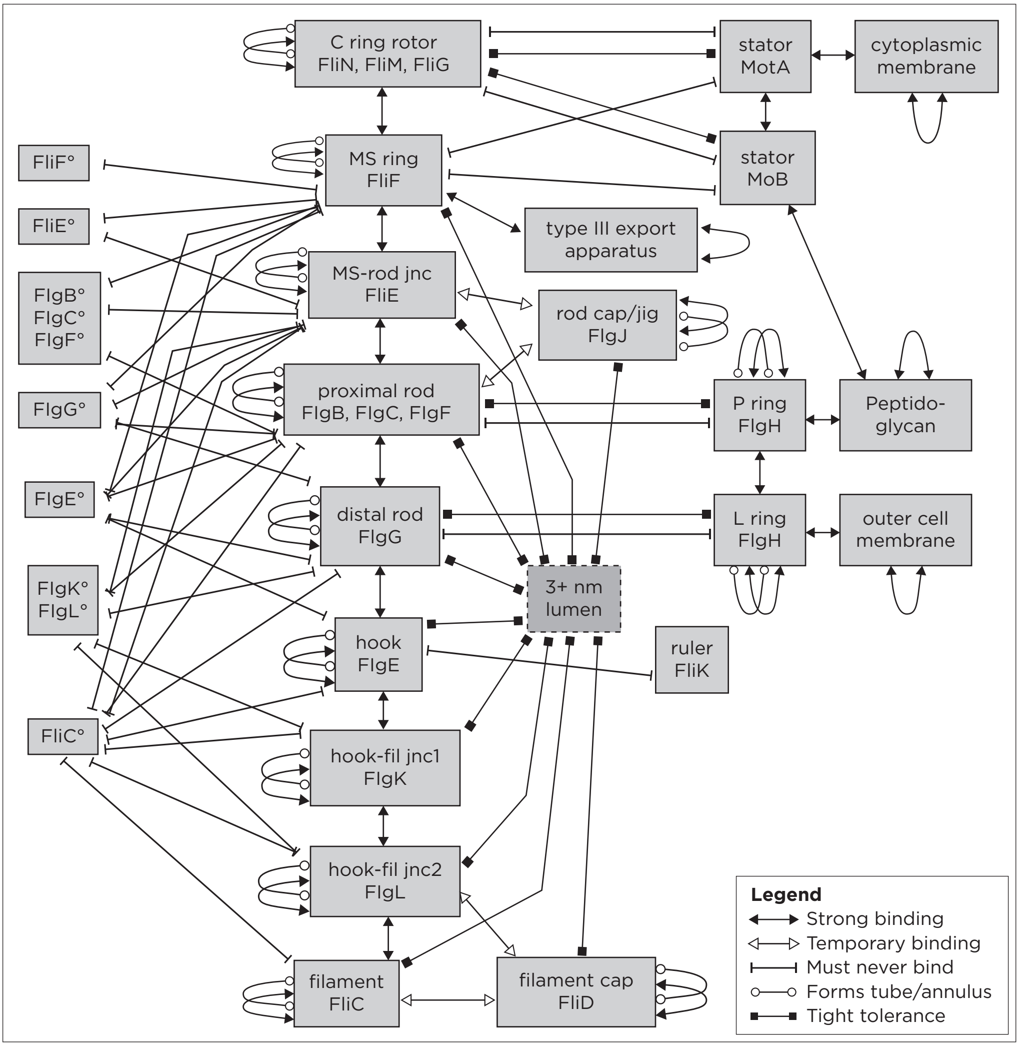
Rotational subassemblies are light gray.
Static subassemblies are black.
The membranes and peptidoglycan are dark gray.

Source: Schulz (2021a).

FIGURE 7.4: Structure of an archetypical flagellum.

He then reviewed the literature on actual flagellar operations starting with the processes at the bottom organisational level (Schulz 2021b). Finally, he compared the top-down and bottom-up analyses (Schulz 2021c). Schulz's expectations for the design architecture, interrelationships and constraints match the actual operations to a remarkable extent.

In addition, he identified numerous tight constraints that must be met for the flagellum to function at an efficiency that would provide any benefit to the cell. The constraints include over 80 requirements for the interactions between the individual proteins (see Figure 7.5). For instance, some proteins must bind together permanently, others temporarily, others must never bind. If any one of these criteria is not met, the flagellum would provide no benefit to the cell. It would instead disadvantage the cell by wasting resources.



Source: Schulz (2021b).

FIGURE 7.5: Binding and geometrical properties of the proteins.

Schulz's analysis demonstrates that the flagellum was engineered around a clear overarching design logic where every system and component was optimally designed to integrate with multiple other systems and components in symphonic harmony. Each of these systems is required for proper operations, and they must coordinate with each other with extremely high efficiency. The number of essential components, interrelationships, requirements and constraints in the flagellum proves that the system must have originated at once through the act of an intelligent agent. Schulz's work is simply a foretaste of the long-term clarity and insights engineering-based models will bring to the study of living systems.

Future research

Future researchers can follow Schulz's example by identifying the engineering logic underlying other living systems. They can then also anticipate the core components, their interrelationships and the operational constraints by comparing the systems to comparable human creations. This task is only possible because life does not employ design patterns and processes that are analogous to those used in human engineering. But they are the same patterns and processes.

Life does not employ systems analogous to information-processing, but they are synonymous with information-processing. And cells do not replicate DNA using systems analogous to error correction, but they perform error correction. This recognition will avoid the misdirection that often occurs from the false assumptions attached to scientific materialism (e.g. suboptimal bottom-up design), and it will accelerate progress in biological research.

Conclusion

The field of biology has just begun to enter the next great scientific revolution where the philosophical pendulum has started to swing away from scientific materialism and back towards the design-based philosophical traditions of Plato and Aristotle. The sheer weight of the evidence has forced this shift upon the scientific community. In particular, the central predictions of evolutionary theory have consistently failed while the predictions of ID have been increasingly confirmed. This paradigm shift is clearest where scientists have most incorporated engineering principles and insights into their biological research.

Incorporation of design concepts: Biologists have only now begun to tap into engineering models' explanatory and predictive power. Schulz's application of engineering principles to analysing the flagellum allowed him to anticipate much of the rotary system's structure and operations. As his top-down integrated with bottom-up approach is applied to other systems, investigators will increasingly recognise that the only viable framework for understanding life is starting from the assumption of design. This trend will only accelerate as discoveries continue to demonstrate the top-down nature of biological design, the optimality of living systems and the tight constraints intrinsic to biological systems.

Many systems biologists have already come to recognise that they must incorporate the core ID concepts into their analyses, albeit using different language, to advance their research. The heuristic of ID is simply a more general rubric for the application of engineering principles to the study of life. More specifically, Behe's concept of irreducible complexity is implicit in the tenet of holism as described earlier. William Dembski's formulation of specified complexity is a more general category for biologists' understanding of design modules.

The argument for design: This last example is of critical importance. Specified complexity entails a pattern that is not the product of a natural process, extremely rare and matches a special externally defined pattern (Dembski 2006). Patterns that demonstrate specified complexity beyond a certain threshold are always the product of design. An example would be Scrabble letters arranged to spell out an intelligible paragraph. Life demonstrates many examples of specified complexity; therefore, Dembski has argued that the conclusion that life is designed is nearly certain.

Yet evolutionists challenged Dembski by countering that one cannot conclusively demonstrate that a pattern in biology is in any way special. They also asserted that a biological entity might appear highly improbable to have originated by chance, but many other biological solutions might also have played the needed role. The probability of finding one solution out of the multitude might be tractable.

The observation that life employs the same design motifs seen in human engineering as modules overturns these objections. A design motif is a highly improbable, special pattern. Relatively few exist in biology that solve engineering tasks such as RPA. In addition, the fact that the same motifs used in human engineering are implemented repeatedly in life demonstrates that multiple other options do not exist that life could have stumbled across by chance.

The theological implications: This conclusion and the corresponding paradigm shift in biology entail substantial theological implications. Many Christians have attempted to reconcile evolutionary theory with Christian theology, but their efforts have often resulted in jettisoning or distorting historic Christian doctrines and twisting biblical texts. Or they have portrayed evolutionary theory in terms that directly conflict with how the theory is generally understood and taught (Moreland et al. 2017). Now, the scientific evidence is so decisively in favour of design that Christians no longer need to waste time in the futile task of accommodating Christian theology to secular creation narratives.

In addition, the design patterns seen in life demonstrate that God created the world so that specific engineering motifs work effectively to achieve such goals as vision or locomotion. This realisation explains the striking similarities between human creations and living systems, and it explains how Schulz was able to predict so many details of the flagellum's structure and operations.

Christians can now speak with complete confidence about the clear evidence of God's hand in life. Many atheists and agnostics who hear the truth will continue to suppress it, but for others the evidence will break their minds free from secular philosophies. They will then gain the freedom to pursue a relationship with their Creator.

Chapter 8

The evidence of foresight in nature

Marcos Eberlin
Discovery-Mackenzie Research Centre for Science, Faith and Society,
Mackenzie University,
São Paulo, Brazil

Introduction[59]

Advances in multiple scientific disciplines have identified in nature evidence that a mind designed the laws of nature, our planetary system and life. Nature demonstrates foresight where ingenious solutions were devised to confront problems and challenges related to sustaining and propagating life. Examples include the cell membrane, the genetic code, bacteria acting as ecosystem engineers, bird navigation, water and our planet. This evidence points not to life resulting from blind, undirected processes but to every aspect of nature being designed by God.

Biology is amid a gold rush of discovery. At my previous academic institution, the University of Campinas in São Paulo, Brazil, I ran the Thomson Mass Spectrometry Laboratory for 25 years. There, my team and I delved into many areas of chemistry, biochemistry and medical science that until recently

---

[59] The content of this chapter are excerpts from my book *Foresight: How the Chemistry of Life Reveals Planning and Purpose* (Eberlin 2019). The book includes expanded discussions on the content covered in this chapter and on many additional examples of foresight displayed in nature.

How to cite: Eberlin, B 2022, 'The evidence of foresight in nature', in F van Niekerk & N Vorster (eds.), *Science and Faith in Dialogue*, in Reformed Theology in Africa Series, Vol. 10, AOSIS Books, Cape Town, pp. 213–242. https://doi.org/10.4102/aosis.2022.BK334.08

were still too new to have names – everything from proteomics, lipidomics and mass spectrometry imaging to petroleomics and bacteria fingerprinting.

My research, along with my role as president of the Brazilian Mass Spectrometry Society and the International Mass Spectrometry Foundation, has brought me into contact with other leading researchers in Brazil and around the globe. And when we come together at conferences, the excitement is tremendous. Due to a cluster of breakthrough technologies and techniques, almost every week reveals some new wonder in the biological realm.

Some of these discoveries yield new medicines or medical techniques, such as the abundantly awarded cancer pen recently developed by my daughter, Livia Eberlin. Others give engineers new ideas for inventions in the burgeoning field of biomimetics. Still others have no immediate practical application; they are just revelations of beautiful biological ingenuity – scientific discovery for its own sake.

All of this new knowledge is exhilarating in its own right. At the same time, I am now convinced that many of these discoveries, taken together, point beyond themselves to something even more extraordinary. This new age of discovery is revealing a myriad of artful solutions to major engineering challenges, solutions that for all of us appear to require something that matter alone lacks. I will put this as plainly as I can: This rush of discovery seems to point beyond any purely blind evolutionary process to the workings of an attribute unique to minds – *foresight*!

And yes, I know: We are told that it is out of bounds for science to go there. We will take up that claim in subsequent chapters. But regardless of where you ultimately land on the question of what conclusions science should or should not allow and whether or not you ultimately affirm that this gold rush of new evidence points to the workings of foresight, I urge you to inspect the evidence. Curiosity may have killed the cat, but it has done wonders for the scientific enterprise.

The many and ingenious examples uncovered in recent years are so numerous they could fill many large volumes. The pages that follow highlight only a small fraction of the total. But that fraction is filled with marvels. We will look at the cell membrane, the genetic code, bacteria that act as ecosystem engineers, avian navigation, water and our planet.

■ The cell membrane

Life thrives in our diverse planetary environment, due in no small part to the many ways Earth is fine-tuned for life. But Earth can also be extremely hostile to life. The oxygen molecule (O_2) is, for instance, essential to life, but only a life form that can efficiently wrap and transport the ‘*devil*’ O_2 exactly to a place where it can be used as an energy source would benefit from its angelic side. Otherwise, O_2 becomes life’s greatest enemy.

Rupture the membrane of a living cell, exposing it to the air, and you will see the great damage O_2 and a myriad of other chemical invaders can do to a perforated cell. Death would be swift and sure. From an engineering standpoint, then, it was essential that a way be found to protect the cell, life's most basic unit. The solution was clever: the cell was surrounded by a strong chemical shield from the very beginning.

Murphy's law dictates that a solution always brings with it two additional problems, and a cellular membrane shield is no exception. A simple shield could indeed protect the cell interior from deadly invaders, but such a barrier would also prevent cell nutrients from reaching the inside of the cell, and it would trap cellular waste within. Small neutral molecules could pass through the membrane but not larger and normally electrically charged biomolecules. A simple shield would be a recipe for swift, sure death. For early cells to survive and reproduce, something more sophisticated was needed. Selective channels through these early cell membranes had to be in place right from the start.

Cells today come with just such doorways, specialised protein channels used in transporting many key biomolecules and ions. How was this selective transport of both neutral molecules and charged ions engineered? Evolutionary theory appeals to a gradual, step-by-step process of small mutations sifted by natural selection, what is colloquially referred to as '*survival of the fittest*'. But a gradual step-by-step evolutionary process over many generations seems to have no chance of building such wonders, as there apparently cannot be many generations of a cell, or even one generation, until these channels are up and running. *No channels, no cellular life*!

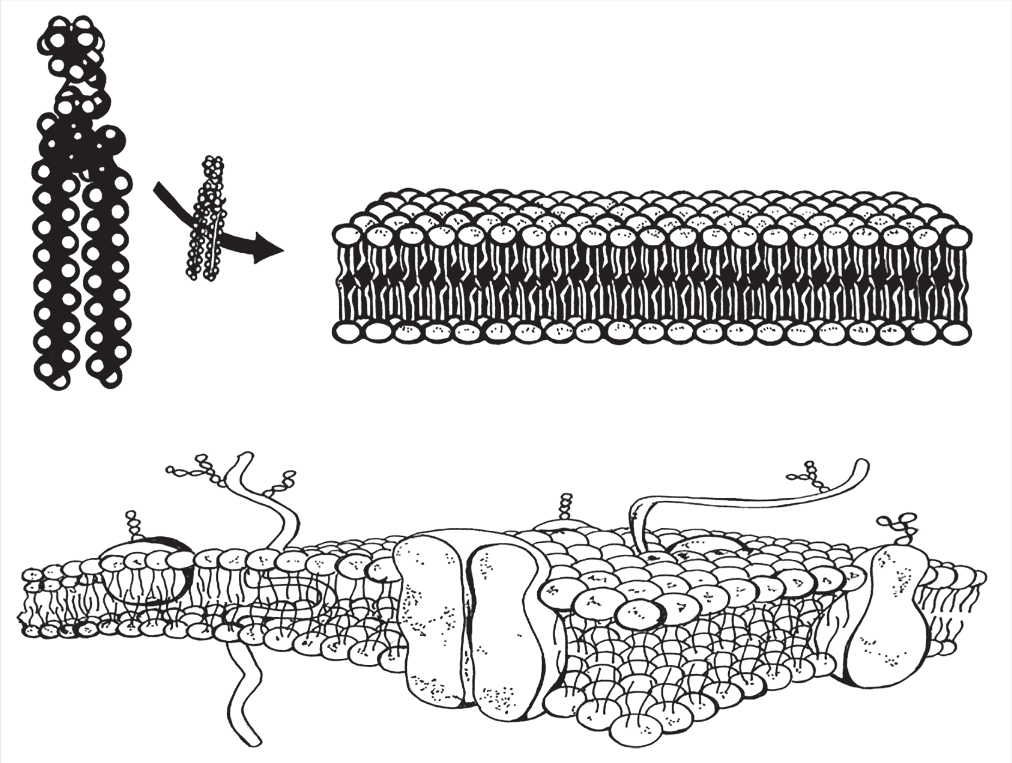
So then, the key question is: How could the first cells acquire proper membranes and co-evolve the protein channels needed to overcome the permeability problem?

Even some committed evolutionists have confessed the great difficulty here. As Sheref Mansy and his colleagues put it in the *Nature*, 'The strong barrier function of membranes has made it difficult to understand the origin of cellular life' (Mansy et al. 2008).

And that is putting it delicately. Somehow, a double-layer membrane – flexible, stable and resistant – needed to be engineered, one that would promptly and efficiently protect the cell from the devastating O_2 permeation, remain stable in aqueous acid media, and ably handle fluctuations in temperature and pH (Figure 8.1). To do all these tasks, the cell's molecular shield also would need a mechanism to sense changes in temperature and pH,[60] and react accordingly, adjusting the membrane's chemical composition to handle these physical and chemical changes.

---

[60] Here I recall the intricacy of electronic temperature meters and pH meters used in my work as a chemist.

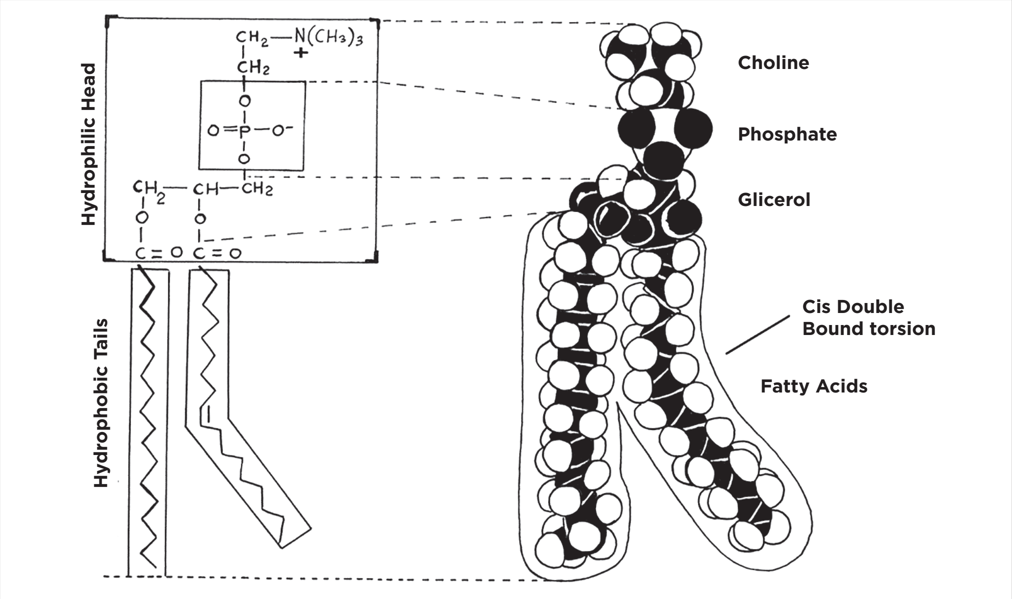


Source: Eberlin (2019).

FIGURE 8.1: The double-layer membrane encloses our cells. It is very flexible, but it also has high mechanical and chemical resistance. The many intricate membrane components and the capacities it possesses that are required to keep a cell alive strongly points to *foresight*.

For instance, as Diego de Mendoza explains, bacterial cells ‘remodel the fluidity of their membrane bilayer’ by incorporating ‘proportionally more unsaturated fatty acids (or fatty acids with analogous properties) as growth temperature decreases’. The process is known as homoviscous adaptation. Cell membranes had to therefore have, from the beginning, a series of cellular responses that react to a change in environmental temperature (De Mendoza 2014).

If you were to bid this demanding, multifaceted job out to the most technologically advanced engineering firms in the world, their top engineers might either laugh in your face or run screaming into the night. The requisite technology is far beyond our most advanced human know-how. And remember, getting two or three things about this membrane job right – or even 99% of the job – would not be enough. *It is all or death*! A vulnerable cell waiting for improvements from the gradual Darwinian process would promptly be attacked by a myriad of enemies and die, never to reproduce, giving evolution no time at all to finish the job down the road.



Source: Eberlin (2019).

FIGURE 8.2: This simple caricature only hints at the phospholipids' complex molecular structure.

It seems, then, from all the biochemical knowledge we now have, that the many crucial requirements of the cell membranes had to be foreseen and delivered on time for the earliest cells to survive and reproduce in an aqueous environment.

And that is just the beginning of the foresight apparently required to deliver a membrane good enough to make cellular life viable. Such a membrane wall, with its many intricate abilities, also requires a veritable Swiss Army knife of biomolecules. And happily, these were provided in the form of an amazing class of exquisitely designed biomolecules: the phospholipids (Figure 8.2).

Phospholipids

These biomolecular pieces had to be just right. To construct a chemical shield sophisticated enough to allow cells to survive and thrive, there seems to be no substitute for phospholipids. Sometimes I come across articles in journals such as *Science* and *Nature* (Szostak, Bartel & Luisi 2001) theorising about simpler, primordial cell membranes made of 'rudimentary' molecules such as fatty acids. But such flights of fancy ignore key chemical details of what is needed to render cellular life viable. Once we confront those details, we find that no other biomolecule appears able to sustain life by fulfilling the many intricate roles phospholipids perform.

The structure of a phospholipid can be divided into two main regions that possess quite opposite physical-chemical properties: The head is polar and water-loving (hydrophilic), whereas the tail is non-polar and water-hating (hydrophobic). This dichotomy of 'tastes' is crucial, because it allows for a marvellous trick: In the presence of water, these biomolecules automatically arrange themselves so as to form round, double-layer structures (Figure 8.1) with all the polar heads lining up next to each other and the elongated non-polar tails packed very tight.

Attracted by finely-tuned chemical forces, two such monolayers come together so that the tails from both layers will also contact each other in a tail-to-tail arrangement. This automatic 3D, multi-component packing ensures that the water-hating tails are hidden from water whereas the water-loving heads on the outer and inner surfaces are exposed to water. Water is therefore placed inside and outside the cell but is helpfully expelled from the interior of the phospholipid membranes that enclose the aqueous cells.

The cell membrane needs to be elastic but at the same time also mechanically and chemically resistant so that it can continuously protect the cell from its fluctuating surroundings. Fortunately for life, phospholipid bilayers are flexible but also highly stable, being resistant to mechanical stress and pH and temperature fluctuations. So, how are all these properties obtained? By means of a fine, dynamic balance of the various physico-chemical properties of the many molecular constituents of the wall.

The control of these chemical properties is accomplished primarily through the regulation of the strength, length and 3D orientation of carbon-carbon bonds in the lipid tails. It is also controlled by the cell manufacturing shorter or longer carbon chains and different polar 'heads': an apparent master play of foresight guided by superb chemical wisdom.

Note that if we attribute the origin of biomembranes to blind material processes, we will need to appeal to a myriad of chemical 'miracles'. Firstly, an accident would have to construct rather long carbon (C-C) chains containing from 12 to 18 carbon atoms. Such an accident is extraordinarily unlikely, statistically and chemically. Secondly, two of these chains would have to bind to a triol molecule – glycerine. Less stable C=C carbon bonds would also have to be inserted at the exact positions and in the proper ratio to produce the proper fluidity. A phosphate anion (PO_4^-) and another group of atoms must also all be available at the same time and be properly connected to the final 'molecular Lego' (Figure 8.2). As a chemist, one should never take this cascade of chemical miracles for granted.

The intimation of foresight is powerful. An exquisite phospholipid membrane apparently had to be anticipated, engineered and made available just as the cell interior appeared on the scene, lest a skinless cell meet a swift, sure end. And as early cells obviously did survive, thrive and reproduce, leaving offspring down to the present, it is scientifically plausible to conclude that by some means this extraordinary membrane did appear on the scene in that original moment of need. Some insist it was a blind fortune. But I disagree and urge you to consider a second possibility – *engineering foresight*!

Aquaporins: Water filters extraordinaire

Lipid bilayer membranes protect and accommodate life, but as previously noted, the cell also needs channels to ferry essential materials in and out. If we had contracted out the job to a top nanotech company employing all its powers of engineering foresight, we could not have been more pleased with the result. These lipid bilayer membranes come with 3D protein assemblies that work beautifully as selective channels. These channels are smart enough to let in what needs to be let in and keep out what needs to be kept out.

For an evolutionary model of membrane origins to work, it must account for the co-evolution of membrane-associated proteins, membrane bioenergetics and lipid bilayers (Mulkidjanian, Galperin & Koonin 2009) – a triple concatenated miracle. Attempts to wrestle with this question often begin with a confession of bafflement, as when A. Y. Mulkidjanian and his colleagues wrote: 'the origin(s) of the membrane(s) and membrane proteins remains enigmatic' (Mulkidjanian et al. 2009).

One thing membrane channels must permit is the passage of water. For this essential task, biomembranes contain special channels called 'aquaporins'. Cells are cybernetic, multimolecular cities full of high-tech machines, power plants and even nano-robots. But for all that nanotech to properly work, it needs the same thing you and I need in large quantities – *water*. Indeed, this simple but essential and wondrous molecule, H_2O, with so many cellular functions, must be able to enter and exit the cell interior if the cell is to survive and thrive.

However, water entry and exit must be carefully controlled if the cell is to survive. This need for control arises because water molecules are connected by hydrogen bonds, and its hydrogen-bonding network makes water function as a 'proton wire' that carries protons (H^+) down it, much as an electrical wire carries electrons. But for metabolic reasons, all cells must keep their interiors electrically negative. Cells manage this with special membrane channels that control the transport of sodium (Na^+) and potassium (K^+) ions. If aquaporins were to let water enter the cell freely, the proton wires would allow positively charged hydrogen ions (H^+) to overwhelm the cell's efforts to remain electronegative. So, a simple water gate is not enough.

Fortunately, an ingenious solution was foresighted: specialised channel proteins known as aquaporins. These exquisite gates (Borgnia et al. 1999) in cell membranes not only let H_2O into and out of the cell but also keep out impurities such as undesirable ions and other harmful biomolecules, as well as the positively charged hydrogen ions (H^+) that normally travel freely along H_2O's proton wires. So how is this intricate task accomplished?

In the aquaporin water gates, a special amino acid known as asparagine is perfectly positioned, at the exact point of the passage of a single H_2O molecule (Mansy et al. 2008). Asparagine is a member of the marvellous set of amino acids that are important for building and shaping the structures of proteins, but in addition it possesses a side group able to establish two very strong and spatially oriented H-bonds with H_2O molecules. The perfect 3D alignment of this amino acid, perpendicular to the passage of the H_2O proton wire, then can function as a true 'molecular plier' to cut the H_2O wire.

Here is how it works. Exactly at the moment it passes through the filter orifice, H_2O is twisted by asparagine. This exquisitely orchestrated manoeuvre, driven by stronger H-bonds, breaks the network of water's H-bonds, thereby cutting the H^+ wire. With a broken H^+ wire, H_2O freely enters the cell while its uninvited sidekick, H^+, is blocked at the door. Another life-or-death problem anticipated and neutralised.

Aquaporins, then, are an ingenious solution to a fiendishly tricky engineering problem. But in our uniform and repeated experience, ingenious engineering solutions are accomplished by geniuses – minds that apply expertise and foresight to a problem that could not be solved even by other engineers, much less by mindless natural forces.

So, was the cellular membrane's ingenious solution to the proton wire problem a work of blind fortune or brilliant foresight? The discovery of this marvel of molecular ingenuity earned the 2003 Nobel Prize in Chemistry, 'for the discovery of water channels' and 'for structural and mechanistic studies of ion channels' (*The Nobel Prize in Chemistry 2003 – NobelPrize.org* 2013). But if Nobel-calibre intelligence was required to figure out how this existing engineering marvel works, what was required to invent it in the first place?

The requirement of foresight

The dominant explanation in origins biology involves some form of the random variation or natural selection mechanism, by which nature is said to have climbed the various Mount Improbables (Dawkins 1997) we find in biology, one small mutational step at a time. Yes, there are additions and other adjustments to this basic mechanism in modern evolutionary theory, but these have significant shortcomings. Also, dig long enough and you find some version of the chance or selection mechanism playing a key role in every leading model of biological origins. The problem is that natural selection can only go to work once a viable, self-reproducing cell exists, and it can only progress if each stage in the proposed evolutionary process of construction can somehow be preserved and passed along. Yet nothing gets preserved and passed along if the first protocells die a swift death for lack of a fully functioning cell membrane, able to accomplish the many essential tasks outlined (among many others).

No multi-tasking cell membrane, no life! No life, no gradual evolution by random variation and natural selection. A hypothetical primitive membrane with a partly evolved aquaporin, one that allowed water in but had not yet evolved the ability to block the entry of H^+, would have no chance of survival. Such a cell, surrounded by the many enemies of a primordial ocean or 'warm little pond', would quickly die. *No survival, no reproduction*!

The fully functioning H_2O-only gates (no H^+ allowed) are a 'must' for any type of cell, from the most sophisticated to the most 'rudimentary' if any such rudimentary cells ever existed on this planet. These highly selective and exquisitely engineered gates need to be there from the very beginning. *No H^+-free water, no life*!

And with the proton-wire challenge, remember: H^+ is just one of the problems in need of a solution. An only partly evolved water gate with holes either too small or too big would either block water altogether or allow other contaminant molecules to enter the cell and destroy it. A successful water gate in this instance poses an 'all or nothing' challenge for life. Foresee the need for these exquisitely precise water gates and somehow engineer them for JIT delivery or the grand startup called life quickly goes bust.

And what is true of the water gates is true of many other aspects of the cell membrane. If we are guided only by the evidence, this complex and multifaceted engineering marvel appears well out of reach of the random variation or natural selection mechanism. Another type of cause appears necessary, one that can foresee and engineer a cell membrane in all its marvellous sophistication, for JIT delivery. And indeed, multifaceted solutions of this sort, ones that anticipate problems that otherwise would stop any potential evolutionary development in its tracks are evident throughout life.

■ The code of life

The cell has its own sophisticated information-processing system, much like a computer. Computer programs require programmers, conscious agents with knowledge and foresight who can code the needed instructions, in the right sequence, to generate a functioning and information-rich program. Is there any reason to think that the information in cells also was programmed by a programmer rather than by random processes? Let us dive into the details and consider our options.

Foresight in deoxyribonucleic acid

The cell's genetic information is a foundational and most ancient characteristic of life (Eigen et al. 1989). It is essential to how all living things on Earth are formed, move and reproduce. Without it, no cellular organism would produce the biomolecules essential to life.

If matter evolved into living cells through purely blind processes, as evolutionary theory holds, then this information somehow was generated from matter and energy, through unguided natural processes. Origin-of-life theorists committed to a purely naturalistic account of life must therefore explain how both this genetic information and the cell's information-processing system appeared virtually all at once, as such things by their very nature work in direct synergy and thus cannot evolve bit by bit.

This impossibility should not be surprising, as the genetic information and the genetic code together include features such as semantic logic and the meaningful ordering of characters – things not dictated by any laws of physics or chemistry.

The genome sequence of a cell is essentially an operating system, the code that specifies the cell's various genetic functions, affecting everything from the cellular chemistry and structure to replication machinery and timing. Because certain functions are shared by all forms of life, genomes are all similar to a considerable extent. For example, all mammals share more than 90% of their genomes (Yue et al. 2014). It has been estimated that even life forms as distinctive as humans and bananas share 60% of their genetic information (Ramsey & Lee 2016). The unique portions are specific instructions for the varying needs of different genera and species.

Because it is so crucial to life on Earth, genetic information had to be transmitted and stored in a way that was as compact, efficient and error-free as possible. This need presents a set of problems that had to be solved and implemented virtually simultaneously, so that molecules able to store and transmit genetic information were ready to go in the very first organism.

Deoxyribonucleic acid (DNA) is made up of three classes of chemicals. One is the phosphate anion PO_4^{3-}, with its four oxygen atoms distributed in a tetrahedral fashion around the phosphorous atom, producing a triple-negative charge. Another is the five-membered cyclic sugar molecule – ribose – with four available OH linking sites. DNA uses a special form of ribose called deoxyribose, which has an OH replaced with an H. The third class of chemical comprises four different kinds of stable, rigid and heterocyclic bases, two purines and two pyrimidines, each with the ability to firmly attach to ribose via covalent bonds and to each other via two or three H-bonding supramolecular arms. The bases are designated A, C, T and G. Put all together, this trio forms ribonucleotides that turn out to be ideal for transmitting information. Why is that? Let us take it in stages.

Phosphate ion

If it is to be viable, life's long-term storehouse of genetic information cannot break down in the presence of water. The hydrolysis problem, therefore, has to be solved in advance or life's information storehouse would dissolve as quickly as a sandcastle struck by the incoming tide. How DNA meets this challenge is a wonder of engineering finesse.

DNA is what is known as a polymeric ester, composed of a very long phosphate (PO_4^{3-}) wire – the wire runs close to two meters in humans – interspersed with ribonucleotides. This molecular architecture is perfectly suited for DNA for several reasons. The 3D structure and charge of PO_4^{3-} allow it to bind to two nucleotides creating the long DNA chain. It also prevents water from breaking the DNA apart, and it prevents DNA from penetrating the cell membrane keeping it inside the nuclear membrane (Westheimer 1987). This exquisitely engineered molecular arrangement, which protects DNA, had to be present for any cell to live. *It makes or breaks*!

For DNA to function properly, another problem remained to be solved. Inorganic PO_4^{3-} is the perfect link for DNA, but as a link for the long, polymeric molecule, its reaction with deoxyribose is too slow. The cell needed therefore a proper catalyst to speed up this slow but crucial reaction. Enzymes – large, exquisitely designed biomolecules – fulfil this task by accelerating the formation of such links by many orders of magnitude. Making enzymes is another whole incredible process I will discuss later. They would have been needed from the very beginning to make DNA. Yet they themselves have to be made using the DNA sequence they 'were born' to make.

So we have two ingenious solutions to do-or-die challenges: an engineering marvel – an electrical shield – that protects DNA from breaking down in the presence of water; and another engineering marvel – enzymes – that speeds a crucial reaction that would otherwise be far too slow. And these two ingenious solutions could not come one after the other because the DNA sequence is necessary to make the enzyme, whereas the enzyme is necessary for making the DNA. Both the polymeric DNA, with its multiple phosphate–sugar bonds and very slow kinetics, and the proper enzymes to accelerate the formation of the DNA phosphate–sugar bonds, have to be in place at the same time. *If only one exists without the other, no cell at all*!

Ribose

The ribose sugar is ideal for maintaining the stable DNA structure. Researchers have constructed DNA analogues using sugars besides ribose and measured their properties. So was ribose, this very specific five-membered cyclic sugar, just one good option out of many? It appears not (Banfalvi 2006). The final molecule had to be both stable and capable of carrying the code of life.

For these jobs, only ribose would be suitable. DNA analogues using other sugars are not suitable information-storage molecules. Some DNA made of the other sugars fails to form stable double helices, or their intermolecular interactions are too strong or too weak, or their associations are insufficiently selective. Other DNA analogues adopt various conformations that would hinder the cell machinery from replicating them. Effectively, ribose was the only choice that would work.

Ribose is also ideal at forming a 3D molecular structure. True, it is not the only sugar that allows for DNA to form a stable double helix, but it is far and away the best. The resulting inner space within the double helix is about 25 Å, and this distance is just perfect for one monocyclic nitrogen base (T or C) and one bicyclic base (A or G). This perfect space forms base pairs, in which A pairs with T and C pairs with G, establishing crucial selective criteria for the genetic code. If any sugar other than ribose were used, that distance would be too wide or too narrow.

Darwin suggested that life emerged by chance in a 'warm little pond'. That is, a *chemical accident* formed a masterful information-storage molecule equipped with the only sugar that could make it work. But judging from the myriad of molecules bearing two OH groups that could mimic it, the task of making, finding and specifically selecting this particular and life-essential sugar at random in the 'primordial soup' would be dauntingly improbable (Tour 2016).

DNA's four bases

Another crucial question: Why did life 'choose' the very specific ATGC quartet of N bases? Another indication of the planning involved in the DNA chemical architecture arises from the choice of a four-character alphabet used for coding units three characters long. Why not more alphabetic characters or longer units? Some of my fellow scientists are working on precisely such genetic Frankensteins. It is fascinating work. But DNA should be as economical as possible, and for DNA to last, it had to be highly stable chemically. And these four bases are exactly what is needed. They are highly stable and can bind to ribose via strong covalent N–O bonds that are very secure. Each base of this 'Fantastic Four' can establish perfect matchings with precise molecular recognition through supramolecular H-bonds. The members of the G≡C pair align precisely to establish three strong, supramolecular hydrogen bonds. The A=T pair align to form two strong hydrogen bonds. A and G fail to work, and neither do C and T nor C and A nor G and T. Only G≡C and A = T work.

A stable double helix formed by the perfect phosphate-ribose polymeric wire, with proper internal space in which to accommodate either A=T or G≡C couplings with either two or three H-bonds is necessary to code for life. And fortunately, that is precisely what we have.

Genetic redundancy

In addition to referring to the DNA sequences that contain information for synthesising entire proteins, the term ‘genetic code’ can also mean the set of rules that matches an amino acid to a specific DNA triplet (a combination of three nucleotides called a ‘codon’). The genetic code in this second sense features yet another hallmark of foresight and sound engineering: *redundancy*.

This redundancy is possible because of the genetic code’s basic architecture, in which each of the three ‘letters’ in a nucleotide triplet in sequence can be any of four different alphabetic characters, yielding 4 × 4 × 4 total possibilities – 64 all together. But there are 64 possibilities and only 20 amino acids. That leaves a lot of room for possible redundancies. Therefore, more than one three-letter combination might code for a given amino acid, and that is in fact what we find.

This redundancy was initially interpreted as an inefficient artifact of evolution’s sometimes messy trial-and-error process. At first, scientists thought that only 20 codons were needed for the amino acids, plus two more codons to signal the start and stop of protein synthesis (called ‘translation’). Since then, however, we have discovered that the redundancy is actually vital. The apparent overkill minimises reading and transmitting errors so that the same amino acid is transferred to each generation.

But if carefully inspected, the redundancies themselves do not seem to be random, as they involve mainly changes in the third letter of each triplet. For example, the simplest amino acid, glycine, has four codons that specify it: GGA, GGC, GGG and GGT. The only position that varies is the third, and any nucleotide in that position will still specify glycine.

Changes in the first and second letters are less common and are offset by the expression of amino acids with chemically similar properties and that do not significantly alter the structure and properties of the final protein. For example, the CTT codon that codes for leucine becomes the chemically similar isoleucine when the C is replaced by A (ATT). Such redundancies establish a chemical buffer between amino acids when common errors occur. That is, the code of life was foresighted with built-in safeguards against potentially damaging genetic typos.

But, as more recently demonstrated, that is not the only purpose of the redundancy in our genetic code (D’Onofrio & Abel 2014). The use of different codons to express a single amino acid also allows the speed of protein synthesis to be controlled. For example, four different codons may specify the same amino acid, but the four differ in their effects on how fast or slow a bond is made and the protein folds (Brule & Grayhack 2017). This kinetic control gives each protein the exact time it needs to form the correct 3D shape.

There are other nuances in our genetic code that seem to suggest foresight, such as the grouping of codons for amino acids with either acid or alkaline side chains (Butler et al. 2009). Therefore, if environmental stimuli require exchanging an alkaline (basic) amino acid for an acidic amino acid in a protein, this exchange is aided by such grouping. Again, *what a wonderful chemical trick*! For example, a basic lysine coded by either AAA or AAG can easily be changed to the acidic glutamic acid by only a single-letter substitution: GAA or GAG. Having such a flexible code helps the organism to stay alive.

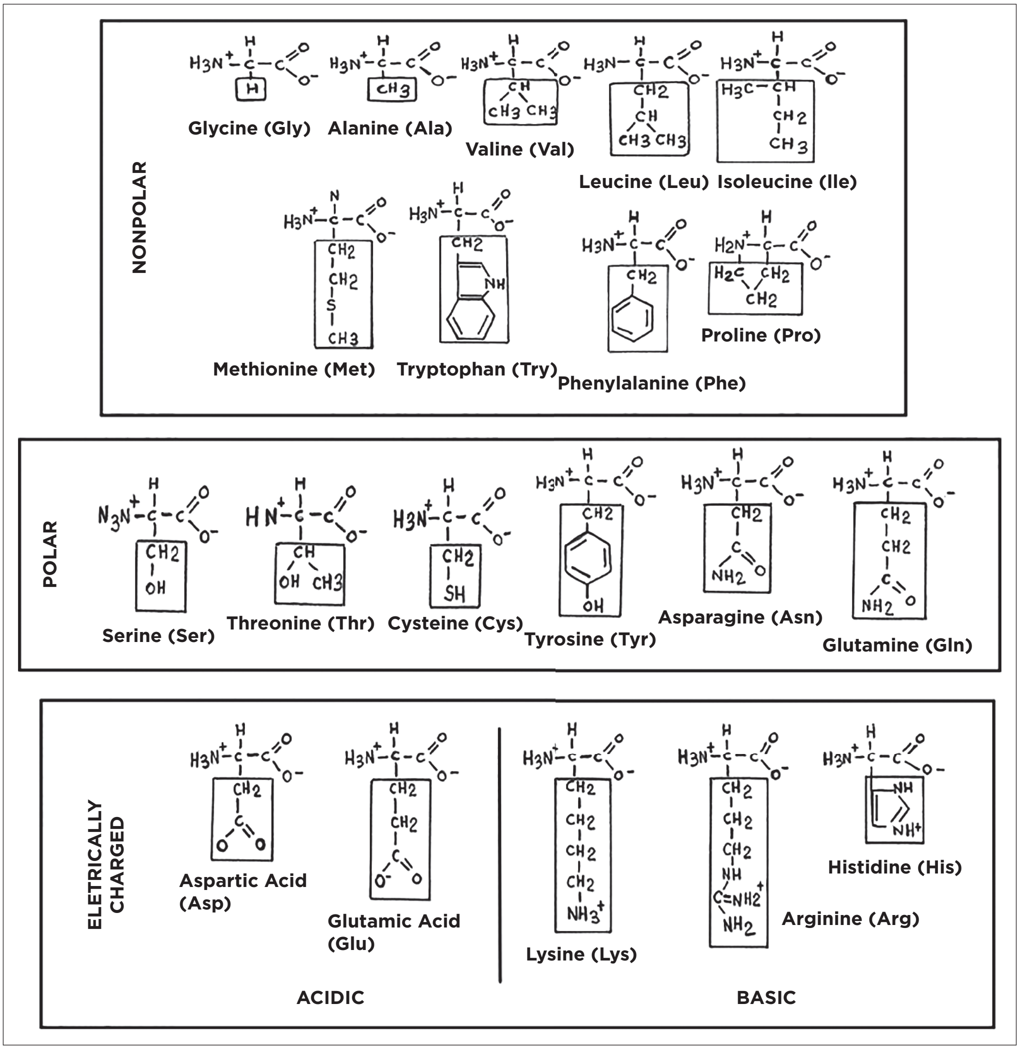
The code also anticipates and has safeguards against the most common single-point mutations. For instance, leucine is encoded by no less than six codons. The CTT codon encodes leucine, but all the third-letter mutation variations – CTC, CTA and CTG – are ‘synonymous’ and also encode leucine.

First-letter mutations are rarer but potentially more dangerous because they do change the amino acid specified – if C is exchanged for T, forming the TTT codon, a different amino acid (phenylalanine) will be expressed. But even for this threat, the genetic code has a safeguard: phenylalanine’s chemical properties are similar to leucine’s, so the protein will still retain its shape and function. If the first letter C in CTT (leucine) is replaced by A or G, something similar happens, as ATT (isoleucine) and GTT (valine) have physicochemical properties similar to leucine as well.

Amino esters and ribosomes

DNA’s four-character alphabet is used to compose the larger 20-character alphabet of alpha-amino acids (α-amino acids). Life needs this collection of 20 building blocks, each distinct, to make a protein. These building blocks must react with each other to form specific chemical connections called peptide bonds. Chemists have learned to use this reaction to make polymers such as nylon, for which they used $H_2N\text{-}(CH_2)_6\text{-}COOH$ molecules as the specific building blocks. The reaction occurs without much guidance because NH_2 has no option but to react with COOH.

But the task is much more complicated for proteins, however, as α-amino acids have 20 different side chains (called ‘R groups’; see Figure 8.3) attached to their backbones. Each protein is a polymer, a chain made of many subunits linked together like nylon but composed of amino acids. But the amino acid R groups pose a serious problem for protein synthesis because they can react favourably with both themselves as well as the COOH and NH_2 groups of the other α-amino acids. The desired peptide reactions, on the contrary, are usually unfavourable, requiring a positive change in free energy (abbreviated ΔG) (Oliveira & Harada 2015). All the other viable side reactions will interfere with the formation of a protein polymer. So how does life get around this severe competition problem? Life relies on a chemical trick often used in synthetic chemistry: *derivatisation*!



Source: Eberlin (2019).

FIGURE 8.3: The 20 α-L-amino acids, masterfully engineered to form a comprehensive yet economical set of building blocks for the proteins of life, displaying a range of all major intermolecular forces, from London dispersion forces of non-polar carbon chains, H-bonding and charge attraction, to acid and alkaline properties.

What follows is considerably technical, but I have attempted to provide a glimpse of its chemical beauty.

Ribosomes are large multimolecular machines that synthesise proteins from amino acids in living cells. But before going to ribosomes, each α-amino acid is converted into an amino ester, a process called ‘derivatisation’, and attached to a ‘transfer RNA’ (tRNA) by an enzyme called a tRNA synthetase. There are distinct tRNAs and tRNA synthetases for each amino acid. Competition from energetically more favourable R-with-R or even R-with-NH_2

or R-with-COOH reactions would be fatal to protein synthesis if it were not for the ribosome. Here is what happens during the process of translation, as α-amino acids get attached to their specific tRNA by their specific tRNA synthetases. In a very elegant and ingenious process, amino esters are first phosphorylated by ATP and then, via a trans-esterification reaction, a tRNA-linked amino ester is formed.

To ensure the desirable NH_2-with-COOH reaction takes place, the amino acids are first esterified (which makes the chemical bond easier to form), then brought together by the mechanical hands of a ribosome, holding them in the correct position to prevent competing R reactions from taking place and providing the necessary energy for the bond to form.

Again, this ribosome-driven reaction does not seem to be an advantage that life could acquire little by little, by trial and error. Chemically, it is impossible to produce a functional protein without ribosomes that have already solved the competing reaction problem or without the collection of 20 specific tRNAs and tRNA synthetases that would feed it with amino esters. As in so many other cases with the cell and its code, if this need is not foreseen and planned for, there will be no cell at all.

Codes and coders

Now let us step back a moment and review, focusing just on DNA. With its double-helix structure, DNA is the most efficient, most protected, best calibrated in chemical stability and most compact form of information-storage known on Earth. How did this perfect, polymeric, nearly 2-m long, 3.2 billion-piece (for humans) molecular wonder form without anything telling it to? A cell does not know that only ribose will work, or that it needs an intact D-ribose for RNA but a D-deoxyribose for DNA or a U/T exchange or four bases with perfect fittings and sizes or a stable and protective phosphate anion wire or an electric shield and more. And yet it has all these things, and, indeed, it must have had them from the very first cell.

Antony Flew, a famous atheist philosopher who converted to theism late in his life after studying this evidence, concluded, ‘Fifty years of DNA research have provided materials for a new and enormously powerful argument to design’ (Habermas 2004).

Morse code was created by an intelligent mind, that of Samuel F. B. Morse. The barcode was invented by the brilliant Norman Joseph Woodland, and the ASCII code by the visionary Robert Bemer. *Codes always have code makers*!

DNA, RNA and the genetic code (in the sense of sequences needed for protein synthesis) serve as beautiful examples of foresight, in their coordinated structure, maintenance and back-up plans. Francis Crick, co- discoverer of the double helix, proposed a ‘frozen accident’ scenario for the evolution of the genetic code (Crick 1968), but he was unable to fill in all the many details of this hypothetical accident, and 50 years later, naturalistic explanations for the origin of the code of life have not been forthcoming.

The genetic code dwarfs any human code in its sophistication and capacities. That by itself should be enough to suggest the possibility of foresight and design.

Bacteria as ecosystem engineers

So far, we have looked at examples of foresight in the tiniest life forms on Earth: cells and the unimaginably small molecular machines that keep them running. But beautiful examples of planning are not limited to cells. They exist in all forms of life, from the smallest to the largest. In this chapter, we will look at how some of Earth's smallest creatures have features that anticipate problems and solve them in many ingenious ways.

Microbes: Another chicken-and-egg paradox

Planet Earth is magnificently equipped to host life. But the phenomenon of life itself creates life-threatening problems. For example, the nitrogen molecule N_2, or N≡N, is the perfect 'inert' gas for our atmosphere. But we also need nitrogen available in a more reactive form, atomic nitrogen (N), to make amino acids (general formula $RCHNH_2COOH$) and proteins. So how can N≡N, a very stable molecule connected by a triple bond, be converted into atomic N? How can it be preserved in useful chemical forms? And how can N_2 be replenished? The supply of N_2 would eventually run out as living things constantly consumed it. A way of restoring N_2 was therefore needed.

The solution? Microbes. Microbes are co-inhabitants on our planet and play a crucial role in maintaining life on Earth (*How Microbes Make Earth Habitable* 2016; *More on How Microbes Make Earth Habitable* 2016). In the oceans, plankton maintains the carbon cycle and single-celled algae called diatoms provide a fifth of our atmosphere's oxygen (O_2). On land and in the oceans, microbes break apart N_2 and fix it into compounds such as ammonia (NH_3). Other bacteria take NH_3 and convert it back to N_2 in what is called the nitrogen cycle. The tiniest creatures on Earth maintain its habitability for all of us.

Free oxygen (O_2) and carbon (C) are also essential for the habitability of Earth, and they too have refreshment cycles that rely on microbes as well as plants. Much of the free O_2 on Earth is produced by photosynthesis in autotrophic microbes. (Autotrophs make energy-containing organic molecules from inorganic molecules; heterotrophs make use of food that comes from other organisms.) Autotrophic microbes have the know-how to 'fix' nitrogen by dismantling the triple bonds of atmospheric N_2 into NH_3 and other useful compounds. These microbial workhorses also maintain the balance of many other essential atmospheric elements. Without that balance, complex life could not exist. *No microbes, no other life*!

Anammox and its rocket chemistry

Bacteria are often seen as rudimentary forms of life. But one look at their molecular structure is enough to convince us otherwise. Bacteria are extremely sophisticated, fully equipped with many exquisite molecular machines.

One very strange group of bacteria discovered in the early 1990s, called ‘anammox’ (Kuenen 2008), provides a great example of the high-tech characteristics of bacteria. According to Laura van Niftrik and Mike Jetten, anammox bacteria are found in a wide variety of environments, including low-oxygen marine zones, treatment plant wastewater, coastal sediments and lakes (Van Niftrik & Jetten 2012). It turns out that these bacteria are crucial to life on Earth: It is estimated that they contribute up to 50% of N_2 production from marine environments (Jetten et al. 2009), resulting in the removal of fixed nitrogen.

When discovered, anammox bacteria caused a real scientific stir. They were found to be major players in Earth’s biogeochemical nitrogen cycle, and scientists wondered how such simple bacteria could perform a reaction previously considered impossible (Jetten et al. 2009). Anammox converts NH_3 and NO_2^- into N_2 under anaerobic conditions, that is, in the absence of O_2. That is where it got its name: ANaerobic AMMonium Oxidation (Kuypers et al. 2003). Van Niftrick and Jetten (2012) note that:

> Anammox bacteria do not conform to the typical characteristics of bacteria but instead share features with all three domains of life, Bacteria, Archaea, and Eukarya, making them extremely interesting from an evolutionary perspective. (p. 585)

I would go further and say that the existence of these crucial and unusual bacteria is in fact not ‘extremely interesting’ but extremely difficult to explain from an evolutionary perspective.

How does an anammox bacterium fulfil its indispensable mission of replenishing nitrogen? It uses rocket science and some highly sophisticated organic synthesis skills.

The bacterium has an internal organelle covered by a double-layer membrane, not at all peculiar in prokaryotic cells. The greatest surprise was what was inside the organelle. Inside, scientists found hydrazine, which has a variety of uses, including for *rocket fuel*! Anammox somehow makes, stores and uses a highly toxic, corrosive and explosive liquid.

Can you imagine a creature evolving one step at a time to store this stuff inside itself? Imagine trying to synthesise pure hydrazine by trial and error inside a bacterium. It would not take long to kill it! How would a bacterium evolve a hydrazine synthesis protocol without all the machinery to safely hold and use hydrazine? Is it plausible that a bacterium gained the ability to use pure, toxic and explosive hydrazine by a step-by-step process that has no way to predict the future advantages of the poison? Why would a proto-anammox bacterium, which had previously not used hydrazine and survived just fine without it, risk its life to evolve the ability to produce and store hydrazine, before hydrazine would do it any good?

Another surprise is that anammox bacteria store hydrazine in internal compartments called anammoxosomes (Van Niftrik et al. 2004). Obviously, anammox bacteria must handle this explosive molecule with the greatest care. Chemical and microscopic analysis of the anammoxosome double-layer membrane, which encloses the hydrazine, revealed another surprise: The membrane consists of unique and bizarre lipids made from 'ladderanes' (Sinninghe Damsté et al. 2002). These are highly sophisticated chemical structures that many synthetic chemists would not even attempt to make.

A typical ladderane is pentacycloanammoxic acid, which is composed of five fused rings of cyclobutane. It resembles a ladder and contains concatenated square ring structures formed by fused four-carbon rings. Concatenated four-membered rings are one of the hardest to make because kinetics and thermodynamics work against them. But anammox bacteria seem to have skipped organic synthesis classes and gone ahead and built them anyway.

But why go to all the effort? It appears that anammox bacteria did it only to use hydrazine as an agent to convert NH_3 and NO_2^- into N_2 in the absence of O_2. So why would a bacterium synthesise N_2, an almost inert gas that is practically useless for life as such? Anammox bacteria live all over the world. They are abundant in the oceans, where they undertake this nearly impossible task simply to produce N_2. But because of this 'charity effort', they regulate the N_2 cycle and maintain the O_2/N_2 ratio of the earth's atmosphere (Van De Vossenberg et al. 2008). This little nanomolecular machine keeps the N_2 at the balance needed for all life forms on our planet to survive. In essence, this little microbe uses rocket science (*Rocket Science in a Microbe Saves the Planet* 2015) to make life on earth possible and sustainable.

And we are only beginning to understand this extraordinary bacterium. The enzymatic mechanism that makes hydrazine must also be incredible. As described by Andreas Dietl et al. (2015):

> The crystal structure implies a two-step mechanism for hydrazine synthesis: a three-electron reduction of nitric oxide to hydroxylamine at the active site of the γ-subunit and its subsequent condensation with ammonia. (p. 394)

The authors of the *Nature* paper go on to note a striking parallel: 'Interestingly, the proposed scheme is analogous to the Raschig process used in industrial hydrazine synthesis' (Dietl et al. 2015).

So, again we find that another of our carefully planned inventions is only following in nature's footsteps. The N_2 gas that pairs with O_2 in our atmosphere and is essential for life on Earth is, as another article puts it, 'a by-product of an exquisitely designed, precision nanomachine that knows a lot about organic redox chemistry and safe handling of rocket fuel' (*Rocket Science in a Microbe Saves the Planet* 2015).

The world of microbes proves more sophisticated with every discovery, manifesting more and more 'surprises' – that is, evidence of foresight. Recently, we discovered another microbial wonder: the enigmatic comammox (Daims et al. 2015), or 'complete ammonia oxidizer'. This bacterium can be found almost everywhere and does an even more spectacular job than anammox. Comammox performs complete nitrification on its own, a milestone of microbiology. Two different classes of nitrifier microbes have long been known to cooperate in carrying out the nitrification process where NH_3 is oxidised to NO_2^-, which is subsequently oxidised to NO_3^-. But the comammox does not share labour in nitrification. It catalyses both nitrification steps doing complete ammonia oxidation and thus conserving energy.

It is difficult to escape the implications of all this: the need to sustain an atmosphere suited to life had to be anticipated from the start. And an array of microbes, equipped with a sophisticated arsenal of chemicals and capacities, had to be provided to meet that need.

Birds: A case study in foresight

The living world manifests numerous engineering solutions combined with ingenious chemistry far beyond the reach of unguided evolutionary mechanisms. A particularly striking example: *birds*! There are many aspects of bird biochemistry and architecture I could focus on as being suggestive of foresight, planning and marvellous ingenuity. Here I will focus solely on bird navigation.

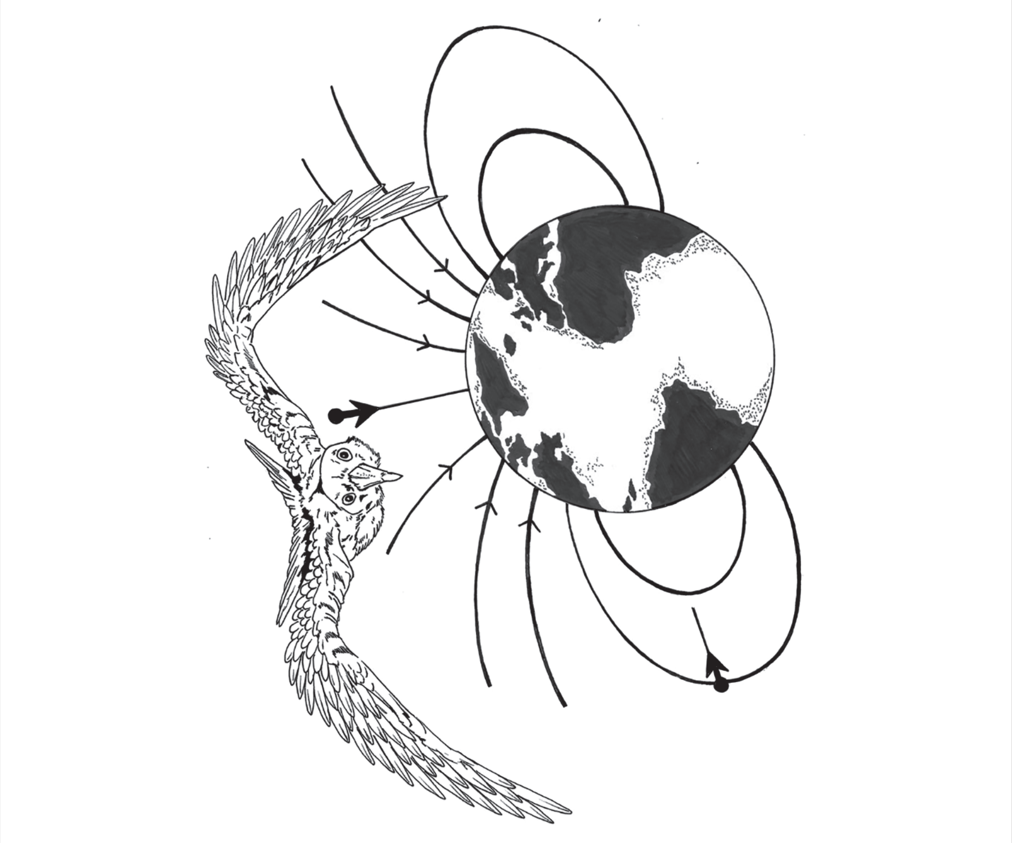
Birds' global positioning system

Migrating birds have out-of-this-world capabilities. Some birds, such as the common swift (*Apus apus*), have been reported to fly for up to 10 months, during which they rarely and only briefly land while migrating from Europe to Africa and back again (Hedenström et al. 2016). But perhaps even more impressive: They fly over long distances and diverse and changing landscapes without getting lost. It is as though they have a built-in global positioning system (GPS).

A human GPS relies on the ingenuity of the mind and radio signals from artificial satellites orbiting the earth. By integrating the signals from several satellites, a GPS can pinpoint its location on the earth, sometimes within a few inches. Scientists have known for decades that birds have a GPS based on a more elegant principle: they sense the earth's magnetic field (Wiltschko & Wiltschko 1996). The phenomenon is called magnetoreception.

Migratory birds navigate using this magnetic compass, but even non-migrating birds have this sense and navigate using their internal magnetic compass. It was once proposed that iron in birds' beaks provided them with, in effect, a magnetic compass. It now appears that the sensor system is far more sophisticated: special molecules in their eyes enable birds to see lines of the earth's magnetic field (Figure 8.4) and use them as navigational guides.

The special molecules are highly sophisticated proteins called cryptochromes. Most cryptochromes are light-sensitive and are involved in the 'circadian clock' that regulates the 24-h metabolic and behavioural cycles in animals. But recent evidence suggests that one cryptochrome, designated Cry4, is involved in magnetoreception in birds (Günther et al. 2018; Pinzon-Rodriguez, Bensch & Muheim 2018).



Source: Eberlin (2019).

FIGURE 8.4: The common swift can fly for months at a time without landing and navigates by seeing the lines of Earth's magnetic field, apparently by using the state-of-the-art Cry4 protein molecule in its eyes. Also impressive, it can fly and navigate while 'half-brain and single-eye' asleep.

How might Cry4 detect magnetic field lines? When energised by light, Cry4 separates an electron from one of its electron pairs, forming what is called a ‘radical pair’ (in vertebrates, cryptochromes are the only molecules that do this). In an atom or molecule, an ‘orbital’ is a specific quantum state that defines the energy, spin and probable location of an electron relative to the nucleus. Normally, each orbital contains a pair of electrons with opposite spins and oppositely directed magnetic fields. A radical is formed when a chemical species bears one unpaired electron, and a radical pair is formed when it has two unpaired electrons that are connected by what is known as quantum entanglement, one of the strangest phenomena discovered by modern physics.

Quantum entanglement

As David Kaiser (2014) has elegantly described it:

> Entanglement concerns the behavior of tiny particles, such as electrons, that have interacted in the past and then moved apart. Tickle one particle here, by measuring one of its properties – its position, momentum or ‘spin’ – and its partner should dance, instantaneously, no matter how far away the second particle has traveled. (p. SR10)

It sounds like science fiction, does not it? Albert Einstein, Boris Podolsky and Nathan Rosen deduced this phenomenon from the theory of quantum mechanics, but they doubted it, concluding that the theory must therefore be incomplete (Einstein, Podolsky & Rosen 1935). But quantum entanglement was subsequently demonstrated experimentally. In 2013, a team of Chinese scientists showed that the communication between two entangled objects could not be less than 10 000 times the speed of light (Yin et al. 2013).

It has been known for decades that radical pairs are affected by magnetic fields under laboratory conditions (Schulten & Weller 1978). In 1996, chemists Brian Brocklehurst and Keith Alan McLauchlan suggested that the same phenomenon might occur in biological systems (Brocklehurst & McLauchlan 1996). And in 2000 biophysicists Thorsten Ritz, Salih Adem and Klaus Schulten proposed that the phenomenon might be the basis for magnetoreception in birds (Ritz, Adem & Schulten 2000).

When a radical pair forms in a light-activated Cry4 protein, the two members of the pair are only a few billionths of a meter away from each other. But even at this small molecular distance, the two unpaired electrons could be affected differently by the earth’s magnetic field. Theoretically, many such entangled pairs could produce a picture in the bird’s eye that enables it to navigate.

One problem for this proposal is that radical pairs connected by quantum entanglement are very short-lived. In a laboratory, the best molecule for maintaining quantum entanglement is a ‘Buckminsterfullerene’, so named because it structurally resembles the geodesic domes designed by Buckminster Fuller in the 1940s. These beautiful carbon-based molecules are also called ‘buckyballs’ or ‘fullerenes’. Within a fullerene at room temperature, a radical pair in quantum entanglement can be maintained for about 80 ms.

In 2011, a team of physicists used quantum information theory and the widely accepted ‘radical pair’ model to analyse recent experimental observations of the avian compass. The team concluded that quantum entanglement in the bird’s eye lasts about 100 μs, ‘exceeding the durations achieved in the best comparable manmade molecular systems’ (Gauger et al. 2011).

Physicist Simon Benjamin, a member of the team, put this in perspective by comparing the Cry4 protein to a fullerene. ‘How can a living system have evolved to protect a quantum state as well – no, better – than we can do in the lab with these exotic molecules?’ he asked. ‘The bird, however it works, whatever it’s got in there, it’s somehow doing better than our specially designed, very beautiful molecule. That’s just staggering’ (Grossman 2011).

If a bird navigates through the earth’s magnetic field using radical pairs and quantum entanglement, it is implausible to suppose that such an amazing ability evolved one small, functional step at a time. The bird would have needed not only the ingenious magnetically sensitive molecules as sensors but also the channels to transmit signals from the sensors to the right region of the brain. And the brain would have needed the apparatus to properly interpret and respond to that specific information. To provide a functional advantage, the entire ‘out-of-this-world’ system had to be implemented all at once. It seems therefore, as Fred Hoyle once concluded about our universe and life, that a ‘superintellect’, capable of foresight and of anticipating scientific discoveries, has ‘monkeyed’ with quantum physics, along with chemistry and biology (Hoyle 1982).

A world foreseen for biochemistry

I still vividly remember the first time I saw the ocean. It was in the 1960s during summer break. Time for fun, so my father drove our family of six in our Volkswagen Kombi van to Santos, a seashore in Brazil where Pelé used to play football. Our parents had told us so much about the ocean and, burning with anticipation, my brother, two sisters and I kept asking from the back seat, ‘how long?’ until at last we heard the waves and felt the salty breeze coming through the open windows.

I will never forget that feeling: the smell of the sea, the blue sky and green water, the grainy sand under my feet, the warm sun on my skin, the water lapping my feet. In that moment, I was wide awake to the wonders of Earth. But Earth’s wonders are with us every day; our eyes simply grow dim to them.

We were not yet to our destination, but my father, knowing how eager we were, pulled over at a spot close to the shore and stopped the Kombi so we could pile out of the van and take in the ocean for the first time. Earth is packed with marvels, from a transparent atmosphere to colourful rainbows, the aurora borealis, starry nights, birds, dragonflies and whales, sunrises, buzzing bees and flowers great and small.

For a young child, the first sight of some new vista of natural wonders is often unforgettable; but as we grow older we sometimes forget to keep contemplating, to keep seeing a world full of smells, textures, colours and sounds, to keep appreciating the amazing things around us.

Fortunately, science has helped me maintain that sense of wonder into adulthood. Absolute wonder and gratitude.

Earlier, I discussed how the cell is carefully engineered with a lipid bilayer membrane and selective channels. These components are essential from the start. There would be no hope for it to become viable if the cell had to tinker around with mutations over thousands of generations in search of a functional membrane. It would be anticipated to die. We have also seen how this need to anticipate is also true of numerous other systems and features throughout life, from the simplest cell to complex navigation systems. The evidence of foresight is abundant, appearing almost everywhere you turn your eyes in biology.

There is also this: All of those marvels depend on deeper levels of foresight. Science has revealed that Earth and the cosmos display layer upon layer of features essential to life. It is a wondrous discovery, and it is the subject of this section.

Water: An ideal chemical matrix

Earth is ideally suited in many ways to host life. With its carefully timed 24-h rotation, its large stabilising moon, its location in the Milky Way's GHZ, its perfect distance from a special star and its neighbourly gas giant planets that protect it from many of space's dangers, Earth is curiously life-friendly.

But despite all these conditions, Earth would still have been unable to host life if it lacked special properties to allow biochemistry. For instance, its crucial solid crust could easily have been a desert, blazing hot during the day and freezing at night. Had this been the case, no careful tuning of distances, physical or chemical properties or rotation period would have made a difference. Luckily, a marvellous molecule with dozens of unique properties provided Earth with a solution that perfectly anticipated this need: *water*!

For most of us, pure water, odourless and colourless, is easy to take for granted. But in fact, water is a great chemical miracle. Myriad properties and values of chemistry and physics had to be just so to make possible water and its many life-essential anomalies (*The Peculiar Properties of Ice* 2012).

Also fortunate: although liquid water is very elusive elsewhere in our solar system, Earth's surface has a significant amount of both land and liquid water on its surface – specifically, a 2:1 ratio of water to land. This is a stroke of good fortune because liquid water is critical to life and is the only liquid in a relatively narrow range of temperatures and pressures. This range is unimaginably narrow compared to the wide range of temperatures and pressures found in the universe, and yet they are exactly the ones present on Earth.

The solar system and beyond is indeed 'awash in water' (*The Peculiar Properties of Ice* 2012), but mainly in solid or gaseous forms that do life little good. Only on Earth, however, do we have water in all three states. And we need all three states for life to thrive here. If this need had not been anticipated, and Earth was typical of other planets in our galaxy, life could never have existed here.

Water's diverse set of chemical features solves many problems that would otherwise be dead-ends for life (Denton 2017). Its high specific heat moderates temperature changes between night and day, stabilising the temperature by absorbing heat during the day and releasing it at night. The great amount of heat needed to evaporate water also helps us to cool down on hot summer days through evaporative cooling from our naked skin.

Water is not only crucial on Earth's surface and in the atmosphere. It is also crucial to the biochemistry of our bodies. Accounting for close to two-thirds of our body weight, water is so important to human functioning that we die in a matter of days from lack of it. It serves this crucial role thanks to many of its unusual properties. To give one example: water is a relatively poor heat conductor, and this anomaly prevents organisms from boiling or freezing too easily.

Other unusual properties allow water to penetrate cell membranes, ascend via a strong capillary effect to the top of even very tall trees and evaporate from the surface of leaves as needed, enabling plants to both transport nutrients and successfully conduct a myriad of biochemical operations. Another striking chemical property of water that makes it so important to life on Earth is its ability to dissolve so many different substances, transporting all sorts of nutrients and waste products throughout – as well as in and out of – the cells of plants and animals.

As a last example, frozen water floats. For the laws of physics, the solid state of a substance is almost always denser than its liquid state. There is, however, a major exception to the rule: water. Reaching maximum density at about 39 °F (4 °C), water is actually less dense when it is frozen. This anomalous feature allows water to circulate and revitalise water bodies on Earth, transporting noxious gases to the surface and oxygen to the bottom. It also prevents lakes and oceans freezing from the bottom up, which would prove devastating for aquatic life.

The groundwork for these and many other life-essential properties of water appears to have been laid before water arose in the universe. These factors include:

1. The specific masses and electrical charges of the neutrons, protons and electrons that make up its H and O atoms.
2. The precise strengths of the nuclear forces that stabilise protons and neutrons and hold them together in the nucleus.
3. The precise strength of the electromagnetic force.
4. The chemical rules and physical quantum laws that shape water's bonding and non-bonding molecular orbitals that hold pairs of the original electrons of both hydrogen (H) and oxygen (O) in specific energy levels in the H_2O molecule.
5. The Pauli Exclusion Principle that limits to two the number of electrons in each of these molecular orbitals.
6. The strength of the repulsion forces for bound and unbound pairs of the electrons that surround the central oxygen atom, a strength determined by a series of universal constants that directly and indirectly control the behaviour of such atoms and the precise angle (104.45°) of the H–O–H configuration.

These many details had to be precisely balanced – in advance – to create the dozens of exquisite anomalies of water that make life on Earth possible. It looks like it was planned ahead of time.

The perfect atmosphere

Our atmosphere is also amazing and necessary. Among other things, it protects us from bombardments from space. It filters out the dangerous radiation from the Sun while allowing crucial light through. And it moderates Earth's temperature.

Our atmosphere is made up of just the right gases in just the right proportions to support life on Earth: 21% oxygen (O_2), 78% nitrogen (N_2) and a little argon (Ar), carbon dioxide (CO_2) and water vapour (H_2O). These gases are also unreactive with each other – a crucial factor for long-term stability.

We know that O_2 is what we need to breathe to produce chemical energy in our bodies, so why are all those other gases necessary? An atmosphere with pure O_2 would be disastrous for life on Earth. Plants, which require CO_2, would be impossible. Wildfires would rage uncontrollably. And even oxygen-breathers, including animals, would suffer from excess O_2. Nitrogen is a stable and rather unreactive gas that dilutes O_2 to a life-friendly proportion.

Earth's atmosphere also contains traces of other gases, such as Ar, CO_2 (from volcanoes) and CH_4 (from cattle). Though they are only present in tiny amounts, they are necessary to life, forming the perfect greenhouse effect for life to stay warm and have access to enough energy.

N_2 is also essential for life on Earth and is perfectly suited to be the major constituent of our atmosphere, as it creates an atmosphere sufficiently thick to stabilise the planet's liquid water and resist cosmic bombardment. N_2 is a highly stable, chemically inert molecule made of two tightly, triply bound N≡N atoms, providing a perfect 'solvent' for O_2. The final mixture has the right air pressure and density to facilitate breathing and destroy most debris from space. N_2 also provides nitrogen atoms for amino acids, the building blocks of proteins and also for a wonderful array of other crucial nitrogen-containing biomolecules.

N_2 and O_2 are therefore both essential for life on Earth and in roughly the specific 2:1 ratio they are found in our atmosphere.

Our N_2-plus-O_2 atmosphere is transparent to radio waves and visible light; hence we can appreciate that multitude of stars in the night sky while the atmosphere creates a blue sky during the daytime and a reddish sunset. This perfect mixture of gases blocks the harmful radiation from the Sun even while letting us see so much of space and send and receive radio waves. *What an exquisite balance*!

But even with such a superb atmosphere, there remains a problem to solve: animals would quickly consume O_2 and N_2, converting O_2 into CO_2 and burning up Earth from an excessive greenhouse effect. Earth also needed processes to systematically fix N_2 to the soil and oceans in a biochemically useful form. And indeed, these processes are in place. A highly intricate network that includes lightning, microbes, plants and animals creates the earth's O_2 and N_2 cycles (Ward & Jensen 2014).

Ozone

I have saved for last the best example of the foresight evident in our atmosphere: the ozone layer.

The ozone layer displays an exquisite interplay of carefully crafted solutions. The Sun emits about 90% of its radiation in the visible and infrared (IR) ranges, perfect for life and photosynthesis. But the other 10% of sunlight is composed of different subsets of ultraviolet (UV) radiation, some of which is harmful and some of which is beneficial to life. For example, a little of UV-B is beneficial as it is required to produce bone-strengthening vitamin D, whereas some birds, insects and mammals can see UV-A and use it to hunt. UV rays are also used to treat some skin conditions, such as psoriasis, vitiligo, localised scleroderma and atopic dermatitis (Juzeniene & Moan 2012). But other portions of UV light are harmful.

The atmosphere is perfectly equipped to solve this ‘devil/angel’ dilemma, blocking the great majority of the harmful stuff and letting the good stuff through. What is known as the ozone layer plays a crucial role here.

This atmospheric layer occupies the lower swath of the stratosphere, a portion stretching from 9 to 22 miles above the earth’s surface. It is not pure ozone, but it is richer in ozone (O_3) than are other parts of the atmosphere, containing a few parts per million of this essential triatomic molecule. The UV light emitted by the Sun is mainly composed of three subtypes: UV-A, UV-B and UV-C, as well as a little UV-E. The ozone layer absorbs 97%–99% of UV-B light, which would be potentially damaging to life in higher doses but provides a net benefit at lower doses. At the same time, it is mostly transparent to UV-A, the life-friendliest of the ultraviolet lights.

But what is really amazing about the O_3 layer is that it works in perfect synchrony with N_2 and O_2, forming an $O_2 + O \rightleftharpoons O_3$ perfectly balanced equilibrium mediated by both UV-C and UV-E radiation. The O_3 layer also seems to contain exactly the concentration at exactly the right altitude to block bad UV-C and excess UV-B radiation while letting UV-A and a useful amount of UV-B pass through.

O_3 also occurs in a layer close to the earth’s surface, but as the United States (US) Environmental Protection Agency explains, we create that ozone through industrial ‘chemical reactions of oxides of nitrogen (NO_x) with volatile organic compounds (VOC) in the presence of sunlight’, leading to urban smog. The main sources of NO_x and VOC are emissions from electrical utilities and industrial facilities, vehicle exhaust, gasoline vapours and chemical solvents. O_3 is harmful to our lungs and damages crops, trees and vegetation in general (*Ozone: Good Up High Bad Nearby* 2003).

The problem would be much worse if not for the providence that O_3 is a rather reactive molecule in the lower atmosphere, preventing it from accumulating to levels that would prove far more dangerous. And also fortunately, O_3 is long-lived in the diluted (and colder) stratosphere where the O_3 layer resides. The naturally formed O_3, nine-plus miles above us, protects rather than harms us because of its precise positioning.

Ozone is created there when the most harmful and energetic portion of the UV-C light strikes O_2. It is also amazing to discover that UV-C carries all the energy required to split the tightly covalently bonded O=O molecule into two O atoms. This highly reactive atomic oxygen then combines with molecular O_2 to yield O_3. This means that O_2 chemically blocks the harmful radiation (UV-C) while creating beneficial O_3 via a very reactive O atom. This forms the protective O_3 layer that filters excess harmful UV-B. But remember that O_3 is by itself harmful to life, so it is a good thing these reactions occur high in the sky.

Facts indicate therefore that this intricate cascade of reactions induced by radiation required careful planning to get everything right – gas densities, air pressures, temperatures and reactivity – to limit this biologically harmful, pungent and heavier-than-air O_3 molecule to the right altitude and the right amount in our atmosphere.

■ Conclusion

The Foresight-or-Death Principle: The need to anticipate – to look into the future, predict potentially fatal problems and implement a plan to solve them ahead of time – is observable all around us. It is clear from the many examples in this chapter that life is full of solutions whose need had to be predicted to avoid various dead-ends. Put another way, many biological functions and systems required planning to work. These features speak strongly against modern evolutionary theory in all its forms, which remains wedded to blind processes.

Also, as I discussed in the previous section, the evidence of foresight in nature goes beyond the examples from the life sciences. As we investigated Earth and the cosmos, we saw how it appears that an ingenious mind anticipated and steered around a host of potential dead-ends, in everything from physics and cosmology to chemistry and geology, situations that otherwise would have made life impossible.

No foresight, no life! In this chapter, I have examined many instances that manifest this principle. And these barely scratch the surface. The many examples of solutions that anticipated problems before they arose, the ingenuity evident in those solutions and the need for the orchestrated, simultaneous delivery of multiple, fully functioning components right from the beginning of a given system, pose a significant challenge to blind evolution. And not just blind evolution but the materialism that undergirds it, for foresight requires something far beyond matter in motion. Foresight is a hallmark of mind.

Foresight demands wisdom and intelligence! We humans have thrived on Earth thanks to many of our unique abilities. We reason, possess the power of speech, craft sophisticated tools, grow crops and breed livestock. We fly airplanes and spaceships and go deep into the oceans with submarines. We write software that commands mobile phones and robots. We synthesise polymers to make clothes and drugs to cure us from pathologies. We sing, compose songs and plays and much more.

What most sets us apart in the animal kingdom, then, is not something mechanical or material; rather, it is our minds. With our minds, we can study the past, comprehend the present and anticipate the future to a degree unparalleled in the animal kingdom. We, more than any other animal, *foresee*!

And yet, as we have witnessed throughout this chapter, acts of extraordinary foresight are evident throughout the natural world – in everything from cell membranes to the mechanisms of bird migration. And these examples far exceed in sophistication any examples of engineering foresight that we could point to in human culture.

Where does this evidence invite us? Let us take the case for foresight in nature in steps:

1. We see many examples of apparent foresight in the natural world – of problems being anticipated before they arose and ingeniously solved with on-time delivery of multiple, essential and well-orchestrated parts.
2. We know from our uniform experience that the ability to anticipate and solve such problems is a characteristic of intelligent minds.
3. There are no demonstrated examples of unguided, mindless processes anticipating and solving problems that require a sophisticated orchestration of fine-tuned parts, all brought together on the ground floor of an origin event. Hand-waving references to cases that are assumed rather than demonstrated do not count. Neither do arguments based on question-begging logic – for example: 'Common features must mean common descent' and 'Common descent must mean blind evolution'.
4. Therefore, our uniform experience provides us with only one type of cause with the demonstrated capacity to anticipate and solve such problems – *intelligent design*!
5. Intelligent design thus represents the best and, indeed, the only causally adequate explanation for the many examples of apparent foresight in the natural world, of situations where problems are ingeniously solved with on-time delivery of multiple, essential and well-orchestrated parts. The foresight is not merely apparent, but real.

This is not to say that there were no secondary causes in action, that nothing unfolded from law-like patterns and pre-existing conditions. Being open to the evidence of foresight leaves us open to consider both primary and secondary means. In each case under consideration, we can simply follow the evidence rather than being constrained by a question-begging rule.

And whether the evidence points to primary causation, secondary causation or a combination, it still follows that a mind was required to foresee the many potential dead-ends and escape them. Life and the universe are full of these clever escapes, ingenious solutions that speak strongly in favour of ID.

Chapter 9

Evolutionary models of palaeoanthropology, genetics and psychology fail to account for human origins: A review

Casey Luskin
Center for Science and Culture,
Discovery Institute,
Seattle, Washington, United States of America

Introduction[61]

According to the modern consensus of palaeoanthropology, *Homo sapiens* evolved from ape-like species through apparently unguided processes driven by natural selection acting upon random mutations. But is this conclusion required by the evidence? The hominin fossil record is characterised by fossils that are highly fragmented, where the genus *Homo* appears abruptly and is

---

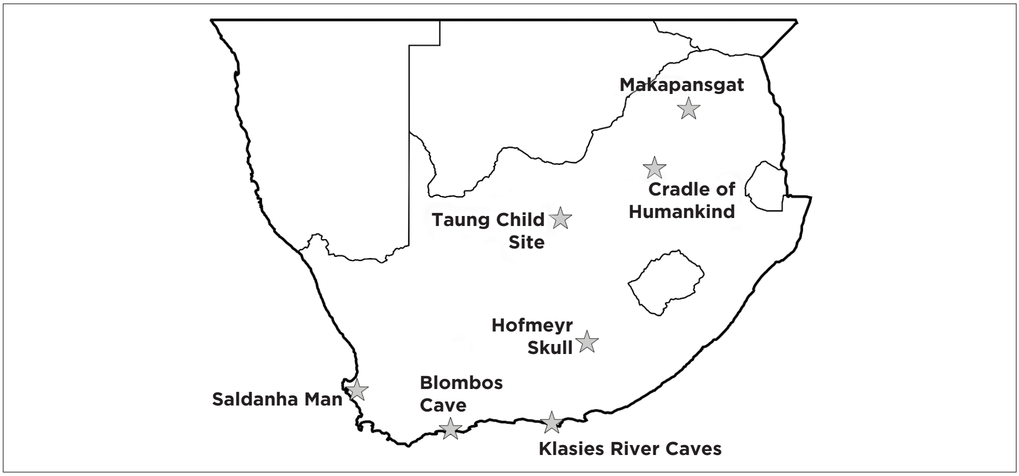
[61] This essay is extensively updated and adapted with permission from the publishers: (Luskin 2012, pp. 45–83, 2017, pp. 437–473, 2021).

How to cite: Luskin, C 2022, 'Evolutionary models of palaeoanthropology, genetics and psychology fail to account for human origins: A review', in F van Niekerk & N Vorster (eds.), *Science and Faith in Dialogue*, in Reformed Theology in Africa Series, Vol. 10, AOSIS Books, Cape Town, pp. 243–281. https://doi.org/10.4102/aosis.2022.BK334.09

separated from its purported australopithecine ancestors by large, unbridged morphological and temporal gaps. Significant South African fossil finds over the past two decades (e.g. *Australopithecus sediba* and *Homo naledi*) have left this long-recognised conundrum unresolved. The archaeological record shows an abrupt 'explosion' of human creativity about 30–40 thousand years ago, unanticipated by previous evolutionary trends. The ~6–8 million years allowed for human evolution from our most recent common ancestor with chimpanzees is insufficient time for necessary genetic mutations to arise blindly and become fixed into our lineage. Traditional 'junk DNA' models of evolutionary genetics have failed to predict the mass functionality in non-coding portions of the human genome. A South African museum claims that human beings are mere 'survival machines', but multiple converging lines of evidence contradict evolutionary psychology models and suggest humans were designed for purposes higher than simply passing on our genes. Given the ensemble of evidence pointing towards the design of the human species, South Africa may wish to consider its paleoanthropological roots which also affirmed ID.

Palaeoanthropology in South Africa

South Africa has an extremely rich history of paleoanthropological research – in fact the field of palaeoanthropology had its birth in South Africa – and the country boasts many important hominid fossil sites (Figure 9.1). According to the Maropeng Museum, perhaps the world's premiere palaeoanthropology museum located at the Cradle of Humankind World Heritage Site a short 50 km drive northwest of Johannesburg, 48% of all hominid fossil finds worldwide come from South Africa.



Source: Author's own work.

FIGURE 9.1: Map of major South African hominid fossil sites.

In 1924, Australian anatomist Raymond Dart discovered the first famous South African hominid specimen of *Australopithecus africanus* when he described the 'Taung Child', a small skull taken from a quarry in the town of Taung in South Africa's Northwest Province. In 1947, South African scientists Robert Broom and John Robinson discovered 'Mrs. Ples', a skull of the species *A. africanus*, at the Sterkfontein cave site located in the Cradle of Humankind. In the 1990s, Sterkfontein yielded another famous *Australopithecus* find, a nearly complete foot skeleton nicknamed 'Little Foot', discovered by palaeoanthropologist Ronald J. Clarke. These finds helped put South Africa on the palaeoanthropology map. But it was not until the 2000s that a series of finds catapulted South Africa to arguably become the world's leader in the field.

In 2008, the young son of Lee Berger, a prominent paleoanthropologist at the University of Witwatersrand, was walking in the Cradle of Humankind when he stumbled upon a hominid bone. Further excavation showed it was part of two of the most complete hominid skeletons ever found, belonging to a newly discovered species *Australopithecus sediba*. In 2015, Berger announced the largest cache of hominid bones ever found, discovered at the Rising Star Cave system also located at the Cradle. In this spectacular find, over a thousand bones belonging to dozens of individuals helped introduce the world to the newly discovered species, *Homo naledi*.

South Africa has other lesser-known hominid finds that are also important, including:

1. Saldanha man, a cranium of *Homo heidelbergensis*, located in the Northern Cape – possibly the southernmost known hominid fossil that lived prior to modern humans.
2. The Blombos Cave along South Africa's southern coast, bearing Stone Age tools.
3. The Klasies River Caves, inhabited by Stone Age hominins about 125,000 years ago.
4. The Makapan Valley in the northern Limpopo Province, containing *Australopithecus* fossils.

Introduction to the field of palaeoanthropology

Paleoanthropologists have discovered an impressive diversity of hominid fossils over the past century, leading to numerous assertions that our own species, *Homo sapiens*, is descended from ape-like ancestors. Yet, generally speaking, hominid fossils can be partitioned into two distinct groups: ape-like and human-like species, separated by a large, unbridged gap.

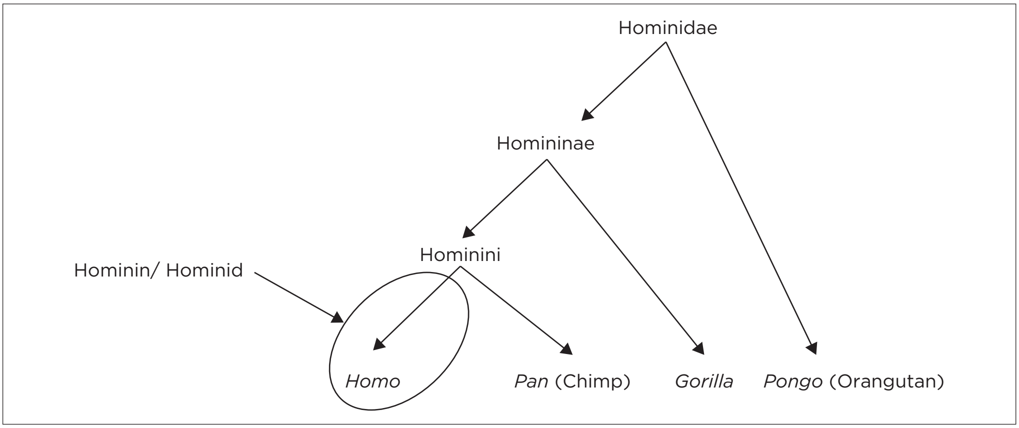
The field of palaeoanthropology sometimes uses inconsistent terminology, which can lead to confusion. Strictly speaking, hominids are members of the family Hominidae, which includes the great apes, humans and any organisms tracing back to what is thought to be their most recent common ancestor. However, 'hominid' is also often used as a synonym for 'hominin', which usually means any organisms on the branch that includes humans, tracing back to our (supposed) most recent common ancestor with chimpanzees (*Pan*), but excluding hominins on the branch that led to chimps. Following White et al. (2009), this chapter will define 'hominid' in the latter sense (Figure 9.2).

The hominid fossil record and the field of palaeoanthropology are fragmented in multiple senses, complicating efforts to establish an evolutionary account of human origins.

Firstly, the record itself is fragmented. Hominid fossils are rare, and the hominid record contains temporal gaps (Gibbons 2002; Johanson & Edgar 1996; Kimbel 2013). Richard Lewontin (1995), a prominent evolutionary biologist who spent much of his career at Harvard, stated:

> When we consider the remote past, before the origin of the actual species *Homo sapiens*, we are faced with a fragmentary and disconnected fossil record. Despite the excited and optimistic claims that have been made by some palaeontologists, no fossil hominid species can be established as our direct ancestor. (p. 163)

A second challenge is the fragmented nature of the specimens themselves. Typical hominid fossils are represented by only a few fragments, complicating the study of their morphology, behaviour and relationships. Stephen Jay Gould, the late Harvard palaeontologist wrote that, '[m]ost hominid fossils, even though they serve as a basis for endless speculation and elaborate storytelling, are fragments of jaws and scraps of skulls' (Gould 1980, p. 126).



Source: Author's own work.

FIGURE 9.2: What is a Hominid?

Additionally, it can be difficult to predict or properly infer unpreserved characters of extinct species, such as their soft tissue, intelligence and behaviour. Frans De Waal argues that no primatologist 'would have dared to propose' the 'dramatic behavioural differences' between chimpanzees and bonobos if all they had available to study was the nearly identical skeletal morphology of the two species. These of course are living species where we have complete skeletons to work with, but paleoanthropologists who study fossil species usually only have 'a few bones and skulls' (De Waal 2001, p. 68). Oxnard (1975) elaborated the difficulties of properly reconstructing anatomy from limited material:

> A series of associated foot bones from Olduvai [*a locality bearing australopithecine fossils*] has been reconstructed into a form closely resembling the human foot today although a similarly incomplete foot of a chimpanzee may also be reconstructed in such a manner. (p. 389)

Fossil reconstructions are often highly subjective, and textbooks or popular museum exhibits often commit what anthropologist Jonathan Marks calls the fallacy of 'humanizing apes and ape-ifying humans' (Marks 2003:xv). Neanderthals (*Homo neanderthalensis*) may be portrayed as unintelligent brutes even though many paleoanthropologists believe they created art and had ritualistic culture, while *Homo erectus* – which literally means 'upright man' – is stereotyped as a stooped beast, staring blankly. Yet the more primitive australopithecines – which had a brain size comparable to the chimpanzee and spent much of their time in trees – may be shown walking fully upright like a modern human and gifted with eyes reflecting emotion and high intelligence (e.g. Biggs et al. 2000, p. 438). Decades ago, Harvard anthropologist Earnest Hooton (1946, p. 329) warned that 'alleged restorations of ancient types of man have very little, if any, scientific value and are likely only to mislead the public'. His words should not be forgotten.

Because of the fragmented data and the emotional nature of the topic, the field of palaeoanthropology itself is fragmented. Reviews in top journals like *Science* and *Nature* have characterised palaeoanthropology as 'a notorious arena for splenetic debate' over an 'extremely paltry' amount of evidence, making it 'difficult to separate the personal from the scientific disputes raging in the field' (Holden 1981; Nature 2006). Evolutionary biologist Jerry Coyne affirms the limited nature of the evidence, observing, 'palaeoanthropology is a field in which the students far outnumber the objects of study' (Coyne 2009, p. 214). Science writer Roger Lewin similarly notes that an 'emotionally charged atmosphere' permeates the field because of something akin to 'ancestor worship', causing 'bitter rivalries' such that 'palaeoanthropology literature is replete with references [...] to controversy, disagreements, and even personal battles' (Lewin 1987). He continues:

> With a limited number of fossil sites available to work, and a still pitifully small inventory of fossils to analyse, all of which may be in the control of just a few people, research access has always been a sensitive issue. (p. 23)

Career interests and competition to gain recognition, research access and funding can cause paleoanthropologists to be hesitant to admit when they are wrong (Johanson & Edgar 1996, p. 32; Holden 1981). Intense contempt between fellow researchers is not unknown. After producing a Public Broadcasting Service (PBS) NOVA documentary on Neanderthals, Mark Davis remarked that, 'Each Neanderthal expert thought the last one I talked to was an idiot, if not an actual Neanderthal' (Davis 2002). *Nature* editor Henry Gee (2001) summarises the state of the field thusly: 'Fossil evidence of human evolutionary history is fragmentary and open to various interpretations'.

While sharp disputes and controversies are common, most paleoanthropologists have a general agreement over a standard evolutionary account of human origins which can be found in numerous textbooks, news media stories and museum displays – including the Maropeng Museum. A typical hominid phylogeny is portrayed in Figure 9.3.

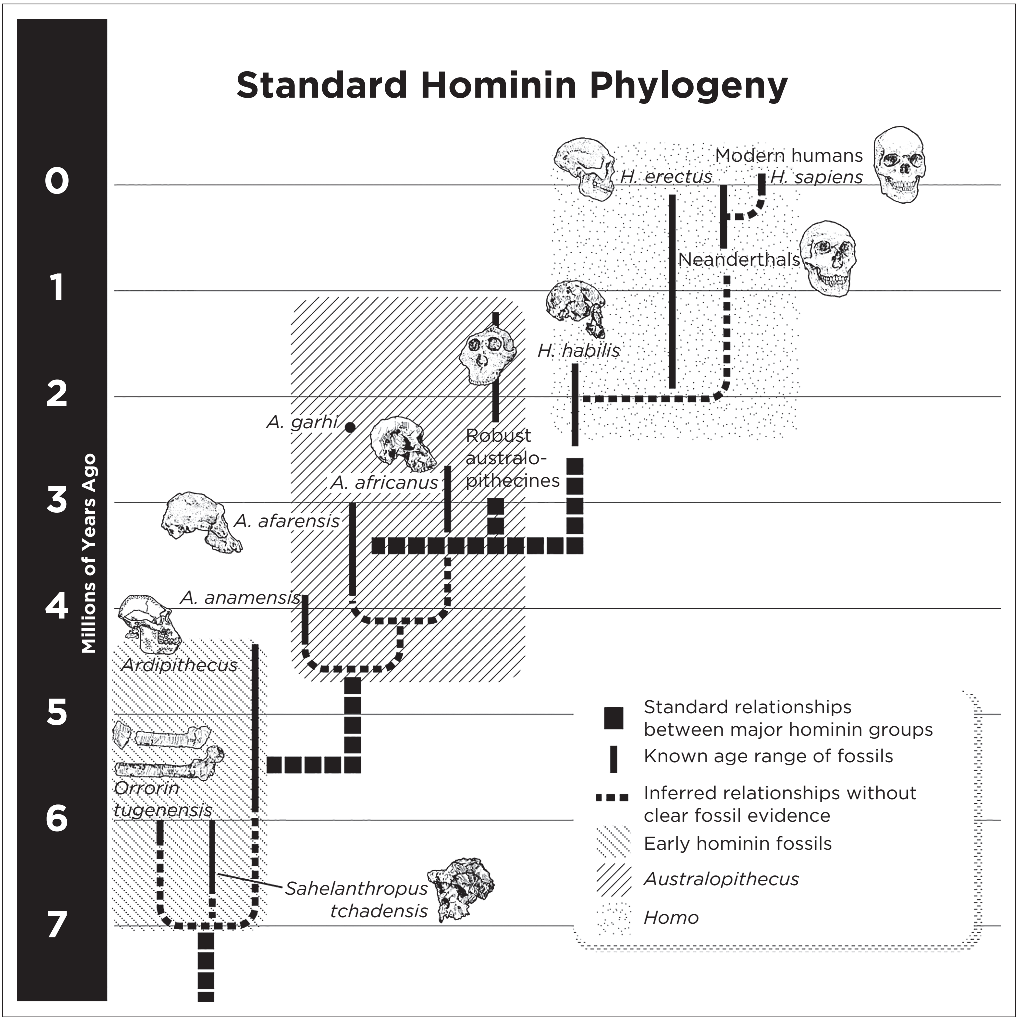
This chapter will roughly follow the discussion in the Maropeng Museum, first covering the early hominids and then moving forward in time to the australopithecines and finally covering the genus *Homo*. The fossil evidence does not support the claim that humans evolved from ape-like precursors and in fact reveals a distinct break between the ape-like australopithecines and human-like members of the genus *Homo*.

Early Hominins

Museums are frequently viewed by the scientific community as forums for increasing public acceptance of evolution (Smith 2020b), and the Maropeng Museum is no exception (Lelliott 2016; Sanders 2018). The museum states, 'humans and some great apes share a common ancestor, which probably lived over 7-million years ago'. But what is the evidence for this? A few candidate species are listed, but do these really document such an evolutionary relationship?

One candidate that has been proposed as the most recent human-ape common ancestor is *Sahelanthropus tchadensis* ('Toumai skull', Figure 9.4), represented by limited remains – a skull, a few jaw fragments and a femur. It is been called 'the earliest known hominid' (Brunet 2002a) and potentially 'the ancestor of all later hominids, that is, as the ancestor of the human lineage' (Brunet 2002b). Even the Maropeng Museum says *Sahelanthropus* 'is perhaps the closest we have to come to finding an ancestor near to both humans and apes' and 'perhaps represents the earliest known ancestor of humans'.

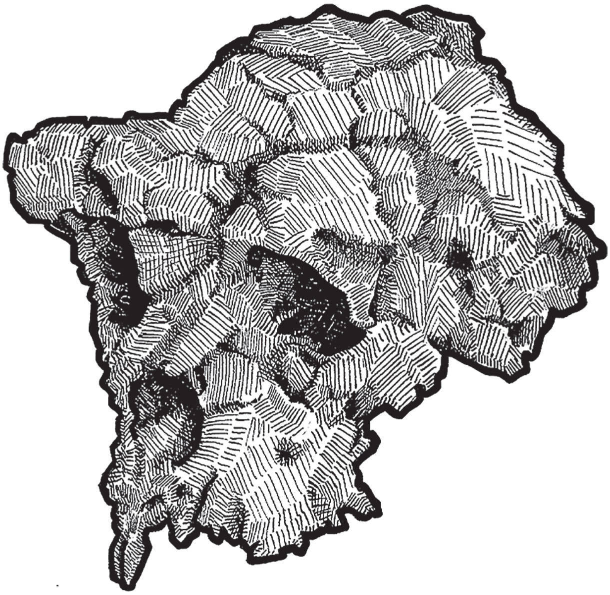
But many think *Sahelanthropus* was not a human ancestor. According to French paleoanthropologist Brigitte Senut, Toumai was 'the skull of a female gorilla' (BBC 2002). A 2002 article in *Nature* similarly maintained that, '*Sahelanthropus* was an ape', not bipedal and that 'many [...] features [...] link



Source: Figure generated by Jonathan Jones, published with permission from Jonathan Jones. Based on the work of Leakey and Walker (2003), Zimmer (2005), Gibbons (2006) and Potts and Sloan (2010).

FIGURE 9.3: A standard phylogeny of hominids or hominins.

the specimen with chimpanzees, gorillas or both, to the exclusion of hominids' (Wolpoff et al. 2002). A 2020 paper found that the femur of *Sahelanthropus* was characteristic of a chimp-like quadruped (Macchiarelli et al. 2020). The femur 'is curved, not straight, typical of apes like chimps', causing a lead investigator to caution that the evidence should 'deeply discourage bipedal gait' (Marshall 2020). German palaeontologist Madelaine Böhme similarly concluded, 'it's more similar to a chimp than to any other hominin' (Marshall 2020). Another commentary explained the implications: this species 'was not a hominin and thus was not the earliest known human ancestor' (Yirka 2020).

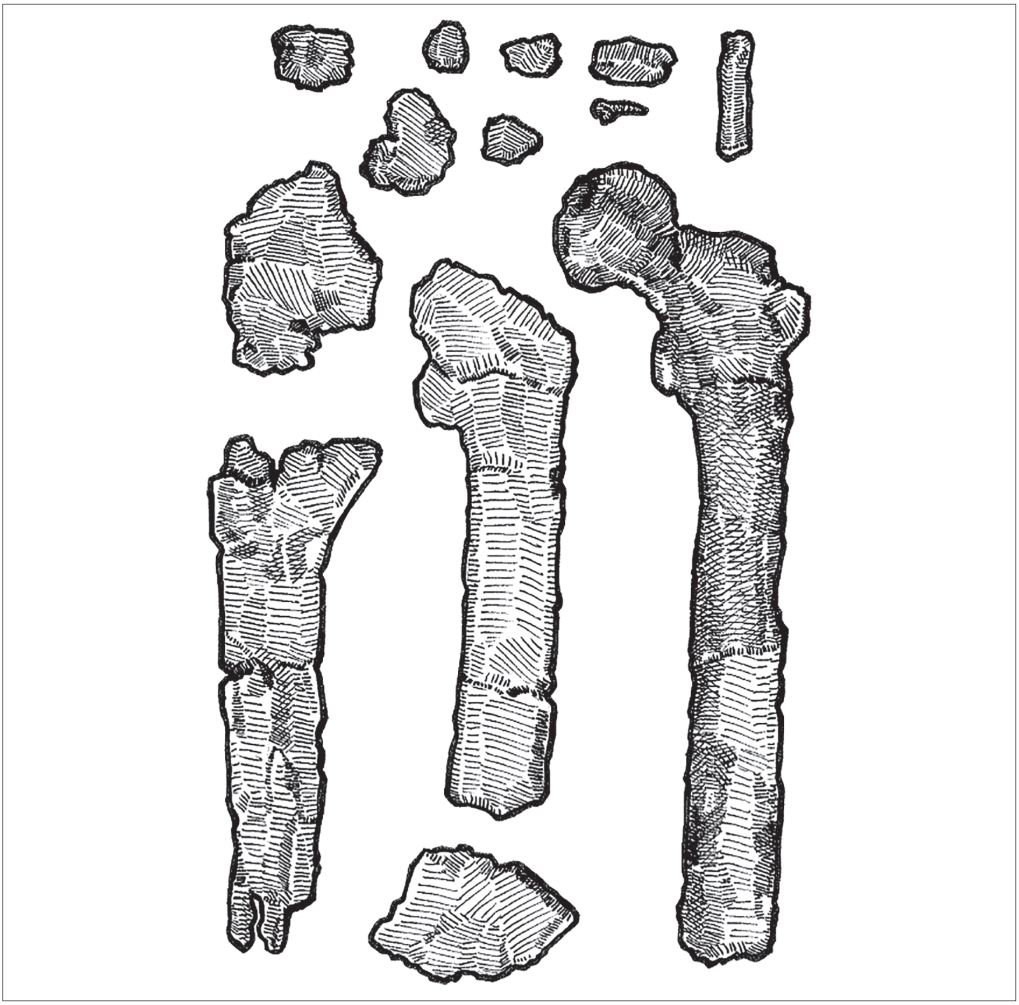


Source: Figure generated by Jonathan Jones, published with permission from Jonathan Jones.

FIGURE 9.4: The Toumai Skull.

Another candidate given is *Orrorin tugenensis*, which translates as 'original man' in the Tugen language. The Maropeng Museum says this chimp-sized species 'could represent the proverbial "missing link" between apes and hominids' although it acknowledges that 'its position in the hominid family tree is highly contested'. A major reason for controversy over this fossil is that all we have is an 'assortment of bone fragments' (Potts & Sloan 2010, p. 38), depicted in Figure 9.5. Upon the first public announcement of *Orrorin*, the *New York Times* reported, 'Fossils May Be Earliest Human Link' (Wilford 2001b) and predicted that it 'may be the earliest known ancestor of the human family' (Wilford 2001a). Paleoanthropologists initially thought that the femur indicated a form of bipedalism 'appropriate for a population standing at the dawn of the human lineage' (Galik et al. 2004), but a Yale University Press commentary later conceded, 'there is currently precious little evidence bearing on how *Orrorin* moved' (Sarmiento, Sawyer & Milner 2007, p. 35). Two critics argued in *Nature*, '*Orrorin* is not a hominin' and 'we are a long way from a consensus on its role in human evolution' (Aiello & Collard 2001). The journal *Nature* responded to such hype over *Orrorin* by warning that 'excitement needs to be tempered with caution in assessing the claim of a six-million-year-old direct ancestor of modern humans' (Aiello & Collard 2001). Unfortunately, this advice has not always been heeded.

Ardipithecus ramidus, informally called 'Ardi', is another early hominin that dates to 4.4 million years ago (mya). First discovered in 1994, expectations



Source: Figure generated by Jonathan Jones, published with permission from Jonathan Jones.

FIGURE 9.5: Illustration of the femur and limited bones known from *Orrorin tugenensis.*

mounted in 2002 after Ardi's lead discoverer hyped it in *Science* as a 'phenomenal individual' that could be a long-sought-after 'Rosetta stone for understanding bipedalism' (Gibbons 2002). When the technical papers were finally published in 2009 – a year of great fanfare as that was the bicentennial of Darwin's birth – the media launched an effort to promote human evolution to the public.

'"Ardi," Oldest Human Ancestor, Unveiled', declared the Discovery Channel, with lead researcher Tim White calling the fossil 'as close as we have ever come to finding the last common ancestor of chimpanzees and humans' (Viegas 2009). The Associated Press printed a similar headline – 'World's oldest human-linked skeleton found' – and claimed that Ardi shows that 'chimps and humans evolved from some long-ago common ancestor' (Schmid 2009). *Science* hailed Ardi's discovery as 'breakthrough of the year' (Gibbons 2009a), further dubbing her, 'A New Kind of Ancestor' (Gibbons 2009b).

Ardi was not really 'new' because, as noted, she had been discovered back in 1994. Why did it take a decade and a half for the first technical analyses to be published? The aforementioned 2002 article in *Science* sheds light. It reports that Ardi's fossilised remains were 'soft', 'crushed', 'squished' and 'chalky', with Tim White confessing, 'when I clean an edge it erodes, so I have to mold every one of the broken pieces to reconstruct it' (Gibbons 2002). Another report noted that 'some portions of Ardi's skeleton were found crushed nearly to smithereens and needed extensive digital reconstruction' and compared the pelvis's initial state to an 'Irish stew' (Lemonick & Dorfman 2009). Another article in *Science* admitted the fossil's 'terrible condition', comparing Ardi to 'road kill' as 'parts of the skeleton had been trampled and scattered into more than 100 fragments' and her 'skull was crushed to 4 centimetres in height' (Gibbons 2009b). *National Geographic* affirmed the road kill analogy, reporting that Ardi was 'trampled down into mud by hippos and other passing herbivores' making the bones 'badly crushed and distorted' and 'so fragile they would turn to dust at a touch' (Shreeve 2009).

Demonstrating that a hominin is bipedal requires precise measurements of key bones – especially the pelvis. Can one maintain confidence in Ardi as a 'Rosetta stone' for bipedalism if her remains were 'crushed nearly to smithereens and needed extensive digital reconstruction' and the pelvis initially resembled an 'Irish stew'? According to *Science*, various paleoanthropologists were appropriately 'skeptical that the crushed pelvis really shows the anatomical details needed to demonstrate bipedality'. Carol Ward observed that Ardi 'does not appear to have had its knee placed over the ankle, which means that when walking bipedally, it would have had to shift its weight to the side' and William Jungers concluded the post-cranial bones 'would not unequivocally signal hominin status' (Gibbons 2009b).

Subsequent technical papers bore out these critiques. Primatologist Esteban Sarmiento wrote in the journal *Science* that 'All of the *Ar. Ramidus* bipedal characters cited also serve the mechanical requisites of quadrupedality' and that Ardi's foot proportions 'find their closest functional analogue to those of gorillas, a terrestrial or semiterrestrial quadruped and not a facultative or habitual biped' (Sarmiento 2010). Bernard Wood (cited in Wood & Harrison 2011), a leading paleoanthropologist from George Washington University, co-published strong criticisms in *Nature*:

> [*T*]he claim that *Ardipithecus ramidus* was a facultative terrestrial biped is vitiated because it is based on highly speculative inferences about the presence of lumbar lordosis and on relatively few features of the pelvis and foot [...]. (n.p.)

This implies that if Ardi was a hominin ancestral to humans, then her many ape-like features suggest ‘remarkably high levels of homoplasy [convergence] among extant great apes’ (Wood & Harrison 2011). A 2021 study in *Science Advances* further found that the hand of *Ardipithecus ramidus* was suited for climbing and swinging in trees and possibly also for knuckle-walking, much like chimps (Prang et al. 2021). Another commentary stated that classifying Ardi as ‘a human ancestor is by no means the simplest, or most parsimonious explanation’ (New York University 2011). Richard Klein of Stanford University agreed: ‘I frankly do not think Ardi was a hominid, or bipedal’ (Wilford 2010). In light of these challenges to the official story about Ardi, Sarmiento stated that he ‘regards the hype around Ardi to have been overblown’ (Harrell 2010).

Australopithecus – Upright-walking ancestors of our genus *Homo*?

The Maropeng Museum promotes the standard evolutionary view that the australopithecines were upright-walking small-brained species that were direct ancestors to human beings. The Maropeng Museum (n.d.) states, ‘*Australopithecus* walked upright and had human-like teeth and hands’. But is this view well supported?

By far the most famous australopithecine specimen is Lucy (species *Australopithecus afarensis*), often described as a small-brained, bipedal ape-like creature that was ancestral to humans. It is commonly stated that only 40% of Lucy was found although the Maropeng Museum (n.d.) states that her skeleton ‘consists of only 47 of the 206 bones in the human body’, with a large percentage entailing rib fragments. Very few fragments were found from Lucy’s skull, yet she is considered one of the most significant specimens.

The Maropeng exhibit notes that the australopithecines ‘had ape-like features, including a small brain, flattened nose, and forward-projecting jaws’. Lee Berger affirms her chimp-like head, writing, ‘Lucy’s face would have been prognathic, jutting out almost to the same degree as a modern chimpanzee’ (Berger & Hilton-Barber 2000, p. 114). But Bernard Wood (1992) explains misconceptions about this group:

> Australopithecines are often wrongly thought to have had a mosaic of modern human and modern ape features, or, worse, are regarded as a group of ‘failed’ humans. Australopithecines were neither of these. (p. 232).

Importantly, many have questioned whether Lucy was a habitual biped (like humans) and have suggested australopithecines spent much of their time in trees. An article in *Nature* reports that much of Lucy’s body was ‘quite ape-like’, such as her ‘relatively long and curved fingers, relatively long arms, and funnel-shaped chest’ (Collard & Aiello 2000). That article examined the hand bones of Lucy and found good evidence’’ that she ‘“knuckle-walked,” as chimps and gorillas do' (Collard & Aiello 2000; Richmond & Strait 2000). A *New Scientist* article adds that Lucy appears well-adapted for climbing, as 'Everything about her skeleton, from fingertips to toes, suggests that Lucy and her sisters retain several traits that would be very suitable for climbing in trees' (Cherfas 1983). Richard Leakey and Roger Lewin argue that australopithecines 'almost certainly were not adapted to a striding gait and running, as humans are' (Leakey & Lewin 1993, p. 195). They recount the surprise expressed by Peter Schmid upon realising that Lucy had so many nonhuman qualities (Leakey & Lewin 1993):

> Everyone had talked about Lucy as being very modern, very human, so I was surprised by what I saw […] What you see in *Australopithecus* is not what you'd want in an efficient bipedal running animal […] The shoulders were high, and, combined with the funnel-shaped chest, would have made arm swinging very improbable in the human sense. It wouldn't have been able to lift its thorax for the kind of deep breathing that we do when we run. The abdomen was potbellied, and there was no waist, so that would have restricted the flexibility that's essential to human running. (pp. 193–194)

There are additional differences between australopithecines and humans and similarities between australopithecines and apes. In primates, inner ear canals are crucial for balance and have shapes related to locomotion. Yet australopithecine ear canals are different from those of the genus *Homo* and similar to the ear canals of apes (Spoor, Wood & Zonneveld 1994). Their ape-like developmental patterns (Bromage & Dean 1985) and prehensile grasping by toes (Clarke & Tobias 1995) led a *Nature* article to observe that 'ecologically they [australopithecines] may still be considered as apes' (Andrews 1995). Another analysis in *Nature* found the australopithecine skeleton to be 'a mosaic of features unique to themselves and features bearing some resemblances to those of the orangutan', concluding: 'the possibility that any of the australopithecines is a direct part of human ancestry recedes' (Oxnard 1975). A 2007 paper reported '[g]orilla-like anatomy on *Australopithecus afarensis* mandibles' – a finding called 'unexpected', as it 'cast[s] doubt on the role of *Au. Afarensis* as a modern human ancestor' (Rak, Ginzburg & Geffen 2007).

Lucy's pelvis has been a subject of controversy for similar reasons that made Ardi's pelvis controversial: it was initially 'badly crushed' with 'distortion' and 'cracking' (Johanson et al. 1982). One paper concluded that Lucy's pelvis is 'different from other australopithecines and so close to the human condition' because of 'error in the reconstruction… creating a very "human-like" sacral plane' (Marchal 2000). Another study concluded there is insufficient fossil evidence to conclusively address whether Lucy walked upright: 'Prevailing views of Lucy's posture are almost impossible to reconcile […] To resolve such differences, more anatomical (fossil) evidence is needed. The available data at present are open to widely different interpretations' (Abitbol 1995).

None of these differences in locomotion or hand or dental anatomy between australopithecines and humans are mentioned by the Maropeng Museum. Instead, it leaves visitors with the impression that the australopithecines were like small-brained, upright-walking early versions of human beings. But even in the best case, *Australopithecus* was highly different from the earliest members of the genus *Homo* (see Figure 9.6 for a comparison).

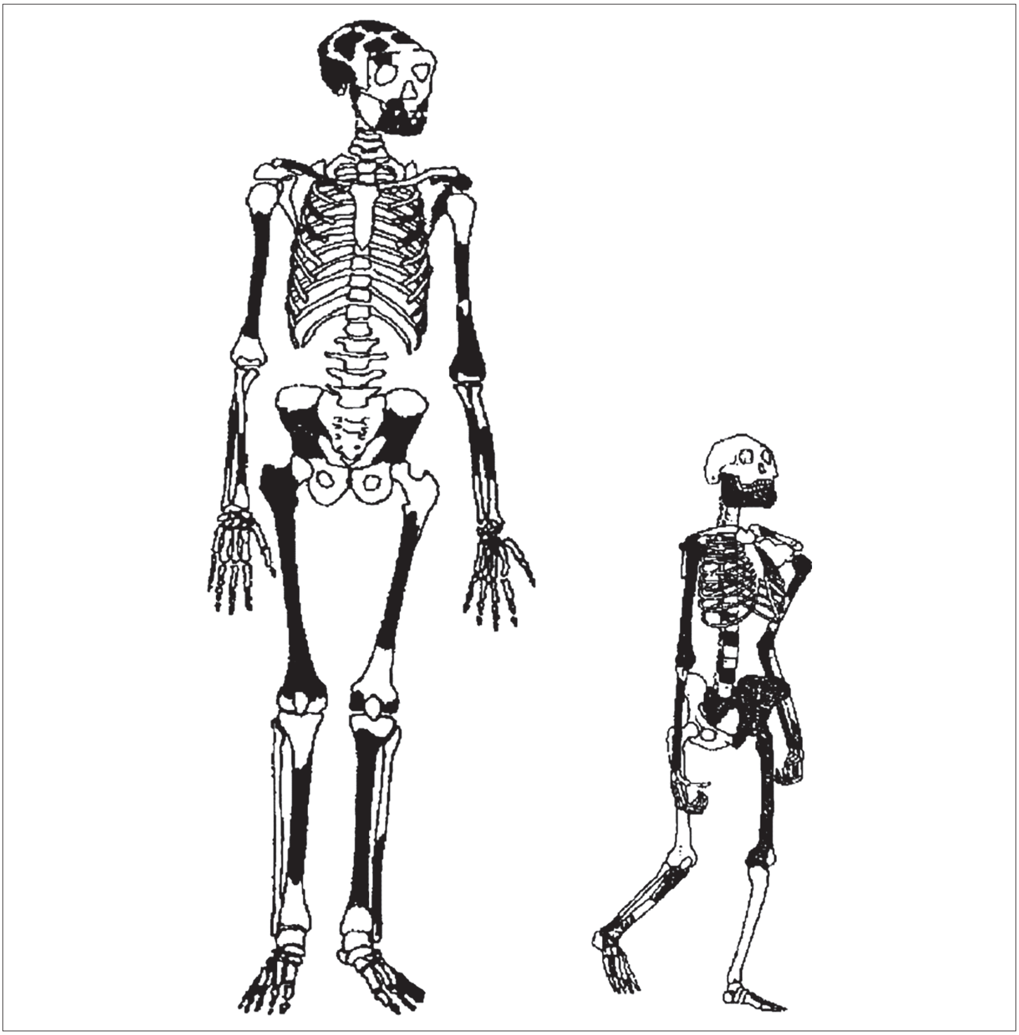
According to University College London paleoanthropologist Leslie Aiello, '[a]ustralopithecines are like apes, and the *Homo* group are like humans. Something major occurred when *Homo* evolved, and it was not just in the brain' (Leakey & Lewin 1993, p. 196). As will be seen, the 'something major' was the sudden appearance of the novel *Homo* body plan without transitions linking back to the supposed australopithecine ancestors of *Homo*.

Homo naledi and *Australopithecus sediba*

To be sure, many have sought to find intermediates between *Australopithecus* and *Homo*. In 2015, media outlets were again buzzing when a new species, *Homo naledi*, was reported from South Africa. CNN ran the headline, '*Homo naledi*: New species of human ancestor discovered in South Africa' (McKenzie & Wende 2015). *The Daily Mail* announced: 'Scientists discover skull of new human ancestor *Homo Naledi*' (Reilly 2015). *PBS* declared: 'Trove of fossils from a long-lost human ancestor' (PBS 2015). And so on. To be sure, the find was extremely important because it represented probably the largest cache of hominin bones – many hundreds, if not thousands – ever found. In a field where a jaw scrap ignites the community, these finds were a major boost to South Africa's status as a world leader in palaeoanthropology. But do we know that *Homo naledi* is a 'human ancestor' as news outlets declared? Later research has established that the answer is clearly 'No'.

The strongest claims about *Homo naledi* held that it is a 'transitional form' or 'mosaic'. Yet within evolutionary systematics, the term 'mosaic' often indicates that a fossil exhibits a complement of traits that do not fit neatly into the accepted evolutionary tree. This is the case with *Homo naledi*.

Specifically, the claim was made that *Homo naledi* was a small-brained, upright-walking hominin with a trunk similar to the australopithecines and human-like hands and feet. But the technical material shows that some of *naledi*'s supposedly human-like traits exhibit unique features. For example, the hands showed 'a unique combination of anatomy' (University of the Witwatersrand 2015) including 'unique first metacarpal morphology' (Berger et al. 2015) and long, curved fingers that suggest *naledi* was, unlike humans, well suited for 'climbing and suspension' (Kivell et al. 2015). As for the foot, it 'differs from modern humans in having more curved proximal pedal phalanges and features suggestive of a reduced medial longitudinal arch' giving it an



Source: Hawks et al. (2000, pp. 2–22, fig. 1).
Note: Bones that have been found are shaded. The original caption states: 'The first members of early *Homo sapiens* are really quite distinct from their australopithecine predecessors and contemporaries'.
FIGURE 9.6: A comparison of Lucy (right) to early *Homo* (left).

overall 'unique locomotor repertoire' (Harcourt-Smith et al. 2015). The foot indicates *naledi* was 'likely comfortable climbing trees' (American Museum of Natural History 2015) – a stark contrast to humans.

Homo naledi also had 'unique features in the femur and tibia', reflecting a hindlimb that 'differs from those of all other known hominins' (Berger et al. 2015). Similarly, for the head, 'Cranial morphology of *H. naledi* is unique [...]' (Berger et al. 2015). The discoverers of the species called it, 'a unique mosaic previously unknown in the human fossil record' (Harcourt-Smith et al. 2015). As noted, this 'mosaic' terminology should raise a red flag as it usually indicates the fossil is difficult to place within current evolutionary phylogenetic schemes. Whatever it was, overall *naledi* appears highly unique.

In 2010, a team led by Lee Berger – some of the same scientists who discovered *naledi* – were promoting a *different* hominin species, *Australopithecus sediba*, as an intermediate link between the *Australopithecus* and *Homo* genera. However, *sediba* and *naledi* differ in important ways that make them unlikely partners in an evolutionary lineage. Specifically, *sediba* (classified within *Australopithecus*), had an advanced '*Homo*-like pelvis' (Bryn 2011; Wong 2012), human-like hands, 'surprisingly human teeth' (Gibbons 2013; Ramlagan 2013) and a 'human-like' lower trunk (Choi 2013; Schmid et al. 2013). However, *naledi* – placed within *Homo* – bears an 'australopith-like' and 'primitive' pelvis (Vansickle et al. 2016), 'primitive' teeth and hands and a 'primitive or australopith-like trunk' (Berger et al. 2015). An australopithecine with apparently advanced *Homo*-like pelvis, teeth and hands seems a poor candidate to evolve *into* a member of *Homo* characterised by primitive australopith-like pelvis, teeth and hands. If the goal is to elucidate a lineage ending with modern humans, key traits are evolving in the wrong direction. Thus, although both *sediba* and *naledi* have been described as ancestors of humans – by some of the same researchers – evolutionarily speaking, both claims should not be true (unless you are willing to tolerate a very messy tree). A news report explained why this is the case: 'Each [*sediba* and *naledi*] has different sets of australopith-like and human-like traits that cannot be easily reconciled on the same family tree' (Yong 2015).

Paleoanthropologists have also criticised claims that *sediba* was our ancestor. One called it 'way too primitive to be the ancestor of the human genus *Homo*' and warned the fossil 'is surrounded by hype and over-interpretation' (Macknight 2010). Another thought it merely represents *Australopithecus africanus* (Balter 2010). Others have observed that *sediba* post-dates *Homo* and had the wrong traits to be our direct ancestor (Gibbons 2011, 2013; Kimbel 2013; Wade 2011; Wilford 2012; White 2013). In any case, because *sediba* postdates its supposed descendent group *Homo* by 800,000 years, one paper found it 'highly unlikely that *A. sediba* is ancestral to *Homo*' – with the statistical probability that it is our ancestor being given as less than 0.001 (Du & Alemseged 2019). Commenting on *sediba*, Harvard's Daniel Lieberman said, 'The origins of the genus *Homo* remain as murky as ever' (Zimmer 2010) and Donald Johanson remarked, 'The transition to *Homo* continues to be almost totally confusing' (Balter 2010). Even Lee Berger acknowledged when publishing on *sediba* that, 'the ancestry of *Homo* and its relation to earlier australopithecines remain unresolved' (Berger et al. 2010).

Homo naledi faces even greater challenges to claims of its status as a human ancestor. One dubious hypothesis is that it intentionally buried its dead – supposedly reflecting an advanced intellect. Yet burying dead in the cave where it was found would have been seemingly physically impossible even for an intelligent species like modern humans: the individual would have had to shimmy through a steep, narrow crevice while dragging a dead body a long distance in pitch darkness. For many reasons, multiple scientists dispute the intentional burial hypothesis (Farber 2016; Val 2016; Wong 2016). Alison Brooks of George Washington University commented that claims of intentional burial are 'so far out there that they really need a higher standard of proof' (Wong 2015).

When first published, the *Homo naledi*'s promoters suggested – strictly on the basis of evolutionary considerations rather than geological evidence – that it lived 2–3 mya. But at that time the fossil had not been dated geologically, leading paleoanthropologist Carol Ward to warn, 'Without dates, the fossils reveal almost nothing about hominin evolution' (Yong 2015). This did not stop paleoanthropologists from speculating about its evolutionary importance. 'Many scientists', writes the Maropeng Museum (n.d.), 'looking only at the form of *Homo naledi*, thought it would be much older, maybe even two million years or more'. If such an old age were correct, then some hoped that *naledi* represented 'early *Homo*' and was 'an intermediate between *Australopithecus* and *Homo erectus*' (Ghosh 2015; Rincon 2017; University of Colorado Anschutz Medical Campus 2015).

Definitive evidence against *Homo naledi*'s status as a transitional form came in 2017 when it was 'surprisingly' dated to the 'startlingly young' age of 236,000–335,000 years (Dirks et al. 2017; University of the Witwatersrand 2017). This age was an order of magnitude younger than the 2 to 3 million year age that was expected under the evolutionary model and far too young to be ancestral to our species or even related to human evolution. One anthropologist candidly admitted (Kidder 2017):

> Nearly everyone in the scientific community thought that the date of the *Homo naledi* fossils, when calculated, would fall within the same general time period as other primitive early *Homo* remains. We were wrong. (n.p.)

To the credit of the Maropeng Museum, it admits errors about initial guesses over *naledi*'s age, but it does not acknowledge that evolutionary thinking is what led to those errors. Despite the geological evidence, the Maropeng Museum (n.d.) tries to force *naledi* into an older evolutionary context, proposing (without hard evidence) that it 'really did branch from our family tree much earlier, more than a million and maybe up to two million years ago'. Yet given the known hominin record, the likelihood of *Homo naledi* being ancestral to humans is *much* less than 0.001 (Luskin 2019).

Five years before the unveiling of *naledi*, the media touted *sediba* as a human ancestor. But objectivity prevailed and eventually it was demonstrated that *sediba* could not have been our ancestor. What will become of *Homo naledi*?

Many have already protested the ‘hype’ over this fossil find (Curnoe 2015; Shermer 2016a, 2016b; Stringer 2015), and its trajectory resembles other hominins for which hyped claims of ‘transitional’ or ‘ancestral’ status eventually failed.

Homo habilis: A tool-using transitional species?

Although the Maropeng Museum does not do so, in the past many have cited *Homo habilis* (literally ‘handy man’) as a tool-using species that was a transitional ‘link’ between the australopithecines and *Homo* (Walker & Shipman 1996, p. 133). Indeed, the museum states that *habilis* is ‘the earliest species of the genus *Homo*’ and claims it ‘was probably the first hominin to make stone tools’. But its association with tools is doubtful and appears driven mainly by evolutionary considerations, not direct evidence of discovery with tools (Schwartz & Tattersall 2015).

Various studies of the morphology of *Homo habilis* have cast doubt upon claims that it was transitional between *Australopithecus* and *Homo*. Some studies conclude that because *habilis* differs from *Homo* in terms of its body size, shape, mode of locomotion, jaws and teeth, developmental patterns and brain size, which it should removed from *Homo* and reclassified as *Australopithecus habilis* (Collard & Wood 2015; Wood & Collard 1999). Another study found that *habilis* ‘matured and moved less like a human and more like an australopithecine’ and had a diet ‘more like Lucy’s than that of *H. erectus*’ (Gibbons 2011). Another paper found ‘post-cranial remains of *H. habilis* appear to reflect an australopith-like body plan’ (Berger et al. 2015).

Similar to the australopithecines, *habilis* has many features that were more ape-like than human-like. Bernard Wood notes that members of *habilis* ‘grew their teeth rapidly, like an African ape, in contrast to the slow dental development of modern humans’ (Gibbons 2011; Wood & Collard 1999). The ear canals of *habilis* (again, related to the mode of locomotion) are most similar to baboons, leading a *Nature* study to suggest that *habilis* ‘relied *less* on bipedal behaviour than the australopithecines’. The conclusion was striking: ‘the unique labyrinth of [the *habilis* skull] represents an unlikely intermediate between the morphologies seen in the australopithecines and *H. erectus*’ (Spoor et al. 1994).

A comprehensive study determined that the skeleton of *habilis* was *more* similar to living apes than were other australopithecines, concluding: ‘It is difficult to accept an evolutionary sequence in which *Homo habilis*, with less human-like locomotor adaptations, is intermediate between *Australopithecus afarensis* […] and fully bipedal *Homo erectus*’ (Hartwig-Scherer & Martin 1991). Alan Walker and Pat Shipman similarly called *habilis* ‘more ape-like than Lucy’ and remarked, ‘Rather than representing an intermediate between Lucy and humans, [*habilis*] looked very much like an intermediate between the ancestral chimp-like condition and Lucy' (Walker & Shipman 1996, p. 130, 132). In light of this evidence, Sigrid Hartwig-Scherer explains that *habilis* 'displays much stronger similarities to African ape limb proportions' than does Lucy, leading her to call these results 'unexpected in view of previous accounts of *Homo habilis* as a link between australopithecines and humans' (Hartwig-Scherer 1998, p. 226).

The abrupt origin of *Homo*

In 2015, two leading paleoanthropologists reviewed the fossil evidence regarding human evolution in a prestigious scientific volume titled, *Macroevolution*. They acknowledged the 'dearth of unambiguous evidence for ancestor-descendent lineages' and stated (Wood & Grabowski 2015):

> [*T*]he evolutionary sequence for the majority of hominin lineages is unknown. Most hominin taxa, particularly early hominins, have no obvious ancestors, and in most cases ancestor-descendent sequences (fossil time series) cannot be reliably constructed. (p. 365)

This problem is hinted at, though not explicitly acknowledged, in a diagram at the Maropeng Museum. The diagram presents a standard hominin phylogeny, but places question marks at key nodes that represent the origin of major hominin species, such as *Homo erectus* (equivalent to the origin of *Homo* in the diagram) or the origin of our own species (*Homo sapiens*) from earlier types of *Homo*. Though it is not stated clearly, these question marks indicate major instances where there are not fossils documenting key evolutionary ancestors or transitions.

From its first appearance, *Homo erectus* was very human-like and differed markedly from prior hominins that were *not* human-like. Yet *Homo erectus* appears *abruptly* in the record, without apparent evolutionary precursors. An article in *Nature* explains this saltation (Asfaw et al. 2002):

> The origins of the widespread, polymorphic, Early Pleistocene *H. erectus* lineage remain elusive. The marked contrasts between any potential ancestor (*Homo habilis* or other) and the earliest known *H. erectus* might signal an abrupt evolutionary emergence some time before its first known appearance in Africa at ~1.78 Myr. Uncertainties surrounding the taxon's appearance in Eurasia and southeast Asia make it impossible to establish accurately the time or place of origin for *H. erectus* [...] Whatever its time and place of origin, and direction of spread, this species dispersed widely, and possibly abruptly, before 1.5 Myr. (p. 319)

That article was written in 2002, but the problem remains. A 2016 paper admits (Kimbel & Villmoare 2016):

> Although the transition from *Australopithecus* to *Homo* is usually thought of as a momentous transformation, the fossil record bearing on the origin and earliest evolution of *Homo* is virtually undocumented. (p. 1)

While that paper argues that the evolutionary distance between *Australopithecus* and *Homo* is small, it nonetheless concedes that (Kimbel & Villmoare 2016):

> [*B*]y almost all accounts, the earliest populations of the *Homo* lineage emerged from a still unknown ancestral species in Africa at some point between approximately 3 and approximately 2 million years ago. (p. 1)

The earliest members of *Homo*, namely *Homo erectus*, show unique and previously unseen features that contributed to this 'abrupt' appearance. The technical literature observes an 'explosion' (Rice 2007, p. 241), 'rapid increase' (Leonard, Snodgrass & Robertson 2007; Shultz, Nelson & Dunbar 2012; Wuketits 2015) and 'approximate doubling' (Falk 1998), in brain size associated with the appearance of *Homo*. Wood and Collard's major *Science* review found that *only one single trait of one hominin species qualified as* 'intermediate' between *Australopithecus* and *Homo*: the brain size of *Homo erectus.*[62] However, this one 'intermediate' trait does not necessarily demonstrate that humans are descended from less advanced hominids.

Intelligence is a complex feature, determined largely by internal brain organisation and cannot be reduced to a single dimension like brain size (Deacon 1990, 1997; Molnar 2002, p. 189). Neanderthals, for example, had a larger brain size than modern humans, but few would say they were more intelligent. As brain scientist Christof Koch observes, 'total brain volume weakly correlates with intelligence […] brain size accounts for between 9 and 16 percent of the overall variability in general intelligence' (Koch 2016). Cranial capacity is also not always a reliable guide for reconstructing evolutionary relationships. As a review in *Science* explained, 'Relative brain size does not group the fossil hominins in the same way as the other variables. This pattern suggests that the link between relative brain size and adaptive zone is a complex one' (Wood & Collard 1999).

Modern human skull sizes have a wide amount of variation. Because of this, a sequence of relatively small to large skulls could easily be constructed from the skulls of living humans, creating the false impression of an evolutionary lineage (Figure 9.7). *Homo erectus*, *Homo ergaster* and *Homo heidelbergensis* are said to have had cranial capacities ranging from 800 to 1 400 cubic centimetres (cc) (Toth & Schick 2015) – all within the range of modern human genetic variation (Table 9.1). Even the Maropeng Museum states that *Homo ergaster*, an early form of *Homo erectus*, had a cranial capacity of '800 cc to 1200 cc, with an average of about 900 cc' – smaller than modern human averages but still within the range of modern human variation. Table 9.1 shows that the average brain size of *erectus* was well within modern variation.

---

[62] Specifically, *Homo erectus* is said to have intermediate brain size, and *Homo ergaster* is said to have a *Homo*-like postcranial skeleton with a smaller more australopith-like brain size.

Source: Figure generated by Jonathan Jones, published with permission from Jonathan Jones.
Note: Cranial capacity does not necessarily correlate with intelligence nor does it reliably indicate evolutionary relationships. An artificial line-up of small to large skulls from normal living humans could easily be created, implying an evolutionary lineage when it is no such thing.

FIGURE 9.7: Cranial capacity and intelligence.

TABLE 9.1: Cranial capacities of living and extinct hominids.

Taxon	Cranial capacities	Taxon resembles
Gorilla (*Gorilla gorilla*)	340–752 cc (Molnar 1998, p. 203)	Modern Apes
Chimpanzee (*Pan troglodytes)*	275–500 cc (Molnar 1998, p. 203)	
Australopithecus	370–515 cc (Avg. 457 cc) (Conroy et al. 1998; Wood & Collard 1999)	
Homo habilis	Avg. 552 cc (Wood & Collard 1999)	
Homo erectus	800–1 250 cc (Avg. 1 016 cc) (Molnar 1998, p. 203; Wood & Collard 1999)	Modern Humans
Neanderthals	1100–1 700 cc (Avg. 1 450 cc) (Molnar 1998, p. 203, 2002, p. 189)	
Homo sapiens	800–2 200 cc (Avg. 1 345 cc) (Molnar 1998, p. 203, 2002, p. 189; Odokuma et al. 2010)	

Occasional skulls of ‘intermediate’ size are recovered, but this does not demonstrate that humans evolved from primitive ancestors. Of all the *Homo*-linked skulls that have been found, only about six are arguably of ‘intermediate’ size, and five of them were recovered from a single cave in Dmanisi, Georgia, in 2005 (Rightmire et al. 2017). The cranial capacities of these ~1.8 million-year-old Dmanisi skulls range from 546 to 730 cc (Rightmire et al. 2017), but the case to link them to *Homo* is weak and their import for human evolution is unclear. The ‘primitive face, primitive teeth, primitive size of the brain’ (Black 2013) and ‘large face, heavy brow and protruding jaw, as well as a very small brain case—about one-third the size of modern humans’ (Morin 2013) may not represent *Homo* but could be reminiscent of robust australopithecines known to have lasted well after this time period (Constantino 2013; De Ruiter et al. 2009). Post-cranial remains are said to exhibit a variety of *Homo*- and australopith-like traits (Lordkipanidze et al. 2007), but no post-cranial bones were contiguous with the skulls, making it difficult to link any particular skull with particular post-cranial material. Moreover, it is not clear that the bones in the cave derive even from a single species. The skulls show ‘high variability’ (Craze 2013) and it has been suggested that ‘the hominin fossils recovered from Dmanisi may sample more than one taxon’ (Wood 2011). Wood (2011) maintains that the ‘meager evidence' from Dmanisi is inadequate to support any particular interpretation, and Craze (2013) likewise warns that such 'small amounts of data' are insufficient to determine how many species are present, emphasising that 'we need more fossils before we can draw any firm conclusions'. What is clear is that the Dmanisi cave was a site for cat predation (Craze 2013), meaning there could be bones from many individuals representing multiple species dragged in over long periods. Too many questions remain unresolved regarding the Dmanisi skulls to conclude that these small-brained individuals represent a single species that belonged to *Homo*.

Much like the explosive increase in skull size, a study comparing the pelvic bones of australopithecines and *Homo* inferred 'a period of very rapid evolution corresponding to the emergence of the genus *Homo*' (Marchal 2000). One *Nature* paper noted that early *Homo erectus* shows (Dennell & Roebroeks 2005):

> [*S*]uch a radical departure from previous forms of *Homo* (such as *H. habilis*) in its height, reduced sexual dimorphism, long limbs and modern body proportions that it is hard at present to identify its immediate ancestry in east Africa. (p. 1099)

Or anywhere else for that matter. Another review similarly notes, 'it is this seemingly abrupt appearance of *H. erectus* that has led to suggestions of a possible origin outside Africa' (Turner & O'Regan 2015). An important study in the *Journal of Molecular Biology and Evolution* found that *Homo* and *Australopithecus* have major differences including not only brain size but also body height, dental anatomy, degree of cranial buttressing, vision and respiratory-related anatomy. The article concludes (Hawks et al. 2000):

> We, like many others, interpret the anatomical evidence to show that early *H. sapiens* was significantly and dramatically different from […] australopithecines in virtually every element of its skeleton and every remnant of its behaviour. (p. 3)

The study thus described the origin of our genus *Homo* as, 'a real acceleration of evolutionary change from the more slowly changing pace of australopithecine evolution', and stated that such a transformation would have required radical changes (Hawks et al. 2000):

> The anatomy of the earliest *H. sapiens* sample indicates significant modifications of the ancestral genome and is not simply an extension of evolutionary trends in an earlier australopithecine lineage throughout the Pliocene. In fact, its combination of features never appears earlier. (p. 4)

These rapid and unique changes are strikingly characterised as 'a genetic revolution' where 'no australopithecine species is obviously transitional' (Hawks et al. 2000, p. 4).

But how do we know that there was an evolutionary transition between the ape-like australopithecines and our genus *Homo*? Three Harvard paleoanthropologists described the paucity of evidence for this 'critical' transition using a bad news, good news scenario (Lieberman, Pilbeam & Wrangham 2009):

> Of the various transitions that occurred during human evolution, the transition from *Australopithecus* to *Homo* was undoubtedly one of the most critical in its magnitude and consequences. As with many key evolutionary events, there is both good and bad news. First, the bad news is that many details of this transition are obscure because of the paucity of the fossil and archaeological records. (p. 1)

And how good was the 'good news'? They describe it as follows (Lieberman et al. 2009):

> [*A*]lthough we lack many details about exactly how, when, and where the transition occurred from *Australopithecus* to *Homo*, we have sufficient data from before and after the transition to make some inferences about the overall nature of key changes that did occur. (p. 1)

To summarise, in the hominid fossil record, we find ape-like australopithecines ('before') and human-like *Homo* ('after'), but we do not find transitional fossils documenting how one group evolved into the other. Lacking intermediates, they propose we infer a transition based upon the assumption of evolution. We are left with an undocumented transition that occurred somehow, sometime and someplace.

Ernst Mayr (2004), one of the architects of the modern theory of evolution, also recognised the abrupt appearance of our genus:

> The earliest fossils of *Homo*, *Homo rudolfensis* and *Homo erectus*, are separated from *Australopithecus* by a large, unbridged gap. How can we explain this seeming saltation? Not having any fossils that can serve as missing links, we have to fall back on the time-honored method of historical science, the construction of a historical narrative. (p. 198)

One commentator described the evidence as suggesting a 'Big Bang' origin of *Homo* (University of Michigan News Service 2000). This large, unbridged gap between the ape-like australopithecines and the genus *Homo* challenges evolutionary accounts of human origins. Unfortunately, these serious issues with the evidence for human evolution are rarely disclosed to the public, and are certainly obscured at the Maropeng Museum.

Human-chimp genetic similarity

Popular arguments for common ancestry often cite a statistic that claims human and chimp DNA is 98%–99% identical. Once common ancestry has been established, this statistic is then used to promote a broader philosophical position that humans are mere apes slightly modified and not exceptional compared with the animals. Science populariser Bill Nye 'The Science Guy' provides a good example of this thinking (Nye 2014):

> As our understanding of DNA has increased, we have come to understand that we share around 98.8 percent of our gene sequence with chimpanzees. This is striking evidence for chimps and chumps to have a common ancestor. (p. 248)

Some of these points are also articulated by leading science museums. The Maropeng Museum (n.d.) states, ‘By studying DNA, scientists can unlock the secrets of our ancestors’. The American Museum of Natural History goes further, noting that, ‘Humans and chimps share a surprising 98.8 percent of their DNA’ and concludes, ‘Human and chimp DNA is so similar because the two species are so closely related’ (American Museum of Natural History 2019). The Smithsonian Museum of Natural History (2010) likewise states:

> DNA is thus especially important in the study of evolution. The amount of difference in DNA is a test of the difference between one species and another – and thus how closely or distantly related they are.
>
> While the genetic difference between individual humans today is minuscule – about 0.1%, on average – study of the same aspects of the chimpanzee genome indicates a difference of about 1.2%. (n.p.)

But how far can we trust claims of extremely high degrees of chimp–human genomic similarity? When the chimpanzee genome was first sequenced in 2005 it quickly became clear that the picture was more complex than was previously thought. A review appeared in *Science* titled ‘Relative Differences: The Myth of 1%,’ which strongly criticised claims that humans are only 1% genetically different from chimps – calling it a ‘myth’ or a ‘truism [that] should be retired’. According to the article, the genetic differences between humans and chimps tally up at ‘35 million base-pair changes, 5 million indels [insertions or deletions of sequences of multiple nucleotide bases] in each species, and 689 extra genes in humans’ (Cohen 2007). Another method of measuring genomic similarity is to compare copy numbers of orthologous genes. By this metric, the ‘Myth of 1%’ article reported that human and chimp gene copy numbers diverge ‘by a whopping 6.4%’.

Today, the statistic that humans are some 98%–99% genetically similar to chimps has been effectively debunked. It only ever applied to protein-coding sequences that are similar enough that they can be aligned. Indeed, the original 1% statistic was derived from a single protein-protein comparison! But many *non*-coding sequences between the two species are highly dissimilar – too different to allow for an alignment. This problem pertains especially to the human y chromosome, which has radical differences from chimps (Hughes et al. 2010). These effectively unique sections of DNA should be considered in any comparison of human-chimp genetic similarity.

Geneticist Richard Buggs has sought to improve methods of human-chimp genomic comparisons. He reports a significant statistic: ‘The percentage of nucleotides in the human genome that had one-to-one exact matches in the chimpanzee genome was 84.38%’ (Buggs 2018). In a 2020 paper, Buggs used a different method to estimate human-chimp genetic similarity at 96% (Seaman & Buggs 2020). This estimate includes coding and non-coding DNA but excludes centromeric DNA. If centromeric DNA were included, then human-chimp similarity could drop to as low as ~93%. Computational biologist Steve Schaffner has made a similar rough estimate of human-chimp genetic similarity at ~95% (Schaffner 2018). One difficulty is that all estimates of human-chimp genetic similarity to date rely upon chimp genome drafts that used portions of the human genome as 'scaffolding' during their construction, effectively 'humanising' certain sections. This practice artificially makes chimp genome sequences appear more similar to humans than they truly are (NCBI 2007).

At present, human-chimp genetic similarity statistics are probably overestimates, although this could change when more accurate and complete chimp genomes are sequenced. Nonetheless, any of the mentioned statistics – 96%, 95%, 93%, 84% – carry different meanings. What exactly do they tell us about our relationship to the apes?

Someday scientists will probably obtain a reliable estimate of human-chimp genetic similarity. Whatever it is, we can assume it will be relatively high – probably at least 84%. Would such a percent similarity imply human-ape common ancestry? If a 1% genetic difference is said to demonstrate common ancestry, but then that statistic is shown to be incorrect, does a 5% genetic difference imply common ancestry is false? How about 10%? 25%? Can the case for common ancestry based upon the degree of similarity ever be scientifically falsified? If so, at what point?

If we assume an evolutionary model, then the degree of genetic similarity should reflect the closeness of an evolutionary relationship. But how do we know an evolutionary context is the proper one for interpretating the data in the first place? If we are trying to assess whether common ancestry is correct, why does the percent genetic similarity even matter? The point should be clear: percent genetic similarity statistics do not provide an objective metric for concluding common ancestry. Biologist and evolution advocate Dennis Venema acknowledges this point, writing that the '% genome identity' is 'just not a precise value that scientists are interested in, because it does not answer interesting scientific questions in the way other values do [...]' (Venema 2018).

Yet there are alternative explanations for a high degree of similarities between genomes. Functional genetic similarity does not require common ancestry because intelligent agents often re-deploy the components or modules independently in different designs to fulfil similar functional requirements. Compare the schematics for a Dell laptop and a Lenovo laptop. There will be many similarities that represent functional requirements of a laptop computer and reflect the fact that intelligent agents have designed those systems to fulfil those requirements. Re-usage of functional components is in fact a standard practice within engineering and computer programming. Wheels are re-used on motorcycles, cars, trucks and aircraft. Touchscreen keyboards – and the code that controls them – are deployed on both smartphones and tablets. Even the eminent geneticist Francis Collins (a critic of ID) acknowledges that some functional similarities between organisms could reflect how a designer ‘used successful design principles over and over again’ (Collins 2006, p. 134). This idea is often called ‘common design’.

Arguments for common design do not try to prove that species were designed or created independently. Rather, they defeat the common assertion from evolutionary biologists that the *only* possible explanation for genetic similarity is common ancestry. A high percentage of genetic similarity could therefore reflect a design based upon a common blueprint that meets functional constraints rather than inheritance from a common ancestor. In such cases, ‘the trait is most likely shared because the organisms use similar solutions to a physiological need’ (Gauger et al. 2017, p. 496).

Functional similarities are easy to explain through common design. But *non*-functional genetic similarities between humans and chimps are also cited as evidence for common ancestry. This is a reasonable argument, for designers typically emplace structures for a reason, but shared non-functional DNA is better explained by material causes (e.g. common ancestry) than design. Of course, the argument depends upon the shared DNA sequences truly being *non-functional*. Francis Collins made such an argument in *The Language of God*, where he claimed that ‘45 percent of the human genome [is] made up of…genetic flotsam and jetsam’, indicating our common ancestry. with other mammals (Collins 2006, p. 136). But over the past two decades, numerous functions have been discovered for non-coding DNA, overturning such ‘junk DNA’ arguments.

A ground-breaking 2012 study published in *Nature* by an international group of hundreds of research scientists known as the ENCODE Consortium reported ‘biochemical functions for 80% of the genome, in particular outside of the well-studied protein-coding regions’ and found ‘[t]he vast majority (80.4%) of the human genome participates in at least one biochemical [function]’ (ENCODE Project Consortium 2012). The ENCODE project only analysed a minority of human cell types, but after more cell types are studied its lead scientists predicted that ‘80 percent will go to 100 percent’, because ‘almost every nucleotide [in the human genome] is associated with a function of some sort’ (Yong 2012). Another *Nature* article described these findings as ‘dispatching the widely held view that the human genome is mostly “junk DNA”’ (Ecker 2012).

Evidence for function in non-coding DNA has continued to mount. A 2019 paper proposed a ‘genomic code’ which spans large sections of DNA between genes across the genome (Bernardi 2019). A 2021 review in *Nature* found that over 130,000 discrete genetic elements ‘previously called junk DNA’ have been already reported in the literature to have biological functions – and showed that functions for non-coding DNA are being discovered at a rapid pace (Gates et al. 2021). Even pseudogenes, frequently cited as a form of genetic junk that demonstrates common ancestry, are no longer considered to necessarily be genetic 'junk' (Cheetham, Faulkner & Dinger 2020; Kovalenko & Patrushev 2018; Pink et al. 2011; Poliseno 2012; Poliseno et al. 2010; Troskie, Faulkner & Cheetham 2021). The assumption that non-coding DNA that we share with apes is merely functionless 'junk' reflecting our common ancestry is no longer sustainable. As a 2021 paper proclaimed, 'The days of "junk DNA" are over' (Stitz et al. 2021).

If the non-coding DNA is not coding for proteins, but also is not junk, then what is it doing? Much of the gene-coding DNA between humans and chimps is highly similar – this is expected as these genes encode the basic proteins and building blocks that construct our bodies. But building blocks can be used in many different ways. Starting with the same building materials – bricks, mortar, wood and nails – one could construct a church, a football stadium, or a crematorium. The key to predicting the final morphology is not similarities between the building blocks but how they are used. Non-coding DNA functions in part like a blueprint that likely controls how similar genes are used; small differences in non-coding DNA could yield great differences to an organism's body plan. Gauger et al. (2017) thus explain that the percent genetic similarity can never fully capture human-chimp differences:

> [*C*]ounting raw difference is not the best way to calculate how different we are genetically speaking […] We now know that when, where, and how our DNA is used matters much more than an overall count of nucleotide differences. Human-specific differences in gene regulation […] are what make us unique. (pp. 481–482)

When evaluating human-chimp similarity we must not only consider genetic or genomic similarity but also differences in the transcriptome, proteome, epigenome and physiology of humans and chimps. These include:

1. Humans have over 600 unique genes, as well as different numbers of copies of genes, such that 'humans and chimpanzees differ by at least 6% […] in their complement of genes' and gene copy numbers in humans and chimps differ by 6.4% (Cohen 2007; Demuth et al. 2006; Ruiz-Orera et al. 2015).
2. Alternative splicing allows the existence of multipurpose genes – where multiple different proteins are encoded by a single gene. Because alternative splicing adds an additional step to the central dogma of DNA à RNA à protein, the protein-variants produced by these multipurpose genes cannot be predicted simply by sequencing the nucleotide bases. Studies report that 'Eighty percent of proteins are different [i.e. non-identical] between humans and chimpanzees' (Glazko et al. 2005) and 'six to eight per cent of the alternative splicing events […] [show] differences' between chimps and humans (Calarco et al. 2007; University of Toronto 2007).
3. Important DNA sequence differences exist in both coding and non-coding DNA, including 856 genes associated with 'human-specific characteristics' including 'neuronal, immunological and metabolic features' (Bitar et al. 2019),

as well as thousands of human-specific SINE elements, LINE elements and long non-coding RNAs, which are often vital for human brain development (Johansson et al. 2022; Levchenko et al. 2017; Paz-Yaacov et al. 2010; Suntsova & Buzdin 2020). Human accelerated regions (HARs) are portions of our genome that exhibit major differences compared to chimps. The 'genes located near HARs are predominantly related to interaction with DNA, transcriptional regulation and neuronal development' (Suntsova & Buzdin 2020).

4. Differential gene expression and differences in gene regulatory networks play a major role in human-chimp transcriptional and proteomic differences. Significant differences in human-chimp gene expression are found in genes related to the brain (Johansson et al. 2022; Oldham, Horvath & Geschwind 2006; Suntsova & Buzdin 2020; Varki, Geschwind & Eichler 2008).
5. Epigenetic differences are also important, including differential methylation of genes involved with the human brain (Suntsova & Buzdin 2020).
6. Humans and chimps exhibit many morphological, metabolic and developmental differences, including timing of development, teeth, brain formation, musculature and physical strength, diet, locomotion, neck, rib cage and gait, shoulder, pelvis and hip, inner ear canals, hands (designed for tool use in humans rather and knuckle-walking in apes), jaws and hair (Almécija, Smaers & Jungers 2015; Bitar et al. 2019; Bramble & Lieberman 2004; Humphrey, Dean & Stringer 1999; O'Neill et al. 2017).

Whatever the exact percent nucleotide similarity or difference between humans and chimps turns out to be, it cannot demonstrate common ancestry. Moreover, humans have significant genetic, epigenetic and physiological differences from chimpanzees. Yet there is also a vast cognitive and behavioural gulf between the two species.

The origin of the human mind

The Maropeng Museum (n.d.) states that:

> The development of the brain enabled hominids to make and use tools and fire, communicate using language, develop culture and society, adapt to new environments and, finally, to become self-aware and creative. (n.p.)

Our advanced cognitive abilities are undoubtedly vital to human culture and society, but as noted, human brain size does not increase in a gradual Darwinian manner in the fossil record.[63] Moreover, many researchers have recognised an 'explosion' or 'revolution' (Bar-Yosef 2002; Mellars 2004; Nowell 2006) of modern human-like culture in the archaeological record about 30 to

---

[63] As noted, the technical literature observes an 'explosion' (Rice 2007, p. 241), 'rapid increase' (Leonard et al. 2007; Shultz et al. 2012; Wuketits 2015), and 'approximate doubling' (Falk 1998) in brain size associated with the appearance of our genus *Homo*.

40 thousand years ago, showing the abrupt appearance of human creativity (White 2003, p. 11, 231), technology, art (Rice 2007, p. 104, 187, 194) and even paintings (Kelly & Thomas 2010, p. 303) – showing the rapid emergence of self-awareness, group identity and symbolic thought (Bar-Yosef 2002). One review of Palaeolithic archaeology dubbed this the 'Creative Explosion' (Toth & Schick 2015, p. 2459). This abrupt appearance of modern human-like morphology, intellect and culture contradicts evolutionary models and may even indicate a design event in human history.

Human language challenges Darwinian evolution

The museum further outlines a vague scheme of how human language might have evolved (Maropeng Museum n.d.):

> Maybe speech and vocabulary evolved gradually, with names being assigned to objects like tools and animals, and later words being attached to concepts like 'go hunt' or 'fetch water'. As hominid brains grew with the emergence of different *Homo* species, these symbols may have eventually led to complex language. (n.p.)

Humans are the only species that uses complex language – as one paper put it, 'Language is a uniquely human ability [...]' (Carreiras et al. 2009). In the technical literature, experts acknowledge severe difficulties accounting for the evolutionary origin of language. Multiple leading paleoanthropologists admitted in an article in the journal *Frontiers in Psychology* that we have 'essentially no explanation of how and why our linguistic computations and representations evolved' as 'nonhuman animals provide virtually no relevant parallels to human linguistic communication' (Hauser et al. 2014). The article concludes: 'the most fundamental questions about the origins and evolution of our linguistic capacity remain as mysterious as ever' (Hauser et al. 2014). Similarly, MIT linguist Noam Chomsky (2006) observes that the uniqueness of human language makes it difficult to explain its evolutionary origin:

> Human language appears to be a unique phenomenon, without significant analogue in the animal world. [...] There is no reason to suppose that the 'gaps' are bridgeable. (p. 59)

The Maropeng Museum tries to reduce evolutionary explanations of the human mind to just a few mutations. 'A mutation of the *FOXP2* gene estimated at about 200,000 years ago, contributed to changes in the capacity for speech, influencing the development of language', the museum claims in an exhibit. What the museum is proposing – essentially that a few small mutations in one or more specific genes were vital to the evolution of our language abilities – is a common theme in evolutionary explanations. In 2006, Francis Collins proposed in *The Language of God* that just a few specific changes in *FOXP2* somehow created our major linguistic abilities (Collins 2006, pp. 131–141). An article in *Time* magazine that same year similarly asserted that two mutations in *FOXP2* resulted in 'the emergence of all aspects of human speech, from a baby's first words to a Robin Williams monologue' (Lemonick & Dorfman 2006). More recently, Yuval Noah Harari argued in *Sapiens* that humans experienced a 'Tree of Knowledge mutation' that occurred because of 'pure chance' and caused a 'cognitive revolution' (Harari 2015, p. 21). Such evolutionary explanations fail to satisfy for multiple reasons.

Firstly, such a 'miracle mutation' accounts of the origin of human cognition imply a teleology and design to evolution that betray standard theories of evolution. If our cognitive abilities suddenly did evolve by just one or two single mutational events, it implies that our profound human intelligence was sitting on a precipice, just waiting for certain specific mutations to occur before modern human minds could arise. But how did our minds get to that evolutionary precipice, where just one or two mutations could produce everything from Lao Tzu to Beethoven or Einstein? Again, if the story were true, it implies a teleological, directed and designed course to the origin of our cognition.

Secondly, such optimistic arguments that one or a few mutations magically created humanity's advanced intellectual abilities strain neurobiological credulity. A 2018 article in *Nature* reported that *FOXP2* is not special in humans and was not under strong selection pressure: 'an analysis now suggests that this gene, *FOXP2*, did not undergo changes in *Homo sapiens*' recent history after all – and that previous findings might simply have been false signals' (Warren 2018; Atkinson et al. 2018). Most likely the origin of human cognition and speech would have required not just one or two mutations, but numerous changes that represent a complex suite of novel interdependent traits. As primate psychologist Charles Snowdon (2001) explains:

> [*The*] proposal of a single-gene mutation is, I think, too simplistic. Too many factors are involved in language learning – production, perception, comprehension, syntax, usage, symbols, cognition – for language to be the result of a single mutation event. (p. 224)

This point is even affirmed by an author of the original study which proposed *FOXP2* is important to the evolution of language (Enard et al. 2002) (Warren 2018):

> Language is complicated, and was never going to be explained by a single mutation in modern humans, Fisher adds. 'We need to embrace more complex accounts that involve changes of multiple genes. In that sense, *FOXP2* was only ever going to be one piece of a complex puzzle'. (n.p.)

If multiple genes are needed to account for the origin of language, this suggests a potential challenge to Darwinian explanations. Neo-Darwinism proposes that traits arise and spread via random mutation acted upon by natural selection as well as other standard evolutionary mechanisms like genetic drift. These are all blind processes that operate without any intelligent oversight. Such a blind trial-and-error mechanism is able to produce small changes which require only one mutation to provide an advantage. But the mechanism is highly inefficient at producing complex features that require multiple mutations to be present before conferring an advantage.

To understand this challenge, consider a seemingly simple example. In 2004, a study in *Nature* proposed that a single mutation that inactivated a protein could cause 'marked size reductions in individual muscle fibres and entire masticatory muscles' leading to 'loss of masticatory strength', which could have loosened jaw muscles, allowing our brains to grow larger (Stedman et al. 2004). A news story widely circulated titled 'Missing link found in gene mutation', framed the finding this way: 'an ancient genetic mutation for weaker jaws helped increase brain size, a twist that first separated the earliest humans from their ape-like ancestors' (Verrengia 2004). The story sounds plausible, but there is a lot more to it. Bernard Wood noted that this mutation alone could never have provided a selectable advantage and would have required additional changes (Verrengia 2004):

> The mutation would have reduced the Darwinian fitness of those individuals. […] It only would've become fixed if it coincided with mutations that reduced tooth size, jaw size and increased brain size. What are the chances of that? (n.p.)

We thus have a situation where multiple coordinated mutations would be necessary to provide the advantage. These mutations must arise and be fixed into the human lineage within the ~6–8 million years as we are thought to have shared a most recent common ancestor with chimpanzees. Can neo-Darwinian mechanisms accomplish this? A 2008 study in *Genetics* found that for just two specific mutations to evolve via Darwinian evolution 'for humans with a much smaller effective population size, this type of change would take > 100 million years'. The authors admitted that this modest evolutionary change was 'very unlikely to occur on a reasonable timescale' (Durrett & Schmidt 2008).

In other words, if we consider all of the genetic, physiological and cognitive differences between humans and chimps presented in this chapter if any of those traits required two or more mutations to arise in humans before providing an advantage, it would require over 100 million years to evolve by unguided Darwinian mechanisms. The exact timespan the study calculated was 216 million years – far greater than the amount of time (again, 6 to 8 million years) as we are said to have diverged from apes. The importance of this paper's conclusion should not be underappreciated. To reiterate, if just two of the known 35 million base-pair differences between the human and chimp genomes were both required to produce some evolutionary advantage in humans, then this trait could never evolve by unguided neo-Darwinian mechanisms in the time allowed by the fossil record since we split from apes. This represents a potent challenge to the neo-Darwinian evolution of human cognition that flows directly out of the mathematics of population genetics.

Evolutionary psychology and human morality

As we have seen, there are serious fossil and genetics-based challenges to standard evolutionary accounts of human origins. But the Maropeng Museum does not just rely on fossils or genetics to make its case for human evolution. The museum also turns to evolutionary psychology. In particular, consider quotes from Richard Dawkins, the famous new atheist author and evolutionary biologist, shown to visitors as they enter the main fossil hall at the museum (Dawkins 2006):

> We are survival machines – robot vehicles blindly programmed to preserve the selfish molecules known as genes. (p. xxix)

This quote is displayed in not one but *two* places in the main fossil hall at Maropeng. One instance of the quote is prominently displayed – stretching from floor to ceiling – and shows a young man and a chimp. It seems that the museum's creators do not want visitors to miss Dawkins's materialistic message.

And what is this materialistic message? Simply put, it is that the purpose of human beings is nothing more than to survive and reproduce. We evolved and we evolved to pass on our genes – nothing more and nothing less. It is difficult to imagine a more materialistic message from a science museum. However, rather than showing humans to be mere 'survival machines', we have many special behaviours that far exceed the requirements for survival and reproduction.

Evolutionary psychology (also called 'evo psych') is a field that aims to explain human behaviour, mental capacity and intellectual abilities strictly as the result of unguided natural selection preserving beneficial traits. Under this view, it is not just our bodies that evolved, but also our brains and behaviours, including our moral and religious impulses. In other words, evo psych desires to explain, in strictly naturalistic terms, all of human nature. The project traces its roots to Darwin himself, who wrote in *The Descent of Man* that he sought 'to shew that there is no fundamental difference between man and the higher mammals in their mental faculties' (Darwin 1878, p. 66). A modern interpretation is articulated by philosopher Daniel Dennett (2006):

> Everything we value – from sugar and sex and money to music and love and religion – we value for […] evolutionary reasons, free-floating rationales that have been endorsed by natural selection. (p. 93)

The field of evolutionary psychology has long-faced accusations of purveying 'just-so stories.' In an article titled 'How the Human Got Its Spots', psychologist Henry Schlinger writes that 'evolutionary psychology, while different in many respects from its predecessor sociobiology, is still subject to the accusation of telling just so stories' (Schlinger 1996). Proponents of evolutionary psychology reply that they are merely making inferences to the best explanation (Holcomb 1996). But are all possible explanations even considered within this field? Evo psych defenders David Barash and Judith Eve Lipton recommend embracing just-so stories – even when they entail ‘mere guessing’ – because ‘the alternative to proposing a just-so story’ means the possibility that ‘God did it’ (Barash & Lipton 2010). Design-based explanations are therefore rejected by evolutionary psychologists *a priori* because of philosophical bias, not because of compelling evidence. This key point will be revisited shortly.

The field has many critics, even from within. Philosopher Subrena Smith argues that evolutionary psychologists cannot merely speculate why a given modern-day behaviour might have provided some evolutionary advantage to our ancestors in the Pleistocene environment of evolutionary adaptedness (‘EEA’). Smith (2020a) argues that evo psych cannot adequately address what she terms the ‘matching problem’:

> [*E*]volutionary psychological claims fail unless practitioners can show that mental structures underpinning present-day behaviors are structures that evolved in the EEA for the performance of adaptive tasks that it is still their function to perform. (p. 41)

In other words, evolutionary psychologists must establish that modern behaviours (1) are similar to ancient behaviours and (2) are caused by the same neural modules that evolved in the past to program those ancient behaviours. Smith doubts that this can be demonstrated and poses an existential question for her field: ‘Is evolutionary psychology possible?’ She (Smith 2020a) answers in the negative:

> Evolutionary psychologists simply do not have the methodological resources to justify the claim that the psychological causes of contemporary behaviours are strong vertical homologs of the psychological causes of corresponding behaviours in the EEA. (p. 48)

Most evolutionary psychologists ignore these epistemological and methodological difficulties and accept evo psych explanations provided they fulfil a simple requirement: speculate how a given behaviour might have helped our ancestors pass on their genes. To play the game of evo psych, all one must do is speculate how some given behaviour provided an evolutionary benefit in some given situation.

To this end, some evo psych explanations sound plausible. For example, snake phobia could have evolved because it provided a survival benefit to protect us from dangers in the wild (Öhman 2009). But is that the only possible explanation? Could not a fear of snakes be explained equally well by ID? It would seem a good design strategy to implement organisms with a survival instinct to avoid dangerous predators. Or consider this evo psych hypothesis: the ability of children to scream and whine loudly evolved so that they could attract attention when in need or danger and call others to help them (Grose 2019). Again, this sounds reasonable, but why must naturalistic evolution be the only possible cause? Could not a designer find it expedient to give vulnerable members of society the ability to call for help loudly and attract those who can defend them? Thus, if the only goal is to explain the origin of behaviours that help an organism to survive, reproduce and pass on genes to the next generation, in many cases either natural selection or ID are viable models.

Evo psych explanations for other human behaviours are less compelling. For example, it is said that laughter evolved from 'laboured breathing during play such as tickling, which encourage cooperative and competitive behaviour in young mammals', and this led to stronger bonds between individuals in a group (Raine 2016). Perhaps, but does this really capture the totality of our experience with laughter? What makes a joke funny? Why do some people have brilliant senses of humour? Can hypotheses like this be tested or refuted?

In some cases, they can be refuted. Raymond Tallis, a former professor of medicine at the University of Manchester, critiques 'Darwinitis' – the push to explain everything under Darwinian terms. He (Tallis 2011) illustrates how 'Darwinitis' leads evolutionary psychologists to propose persuasive but false hypotheses:

> Consider the recent claim that evolutionary psychology can explain why pink is associated with femininity and blue with masculinity. Women in prehistory were the principal gatherers of fruit and would have been sensitive to the colours of ripeness: deepening shades of pink. Men, on the other hand, would have looked for good hunting weather and sources of water, both of which are connected with blue. In fact, in Victorian Britain blue was regarded as the appropriate colour for girls […] and pink for boys […] Colour preferences are therefore scarcely rooted in the properties of brain shaped in the Pleistocene epoch. (p. 48)

Evolutionary psychology is also critiqued because it is not predictive and can explain the opposite of a given behaviour as well as the behaviour itself. For example, one could imagine that fear of water evolved to help us avoid drowning in certain dangerous situations, like a fast-flowing river. On the other hand, one could envision that the love of water and swimming evolved to help us enter the water when it was advantageous, perhaps to avoid predators or find food. Or one could propose that sharing evolved because doing so would build bonds within a community, perhaps leading others to share their food with us, providing a benefit. But then stealing also evolved to help us get extra food in other situations when that behaviour happened to be advantageous. Almost any behaviour and its opposite can be justified under the rules of the evo psych game, leading one to wonder what sort of behaviours the theory actually predicts. As the old adage goes, the theory that explains everything actually explains nothing. Philip Skell (2005), a late member of the US Natural Academy of Sciences, explained this point:

> Darwinian explanations for such things are often too supple: Natural selection makes humans self-centered and aggressive – except when it makes them altruistic and peaceable. Or natural selection produces virile men who eagerly spread their seed – except when it prefers men who are faithful protectors and providers.

> When an explanation is so supple that it can explain any behaviour, it is difficult to test it experimentally, much less use it as a catalyst for scientific discovery. (p. 10)

Evolutionary psychologists have long focused on trying to provide Darwinian explanations for the origin of human moral, intellectual and religious inclinations – in part because such explanations seem difficult to produce. Former Harvard evolutionary psychologist Marc Hauser believes 'people are born with a moral grammar wired into their neural circuits by evolution' (Wade 2006). Hauser is right because we *do* seem to be hard-wired for morality – but a great challenge to evo psych is explaining *the origin* of humanity's hard-wired morality because our 'moral' behaviours often involve helping someone else to survive rather than benefitting the individual exhibiting the behaviour. Evolutionary psychologists have thus envisioned a myriad of scenarios where it might be beneficial to an individual to help someone else. For example, in kin selection, you help other members of your family survive because they share some of your genes and in helping them survive some of your genes become passed on. Or according to the principle of reciprocal altruism, sharing food with others evolved because your friend might share food with you later when you are hungry. This helps you and your kin survive and pass on your genes. Perhaps in other cases, people do charitable acts in public simply to earn praise and respect, potentially enhancing their own social status and likelihood of evolutionary success. This is called competitive altruism.

Under these staple evo psych concepts, there cannot ever be such a thing as truly selfless love. Instead, it is said that we exhibit 'altruism' – seemingly unselfish behaviour that is actually programmed by evolution simply to benefit our selfish genes. Yet human behaviours that appear to be truly selfless and 'loving' are the most difficult for evo psych to explain.

Specifically, Darwinian evolution has no basis to account for extreme acts of human kindness. Most people who stumble across strangers trapped in a burning car will help them escape – a risky action that promises no evolutionary benefit to the rescuers. Evolutionary biologist Jeffrey Schloss (1998) explains how Holocaust rescuers took precisely these kinds of risks:

> The rescuer's family, extended family and friends were all in jeopardy, and they were recognized to be in jeopardy by the rescuer. Moreover, even if the family escaped death, they often experienced deprivation of food, space and social commerce; extreme emotional distress; and forfeiture of the rescuer's attention. (p. 251)

A prime example is Oskar Schindler, the German businessman who risked his life and social status during World War II to prevent the deaths of hundreds of Jews at the hands of the Nazis. Why would he do this if it is 'opposite of saving his genes' (Cray 2006)? Schloss provides additional examples of 'radically sacrificial' behaviour that 'reduces reproductive success' and offers no evolutionary benefit, including voluntary poverty, celibacy and martyrdom (Schloss 2002, p. 221).

Explaining the origin of religion has thus also been a major challenge for evo psych. A popular explanation is group selection, where shared religious beliefs helped fostered group cohesion that aided in survival (see e.g. Harari 2015, p. 24). But does that really account for the essence or totality of religion by reducing it to group cooperation? How does group cooperation explain total religious devotion to a deity? When young men or women enter monasteries or convents to pray and serve others, they sacrifice their reproductive success. Why would such sacred religious practices arise in an evolutionary world? Or consider the religious ascetic who willingly dies at the hands of his worst enemies, believing that his own death will save them. Under an evolutionary view, he became a dead end, yet we hold his actions in the highest regard. How do those behaviours help you 'pass on your genes'? Evo psych explanations of religion fail to capture the totality of the religious experience and struggle to explain many religious beliefs and behaviours that are strikingly non-adaptive.

It is here that a design-based model seems superior to a Darwinian one. Darwinian evolution simply demands that you survive and pass on your genes. But if human behaviour evolved, why do humans exhibit selfless behaviour that often prevents evolutionary success? More importantly, if human morality evolved, why do humans universally have internal moral compasses that oddly whisper that selfless love is the 'right' option – often whispering the loudest in our most selfish moments?

Many of the most sacred aspects of human life seem not tuned to survival and reproduction but higher purposes. Our most cherished charitable, artistic and intellectual activities seem far beyond the demands of Darwinian evolution. Assuming we are programmed only to survive and reproduce, then why do we invest so much energy composing music, exploring the mysteries of the universe through science, worshipping God and erecting grand buildings like cathedrals or the Maropeng Museum? Of course, intelligence helps us survive, but why would the genius necessary to fly to the moon be required among our ancestors whose only requirements were to survive and reproduce in the African Savannah 1 mya? Contrary to Dawkins and the Maropeng Museum, human beings are not mere 'survival machines'. We seem designed for higher purposes.

The possibility of intelligent design

Given the explanatory viability of ID, why are design-based explanations disallowed from evo psych? They are excluded *a priori* by philosophical preferences, *not* because of the evidence. In 2007, the world's top journal *Nature* published a letter from its editors that essentially admitted this bias (Nature 2007):

> With all deference to the sensibilities of religious people, the idea that man was created in the image of God can surely be put aside. [...] [*T*]he idea that human

> minds are the product of evolution is not atheistic theology. It is unassailable fact. […] It is fairly easy to accept the truth of evolution when it applies to the external world – the adaptation of the orchid to wasps, for example, or the speed of the cheetah. It is much harder to accept it internally – to accept that our feelings, intuitions, the ways in which we love and loathe, are the product of experience, evolution and culture alone. […] Scientific theories of human nature may be discomforting or unsatisfying, but they are not illegitimate. And serious attempts to frame them will reflect the origins of the human mind in biological and cultural evolution, without reference to a divine creation. (p. 753)

Let us briefly dissect this quote. Firstly, *Nature*'s editors patronise religious readers by expecting them to believe the editors offer 'all deference to the sensibilities of religious people' while simultaneously maintaining that a fundamental tenet of Western religion – 'the idea that man was created in the image of God' is false and must be 'set aside'. Secondly, they treat evolutionary psychology in a highly dogmatic and unscientific manner, claiming that the conclusions of this field are 'unassailable fact' and beyond question. Should any scientific claim ever be elevated to 'unassailable fact'? And how do we know they are unassailable fact? The answer seems to be that any non-evolutionary explanations are ruled out *a priori* because they are demeaned as not 'serious'. Any model that makes 'reference to a divine creation' is simply thrown out of court before the evidence can be evaluated. This approach to scientific investigation is also called methodological materialism, and its unshakable reign over evolutionary science was plainly articulated by Richard Lewontin (1997):

> [*W*]e have a prior commitment, a commitment to materialism. It is not that the methods and institutions of science somehow compel us to accept a material explanation of the phenomenal world, but, on the contrary, that we are forced by our *a priori* adherence to material causes to […] produce material explanations […] that materialism is absolute, for we cannot allow a Divine Foot in the door. (n.p.)

Intelligent design is a scientific theory that does not appeal to the 'divine'. Rather it holds that some aspects of the universe are best explained by an intelligent cause because in our experience, intelligence is the only known cause of information and complexity we find in nature. The theory of design thus invokes the cause of intelligent agency – a legitimate explanatory tool within science as we have so much experience with intelligent agents in the world around us. When we understand how information and complexity can be produced by intelligent agents, we can learn to recognise it in the historical record and thereby infer when an intelligent cause was at work.

In particular, our observations of the world around us consistently show that when intelligent agents design new systems they introduce them into the world 'fully formed' and ready to function. Darwinian evolution is a blind, gradual search for functional advantages that are small genetic steps away from current phenotypes. But technological innovation proceeds in a completely different manner and produces major revolutions in morphology and form in a very short period. Intelligent agents rapidly infuse large amounts of new information into the world. Tech manufacturers will often release newly upgraded models distinct from old ones, reflected as abrupt shifts the design of computers, cell phones, cars or other technologies. This pattern of rapid technological innovation parallels what we see in the historical record with regards to the origin of humans: a new form, genetically, morphologically and cognitively distinct, appears abruptly, with new physical, intellectual, technological, moral and religious capabilities. The rapid appearance of the human body plan in the fossil record is more consistent with ID than a gradual process of Darwinian evolution. This inference is based upon our knowledge of the causes of rapid and major transitions in complex designs.

Intelligent design allows for material causes when they are the best explanations, but it is not wedded to *strictly materialistic* explanations of human origins. It does not invoke the divine, but rather claims we can recognise in nature the prior action of an intelligent agent. Palaeoanthropology, evolutionary psychology and most other fields that study human origins today are strictly committed to only materialistic explanations. Misplaced fear of the 'Divine foot' causes them to close their eyes to legitimate alternative scientific explanations like ID.

■ Restoring South Africa's tradition of intelligent design in palaeoanthropology

Because of these philosophical guardrails, most paleoanthropologists will not even engage with the possibility of design. In the opening entry of the 2015 edition of *Handbook of Palaeoanthropology*, lead editor Winfried Henke (2015) explains and illustrates his field's orientation towards serious dialogue over ID:

> It is wasting time to discuss pseudoscientific theories of intelligent design proponents at eye level; I am tempted to quote Berthold Brecht: '*Wie kommt die Dummheit in die Intelligenz?*' ['*How does stupidity invade intelligence?*']. (p. 10)

Despite this dismissive and condescending attitude, there is precedent for palaeoanthropology to engage seriously with ID. If South African scientists wish to consider design-based models, the theory of ID has a rich history in South African science. In multiple exhibits, the Maropeng Museum pays homage to the eminent South African paleoanthropologist Robert Broom (Figure 9.8), who in 1947 co-discovered 'Mrs. Ples', a famous fossil specimen of *Australopithecus africanus*, at the Sterkfontein caves at the Cradle of Humankind. Broom made important contributions to palaeoanthropology and was an accomplished South African scientist. But the museum never discloses that he was a proponent of ID who believed that humans did not

Source: https://commons.wikimedia.org/wiki/File:Robert_Broom00.jpg, published under public domain permissions as allowed by Wikimedia Commons.

FIGURE 9.8: Robert Broom.

evolve by strictly unguided natural mechanisms. In 1933, he published an article in the *South African Journal of Science*, titled 'Evolution – Is There Intelligence Behind It?' where he argued that an 'intelligent foreseeing agency' is necessary to explain the origin of many animals and concludes (Broom 1933a):

> Lamarckism and Darwinism seem to fail completely, and one feels that mutation is quite out of the question if it is the result of pure accident, and only conceivable if an intelligent agency is behind it. (p. 7)

Likewise, in his book *The Coming of Man: Was It Accident or Design,* Broom (1933b, p. 207) writes 'One feels driven to the conclusion that some intelligent power has played a part in the evolution' and argues that ID is found throughout vertebrate history (Broom 1933b):

> Many see nothing in it but a succession of fortuitous mutations which, by the selection of the blind forces of nature, have resulted in the evolution of a Shakespeare and a Newton from a fish. I fancy I can trace intelligence behind it all. (p. 11).

Broom is a giant in the history of South African science, one of the founders of the field of palaeoanthropology. He also was an unmistakable proponent of ID – especially in human origins. Returning to its tradition of ID within human origins would be a controversial move for South Africa to make. But it could help South Africa's community of scientists further solidify their leadership in this field, by following the evidence and inferring ID as the best explanation for many aspects of the fossil, genetic and psychological evidence regarding human origins.

■ Conclusion

From palaeoanthropology to genetics to evolutionary psychology – diverse disciplines can inform our understanding of human origins. In palaeoanthropology, we find a distinct break in the fossil record associated with the abrupt appearance of our genus *Homo*. This non-Darwinian pattern suggests a rapid infusion of information into the biosphere that reflects an instance of design. In genetics, we see that humans have significant biomolecular differences from other species, and there is no objective standard for concluding that functionally similar genetic traits require human-ape common ancestry. Moreover, functional similarities between humans and chimps can be explained by the common design, and discoveries of mass functionality in junk DNA undermine arguments for common ancestry. Population genetics has mathematically demonstrated that the numerous genetic differences between humans and chimps could not evolve by random mutation and natural selection in the 6–8 million years since our supposed most recent common ancestor. In evolutionary psychology, humans are revealed to exhibit behaviours that vastly outstrip the requirements that they survive and reproduce on the African Savanna. Humans appear designed for purposes much higher than merely winning some ancient contest of Darwinian selection. Intelligent design has a long tradition within palaeoanthropology, and it remains a viable scientific explanation for those open to considering it.

Chapter 10

Rumours of war and evidence for peace between science and Christianity

Michael N. Keas
Talbot School of Theology,
Biola University,
La Mirada, California, United States of America

Introduction[64]

'The idea of a ceaseless conflict between' science and religion 'seems to be an integral part of the public consciousness' (Elsdon-Baker & Lightman 2020,

---

[64] This chapter represents a substantial reworking and amalgamation of the following primary sources, published by the author: (1) The Dark Myth: Christianity produced 1000 years of anti-science 'Dark Ages'. Adapted and expanded by permission from https://evolutionnews.org/2019/01/atheisms-myth-of-a-christian-dark-ages-is-unbelievable/; (2) The Flat Myth: Church-induced ignorance caused European intellectuals to believe in a flat earth. Adapted and expanded by permission from https://stream.org/dont-believe-flat-earth-myth/; (3) The Big Myth: A big universe became a problem for Christianity. Adapted and expanded by permission from https://evolutionnews.org/2021/10/the-big-myth-big-universe-is-a-problem-for-religion/; (4) The Demotion Myth: Copernicus demoted us from the cosmic centre and thereby destroyed confidence in a divine plan for humanity. Adapted and expanded by permission from https://evolutionnews.org/2020/04/neil-degrasse-tyson-and-cosmos-peddle-the-myth-that-copernicus-demoted-earth/; (5) The Galileo Myth: Galileo's clash with the Catholic Church shows how Christianity opposed science. Adapted by permission from Chapter 5 of my book listed in the bibliography: Keas (2019b) and (6) The Sceptic Myth: The main heroes of early modern science were sceptics, not believers in God. Adapted and expanded by permission from https://evolutionnews.org/2020/03/the-biggest-myth-so-far-in-cosmos-3-0-baruch-spinoza-as-science-hero/

How to cite: Keas, MN 2022, 'Rumours of war and evidence for peace between science and Christianity', in F van Niekerk & N Vorster (eds.), *Science and Faith in Dialogue*, in Reformed Theology in Africa Series, Vol. 10, AOSIS Books, Cape Town, pp. 283–307. https://doi.org/10.4102/aosis.2022.BK334.10

pp. 3–10). So observe two historians in a recent academic anthology about science and religion. The historians go on to argue that this 'conflict thesis' is largely faulty while noting that it is 'more ingrained in the scholarship than previously imagined' (Elsdon-Baker & Lightman 2020, pp. 3–10). Curiously, proponents of the warfare thesis have focused most of their criticism on Christianity. The impression that Christianity is typically at war with science has been perpetuated by many specific myths about the history of science. This chapter helps debunk six of these myths:

1. **The Dark Myth:** Christianity produced 1000 years of anti-science 'Dark Ages'.
2. **The Flat Myth:** Church-induced ignorance caused European intellectuals to believe in a flat earth.
3. **The Big Myth:** A big universe became a problem for Christianity.
4. **The Demotion Myth:** Copernicus demoted us from the cosmic centre and thereby destroyed confidence in a divine plan for humanity.
5. **The Galileo Myth:** Galileo's clash with the Catholic Church shows how Christianity opposed science.
6. **The Sceptic Myth:** The main heroes of early modern science were sceptics, not believers in God.

While debunking these six myths we will also see evidence for peace between science and Christianity.[65]

The Dark Myth: Christianity produced 1000 years of anti-science 'Dark ages'

Atheist biologist Jerry Coyne (2013) once wrote:

> Had there been no Christianity, if after the fall of Rome atheism had pervaded the Western world, science would have developed earlier and be far more advanced than it is now. (n.p.)

Did Christianity really drag the West into an anti-scientific 'Dark Ages', a period said stretching from the fall of Rome to 1450 AD? Although we do not have the space here to fully settle this question, the vignettes that follow show where recent scholarship points (Keas 2019a, pp. 27–40).

Early medieval light: 400–1100

The great Church Father Saint Augustine (354–430) laid some of the foundations for science. He contributed to Aristotelian physics in his *Literal Commentary on Genesis* (Lindberg 2003, p. 17). More broadly, Augustine expressed confidence in our ability to read the 'book of nature' because it is the 'production of the Creator' (Harrison 2006, p. 118). He insisted we should

---

[65] This section in the chapter represents a substantial reworking of excerpts from Keas (2019b)

proceed 'by most certain reasoning or experience' to discern the most likely way God established the natures of things', a phrase that became a popular medieval book title for works emulating Augustine's investigative approach (Eastwood 2013, p. 305).

The English monk Bede (673–735) studied and wrote about astronomy in the tradition of Augustine and Ptolemy. Historian Bruce Eastwood called Bede's book *The Nature of Things* (*c*. 701) ' a model for a purely physical description of the results of divine creation, devoid of allegorical interpretation, and using the accumulated teachings of the past, both Christian and pagan' (Eastwood 2013, p. 307). Note how Bede's Christian worldview was compatible with analysis of the natural world as a coherent system of natural causes and effects.

The light of the high Middle Ages: 1100–1450

Around 1100, European intellectuals graduated from limited translations and commentaries on Aristotle to a more extensive recovery and further development of Aristotelian logic. As refined within a Christian worldview, this advance included a reasoning method well suited to natural science.

Scholars called this form of argument '*ratio*' (reason), contrasting it with mathematical demonstration. Mathematics begins with first principles thought to be certain and deduces conclusions that carry the same certainty. *Ratio*, in contrast, uses premises inferred as likely true from sensory experience and then reasons from there to probable conclusions (Burnett 2013, pp. 379–381).

Ratio, a logic appropriate to observational science, enriched the study of motion and change in the natural world.[66] Historian Walter Laird (2013) writes:

> The study of motion in the Middle Ages, then, was not a slavish and sterile commentary on the words of Aristotle [...] Part of the measure of their success [...] is that some of these insights and results had to be rediscovered later by Galileo and others in the course of the Scientific Revolution. (p. 435)

The institution in which most scholars investigated natural motion is also noteworthy – the university. This Christian invention began with the University of Bologna in 1088, followed by Paris and Oxford before 1200 and more than 50 others by 1450. The papacy supported this unprecedented intellectual ferment.

Universities provided additional stimulus to the medieval translation movement already underway, in which Greek and Arabic texts were rendered in the common European intellectual tongue of Latin. This movement greatly

---

[66] There were some notable deficiencies in scholastic (medieval) methodology, but there is insufficient space here to cover this topic. For example, scholasticism often focused on logical abstractions that did not lead to rigorous knowledge of nature.

outperformed the comparative trickle of imperial Roman translations. If European Christians had been closed-minded to the earlier work of pagans, as the Dark Myth alleges, then it would be difficult to explain this ferocious appetite for translations.

The Franciscan cleric and university scholar Roger Bacon (*c*. 1220–1292) read much of the newly translated work of earlier Greek and Islamic investigators, including Euclid, Ptolemy and Ibn al – Haytham, or Alhazen (*c*. 965–1040). By evaluating them and introducing some controlled observations – what we now call experiments – Bacon substantially advanced the science of light (Lindberg & Tachau 2013, pp. 503–504).

Subsequent authors summarised and reevaluated Bacon's work, transmitting it through books used in university instruction. That is how it came to the attention of Johannes Kepler (1571–1630), whose account 'helped spur the shift in analytic focus that eventually led to modern optics', in the words of historian A. Mark Smith (2014).

By one estimate (Grant 1984), 30% of the medieval university liberal arts curriculum addressed roughly what we call science (including mathematics). Between 1200 and 1450, hundreds of thousands of university students studied Greco-Arabic-Latin science, medicine and mathematics – as progressively digested and improved by generations of European university faculty.

Contrary to the Dark Myth, medieval European Christians cultivated the idea of 'laws of nature', a logic friendly to science, the science of motion, human dissection, vision-light theories, mathematical analysis of nature and the superiority of reason and observational experience (sometimes even experiment) over authority in the task of explaining nature.

Medieval trailblazers also invented self-governing universities, eyeglasses, towering cathedrals with stained glass and much, much more. Although labelling *any* age with a single descriptor is problematic, the so-called Dark Ages would be far better labelled an 'Age of Illumination' or even an 'Age of Reason'.

The Flat Myth: Church-induced ignorance caused European intellectuals to believe in a flat earth

Celebrity astrophysicist Neil deGrasse Tyson is relatively ignorant about the early history of his own scientific discipline. Back in 2016, he responded to rapper B.o.B., a flat-earth promoter, with a tweet. Tyson (2016) wrote, 'Dude – to be clear: Being five centuries regressed in your reasoning doesn't mean we all can't still like your music'. Tyson follower Andy Teal responded: 'Five centuries? I believe the knowledge of Earth's shape goes back a bit farther than that'. Tyson tweeted back: 'Yes. Ancient Greece inferred from Earth's shadow during Lunar Eclipses. But it was lost to the Dark Ages'. This modern perception of widespread medieval flat-earth belief has been common in textbooks and popular literature since the 19th century.[67]

Church-induced ignorance?

People stopped believing in a spherical earth during the Middle Ages? No. Medieval intellectuals had many reasons for grasping that the earth is round. Those reasons included the curved shadow of the earth projected on the moon during a lunar eclipse. To deny medieval belief in a round earth is to be guilty of what I call the *Flat Myth*. This is the most enduring component of the larger myth of the 'Dark Ages'. The allegedly anti-science 'Christian Dark Ages' never happened as typically claimed, as I argued.

Tyson is obviously right about how ridiculous contemporary flat-earth belief is. Some 'believers' such as Shaquille O'Neal and Kyrie Irving of National Basketball Association (NBA) fame have said they were only joking. And who can tell what the small number of people behind today's flat-earth societies *actually* think? If most of them are joking, it would come as little surprise. But the fact is that Tyson, probably the world's most influential voice for science, is spreading misinformation about medieval views.

Tyson's false ideas have a history. They trace back to writers in the 1800s. For example, the 19th-century chemist-historian John William Draper (1874, pp. 157–159) claimed that medieval Christians believed the Scriptures contain the sum of all knowledge. They therefore 'discouraged any investigation of Nature', including the study of the earth's shape. Supposedly this ignorance continued until the time of Columbus.

Consider the 1200 American college students I have taught astronomy. The vast majority (as indicated by a show of hands each semester) learned something false from their precollege teachers. They were told that Europeans in the Middle Ages were ignorant of the earth's roundness until Christopher Columbus proved it in 1492. Now they better understand how this fake history often perpetuates the myth of warfare between science and Christianity.

---

[67] Astronomy textbooks that have taught the false idea that medieval Christians believed in a flat earth include Fix (2011, p. 58) and Birney (1969, p. 15) where Birney says medieval 'Church scholars refused to accept the notion that the earth was round. Anyone, they reasoned, could see that is was flat'. Other astronomy textbooks in my possession do likewise, with publication dates of 1944, 1906, 1897, 1830, 1824 and 1818. These textbooks sometimes cast supposed medieval flat earth belief as due to alleged anti-science Catholicism or due to a more general warfare between science and Christianity. Sometimes they do not explicitly convey any warfare between science and any form of Christianity. But as Russell (1991) shows, many other more popular accounts (since the mid-nineteenth century) of the history of ideas about Earth's shape have tended to push the science–Christianity warfare thesis.

Medieval round-earth arguments

Imagine the year is 1300. You are a student at the University of Salamanca, Spain's oldest university. In class you have studied Aristotle's argument for a spherical earth based on the changing positions of the stars as one travels north or south. This was standard in the medieval curriculum (Cormack 2009, p. 31). You wish to demonstrate it for yourself. How will you do this?

Firstly, you note that the apparently motionless North Star is located about 40° above your horizon in Salamanca. Then you travel to the southernmost point of Europe. There you find that this star appears only about 35° above the horizon. Why the change of angle? Most medieval university students learned a simple explanation: the earth is round. This and other reasonable arguments combined to present a very strong case.

Back around to today

Here is a surprise. Most students of the author have typically been *less* able to defend the earth's roundness by such scientific arguments than the average medieval student. Upon completing their astronomy course, they finally caught up to the Middle Ages (as indicated by interactions with my students in laboratory settings in which they re-enacted historical dialogues and observations concerning the science of Earth's shape)!

Most students today accept the roundness of Earth as a mere fact. But they are unable to reason from observations to this conclusion. This is not an isolated observation, unfortunately. Science today is, more often than not, taught this way: as something to be accepted (for example contemporary Darwinism), not understood through arguments for and against particular theories. That is a loss for students. Things were, in this respect, brighter in the so-called Dark Ages.

This section helps debunk the anti-Christian myth about Earth's *shape*. Let us examine a popular myth about its *size* – its utter smallness in relation to a really big universe.

The Big Myth: A big universe became a problem for Christianity

Self-appointed spokesmen for science often use the enormous size of the cosmos, with its billions of galaxies, as a club to beat up on Christianity. They say people in the Western tradition had to wait till modern science to grasp that the universe was huge, and had to shed historic Judeo-Christian views to do so. This is not true.

Ancient and medieval thinkers in the Western tradition already had good reasons to believe in a vast cosmos. 'The earth has, to the senses, the ratio of a point to the distance of the sphere of the so-called fixed stars', wrote Ptolemy, in his famous work *Almagest* (*c*. 150 AD). He established that Earth was merely 'a point', virtually dimensionless, compared with the vast distance to the stars. The arguments he used to support this thesis of cosmic immensity were studied in medieval universities. So the 'Big Myth' gets this part of premodern history wrong.

Although early modern estimates of cosmic size did increase, scientists such as Nicolaus Copernicus (1473–1543) and Blaise Pascal (1623–1662) saw in this no contradiction with their Christian faith (Keas 2019a, pp. 13–24).

Bill Nye, the scientism guy

Yet celebrity TV science educator Bill Nye, the 'Science Guy', is among those who suggest that the sheer scale of the cosmos means humans are insignificant in any traditionally religious sense. In the last part of his 'Humanist of the Year' acceptance speech, Nye (2010) – speaking for science and all humanity – delighted the American Humanist Association with this:

> I am insignificant [...] I am just another speck of sand. And the earth really in the cosmic scheme of things is another speck. And the sun an unremarkable star. [...] And the galaxy is a speck. I am a speck on a speck orbiting a speck among other specks among still other specks in the middle of specklessness. I suck. (n.p.)

Nye's primarily atheist-agnostic audience laughed approvingly because they believed that 'I suck' really means 'religion sucks', or the religious basis for human significance is worthless. This interpretation is consistent with an assertion Nye made later in his speech. He assured his audience that humans *are* significant on *non-religious* grounds because we have learned profound truths about the cosmos through science. Our ability to do science saves us from insignificance!

So Bill Nye is not so much *the science guy* as he is *the scientism guy*. Scientism is the view that only science (not religion) is rational. It thrives, in part, by perpetuating (inaccurate) stories of science and Christianity at war with each other. Scientism really amounts to atheistic dogma masquerading as objective science and accurate history of science.

C.S. Lewis on Dogma and the universe

The British philosopher and literary scholar C.S. Lewis (1970, pp. 39–42) in his witty essay 'Dogma and the Universe' demolished Nye's scientistic way of thinking how about cosmic immensity. Lewis begins with an analogy. Imagine how a doctor determines that someone has been poisoned to death.

The doctor can conclude this reasonably if 'he has a clear idea of that opposite state in which the organs would have been found if no poison were present' (Lewis 1970, pp. 39–42). Similarly, if we try to disprove God by pointing out how small we are in a huge cosmos, we should clearly identify the kind of universe that is expected if God did exist.

But Lewis (1970, pp. 39–42) argues that such a project fails. 'Whatever space may be in itself [...] we certainly perceive it as three-dimensional, and to three-dimensional space we can conceive no boundaries', he writes. So we naturally feel that the cosmos is huge. What if we discovered nothing but our own sun and moon in such seemingly infinite space? 'This vast emptiness would certainly be used as a strong argument against the existence of God', Lewis notes. In that case, atheists would argue that no God would create such vast amounts of wasted empty space.

Lewis (1970, pp. 39–42) runs through the other options: 'If we discover other bodies, they must be habitable or uninhabitable: and the odd thing is that both these hypotheses are used as grounds for rejecting Christianity'. If there are billions of habitable planets, then the sceptic would likely say that this means humans are not special. We would be lost in a crowd of aliens, or so the story goes.

Lewis (1970, pp. 39–42) continues: 'If, on the other hand, the earth is really unique, then that proves that life is only an accidental by-product in the universe, and so again disproves our religion'. Atheists in that case might further complain that no God would create trillions of sterile planets – what a lousy design.

Do you see the problem? No matter how God might have made the universe and life, sceptics would surely complain about something to the point of disbelief. What we have here is not truth-seeking. It is game rigging (cf. Keas 2020).

Spinning the universe

Atheists would find ways to spin a story that ridicules belief in God no matter what the size or contents of the cosmos. Bill Nye's God-bashing cosmic storytelling fails the credibility test. Keep all this in mind next time you hear this popular myth invoked to mock religious believers.

For both Jews and Christians, here is the situation: It is reasonable to believe in an omnipotent omniscient God who created humans capable of discovering the fingerprints of God in the cosmos. Modern astronomical discoveries have confirmed that we inhabit an enormous and finely-tuned universe befitting just such a creator. The Psalmist expressed a similar thought about 3000 years ago (Ps 8):

> When I look at your heavens, the work of your fingers, the moon and the stars, which you have set in place, what is man that you are mindful of him and the son of man that you care for him? Yet you have made him a little lower than the heavenly beings and crowned him with glory and honor. (vv. 3–5; English Standard Version)

Indeed, Psalm 8 is of the most often quoted biblical passages in astronomy textbooks up through the 19th century. Based on the author's study of a sample of 130 heliocentric astronomy textbooks spanning four centuries this can be confirmed.

But what about our position within this enormous universe? Has modern science shown it to be mediocre? Our next myth gets the wrong answer.

The Demotion Myth: Copernicus demoted humans from the cosmic centre and thereby destroyed confidence in a divine plan for humanity

In episode 8 of the 2020 *Cosmos* season, 'Possible Worlds', host Neil deGrasse Tyson delivered a favourite bit of wrong revisionist history: the claim that astronomer Nicolaus Copernicus (1473–1543) demoted humans from the privileged centre of the universe. This supposedly challenged the religious idea of human importance. 'Demoting the earth from the center of the universe was a severe blow to human self – esteem', Tyson claimed on this TV documentary episode.

The real Copernicus

Copernicus argued against earth-centred astronomy, but he did not think this challenged Christianity. He even once said that God had 'framed' the cosmos 'for our sake' (Danielson 2001, p. 106). Copernicus was not alone in this opinion. Most other early supporters of sun-centred astronomy thought the Bible and science are in complete harmony.

The myth that Copernicus demoted humans makes a false assumption. It assumes that earlier earth-centred astronomy exalted humans. But according to the earth-centred astronomy of the ancient Greeks – widely accepted well into the 19th century – Earth was at the bottom of the universe. 'Up' pointed to the perfect cosmic heaven. Earth was in the 'dead centre' of corruption, they thought.

This makes sense of what Galileo wrote in the century after Copernicus. He said: 'I will prove that the earth does have motion [...] and that it is not the sump where the universe's' filthy things 'collect' (Danielson 2001, p. 150). He framed his argument as a promotion, not a demotion, for Earth and its inhabitants.

Distorting Copernicus

The idea that Copernicus demoted humans was invented in the mid-1600s to bash Christianity. By the mid-1800s, the myth had entered astronomy textbooks, and by the 1960s, it had become textbook orthodoxy (Keas 2019, p. 102).

The latest version of this story in a college textbook might surprise you. It is built on the view that exotic dark matter is more common than ordinary matter. 'It is interesting to consider how far we have moved from our Earth-centered view', write Schneider and Arny (2018, p. 629). They claim that our cosmic location is not special despite recent evidence otherwise that they ignore (Klinghoffer 2019). They continue: 'And now we are realising that the kind of matter that makes up everything we know is just a minor kind of matter in the universe. This is the Copernican revolution taken to extremes!'

This is subjective storytelling, not science. One could just as easily have declared humans unimportant because our bodies are mostly common, ordinary hydrogen, oxygen and carbon. 'See, there's nothing special about the material me!' Thus, one could make use of either the commonness or rarity of our material parts as grounds for our unimportance. Humans in any conventionally religious sense are losers either way: heads or tails. It is a rigged game, not a serious argument for a godless view of life and the cosmos.

Spiritual atheism[68]

Some atheists attempt to salvage some meaning and specialness from the Copernican 'demotion'. Consider a recent astronomy textbook foreword by Neil Tyson. He argues that despite a series of scientific discoveries humiliating humanity, there is hope without God. We can still find meaning and purpose. How? Because Tyson (2010, p. xxviii) says 'the cosmic perspective is spiritual – even redemptive – but not religious'. Science is our saviour! That is the message of this leading college astronomy textbook.

Tyson insists in this college textbook that the Copernican demotion story redeems us from religious ignorance. He (Tyson 2010, p. xxviii) writes: 'The cosmic perspective opens our eyes to the universe, not as a benevolent cradle designed to nurture life but as a cold, lonely, hazardous place'. In other words, life is extremely rare in the cosmos. Agreed. But notice how he tries to spin this to the advantage of the atheist. If Tyson had discovered that our solar system hosts dozens of smart extra-terrestrial species (and many of other kinds of intelligent life 'out there' further), he surely would have used this as an excuse to remove humanity from any special place within a divine plan. Because of never-ending godless stunts like this (regardless of the evidence), C.S. Lewis (as cited earlier) identifies such manoeuvers as hopelessly subjective.

Tyson's *Cosmos* series will broadcast this spiritual atheism to middle school and high school. How so? Darwin is said to be the 'greatest spiritual teacher of the last 1000 years'. He 'worshiped nature', Tyson (2010) proclaims approvingly. 'Life is an emergent property of chemistry. Science is an emergent property of life.

---

[68] This section of chapter represents a substantial reworking of excerpts from Keas (2021, p. 132).

Life can begin to know itself'. In *Cosmos* episode 7, Tyson shares his strange belief that bees and trees can think much like us. But, of course, they cannot do science! So humans are special after all in the spirituality of the new cosmic atheism.

So the new atheists want it both ways. On the one hand, they claim humans are insignificant – provided we conflate significance with size and geometric centrality. On the other hand, the process of 'scientific discovery' that allegedly implicates God's nonexistence renders us significant because we are smart and brave enough to reach this conclusion. This is confused atheist sentimentality parading as though it were science.

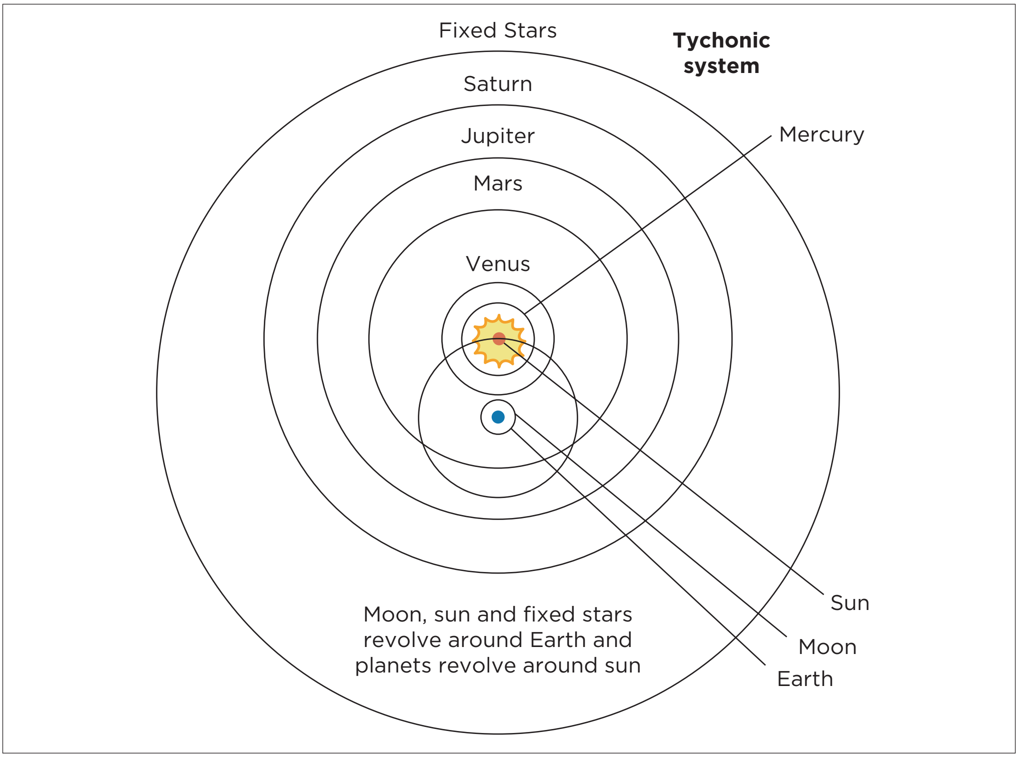
Atheists and agnostics, such as the makers of the *Cosmos* TV series, do not inspire confidence today. But what about sceptics at the time of the Scientific Revolution? Were they primarily responsible for forging modern science? Although Galileo is often depicted as such a pioneering sceptic, we will see that he was a Catholic who believed in the full harmony of the Bible with science. After debunking the Galileo Myth, we will look at an alleged scientific innovator during Galileo's time who actually was a prominent sceptic but who contributed very little to scientific progress.

The Galileo Myth: Galileo's clash with the Catholic Church shows how Christianity opposed science

According to the warfare thesis, Galileo Galilei (1564–1642) represents unbiased scientific objectivity and the Catholic Church stands for ignorant superstition that has hindered science. According to this storyline, Catholic officials rejected Galileo's telescopic observations and his rational arguments that had allegedly proven the Copernican system. The real story is more complex and shows how both science and theology are rational disciplines that need to be in conversation with one another.

Galileo's startling telescopic discoveries

In 1609, Galileo constructed a telescope that magnified objects 20 times. This is the strength of a good pair of binoculars today. Galileo could see that the moon seemed to have mountains and valleys – many with circular shapes now known as craters. Although he overestimated lunar mountains at almost five miles tall, he left humanity little doubt that the moon was not a perfectly smooth sphere, as Aristotle had taught. 'I thank God from the bottom of my heart that he has pleased to make me the sole initial observer of so many astounding things, concealed for all these ages,' he wrote to the Tuscan secretary of state on 30 January 1610 (Heilbron 2010, p. 153).



Source: Image drawn and provided by Michael N. Keas, published with suitable permission granted by Michael N. Keas.

FIGURE 10.1: Tychonic system.

In July 1610, the Grand Duke of Tuscany (an Italian country just north of the Papal State) appointed Galileo his chief mathematician and philosopher. The appointment was for life. This honour allowed him to return to his country of birth, but it came only after strategic acts of kindness towards the ruling Medici family. Galileo gave the name 'Medicean Stars' to the four satellites (later called moons) that he discovered revolving around Jupiter. He first thought they were ordinary stars, but then he observed them change positions relative to Jupiter. His telescope also revealed that the number of stars vastly exceeded naked eye estimates.

After his appointment in Tuscany, Galileo observed that the planet Venus goes through phases analogous to those of the moon: from virtually full, to half, to crescent and back to half and virtually full. The phases of Venus could be explained if the planet revolved around the sun. So this finding refuted the ancient geocentric Ptolemaic system of astronomy, which had Venus going around a motionless earth, not around the Sun.

But the discovery did not prove the Copernican system. Although Copernicus had argued that Venus revolves around the sun (in a path closer to the sun than Earth's annual revolution), Tycho Brahe had proposed a third system that also proved consistent with Galileo's telescopic wonders. In the Tychonic system (Figure 10.1), the planets revolve around the sun, which in turn revolves around a motionless earth. When Galileo showed that Jupiter revolves around the sun while also carrying its four moons for the ride, this supported the Tychonic system's contention that the sun could revolve around a central point (Earth) while carrying with it other celestial objects (planets) that revolve around it. Galileo had emphasised only the support the moons of Jupiter lent to the Copernican system, as that finding showed it was reasonable to believe that maybe Earth was not alone as a planet that carried with it a revolving moon.

The astronomers at the Roman College, the flagship Jesuit educational institution, embraced the Tychonic geoheliocentric system. The Tychonic system fits common sense: Earth seems to be at rest rather than moving thousands of miles per hour. Furthermore, a central stationary earth fit the prevailing Aristotelian scientific theory of how ordinary material objects with weight behave. Heavy (earthy and moist) things fall downward, towards the cosmic centre, naturally making the roughly spherical object on which we live: Earth and its surface water. No wonder that after the marvels of the telescope, most university scientists embraced Tychonic cosmology.[69]

There also appeared to be theological advantages to a geocentric cosmology – Tychonic or Ptolemaic. At least this is how the vast majority of Catholic and Protestant leaders assessed the situation up through Galileo's lifetime. The Bible seemed to affirm a stationary earth around which the sun moves. Although opposition to Galileo first came from Aristotelian professors, many pastors and theologians saw no reason to reinterpret the Bible in the face of unsettled scientific ideas.

Galileo and the grand inquisitor

Even if church officials typically embraced geocentric cosmology, that did not mean they reviled Galileo. On the contrary, Galileo travelled to Rome in 1611 to celebrate his telescopic discoveries with Pope Paul V, many cardinals and others. Numerous banquets were held in his honour. The Roman College even granted him the equivalent of a modern honorary doctorate in a lavish ceremony (Shea & Artigas 2003, pp. 30–43). The respect among Catholic leaders continued through Galileo's trial and final days though the number of his supporters dwindled. The reasons for this reduction in

---

[69] Additional strengths at the time included: the Tychonic system expected a *lack* of stellar parallax and it better made sense of the presence of detectable stellar widths. Both of these strengths were later erased by better technology and new scientific discoveries. Even so, at the time, the Tychonic system was very well supported by evidence. See Graney (2015).

support are complicated. The pride and vanity of both Galileo and Pope Urban VIII were contributing factors.

Galileo did have to answer theological objections to Copernicanism. In response, he wrote two widely circulated letters. The first, in 1613, went to his disciple and friend, Benedetto Castelli. Galileo enlarged that work in a 1615 letter to the Tuscan Grand Duchess Christina. In the Christina letter, he pondered the principles of biblical interpretation specified by the Council of Trent (1545–1563). That council was the Catholic response to the Protestant Reformation. The interpretive principle, especially at issue, declared that the Bible should be understood in a way consistent with the consensus of earlier church theologians – the Holy Fathers. Galileo, however, argued that this principle applied only to cases in which the Holy Fathers explicitly examined a specific question with appropriate intellectual tools. Such was not the case regarding whether the sun revolved around a stationary earth. Most previous commentators merely assumed that the Bible reflected a common sense understanding of a motionless earth. They did not adequately address this question, and so their less-than-rigorous consensus about the Sun's revolving around Earth did not present a binding biblical interpretation, he insisted (Galilei 2012, pp. 82–83).

Galileo also noted the respected theological tradition of understanding biblical descriptions of natural phenomena as reflecting how things appear to the human observer. The Holy Spirit, inspiring the human biblical authors, did not intend to teach cosmology or the subtle mechanics of nature. Such things were unknown to the original audience and would have only confused them (Galilei 2012, pp. 80–81). Galileo quoted Cardinal Cesare Baronio (1538–1607) to make the lesson memorable: 'The intention of the Holy Spirit is to teach us how one goes to heaven, not how the heaven goes' (Galilei 2012, p. 70). Galileo pointed out how Copernicus himself had taken this approach in his famous book *On the Revolutions of the Heavenly Spheres* (1543). He used common expressions like sunrise and sunset, even though he argued that such appearances actually resulted from the earth's rotating rather than from the sun's revolving (Galilei 2012, p. 82).

As to cosmology, Galileo argued that the Bible was not intended to teach *any* of the major candidates for world systems in the 17th century: Ptolemaic, Tychonic or Copernican.[70] God expected us to resolve cosmological questions

---

[70] In his letter to Christina, Galileo seems to say that the Bible supports one element of his updated version of the Copernican system. This argument appears inconsistent with Galileo's earlier principle according to which the Bible teaches *no* cosmology. Galileo cited Joshua's long day, when Joshua commanded the sun to stand still and the 'sun stopped in the midst of heaven' (Jos 10, v. 13). The astronomer suggested that this meant the sun stopped spinning on its axis in the center (midst) of the cosmos (heaven), which stopped all other planetary motion. This one miracle would lengthen that particular day on Earth to enable the Israelites to extend a winning battle. But Galileo might have been 'reducing to absurdity' the counterclaim that the Bible supports Ptolemaic cosmology. In effect, he might have been saying, if you want to play the illegitimate game of using

by using the rational tools he gifted to us. Observational tools like the telescope were also required. Galileo put down his pen hoping that his oversized letter would convert the luminaries of his own beloved Catholic Church.

Between the time of Galileo's letter to Castelli and the letter to Christina, Cardinal Robert Bellarmine (1542–1621) wrote a letter to the Copernican enthusiast and theologian Paolo Antonio Foscarini. It was intended also as a response to Galileo's letter to Castelli. Thus Galileo used his letter to Christina also to reply to Bellarmine's letter to Foscarini.

Who was this theologian with whom Galileo indirectly dialogued? In 1576, Bellarmine began his rise as the chief defender of Catholicism. He became a cardinal in 1599 and soon thereafter emerged as the leading Catholic theologian and inquisitor. For Protestants, he was theological enemy number one. Yet he was also widely known for kindness – even to Galileo (Fantoli 2005, pp. 124–126). Historians generally agree that he was very intelligent and a man of principle. The principles that he applied to limit Galileo's intellectual freedom were faulty, no doubt. But even smart people known for kindness, whether ethical atheists or misguided theologians, can feel duty-bound to do horrible things.

Scholars still debate how to interpret Bellarmine's April 1615 letter. In it, Bellarmine instructed Foscarini (and Galileo) that if a 'true demonstration' were to firmly establish Copernicanism, then 'one would have to proceed with great care in explaining the Scriptures that appear contrary'. He said he had 'very great doubts' that such a demonstration of heliocentrism would ever be accomplished. 'In the case of doubt one must not abandon the Holy Scripture as interpreted by the Holy Fathers' – that is, the Council of Trent's rule about the consensus of earlier church theologians (Finocchiaro 2008, p. 147).

But what if scientific discovery were to remove reasonable doubt about the Copernican system? In this case, it appears Bellarmine said that we should go with Copernicus, and theologians would need to reinterpret the Bible accordingly.

Contrary to what some historians of science have concluded, Bellarmine's letter does not oppose scientific progress in principle (McMullin 2005, pp. 180–181). The cardinal was also correct in thinking that the Copernican system had not yet (in 1615) been supported beyond a reasonable doubt. Even in 1633, when Galileo was put on trial, most scientists had good reasons to

---

(footnote 70 continues...)
the Bible to support a particular cosmology, then I can do that too – see how ridiculous it is! See 'Letter to the Grand Duchess Christina', in Finocchiaro (2008, pp. 140–144). Alternatively, Galileo might have been arguing that once you settle by science whether the sun or the earth moves, then you should interpret the Bible in a way that is consistent with such truths. This interpretation is consistent with another passage in Galileo's letter to Christina regarding Joshua's long day: 'It is necessary to gloss and interpret the meaning of the text of the book of Joshua regardless of the view we take of the structure of the universe' (Galilei 2012, p. 84).

reject sun-centred astronomy. Only much later did the Copernican system advance to a position beyond a reasonable doubt (Graney 2015).

The 1616 condemnation of Copernicanism

In December 1615, Galileo travelled 200 miles from Florence to Rome to defend himself against the recent accusations of a few Catholic clerics. Although many influential Church officials received him well, the Inquisition soon gave Galileo a private warning to abandon Copernicanism. Bellarmine delivered the message and later reported that Galileo had promised to obey.

In March 1616, the Congregation of the Index, the office responsible for book censorship, issued a decree declaring the idea of a moving earth false, 'altogether contrary to Holy Scripture', and a source of illegitimate 'prejudice' against Catholicism. The decree 'completely condemned and prohibited' Foscarini's theological defense of Copernicus, to which Bellarmine had responded in his April 1615 letter (Finocchiaro 2008, p. 177). The Congregation of the Index temporarily banned Copernicus's famous 1543 book, pending corrections. The decree did not mention Galileo.

Why did the Church condemn Copernicanism? Did the decree reveal a war between science and religion?

A 02 May 1633, entry in the diary of Galileo's friend Gianfrancesco Buonamici gives an important detail about the 1616 Index meeting that crafted the Copernican condemnation. Two of the participating cardinals successfully argued for a weaker censure than the 'heretical' label that the Inquisition qualifiers had recommended. So the Congregation of the Index chose the milder phrase 'altogether contrary to Holy Scripture' for the decree (Fantoli 2003, p. 454). One of these moderate cardinals was Maffeo Barberini, who was to become Pope Urban VIII during the latter part of Galileo's life. In 1630, Urban VIII would tell his adviser Tommaso Campanella that 'it was never our intention [to prohibit Copernicus]; and if it had been left to us, that decree would not have been made' (Fantoli 2003, p. 454).[71]

Why, then, did Pope Urban VIII take a hard line on Galileo's 1632 book *Dialogue Concerning the Two Chief World Systems*?

Cardinal Barberini became Pope Urban VIII in 1623, two years after Bellarmine's death. Galileo met with his well-educated friend the new pope to see whether Urban would support his plan to further investigate Copernican astronomy. After six exploratory conversations over six weeks, Galileo detected sufficient freedom to begin writing a book that would defend Copernicanism

---

[71] I corrected a typo in this quotation by noting its correct translation in Shea and Artigas (2003, p. 134). The contextual cues in brackets are Fantoli's. Galileo learned of this conversation from a letter dated 16 March 1630 from his disciple Castelli.

implicitly through a dialogue among three fictional characters. The book did not present the pro-Copernican arguments as conclusive, and it voiced the arguments against Earth's motion though they seemed much weaker.

But it soon became clear to the majority of Inquisition decision-makers that Galileo had violated at least the spirit of Bellarmine's warning and the Index's decree. For example, Galileo vastly overstated the value of his leading argument for a moving earth: his theory of tides. He argued that water sloshed around within a container as the container moved and that Earth was a big, and moving, container for the oceans. His theory specified one high tide and one low tide per day. Shortly before he finished his book, however, Galileo's theory collided with the inconvenient fact that each day brings two high tides and low tides. Galileo bandaged up his bleeding theory and hoped for the best. Perhaps the odd shapes and the varying depth of the ocean floor could account for the gap between his initial theory and what sailors reported.

Inquisition officials were concerned not just with Galileo's unbalanced treatment of the competing views of cosmology. They also discovered in the file of the 1616 proceedings a special injunction that had prohibited Galileo from even *discussing* the earth's motion in *any* manner (Finocchiaro 2009, p. 70). The *Dialogue* clearly violated that requirement. So he was summoned to Rome for trial.

The 1633 trial of Galileo

The early 1630s were politically perilous for Urban VIII. Europe was in the middle of the 30 Years' War (1618–1648), which had begun along Catholic-Protestant fault lines. The pope was especially troubled over the Catholic monarchs of France and Spain, who competed for control of the shrinking Holy Roman Empire. Ecclesiastical politics within the Vatican were also burdensome, driving the pope to questionable legal actions in some instances (Mayer 2015, pp. 217–218). This was not a convenient time to wrangle over the edgy cosmology of a troublesome genius.

The Galileo affair became very personal for Urban VIII. Galileo had put the pope's favourite argument for doubting Copernicanism in the mouth of the *Dialogue*'s character Simplicio, which sounds like 'simpleton' in Italian. Simplicio is persistently ill-informed and less than politely reasonable. The pope's old friend had betrayed him. Urban VIII was not the only one to see it this way. Regional and local politics, Galileo's insensitivity, the pope's overreaction and other peculiar factors flung the trial into orbit. Nobody enjoyed the turbulent ride.

Galileo did not spend months or years in jail as is often claimed. When he arrived in February 1633, he enjoyed pleasant lodging and fine cuisine at the large residence of the Tuscan embassy. Roman officials had spared him the usual procedure of waiting for trial in the Inquisition prison.

In April, when the trial began, he stayed in the apartment that the Vatican notary had vacated for him. The chef of the Tuscan embassy delivered meals to him (Shea & Artigas 2003, p. 176). He might have stayed in a prison cell for just a few days around the time of his condemnation. Even if true, this is nothing close to the exaggerated claims of imprisonment perpetuated by the Galileo Myth. Immediately after his condemnation, he lived temporarily at several palatial residences before returning to Florence for the remainder of his life under house arrest. House arrest, although restrictive, meant that Galileo lived at his own comfortable country residence. I enjoyed an hour at that beautiful residence in 2019.

At the first hearing on April 1633, Galileo admitted that Bellarmine had warned him not to hold or defend Copernicanism. He denied receiving the newly discovered special injunction prohibiting him from even discussing the topic (Finocchiaro 2009, p. 7). In his defense, he handed over a signed certificate Bellarmine had granted him in 1616 that prohibited him only from holding or defending the theory of a moving earth. Galileo claimed that the *Dialogue* did not defend the earth's motion but rather surveyed the arguments for and against it. Later in the trial, he even claimed that his book was aimed at refuting the Copernican theory (Shea & Artigas 2003, p. 186). That was obviously a lie!

As Maurice Finocchiaro (2009), a leading authority on Galileo, observes, Bellarmine's certificate and certain legal irregularities with the special injunction led the Inquisition to offer Galileo a plea bargain:

> [*T*]hey promised not to press the most serious charge (violation of the special injunction) if Galileo would plead guilty to a lesser charge (transgression of the warning not to defend Copernicanism). (p. 71)

Galileo agreed and eventually admitted that his book gave readers the impression of a Copernican defense.

The trial verdict declared Galileo guilty not of heresy but of a lesser offense, 'vehement suspicion of heresy'. He had to retract his Copernican beliefs by reciting a statement prepared for him. The *Dialogue* was also banned. End of story?

The proliferation of Galileo stories

Actually that was just the beginning of centuries of Galileo stories. The Galileo affair has been reassessed through subsequent generations in an effort to grasp the significance of this perplexing event. It has been commonly misconceived as a typical expression of the inevitable warfare between science and Christianity.

The Inquisition publicised the sentencing document and Galileo's required confession as a warning to all. These documents implied, but did not state, that Galileo had been tortured and would spend more time in prison. This false impression lingered long. Public access to the documents needed to debunk the jail myth came about 150 years later. The records needed to undo the torture story took about 250 years to enter the public domain. (Finocchiaro 2009, p. 73). Given the documents now available, we are even more confident that Galileo's interrogation came with the threat of torture but not actual torture. It is even fairly clear that, given his age and popularity, his accusers never actually planned to torture him (Finocchiaro 2009, pp. 76–78).

Many astronomy textbooks have proliferated various components of the Galileo Myth. One of America's leading astronomers, Ormsby Mitchel (1809–1862), published the textbook *Popular Astronomy*. In it, he described the alleged intellectual landscape of Europe just after Galileo's telescopic discoveries: 'The most honest, intelligent, and powerful minds had already adopted the Copernican theory, but in the universities and other schools of science, as well as in the church, the system of Ptolemy still reckoned among its supporters a host of learned and dignified men' (Mitchel 1860, p. 142).[72] Mitchel mistakenly implies that the Copernican system was virtually proven by this time.

Joel Dorman Steele (1836–1886), one of the most prolific American textbook authors of the 19th century, intensified the Galileo Myth. His frequently reprinted astronomy textbook stated (Steele 1869):

> Many refused to look through the telescope lest they might become victims of the philosopher's magic. Some prated of the wickedness of digging out valleys in the fair face of the moon. Others doggedly clung to the theory they had held from their youth. (p. 31)

It is true that Galileo complained that some natural philosophy (science) professors at the University of Padua had refused to look through a telescope.[73] This behaviour, though, probably resulted more from a firm commitment to Aristotelian cosmology rather than theology. One of the telescope-refusing scientists at Padua that Galileo mentioned was Cesare Cremonini (1550–1631), whom John Heilbron (2010, p. 372) in a biography of Galileo identifies as a 'popular professor of philosophy at Padua, friend of Galileo, constantly in trouble with the Inquisition for his faithful teaching of Aristotle'. So both Galileo and the Inquisition criticised his excessive Aristotelian views.

Furthermore, there is no record of priests or theologians refusing to look through a telescope. In fact, when Cardinal Bellarmine asked about Galileo's telescopic discoveries, the Jesuit astronomers at the Roman College *confirmed* their accuracy. Bellarmine had himself gazed at the heavens through a telescope, probably because he wanted to be informed about discoveries of

---

[72] The same passage persists in the final (seventh) edition of the book, which was printed almost a dozen times by the same publisher from the mid-1860s up through the mid-1870s.

[73] Galileo's letter to Kepler, 19 August 1610, as cited in Fantoli (2003, p. 92).

relevance to theology. The only telescopic interpretation of Galileo that the Jesuit astronomer Christoph Clavius contested was the claim that our moon's surface is irregular, with mountains and valleys. Several of his astronomy colleagues at the Roman College agreed with Galileo's interpretation (Fantoli 2003, pp. 101–102).

Even before Galileo's telescopic discoveries of the moon's uneven surface, Bellarmine had already concluded that heavenly bodies shared some of the imperfect features of our humble terrestrial realm. He based this opinion on the Bible. For example, Psalm 102 (vv. 25–26) says both heaven and earth 'wear out like a garment'. Kepler (1952, pp. 845–848) invoked this passage to show that science and Scripture had converged on the same answer: the stars are not imperishable, as Aristotle had thought. This is a rare exception to the general interpretive rule regarding the Bible's accommodation to *appearances only* when treating natural phenomena. Both Kepler and Galileo had passionately defended such a general rule.

Galileo's legacy for science and Christianity

In the end, the Galileo affair, although embarrassing for the Catholic Church, does not support the common belief that Christianity typically suppresses science. Like his fellow Christian (Lutheran) contemporary Kepler, Galileo was guided in his scientific work by the belief that God composed his book of the cosmos 'in mathematical language'. God's cosmic book 'is constantly open before our eyes', Galileo assured his readers in his book *The Assayer* (1623) (Finocchiaro 2008, p. 183). Those readers included the learned and appreciative Pope Urban VIII, to whom Galileo dedicated the book.

The Galileo affair was not a simple or inevitable episode of science versus Christianity. Many complicated alliances and personal idiosyncrasies came into play. The majority of Church leaders had allied themselves with the majority Aristotelian scientific viewpoint of the day. Together they opposed Copernican astronomy, which a theological and scientific minority held. If Galileo had been more tactful, modest and patient in his attempt to reform his own church, there might have been no trial of 1633. Minority scientists such as Galileo argued that a heliocentric cosmos was scientifically superior. But given the scientific data available up through 1633, the Copernican system had *not yet* been shown to be superior to the Tychonic system of astronomy. Tycho Brahe's theory included many of the most defensible parts of the other two theories and was endorsed by the Jesuit astronomers in Rome. Galileo strategically sidelined the Tychonic system in his *Dialogue on the Two Chief Systems of the World*.[74] He was a master rhetorician. He made the arguments

---

[74] Finocchiaro (2014, pp. 257–258) argues that 'although Galileo does not discuss Tycho's alternative explicitly, he does so implicitly, and hence he is not really neglecting it. One reason stems from the fact that the Tychonic

for the Copernican system seem stronger than they were at the time. The Inquisition had good scientific and theological reasons to question Galileo.

Although Galileo said that God's 'book' of creation 'is constantly open before our eyes', accurately reading that book can be challenging. Skilled interpretation required both telescopic wisdom and the newly developed techniques of mathematical physics, Galileo and Kepler argued. God's other book, the Bible, typically used ordinary observational expressions 'of appearance' when referring to the natural world. So the Bible, like Copernicus himself, could describe a wondrous 'sunset' without error. Rather than reflecting a fundamental conflict between science and Christianity, the Galileo affair is better characterised as the sour fruit of overstated scientific arguments, political turmoil and personal vanity.

Although Copernicus, Galileo and Kepler were not sceptical of theistic religion, Baruch Spinoza certainly was. However, Spinoza contributed very little to scientific progress. This chapter explains why this is so and helps finish debunking the final myth addressed in this chapter.

■ The Sceptic Myth: The main heroes of early modern science were sceptics, not believers in God[75]

The author's coverage of Copernicus, Galileo and Kepler has already contributed positively towards debunking the Sceptic Myth by showing that these men – like many other pioneers of early modern science – embraced Christianity. Now the negative side of this myth is dealt with using a prominent case study: Spinoza.

Episode 1 of the 2020 *Cosmos* TV series gives the impression that the main heroes of early modern science were sceptics rather than believers in God. The series designates Baruch Spinoza (1632–1677) as the next greatest persecuted hero of science after Giordano Bruno (as depicted in the *Cosmos* 2014 season). Although Bruno was burned to death in 1600 primarily for his religious-philosophical (not scientific) views (Keas 2019a, pp. 57–74), the attempted murder of Spinoza, if it occurred, was likely because of a disputed

---

(footnote 74 continues...)
theory does, after all, share a crucial common element with the Ptolemaic system; that is, both hold the earth to be motionless at the center of the universe. That is, in both systems, the diurnal motion belongs to the whole universe except the earth, and the annual motion belongs to the sun. Therefore, all the Galilean arguments for the earth's motion and against the geostatic, geocentric thesis undermine Tycho's as well as Ptolemy's world view. This is the case, for example, with the sunspot argument, the tidal argument, and the argument from the law of revolution'. Despite this, Galileo still gives the impression that his arguments were stronger than they actually were, given the Tychonic option in the light of the available evidence (Graney 2015).

[75] See especially cf. Keas (2020).

business transaction (not science or religion) (Nadler 2019). For *Cosmos* to suggest that Spinoza's life was threatened because of his scientific views is just the beginning of an enormous misrepresentation.

Like the heretical Catholic philosopher Bruno, Spinoza traded belief in the biblical God for a necessitarian philosophical creed. Both believed 'God' had no choice in creation, and an infinite cosmos resulted. Consequently, both had philosophical reasons for believing in an infinite number of inhabited worlds. There was, and still is, no scientific support for the idea of an infinite cosmos. Science is not well-equipped to even address this kind of question.

In *Cosmos*, Tyson equates traditional religion with ignorance, especially the biblical religions of Judaism and Christianity. Spinoza was a wayward Jewish philosopher whom Albert Einstein, a secular Jew, later celebrated as likeminded. *Cosmos* depicts this connection with film footage of Einstein visiting the Spinoza museum. Indeed, Einstein publicly confessed his faith in 'Spinoza's God'.

Spinoza's God

Spinoza's God was nature or some aspect of it. Scholars debate how to interpret his ambiguous views. 'From the necessity of the divine nature there must follow infinitely many things in infinitely many modes', Spinoza wrote (Nadler 2020). Nature could not have been other than what it is.

This necessitarian vision, which traces back to the ancient Greeks, is precisely the view that the Judeo-Christian tradition overcame. This transformation was one of the key ingredients for a cultural context conducive to modern science (as I explain in my video, 'Three Big Ways Christianity Supported the Rise of Modern Science').[76] Consequently, *Cosmos* 2020 celebrates as a science hero a philosopher who opposed the very Judeo-Christian cultural context that helped make modern science possible.

Spinoza's God versus Science

The Christian belief in divine freedom undercut the view, established by Plato and Aristotle, that the structure of the cosmos is a necessary one. Christians insisted that God could have created a universe quite different from ours, and so testing multiple hypotheses by experiment was an effective way to determine which set of natural laws God actually created to govern our cosmos. So in his departure from theism, Spinoza undercut some of this science-fostering culture.

Upon delving deeper as to why Spinoza was no science hero. Scholarship on Spinoza in the last decade has increasingly recognised that he opposed

---

[76] https://youtu.be/HHcF-ffKkeg.

the observational (empirical) and mathematical analyses of nature advanced by the likes of Kepler and Galileo. ‘Skepticism about the very *possibility* of empirical knowledge of nature runs through Spinoza’s books’, notes Eric Schliesser in *The Oxford Handbook of Spinoza* (Schliesser 2014). More specifically, ‘Spinoza was very critical of applying mathematics and measurement in understanding nature’. That is even more damaging for science! Similarly, Alison Peterman, writes: ‘Spinoza took a dim view of the extent to which the application of mathematics to physics and the empirical investigation of the physical can give us knowledge of nature’ (Peterman 2014, pp. 214–223).

Here is one memorable expression of Spinoza’s criticism of the application of mathematics to science (Peterman 2014):

> There are men lunatic enough to believe, that even God himself takes pleasure in harmony; indeed there are philosophers who have persuaded themselves that the motions of the heavens produce a harmony. (pp. 214–223)

Spinoza attacked the view of Johannes Kepler and Christiaan Huygens (the leading Dutch scientist and a Spinoza acquaintance, also highlighted in *Cosmos* 2020) that God infused mathematical harmonies into the fabric of the cosmos. This is a projection of mathematical harmony into nature where none exists, Spinoza insisted (Peterman 2014, pp. 214–223). Fortunately, astronomy textbooks over the past four centuries ignored Spinoza’s attack on Kepler and instead have affirmed Kepler’s third mathematical law of planetary motion, also called the ‘harmonic law’.

The book of nature[77]

Christianity has a long and remarkable track record of contributing to the foundations of science. As mentioned earlier, Saint Augustine (354–430) expressed confidence in our ability to discover and read the ‘book of nature’ because it is the ‘production of the Creator’.

Galileo, Kepler and many other early modern scientists used this traditional Christian metaphor of the ‘book of nature’. They sought to convey the idea that God wrote two books that are consistent with one another: nature and the Bible. Nature is largely written in the language of mathematics, many of these scientists argued, and so it can be read only by those who know this language. Galileo argued as much in his book *The Assayer* (1623). He wrote (Finocchiaro 2008):

> Philosophy [*natural science*] is written in this all-encompassing book that is constantly open before our eyes, that is the universe; but it cannot be understood unless one first learns to understand the language and knows the characters in which it is written. It is written in mathematical language. (p. 183)

---

[77] This section of the chapter represents a substantial reworking of cf. Keas (2020)

Consider also these three utterances of Kepler, similarly celebrating the theological aspects and implications of science. Kepler wrote in a letter to Michael Maestlin in 1595 (cited in Rothman 2011):

> I truly desire that these things are published as quickly as possible for the glory of God, who wants to be known from the Book of Nature […] I wanted to be a theologian; for a long time I was distressed: behold God is now celebrated too in my astronomical work. (p. 115)

He wrote in a letter to Herwart Von Hohenburg in 1599: 'God wanted us to recognize them [i.e. mathematical natural laws] by creating us after his own image so that we could share in his own thoughts' (Kaiser 2007, p. 175).

He wrote in a letter to Galileo in 1610: 'Geometry is unique and eternal, and it shines in the mind of God. The share of it which has been granted to man is one of the reasons why he is in the image of God' (Rosen 1965, p. 175).

Here is how the significance of these Keplerian sayings is explained in the author's book *Unbelievable: 7 Myths About the History and Future of Science and Religion*, which tells the true story of science and God that Tyson tries to suppress with atheistic mythology.

Kepler was a devout Christian who believed that the Bible and the 'book of nature' were fully compatible and mutually supportive. He recognised them both as God's revelation. He studied both intensely. In fact, he almost finished a doctoral degree in theology before he turned to a career in mathematics and astronomy. Kepler believed that mathematical ideas exist eternally in the divine mind and that God freely selected some of these principles to govern his creation. Because God created humans in his image, we have the intelligence needed to discover those natural laws and in so doing, Kepler announced, we 'share in his own thoughts'. The human mind emulates God's thoughts in ways that reveal the deep structure of the cosmos. Thus God is 'glorified in astronomy', Kepler concluded (Keas 2019a, p. 159).

The Bible and aliens

Kepler also considered the possible existence of intelligent extra-terrestrial life to be consistent with Christianity, even though Scripture does not address this issue. This leads to identifying a final related error coming from today's sceptics as expressed in the *Cosmos* 2020 TV documentary (cf. Keas 2020). Tyson suggests that there was a 'contradiction' between biblical faith and science given that the Bible does not mention extra-terrestrial life (which Tyson thinks is established by science). No wonder that Spinoza is one of Tyson's heroes, because Spinoza believed in an infinite number of inhabited worlds (despite the lack of scientific evidence for this idea then or now). There are countless aspects of the universe that the Bible does not address (e.g. quantum mechanics, thermodynamics and electromagnetic radiation), but that does not make scientific theories about such topics in ‘contradiction’ to the Bible. It simply was not within the communicative intent of the Bible to address whether there are other inhabited worlds – and many other interesting scientific topics. Leading scientists such as Galileo, Kepler, Huygens and Newton understood this general principle about the Bible and science.

Furthermore, Tyson attributes to Spinoza a view of nature that he makes sound daringly novel: ‘His sacred text’, he says of Spinoza, was ‘the book of nature’. But for most early modern scientists, there were *two* sacred texts: the Bible and nature. By turning his back on the former, Spinoza undermined some of the theological foundations for the scientific study of the latter. That is tragic, not heroic.

Of course, it is possible that humans, on many occasions, have misinterpreted either the book of nature or the book of Holy Scripture – or both. In such cases, there might *appear* to be a conflict between science and religion. It is also reasonable to conclude that many ‘holy books’ are not actually inspired by God – particularly because they make conflicting claims about reality. Such books might *actually* conflict in many respects with the way God made the natural world. The author’s colleagues in the history of science and philosophy of science typically do not address such issues, but a comprehensive search for truth would not allow ignoring them.

■ Conclusion

The author has deconstructed six inaccurate stories that depict science and Christianity at war with each other: the Dark Myth, the Flat Myth, the Big Myth, the Demotion Myth, the Galileo Myth and the Sceptic Myth. Most educated people have encountered at least some of these stories presented with the assumption that they are unquestionably true. When recent scholarship in the history of science is examined, it is found that all of these accounts are amalgamations of over-simplification, misunderstanding and exaggeration. The truth about the history of science and religion is more complex and interesting. This includes evidence for peace between science and Christianity that is quite substantial.

References

Chapter 1

Aczel, AD 2014, *Why science does not disprove God*, HarperCollins, New York.

Aristotle 1928, 'Metaphysics', in WD Ross (ed.), *The Oxford translation of Aristotle*, 2nd edn, Oxford University Press, Oxford, p. 980.

Ayala, F 2007, *Darwin's gift: to science and religion*, Joseph Henry Press, Washington, DC.

Bacon, F, Spedding, J & Ellis, R 1884, *The works of Francis Bacon*, eds. W Heath & DD Rawley, Hurd and Houghton, New York.

Behe, MJ 1996, *Darwin's black box: the biochemical challenge to evolution*, Touchstone Books, New York.

Borde, A, Guth, AH & Vilenkin, A 2003, 'Inflationary spacetimes are incomplete in past directions', *Physical Review Letters*, vol. 90, no. 15, a151301. https://doi.org/10.1103/physrevlett.90.151301

Conway, D 2000, *The rediscovery of wisdom*, from Arist, ed. WD Ross, Macmillan Press Ltd., London.

Craig, WL 2001, *The cosmological argument from Plato to Leibniz*, Wipf and Stock Publishers, Eugene.

Darwin, CR 1872, *On the origin of species*, 6th edn, Feedbooks, Paris.

Darwin, CR 1958, *The autobiography of Charles Darwin, 1809–1882*, ed. N Barlow, Collins, London.

Dawkins, CR 1995, *River out of Eden: a Darwinian view of life*, 2nd edn, George Weidenfeld & Nicolson Ltd., London.

Dawkins, R 2015, *The blind watchmaker*, 2nd edn, W.W. Norton & Company, London.

Dembski, W 1998, *The design inference*, Cambridge University Press, Cambridge.

Dembski, WA & Ruse, M 2004, *Debating design*, Cambridge University Press, Cambridge.

Draper, JW 1875, *History of the conflict between religion and science*, 2nd edn, Cambridge University Press, Cambridge.

Ellis, G & Silk, J 2014, 'Scientific method: defend the integrity of physics', *Nature*, vol. 516, no. 7531, pp. 321–323. https://doi.org/10.1038/516321a

Ellis, GFR 2011, 'Does the multiverse really exist?', *Scientific American*, vol. 305, no. 2, pp. 38–43. https://doi.org/10.1038/scientificamerican0811-38

Ellis, GFR 2021, 'The philosophical problems of cosmology', *iai news*, viewed 14 October 2021, <https://iai.tv/articles/the-philosophical-problems-of-cosmology-auid-1883>

Fletcher, WW 1974, *Modern man looks at evolution*, Fontana, Roermond.

Flew, RAV 2007, *There is a God*, HarperCollins Publisher Ltd., London, viewed 02 September 2021, <http://www.uk.harpercollinsebooks.com>

Galilei, G 1957, 'Letter to Madame Christina of Lorraine, Grand Duchess of Tuscany', in *Discoveries and Opinions of Galileo*, inters.org, viewed 04 May 2021, <https://inters.org/Galilei-Madame-Christina-Lorraine>

Goff, P 2021, 'Our improbable existence is no evidence for a multiverse', *Scientific American*, viewed n.d., <https://www.scientificamerican.com/article/our-improbable-existence-is-no-evidence-for-a-multiverse/ >

Gonzalez, G & Richards, J 2004, *The privileged planet: how our place in the cosmos is designed for discovery*, Regnery Publishing, Washington, DC.

Gregory, TR 2009, 'The argument from design: a guided tour of William Paley's natural theology (1802)', *Evolution: Education and Outreach*, vol. 2, no. 4, pp. 602–611. https://doi.org/10.1007/s12052-009-0184-6

Guth, AH 1981, 'Inflationary universe: a possible solution to the horizon and flatness problems', *Physical Review D*, vol. 23, no. 2, pp. 347–356. https://doi.org/10.1103/PhysRevD.23.347

Guth, AH 2007, ‘Eternal inflation and its implications’, *Journal of Physics A: Mathematical and Theoretical*, vol. 40, no. 25, pp. 6811–6826. https://doi.org/10.1088/1751-8113/40/25/S25

Haldane, JJ & Smart, JJC 1996, *Atheism and Theism*, *Atheism and Theism*, Blackwell, Oxford and Cambridge.

Harrison, P 2010, ‘“Science” and “religion”: constructing the boundaries’, in T Dixon, G Cantor & S Pumfrey (eds.), *Science and religion: new historical perspectives*, Cambridge University Press, Cambridge, pp. 23–49.

Hawking, SW 1988, *A brief history of time*, Bantam Books, New York.

Hawking, SW 1993, *Black holes and baby universes*, Bantam, New York.

Hawking, SW & Mlodinow, L 2010, *The grand design*, Bantam Books, New York.

Hiebert, PG 2008, *Transforming worldviews: an anthropological understanding of how people change*, Baker Academic, Grand Rapids.

Himma, KE 2021, *Design arguments for the existence of God*, *Internet Encyclopedia of Philosophy,* viewed 01 August 2021, <https://iep.utm.edu/design/>

Hume, D 1999, *Enquiry concerning human understanding*, ed. TL Beauchamp, Oxford University Press, Oxford.

Hume on Religion 2005, *Stanford encyclopedia of philosophy*, viewed 01 October 2021, <https://plato.stanford.edu/entries/hume-religion/>

Krauss, LM 2012, *A universe from nothing: why there is something rather than nothing*, Free Press, New York.

Lamoureaux, DO 2015, *Views on the origin of universe & life*, viewed 13 August 2019, <https://sites.ualberta.ca/~dlamoure/wlbeyond3/index.html>

Leibniz, GW 1951, ‘The principles of nature and of Grace, based on reason’, in PP Wiener (ed.), *Leibniz selections*, Charles Scribner’s Sons, The Modern Student’s Library, New York, p. 527.

Lennox, J & Shermer, M 2013, *Public debate: belief in God*, *Oxford Union*, *recording*, viewed 02 July 2021, <https://www.youtube.com/watch?v=6GzCou13hXQ>

Leslie, J 2001, *Infinite minds*, Clarendon, Oxford.

Luskin, C 2014a, ‘The new theistic evolutionists: BioLogos and the rush to embrace the “consensus”’, *Christian Research Journal*, vol. 37, no. 3, pp. 32–41.

Luskin, C 2014b, ‘The top ten scientific problems with biological and chemical evolution’, in *More than myth*, Chartwell Press, Leicester, pp. 9–30, 42–50.

Masterson, P 1973, *Atheism and alienation: a study of the philosophical sources of atheism*, P Books, Harmondsworth.

McGrath, AE 1998, *Historical theology*, *an introduction to the history of Christian thought*, Blackwell Publishers, Oxford.

McGrath, AE 2010, *Three landmark debates*, Wiley-Blackwell, Oxford.

Meyer, SC 2013, *Darwin’s doubt: the explosive origin of animal life and the case for intelligent design*, HarperOne, New York.

Meyer, SC 2021, *Return of the God hypothesis*, HarperColl, New York.

Oderberg, DS 2007, ‘The cosmological argument’, in C Meister & P Copan (eds.), *The Routledge companion to philosophy of religion*, Routledge, Abingdon, pp. 341–350.

Plantinga, A 1992, ‘Augustinian Christian philosophy’, *The Monist*, vol. 75, pp. 291–320. https://www.jstor.org/stable/27903295

Plantinga, A 2011, *Where the conflict really lies*, *science*, *religion*, *and naturalism*, Oxford University Press, New York.

Talisse, R & Aikin, SF 2006, ‘Two forms of the Straw Man’, *Argumentation*, vol. 20, no. 3, pp. 345–352. https://doi.org/10.1007/s10503-006-9017-8

Ross, H 2008, *Why the universe is the way it is*, BakerBooks, Grand Rapids.

Ross, H 2016, *Improbable planet: how Earth became humanity’s home*, BakerBooks, Grand Rapids.

Russell, B & Copleston, FC 1964, *The existence of God*, *problems of philosophy series*, ed. J Hick, Macmillan & Co., New York.

Schroeder, G 2021, *The Big Bang creation: God or the Laws of nature*, viewed 01 August 2021, <http://www.geraldschroeder.com/BigBang.aspx>

Sedley, D 2007, *Creationism and its critics in antiquity*, University of California Press, California.

Sire, JW 1998, *The universe next door: a basic world view catalog*, 5th edn, InterVarsity Press, Illinois.

Stanford Encyclopedia of Philosophy 2021, *Scientific method*, viewed 15 October 2021, <https://plato.stanford.edu/entries/scientific-method/>

St. Augustine n.d., *Concerning the city of God against the Pagans*, Penguin Books, Harmondsworth.

Steinhardt, P 2014, 'Big Bang blunder bursts the multiverse bubble', *Nature*, vol. 510, no. 7503, a9. https://doi.org/10.1038/510009a

Stenmark, M 2018, *Scientism: science*, *ethics and religion*, Routledge, Abingdon.

St. Thomas Aquinas 1947, *Summa Theologica*, ed., trans. F of the ED Province, Benziger Bros, New York.

Swinburne, R 2004, *The existence of God*, 2nd edn, Oxford University Press, Oxford.

Teilhard de Chardin, P 2008, *The phenomenon of man*, Harper Perennial Modern Classics, New York.

TIME Magazine 1980, *Religion: modernising the case for God*, viewed 27 August 2021, <http://content.time.com/time/subscriber/article/0,33009,921990,00.html>

Turner, D & Havstad, JC 2019, *Philosophy of macroevolution*, viewed 01 August 2021, <https://plato.stanford.edu/entries/macroevolution/>

Van Niekerk, F 2020, 'Reformation and scientific revolution: historical coincidence or continual renewal?', *In die Skriflig/In Luce Verbi*, vol. 54, no. 2, a2538. https://doi.org/10.4102/ids.v54i2.2538

Varghese, RA 2010, *The wonder of the world: a journey from modern science to the mind of God*, Fountain Hills, Arizona.

Vilenkin, A 2006, *Many worlds in one: the search for other universes*, Hill and Wang, New York.

Weinberg, S 1977, *The first three minutes: a modern view of the origin of the universe*, Trinity Press, London.

White, AD 1895, *A history of the warfare of science with theology in Christendom*, *A history of the warfare of science with theology in Christendom*, Cornell University, New York.

Wood, J 2011a, 'The modern novel and the new atheism', *The New Atheism*, viewed 23 August 2021, <http://podcasts.mml.ox.ac.uk/weidenfeld/index.html>

Wood, J 2011b, *The New Atheism*, viewed 18 March 2021, <https://www.theguardian.com/books/2011/aug/26/james-wood-the-new-atheism>

Chapter 2

Ayala, FJ 1994, 'Darwin's revolution', in JH Campbell & JW Schopf (eds.), *Creative evolution*, Jones and Bartlett, New York.

Barrow, J, Tipler, F & Wheeler, J 1988, *The anthropic cosmological principle*, Oxford University Press, Oxford.

Bertalanffy, LV 1967, *Robots*, *men and minds*, George Braziller, New York.

Bondi, H & Gold, T 1948, 'The steady-state theory of the expanding universe', *Monthly Notices of the Royal Astronomical Society*, vol. 108, no. 3, pp. 252–270. https://doi.org/10.1093/mnras/108.3.252

Bowie, J & Sauer, R 1989, 'Identifying determinants of folding and activity for a protein of unknown structure', *Proceedings of the National Academy of Sciences USA*, vol. 86, no. 7, pp. 2152–2156. https://doi.org/10.1073/pnas.86.7.2152

Briggs, D 1992, 'Science, religion, are discovering commonality in Big Bang Theory', *Los Angeles Times*, 02 May, pp. B6–7.

Browne, MW 1978, 'Clues to universe origin expected', *New York Times*, 12 March, p. 54.

Brush, S 1989, 'Prediction and theory evaluation: the case of light bending', *Science*, vol. 246, pp. 1124–1127.

Butterfield, H 1967, *The origins of modern science 1300–1800*, The Free Press, New York, NY, pp. 16–17, 19.

Cairns-Smith, AG 1971, *The life puzzle*, Oliver and Boyd, Edinburgh, pp. 92–96.

Chaisson, E & McMillan, S 1993, *Astronomy today*, Prentice Hall, Englewood Cliffs, pp. 604–605.

Chamberlin, TC 1965, 'The method of multiple working hypotheses', reprinted in *Science*, vol. 148, pp. 754–759.

Collins, R 2017, 'A scientific argument for the existence of God: the fine-tuning design argument', in KJ Clark (ed.), *Readings in the philosophy of religion*, 3rd edn, Broadview Press, Peterborough.

Conant, JB 1953, *Modern science and modern man*, Doubleday Anchor, New York, pp. 139–140.

Craig, WL 1988, 'Barrow and Tipler on the anthropic principle vs. divine design', *The British Journal for the Philosophy of Science*, vol. 39, no. 3, pp. 389–395. https://doi.org/10.1093/bjps/39.3.389

Craig, WL 1994, *Reasonable faith*, Crossway Books, Wheaton, pp. 79–83.

Craig, WL 2000, *The Kalām cosmological argument*, Wipf & Stock Publishers, Eugene.

Craig, WL 2001, *The cosmological argument from Plato to Leibniz*, Wipf & Stock Publishers, Eugene.

Crick, F 1981, *Life itself*, Simon & Schuster, New York, pp. 95–166.

Crick, FH 1958, 'On protein synthesis', *Symposia of the Society for Experimental Biology*, vol. 12, pp. 138–163.

Darwin, C 1985, *The origin of species*, Penguin Classic Edition, Penguin, London.

Davies, P 1988, *The cosmic blueprint*, Simon & Schuster, New York.

Davies, PCW 1978, 'Spacetime singularities in cosmology', in JT Fraser (ed.), *The study of time III*, Springer, New York, pp. 74–93.

Dawkins, R 1986, *The blind watchmaker*, Longman, London.

Dawkins, R 1996, *River out of Eden: a Darwinian view of life*, Basic Books, New York.

Dembski, W & Meyer, SC 1998, 'Fruitful interchange or polite chit-chat?: The dialogue between science and theology?', *Zygon*, vol. 33, no. 3, pp. 415–430. https://doi.org/10.1111/0591-2385.00158

Dembski, WA 1998, *The design inference: eliminating chance through small probabilities*, Cambridge University Press, Cambridge.

Dobzhansky, T 1965, 'Discussion of G. Schramm's paper', in SW Fox (ed.), *The origins of prebiological systems and of their molecular matrices*, Academic Press, New York, p. 310.

Drake, S 1957, *Discoveries and opinions of Galileo*, Doubleday, New York, NY.

Eddington, AS 1930, 'On the instability of Einstein's Spherical world', *Monthly Notices of the Royal Astronomical Society*, vol. 90, no. 7, pp. 668–678. https://doi.org/10.1093/mnras/90.7.668

Eddington, AS 1956, 'The end of the world: from the standpoint of mathematical physics', *Nature*, vol. 127, a450.

Einstein, A 1915, 'Die Feldgleichungen der Gravitation', *Sitzungsberichte der Koniglich Preussischen Akademie der Wissenschaften*, vol. 25, pp. 844–847.

Einstein, A 1916, 'Die Grundlage der allgemeinen Relativitatstheorie', *Annalen der Physik*, vol. 49, pp. 769–822. https://doi.org/10.1002/andp.19163540702

Einstein, A 1917, 'Kosmologische Betrachtungen zur allgemeinen Relativitatstheorie', *Sitzungsberichte der Koniglich Preussischen Akademie der Wissenschaften*, vol. 8, pp. 142–152. https://doi.org/10.1002/3527608958.ch2

Eisley, L 1961, *Darwin's century: evolution and the men who discovered It*, Anchor, Garden City.

Feeney, SM, Johnson, MC, Mortlock, DJ & Peiris, HV 2011, 'First observational tests of eternal inflation', *Physical Review Letters*, vol. 107, a071301. https://doi.org/10.1103/PhysRevLett.107.071301

Foster, MB 1934, 'The Christian Doctrine of creation and the rise of modern natural science', *Mind*, vol. 43, no. 172, a446. https://doi.org/10.1093/mind/XLIII.172.446

Futuyma, D 1986, *Evolutionary biology*, Sinauer Associates, Sunderland, MA.

Galilei, G 1615, *Letter to Madame Christina of Lorraine*, *Grand Duchess of Tuscay*, *concerning the use of biblical quotations in matters of science*, 1615, cited in NS.

Hetherington 1993, *Cosmology: historical*, *literary*, *philosophical*, *religious and scientific perspectives*, CRC Press, Boca Rotan.

Gamow, G 1946, 'Expanding universe and the origin of the elements', *Physical Review*, vol. 70, no. 7 and 8, pp. 572–573. https://doi.org/10.1103/PhysRev.70.572.2

Gamow, G 1970, *My world line: an informal autobiography*, Viking Press, New York.

Gates, B 1998, *The road ahead: completely revised and up-to-date*, Penguin Books, London.

Gingerich, O 1982, 'The Galileo affair', *Scientific American*, vol. 247, no. 2, pp. 133–143.

Gingerich, O 1992, *The Galileo affair*, Sky Publishing, Cambridge.

Gordon, BL 2010, 'Inflationary cosmology and the string multiverse', in RJ Spitzer (ed.), *New proofs for the existence of God: contributions of contemporary physics and philosophy*, Eerdmans, Grand Rapids.

Gordon, B 2014, 'Balloons on a string: a critique of multiverse cosmology', in BL Gordon & WA Dembski (eds.), *The nature of nature: examining the role of naturalism in science*, ISI Books, Wilmington, pp. 558–601.

Gould, SJ 1999, *Rocks of ages: science and religion in the fullness of life*, Ballantine Books, New York.

Greenstein, G 1988, *The symbiotic universe: life and mind in the cosmos*, Morrow, New York.

Gruenwald, O 1994, 'Science and religion: the missing link', *Journal of Interdisciplinary Studies*, vol. 6, pp. 1–23. https://doi.org/10.5840/jis199461/21

Guth, A 2002, 'Inflation and the new era of high-precision cosmology', *MIT Physics Annual*, no. 2002, pp. 28–39.

Guth, A & Sher, M 1983, 'The impossibility of a bouncing universe', *Nature*, vol. 302, pp. 505–507. https://doi.org/10.1038/302505a0

Haeckel, E 1883, *The history of creation*, vol. 1, 3rd edn, trans. E Ray Lankester, Kegan Paul, Trench & Co., London.

Hartle, JB & Hawking, S 1983, 'Wave function of the universe', *Physical Review D*, vol. 28, no. 12, pp. 2960–2975. https://doi.org/10.1103/PhysRevD.28.2960

Hawking, S 1988, *A brief history of time*, Bantam Books, New York.

Hawking, S & Penrose, R 1970, 'The singularities of gravitational collapse and cosmology', *Proceedings of the Royal Society of London*, *Series A*, vol. 314, pp. 529–548.

Hazen, RM, Griffin, PL, Carothers, JM & Szostak, JW 2007, 'Functional information and the emergence of biocomplexity', *Proceedings of the National Academy of Sciences*, vol. 104, no. Suppl 1, pp. 8574–8581. https://doi.org/10.1073/pnas.0701744104

Hetherington, NS 1997, 'Nebular hypothesis: Kant – Laplace', in JH Shirley & RW Fairbridge (eds.), *Encyclopedia of planetary science. Encyclopedia of earth science*, Springer, Dordrecht, pp. 519–520.

Hodgson, PE 1974, 'Review of *Science and Creation* by S.L. Jaki', *Nature*, vol. 251, a747. https://doi.org/10.1038/251747a0

Hood, L & Galas, D 2003, 'The digital code of DNA', *Nature*, vol. 421, no. 6921, pp. 444–448. https://doi.org/10.1038/nature01410

Hooykaas, R 1972, *Religion and the rise of modern science*, William B. Eerdmans, Grand Rapids.

Hoyle, F 1982, 'The universe: past and present reflections', *Annual Review of Astronomy and Astrophysics*, vol. 20, a245. https://doi.org/10.1146/annurev.aa.20.090182.000245

Hubble, E 1929, ‘A relation between distance and radial velocity among extra-galactic nebulae’, *Proceedings of the National Academy of Sciences*, vol. 15, no. 3, pp. 168–173. https://doi.org/10.1073/pnas.15.3.168

Hume, D., 1989, *Dialogues concerning natural religion*, Prometheus Books, Buffalo, pp. 61–66.

Kant, I 1963, *Critique of pure reason*, trans. NK Smith, Macmillan, London.

Kok, RA, Taylor, JA & Bradley, WL 1988, ‘A statistical examination of self-ordering of amino acids in proteins’, *Origins of Life and Evolution of the Biosphere*, vol. 18, pp. 135–142. https://doi.org/10.1007/BF01808787

Kragh, H 1993, ‘The steady state theory’, in NS Hetherington (ed.), *Cosmology: historical*, *literary*, *philosophical*, *religious*, *and scientific perspectives*, Garland, New York, pp. 391–404.

Kragh, H 1996, *Cosmology and controversy*, Princeton University Press, Princeton, NJ, pp. 179–187.

Kuppers, B 1987, ‘On the prior probability of the existence of life’, in L Kruger, G Gigerenzer & MS Morgan (eds.), *The probabilistic revolution*, MIT Press, Cambridge, pp. 355–372.

Lazcano, A 2010, ‘Historical development of origins research’, *Cold Spring Harbor Perspectives in Biology*, vol. 2, no. 11, a002089. https://doi.org/10.1101/cshperspect.a002089

Lehrer, K 1987, ‘Beyond impressions and ideas: Hume vs. reid’, *The Monist*, vol. 70, no. 4, pp. 383–397. https://doi.org/10.5840/monist198770432

Linde, A 2002, ‘Inflationary theory versus ekpyrotic/cyclic scenario’, *arXiv* preprint hep-th/0205259.

Lipton, P 1991, *Inference to the best explanation*, Routledge, London. pp. 1–8, 56–74, 92–96.

Longley, C 1989, ‘Focusing on theism’, *London Times*, 21 January, p. 10.

Lorentz, HA, Einstein, A, Minkowski, H & Weyl, H 1923, *The principle of relativity*, pp. 109–164, Methuen and Co., London.

Luminet, J 2007, ‘The rise of Big Bang models, from myth to theory and observations’, *arXiv*: 0704.3579 [astro-ph] – viewed n.d., <https://arxiv.org/abs/0704.3579>

Luminet, J 2016, ‘Creation, chaos, time: from myth to modern cosmology’, *Cosmology*, vol. 24, pp. 501–515.

Lyell, C 1830–1833, *Principles of Geology: being an attempt to explain the former changes of the earth’s surface*, *by reference to causes now in operation*, vol. 1–3, John Murray, London.

MacKay, DM 1974, *The clock work image*, InterVarsity Press, Downers Grove, IL, pp. 51–55.

Manson, NA (ed.) 2003, *God and design: the teleological argument and modern science*, Routledge, New York, pp. 1–4.

McMullin, E 1981, ‘How should cosmology relate to theology?’, in AR Peacocke (ed.), *The sciences and theology in the twentieth century*, University of Notre Dame Press, Notre Dame, pp. 17–57.

Meyer, SC 1990, ‘Of clues and causes: a methodological interpretation of origin of life studies’, PhD dissertation, Cambridge University, Cambridge.

Meyer, SC 1994, ‘The methodological equivalence of design and descent: can there be a scientific theory of creation?’, in JP Moreland (ed.), *The creation hypothesis*, InterVarsity Press, Downers Grove, IL, pp. 67–112, 300–312.

Meyer, SC 1999a, ‘Teleological evolution: the difference it doesn’t make’, in R Clements (ed.), *Darwinism defeated*, Regent Publishing, Vancouver, pp. 89–100.

Meyer, SC 1999b, ‘The return of the God hypothesis’, *Journal of Interdisciplinary Studies*, vol. XI, pp. 1–38.

Meyer, SC 2000a, ‘Qualified agreement: modern science and the return of the God hypothesis’, in R Carlson (ed.), *Science and Christianity: four views*, InterVarsity Press, Downers Grove, pp. 129–175.

Meyer, SC 2000b, ‘The demarcation of science and religion’, in G Ferngren, E Larson & DW Amundsen (eds.), *The history of science and religion in the Western tradition: an encyclopedia*, Garland, New York, pp. 17–23.

Meyer, SC 1999, ‘The restoration of philosophy’, *Journal of Interdisciplinary Studies*, vol. 11, no. 1/2, pp. 1–38. https://doi.org/10.5840/jis1999111/21

Meyer, SC 2006, *A scientific history, and philosophical defense of the theory of intelligent design: current landscape*, viewed 27 April 2022, <https://www.discovery.org/a/6641>

Meyer, SC 2008, 'A scientific history and philosophical defense of the theory of intelligent design', in *Religion – Staat – Gesellschaft: Journal for the Study of Beliefs and Worldviews*, viewed 19 April 2022, <https://www.discovery.org/a/7471/>

Meyer, SC 2010, *Signature in the cell: DNA and the evidence for intelligent design*, HarperOne, San Francisco.

Meyer, SC 2014, *Darwin's doubt: the explosive origin of animal life and the case for intelligent design*, HarperOne, San Francisco.

Meyer, SC 2017, 'The difference it doesn't make: why the "front-end loaded" concept of design fails to explain the origin of biological information', in JP Moreland, SC Meyer, C Shaw & W Grudem (eds.), *Theistic evolution: a scientific, philosophical and theological critique*, Crossway, Wheaton, pp. 209–228.

Meyer, SC 2021, *Return of the God hypothesis: three scientific discoveries that reveal the mind behind the universe*, HarperOne, San Francisco.

Miller, K & Levine, JP 1993, *Biology*, Prentice Hall, Englewood Cliffs.

Mora, PT 1965, 'The Folly of probability', in SW Fox (ed.), *The origins of prebiological systems and of their molecular matrices*, Academic Press, New York, pp. 311–312.

Moreland, JP 1987, *Scaling the secular city*, Baker Book House, Grand Rapids, pp. 42–43.

Morowitz, HJ 1968, *Energy flow in biology*, Academic Press, New York, pp. 5–12.

Newton, I 1959–1977, *The correspondence of Isaac Newton*, eds. HW Turnbull, JF Scott, AR Hall & L Tilling, 7 vols., Cambridge University Press, Cambridge.

Newton, I 1960, *Mathematical principles of natural philosophy*, General Scholium, UC Press, Berkeley.

Newton, I 1713, *Mathematical principles of natural philosophy*, viewed n.d., <https://isaac-newton.org/general-scholium/>

Newton, I 1728, *The chronology of ancient kingdoms amended*, Posthumous, London.

Nussbaumer, H 2014, 'Einstein's conversion from his static to an expanding universe', *European Physics Journal – History*, vol. 39, pp. 37–62. https://doi.org/10.1140/epjh/e2013-40037-6

Pattee, HH 1970, 'The problem of biological hierarchy', in CH Waddington (ed.), *Towards a theoretical biology*, 3 vols., Edinburgh University Press, Edinburgh.

Paine, T 1925, *The life and works of Thomas Paine, vol. 8: the age of reason*, Thomas Paine National Historical Association, New Rochelle.

Paley, W 1802, *Natural theology or evidences of the existence and attributes of the deity*, John Morgan, Philadelphia.

Pearcy, NR & Thaxton, CB 1994, *The soul of science*, Crossway, Wheaton, pp. 17–42, 43–56.

Peirce, CS 1931, *Collected papers*, eds. C Hartshorne & P Weiss, 6 vols., Harvard University Press, Cambridge.

Penrose, R 2004, *The road to reality: a complete guide to the laws of the universe*, Vintage, New York.

Penzias, A & Wilson, R 1965, 'A measurement of excess antenna temperature at 4080 Mc/s', *Astrophysical Journal*, vol. 142, no. 1, pp. 419–421. https://doi.org/10.1086/148307

Peterson, M 1989, *Reason and religious belief*, Oxford University Press, Oxford, pp. 196–216.

Plantinga, A 1974, *The nature of necessity*, Oxford University Press on Demand, Oxford.

Polanyi, M 1968, 'Life's irreducible structure', *Science*, vol. 160, pp. 1308–1312. https://doi.org/10.1126/science.160.3834.1308

Provine, W 1988, 'Evolution and the foundation of ethics', *MBL Science*, vol. 3, no. 1, pp. 25–29.

Quastler, H 1964, *The emergence of biological organization*, Yale University Press, New Haven.

Sagan, C 1980, *Cosmos*, Random House, New York.

Schopf, JW, Kitajima, K, Spicuzza, MJ, Kudryavtsev, AB & Valley, JW 2018, 'SIMS analyses of the oldest known assemblage of microfossils document their Taxon-correlated carbon isotope compositions', *Proceedings of the National Academy of Sciences of the United States of America*, vol. 115, no. 1, pp. 53–58. https://doi.org/10.1073/pnas.1718063115

Scriven, M 1959, 'Explanation and prediction in evolutionary theory', *Science*, vol. 130, pp. 477–482. https://doi.org/10.1126/science.130.3374.477

Shannon, CE 1948, 'A mathematical theory of communication', *Bell System Technical Journal*, vol. 27, no. 3, pp. 379–423. https://doi.org/10.1002/j.1538-7305.1948.tb01338.x

Shapiro, R 1986, *Origins*, New York, Summit Books, pp. 117–131.

Simpson, GG 1967, *The meaning of evolution*, Harvard University Press, Cambridge.

Singh, S 2005, *Big Bang: the origin of the universe*, HarperCollins, New York.

Spitzer, RJ 2010, *New proofs for the existence of God: contributions of contemporary physics and philosophy*, Eerdmans, Grand Rapids.

Sober, E 1993, *Philosophy of biology*, Westview Press, San Francisco.

Swinburne, R 1979, *The existence of God*, Clarendon Press, Oxford, pp. 116–132.

Swinburne, R 2004, *The existence of God*, 2nd edn, Clarendon Press, Oxford.

Thaxton, C, Bradley, W & Olson, RL 1984, *The mystery of life's origin*, Philosophical Library, New York, pp. 113–166.

Thayer, HS (ed.) 2012, *Newton's philosophy of nature: selections from his writings*, with introduction by J.H. Randall, Dover Publications, Mineola, pp. 185–186.

Van Till, H 1986, *The fourth day*, William. B. Eerdmans, Grand Rapids, MI, pp. 208–215.

Van Till, H, Young, D & Menninga, C 1988, *Science held hostage*, InterVarsity Press, Downers Grove, pp. 39–43, 127–168.

Von Weizsacker, CF 1964, *The relevance of science*, Harper and Row, New York.

White, AD 1986, *History of the warfare of science with theology in Christendom*, D. Appleton and Company, New York.

Whitehead, A 1926, *Science and the modern world*, *Macmillan*, New York.

WMAP Science Team 2011, *Cosmology: the study of the universe*, NASA's Wilkinson Microwave Anisotropy Probe, viewed 03 May 2022, <http://map.gsfc.nasa.gov/universe/WMAP_Universe.pdf>

Yockey, HP 1981, 'Self organization origin of life scenarios and information theory', *Journal of Theoretical Biology*, vol. 91, pp. 13–31. https://doi.org/10.1016/0022-5193(81)90370-2

Yockey, HP 1992, *Information theory and molecular biology*, vol. 81, Cambridge University Press, Cambridge.

Chapter 3

Abt, HA 2011, 'The age of the local interstellar bubble', *Astronomical Journal*, vol. 141, no. 5, a165. https://doi.org/10.1088/0004-6256/141/5/165

Ahbel-Rappe, S & Kamtekar, R (eds.) 2009, *A companion to Socrates*, John Wiley & Sons, New York.

Aiola, S, Calabrese, E, Maurin, L, Naess, S, Schmitt, BL, Abitbol, MH, et al. 2020, 'The Atacama cosmology telescope: DR4 maps and cosmological parameters', *Journal of Cosmology and Astroparticle Physics*, vol. 2020, a47.

Alves, MIR, Boulanger, F, Ferrière, K & Montier, L 2018, 'The local bubble: a magnetic veil to our galaxy', *Astronomy & Astrophysics*, vol. 611, aL5. https://doi.org/10.1051/0004-6361/201832637

Ateş, AK, Kilinç, CB & İbanoğlu, C 2013, 'On the M–σ relationship and SMBH mass estimates of selected nearby galaxies', *International Journal of Astronomy and Astrophysics*, vol. 3, no. 3, pp. 1–9. https://doi.org/10.4236/ijaa.2013.33A001

Barros, DA & Lépine, JRD 2014, 'A minimum of stellar density at the corotation radius of the Milky Way spiral pattern', in MS Seigar & P Treuthardt (eds.), *Structure and dynamics of disk galaxies*, *Astronomical Society of the Pacific Conference Series*, vol. 480, Morrilton, Arkansas, 12–16 August 2013, pp. 23–29.

Barrow, JD 2002, *The constants of nature: from alpha to omega – the numbers that encode the deepest secrets of the universe*, Pantheon Books, New York.

Beaton, RL, Majewski, SR, Guhathakurta, P, Skrutskie, MF, Cutri, RM, Good, J, Patterson, RJ, Athanassoula, E & Bureau, M 2007, 'Unveiling the boxy bulge and bar of the Andromeda spiral galaxy', *Astrophysical Journal*, vol. 658, no. 2, pp. 91–94. https://doi.org/10.1086/514333

Bender, R, Kormendy, J, Bower, G, Green, R, Thomas, J, Danks, AC, Theodore, G, Hutchings, JB, Joseph, CL, Kaiser, ME, Lauer, TR, Nelson, CH, Richstone, D, Weistrop, D & Woodgate, B 2005, '*HST* STIS spectroscopy of the triple nucleus of M31: two nested disks in Keplerian rotation around a supermassive black hole', *Astrophysical Journal*, vol. 631, no. 1, pp. 280–300. https://doi.org/10.1086/432434

Berrier, JC, Davis, BL, Kennefick, D, Kennefick, JD, Seigar, MS, Barrows, RS, Hartley, M, Shields, D, Bentz, MC & Lacy, CHS 2013, 'Further evidence for a supermassive black hole mass-pitch angle relation', *Astrophysical Journal*, vol. 769, no. 2, a132. DOI 10.1088/0004-637X/769/2/132

Breitschwerdt, D, Feige, J, Schulreich, MM, De Avillez, MA, Dettbarn, C & Fuchs, B 2016, 'The locations of recent supernovae near the Sun from modelling ^{60}Fe transport', *Nature*, vol. 532, no. 7597, pp. 73–76. https://doi.org/10.1038/nature17424

Block, DL, Bournaud, F, Combes, F, Groess, R, Barmby, P, Ashby, MLN, Fazio, GG, Pahre, MA & Willner, SP 2006, 'An almost head-on collision as the origin of two off-centre rings in the Andromeda galaxy', *Nature*, vol. 443, no. 7113, pp. 832–834. https://doi.org/10.1038/nature05184

Corrales, L, Mon, B, Haggard, D, Baganoff, FK, Garmire, G, Degenaar, N & Reynolds, M 2017, 'Perils at the heart of the Milky Way: systematic effects for studying low-luminosity accretion onto Sgr A*', *American Astronomical Society*, HEAD Meeting #16 in Sun Valley, Idaho, 20–24 August 2017.

Crnojević, D, Grebel, EK, Ferguson, AMN, Cole, AA, Koch, A, Rejkuba, M, De Costa, D, Jerjen, H & Irwin, MJ 2012, 'How unique is the local group? A comparison to the nearby Centaurus A group', in W Aoki & K Tenmondai (eds.), *Galactic archaeology: near-field cosmology and the formation of the Milky Way*, *Astronomical Society of the Pacific Conference Series*, vol. 458, Shuzenji, Japan, 16–20 May 2011, p. 321.

Deason, AJ, Fattahi, A, Frenk, CS, Grand, RJJ, Oman, KA, Garrison-Kimmel, S, Simpson, CM & Navarro, JF 2020, 'The edge of the galaxy', *Monthly Notices of the Royal Astronomical Society*, vol. 496, no. 3, a1711. https://doi.org/10.1093/mnras/staa1711

Deason, AJ, Wetzel, AR, Garrison-Kimmel, S & Belokurov, V 2015, 'Satellites of LMC-mass dwarfs: close friendships ruined by Milky Way mass haloes', *Monthly Notices of the Royal Astronomical Society*, vol. 453, no. 4, pp. 3568–3574. https://doi.org/10.1093/mnras/stv1939

De Nicola, S, Marconi, A & Longo, G 2019, 'The fundamental relation between supermassive black holes and their host galaxies', *Monthly Notices of the Royal Astronomical Society*, vol. 490, no. 1, pp. 600–612. https://doi.org/10.1093/mnras/stz2472

Dias, WS, Monteiro, H, Lépine, JRD & Barros, DA 2019, 'The spiral pattern rotation speed of the Galaxy and the corotation radius with Gaia DR2', *Monthly Notices of the Royal Astronomical Society*, vol. 486, no. 4, pp. 5726–5736. http://dx.doi.org/10.1093/mnras/stz1196

Do, T, Wright, SA, Barth, AJ, Barton, EJ, Simard, L, Larkin, JE, Moore, AM, Wang, L & Ellerbroek, B 2014, 'Prospects for measuring supermassive black hole masses with future extremely large telescopes', *Astronomical Journal*, vol. 147, no. 4, a93. https://doi.org/10.1088/0004-6256/147/4/93

Dobbs, CL & Bonnell, IA 2006, 'Spurs and feathering in spiral galaxies', *Monthly Notices of the Royal Astronomical Society*, vol. 367, no. 3, pp. 873–878. https://doi.org/10.1111/j.1365-2966.2006.10146.x

Dressler, A, Oemler, A, Jr, Sparks, WB & Lucas, RA 1994, 'New images of the distant, rich cluster CL 0939+4713 with WFPC2', *Astrophysical Journal*, vol. 435, pp. 23–26. https://doi.org/10.1086/187585

Drlica-Wagner, A, Bechtol, K, Mau, S, McNanna, M, Nadler, EO, Pace, AB, Li, TS, Pieres, A, Rozo, E, Simon, JD, Walker, AR, Wechsler, RH, Abbott, TMC, Allam, S, Annis, J, Bertin, E, Brooks, D, Burke, DL, Rosell, AC, Carrasco Kind, M, Carretero, J, Costanzi, M, Da Costa, LN, De Vicente, J, Desai, S, Diehl, HT, Doel, P, Eifler, TF, Everett, S, Flaugher, B, Frieman, J, García-Bellido, J, Gaztanaga, E, Gruen, D, Gruendl, RA, Gschwend, J, Gutierrez, G, Honscheid, K, James, DJ, Krause, E, Kuehn, K, Kuropatkin, N, Lahav, O, Maia, MAG, Marshall, JL, Melchior, P, Menanteau, F, Miquel, R, Palmese, A, Plazas, AA, Sanchez, E, Scarpine, V, Schubnell, M, Serrano, S, Sevilla-Noarbe, I, Smith, M, Suchyta, E, Tarle, G & DES Collaboration 2020, 'Milky Way satellite census. I. The observational selection function for Milky Way satellites in DES Y3 and Pan-STARRS DR1', *Astrophysical Journal*, vol. 893, no. 1, a47. https://doi.org/10.3847/1538-4357/ab7eb

Erkal, D, Boubert, D, Gualandris, A, Evans, NW & Antonini, F 2019, 'A hypervelocity star with a Magellanic Origin', *Monthly Notices of the Royal Astronomical Society*, vol. 483, no. 2, pp. 2007–2013. https://doi.org/10.1093/mnras/sty2674

Filistov, EA 2012, 'Polygonal structure of spiral galaxies', *Astronomy Reports*, vol. 56, no. 1, pp. 9–15. https://doi.org/10.1134/S1063772912010027

Fuchs, B, Breitschwerdt, D, De Avillez, MA, Dettbarn, C & Flynn, C 2006, 'The search for the origin of the local bubble redivivus', *Monthly Notices of the Royal Astronomical Society*, vol. 373, no. 3, pp. 993–1003. https://doi.org/10.1111/j.1365-2966.2006.11044.x

Gebauer, I, Weinreuter, M, Kunz, S & Gaggero, D 2015, 'The local bubble as a cosmic-ray isotropizer', *ASTRA Proceedings*, vol. 2, pp. 1–3. https://doi.org/10.5194/ap-2-1-2015

Gebhardt, K, Lauer, TR, Kormendy, J, Pinkney, J, Bower, GA, Green, R, Gull, T, Hutchings, JB, Kaiser, ME & Nelson, CH 2001, 'M33: a galaxy with no supermassive black hole', *Astronomical Journal*, vol. 122, no. 5, pp. 2469–2476. https://doi.org/10.1086/323481

González-Lópezlira, RA, Lomelí-Núñez, L, Álamo-Martínez, K, Órdenes-Briceño, Y, Loinard, L, Georgiev, IY, Munoz, RP, Puzia, TH, Bruzual, A, Gustavo & Stephen, G 2017, 'The relation between globular cluster systems and supermassive black holes in spiral galaxies: the case study of NGC 4258', *Astrophysical Journal*, vol. 835, no. 2, a184. https://doi.org/10.3847/1538-4357/835/2/184

GRAVITY Collaboration 2019, 'A geometric distance measurement to the Galactic center black hole with 0.3% uncertainty', *Astronomy & Astrophysics*, vol. 625, a10. https://doi.org/10.1051/0004-6361/201935656

Gualandris, A & Portegies Zwart, S 2007, 'A hypervelocity star from the Large Magellanic Cloud', *Monthly Notices of the Royal Astronomical Society: Letters*, vol. 376, no. 1, pp. 29–33. https://doi.org/10.1111/j.1745-3933.2007.00280.x

Gültekin, K, Richstone, DO, Gebhardt, K, Lauer, TR, Tremaine, S, Aller, MC, Bender, R, Dressler, A, Faber, SM, Filippenko, AV, Green, R, Ho, LC, Kormendy, J, Magorrian, J, Pinkney, J & Siopis, C 2009, 'The M–σ and M-L relations in galactic bulges, and determinations of their intrinsic scatter', *Astrophysical Journal*, vol. 698, no. 1, pp. 198–221. https://doi.org/10.1088/0004-637X/698/1/198

Hammer, F, Puech, M, Chemin, L, Flores, H & Lehnert, MD 2007, 'The Milky Way, an exceptionally quiet galaxy: implications for the formation of spiral galaxies', *Astrophysical Journal*, vol. 662, no. 1, pp. 322–334. https://doi.org/10.1086/516727

Harris, GLH, Poole, GB & Harris, WE 2014, 'Globular clusters and supermassive black holes in galaxies: further analysis and a larger sample', *Monthly Notices of the Royal Astronomical Society*, vol. 438, no. 3, pp. 2117–2130. https://doi.org/10.1093/mnras/stt2337

Hoyle, F 1952, *The nature of the universe*, 2nd edn rev, Basil Blackwell, Oxford.

Hoyle, F 1965, *Galaxies*, *nuclei, and quasars*, Harper and Row, New York.

Hoyle, F 1975, *Astronomy and cosmology: a modern course*, W.H. Freeman, San Francisco.

Hoyle, F 1982, 'The universe: past and present reflections', *Annual Review of Astronomy and Astrophysics*, vol. 20, pp. 1–36. https://doi.org/10.1146/annurev.aa.20.090182.000245

Indu, G & Subramaniam, A 2015, 'H I kinematics of the Large Magellanic Cloud revisited: evidence of possible infall and outflow', *Astronomy & Astrophysics*, vol. 573, a136. https://doi.org/10.1051/0004-6361/201321133

Karachentsev, ID 2005, ‘The local group and other neighboring galaxy groups’, *Astronomical Journal*, vol. 129, no. 1, pp. 178–188. https://doi.org/10.1086/426368

Kim, W-T & Ostriker, EC 2006, ‘Formation of spiral-arm spurs and bound clouds in vertically stratified galactic gas disks’, *Astrophysical Journal*, vol. 646, no. 1, pp. 213–231. https://doi.org/10.1086/504677

Kormendy, J & Ho, LC 2013, ‘Coevolution (or not) of supermassive black holes and host galaxies’, *Annual Review of Astronomy and Astrophysics*, vol. 51, no. 1, pp. 511–653. https://doi.org/10.1146/annurev-astro-082708-101811

Laporte, CFP, Gómez, FA, Besla, G, Johnston, KV & Garavito-Camargo, N 2018, ‘Response of the Milky Way’s disc to the Large Magellanic Cloud in a first infall scenario’, *Monthly Notices of the Royal Astronomical Society*, vol. 473, no. 1, pp. 1218–1230. https://doi.org/10.1093/mnras/stx2146

Levine, ES, Blitz, L & Heiles, C 2006, ‘The spiral structure of the outer Milky Way in hydrogen’, *Science*, vol. 312, no. 5781, pp. 1773–1777. https://doi.org/10.1126/science.1128455

Li, Z, Garcia, MR, Forman, WR, Jones, C, Kraft, RP, Lal, DV, Murray, SS & Wang, QD 2011, ‘The murmur of the hidden monster: *Chandra’s* decadal view of the supermassive black hole in M31’, *Astrophysical Journal Letters*, vol. 728, no. 1, aL10. https://doi.org/10.1088/2041-8205/728/1/L10

Loewenstein, M, Hayashida, K, Toneri, T & Davis, DS 1998, ‘On the nature of the x-ray emission from M32’, *Astrophysical Journal*, vol. 497, no. 2, pp. 681–688. https://doi.org/10.1086/305504

López-Corredoira, M, Prieto, CA, Garzón, F, Wang, H, Liu, C & Deng, L 2018, ‘Disk stars in the Milky Way detected beyond 25 Kpc from its center’, *Astronomy & Astrophysics*, vol. 612, aL8. https://doi.org/10.1051/0004-6361/201832880

Lucchini, S, D’Onghia, E, Fox, AJ, Bustard, C, Bland-Hawthorn, J & Zweibel, E 2020, ‘The Magellanic corona as the key to the formation of the Magellanic Stream’, *Nature*, vol. 585, no. 7824, pp. 203–206. https://doi.org/10.1038/s41586-020-2663-4

Marconi, A & Hunt, LK 2003, ‘The relation between black hole mass, bulge mass, and near-infrared luminosity’, *Astrophysical Journal*, vol. 589, no. 1, pp. 21–24. https://doi.org/10.1086/375804

Marsden, C, Shankar, F, Ginolfi, M & Zubovas, K 2020, ‘The case for the fundamental M_{BH}-σ relation’, *Frontiers in Physics*, vol. 8, a61. https://doi.org/10.3389/fphy.2020.00061

McConnachie, AW 2012, ‘The observed properties of dwarf galaxies in and around the Local Group’, *Astronomical Journal*, vol. 144, no. 1, a4. https://doi.org/10.1088/0004-6256/144/1/4

McConnachie, AW, Higgs, CR, Thomas, GF, Venn, KA, Côté, P, Battaglia, G & Lewis, GF 2021, ‘Solo dwarfs – III. Exploring the orbital origins of isolated local group galaxies with *Gaia* data release 2’, *Monthly Notices of the Royal Astronomical Society*, vol. 501, no. 2, pp. 2363–2377. https://doi.org/10.1093/mnras/staa3740

McConnachie, AW, Ibata, R, Martin, N, Ferguson, AMN, Collins, M, Gwyn, S, Irwin, M, Lewis, GF, Mackey, AD, Davidge, T, Arias, V, Conn, A, Côté, P, Crnojević, D, Huxor, A, Peñarrubia, J, Spengler, C, Tanvir, N, Valls-Gabaud, D, Babul, A, Barmby, P, Bate, NF, Bernard, E, Chapman, S, Dotter, A, Harris, W, McMonigal, B, Navarro, J, Puzia, TH, Rich, RM, Thomas, G & Widrow, LM 2018, ‘The large-scale structure of the halo of the Andromeda Galaxy. II. Hierarchical structure in the Pan-Andromeda Archaeological Survey’, *Astrophysical Journal*, vol. 868, no. 1, a55. https://doi.org/10.3847/1538-4357/aae8e7

McMillan, PJ 2017, ‘The mass distribution and gravitational potential of the Milky Way’, *Monthly Notices of the Royal Astronomical Society*, vol. 465, no. 1, pp. 76–94. https://doi.org/10.1093/mnras/stw2759

Merritt, D, Ferrarese, L & Joseph, CL 2001, ‘No supermassive black hole in M33?’, *Science*, vol. 293, no. 5532, pp. 1116–1118. https://doi.org/10.1126/science.1063896

Miki, Y, Mori, M, Kawaguchi, T & Saito, Y 2014, ‘Hunting a wandering supermassive black hole in the M31 halo hermitage’, *Astrophysical Journal*, vol. 783, no. 2, a87. https://doi.org/10.1088/0004-637X/783/2/87

Oberhummer, H, Csótó, A & Schlattl, H 2000, ‘Stellar production rates of carbon and its abundance in the universe’, *Science*, vol. 289, no. 5476, pp. 88–90. https://doi.org/10.1126/science.289.5476.88

Pardy, SA, D'Onghia, E & Fox, AJ 2018, 'Models of tidally induced gas filaments in the Magellanic Stream', *Astrophysical Journal*, vol. 857, no. 2, a101. https://doi.org/10.3847/1538-4357/aab95b

Pelgrims, V, Ferrière, K, Boulanger, F, Lallement, R & Montier, L 2020, 'Modeling the magnetized Local Bubble from dust data', *Astronomy & Astrophysics*, vol. 636, a17. https://doi.org/10.1051/0004-6361/201937157

Peñarrubia, J, Gómez, FA, Besla, G, Erkal, D & Ma, Y-Z 2016, 'A timing constraint on the (total) mass of the Large Magellanic Cloud', *Monthly Notices of the Royal Astronomical Society: Letters*, vol. 456, no. 1, pp. 54–58. https://doi.org/10.1093/mnrasl/slv160

Piffl, T, Binney, J, McMillan, PJ, Steinmetz, M, Helmi, A, Wyse, RFG, Bienaymé, O, Bland-Hawthorn, J, Freeman, K, Gibson, B, Gilmore, G, Grebel, EK, Kordopatis, G, Navarro, JF, Parker, Q, Reid, WA, Seabroke, G, Siebert, A, Watson, F & Zwitter, T 2014, 'Constraining the galaxy's dark halo with RAVE stars', *Monthly Notices of the Royal Astronomical Society*, vol. 445, no. 3, pp. 3133–3151. https://doi.org/10.1093/mnras/stu1948

Planck Collaboration 2020, 'Planck 2018 results. VI. Cosmological parameters', *Astronomy & Astrophysics*, vol. 641, aA6. https://doi.org/10.1051/0004-6361/201833910

Plato 1952 *Great books of the Western world*, vol. 7, ed. RM Hutchins, trans. B Jowett & J Harward, Encyclopaedia Britannica, Chicago.

Rees, MJ 1983, 'Large numbers and ratios in astrophysics and cosmology', *Philosophical Transactions of the Royal Society A*, vol. 310, no. 1512, pp. 311–322. https://doi.org/10.1098/rsta.1983.0093

Reid, MJ, Menten, KM, Brunthaler, A, Zheng, XW, Dame, TM, Xu, Y, Li, J, Sakai, N, Wu, Y, Immer, K, Zhang, B, Sanna, A, Moscadelli, L, Rygl, KLJ, Bartkiewicz, A, Hu, B, Quiroga-Nuñez, LH & Van Langevelde, HJ 2019, 'Trigonometric parallaxes of high-mass star-forming regions: our view of the Milky Way', *Astrophysical Journal*, vol. 885, no. 2, a11. https://doi.org/10.3847/1538-4357/ab4a11

Reid, MJ, Menten, KM, Brunthaler, A, Zheng, XW, Dame, TM, Xu, Y, Wu, Y, Zhang, B, Sanna, A, Sato, M, Hachisuka, K, Choi, YK, Immer, K, Moscadelli, L, Rygl, KLJ & Bartkiewicz, A 2014, 'Trigonometric parallaxes of high mass star forming regions: the structure and kinematics of the Milky Way', *Astrophysical Journal*, vol. 783, no. 2, a130. https://doi.org/10.1088/0004-637X/783/2/130

Reid, MJ., Menten, KM, Zheng, XW, Brunthaler, A, Moscadelli, L, Xu, Y, Zhang, B, Sato, M, Honma, M, Hirota, T, Hachisuka, K, Choi, YK, Moellenbrock, GA & Bartkiewicz, A 2009, 'Trigonometric parallaxes of massive star-forming regions. VI. Galactic structure, fundamental parameters, and noncircular motions', *Astrophysical Journal*, vol. 700, no. 1, a137. https://doi.org/10.1088/0004-637X/700/1/137

Rhode, KL 2012, 'Exploring the correlations between globular cluster populations and supermassive black holes in giant galaxies', *Astronomical Journal*, vol. 144, no. 5, a154. https://doi.org/10.1088/0004-6256/144/5/154

Robotham, ASG, Baldry, IK, Bland-Hawthorn, J, Driver, SP, Loveday, J, Norberg, P, Bauer, AE, Bekki, K, Brough, S, Brown, M, Graham, A, Hopkins, AM, Phillipps, S, Power, C, Sansom, A & Staveley-Smith, L 2012, 'Galaxy and mass assembly (GAMA): in search of Milky Way Magellanic Cloud analogues', *Monthly Notices of the Royal Astronomical Society*, vol. 424, no. 2, pp. 1448–1453. https://doi.org/10.1111/j.1365-2966.2012.21332.x

Ross, H 2008, *Why the universe is the way it is*, Baker Books, Grand Rapids.

Ross, H 2016, *Improbable planet: how earth became humanity's home*, Baker Books, Grand Rapids.

Ross, H 2018, *The creator and the cosmos: how the latest scientific discoveries reveal God*, 4th edn, RTB Press, Covina.

Ross, H 2020, *Weathering climate change: a fresh approach*, RTB Press, Covina.

Ross, H 2021, "Does the puddle analogy explain cosmic fine-tuning?" *Today's new reason to believe*, viewed 07 June 2021, <https://reasons.org/explore/blogs/todays-new-reason-to-believe/does-the-puddle-analogy-explain-cosmic-fine-tuning>

Ross, H 2022, *Designed to the core*, RTB Press, Covina.

Sakai, N, Reid, MJ, Menten, KM, Brunthaler, A & Dame, TM 2019, ‘Noncircular motions in the outer Perseus spiral arm’, *Astrophysical Journal*, vol. 876, no. 1, a30. https://doi.org/10.3847/1538-4357/ab12e0

Seigar, MS, Kennefick, D, Kennefick, J & Lacy, CHS 2008, ‘Discovery of a relationship between spiral arm morphology and supermassive black hole mass in disk galaxies’, *Astrophysical Journal*, vol. 678, no. 2, pp. 93–96. https://doi.org/10.1086/588727

Seth, AC, Cappellari, M, Neumayer, N, Caldwell, N, Bastian, N, Olsen, K, Blum, RD, Debattista, VP, McDermid, R, Puzia, T & Stephens, A 2010, ‘The NGC 404 nucleus: star cluster and possible intermediate-mass black hole’, *Astrophysical Journal*, vol. 714, no. 1, pp. 713–731. https://doi.org/10.1088/0004-637X/714/1/713

Shankar, F, Weinberg, DH, Marsden, C, Grylls, PJ, Bernardi, M, Yang, G, Moster, B, Fu, H, Carraro, R, Alexander, DM, Allevato, V, Ananna, TT, Bongiorno, A, Calderone, G, Civano, F, Daddi, E, Delvecchio, I, Duras, F, La Franca, F, Lapi, A, Lu, Y, Menci, N, Mezcua, M, Ricci, F, Rodighiero, G, Sheth, RK, Suh, H, Villforth, C & Zanisi, L 2020, ‘Probing black hole accretion tracks, scaling relations, and radiative efficiencies from stacked x-ray active galactic nuclei’, *Monthly Notices of the Royal Astronomical Society*, vol. 493, no. 1, pp. 1500–1511. https://doi.org/10.1093/mnras/stz3522

Shetty, R & Ostriker, EC 2006, ‘Global modeling of spur formation in spiral galaxies’, *Astrophysical Journal*, vol. 647, no. 2, pp. 997–1017. https://doi.org/10.1086/505594

Sick, J, Courteau, S, Cuillandre, JC, Dalcanton, J, De Jong, R, McDonald, M, Simard, D & Tully, RB 2014, ‘The stellar mass of M31 as inferred by the Andromeda optical & infrared disk survey’, *Proceedings of the International Astronomical Union* 10(311): *Galaxy Masses as Constraints of Formation Models*, vol. 10, no. 311, pp. 82–85. https://doi.org/10.1017/S1743921315003440

Skowron, DM, Skowron, J, Mróz, P, Udalski, A, Pietrukowicz, P, Soszyński, I, Szymański, MK, Poleski, R, Kozłowski, S, Ulaczyk, K, Rybicki, K & Iwanek, P 2019, ‘A three-dimensional map of the milky way using classical Cepheid variable stars’, *Science*, vol. 365, no. 6452, pp. 478–482. https://doi.org/10.1126/science.aau3181

Slavin, JD 2017, ‘Structures in the interstellar medium caused by supernovae: the local bubble’, in A Alsabti & P Murdin (eds.), *Handbook of supernovae*, Springer International Publishing AG, Cham, pp. 2287–2299. https://doi.org/10.1007/978-3-319-21846-5_14

Valluri, M, Ferrarese, L, Merritt, D & Joseph, CL 2005, ‘The low end of the supermassive black hole mass function: constraining the mass of a nuclear black hole in NGC 205 via stellar kinematics’, *Astrophysical Journal*, vol. 628, no. 1, pp. 137–152. https://doi.org/10.1086/430752

Van der Marel, RP, Cretton, N, De Zeeuw, PT & Rix, H-W 1998, ‘Improved evidence for a black hole in M32 from *HST*/FOS spectra. II. Axisymmetric dynamical models’, *Astrophysical Journal*, vol. 493, no. 2, pp. 613–631. https://doi.org/10.1086/305147

Vasiliev, E, Belokurov, V & Erkal, D 2021, ‘Tango for three: Sagittarius, LMC, and the Milky Way’, *Monthly Notices of the Royal Astronomical Society*, vol. 501, no. 2, pp. 2279–2304. https://doi.org/10.1093/mnras/staa3673

Voglis, N, Stavropoulos, I & Kalapotharakos, C 2006, ‘Chaotic motion and spiral structure in self-consistent models of rotating galaxies’, *Monthly Notices of the Royal Astronomical Society*, vol. 372, no. 2, pp. 901–922. https://doi.org/10.1111/j.1365-2966.2006.10914.x

Wilczek, F 2007, ‘Hard-core revelations’, *Nature*, vol. 445, no. 7124, pp. 156–157. https://doi.org/10.1038/445156a

Wu, YW, Sato, M, Reid, MJ, Moscadelli, L, Zhang, B, Xu, Y, Brunthaler, A, Menten, KM, Dame, TM & Zheng, XW 2014, ‘Trigonometric parallaxes of star-forming regions in the Sagittarius spiral arm’, *Astronomy & Astrophysics*, vol. 566, a17. https://doi.org/10.1051/0004-6361/201322765

Yang, G, Brandt, WN, Alexander, DM, Chen, C-TJ, Ni, Q, Vito, F & Zhu, F-F 2019, ‘Evident black hole-bulge coevolution in the distant universe’, *Monthly Notices of the Royal Astronomical Society*, vol. 485, no. 3, pp. 3721–3737. https://doi.org/10.1093/mnras/stz611

Zhang, D, Luo, Y & Kang, X 2019, ‘The effect of the Large Magellanic Cloud on the satellite galaxy population in Milky Way analogous galaxies’, *Monthly Notices of the Royal Astronomical Society*, vol. 486, no. 2, pp. 2440–2448. https://doi.org/10.1093/mnras/stz957

Zinchenko, IA, Berczik, P, Grebel, EK, Pilyugin, LS & Just, A 2015, 'On the influence of minor mergers on the radial abundance gradient in disks of Milky-Way-like galaxies', *Astrophysical Journal*, vol. 806, no. 2, a267. https://doi.org/10.1088/0004-637X/806/2/267

Zubovas, K, Nayakshin, S & Markoff, S 2012, 'Sgr A* flares: tidal disruption of asteroids and planets?', *Monthly Notices of the Royal Astronomical Society*, vol. 421, no. 2, pp. 1315–1324. https://doi.org/10.1111/j.1365-2966.2011.20389.x

Chapter 4

Adams, F & Laughlin, F 1997, 'A dying universe: the long-term fate and evolution of astrophysical objects', *Reviews of Modern Physics*, vol. 69, pp. 337–372. https://doi.org/10.1103/RevModPhys.69.337

Agee, CB 2004, 'Hot metal', *Nature*, vol. 429, pp. 33–35. https://doi.org/10.1038/429033a

Allen, AP, Brown, JH & Gillooly, JF 2002, 'Global biodiversity, biochemical kinetics, and the energetic-equivalence rule', *Science*, vol. 297, no. 5586, pp. 1545–1548. https://doi.org/10.1126/science.1072380

Armitage, PJ 2003, 'A reduced efficiency of terrestrial planet formation following giant planet migration', *Astrophysical Journal*, vol. 582, no. 1, pp. 47–50. https://doi.org/10.1086/346198

Atobe, K & Ida, S 2007, 'Obliquity evolution of extrasolar terrestrial planets', *Icarus*, vol. 188, no. 1, pp. 1–17. https://doi.org/10.1016/j.icarus.2006.11.022

Atobe, K, Ida, S & Ito, T 2004, 'Obliquity variations of terrestrial planets in habitable zones', *Icarus*, vol. 168, no. 2, pp. 223–236. https://doi.org/10.1016/j.icarus.2003.11.017

Ball, P 2008, 'Water as an active constituent in cell biology', *Chemical Review*, vol. 108, no. 1, pp. 74–108. https://doi.org/10.1021/cr068037a

Barrow, JD & Tipler, FJ 1986, *The anthropic cosmological principle*, Oxford University Press, Oxford.

Basu, S, Stuart, FM, Schnabel, C & Klemm, V 2007, 'Galactic-cosmic-ray-produced He-3 in a ferromanganese crust: any supernova Fe-60 excess on earth?', *Physical Review Letters*, vol. 98, a141103. https://doi.org/10.1103/PhysRevLett.98.141103

Beer, ME, King, AR, Livio, M & Pringle, JE 2004, 'How special is the solar system?', *Monthly Notices of the Royal Astronomical Society*, vol. 354, no. 3, pp. 763–768. https://doi.org/10.1111/j.1365-2966.2004.08237.x

Begelman, MC & Rees, MJ 1976, 'Can cosmic clouds cause climatic catastrophes?', *Nature*, vol. 261, pp. 298–299. https://doi.org/10.1038/261298a0

Benitez, N, Maiz-Apellaniz, J & Canelles, M 2002, 'Evidence for nearby supernova explosions', *Physical Review Letters*, vol. 88, a081101. https://doi.org/10.1103/PhysRevLett.88.081101

Berger, A & Loutre, MF 1994, 'Astronomical forcing through geological time', in P De Boer & DG Smith (eds.), *Orbital forcing and cyclic sequences: special publication of the International Association of Sedimentologists*, Blackwell Scientific Publications, Malden, pp. 15–24.

Berner, RA, Petsch, ST, Lake, JA, Beerling, DJ, Popp, BN, Lane, RS, Laws, EA, Westley, MB, Cassar, N, Woodward, FI & Quick, WP 2000, 'Isotope fractionation and atmospheric oxygen: implications for Phanerozoic O_2 evolution', *Science*, vol. 287, no. 5458, pp. 1630–1633. https://doi.org/10.1126/science.287.5458.1630

Bond, G, Kromer, B, Beer, J, Muscheler, R, Evans, MN, Showers, W, Hoffman, S, Lotti-Bond, R, Hajdas, I & Bonani, G 2001, 'Persistent solar influence on north Atlantic climate during the Holocene', *Science*, vol. 294, no. 5549, pp. 2130–2136. https://doi.org/10.1126/science.1065680

Bounama, C, Franck, S & Von Bloh, W 2001, 'The fate of earth's ocean', *Hydrology and Earth System Science*, vol. 5, pp. 569–575. https://doi.org/10.5194/hess-5-569-2001

Brack, A 2002, 'Water, spring of life', in G Horneck & C Baumstark-Khan (eds.), *Astrobiology: the quest for the conditions of life*, Springer-Verlag, Heidelberg, pp. 79–88.

Caldeira, K & Kasting, JF 1992, 'Life span of the biosphere revisited', *Nature*, vol. 360, pp. 721–723. https://doi.org/10.1038/360721a0

Calura, F & Matteucci, F 2004, 'Cosmic metal production and the mean metallicity of the universe', *Monthly Notes of the Royal Astronomical Society*, vol. 350, no. 1, pp. 351–364. https://doi.org/10.1111/j.1365-2966.2004.07648.x

Canup, RM 2004, 'Simulations of a late Lunar-Forming impact', *Icarus*, vol. 168, no. 2, pp. 433–456. https://doi.org/10.1016/j.icarus.2003.09.028

Canup, RM & Ward, WR 2006, 'A common mass scaling for satellite systems of gaseous planets', *Nature*, vol. 441, pp. 834–839. https://doi.org/10.1038/nature04860

Cappellaro, E 2004, 'The evolution of the cosmic SN rate', *Memorie della Società Astronomica Italiana*, vol. 75, pp. 206–213.

Carigi, L, Peimbert, M, Esteban, C & Garcia-Rojas, J 2005, 'Carbon, nitrogen, and oxygen galactic gradients: a solution to the carbon enrichment problem', *Astrophysical Journal*, vol. 623, no. 1, pp. 213–224. https://doi.org/10.1086/428491

Case, GL & Bhattacharya, D 1998, 'A new Σ-*D* relation and its application to the galactic supernova remnant distribution', *Astrophysical Journal*, vol. 504, no. 2, pp. 761–772. https://doi.org/10.1086/306089

Catling, DC, Glein, CR, Zahnle, KJ & McKay, CP 2005, 'Why O_2 is required by complex life on habitable planets and the concept of planetary oxygenation time', *Astrobiology*, vol. 5, no. 3, pp. 415–438. https://doi.org/10.1089/ast.2005.5.415

Chaplin, M 2006, 'Do we underestimate the importance of water in cell biology?', *Nature, Reviews in Molecular Cell Biology*, vol. 7, pp. 861–866. https://doi.org/10.1038/nrm2021

Chiang, EI, Fischer, D & Thommes, E 2002, 'Excitation of orbital eccentricities of extrasolar planets by repeated resonance crossings', *Astrophysical Journal*, vol. 564, pp. 105–109. https://doi.org/10.1086/338961

Clarke, JN 1981, 'Extraterrestrial intelligence and galactic nuclear activity', *Icarus*, vol. 46, no. 1, pp. 94–96. https://doi.org/10.1016/0019-1035(81)90078-6

Clavelli, L & White, RE III 2006, 'Problems in a weakless universe', hep-ph/0609050, viewed n.d., <https://arxiv.org/abs/hep-ph/0609050>

Collins, R 2003, 'Evidence for fine-tuning', in NA Manson (ed.), *God and design*, Routledge, London, pp. 178–199.

Correia, ACM & Laskar, J 2003, 'Long-term evolution of the spin of Venus II. Numerical simulations', *Icarus*, vol. 163, no. 1, pp. 24–45. https://doi.org/10.1016/S0019-1035(03)00043-5

Correia, ACM, Laskar, J & Neron De Surgy, O 2003, 'Long-term evolution of the spin of Venus I. Theory', *Icarus*, vol. 163, no. 1, pp. 1–23. https://doi.org/10.1016/S0019-1035(03)00042-3

Dar, A, Laor, A & Shaviv, NJ 1998, 'Life extinctions by cosmic ray jets', *Physical Review Letters*, vol. 80, pp. 5813–5816. https://doi.org/10.1103/PhysRevLett.80.5813

Dar, A & De Rújula, A 2002, 'The threat to life from Eta Carinae and gamma ray bursts', in A Morselli & P Picozza (eds.), *Astrophysics and gamma ray physics in space*, Frascati Physics Series, XXIV, pp. 513–523.

Davies, RE & Koch, RH 1991, 'All the observed universe has contributed to life', *Philosophical Transactions of the Royal Society B*, vol. 334, no. 1271, pp. 391–403. https://doi.org/10.1098/rstb.1991.0124

Dermer, CD & Holmes, JM 2005, 'Cosmic rays from gamma-ray bursts in the galaxy', *Astrophysical Journal*, vol. 628, no. 1, pp. 21–24. https://doi.org/10.1086/432663

Dias, WS & Lépine, JRD 2005, 'Direct determination of the spiral pattern rotation speed of the galaxy', *Astrophysical Journal*, vol. 629, no. 2, pp. 825–831. https://doi.org/10.1086/431456

Dicke, RH 1961, 'Dirac's cosmology and Mach's principle', *Nature*, vol. 192, pp. 440–441. https://doi.org/10.1038/192440a0

Dragicevich, PM, Blair, DG & Burman, RR 1999, 'Why are supernovae in our galaxy so frequent?', *Monthly Notes of the Royal Astronomical Society*, vol. 302, pp. 693–699. https://doi.org/10.1046/j.1365-8711.1999.02145.x

EPICA Community Members 2004, 'Eight glacial cycles from an Antarctic ice core' *Nature*, vol. 429, pp. 623-628. https://doi.org/10.1038/nature02599

Ferrière, KM 2001, 'The interstellar environment of our galaxy', *Reviews of Modern Physics*, vol. 73, pp. 1031–1066. https://doi.org/10.1103/RevModPhys.73.1031

Fischer, DA & Valenti, J 2005, 'The planet-metallicity correlation', *Astrophysical Journal*, vol. 622, no. 2, a1102. https://doi.org/10.1086/428383

Florinski, V, Zank, GP & Axford, WI 2003, 'The solar system in a dense interstellar cloud: implications for cosmic-ray fluxes at earth and 10Be records', *Geophysical Research Letters*, vol. 30, no. 23, a2206. https://doi.org/10.1029/2003GL017566

Franck, S, Block, A, Von Bloh, W, Bounama, C, Garrido, I & Schellnhuber, H-J 2001, 'Planetary habitability: is earth commonplace in the Milky Way?', *Naturwissenschaften*, vol. 88, pp. 416–426. https://doi.org/10.1007/s001140100257

Garriga, J, Livio, M & Vilenkin, A 2000, 'Cosmological constant and the time of its dominance', *Physical Review D*, vol. 61, a023503. https://doi.org/10.1103/PhysRevD.61.023503

Gaston, KJ 2000, 'Global patterns in biodiversity', *Nature*, vol. 405, pp. 220–227. https://doi.org/10.1038/35012228

Gehrels, N, Laird, CM, Jackman, CH, Cannizo, JK, Mattson, BJ & Chen, W 2003, 'Ozone depletion from nearby supernovae', *Astrophysical Journal*, vol. 585, no. 2, pp. 1169–1176. https://doi.org/10.1086/346127

Genda, H & Abe, Y 2003, 'Survival of a proto-atmosphere through the stage of giant impacts: the mechanical aspects', *Icarus*, vol. 164, no. 1, pp. 149–162. https://doi.org/10.1016/S0019-1035(03)00101-5

Genda, H & Abe, Y 2004, 'Hydrodynamic escape of a proto-atmosphere just after a giant impact', *Lunar Planetary Science*, vol. 35, a1518.

Gershberg, RE, Katsova, MM, Lovkaya, MN, Terebizh, AV & Shakhovskaya, NI 1999, 'Catalogue and bibliography of the UV Ceti-type flare stars and related objects in the solar vicinity', *Astronomy and Astrophysics, Supplement*, vol. 139, no. 3, pp. 555–558. https://doi.org/10.1051/aas:1999407

Goldreich, P & Sari, R 2003, 'Eccentricity evolution for planets in gaseous disks', *Astrophysical Journal*, vol. 585 no. 2, pp. 1024–1037. https://doi.org/10.1086/346202

Gonzalez, G 1999, 'Are stars with planets anomalous?', *Monthly Notes of the Royal Astronomical Society*, vol. 308, no. 2, pp. 447–458. https://doi.org/10.1046/j.1365-8711.1999.02717.x

Gonzalez, G 2005, 'Habitable zones in the universe', *Origins of Life and Evolution of Biospheres*, vol. 35, pp. 555–606. https://doi.org/10.1007/s11084-005-5010-8

Gonzalez, G 2006, 'The chemical compositions of stars with planets: a review', *Publications of the Astronomical Society of the Pacific*, vol. 118, pp. 1494–1505. https://doi.org/10.1086/509792

Gonzalez, G 2014, 'Habitable zones and fine-tuning', in B Gordon & W Dembski (eds.), *The nature of nature: Examining the role of naturalism in science*, Open Road Media, New York, pp. 602–638.

Gonzalez, G, Brownlee, D & Ward, P 2001a, 'The galactic habitable zone: galactic chemical evolution', *Icarus*, vol. 152, pp. 185–200. https://doi.org/10.1006/icar.2001.6617

Gonzalez, G, Brownlee, D & Ward, P 2001b, 'The galactic habitable zone', *Scientific American*, vol. 285, pp. 60–67. https://doi.org/10.1038/scientificamerican1001-60

Griebmeier, J-M, Stadelmann, A, Motschmann, U, Belisheva, NK, Lammer, H & Biernat, HK 2005, 'Cosmic ray impact on Extrasolar earth-like planets in close-in habitable zones', *Astrobiology*, vol. 5, no. 5, pp. 587–603. https://doi.org/10.1089/ast.2005.5.587

Gordon, B & Dembski, W (eds.) 2014, *The nature of nature: examining the role of naturalism in science*, ISI Books, Wilmington, DE.

Güdel, M 2003, 'The sun in time: from PMS to main sequence', in J Arnaud & N Maunier (eds.), *Magnetism and activity of the sun and stars*, proceedings of the conference, Toulouse, France, 17–21 September 2002, pp. 339–349.

Gursky, H & Schwartz, DA 1977, 'Extragalactic X-ray sources', *Annual Review of Astronomy and Astrophysics*, vol. 15, pp. 541–568. https://doi.org/10.1146/annurev.aa.15.090177.002545

Hammer, F, Flores, H, Elbaz, D, Zheng, XZ, Liang, YC & Cesarsky, C 2005, 'Did most present-day spirals form during the last 8 Gyrs?: a formation history with violent episodes revealed by panchromatic observations', *Astronomy and Astrophysics*, vol. 430, no. 1, pp. 115–128. https://doi.org/10.1051/0004-6361:20041471

Harnik, R, Kribs, GD & Perez, G 2006, 'A universe without weak interactions', *Physical Review D*, vol. 74, a035006. https://doi.org/10.1103/PhysRevD.74.035006

Hart, MH 1982, 'The effect of a planet's size on the evolution of its atmosphere', in PF Gott & PS Riherd (eds.), *Southwest Regional conference for astronomy and astrophysics*, held 23 May, 1981 in Albuquerque, New Mexico, vol. 7, pp. 111–126.

Hartman, RC, Bertsch, DL, Bloom, SD, Chen, AW, Deines-Jone, P, Esposito, JA, Fichtel, CE, Friedlander, DP, Hunter, SD, McDonald, LM, Sreekumar, P, Thompson, DJ, Jones, BB, Lin, YC, Michelson, PF, Nolan, PL, Tompkins, WF, Kanbach, G, Mayer-Hasselwander, HA, Mücke, A, Pohl, M, Reimer, O, Kniffen, DA, Schneid, EJ, Von Montigny, C, Mukherjee, R & Dingus, BL 1999, 'The third EGRET catalog of high-energy gamma-ray sources', *Astrophysical Journal*, vol. 123, no. 1, pp. 79–202. https://doi.org/10.1086/313231

Hauck, SA & Phillips, RJ 2002, 'Thermal and crustal evolution of Mars', *Journal of Geophysical Research*, vol. 107, no. E7, a1801. https://doi.org/10.1029/2001JE001801

Heavens, A, Panter, B, Jimenez, R & Dunlop, J 2004, 'The star-formation history of the universe from the stellar populations of nearby galaxies', *Nature*, vol. 428, pp. 625–627. https://doi.org/10.1038/nature02474

Heisler, J & Tremaine, S 1986, 'Influence of the galactic tidal field on the Oort cloud', *Icarus*, vol. 65, no. 1, pp. 13–26. https://doi.org/10.1016/0019-1035(86)90060-6

Hoyle, F 1948, 'A new model for the expanding universe', *Monthly Notes of the Royal Astronomical Society*, vol. 108, no. 5, pp. 372–382. https://doi.org/10.1093/mnras/108.5.372

Hut, P & Tremaine, S 1985, 'Have interstellar clouds disrupted the Oort Comet cloud?', *Astronomical Journal*, vol. 90, pp. 1548–1557. https://doi.org/10.1086/113868

Ida, S & Lin, DNC 2004, 'Toward a deterministic model of planetary formation. II. The formation and retention of gas giant planets around stars with a range of metallicities', *Astrophysical Journal*, vol. 616, no. 1, pp. 567–572. https://doi.org/10.1086/424830

Ida, S & Lin, DNC 2005, 'Dependence of exoplanets on host stars' metallicity and mass', *Progress in Theoretical Physics Supplement*, vol. 158, pp. 68–85. https://doi.org/10.1143/PTPS.158.68

Jackman, CH, Fleming, EL & Vitt, FM 2000, 'Influence of extremely large solar proton events in a changing stratosphere', *Journal of Geophysical Research*, vol. 105, no. D9, pp. 11659–11670. https://doi.org/10.1029/2000JD900010

Jakosky, BM & Phillips, RJ 2001, '"Mars" volatile and climate history', *Nature*, vol. 412, pp. 237–244. https://doi.org/10.1038/35084184

Johnson, JA, Butler, RP, Marcy, GW, Fischer, DA, Vogt, SS, Wright, JT & Peek, KMG 2007, 'A new planet around an M Dwarf: revealing a correlation between exoplanets and stellar mass', *Astrophysical Journal*, vol. 670, no. 1, pp. 833–840. https://doi.org/10.1086/521720

Kasting, JF, Whitmire, DP & Reynolds, RT 1993, 'Habitable zones around main sequence stars', *Icarus*, vol. 101, no. 1, pp. 108–128. https://doi.org/10.1006/icar.1993.1010

Kirkby, J 2007, 'Cosmic rays and climate', *Survey of Geophysics*, vol. 28, pp. 333–375. https://doi.org/10.1007/s10712-008-9030-6

Knauth, LP 2005, 'Temperature and salinity history of the Precambrian Ocean: implications for the course of microbial evolution', *Palaeogeography, Palaeoclimatology, and Palaeoecology*, vol. 219, no. 1–2, pp. 53–69. https://doi.org/10.1016/j.palaeo.2004.10.014

Knie, K, Korschinek, G, Faestermann, T, Dorfi, EA, Rugel, G & Wallner, A 2004, '60Fe anomaly in a deep-sea manganese crust and implications for a nearby supernova source', *Physical Review Letters*, vol. 93, a171103. https://doi.org/10.1103/PhysRevLett.93.171103

Kokubo, E & Ida, S 2007, 'Formation of terrestrial planets from protoplanets II. Statistics of planetary spin', *Astrophysical Journal*, vol. 671, no. 2, pp. 2082–2090. https://doi.org/10.1086/522364

Komatsu, E, Dunkley, J, Nolta, MR, Bennett, CL, Gold, B & Hinshaw, G, Jarosik, N, Larson, D, Limon, M, Page, L, Spergel, DN, Halpern, M, Hill, RS, Kogut, A, Meyer, SS, Tucker, GS, Weiland, JL, Wollack, E & Wright, EL 2008, 'Five-year Wilkinson Microwave Anisotropy Probe (WMAP) observations: cosmological interpretation', *Astrophysical Journal, Supplement*, vol. 180, pp. 330–376.

Kuchner, MJ 2003, 'Volatile-rich earth-mass planets in the habitable zone', *Astrophysical Journal*, vol. 596, no. 1, pp. 105–108. https://doi.org/10.1086/378397

Kump, LR, Kasting, JF & Crane, RG 1999, *The earth system*, Prentice Hall, Hoboken.

Laskar, J, Joutel, F & Robutel, P 1993, 'Stabilization of the earth's obliquity by the moon', *Nature*, vol. 361, pp. 615–617. https://doi.org/10.1038/361615a0

Laskar, J 1994, 'Large-scale chaos in the solar system' *Astronomy & Astrophysics*, vol. 287, pp. 9–12.

Laskar, J & Robutel, P 1993, 'The chaotic obliquity of the planets', *Nature*, vol. 361, pp. 608–612. https://doi.org/10.1038/361608a0

Laughlin, G, Bodenheimer, P & Adams, F 2004, 'Core-accretion model predicts few Jovian-mass planets orbiting red dwarfs', *Astrophysical Journal, Letters*, vol. 612, no. 1, pp. 73–76. https://doi.org/10.1086/424384

Laws, C, Gonzalez, G, Walker, KM, Tyagi, S, Dodsworth, J, Snider, K & Suntzeff, NB 2003, 'Parent stars of extrasolar planets VII. New abundance analyses of 30 systems', *Astronomical Journal*, vol. 125, no. 5, pp. 2664–2677. https://doi.org/10.1086/374626

Lee, H, Skillman, ED, Cannon, JM, Jackson, DC, Gerhz, RD, Polomski, EF & Woodward, CE 2006, 'On extending the mass-metallicity relation of galaxies by 2.5 decades in stellar mass', *Astrophysical Journal*, vol. 647, no. 2, pp. 970–983. https://doi.org/10.1086/505573

Léger, A, Selsis, F, Sotin, C, Guillot, T, Despois, D, Mawet, D, Ollivier, M, Labeque, A, Valette, C, Brachet, F, Chazelas, B & Lammer, H 2004, 'A new family of planets? "Ocean-planets"', *Icarus*, vol. 169, no. 2, pp. 499–504. https://doi.org/10.1016/j.icarus.2004.01.001

Lemasle, B, Francois, P, Bono, G, Mottini, M, Primas, F & Romaniello, M 2007, 'Detailed chemical composition of Galactic cepheids. A determination of the Galactic abundance gradient in the 8–12 kpc region', *Astronomy and Astrophysics*, vol. 467, no. 1, pp. 283–294. https://doi.org/10.1051/0004-6361:20066375

Lépine, JRD, Acharova, IA & Mishurov, YN 2003, 'Corotation, stellar wandering, and fine structure of the galactic abundance pattern', *Astrophysical Journal*, vol. 589, no. 1, pp. 210–216.

Lépine, JRD, Mishurov, YN & Dedikov, SY 2001, 'A new model for the spiral structure of the galaxy: superposition of 2- and 4-armed patterns', *Astrophysical Journal*, vol. 546, no. 1, pp. 234–247. https://doi.org/10.1086/374596

Levison, HF, Dones, L & Duncan, MJ 2001, 'The origin of Halley-type comets: probing the inner Oort cloud', *Astronomical Journal*, vol. 121, no. 4, pp. 2253–2267. https://doi.org/10.1086/319943

Lin, DNC, Bodenheimer, P & Richardson, DC 1996, 'Orbital migration of the planetary companion of 51 Pegasi to its present location', *Nature*, vol. 380, pp. 606–607. https://doi.org/10.1038/380606a0

Lineweaver, CH 2001, 'An estimate of the age distribution of terrestrial planets in the universe: quantifying metallicity as a selection effect', *Icarus*, vol. 151, no. 2, pp. 307–313. https://doi.org/10.1006/icar.2001.6607

Lineweaver, CH, Fenner, Y & Gibson, BK 2004, 'The galactic habitable zone and the age distribution of complex life in the milky way', *Science*, vol. 303, no. 5654, pp. 59–62. https://doi.org/10.1126/science.1092322

Lissauer, JJ 1993, 'Planet formation', *Annual Review of Astronomy and Astrophysics*, vol. 31, pp. 129–174. https://doi.org/10.1146/annurev.aa.31.090193.001021

Lissauer, JJ 1995, 'Urey prize lecture: on the diversity of plausible planetary systems', *Icarus*, vol. 114, no. 2, pp. 217–236. https://doi.org/10.1006/icar.1995.1057

Lissauer, JJ 1999, 'How common are habitable planets?', *Nature*, vol. 402, pp. 11–14. https://doi.org/10.1038/35011503

Lissauer, JJ, Dones, L & Ohtsuki, K 2000, 'Origin and evolution of terrestrial planet rotation', in RM Canup & K Righter (eds.),*Origin of the earth and moon*, The University of Arizona Press and Lunar and Planetary Institute, Tucson and Houston, pp. 101–112.

Luck, RE, Kovtyukh, VV & Andrievsky, SM 2006, 'The distribution of the elements in the Galactic disk', *Astronomical Journal*, vol. 132, no. 2, pp. 902–918. https://doi.org/10.1086/505687

Lunine, JI 2001, 'The occurrence of Jovian planets and the habitability of planetary systems', *Proceedings of the National Academy of Sciences*, vol. 98, no. 3, pp. 809–814. https://doi.org/10.1073/pnas.98.3.809

Lunine, JI, Chambers, J, Morbidelli, A & Leshin, LA 2003, 'The origin of water on Mars', *Icarus*, vol. 165, no. 1, pp. 1–8. https://doi.org/10.1016/S0019-1035(03)00172-6

Maciel, WJ, Lago, LG & Costa, RDD 2005, 'An estimate of the time variation of the abundance gradient from planetary Nebulae II. Comparison with open clusters, Cepheids and young objects', *Astronomy and Astrophysics*, vol. 433, no. 1, pp. 127–135. https://doi.org/10.1051/0004-6361:20042171

Marconi, A, Risaliti, G, Gilli, R, Hunt, LK, Maiolino, R & Salvati, M 2004, 'Local supermassive black holes, relics of active galactic nuclei and the X-ray background', *Monthly Notes of the Royal Astronomical Society*, vol. 351, pp. 169–185. https://doi.org/10.1111/j.1365-2966.2004.07765.x

Marcy, G, Butler, RP, Fischer, D, Vogt, S, Wright, JT, Tinney, CG & Jones, HRA 2005, 'Observed properties of exoplanets: masses, orbits, and metallicites', *Progress of Theoretical Physics Supplement*, vol. 158, pp. 24–42. https://doi.org/10.1143/PTPS.158.24

Marochnik, LS 1983, 'On the origin of the solar system and the exceptional position of the sun in the galaxy', *Astrophysics and Space Science*, vol. 89, pp. 61–75. https://doi.org/10.1007/BF01008385

Marsh, N & Svensmark, H 2005, 'Solar influence on earth's climate', *Space Science, Reviews*, vol. 107, pp. 317–325. https://doi.org/10.1023/A:1025573117134

Marzari, F & Weidenschilling, SJ 2002, 'Eccentric extrasolar planets: the jumping Jupiter model', *Icarus*, vol. 156, no. 2, pp. 570–579. https://doi.org/10.1006/icar.2001.6786

Masi, M, Secco, L & Vanzani, V 2003, 'Dynamical effects of the Galaxy on the Oort's Cloud', *Memorie della Società Astronomica Italiana*, vol. 74, pp. 494–495.

Matese, JJ & Lissauer, JJ 2002, 'Characteristics and frequency of weak stellar impulses of the Oort cloud', *Icarus*, vol. 157, no. 1, pp. 228–240. https://doi.org/10.1006/icar.2001.6799

Matese, JJ, Whitman, PG, Innanen, KA & Valtonen, MJ 1995, 'Periodic modulation of the Oort cloud comet flux by the adiabatically changing galactic tide', *Icarus*, vol. 116, no. 2, pp. 255–268. https://doi.org/10.1006/icar.1995.1124

Matese, JJ, Whitman, PG & Whitmire, DP 1999, 'Cometary evidence of a massive body in the outer Oort cloud', *Icarus*, vol. 141, no. 2, pp. 354–366. https://doi.org/10.1006/icar.1999.6177

Matonick, DM & Fesen, RA 1997, 'Optically identified supernova remnants in the nearby spiral galaxies: NGC 5204, NGC 5585, NGC 6946, M81, and M101', *Astrophysical Journal, Supplement*, vol. 112, no. 1, pp. 49–107. https://doi.org/10.1086/313034

Melosh, HJ 2003, 'The history of air', *Nature*, vol. 424, pp. 22–23. https://doi.org/10.1038/424022a

Melott, AL, Lieberman, BS, Laird, CM, Martin, LD, Medvedev, MV, Thomas, BC, Cannizzo, JK, Gehrels, N & Jackman, CH 2004, 'Did a gamma-ray burst initiate the late Ordovician mass extinction?', *International Journal of Astrobiology*, vol. 3, no. 1, pp. 55–61. https://doi.org/10.1017/S1473550404001910

Méndez, A 2001, 'Planetary habitable zones: the spatial distribution of life on planetary bodies', *Lunar and Planetary Science*, vol. 32, pp. 211–214. https://doi.org/10.1007/978-94-010-1017-7_37

Méndez, A 2002, 'Habitability of near-surface environments on Mars', *Lunar and Planetary Science*, vol. 33, a1999.

Miller, CJ, Nichol, RC, Gómez, PL, Hopkins, AM & Bernardi, M 2003, 'The environment of active galactic nuclei in the Sloan digital sky survey', *Astrophysical Journal*, vol. 597, no. 1, pp. 142–156. https://doi.org/10.1086/378383

Morbidelli, A, Chambers, J, Lunine, JI, Petit, JM, Robert, F, Valsecchi, GB & Cyr, E 2000, 'Source regions and timescales for the delivery of water on earth', *Meteoritics and Planetary Science*, vol. 35, no. 6, pp. 1309–1320. https://doi.org/10.1111/j.1945-5100.2000.tb01518.x

Morris, M, Ghez, AM & Becklin, EE 1999, 'The galactic center black hole: clues for the evolution of black holes in galactic nuclei', *Advances in Space Research*, vol. 23, no. 5–6, pp. 959–968. https://doi.org/10.1016/S0273-1177(99)00219-7

Nimmo, F & Stevenson, DJ 2000, 'Influence of early plate tectonics on the thermal evolution and magnetic field on Mars', *Journal of Geophysical Research*, vol. 105, no. E5, pp. 11969–11980. https://doi.org/10.1029/1999JE001216

Nisbet, EG & Sleep, NH 2001, 'The habitat and nature, of early life', *Nature*, vol. 409, pp. 1083–1091. https://doi.org/10.1038/35059210

Oberhummer, H, Csótó, A & Schlattl, H 2000, 'Stellar production rates of carbon and its abundance in the universe', *Science*, vol. 289, no. 5476, pp. 88–90. https://doi.org/10.1126/science.289.5476.88

O'Neill, C & Lenardic, A 2007, 'Geological consequences of super-sized earths', *Geophysical Research Letters*, vol. 34, no. 19, aL19204. https://doi.org/10.1029/2007GL030598

Pace, NR 2001, 'The universal nature, of biochemistry', *Proceedings of the National Academy of Sciences*, vol. 98, no. 3, pp. 805–808. https://doi.org/10.1073/pnas.98.3.805

Pavlov, AA, Pavlov, AK, Mills, MJ, Ostryakov, VM, Vasilyev, GI & Toon, OB 2005a, 'Catastrophic ozone loss during passage of the solar system through an interstellar cloud', *Geophysical Research Letters*, vol. 32, aL01815. https://doi.org/10.1029/2004GL021601

Pavlov, AA, Toon, OB, Pavlov, AK, Bally, J & Pollard, D 2005b, 'Passing through a giant molecular cloud: 'snowball' glaciations produced by interstellar dust', *Geophysical Research Letters*, vol. 32, aL03705. https://doi.org/10.1029/2004GL021890

Pepin, RO 1997, 'Evolution of earth's noble gases: consequences of assuming hydrodynamic loss driven by giant impact', *Icarus*, vol. 126, pp. 148–156.

Pollack, JB, Hubickyj, O, Bodenheimer, P, Lissauer, JJ, Podolak, M & Greenzweig, Y 1996, 'Formation of the giant planets by concurrent accretion of solids and gas', *Icarus*, vol. 124, no. 1, pp. 62–85. https://doi.org/10.1006/icar.1996.0190

Radick, RR, Lockwood, GW, Henry, GW & Baliunas, SL 2004, 'The variability of Sunlike Stars on decadal timescales', in AK Dupree & AO Benz (eds.), *Stars as suns: activity*, *evolution*, *and planets*, Astronomical Society of the Pacific, San Francisco, pp. 264–268.

Rampino, MR 1998, 'The galactic theory of mass extinctions: an update', *Celestial Mechanics and Dynamical Astronomy*, vol. 69, pp. 49–58. https://doi.org/10.1023/A:1008365913573

Raymond, SN 2008, 'Terrestrial planet formation in extra-solar planetary systems', in Y-S Sun, S Ferraz-Mello & J-L Zhou (eds.), *Exoplanets: detection, formation and dynamics (IAU S249)*, held in Suzhou, China, 22–26 October 2007, pp. 233–250. https://doi.org/10.1017/S1743921308016645

Raymond, SN, Mandell, AM & Sigurdsson, S 2006, 'Exotic earths: forming habitable worlds with giant planet migration', *Science*, vol. 313, no. 5792, pp. 1413–1416. https://doi.org/10.1126/science.1130461

Raymond, SN, Quinn, T & Lunine, JI 2004, 'Making other earths: dynamical simulations of terrestrial planet formation and water delivery', *Icarus*, vol. 168, no. 1, pp. 1–17. https://doi.org/10.1016/j.icarus.2003.11.019

Raymond, SN, Scalo, J & Meadows, VS 2007, 'A decreased probability of habitable planet formation around low-mass stars', *Astrophysical Journal*, vol. 669, no. 1, pp. 606–614. https://doi.org/10.1086/521587

Rees, M 2000, *Just six numbers: the deep forces that shape the universe*, Basic Books, New York.

Rees, M 2003, 'Numerical coincidences and "Tuning" in cosmology', *Astrophysics and Space Science*, vol. 285, no. 12, pp. 375–388. https://doi.org/10.1063/1.1341923

Regenauer-Lieb, K, Yuen, DA & Branlund, J 2001, 'The initiation of subduction: criticality by addition of water?" *Science*, vol. 294, no. 5542, pp. 578–580. https://doi.org/10.1126/science.1063891

Ribas, I, Guinan, EF, Güdel, M & Audard, M 2005, 'Evolution of the solar activity over time and effects on planetary atmospheres: I. High-energy irradiances (1–1700 Å)', *Astrophysical Journal*, vol. 622, no. 1, pp. 680–694. https://doi.org/10.1086/427977

Richardson, D, Branch, D, Casebeer, D, Millard, J, Thomas, RC & Baron, E 2002, 'A comparative study of the absolute magnitude distributions of supernovae', *Astronomical Journal*, vol. 123, no. 2, pp. 745–752. https://doi.org/10.1086/338318

Santos, NC, Israelian, G & Mayor, M 2004, 'Spectroscopic [Fe/H] for 98 extra-solar planet-host stars – exploring the probability of planet formation', *Astronomy & Astrophysics*, vol. 415, no. 3, pp. 1153-1166. https://doi.org/10.1051/0004-6361:20034469

Santos, NC, Israelian, G, Mayor, M, Bento, JP, Almeida, PC, Sousa, SG & Ecuvillon, A 2005, 'Spectroscopic metallicities for planet-host stars: extending the samples', *Astronomy & Astrophysics*, vol. 437, no. 3, pp. 1127–1133. https://doi.org/10.1051/0004-6361:20052895

Sasaki, M, Breitschwerdt, D & Supper, R 2004, 'SNR surface density distribution in nearby galaxies', *Astrophysics and Space Science*, vol. 289, pp. 283–286. https://doi.org/10.1023/B:ASTR.0000014956.12840.47

Scalo, J & Wheeler, JC 2002, 'Astrophysical and astrobiological implications of gamma-ray burst properties', *Astrophysical Journal*, vol. 566, no. 2, pp. 723–737. https://doi.org/10.1086/338329

Scherer, K, Fichtner, H & Stawicki, O 2002, 'Shielded by the wind: the influence of the interstellar medium on the environment of earth', *Journal of Atmospheric and Solar-Terrestrial Physics*, vol. 64, pp. 795–804. https://doi.org/10.1007/BF01238186

Schlattl, H, Heger, A, Oberhummer, H, Rauscher, T & Csótó, A 2004, 'Sensitivity of the C and O production on the 3-alpha rate', *Astrophysics and Space Science*, vol. 291, pp. 27–56. https://doi.org/10.1023/B:ASTR.0000029953.05806.47

Schneider, SM & Rey-Benayas, JM 1994, 'Global patterns of plant diversity', *Evolutionary Ecology*, vol. 8, pp. 331–347. https://doi.org/10.1007/BF01238186

Schopf, J, Kudryavtsev, A, Agresti, D, Wdowiak, TJ & Czaja, AD 2002, 'Laser–Raman imagery of earth's earliest fossils', *Nature*, vol. 416, pp. 73–76. https://doi.org/10.1038/416073a

Scott, C, Lyons, TW, Bekker, A, Shen, Y, Poulton, SW, Chu, X & Anbar, AD 2008, 'Tracing the stepwise oxygenation of the Proterozoic ocean', *Nature*, vol. 452, pp. 456–459.

Sellwood, JA & Binney, JJ 2002, 'Radial mixing in galactic discs', *Monthly Notices of the Royal Astronomical Society*, vol. 336, no. 3, pp. 785–796. https://doi.org/10.1046/j.1365-8711.2002.05806.x

Sepkoski, JJ 1995, 'Patterns of Phanerozoic extinction: a perspective from global databases', in OH Walliser (ed.), *Global events and event stratigraphy in the Phanerozoic,* Springer, Berlin, a3551.

Shaviv, NJ 2003, 'The spiral structure of the Milky way, cosmic rays, and ice age epochs on earth', *New Astronomy Reviews*, vol. 8, no. 1, pp. 39–77. https://doi.org/10.1016/S1384-1076(02)00193-8

Shaviv, NJ 2005, 'On climate response to changes in the cosmic ray flux and radiative budget', *Journal of Geophysical Research*, vol. 110, no. A8, a08105. https://doi.org/10.1029/2004JA010866

Shklovsky, JS & Sagan, C 1966, *Intelligent life in the universe*, Holden-Day, San Francisco.

Smith, DS, Scalo, J & Wheeler, JC 2004, 'Importance of biologically active and aurora-like ultraviolet emission: stochastic irradiation of earth and Mars by Flares and explosions', *Origins of Life and Evolution of Biospheres*, vol. 34, pp. 513–532. https://doi.org/10.1023/B:ORIG.0000043120.28077.c9

Spohn, T, Acuña, MH, Breuer, D, Golombek, M, Greeley, R, Halliday, A, Hauber, E, Jaumann, R & Sohl, F 2001, 'Geophysical constraints on the evolution of Mars', *Space Science*, *Reviews*, vol. 96, pp. 231–262. https://doi.org/10.1023/A:1011949306989

Stern, SA 2003, 'The evolution of comets in the Oort cloud and Kuiper belt', *Nature*, vol. 424, pp. 639–642. https://doi.org/10.1038/nature01725

Svensmark, H 2006, 'Cosmic rays and the biosphere over 4 billion years', *Astronomische Nachricheten*, vol. 327, no. 9, pp. 871–875. https://doi.org/10.1002/asna.200610651

Svensmark, H, Pederson, JOP, Marsh, ND, Enghoff, NB & Uggerhoj, UI 2006, 'Experimental evidence for the role of ions in particle nucleation under atmospheric conditions', *Proceedings of the Royal Society A*, vol. 463, no. 2078, pp. 385–396.

Talbot, RJ Jr & Newman, MJ 1977, 'Encounters between stars and dense molecular clouds', *Astrophysical Journal, Supplement*, vol. 34, pp. 295–308. https://doi.org/10.1086/190452

Thomas, BC & Melott, AL 2006, 'Gamma-ray bursts and terrestrial planetary atmospheres', *New Journal of Physics*, vol. 8, a120. https://doi.org/10.1088/1367-2630/8/7/120

Thomas, BC, Melott, AL, Jackman, CH, Laird, CM, Medvedev, MV, Stolarski, RS, Gehrels, N, Cannizzo, JK, Hogan, DP & Ejzak, LM 2005, 'Gamma ray bursts and the earth: exploration of atmospheric, biological, climatic, and biogeochemical effects', *Astrophysical Journal*, vol. 634, no. 1, pp. 509–533. https://doi.org/10.1086/496914

Thommes, EW & Lissauer, JJ 2003, 'Resonant inclination excitation of migrating giant planets', *Astrophysical Journal* 597(1), 566–580. https://doi.org/10.1086/378317

Touma, J & Wisdom, J 2001, 'Nonlinear core-mantle coupling', *Astronomical Journal*, vol. 122, no. 1, pp. 1030–1050. https://doi.org/10.1086/321146

Valencia, D, O'Connell, RJ & Sasselov, DD 2007, 'Inevitability of plate tectonics on super-earths', *Astrophysical Journal*, vol. 670, no. 1, pp. 45–48. https://doi.org/10.1086/524012

Vallée, JP 2008, 'New velocimetry and revised cartography of the spiral arms in the Milky way – a consistent symbiosis', *Astronomical Journal*, vol. 135, no. 4, pp. 1301–1310. https://doi.org/10.1088/0004-6256/135/4/1301

Van den Bergh, S 1997, 'Distribution of supernovae in spiral galaxies', *Astronomical Journal*, vol. 113, pp. 197–200. D https://doi.org/10.1086/118244

Veras, D & Armitage, PJ 2005, 'The influence of massive planet scattering on nascent terrestrial planets', *Astrophysical Journal*, vol. 620, no. 2, pp. 111–114. https://doi.org/10.1086/428831

Vogt, NP, Haynes, MP, Giovanelli, R & Herter, T 2004, 'M/L, HαRotation curves, and H I gas densities for 329 nearby cluster and field spirals. III. Evolution in fundamental galaxy parameters', *Astronomical Journal*, vol. 127, pp. 3325–3337. https://doi.org/10.1086/420703

Von Bloh, W, Franck, S, Bounama, C & Schellnhuber, H-J 2003, 'Maximum number of habitable planets at the time of earth's origin: new hints for Panspermia?', *Origins of Life and Evolution of Biospheres*, vol. 33, pp. 219–231. https://doi.org/10.1023/A:1024627326871

Waide, RB, Willig, MR, Steiner, CF, Mittelbach, G, Gough, L, Dodson, SI, Juday, GP & Parmenter, R 1999, 'The relationship between productivity and species richness', *Annual Review of Ecology and Systematics*, vol. 30, pp. 257–300. https://doi.org/10.1146/annurev.ecolsys.30.1.257

Wallner, C, Faestermann, T, Gerstmann, U, Knie, K, Korschinek, G, Lierse, C & Rugel, G 2004, 'Supernova produced and anthropogenic ^{244}Pu in deep sea manganese encrustations', *New Astronomy Review*, vol. 48, no. 1–4, pp. 145–150. https://doi.org/10.1016/j.newar.2003.11.020

Ward, PD & Brownlee, D 2000, *Rare earth: why complex life is uncommon in the universe*, Copernicus, New York.

Ward, WR, Agnor, CB & Canup, RM 2002, 'Obliquity variations in planetary systems', *Lunar and Planetary Science*, vol. 33, a2017.

Watt, GD 1985, 'Time-dependent chemistry. II – Dependence of the chemistry on the initial C/O abundance ratio', *Monthly Notes of the Royal Astronomical Society*, vol. 212, no. 1, pp. 93–103. https://doi.org/10.1093/mnras/212.1.93

Waxman, E 2004, 'High-energy cosmic rays from gamma-ray burst sources: a stronger case', *Astrophysical Journal*, vol. 606, pp. 988–993. https://doi.org/10.1086/383116

West, AA, Hawley, SL, Walkowicz, LM, Covey, KR, Silvestri, NM, Raymond, SN, Harris, HC, Munn, JA, McGehee, PM, Ivezic, Z & Brinkmann, J 2004, 'Spectroscopic properties of cool stars in the Sloan Digital Sky Survey: an analysis of magnetic activity and a search for subdwarfs', *Astronomical Journal*, vol. 128, no. 1, pp. 426–436. https://doi.org/10.1086/421364

Wilkinson, DM 2003, 'The fundamental processes in ecology: a thought experiment on extraterrestrial biospheres', *Biological Reviews*, vol. 78, no. 2, pp. 171–179. https://doi.org/10.1017/S1464793102006048

Williams, DM, Kasting, JF & Wade, RA 1997, 'Habitable moons around extrasolar giant planets', *Nature*, vol. 385, pp. 234–236. https://doi.org/10.1038/385234a0

Williams, DM & Pollard, D 2002, 'Earth-like planets on eccentric orbits: excursions beyond the habitable zone', *International Journal of Astrobiology*, vol. 1, no. 1, pp. 61–69. https://doi.org/10.1017/S1473550402001064

Wolstencroft, RD & Raven, JA 2002, 'Photosynthesis: likelihood of occurrence and possibility of detection on earth-like planets', *Icarus*, vol. 157, no. 2, pp. 535–548. https://doi.org/10.1006/icar.2002.6854

Yeghikyan, A & Fahr, H 2004a, 'Effects induced by the passage of the sun through dense molecular clouds I. Flows outside of the compressed heliosphere', *Astronomy and Astrophysics*, vol. 415, no. 2, pp. 763–770. https://doi.org/10.1051/0004-6361:20034609

Yeghikyan, A & Fahr, H 2004b, 'Terrestrial atmospheric effects induced by counterstreaming dense interstellar cloud material', *Astronomy and Astrophysics*, vol. 425, no. 3, pp. 1113–1118. https://doi.org/10.1051/0004-6361:20041100

Yusifov, I & Küçük, I 2004, 'Revisiting the radial distribution of pulsars in the galaxy', *Astronomy and Astrophysics*, vol. 422, pp. 545–553. https://doi.org/10.1051/0004-6361:20040152

Zheng, JQ & Valtonen, MJ 1999, 'On the probability that a Comet that has escaped from another solar system will Collide with the earth', *Monthly Notes of the Royal Astronomical Society*, vol. 304, no. 3, pp. 579–582. https://doi.org/10.1046/j.1365-8711.1999.02337.x

Zuber, MT 2001, 'The crust and mantle of Mars', *Nature*, vol. 412, pp. 220–227. https://doi.org/10.1038/35084163

Chapter 5

Archer, GL 2001, *Reading between the fossil lines*, viewed 04 May, <https://reasons.org/explore/publications/rtb-101/reading-between-the-fossil-lines>

Axe, D 2016, *Undeniable: how biology confirms our intuition that life is designed*, HarperCollins, New York.

Behe, M 2006, *Darwin's black box: the biochemical challenge to evolution*, 2nd edn, Free Press, New York.

Bernhardt, HS 2012, 'The RNA world hypothesis: the worst theory of the early evolution of life (except for all the others)', *Biology Direct*, vol. 7, a23. https://doi.org/10.118611745-6150-7-23

Chyba, CF & Sagan, C 1997, 'Comets as a source of prebiotic organic molecules for the early earth', in PJ Thomas, CF Chyba & CP McKay (eds.), *Comets and the origin and evolution of life*, Springer-Verlag, New York, pp. 147–173.

Conway Morris, S 2003, *Life's solution: inevitable humans in a lonely universe*, Cambridge University Press, New York.

Davies, P 1999, *The fifth miracle: the search for the origin and meaning of life*, Simon & Schuster, New York.

Dawkins, R 1987, *The blind watchmaker: why the evidence of evolution reveals a universe without design*, W.W. Norton, New York.

Deamer, DW 1998, 'Membrane compartments in prebiotic evolution', in A Brack (ed.), *The molecular origins of life: assembling pieces of the puzzle*, Cambridge University Press, Cambridge, pp. 189–205.

Deamer, DW 2011, *First life: discovering the connection between stars, cells, and how life began*, University of California Press, Berkeley.

Dembski, W 2001, *No free lunch: why specified complexity cannot be purchased without intelligent design*, Rowman & Littlefield, Lanham.

Eberlin, M 2019, *Foresight: how the chemistry of life reveals planning and purpose*, Discovery Institute Press, Seattle.

Ferris, JP 1998, 'Catalyzed RNA synthesis for the RNA world', in A Brack (ed.), *The molecular origins of life: assembling pieces of the puzzle*, Cambridge University Press, Cambridge, pp. 255–268.

Ferris, JP 2003, ‘From building blocks to the polymers of life’, in JW Schopf (ed.), *Life’s origin: the beginnings of biological evolution*, University of California Press, Berkeley, pp. 113–139.

Ferris, JP & Usher, DA 1984, ‘Origins of life’, in G Zubay (ed.), *Biochemistry*, Addison-Wesley, Reading, pp. 1191–1141.

Fry, I 2000, *The emergence of life on earth: a historical and scientific overview*, Rutgers University Press, New Brunswick.

Gould, SJ 1980, ‘Bathybuis and Eozoon’, in *The Panda’s thumb: more reflections in natural history*, W.W. Norton, New York, pp. 236–244.

Hazen, RM 2005, *Genesis: the scientific quest for life’s origin*, Joseph Henry Press, Washington.

Henry, H & Dyke, DJ 2018, *Hypernaturalism: integrating the Bible and science*, Independently Published, Chicago.

Horgan, J 1997, *The end of science: facing the limits of knowledge in the twilight of the scientific age*, Broadway, New York.

Horning, DP & Joyce, GF 2016, ‘Amplification of RNA by an RNA polymerase ribozyme’, *Proceedings of the National Academy of Sciences U S A*, vol. 113, no. 35, pp. 9786–9791. https://doi.org/10.1073/pnas.1610103113

Ilardo, M, Bose, R, Meringer, M, Rasulev, B, Grefenstette, N, Stephenson, J, Freeland, S, Gilliams, RJ, Butch, CJ & Cleaves II HJ 2019, ‘Adaptive properties of the genetically encoded amino acid alphabet are inherited from its subset’, *Scientific Reports*, vol. 9, a12468. https://doi.org/10.1038/s41598-019-47574-x

Joyce, GF & Szostak, JW 2018, ‘Protocells and RNA self-replication’, *Cold Spring Harbor Perspectives in Biology*, vol. 10, no. 9, a034801. https://doi.org/10.1101/cshperspect.a034801

Kasting, JF & Brown, LL 1998, ‘The early atmosphere as a source of biogenic compounds’, in A Brack (ed.), *The molecular origins of life: assembling pieces of the puzzle*, Cambridge University Press, Cambridge, pp. 35–36.

Luisi, PL 2006, *The emergence of life: from chemical origins to synthetic biology*, Cambridge University Press, Cambridge.

Meyer, SC 2010, *Signature in the cell: DNA and the evidence for intelligent design*, HarperCollins, New York.

Miller, SL 1953, ‘A production of amino acids under possible primitive earth conditions’, *Science*, vol. 117, no. 3046, pp. 528–559. https://doi.org/10.1126/science.117.3046.528

Miller, SL 1955, ‘Production of some organic compounds under possible primitive earth conditions’, *Journal of the American Chemical Society*, vol. 77, no. 9, pp. 2351–2361. https://doi.org/10.1021/ja01614a001

Miller, SL & Lazcano, A 2003, ‘Formation of the building blocks of life’, in JW Schopf (ed.), *Life’s origin: the beginnings of biological evolution*, University of California Press, Berkeley, pp. 78–112.

Miller, SL, Schopf, JW & Lazcano, A 1997, ‘Oparin’s “origin of life”: sixty years later’, *Journal of Molecular Evolution*, vol. 44, pp. 351–353. https://doi.org/10.1525/california/9780520233904.003.0004

Morowitz, HJ 1992, *Beginnings of cellular life: metabolism recapitulates biogenesis*, Yale University Press, New Haven.

Morowitz, HJ, Kostelnik, JD, Yang, J & Cody, GD 2000, ‘The origin of intermediary metabolism’, *The Proceedings of the National Academy of Sciences USA*, vol. 97, no. 14, pp. 7704–7708. https://doi.org/10.1073/pnas.110153997

Muchowska, KB, Varma, SJ & Moran, J 2019, ‘Synthesis and breakdown of universal metabolic precursors promoted by iron’, *Nature*, vol. 569, pp. 104–107. https://doi.org/10.1038/s41586-019-1151-1

Navarro-Gonzalez, R, Molina, MJ & Molina, LT 1999, ‘Production of reactive nitrogen in explosive volcanic clouds’, Lecture at the 9th Meeting of the International Society for the Study of the Origin Life, University of California, San Diego, 11–16 July, 1999.

Orgel, LE 1998, ‘The origin of life – a review of facts and speculations’, *Trends in Biochemical Sciences*, vol. 23, no. 12, pp. 491–495. https://doi.org/10.1016/s0968-0004(98)01300-0

Orgel, LE 2004, 'Prebiotic chemistry and the origin of the RNA world', *Critical Reviews in Biochemistry and Molecular Biology*, vol. 39, no. 2, pp. 99–123. https://doi.org/10.1080/10409230490460765

Oró, J & Lazcano, A 1997, 'Comets and the origin and evolution of life', in PJ Thomas, CF Chyba & CP McKay (eds.), *Comets and the origin and evolution of life*, Springer-Verlag, New York, pp. 3–27.

Rauchfuss, H 2008, *Chemical evolution and the origin of life*, Springer-Verlag, Heidelberg.

Pascal, R 2019, 'A possible non-biological reaction framework for metabolic processes on early earth', *Nature*, vol. 569, pp. 47–49. https://doi.org/10.1038/d41586-019-01322-3

Rana, F 2008, *The cell's design: how chemistry reveals the creator's artistry*, Baker Books, Grand Rapids.

Rana, F 2011, *Creating life in the lab: how new discoveries in synthetic biology make a case for a creator*, Baker Books, Grand Rapids.

Rana, F 2019, *Tag: bioenergetics*, viewed 04 May 2002, <https://twobrothersweblog.com/tag/origin-of-life/>

Rana, F 2020, *Have researchers developed a computer algorithm that explains the origin of life?*, viewed 04 May 2002, <https://reasons.org/explore/blogs/the-cells-design/have-researchers-developed-a-computer-algorithm-that-explains-the-origin-of-life>

Rana, F & Ross, H 2004, *Origins of life: biblical and evolutionary models face-off*, RTB Press, Covina.

Richert, C 2018, 'Prebiotic chemistry and human intervention', *Nature Communications*, vol. 9, a5177. https://doi.org/10.1038/s41467-018-07219-5

Robertson, MP & Joyce, GF 2012, 'The origins of the RNA world', *Cold Spring Harbor Perspectives in Biology*, vol. 4, no. 5, a003608. https://doi.org/10.1101/cshperspect.a003608

Schopf, JW 2002, *Life's origin: the beginnings of biological evolution*, University of California Press, Berkeley.

Smith, E & Morowitz, HJ 2004, 'Universality in intermediary metabolism', *Proceedings of the National Academy of Sciences USA*, vol. 101, no. 36, pp. 13168–13173. https://doi.org/10.1073/pnas.0404922101

Stetter, KO 1998, 'Hyperthermophiles and their possible role as ancestors of modern life', in A Brack (ed.), *The molecular origins of life: assembling pieces of the puzzle*, Cambridge University Press, Cambridge, pp. 315–335.

Stubbs, TR, Yadav, M, Krishnamurthy, R & Springsteen, G 2020, 'A plausible metal-free ancestral analogue of the Krebs cycle composed entirely of α-ketoacids', *Nature Chemistry*, vol. 12, pp. 1016–1022. https://doi.org/10.1038/s41557-020-00560-7

Thaxton, CB, Bradley, WL & Olsen, RL 1984, *The mystery of life's origin: reassessing current theories*, Lewis & Stanley, Dallas, TX.

Thaxton, CB, Bradley, WL & Olsen, RL 2020, *The mystery of life's origin: the continuing controversy*, Discovery Institute Press, Seattle, WA.

Tokyo Institute of Technology 2019, 'Scientists find biology's optimal "molecular alphabet" may be preordained', *ScienceDaily*, 10 September 2019, viewed 30 June 2022, <http://www.sciencedaily.com/releases/2019/09/190910080017.htm>

Wolos, A, Roszak, R, Żądło-Dobrowolska, A, Beker, W, Mikulak-Klucznik, B, Spólnik, G, Dygas, M, Szymkuc, S & Grzybowski, BA 2020, 'Synthetic connectivity, emergence, and self-regeneration in the network of prebiotic chemistry', *Science*, vol. 369, a1955. https://doi.org/10.1126/science.aaw1955

Chapter 6

Abendroth, JM, Bushuyev, OS, Weiss, PS & Barrett, CJ 2015, 'Controlling motion at the nanoscale: rise of the molecular machines', *ACS Nano*, vol. 9, no. 8, pp. 7746–7768. https://doi.org/10.1021/ACSNANO.5B03367

Albertsen, AN, Szymaski, JK & Pérez-Mercader, J 2017, ‘Emergent properties of giant vesicles formed by a Polymerization-Induced Self-Assembly (PISA) reaction’, *Scientific Reports*, vol. 7, no. 1, pp. 1–8. https://doi.org/10.1038/srep41534

Astumian, RD 2001, ‘Making molecules into motors’, *Scientific American*, vol. 285, no. 1, p. 44. https://doi.org/10.1038/SCIENTIFICAMERICAN0701-56

Balzani, V, Credi, A & Venturi, M 2008, ‘Molecular machines working on surfaces and at interfaces’, *Chemphyschem: A European Journal of Chemical Physics and Physical Chemistry*, vol. 9, no. 2, pp. 202–220. https://doi.org/10.1002/CPHC.200700528

Browne, WR & Feringa, BL 2006, ‘Making molecular machines work’, *Nature Nanotechnology*, vol. 1, no. 1, pp. 25–35. https://doi.org/10.1038/nnano.2006.45.

Carothers Equation 2021, viewed 20 November 2021, <https://en.wikipedia.org/wiki/Carothers_equation>

Chiang, PT, Mielke, J, Godoy, J, Guerrero, JM, Alemany, LB & Villagómez, CJ, Saywell, A, Grill, L & Tour, JM 2012, ‘Toward a light-driven motorized nanocar: synthesis and initial imaging of single molecules’, *ACS Nano*, vol. 6, no. 1, pp. 592–597. https://doi.org/10.1021/nn203969b

Chu, PLE, Wang, LY, Khatua, S, Kolomeisky, AB, Link, S & Tour, JM 2013, ‘Synthesis and single-molecule imaging of highly mobile adamantane-wheeled nanocars’, *ACS Nano*, vol. 7, no. 1, pp. 35–41. https://doi.org/10.1021/NN304584A

Claytor, K, Khatua, S, Guerrero, JM, Tcherniak, A, Tour, JM & Link, S 2009, ‘Accurately determining single molecule trajectories of molecular motion on surfaces’, *The Journal of Chemical Physics*, vol. 130, no. 16, a164710. https://doi.org/10.1063/1.3118982

Decker, P, Schweer, H & Pohlamnn, R 1982, ‘Bioids: X. Identification of formose sugars, presumable prebiotic metabolites, using capillary gas chromatography/gas chromatography – mass spectrometry of n-butoxime trifluoroacetates on OV-225’, *Journal of Chromatography A*, vol. 244, no. 2, pp. 281–291. https://doi.org/10.1016/S0021-9673(00)85692-7

Eschenmoser, A 2011, ‘Etiology of potentially primordial biomolecular structures: from vitamin B12 to the nucleic acids and an inquiry into the chemistry of life’s origin: a retrospective’, *Angewandte Chemie (International edn. in English)*, vol. 50, no. 52, pp. 12412–12472. https://doi.org/10.1002/ANIE.201103672

Eschenmoser, A & Loewenthal, E 1992, ‘Chemistry of potentially prebiotic natural products’, *Chemical Society Reviews*, vol. 21, pp. 1–16. https://doi.org/10.1039/cs9922100001

Fuller, WD, Sanchez, RA & Orgel, LE 1972, ‘Studies in prebiotic synthesis. VI. Synthesis of purine nucleosides’, *Journal of Molecular Biology*, vol. 67, no. 1, pp. 25–33. https://doi.org/10.1016/0022-2836(72)90383-X

Gerbelli, BB, Da Silva, ER, Soares, BM, Alves, WA & De Oliveira, EA 2018, ‘Multilamellar-to-unilamellar transition induced by diphenylalanine in lipid vesicles’, *Langmuir*, vol. 34, no. 5, pp. 2171–2179. https://doi.org/10.1021/ACS.LANGMUIR.7B03869

Gibard, C, Bhowmik, S, Karki, M, Kim, E-K & Krishnamurthy, R 2017, ‘Phosphorylation, oligomerization and self-assembly in water under potential prebiotic conditions’, *Nature Chemistry*, vol. 10, no. 2, pp. 212–217. https://doi.org/10.1038/nchem.2878

Gibson, DG, Glass, JI, Lartigue, C, Noskov, VN, Chuang, RY, Algire, MA, Benders, GA, Montagueli, MG, Moodie, MM, Merryman, C, Vashee, S, Krishnakumar, R, Assad-Garcia, N, Andrews-Pfannkoch, C, Denisova, EA, Young, L, Qi, Z-Q, Segall-Shapiro, TH, Calvey, CH, Parmar, PP, Hutchison, III CA, Smith, HO & Venter, JC 2010, ‘Creation of a bacterial cell controlled by a chemically synthesized genome’, *Science*, vol. 329, no. 5987, pp. 52–56. https://doi.org/10.1126/science.1190719

Hutchison, CA, Chuang, RY, Noskov, VN, Assad-Garcia, N, Deerinck, TJ, Ellisman, MH, Gill, J, Kannan, K, Karas, BJ, Ma L, Pelletier, JF, Q, Z-Q, Richter, RA, Strychalski, EA, Sun, L, Suzuki, Y, Tsvetanova, B, Wise, KS, Smith, HO, Glass, JI, Merryman, C, Gibson, DG & Venter, JC 2016, ‘Design and synthesis of a minimal bacterial genome’, *Science*, vol. 351, no. 6280, a6253. https://doi.org/10.1126/science.aad6253

Kay, ER & Leigh, DA 2015, ‘Rise of the molecular machines’, *Angewandte Chemie International Edition*, vol. 54, no. 35, pp. 10080–10088. https://doi.org/10.1002/ANIE.201503375

Khatua, S, Godoy, J, Tour, JM & Link, S 2010, 'Influence of the substrate on the mobility of individual nanocars', *Journal of Physical Chemistry Letters*, vol. 1, no. 22, pp. 3288–3291. https://doi.org/10.1021/jz101375q

Leslie, M 2018, 'Biologists create the most lifelike artificial cells yet', *Science*, viewed 20 November 2021, <https://www.science.org/content/article/biologists-create-most-lifelike-artificial-cells-yet>

Morin, JF, Shirai, Y & Tour, JM 2006, 'En route to a motorized nanocar', *Organic Letters*, vol. 8, no. 8, pp. 1713–1716. https://doi.org/10.1021/ol060445d.

Niederholtmeyer, H, Chaggan, C & Devaraj, NK 2018, 'Communication and quorum sensing in non-living mimics of eukaryotic cells', *Nature Communications*, vol. 9, no. 1, a5027. https://doi.org/10.1038/S41467-018-07473-7

Patel, BH, Percivalle, C, Ritson, DJ, Duffy, CD & Sutherland, JD 2015, 'Common origins of RNA, protein and lipid precursors in a cyanosulfidic protometabolism', *Nature Chemistry*, vol. 7, pp. 301–307. https://doi.org/10.1038/nchem.2202

Pitsch, S, Eschenmoser, A, Gedulin, B, Hui, S & Arrhenius, G 1995, 'Mineral induced formation of sugar phosphates', *Origins of Life and Evolution of the Biosphere*, vol. 25, no. 4, pp. 297–334. https://doi.org/10.1007/BF01581773

Powell, A 2017, 'Mimicking life in a chemical soup', *The Harvard Gazette*, 31st March, viewed 20 November 2021, <https://news.harvard.edu/gazette/story/2017/03/harvard-researcher-creates-chemical-system-that-mimics-early-cell-behavior/>

Powner, MW, Gerland, B & Sutherland, JD 2009, 'Synthesis of activated pyrimidine ribonucleotides in prebiotically plausible conditions', *Nature*, vol. 459, no. 7244, pp. 239–242. https://doi.org/10.1038/nature08013

Wikipedia 2021, *Protocell*, viewed 20 November 2021, <https://en.wikipedia.org/wiki/Protocell>

Richert, C 2018, 'Prebiotic chemistry and human intervention', *Nature Communications*, vol. 9, no. 1, pp. 1–3. *Protocell*.1038/s41467-018-07219-5

Ritson, D & Sutherland, JD 2012, 'Prebiotic synthesis of simple sugars by photoredox systems chemistry', *Nature Chemistry*, vol. 4, no. 11, pp. 895–899. https://doi.org/10.1038/nchem.1467

Robertson, MP & Joyce, GF 2012, 'The origins of the RNA world', *Cold Spring Harbor Perspectives in Biology*, vol. 4, no. 5, a3608. https://doi.org/10.1101/CSHPERSPECT.A003608

Shirai, Y, Osgood, AJ, Zhao, Y, Yao, Y, Saudan, L, Yang, H, Yu-Hung, C, Alemany, LB, Sasaki, T, Morin, J-F, Guerrero, JM, Kelly, KF & Tour, JM 2006, 'Surface-rolling molecules', *Journal of the American Chemical Society*, vol. 128, no. 14, pp. 4854–4864. https://doi.org/10.1021/JA058514R

Steele, EJ, Al-Mufti, S, Augustyn, KA, Chandrajith, R, Coghlane, JP, Coulson, SG, Ghosh, S, Gillmang, M, Gorczynskih, RM, Klyce, B, Louis, G, Mahanamaj, K, Oliverk, KR, Padron, J, Qu, J, Schuster, JA, Smith, WE, Snyder, DP, Steele, JA, Stewart, BJ, Temple, R, Tokoro, G, Tout, CA, Unzicker, A, Wainwright, M, Wallis, J, Wallis, DH, Wallis, MK, Wetherall, J, Wickramasinghe, DT, Wickramasinghe, JT, Wickramasinghe, NC & Liu, Y 2018, 'Cause of Cambrian explosion – terrestrial or cosmic?', *Progress in Biophysics and Molecular Biology*, vol. 136, pp. 3–23. https://doi.org/10.1016/J.PBIOMOLBIO.2018.03.004

Sutherland, JD 2017, 'Opinion: studies on the origin of life – the end of the beginning', *Nature Reviews Chemistry*, vol. 1, no. 2, a12. https://doi.org/10.1038/s41570-016-0012

Szostak, J 2018, 'How did life begin? Innovations-in', *Nature*, vol. 557, no. 7704, pp. 13–15. https://doi.org/10.1038/D41586-018-05098-W

Tompa, P & Rose, GD 2011, 'The Levinthal paradox of the interactome', *Protein Science*, vol. 20, no. 12, pp. 2074–2079.

Tour, J 2016, 'Animadversions of a synthetic chemist', *Inference*, viewed 04 May 2022, <https://inference-review.com/article/animadversions-of-a-synthetic-chemist>

Tour, J 2019 'Time out', *Inference: International Review of Science*, vol. 4, no. 4, viewed 20 November 2021, <https://inference-review.com/article/time-out>

Tour, J 2017b, 'An open letter to my colleagues', *Inference*, viewed 04 May 2022, <https://inference-review.com/article/an-open-letter-to-my-colleagues>

Tour, JM 2017a, *Theistic evolution: a scientific, philosophical, and theological critique*, eds. JP Moreland, SC Meyer, C Shaw, AK Gauger & W Grudem, Crossway, Carol Stream.

Tour, JM, Kozaki, M & Seminario, JM 1998, 'Molecular scale electronics: a synthetic/computational approach to digital computing', *Journal of the American Chemical Society*, vol. 120, no. 33, pp. 8486–8493. https://doi.org/10.1021/JA9808090

University of California – San Diego 2018, 'Copycat cells command new powers of communication', Phys.org, viewed 20 November 2021, <https://ucsdnews.ucsd.edu/feature/copycat-cells-command-new-powers-of-communication>

Van Kranendonk, M, Deamer, D & Djokic, T 2017, 'Life on earth came from a hot volcanic pool, not the sea, new evidence suggests', *Scientific American*, vol. 317, no. 2, pp. 28–35. https://doi.org/10.1038/scientificamerican0817-28

Vives, G, Guerrero, JM, Godoy, J, Khatua, S, Wang, Y-P, Kiappes, JL, Link, S & Tour, JM 2010, 'Synthesis of fluorescent dye-tagged nanomachines for single-molecule fluorescence spectroscopy', *Journal of Organic Chemistry*, vol. 75, no. 19, pp. 6631–6643. https://doi.org/10.1021/JO101468U.

Vives, G & Tour, JM 2009, 'Synthesis of single-molecule nanocars', *Accounts of Chemical Research*, vol. 42, no. 3, pp. 473–487. https://doi.org/10.1021/AR8002317

Chapter 7

Alba, V, Carthew, JE, Carthew, RW & Mani, M 2021 'Global constraints within the developmental program of the *Drosophila* wing', *eLife*, vol. 10, a66750. https://doi.org/10.7554/ELIFE.66750

Araujo, RP & Liotta, LA 2018, 'The topological requirements for robust perfect adaptation in networks of any size', *Nature Communications*, vol. 9, no. 1, pp. 1–12. https://doi.org/10.1038/s41467-018-04151-6

Archer-Hind, RD 1888, *The Timaeus of Plato*, McMillan & Co, London, viewed 21 June 2021, <https://philpapers.org/rec/PLAPT-4>

Aristotle 2010, *On the generation of animals*, Kessinger Publishing, Whitefish.

Axe, DD 2004, 'Estimating the prevalence of protein sequences adopting functional enzyme folds', *Journal of Molecular Biology*, vol. 341, no. 5, pp. 1295–1315. https://doi.org/10.1016/j.jmb.2004.06.058

Ayala, FJ 2007, 'Darwin's greatest discovery: design without designer', *Proceedings of the National Academy of Sciences of the United States of America*, vol. 104, no. Suppl 1, pp. 8567–8573. https://doi.org/10.1073/pnas.0701072104

Baker, JA, Wund, MA, Heins, DC, King, RW, Reyes, ML & Foster, SA 2015, 'Life-history plasticity in female threespine stickleback', *Heredity*, vol. 115, no. 4, pp. 322–334. https://doi.org/10.1038/hdy.2015.65

Ballard, WW 1976, 'Problems of gastrulation: real and verbal', *BioScience*, vol. 26, no. 1, pp. 36–39. https://doi.org/10.2307/1297297.

Ballinger, MA & Nachman, MW 2022, 'The contribution of genetic and environmental effects to Bergmann's rule and Allen's rule in house mice', *The American Naturalist*, vol. 199, no. 5, pp. 691–704. https://doi.org/10.1101/2021.06.14.448454.

Behe, M 2019, *Darwin devolves: the new science about DNA that challenges evolution*, HarperOne, San Francisco.

Behe, MJ 2020, *A mousetrap for Darwin: Michael J. Behe answers his critics*, Discovery Institute, Seattle.

Bershtein, S, Segal, M, Bekerman, R, Tokuriki, N & Tawfik, DS 2006, 'Robustness–epistasis link shapes the fitness landscape of a randomly drifting protein', *Nature*, vol. 444, no. 7121, pp. 929–932. https://doi.org/10.1038/nature05385

Bilandžija, H, Hollifield, B, Steck, M, Meng, G, Ng, M, Koch, AD, Gracan, R, Cetkovic, H, Porter, ML, Renner, KJ & Jeffery, W 2020, 'Phenotypic plasticity as a mechanism of cave colonization and adaptation', *eLife*, vol. 9. https://doi.org/10.7554/ELIFE.51830

Bitner-Mathé, BC & Klaczko, LB 1999, 'Plasticity of *Drosophila melanogaster* wing morphology: effects of sex, temperature and density', *Genetica*, vol. 105, no. 2, pp. 203–210. https://doi.org/10.1023/A:1003765106652

Bloch, JI, Silcox, MT, Boyer, DM & Sargis, EJ 2007, 'From the cover: new Paleocene skeletons and the relationship of plesiadapiforms to crown-clade primates', *Proceedings of the National Academy of Sciences of the United States of America*, vol. 104, no. 4, a1159. https://doi.org/10.1073/PNAS.0610579104

Bos, AP 2003, *The soul and its instrumental body: a reinterpretation of Aristotle's philosophy of living nature*, Brill, Leiden.

Bos, AP 2018, *Aristotle on God's life-generating power and on pneuma as its vehicle*, SUNY Press, Albany.

Bosl, WJ & Li, R 2005, 'Mitotic-exit control as an evolved complex system', *Cell*, vol. 121, no. 3, pp. 325–333.

Braillard, P-A 2010, 'Systems biology and the mechanistic framework', *History and Philosophy of the Life Sciences*, vol. 32, no. 1, pp. 43–62.

Branscomb, E & Russell, MJ 2018a, 'Frankenstein or a Submarine Alkaline Vent: who is responsible for abiogenesis?: Part 1: what is life-that it might create itself?', *BioEssays*, vol. 40, no. 7, a1700179. https://doi.org/10.1002/bies.201700182

Branscomb, E & Russell, MJ 2018b, 'Frankenstein or a Submarine Alkaline Vent: who is responsible for abiogenesis?: Part 2: as life is now, so it must have been in the beginning', *BioEssays*, vol. 40, no. 8, a1700182. https://doi.org/10.1002/bies.201700182

Bucher, E, Reinders, J & Mirouze, M 2012, 'Epigenetic control of transposon transcription and mobility in Arabidopsis', *Current Opinion in Plant Biology*, vol. 15, no. 5, pp. 503–510. https://doi.org/10.1016/J.PBI.2012.08.006

Burgess, SC & Etoundi, AC 2014, 'Performance maps for a bio-inspired robotic condylar hinge joint', *Journal of Mechanical Design, Transactions of the ASME*, vol. 136, no. 11, a115002. https://doi.org/10.1115/1.4028168/375277

Campbell, G 2004, *Lucretius on creation and evolution: a commentary on De Rerum Natura, Book Five*, *Lines 772–1104*, Oxford University Press, Oxford.

Capy, P, Gasperi, G, Biémont, C & Bazin, C 2000, 'Stress and transposable elements: co-evolution or useful parasites?', *Heredity*, vol. 85, no. 2, pp. 101–106. https://doi.org/10.1046/j.1365-2540.2000.00751.x

Carleton, KL, Conte, MA, Malinsky, M, Nandamuri, SP, Sandkam, BA, Meier, JI, Mwaiko, S, Seehausen, O & Kocher, TD 2020, 'Movement of transposable elements contributes to cichlid diversity', *Molecular Ecology*, vol. 29, no. 24, pp. 4956–4969. https://doi.org/10.1111/MEC.15685

Chuong, EB 2018, 'The placenta goes viral: retroviruses control gene expression in pregnancy', *PLoS Biology*, vol. 16, no. 10, a3000028. https://doi.org/10.1371/JOURNAL.PBIO.3000028

Collard, M & Wood, B 2000, 'How reliable are human phylogenetic hypotheses?', *Proceedings of the National Academy of Sciences*, vol. 97, no. 9, pp. 5003–5006. https://doi.org/10.1073/PNAS.97.9.5003

Cooper, WJ, Parsons, K, McIntyre, A, Kern, B, McGee-Moore, A & Albertson, RC 2010, 'Bentho-pelagic divergence of Cichlid feeding architecture was prodigious and consistent during multiple adaptive radiations within African rift-lakes', *PLoS One*, vol. 5, no. 3, a9551. https://doi.org/10.1371/JOURNAL.PONE.0009551

Corral, WDR & Aguirre, WE 2019, 'Effects of temperature and water turbulence on vertebral number and body shape in Astyanax mexicanus (Teleostei: Characidae)', *PLoS One*, vol. 14, no. 7, a0219677. https://doi.org/10.1371/JOURNAL.PONE.0219677

Coyne, JA 2019, 'Intelligent design gets even dumber', *The Washington Post*, 8th March, viewed 29 August 2021, <https://www.washingtonpost.com/outlook/intelligent-design-gets-even-dumber/2019/03/08/7a8e72dc-289e-11e9-b2fc-721718903bfc_story.html>

Davidson, EH 2011, 'Evolutionary bioscience as regulatory systems biology', *Developmental Biology*, vol. 357, no. 1, a004. https://doi.org/10.1016/J.YDBIO.2011.02.004

Dembski, WA 2006, *The design inference: eliminating chance through small probabilities*, Cambridge University Press, Cambridge.

Dietrich, CR, Cui, F, Packila, ML, Li, J, Ashlock, DA, Nikolau, BJ & Schnable, PS 2002, 'Maize Mu transposons are targeted to the 5' untranslated region of the gl8 gene and sequences flanking Mu target-site duplications exhibit nonrandom nucleotide composition throughout the genome', *Genetics*, vol. 160, no. 2, a697. https://doi.org/10.1093/genetics/160.2.697

Dunn, R 2012, 'Your appendix could save your life', *Scientific American*, vol. 306, no. 3, a22. https://doi.org/10.1038/scientificamerican0312-22b

Durrett, R & Schmidt, D 2008, 'Waiting for two mutations: with applications to regulatory sequence evolution and the limits of Darwinian evolution', *Genetics*, vol. 180, no. 3, pp. 1501–1509. https://doi.org/10.1534/genetics.107.082610

El-Samad, H, Kurata, H, Doyle, JC, Gross, CA & Khammash, M 2005, 'Surviving heat shock: control strategies for robustness and performance', *Proceedings of the National Academy of Sciences of the United States of America*, vol. 102, no. 8, pp. 2736–2741.

Etoundi, AC, Burgess, SC & Vaidyanathan, R 2013, 'A bio-inspired condylar hinge for robotic limbs', *Journal of Mechanisms and Robotics*, vol. 5, no. 3, a031011. https://doi.org/10.1115/1.4024471/474904

Evans, LDB, Hughes, C & Fraser, GM 2014, 'Building a flagellum outside the bacterial cell', *Trends in Microbiology*, vol. 22, no. 10, pp. 566–572. https://doi.org/10.1016/j.tim.2014.05.009

Ewert, W 2018, 'The dependency graph of life', *BIO-Complexity*, vol. 2018, no. 2, pp. 1–27.

Ewert, W, Marks, RJ & Dembski, WA 2013, 'On the improbability of algorithmic specified complexity', *paper presented at proceedings of the annual Southeastern symposium on system theory*, Waco, 11 March.

Feilich, KL 2016, 'Correlated evolution of body and fin morphology in the cichlid fishes', *Evolution*, vol. 70, no. 10, pp. 2247–2267. https://doi.org/10.1111/EVO.13021

Feser, E 2019, *Aristotle's revenge: the metaphysical foundations of physical and biological science*, Editiones Scholasticae, Havertown.

Field, GD & Sampath, AP 2017, 'Behavioural and physiological limits to vision in mammals', *Philosophical Transactions of the Royal Society B: Biological Sciences*, vol. 372, no. 1717, a20160072. https://doi.org/10.1098/RSTB.2016.0072

Filmer, AK 2017, *Tracking down the jumping genes of maize: new map will aid research, breeding efforts*, viewed 21 September 2021, <https://www.ucdavis.edu/news/tracking-down-jumping-genes-maize>

Fitzgerald, DM, Bonocora, RP & Wade, JT 2014, 'Comprehensive mapping of the *Escherichia coli* flagellar regulatory network', *PLoS Genetics*, vol. 10, no. 10, a1004807. https://doi.org/10.1371/journal.pgen.1004649

Fondon, JW & Garner, HR 2004, 'Molecular origins of rapid and continuous morphological evolution', *Proceedings of the National Academy of Sciences*, vol. 101, no. 52, pp. 18058–18063. https://doi.org/10.1073/PNAS.0408118101

Fraimout, A, Jacquemart, P, Villarroel, B, Aponte, DJ, Decamps, T, Herrel, A, Cornette, R & Debat, V 2018, 'Phenotypic plasticity of *drosophila suzukii* wing to developmental temperature: implications for flight', *Journal of Experimental Biology*, vol. 221, no. 13, a166868. https://doi.org/10.1242/JEB.166868/33744

Freitas, RA (ed.) 1980, 'Replicating systems concepts: self-replicating lunar factory and demonstration', in *Proceedings of the 1980 NASA/ASEE Summer Study*, 23 June – 20 August 1980, Santa Clara, pp. 189–264.

Frølich, S, Weaver, JC, Dean, MN & Birkedal, H 2017, 'Uncovering nature's design strategies through parametric modeling, multi-material 3D printing, and mechanical testing', *Advanced Engineering Materials*, vol. 19, no. 6, a201600848. https://doi.org/10.1002/ADEM.201600848

Gao, X, Fu, Y, Ajayi, OE, Guo, D, Zhang, L & Wu, Q 2019, 'Identification of genes underlying phenotypic plasticity of wing size via insulin signaling pathway by network-based analysis in Sogatella furcifera', *BMC Genomics*, vol. 20, no. 1, a396. https://doi.org/10.1186/S12864-019-5793-Z

Gatherer, D 2010, ‘So what do we really mean when we say that systems biology is holistic?’, *BMC Systems Biology*, vol. 4, no. 1, pp. 1–12. https://doi.org/10.1186/1752-0509-4-22/METRICS

Gerson, LP 2005, *Aristotle and other platonists*, Cornell University Press, Ithaca.

Gingerich, PD 2006, ‘Environment and evolution through the Paleocene-Eocene thermal maximum’, *Trends in Ecology & Evolution*, vol. 21, no. 5, pp. 246–253. https://doi.org/10.1016/J.TREE.2006.03.006

Graur, D 2013, ‘How to assemble a human genome? Mix generous amounts of junk DNA and indifferent DNA, add a dollop of garbage DNA and a sprinkling of Functional DNA (Lazarus DNA optional)’, lecture slides, 4th Meeting of the Spanish Society for Evolutionary Biology (SESBE), Barcelona, 27–29th November, viewed 14 October 2021, <https://www.slideshare.net/dangraur1953/update-version-of-the-smbesesbe-lecture-on-encode-junk-dna-graur-december-2013>

Guliuzza, RJ & Gaskill, PB 2018, ‘Continuous environmental tracking: an engineering framework to understand adaptation and diversification’, *Proceedings of the International Conference on Creationism*, vol. 8, no. 1, a17. https://doi.org/10.15385/jpicc.2018.8.1.17

Günther, M, Keppler, V, Seyfarth, A & Blickhan, R 2004, ‘Human leg design: optimal axial alignment under constraints’, *Journal of Mathematical Biology*, vol. 48, no. 6, pp. 623–646. https://doi.org/10.1007/S00285-004-0269-3

Hall, S 2012, ‘Hidden treasures in junk DNA’, *Scientific American*, vol. 307, no. 4, pp. 72–75.

Hamadeh, A, Roberts, MAJ, August, E, McSharry, PE, Maini, PK, Armitage, JP & Papachristodoulou, A 2011, ‘Feedback control architecture and the bacterial chemotaxis network’, *PLoS Computational Biology*, vol. 7, no. 5, a1001130. https://doi.org/10.1371/journal.pcbi.1001130

Hanke, D 2004, ‘Teleology: the explanation that bedevils biology’, in J Cornwell (ed.), *Explanations: styles of explanation in science*, Oxford University Press, Oxford, pp. 143–155.

Härer, A, Karagic, N, Meyer, A & Torres-Dowdall, J 2019, ‘Reverting ontogeny: rapid phenotypic plasticity of colour vision in cichlid fish’, *Royal Society Open Science*, vol. 6, no. 7, pp. 1–7. https://doi.org/10.1098/RSOS.190841

Henry, D 2019, *Aristotle on matter, form, and moving causes: the hylomorphic theory of substantial generation*, Cambridge University Press, Cambridge.

Herman, JJ & Sultan, SE 2016, ‘DNA methylation mediates genetic variation for adaptive transgenerational plasticity’, *Proceedings of the Royal Society B: Biological Sciences*, vol. 283, no. 1838, a20160988. https://doi.org/10.1098/RSPB.2016.0988

Hohenlohe, PA, Bassham, S, Etter, PD, Stiffler, N, Johnson, EA & Cresko, WA 2010, ‘Population genomics of parallel adaptation in threespine stickleback using sequenced RAD tags’, *PLoS Genetics*, vol. 6, no. 2, p. a1000862. https://doi.org/10.1371/JOURNAL.PGEN.1000862

Hössjer, O, Bechly, G & Gauger, A 2021, ‘On the waiting time until coordinated mutations get fixed in regulatory sequences’, *Journal of Theoretical Biology*, vol. 524, a110657. https://doi.org/10.1016/J.JTBI.2021.110657

Huttenlocker, A 2009, ‘An investigation into the cladistic relationships and monophyly of therocephalian therapsids (Amniota: Synapsida)’, *Zoological Journal of the Linnean Society*, vol. 157, no. 4, pp. 865–891. https://doi.org/10.1111/J.1096-3642.2009.00538.X

Ishikawa, A, Kabeya, N, Ikeya, K, Kakioka, R, Cech, JN, Osada, N, Leal, MC, Inoue, J, Kume, M, Toyoda, A, Tezuka, A, Nagano, AJ, Yamasaki, YY, Suzuki, Y, Kokita, T, Takahashi, H, Lucek, K, Marques, D, Takehana, Y, Naruse, K, Mori, S, Monroig, O, Ladd, N, Schubert, CJ, Matthews, B, Peichel, CL, Seehausen, O, Yoshizaki, G & Kitano, J 2019, ‘A key metabolic gene for recurrent freshwater colonization and radiation in fishes’, *Science*, vol. 364, no. 6443, pp. 886–889. https://doi.org/10.1126/science.aau5656

Jacka, CV, Cruz, C, Hull, RM, Keller, MA, Ralser, M & Houseley, J 2015, ‘Regulation of ribosomal DNA amplification by the TOR pathway’, *Proceedings of the National Academy of Sciences of the United States of America*, vol. 112, no. 31, pp. 9674–9679. https://doi.org/10.1073/pnas.1505015112

Kalinka, AT & Tomancak, P 2012, ‘The evolution of early animal embryos: conservation or divergence?, *Trends in Ecology & Evolution*, vol. 27, no. 7, pp. 385–393. https://doi.org/10.1016/J.TREE.2012.03.007

Keener, C 2009, *Romans: a new covenant commentary*, Cascade Books, Eugene.

Keum, D, Jang, K-W, Jeon, DS, Hwang, CSH, Buschbeck, EK, Kim, MH Jeong, K-H 2018, '*Xenos peckii* vision inspires an ultrathin digital camera', *Light: Science & Applications*, vol. 7, no. 1, pp. 1–7. https://doi.org/10.1038/s41377-018-0081-2

Kim, HJ, Yoo, W, Jin, KS, Ryu, S & Lee, HH 2017, 'The role of the FliD C-terminal domain in pentamer formation and interaction with FliT', *Scientific Reports*, vol. 7, no. 1, a4418. https://doi.org/10.1038/s41598-017-02664-6

Kitcher, P 2007, *Living with Darwin: evolution, design, and the future of faith*, Oxford University Press, Oxford.

Klassen, GJ, Mooi, RD & Locke, A 1991, 'Consistency indices and random data', *Systematic Biology*, vol. 40, no. 4, pp. 446–457. https://doi.org/10.1093/SYSBIO/40.4.446

Koonin, EV2007, 'The biological Big Bang model for the major transitions in evolution', *Biology Direct*, vol. 2, a21. https://doi.org/10.1186/1745-6150-2-21

Krebs, HA 1954, 'Excursion into the borderland of biochemistry and philosophy', *Bulletin Johns Hopkins Hospital*, vol. 95, no. 1, pp. 45–51.

Lents, N 2018, *Human errors: a panorama of our glitches, from pointless bones to broken genes*, Mariner Books, New York.

Lieberman, D 2013, *The story of the human body: evolution, health, and disease*, Vintage Books, New York.

Lloyd, GE 1970, *Early Greek science: Thales to Aristotle*, WW Norton & Company, New York.

Losos, JB, Creer, DA, Glossip, D, Goellner, R, Hampton, A, Roberts, G, Haskell, N, Taylor, P & Ettling, J 2000, 'Evolutionary implications of phenotypic plasticity in the hindlimb of the lizard *Anolis sagrei', Evolution*, vol. 54, no. 1, pp. 301–305. https://doi.org/10.1111/J.0014-3820.2000.TB00032.X

Lundin, E, Tang, P-C, Guy, L, Näsvall, J & Andersson, DI 2018 'Experimental determination and prediction of the fitness effects of random point mutations in the biosynthetic enzyme HisA', *Molecular Biology and Evolution*, vol. 35, no. 3, pp. 704–718. https://doi.org/10.1093/molbev/msx325

Makarevitch, I, Waters, AJ, West, PT, Stitzer, M, Hirsch, CN, Ross-Ibarra, J & Springer, NM 2015, 'Transposable elements contribute to activation of maize genes in response to abiotic stress', *PLOS Genetics*, vol. 11, no. 1, a1004915. https://doi.org/10.1371/JOURNAL.PGEN.1004915

Mantri, P & Thomas, J 2019, 'Nature's design's: the biology of survival', *MATEC Web of Conferences*, vol. 301, a00023. https://doi.org/10.1051/MATECCONF/201930100023

Martin, WF 2017, 'Too much Eukaryote LGT', *BioEssays*, vol. 39, no. 12, a1700115. https://doi.org/10.1002/BIES.201700115

Maruyama, M & Parker, J 2017, 'Deep-time convergence in Rove beetle symbionts of army ants', *Current Biology*, vol. 27, no. 6, pp. 920–926. https://doi.org/10.1016/j.cub.2017.02.030

Mazzarella, AB, Voje, KL, Hansson, TH, Taugbøl, A & Fischer, B 2015, 'Strong and parallel salinity-induced phenotypic plasticity in one generation of threespine stickleback', *Journal of Evolutionary Biology*, vol. 28, no. 3, pp. 667–677. https://doi.org/10.1111/JEB.12597

McCairns, RJS & Bernatchez, L 2010, 'Adaptive divergence between freshwater and marine sticklebacks: insights into the role of phenotypic plasticity from an integrated analysis of candidate gene expression', *Evolution*, vol. 64, no. 4, pp. 1029–1047. https://doi.org/10.1111/J.1558-5646.2009.00886.X

McDonald, JF 1983, 'The molecular basis of adaptation: a critical review of relevant ideas and observations', *Annual Review of Ecology and Systematics*, vol. 14, pp. 77–102. https://doi.org/10.1146/ANNUREV.ES.14.110183.000453

McGrath, C 2021, 'Highlight – "junk DNA" no more: repetitive elements as vital sources of flatworm variation', *Genome Biology and Evolution*, vol. 13, no. 10, a217. https://doi.org/10.1093/GBE/EVAB217.

Mérel, V, Boulesteix, M, Fablet, M & Vieira, C 2020, 'Transposable elements in *Drosophila*', *Mobile DNA*, vol. 11, no. 1, pp. 1–20. https://doi.org/10.1186/S13100-020-00213-Z/FIGURES/4.

Merhej, V & Raoult, D 2012, 'Rhizome of life, catastrophes, sequence exchanges, gene creations, and giant viruses: how microbial genomics challenges Darwin', *Frontiers in Cellular and Infection Microbiology*, vol. 2, no. 113, pp. 23–39. https://doi.org/10.3389/fcimb.2012.00113

Meyer, SC 2013, *Darwin's doubt: the explosive origin of animal life and the case for intelligent design*, HarperOne, New York.

Meyer, SC 2021, *Return of the God hypothesis: three scientific discoveries that reveal the mind behind the universe*, HarperOne, San Francisco.

Miller, B 2017a, 'Eye evolution: a closer look', *Evolution News & Science Today*, viewed 14 October 2021, <https://evolutionnews.org/2017/02/eye_evolution_a/>

Miller, B 2017b, 'Eye evolution: the waiting is the hardest part', *Evolution News & Science Today*, viewed 14 October 2021, <https://evolutionnews.org/2017/02/eye_evolution_t/>

Miller, B 2018, 'BIO-complexity presents better model than common ancestry for explaining pattern of nature', *Evolution News & Science Today*, viewed 04 May 2022, <https://evolutionnews.org/2018/07/bio-complexity-presents-a-better-model-than-common-ancestry-for-explaining-the-pattern-of-nature/>

Miller, B 2020a, 'Hot wired', *Inference*, vol. 5, no. 2, viewed 14 October 2021, <https://doi.org/10.37282/991819.20.2>

Miller, B 2020b, 'Thermodynamic challenges to the origin of life', in *The mystery of life's origin: the continuing controversy*, Discovery Institute Press, Seattle, pp. 359–374.

Miller, B 2021a, 'End of the road for the intelligent design debate?', *Evolution News & Science Today*, viewed 14 October 2021, <https://evolutionnews.org/2021/08/end-of-the-road-for-the-intelligent-design-debate/>

Miller, B 2021b, 'Engineering-based models better explain the pattern of nature than does common ancestry', *Evolution News & Science Today*, viewed 14 October 2021, <https://evolutionnews.org/2021/12/engineering-based-models-better-explain-the-pattern-of-nature-than-does-common-ancestry/>

Miller, B 2021c, 'How engineers helped save biology from evolutionary theory', *Evolution News & Science Today*, viewed 14 October 2021, <https://evolutionnews.org/2021/08/how-engineers-helped-save-biology-from-evolutionary-theory/>

Miller, B 2021d, 'Studies on Cichlid fish demonstrate the predictive power of engineering models for adaptation', *Evolution News & Science Today*, viewed 14 October 2021, <https://evolutionnews.org/2021/10/studies-on-cichlid-fish-demonstrate-the-predictive-power-of-engineering-models-for-adaptation/>

Miller, B 2021e, 'Studies on insect wings validate engineering models for adaptation', *Evolution News & Science Today*, viewed 14 October 2021, <https://evolutionnews.org/2021/10/studies-on-insect-wings-validate-engineering-models-for-adaptation/>

Miller, B 2021f, 'Studies on Stickleback fish further validate engineering models for adaptation', *Evolution News & Science Today*, viewed 14 October 2021, <https://evolutionnews.org/2021/10/studies-on-stickleback-fish-further-validate-engineering-models-for-adaptation/>

Miller, B 2021g, 'The return of teleology to biology', *Evolution News & Science Today*, viewed 14 October 2021, <https://evolutionnews.org/2021/08/the-return-of-teleology-to-biology/>

Miller, B 2021h, 'Why systems biologists now assume life is optimally designed', *Evolution News & Science Today*, viewed 14 October 2021, <https://evolutionnews.org/2021/08/why-systems-biologists-now-assume-life-is-optimally-designed/>

Miller, B 2022, 'Bacterial flagellum demonstrates the explanatory and predictive power of engineering models', *Evolution News & Science Today*, viewed 14 October 2021, <https://evolutionnews.org/2022/01/bacterial-flagellum-demonstrates-the-explanatory-and-predictive-power-of-engineering-models/>

Miller, SE, Roesti, M & Schluter, D 2019, 'A single interacting species leads to widespread parallel evolution of the stickleback genome', *Current Biology*, vol. 29, no. 3, pp. 530–53. https://doi.org/10.1016/J.CUB.2018.12.044

Miller, WB, Enguita, FJ & Leitão, AL 2021, 'Non-random genome editing and natural cellular engineering in cognition-based evolution', *Cells*, vol. 10, no. 5, a1125. https://doi.org/10.3390/CELLS10051125

Morange, M 2008, 'The death of molecular biology?', *History and Philosophy of the Life Sciences*, vol. 30, no. 1, pp. 31–42.

Moreland, JP, Meyer, SC, Shaw, C, Gauger, AK, Grudem, W, Axe, DD, Collins, CJ, Currid, JD, Waters, GP, Allison, GR, Zaspel, FG, Leisola, M, Tour, JM, Ewert, W, Wells, J, Tyler, S, Bechly, G, Luskin, C, Nelson, PA, Hössjer, O, Reeves, CR, Dilley, S, DeWeese, GJ, Poulimatka, T, West, JG & Fuller, S (eds.) 2017, *Theistic evolution: a scientific, philosophical, and theological critique*, Crossway, Wheaton.

Moses, MS & Chirikjian, GS 2020, 'Robotic self-replication', *Annual Review of Control, Robotics, and Autonomous Systems*, vol. 3, no. 1, pp. 1–24. https://doi.org/10.1146/annurev-control-071819-010010

Mukhopadhyay, R 2013, 'Close to a miracle', *ASBMB Today*, 23 September, viewed 15 October 2021, <https://www.asbmb.org/asbmb-today/science/092313/close-to-a-miracle>

Nagai, H, Terai, Y, Sugawara, T, Imai, H, Nishihara, H, Hori, M & Okada, N 2011, 'Reverse evolution in RH1 for adaptation of cichlids to water depth in lake Tanganyika', *Molecular Biology and Evolution*, vol. 28, no. 6, pp. 1769–1776. https://doi.org/10.1093/MOLBEV/MSQ344

Navon, D, Hatini, P, Zogbaum, L & Albertson, RC 2021, 'The genetic basis of coordinated plasticity across functional units in a Lake Malawi cichlid mapping population', *Evolution*, vol. 75, no. 3, pp. 672–687. https://doi.org/10.1111/EVO.14157

Nordin, M 2021, *Basic biomechanics of the musculoskeletal system*, 5th edn, LWW, Philadelphia.

Ogino, H, Ochiab, H, Rezac, M & Yasudaa, K 2012, 'Transcription factors involved in lens development from the preplacodal ectoderm', *Developmental Biology*, vol. 363, no. 2, pp. 333–347. https://doi.org/10.1016/J.YDBIO.2012.01.006

Ohnishi, K, Ohto, Y, Aizawa, S, Macnab, RM & Iino, T 1994, 'FlgD is a scaffolding protein needed for flagellar hook assembly in Salmonella typhimurium', *Journal of Bacteriology*, vol. 176, no. 8, pp. 2272–2281. https://doi.org/10.1128/JB.176.8.2272-2281.1994

Parker, J, Tsagkogeorga, G, Cotton, JA, Liu, Y, Provero, P, Stupka, E & Rossiter, SJ 2013, 'Genome-wide signatures of convergent evolution in echolocating mammals', *Nature*, vol. 502, no. 7470, pp. 228–231. https://doi.org/10.1038/nature12511

Parsons, KJ, Concannon, M, Navon, D, Wang, J, Ea, I, Groveas, K, Campbell, C & Albertson, RC 2016, 'Foraging environment determines the genetic architecture and evolutionary potential of trophic morphology in cichlid fishes', *Molecular Ecology*, vol. 25, no. 24, pp. 6012–6023. https://doi.org/10.1111/MEC.13801

Petkova, MD, Tkačik, G, Bialek, W, Wieschaus, EF & Gregor, T 2019, 'Optimal decoding of cellular identities in a genetic network', *Cell*, vol. 176, no. 4, pp. 844–855. https://doi.org/10.1016/J.CELL.2019.01.007

Pezzulo, G & Levin, M 2016, 'Top-down models in biology: explanation and control of complex living systems above the molecular level', *Journal of the Royal Society Interface*, vol. 13, no. 124, a0555. https://doi.org/10.1098/rsif.2016.0555

Pfennig, DW (ed.) 2021, *Phenotypic plasticity & evolution: causes, consequences, controversies*, CRC Press, Boca Raton.

Piatigorsky, J 2008, 'A genetic perspective on eye evolution: gene sharing, convergence and parallelism', *Evolution: Education and Outreach*, vol. 1, no. 4, pp. 403–414. https://doi.org/10.1007/s12052-008-0077-0

Piñeros, WD & Tlusty, T 2019, 'Kinetic proofreading and the limits of thermodynamic uncertainty', *Physical Review E*, vol. 101, a022415. https://doi.org/10.1103/PhysRevE.101.022415

Quinodoz, SA, Jachowicz, JW, Bhat, P, Ollikainen, N, Banerjee, AK, Goronzy, IN, Blanco, MR, Chovanec, P, Chow, A, Markaki, Y, Thai, J, Plath, K & Guttman, M 2021, 'RNA promotes the formation of spatial compartments in the nucleus', *Cell*, vol. 184, no. 23, pp. 5775–5790. https://doi.org/10.1016/J.CELL.2021.10.014

Reeves, GT & Hrischuk, CE 2016, 'Survey of engineering models for systems biology', *Computational Biology Journal*, vol. 2016, pp. 1–12. https://doi.org/10.1155/2016/4106329

Reiss, J 2009, *Not by design: retiring Darwin's watchmaker*, University of California Press, Oakland.

Rohner, N, Jarosz, DF, Kowalko, JE, Yoshizawa, M, Jeffery, WR, Borowsky, RL, Lindquist, S & Tabin, CJ 2013, 'Cryptic variation in morphological evolution: HSP90 as a capacitor for loss of eyes in cavefish', *Science*, vol. 342, no. 6164, pp. 1372–1375. https://doi.org/10.1126/SCIENCE.1240276

Sanes, JR & Zipursky, SL 2010, 'Design principles of insect and vertebrate visual systems', *Neuron*, vol. 66, no. 1, pp. 15–36. https://doi.org/10.1016/J.NEURON.2010.01.018

Sarras, MP, Rosenzweig, LJ, Addis, JS & Hossler, FE 1985, 'Plasma membrane biogenesis in the avian salt gland: a biochemical and quantitative electron microscopic autoradiographic study', *American Journal of Anatomy*, vol. 174, no. 1, pp. 45–60. https://doi.org/10.1002/AJA.1001740105

Schulz, WA 2021a, 'An engineering perspective on the bacterial flagellum: part 1 – constructive view', *BIO-Complexity*, vol. 2021, no. 1, pp. 1–14. https://doi.org/10.5048/BIO-C.2021.1

Schulz, WA 2021b, 'An engineering perspective on the bacterial flagellum: part 2 – analytic view', *BIO-Complexity*, vol. 2021, no. 2, pp. 1–16. https://doi.org/10.5048/BIO-C.2021.2

Schulz, WA 2021c, 'An engineering perspective on the bacterial flagellum: part 3 – observations', *BIO-Complexity*, vol. 2021, no. 3, pp. 1–7. https://doi.org/10.5048/BIO-C.2021.3

Sedley, D 2008, *Creationism and its critics in antiquity*, University of California Press, Oakland.

Seo, JT & Yi, BJ 2009, 'Modeling and analysis of a biomimetic foot mechanism', *The 2009 IEEE/RSJ International conference on Intelligent Robots and Systems*, St. Louis, 11–15 October 2009.

Shapiro, JA 2016, 'Nothing in evolution makes sense except in the light of genomics: read-write genome evolution as an active biological process', *Biology*, vol. 5, no. 2, pp. 1–27. https://doi.org/10.3390/BIOLOGY5020027

Shapiro, JA 2017, 'Biological action in read-write genome evolution', *Interface Focus*, vol. 7, no. 5, a0115. https://doi.org/10.1098/rsfs.2016.0115

Sieriebriennikov, B, Prabh, N, Dardiry, M, Witte, H, Röseler, W, Kieninger, MR, Rodelsperger, C & Sommer, RJ 2018, 'A developmental switch generating phenotypic plasticity is part of a conserved multi-gene locus', *Cell Reports*, vol. 23, no. 10, pp. 2835–2843. https://doi.org/10.1016/J.CELREP.2018.05.008

Simpson, ML, Cox, CD, Sayler, GD & Peterson, G 2004, 'Engineering in the biological substrate: information processing in genetic circuits', *Proceedings of the IEEE*, vol. 92, no. 5, pp. 848–863. https://doi.org/10.1109/JPROC.2004.826600

Snoke, DW, Cox, J & Petcher, D 2015, 'Suboptimality and complexity in evolution', *Complexity*, vol. 21, no. 1, pp. 322–327. https://doi.org/10.1002/cplx.21566

Snyder, M, Gingeras, T, Moore, J, Weng, Z, Gerstein, M, Ren, B, et al. 2020, 'Perspectives on ENCODE', *Nature*, vol. 583, no. 7818, pp. 693–698.

Sommer, RJ 2020, 'Phenotypic plasticity: from theory and genetics to current and future challenges', *Genetics*, vol. 215, no. 1, pp. 1–13. https://doi.org/10.1534/GENETICS.120.303163

Sultana, T, Zamborlini, A, Cristofari, G & Lesage, P 2017, 'Integration site selection by retroviruses and transposable elements in eukaryotes', *Nature Reviews Genetics*, vol. 18, no. 5, pp. 292–308. https://doi.org/10.1038/NRG.2017.7

Szallasi, Z, Stelling, J & Periwal, V 2007, *System modeling in cellular biology: from concepts to nuts and bolts*, MIT Press, Cambridge.

Thewissen, JGM, Williams, EM, Roe, LJ & Hussain, ST 2001, 'Skeletons of terrestrial cetaceans and the relationship of whales to artiodactyls', *Nature*, vol. 413, no. 6853, pp. 277–281. https://doi.org/10.1038/35095005

Tibblin, P, Hall, MP, Svensson, A, Merilä, J & Forsman, A 2020, 'Phenotypic flexibility in background-mediated color change in sticklebacks', *Behavioral Ecology*, vol. 31, no. 4, pp. 950–959. https://doi.org/10.1093/BEHECO/ARAA041

Tsiantis, N, Balsa-Canto, E & Banga, JR 2018, 'Optimality and identification of dynamic models in systems biology: an inverse optimal control framework', *Bioinformatics*, vol. 34, no. 14, pp. 2433–2440. https://doi.org/10.1093/BIOINFORMATICS/BTY139

Tsiompanou, E & Marketos, SG 2013, 'Hippocrates: timeless still', *Journal of the Royal Society of Medicine*, vol. 106, no. 7, a288. https://doi.org/10.1177/0141076813492945

Von Herbing, IH, Miyake, T, Hall, BK & Boutilier, RG 1996, 'Ontogeny of feeding and respiration in larval Atlantic cod *Gadus morhua* (Teleostei, Gadiformes): I. Morphology', *Journal of Morphology*, vol. 227, no. 1, pp. 37–50.

Von Neumann, J 1966, *Von Neumann's self-reproducing Automata*, ed. AW Burks, University of Illinois Press, Urbana, viewed 15 October 2021, <https://apps.dtic.mil/dtic/tr/fulltext/u2/688840.pdf>

Waters, RC, O'Toole, PW & Ryan, KA 2007, 'The FliK protein and Flagellar hook-length control', *Protein science: A Publication of the Protein Society*, vol. 16, no. 5, pp. 769–780. https://doi.org/10.1110/ps.072785407

Weber, K, Johnson, N, Champlin, D & Patty, A 2005, 'Many P-element insertions affect wing shape in *Drosophila melanogaster*', *Genetics*, vol. 169, no. 3, a27748. https://doi.org/10.1534/GENETICS.104.027748

Wells, J 2014, 'Membrane patterns carry ontogenetic information that is specified independently of DNA', *BIO-Complexity*, vol. 2014, no. 2, pp. 1–28. https://doi.org/10.5048/BIO-C.2014.2

Wells, J 2017, *Zombie science: more icons of evolution*, Discovery Institute, Seattle.

Wells, JN & Feschotte, C 2020, 'A field guide to eukaryotic transposable elements', *Annual Review of Genetics*, vol. 54, pp. 539–561. https://doi.org/10.1146/ANNUREV-GENET-040620-022145

Why the Royal Society Meeting Mattered, in a Nutshell 2016, *Evolution News & Science Today*, viewed 10 December 2019, <https://evolutionnews.org/2016/12/why_the_royal_s/>

Wolfe, JM 2017, 'Metamorphosis is ancestral for crown euarthropods, and evolved in the Cambrian or earlier', *Integrative and Comparative Biology*, vol. 57, no. 3, pp. 499–509. https://doi.org/10.1093/ICB/ICX039

Xavier, JC, Patil, KR & Rocha, I 2014, 'Systems biology perspectives on minimal and simpler cells', *Microbiology and Molecular Biology Reviews*, vol. 78, no. 3, pp. 487–509. https://doi.org/10.1128/MMBR.00050-13

Chapter 8

Banfalvi, G 2006, 'Why ribose was selected as the sugar component of nucleic acids', *DNA and Cell Biology*, vol. 25, no. 3, pp. 189–196. https://doi.org/10.1089/DNA.2006.25.189

Borgnia, M, Nielsen, S, Engel, A & Agre, P 1999, 'Cellular and molecular biology of the aquaporin water channels', *Annual Review of Biochemistry*, vol. 68, pp. 425–458. https://doi.org/10.1146/ANNUREV.BIOCHEM.68.1.425

Brocklehurst, B & McLauchlan, KA 1996, 'Free radical mechanism for the effects of environmental electromagnetic fields on biological systems', *International Journal of Radiation Biology*, vol. 69, no. 1, pp. 3–24. https://doi.org/10.1080/095530096146147

Brule, CE & Grayhack, EJ 2017, 'Synonymous codons: choose wisely for expression', *Trends in Genetics*, vol. 33, no. 4, pp. 283–297. https://doi.org/10.1016/J.TIG.2017.02.001

Butler, T, Goldenfeld, N, Mathew, D & Luthey-Schulten, Z 2009, 'Extreme genetic code optimality from a molecular dynamics calculation of amino acid polar requirement', *Physical Review. E, Statistical, Nonlinear, and Soft Matter Physics*, vol. 79, no. 6 Pt 1, a060901. https://doi.org/10.1103/PHYSREVE.79.060901

Crick, FH 1968, 'The origin of the genetic code', *Journal of Molecular Biology*, vol. 38, no. 3, pp. 367–379. https://doi.org/10.1016/0022-2836(68)90392-6

Daims, H, Lebedeva, EV, Pjevac, P, Han, P, Herbold, C, Albertsen, M, Jehmlich, N, Palatinszky, M, Vierheilig, J, Bulaev, A, Kirkegaard, RH, Von Bergen, M, Rattei, T, Bendinger, B, Nielsen, PH & Wagner, M 2015, 'Complete nitrification by *Nitrospira* bacteria', *Nature*, vol. 528, no. 7583, pp. 504–509. https://doi.org/10.1038/nature16461

Dawkins, R 1997, *Climbing mount improbable*, WW Norton & Company, New York.

De Mendoza, D 2014, 'Temperature sensing by membranes', *Annual Review of Microbiology*, vol. 68, pp. 101–116. https://doi.org/10.1146/ANNUREV-MICRO-091313-103612

Denton, M 2017, *The wonder of water: water's profound fitness for life on earth and mankind*, Discovery Institute Press, Seattle.

Dietl, A, Ferousi, C, Maalcke, WJ, Menzel, A, De Vries, S, Keltjens, JT, Jetten, MSM, Kartal, B & Barends, TRM 2015, 'The inner workings of the hydrazine synthase multiprotein complex', *Nature*, vol. 527, no. 7578, pp. 394–397. https://doi.org/10.1038/nature15517

D'Onofrio, DJ & Abel, DL 2014, 'Redundancy of the genetic code enables translational pausing', *Frontiers in Genetics*, vol. 5, a140. https://doi.org/10.3389/fgene.2014.00140

Eberlin, M 2019, *Foresight: how the chemistry of life reveals planning and purpose*, Discovery Institute Press, Seattle.

Eigen, M, Lindemann, BF, Tietze, M, Winkler-Oswatitsch, R, Dress, A & Von Haeseler, A 1989, 'How old is the genetic code? Statistical geometry of tRNA provides an answer', *Science (New York, NY)*, vol. 244, no. 4905, pp. 673–679. https://doi.org/10.1126/SCIENCE.2497522

Einstein, A, Podolsky, B & Rosen, N 1935, 'Can quantum-mechanical description of physical reality be considered complete?', *Physical Review*, vol. 47, no. 10, pp. 777–780. https://doi.org/10.1103/PhysRev.47.777

Gauger, EM, Rieper, E, Morton, JJL, Benjamin, SC & Vedral, V 2011, 'Sustained quantum coherence and entanglement in the avian compass', *Physical Review Letters*, vol. 106, no. 4, a040503. https://doi.org/10.1103/PhysRevLett.106.040503

Grossman, L 2011, 'In the blink of bird's eye, a model for quantum navigation', *wired*, viewed 10 December 2021, <https://www.wired.com/author/lisa-grossman/>

Günther, A, Einwich, A, Sjulstok, E, Feederle, R, Bolte, P, Koch, K-W, Solov'yov, IA & Mouritsen, H 2018, 'Double-cone localization and seasonal expression pattern suggest a role in magnetoreception for European robin cryptochrome 4', *Current Biology*, vol. 28, no. 2, pp. 211–223. https://doi.org/10.1016/J.CUB.2017.12.003

Habermas, G 2004, 'My pilgrimage from atheism to theism: a discussion between Antony Flew and Gary Habermas', *Faculty Publications and Presentations*, p. 201, viewed 10 December 2021, <https://digitalcommons.liberty.edu/cgi/viewcontent.cgi?article=1336&context=lts_fac_pubs>

Hedenström, A, Norevik, G, Warfvinge, K, Andersson, A, Bäckman, J & Åkesson, S 2016, 'Annual 10-month aerial life phase in the common swift Apus apus', *Current Biology*, vol. 26, no. 22, pp. 3066–3070. https://doi.org/10.1016/J.CUB.2016.09.014

How Microbes Make Earth Habitable 2016, *Evolution News & Science Today*, viewed 10 December 2021, <https://evolutionnews.org/2016/02/how_microbes_ma/>

Hoyle, F 1982, 'The universe: past and present reflections', *Annual Review of Astronomy and Astrophysics*, vol. 20, no. 1, pp. 1–36. https://doi.org/10.1146/annurev.aa.20.090182.000245

Jetten, MSM, Van Niftrik, L, Strous, M, Kartal, B, Keltjens, JT & Op den Camp, HJM 2009, 'Biochemistry and molecular biology of anammox bacteria', *Critical Reviews in Biochemistry and Molecular Biology*, vol. 44, no. 2–3, pp. 65–84. https://doi.org/10.1080/10409230902722783

Juzeniene, A & Moan, J 2012, 'Beneficial effects of UV radiation other than via vitamin D production', *Dermato-Endocrinology*, vol. 4, no. 2, a20013. https://doi.org/10.4161/DERM.20013

Kaiser, D 2014, 'Is quantum entanglement real?', *The New York Times*, 16 November 2014, p. SR10.

Kuenen, JG 2008, 'Anammox bacteria: from discovery to application', *Nature Reviews Microbiology*, vol. 6, no. 4, pp. 320–326. https://doi.org/10.1038/nrmicro1857

Kuypers, MMM, Sliekers, AO, Lavik, G, Schmid, M, Jørgensen, BB, Kuenen, JG, Damsté, JSS, Strous, M & Jetten, MSM 2003, 'Anaerobic ammonium oxidation by anammox bacteria in the Black Sea', *Nature*, vol. 422, no. 6932, pp. 608–611. https://doi.org/10.1038/nature01472

Mansy, SS, Schrum, JP, Krishnamurthy, M, Tobé, S, Treco, DA & Szostak, JW 2008, 'Template-directed synthesis of a genetic polymer in a model protocell', *Nature*, vol. 454, no. 7200, pp. 122–125. https://doi.org/10.1038/nature07018

More on How Microbes Make Earth Habitable 2016, *Evolution News & Science Today*, viewed 10 December 2021, <https://evolutionnews.org/2016/02/more_on_how_mic/>

Mulkidjanian, AY, Galperin, MY & Koonin, EV 2009, 'Co-evolution of primordial membranes and membrane proteins', *Trends in Biochemical Sciences*, vol. 34, no. 4, a206. https://doi.org/10.1016/J.TIBS.2009.01.005

Oliveira, KMT & Harada, E 2015, 'Synthetic routes of the fundamental building blocks of life: computational study of the reaction free energy', *Revista Processos Químicos*, vol. 9, no. 18, pp. 139–143. https://doi.org/10.19142/RPQ.V9I18.281

Ozone: Good Up High Bad Nearby 2003, *Office of air and radiation*, U.S. Environmental Protection Agency, Washington, DC.

Pinzon-Rodriguez, A, Bensch, S & Muheim, R 2018, 'Expression patterns of cryptochrome genes in avian retina suggest involvement of Cry4 in light-dependent magnetoreception', *Journal of the Royal Society Interface*, vol. 15, no. 140, a58. https://doi.org/10.1098/RSIF.2018.0058

Ramsey, L & Lee, S 2016, *Our DNA is 99.9% the same as the person next to us – and we're surprisingly similar to a lot of other living things*, viewed 29 November 2021, <https://www.businessinsider.com.au/comparing-genetic-similarity-between-humans-and-other-things-2016-5>

Ritz, T, Adem, S & Schulten, K 2000, 'A model for photoreceptor-based magnetoreception in birds', *Biophysical Journal*, vol. 78, no. 2, pp. 707–718. https://doi.org/10.1016/S0006-3495(00)76629-X

Rocket Science in a Microbe Saves the Planet 2015, *Evolution News & Science Today*, viewed 10 December 2021, <https://evolutionnews.org/2015/11/rocket_science_1>

Schulten, K & Weller, A 1978, 'Exploring fast electron transfer processes by magnetic fields', *Biophysical Journal*, vol. 24, no. 1, a295. https://doi.org/10.1016/S0006-3495(78)85378-8

Sinninghe Damsté, JS, Strous, M, Rijpstra, WIC, Hopmans, EC, Geenevasen, JAJ, Van Duin, ACT, Van Niftrik, LA & Jetten, MSM 2002, 'Linearly concatenated cyclobutane lipids form a dense bacterial membrane', *Nature*, vol. 419, no. 6908, pp. 708–712. https://doi.org/10.1038/nature01128

Szostak, JW, Bartel, DP & Luisi, PL 2001, 'Synthesizing life', *Nature*, vol. 409, no. 6818, pp. 387–390. https://doi.org/10.1038/35053176

The Nobel Prize in Chemistry 2003 – NobelPrize.org 2013, viewed 29 November 2021, <https://www.nobelprize.org/prizes/chemistry/2003/summary/>

The Peculiar Properties of Ice 2012, *Evolution News & Science Today*, viewed 10 December 2021, <https://evolutionnews.org/2012/08/the_peculiar_pr_1/>

Tour, J 2016, 'Animadversions of a synthetic chemist', *Inference*, vol. 2, p. 2.

Van de Vossenberg, J, Rattray, JE, Geerts, W, Kartal, B, Van Niftrik, L, Van Donselaar, EG, Damsté, JSS, Strous, M & Jetten, MSM 2008, 'Enrichment and characterization of marine anammox bacteria associated with global nitrogen gas production', *Environmental Microbiology*, vol. 10, no. 11, pp. 3120–3129. https://doi.org/10.1111/J.1462-2920.2008.01643.X

Van Niftrik, LA, Fuerst, JA, Damsté, JSS, Kuenen, JG, Jetten, MSM & Strous, M 2004, 'The anammoxosome: an intracytoplasmic compartment in anammox bacteria', *FEMS Microbiology Letters*, vol. 233, no. 1, pp. 7–13. https://doi.org/10.1016/J.FEMSLE.2004.01.044

Van Niftrik, L & Jetten, MSM 2012, 'Anaerobic ammonium-oxidizing bacteria: unique microorganisms with exceptional properties', *Microbiology and Molecular Biology Reviews*, vol. 76, no. 3, pp. 585–596. https://doi.org/10.1128/MMBR.05025-11

Ward, BB & Jensen, MM 2014, 'The microbial nitrogen cycle', *Frontiers in Microbiology*, vol. 5, a553. https://doi.org/10.3389/fmicb.2014.00553

Westheimer, FH 1987, 'Why nature chose phosphates', *Science (New York, NY)*, vol. 235, no. 4793, pp. 1173–1178. https://doi.org/10.1126/SCIENCE.2434996

Wiltschko, W & Wiltschko, R 1996, ‘Magnetic orientation in birds’, *Journal of Experimental Biology*, vol. 199, no. 1, pp. 29–38. https://doi.org/10.1242/JEB.199.1.29

Yin, J, Cao, Y, Yong, HL, Ren, JG, Liang, H, Liao, SK, Zhou, F, Liu, C, Wu, Y-P, Pan, G-S, Li, L, Liu, N-L, Zhang, Q, Peng, C-Z & Pan, JW 2013, ‘Lower bound on the speed of nonlocal correlations without locality and measurement choice loopholes’, *Physical Review Letters*, vol. 110, no. 26, a260407. https://doi.org/10.1103/PHYSREVLETT.110.260407/FIGURES/4/MEDIUM

Yue, F, Cheng, Y, Breschi, A, Vierstra, J, Wu, W, Ryba, T, et al. 2014, ‘A comparative encyclopedia of DNA elements in the mouse genome’, *Nature*, vol. 515, no. 7527, pp. 355–364.

Chapter 9

Abitbol, MM 1995, ‘Lateral view of *Australopithecus afarensis*: primitive aspects of bipedal positional behavior in the earliest Hominids’, *Journal of Human Evolution*, vol. 28, no. 3, pp. 211–229. https://doi.org/10.1006/jhev.1995.1017

Aiello, LC & Collard, M 2001, ‘Our newest oldest ancestor?’, *Nature*, vol. 410, no. 6828, pp. 526–527. https://doi.org/10.1038/35069164

Almécija, S, Smaers, JB & Jungers, WL 2015, ‘The evolution of human and ape hand proportions’, *Nature Communications*, vol. 6, a8717. https://doi.org/10.1038/ncomms8717

American Museum of Natural History 2015, ‘Foot fossils of human relative illustrate evolutionary “messiness” of bipedal walking’, *ScienceDaily*, viewed 29 November 2021, <http://www.sciencedaily.com/releases/2015/10/151006131938.html>

American Museum of Natural History 2019, *DNA: comparing humans and chimps*, AMNH.org, viewed 29 November 2021, <https://www.amnh.org/exhibitions/permanent/human-origins/understanding-our-past/dna-comparing-humans-and-chimps>

Andrews, P 1995, ‘Ecological apes and ancestors’, *Nature*, vol. 376, pp. 555–556. https://doi.org/10.1038/376555a0

Asfaw, B, Gilbert, WH, Beyene, Y, Hart, WK, Rennie, PR, WoldeGabriel, G, Vrba, ES & White, TD 2002, ‘Remains of *Homo erectus* from Bouri, Middle Awash, Ethiopia’, *Nature*, vol. 416, pp. 317–320. https://doi.org/10.1038/416317a

Atkinson, EG, Audesse, AJ, Palacios, JA, Bobo, DM, Webb, AE, Ramachandran, S & Henn, BM 2018, ‘No evidence for recent selection at FOXP2 among diverse human populations’, *Cell*, vol. 174, no. 6, pp. 1424–1435. https://doi.org/10.1016/j.cell.2018.06.048

Balter, M 2010, ‘Candidate human ancestor from South Africa sparks praise and debate’, *Science*, vol. 328, no. 5975, pp. 154–155. https://doi.org/10.1126/science.328.5975.154

Bar-Yosef, O 2002, ‘The upper paleolithic revolution’, *Annual Review of Anthropology*, vol. 31, pp. 363–393. https://doi.org/10.1146/annurev.anthro.31.040402.085416

Barash, DP & Lipton, JE 2010, ‘How the scientist got his ideas’, *Chronicle of Higher Education*, 03 January, viewed 30 November 2021, <http://chronicle.com/article/How-the-Scientist-Got-His/63287/>

British Broadcasting Channel (BBC) 2002, ‘Skull find sparks controversy’, *BBC News*, 12 July, viewed 29 November 2021, <http://news.bbc.co.uk/2/hi/science/nature/2125244.stm>

Berger, LR, De Ruiter, DJ, Churchill, SE, Schmid, P, Carlson, KJ, Dirks, PHGM & Kibii, JM 2010, ‘*Australopithecus sediba*: a new species of *Homo*-like Australopith from South Africa’, *Science*, vol. 328, no. 5975, pp. 195–204. https://doi.org/10.1126/science.1184944

Berger, LR, Hawks, J, De Ruiter, DJ, Churchill, SE, Schmid, P, Delezene, LK, Kivell, TL, Garvin, HM, Williams, SA, DeSilva, JM, Skinner, MM, Musiba, CM, Cameron, N, Holliday, TW, Harcourt-Smith, W, Ackermann, RR, Bastir, M, Bogin, B, Bolter, D, Brophy, J, Cofran, ZD, Congdon, KA, Deane, AS, Dembo, M, Drapeau, M, Elliott, MC, Feuerriegel, EM, Garcia-Martinez, D, Green, DJ, Gurtov, A, Irish, JD, Kruger, A, Laird, MF, Marchi, D, Meyer, MR, Nalla, S, Negash, EW, Orr, CM, Radovcic, D, Schroeder, L, Scott,JE, Throckmorton, Z, Tocheri, MW, VanSickle, C, Walker, CS, Wei, P & Zipfel, B 2015, ‘*Homo naledi*, a new species of the genus *Homo* from the Dinaledi Chamber, South Africa’, *eLife*, vol. 4, a09560. https://doi.org/10.7554/eLife.09560

Berger, LR & Hilton-Barber, B 2000, *In the footsteps of Eve: the mystery of human origins*, Adventure Press, National Geographic, Washington, DC.

Bernardi, G 2019, 'The genomic code: a pervasive encoding/molding of chromatin structures and a solution of the "non-coding DNA" mystery', *BioEssays*, vol. 41, no. 12, a1900106. https://doi.org/10.1002/bies.201900106

Biggs, A, Gregg, K, Hagins, CW, Kapicka, C, Lundgren, L, Rillero, P, Tallman, D & Zike 2000, *Biology: the dynamics of life*, McGraw Hill, Glencoe, New York.

Bitar, M, Kuiper, S, O'Brien, EA & Barry, G 2019, 'Genes with human-specific features are primarily involved with brain, immune and metabolic evolution', *BMC Bioinformatics*, vol. 20, no. Suppl 9, a406. https://doi.org/10.1186/s12859-019-2886-2

Black, R 2013, 'Beautiful skull spurs debate on human history', *National Geographic*, 19 October, viewed 13 March 2022, <https://www.nationalgeographic.com/culture/article/131017-skull-human-origins-dmanisi-georgia-erectus>

Bramble, DM & Lieberman, DE 2004, 'Endurance running and the evolution of *Homo*', *Nature*, vol. 432, pp. 345–352. https://doi.org/10.1038/nature03052

Bromage, TG & Dean, CM 1985, 'Re-evaluation of the age at death of immature fossil Hominids', *Nature*, vol. 317, pp. 525–527. https://doi.org/10.1038/317525a0

Broom, R 1933a, 'Evolution – is there intelligence behind it?', *South African Journal of Science*, vol. 30, no. 7, pp. 1–19. https://hdl.handle.net/10520/AJA00382353_4294

Broom, R 1933b, *The coming of man: was it accident or design?*, HF & G Witherby, London.

Brunet, M 2002a, '*Sahelanthropus* or "*Sahelpithecus*"?', *Nature*, vol. 419, a582. https://doi.org/10.1038/419582a

Brunet, M 2002b, *Toumaï the human ancestor*, Centre National De La Recherche Scientifique, viewed 29 November 2021, <https://web.archive.org/web/20020807181920/http:/www.cnrs.fr/cw/fr/pres/compress/Toumai/Tounaigb/lienparengb.html>

Bryn, B 2011, '*Australopithecus sediba* may have paved the way for *Homo*', *AAAS News*, 07 September, viewed 29 November 2021, <http://www.aaas.org/news/science-australopithecus-sediba-may-have-paved-way-homo>

Buggs, R 2018, *How similar are human and chimpanzee genomes?* RichardBuggs.com, viewed 26 November 2021, <http://richardbuggs.com/2018/07/14/how-similar-are-human-and-chimpanzee-genomes/>

Calarco, JA, Xing, Y, Cáceres, M, Calarco, JP, Xiao, X, Pan, Q, Lee, C, Preuss, TM & Blencowe, BJ 2007, 'Global analysis of alternative splicing differences between humans and chimpanzees', *Genes & Development*, vol. 21, pp. 2963–2975. https://doi.org/10.1101/gad.1606907

Carreiras, M, Seghier, ML, Baquero, S, Estévez, A, Lozano, A, Devlin, JT & Price, CJ 2009, 'An anatomical signature for literacy', *Nature*, vol. 461, pp. 983–986. https://doi.org/10.1038/nature08461

Cheetham, SW, Faulkner, GJ & Dinger, ME 2020, 'Overcoming challenges and dogmas to understand the functions of pseudogenes', *Nature Reviews Genetics*, vol. 21, pp. 191–201. https://doi.org/10.1038/s41576-019-0196-1

Cherfas, J 1983, 'Trees have made man upright', *New Scientist*, vol. 97, pp. 172–177.

Choi, CQ 2013, 'Humanity's closest ancestor was Pigeon-Toed, research reveals', *LiveScience*, viewed 29 November 2021, <http://www.livescience.com/28656-closest-human-ancestor-was-pigeon-toed.html>

Chomsky, N 2006, *Language and mind*, 3rd edn, Cambridge University Press, Cambridge.

Clarke, RJ &Tobias, PJ 1995, 'Sterkfontein member 2 foot bones of the oldest South African Hominid', *Science*, vol. 269, no. 5223, pp. 521–524. https://doi.org/10.1126/science.7624772

Cohen, J 2007, 'Relative differences: the myth of 1%', *Science*, vol. 316, no. 5833, a1836. https://doi.org/10.1126/science.316.5833.1836

Collard M &Aiello, LC 2000, 'From forelimbs to two legs', *Nature*, vol. 404, pp. 339–340. https://doi.org/10.1038/35006181

Collard, M & Wood, B 2015, ‘Defining the Genus *Homo*’, in W Henke & I Tattersall (eds.), *Handbook of paleoanthropology: principles, methods, and approaches*, 2nd edn, Springer, Heidelberg, pp. 2107–2144.

Collins, F 2006, *The language of God: a scientist presents evidence for belief*, Free Press, New York.

Constantino, PJ 2013, ‘The “Robust” Australopiths’, *Nature Education Knowledge*, vol. 4, no. 1, p. 1. https://www.nature.com/scitable/knowledge/library/the-robust-australopiths-84076648/

Conroy, GC, Weber, GW, Seidler, H, Tobias, PV, Kane, A & Brunsden, B 1998, ‘Endocranial capacity in an early Hominid cranium from Sterkfontein, South Africa’, *Science*, vol. 280, no. 5370, pp 1730–1731. https://doi.org/10.1126/science.280.5370.1730

Coyne, JA 2009, *Why evolution is true*, Oxford University Press, Oxford.

Cray, D 2006, ‘God vs. Science’, *Time*, 05 November, viewed 30 November 2021, <http://content.time.com/time/magazine/article/0,9171,1555132-1,00.html>

Craze, P 2013, ‘Early human evolution and the skulls of Dmanisi’, *Significance*, vol. 10, no. 6, pp. 6–11. https://doi.org/10.1111/j.1740-9713.2013.00703.x

Curnoe, D 2015, *What about Homo naledi’s geologic age?* Phys.org, viewed 29 November 2021, <http://phys.org/news/2015-09-opinion-homo-naledi-geologic-age.html>

Darwin, C 1878, *The descent of man, and selection in relation to sex*, rev. D Appleton and Company, New York.

Davis, M 2002, *Into the fray: the producer’s story*, PBS NOVA, viewed 30 November 2021, <http://www.pbs.org/wgbh/nova/neanderthals/producer.html>

Dawkins, R 2006, *The selfish gene*, 3rd edn, Oxford, New York.

Deacon, TW 1990, ‘Problems of ontogeny and phylogeny in brain-size evolution’, *International Journal of Primatology*, vol. 11, pp. 237–282. https://doi.org/10.1007/BF02192870

Deacon, TW 1997, ‘What makes the human brain different?’, *Annual Review of Anthropology*, vol. 26, pp. 337–357. DOI 10.1146/annurev.anthro.26.1.337

Demuth, JP, De Bie, T, Stajich, JE, Cristianini, N & Hahn, MW 2006, ‘The evolution of mammalian gene families’, *PLoS One*, vol. 1, no. 1, a85. https://doi.org/10.1371/journal.pone.0000085

Dennell, R & Roebroeks, W 2005, ‘An Asian perspective on early human dispersal from Africa’, *Nature*, vol. 438, pp. 1099–1104. https://doi.org/10.1038/nature04259

Dennett, DC 2006, *Breaking the spell: religion as a natural phenomenon*, Viking, New York.

De Ruiter, DJ, Pickering, R, Steininger, CM, Kramers, JD, Hancox, PJ, Churchill, SE, Berger, LR & Backwell, L 2009, ‘New *Australopithecus robustus* fossils and associated U-Pb dates from Cooper’s Cave (Gauteng, South Africa)’, *Journal of Human Evolution*, vol. 56, no. 5, pp. 497–513. https://doi.org/10.1016/j.jhevol.2009.01.009

De Waal, FBM 2001, ‘Apes from Venus: Bonobos and human social evolution’, in BM Frans & De Waal (eds.), *Tree of origin: what primate behavior can tell us about human social evolution*, Harvard University Press, Cambridge, pp. 39–68.

Dirks, PHGM, Roberts, EM, Hilbert-Wolf, Kramers, JD, Hawks, J, Dosseto, A, Duval, M, Elliott, M, Evans, M, Grün, R, Hellstrom, J, Herries, AIR, Joannes-Boyau, R, Makhubela, TV, Placzek, CJ, Robbins, J, Spandler, C, Wiersma, J, Woodhead, J & Berger, LR 2017, ‘The age of *Homo naledi* and associated sediments in the rising star cave, South Africa’, *eLife*, vol. 6, a24231. https://doi.org/10.7554/eLife.24231

Du, A & Alemseged, Z 2019, ‘Temporal evidence shows *Australopithecus sediba* is unlikely to be the ancestor of *Homo*’, *Science Advances*, vol. 5, no. 5, a9038. https://doi.org/10.1126/sciadv.aav9038

Durrett, R & Schmidt, D 2008, ‘Waiting for two mutations: with applications to regulatory sequence evolution and the limits of Darwinian evolution’, *Genetics*, vol. 180, no. 3, pp. 1501–1509. https://doi.org/10.1534/genetics.107.082610

Ecker, JR 2012, ‘Serving up a genome feast’, *Nature*, vol. 489, pp. 52–53. https://doi.org/10.1038/489052a

Enard, W, Przeworski, M, Fisher, SE, Lai, CSL, Wiebe, V, Kitano, T, Monaco, AP & Paabo, S 2002, 'Molecular evolution of *FOXP2*, a gene involved in speech and language', *Nature*, vol. 418, pp. 869–872. https://doi.org/10.1038/nature01025

ENCODE Project Consortium 2012, 'An integrated encyclopedia of DNA elements in the human genome', *Nature*, vol. 489, pp. 57–74. https://doi.org/10.1038/nature11247

Falk, D 1998, 'Hominid brain evolution: looks can be deceiving', *Science*, vol. 280, no. 5370, a1714. https://doi.org/10.1126/science.280.5370.1714

Farber, T 2016, 'Professor's Claims Rattle *Naledi*'s Bones', *Sunday Times*, 24 April, viewed 29 November 2021, <http://www.timeslive.co.za/sundaytimes/stnews/2016/04/24/Professors-claims-rattle-Naledis-bones>

Galik, K, Senut, B, Pickford, M, Gommery, D, Treil, J, Kuperavage, AJ & Eckhardt, RB 2004, 'External and internal morphology of the BAR 1002'00 *Orrorin tugenensis* Femur', *Science*, vol. 305, no. 5689, pp. 1450–1453. https://doi.org/10.1126/science.1098807

Gates, AJ, Gysi, DM, Kellis, M & Barabási, AL 2021, 'A wealth of discovery built on the human genome project – by the numbers', *Nature*, vol. 590, no. 7845, pp. 212–215. DOI 10.1038/d41586-021-00314-6

Gauger, A, Hössjer, O & Reeves, C 2017, 'Evidence for human uniqueness', in JP Moreland, SC Meyer, C Shaw, AK Gauger & W Grudem (eds.), *Theistic evolution: a scientific, philosophical, and theological critique*, Crossway, Wheaton, pp. 475–502.

Gee, H 2001, 'Return to the planet of the apes', *Nature*, vol. 412, pp. 131–132. https://doi.org/10.1038/35084308

Ghosh, P 2015, 'New human-like species discovered in S Africa', *BBC News*, 10 September, viewed 29 November 2021, <http://www.bbc.com/news/science-environment-34192447>

Gibbons, A 2002, 'In search of the first Hominids', *Science*, vol. 295, no. 5558, pp. 1214–1219. https://doi.org/10.1126/science.295.5558.1214

Gibbons, A 2006, *The first human: the race to discover our earliest ancestors*, Doubleday, New York.

Gibbons, A 2009a, 'Breakthrough of the year: *Ardipithecus ramidus*', *Science*, vol. 326, pp. 1598–1599. https://doi.org/10.1126/science.326.5960.1598-a

Gibbons, A 2009b, 'A new kind of ancestor: *Ardipithecus Unveiled*', *Science*, vol. 326, no. 5949, pp. 36–40. https://doi.org/10.1126/science.326.5949.36

Gibbons, A 2011, 'Who was *Homo habilis* – and was it really *Homo*?', *Science*, vol. 332, no. 6036, pp. 1370–1371. https://doi.org/10.1126/science.332.6036.1370

Gibbons, A 2013, 'A human smile and funny walk for *Australopithecus sediba*', *Science*, vol. 340, no. 6129, pp. 132–133. https://doi.org/10.1126/science.340.6129.132

Glazko, G, Veeramachaneni, V, Nei, M & Makałowski, W 2005, 'Eighty percent of proteins are different between humans and chimpanzees', *Gene*, vol. 346, pp. 215–219. https://doi.org/10.1016/j.gene.2004.11.003

Gould, SJ 1980, *The Panda's thumb: more reflections in natural history*, WW Norton & Company, New York.

Grose, J 2019, 'How children evolved to whine', *New York Times*, 09 October, viewed 28 November 2021, <https://www.nytimes.com/2019/10/09/parenting/how-children-evolved-to-whine.html>

Harari, YN 2015, *Sapiens: a brief history of humankind*, Harper Perennial, New York.

Harcourt-Smith, WEH, Throckmorton, Z, Congdon, KA, Zipfel, B, Deane, AS, Drapeau, MSM, Churchill, SE, Berger, LR & DeSilva, JM 2015, 'The foot of *Homo naledi*', *Nature Communications*, vol. 6, a9432. https://doi.org/10.1038/ncomms9432

Harrell, E 2010, 'Ardi: the human ancestor who wasn't?', *Time*, 27 May, viewed 29 November 2021, <http://content.time.com/time/health/article/0,8599,1992115,00.html>

Hartwig-Scherer, S 1998, 'Apes or ancestors?', in W Dembski (ed.), *Mere creation: science, faith & intelligent design*, InterVarsity Press, Downers Grove, pp. 212–235.

Hartwig-Scherer, S & Martin, RD 1991, 'Was "Lucy" more human than her "child"? Observations on early hominid postcranial skeletons', *Journal of Human Evolution*, vol. 21, no. 6, pp. 439–449. https://doi.org/10.1016/0047-2484(91)90094-C

Hauser, M, Yang, C, Berwick, R, Tattersall, I, Ryan, MJ, Watumull, J, Chomsky, N & Lewontin, RC 2014, 'The mystery of language evolution', *Frontiers in Psychology*, vol. 5, a401. https://doi.org/10.3389/fpsyg.2014.00401

Hawks, J, Hunley, K, Lee, SH & Wolpoff, M 2000, 'Population bottlenecks and Pleistocene human evolution', *Molecular Biology and Evolution*, vol. 17, no. 1, pp. 2–22. https://doi.org/10.1093/oxfordjournals.molbev.a026233

Henke, W 2015, 'Historical overview of paleoanthropological research', in W Henke & I Tattersall (eds.), *Handbook of paleoanthropology: principles, methods, and approaches*, 2nd edn, Springer, Heidelberg, pp. 3–95.

Holcomb, HR 1996, 'Just so stories and inference to the best explanation in evolutionary psychology', *Mind and Machines*, vol. 6, pp. 525–540. https://doi.org/10.1007/BF00389657

Holden, C 1981, 'The politics of paleoanthropology', *Science*, vol. 213, no. 4509, pp. 737–740. https://doi.org/10.1126/science.213.4509.737

Hooton, EA 1946, *Up from the ape*, rev. edn. McMillan, New York.

Hughes, JF, Skaletsky, H, Pyntikova, T, Graves, TA, Van Daalen, SKM, Minx, PJ, Fulton, RS, McGrath, SD, Locke, DP, Friedman, C, Trask, BJ, Mardis, ER, Warren, WC, Repping, S, Rozen, S, Wilson, RK & Page, DC 2010, 'Chimpanzee and human Y chromosomes are remarkably divergent in structure and gene content', *Nature*, vol. 463, pp. 536–539. https://doi.org/10.1038/nature08700

Humphrey, LT, Dean, MC & Stringer, CB 1999, 'Morphological variation in great ape and modern human mandibles', *Journal of Anatomy*, vol. 195, no. 4, pp. 491–513. https://doi.org/10.1046/j.1469-7580.1999.19540491.x

Johanson, D & Edgar, B 1996, *From Lucy to language*, Simon & Schuster, New York.

Johanson, DC, Lovejoy, CO, Kimbel, WH, White, TD, Ward, SC, Bush, ME, Latimer, BM & Coppens, Y 1982, 'Morphology of the Pliocene partial Hominid skeleton (A.L. 288-1) from the Hadar formation, Ethiopia', *American Journal of Physical Anthropology*, vol. 57, no. 4, pp. 403–451. https://doi.org/10.1002/ajpa.1330570403

Johansson, PA, Brattås, PL, Douse, CH, Hsieh, P, Adami, A, Pontis, J, Grassi, D, Garza, R, Sozzi, E, Cataldo, R, Jönsson, ME, Atacho, DAM, Pircs, K, Eren, F, Sharma, Y, Johansson, J, Fiorenzano, A, Parmar, M, Fex, M, Trono, D, Eichler, EE & Jakobsson, J 2022, 'A cis-acting structural variation at the ZNF558 locus controls a gene regulatory network in human brain development', *Cell Stem Cell*, vol. 29, no. 1, pp. 1–18. https://doi.org/10.1016/j.stem.2021.09.008

Kelly, RL & Thomas, DH 2010, *Archaeology*, 5th edn, Wadsworth Cengage Learning, Belmont.

Kidder, J 2017, 'What *Homo naledi* means for the study of human evolution', *BioLogos*, viewed 29 November 2021, <http://biologos.org/blogs/guest/what-homo-naledi-means-for-the-study-of-human-evolution>

Kimbel, WH 2013, 'Hesitation on hominin history', *Nature*, vol. 497, pp. 573–574. https://doi.org/10.1038/497573a

Kimbel, WH & Villmoare, B 2016, 'From *Australopithecus* to *Homo*: the transition that wasn't', *Philosophical Transactions of the Royal Society B*, vol. 371, no. 1698, a20150248. https://doi.org/10.1098/rstb.2015.0248

Kivell, TL, Deane, AS, Tocheri, MW, Orr, CM, Schmid, P, Hawks, J, Berger, LR & Churchill, SE 2015, 'The hand of *Homo naledi*', *Nature Communications*, vol. 6, a9431. https://doi.org/10.1038/ncomms9431

Koch, C 2016, 'Does brain size matter?', *Scientific American Mind*, vol. 27, pp. 22–25.

Kovalenko, TF & Patrushev, LI 2018, 'Pseudogenes as functionally significant elements of the genome', *Biochemistry*, vol. 83, no. 11, pp. 1332–1349. https://doi.org/10.1134/S0006297918110044

Leakey, M & Walker, A 2003, 'Early Hominid fossils from Africa', *Scientific American*, vol. 276, no. 6, pp. 74–79. https://doi.org/10.1038/scientificamerican0697-74

Leakey, R & Lewin, R 1993, *Origins reconsidered: in search of what makes us human*, Anchor Books, New York.

Lelliott, A 2016, 'Visitors' views of human origins after visiting the Cradle of Humankind World Heritage', *South African Journal of Science*, vol. 112, pp. 132–139. https://doi.org/10.17159/sajs.2016/20150210

Lemonick, MD & Dorfman, A 2006, 'What makes us different?', *Time*, 01 October, viewed 30 November 2021, <http://content.time.com/time/magazine/article/0,9171,1541283,00.html>

Lemonick, MD & Dorfman, A 2009, 'Ardi is a new piece for the evolution puzzle', *Time*, 01 October, viewed 29 November 2021, <http://content.time.com/time/magazine/article/0,9171,1927289,00.html>

Leonard, WR, Snodgrass, JJ & Robertson, ML 2007, 'Effects of brain evolution on human nutrition and metabolism', *Annual Review of Nutrition*, vol. 27, pp. 311–327. https://doi.org/10.1146/annurev.nutr.27.061406.093659

Levchenko, A, Kanapin, A, Samsonova, A & Gainetdinov, RR 2017, 'Human accelerated regions and other human-specific sequence variations in the context of evolution and their relevance for brain development', *Genome Biology and Evolution*, vol. 10, no. 1, pp. 166–188. https://doi.org/10.1093/gbe/evx240

Lewontin, R 1995, *Human diversity*, Scientific American Library, New York.

Lewontin, R 1997, 'Billions and billions of demons', *New York Review of Books*, 09 January, viewed 30 November 2021, <https://www.nybooks.com/articles/1997/01/09/billions-and-billions-of-demons/>

Lieberman, DE, Pilbeam, DR & Wrangham, RW 2009, 'The transition from *Australopithecus* to *Homo*', in JJ Shea & DE Lieberman (eds.), *Transitions in prehistory: essays in Honor of Ofer Bar-Yosef*, Oxbow Books, Cambridge, pp. 1–22.

Lordkipanidze, D, Jashashvili, T, Vekua, A, Ponce de León, MS, Zollikofer, CPEG, Rightmire, P, Pontzer, H, Ferring, R, Oms, O, Tappen, M, Bukhsianidze, M, Agusti, J, Kahlke, R, Kiladze, G, Martinez-Navarro, B, Mouskhelishvili, A, Nioradze, M & Rook, L 2007, 'Postcranial evidence from early *Homo* from Dmanisi, Georgia', *Nature*, vol. 449, pp. 305–310. https://doi.org/10.1038/nature06134

Luskin, C 2012, 'Human origins and the fossil record', in A Gauger, D Axe & C Luskin (eds.), *Science and human origins*, Discovery Institute Press, Seattle, pp. 45–83.

Luskin, C 2017, 'Missing transitions: human origins and the fossil record', in JP Moreland, SC Meyer, C Shaw, AK Gauger & W Grudem (eds.), *Theistic evolution: a scientific, philosophical, and theological critique*, Crossway, Wheaton, pp. 437–473.

Luskin, C 2019, 'Another human ancestor falsified: study puts *Australopithecus sediba* back in the ground', *Evolution News & Science Today*, 13 May, viewed 29 November 2021, <https://evolutionnews.org/2019/05/another-human-ancestor-falsified-study-puts-australopithecus-sediba-back-in-the-ground/>

Luskin, C 2021, 'Human-Chimp similarity: what is it and what does it mean?', *Evolution News & Science Today*, 20 October 2021, viewed 30 November 2021, <https://evolutionnews.org/2021/10/human-chimp-similarity-what-is-it-and-what-does-it-mean/>

Macchiarelli, R, Bergeret-Medina, A, Marchi, D & Wood, B 2020, 'Nature and relationships of *Sahelanthropus tchadensis*', *Journal of Human Evolution*, vol. 149, a102898. https://doi.org/10.1016/j.jhevol.2020.102898

Macknight, H 2010, 'Experts reject new human species theory', *The Independent*, 08 April, viewed 29 November 2021, <http://www.independent.co.uk/news/science/experts-reject-new-human-species-theory-1939512.html>

Marchal, F 2000, 'A new morphometric analysis of the Hominid pelvic bone', *Journal of Human Evolution*, vol. 38, pp. 347–365. https://doi.org/10.1006/jhev.1999.0360

Marks, J 2003, *What it means to be 98% chimpanzee: Apes, people, and their genes*, University of California Press, Berkeley.

Marshall, M 2020, 'Our supposed earliest human relative may have walked on four legs', *New Scientist*, 18 November, viewed 29 November 2021, <https://www.newscientist.com/article/mg24833093-600-our-supposed-earliest-human-relative-may-have-walked-on-four-legs/>

Maropeng Museum, n.d., *The human brain*, viewed n.d., https://www.maropeng.co.za/content/page/the-human-brain

Mayr, E 2004, *What makes biology unique?: considerations on the autonomy of a scientific discipline*, Cambridge University Press, Cambridge.

McKenzie, D & Wende, H 2015, '*Homo naledi*: new species of human ancestor discovered in South Africa', *CNN*, 10 September, viewed 29 November 2021, <http://www.cnn.com/2015/09/10/africa/homo-naledi-human-relative-species/>

Mellars, P 2004, 'Neanderthals and the modern human colonization of Europe', *Nature*, vol. 432, pp. 461–465. https://doi.org/10.1038/nature03103

Molnar, S 1998, *Human variation: races*, *types*, *and ethnic groups*, 4th edn, Prentice Hall, Upper Saddle River.

Molnar, S 2002, *Human variation: races*, *types*, *and ethnic groups*, 5th edn, Prentice Hall, Upper Saddle River.

Morin, M 2013, 'Find may prune branches from human family tree', *Los Angeles Times*, 18 October, p. A1, viewed 05 July 2022, <https://www.latimes.com/archives/la-xpm-2013-oct-17-la-sci-homo-erectus-20131018-story.html>

Nature 2007, 'Evolution and the brain', *Nature*, vol. 447, a753. https://doi.org/10.1038/447753a

National Center for Biotechnology Information (NCBI) 2007, *Notes for NCBI Chimpanzee Build 2.1*, NCBI Home, viewed 26 November 2021, <https://www.ncbi.nlm.nih.gov/projects/genome/guide/chimp/chimprelease_notes.html>

New York University 2011, 'Fossils may look like human bones: biological anthropologists question claims for human ancestry', *ScienceDaily*, 16 February, viewed 29 November 2021, <https://www.sciencedaily.com/releases/2011/02/110216132034.htm>

Nowell, A 2006, 'From a Paleolithic art to Pleistocene visual cultures (Introduction to two special issues on "Advances in the study of Pleistocene imagery and symbol use')', *Journal of Archaeological Method and Theory*, vol. 13, pp. 239–249. https://doi.org/10.1007/s10816-006-9020-2

Nye, B 2014, *Undeniable: evolution and the science of creation*, St. Martin's Press, New York.

Odokuma, EI, Igbigbi, PS, Akpuaka, FC & Esigbenu, UB 2010, 'Craniometric patterns of three Nigerian ethnic groups', *International Journal of Medicine and Medical Sciences*, vol. 2, pp. 34–37.

Öhman, A 2009, 'Of snakes and faces: an evolutionary perspective on the psychology of fear', *Scandinavian Journal of Psychology*, vol. 50, pp. 543–552. https://doi.org/10.1111/j.1467-9450.2009.00784.x

Oldham, MC, Horvath, S & Geschwind, DH 2006, 'Conservation and evolution of gene coexpression networks in human and chimpanzee brains', *Proceedings of the National Academy of Sciences USA*, vol. 103, no. 47, pp. 17973–17978. https://doi.org/10.1073/pnas.0605938103

O'Neill, MC, Umberger, BR, Holowka, NB, Larson, SG & Reiser, PJ 2017, 'Chimpanzee super strength and human skeletal muscle evolution', *Proceedings of the National Academy of Sciences U S A*, vol. 114, no. 28, pp. 7343–7348. https://doi.org/10.1073/pnas.1619071114

Oxnard, CE 1975, 'The place of the australopithecines in human evolution: grounds for doubt?', *Nature*, vol. 258, pp. 389–395. https://doi.org/10.1038/258389a0

Paz-Yaacov, N, Levanon, EY, Nevo, E, Kinar, Y, Harmelin, A, Jacob-Hirsch, J, Amariglio, N, Eisenberg, E & Rechavi, G 2010, 'Adenosine-to-inosine RNA editing shapes transcriptome diversity in primates', *Proceedings of the National Academy of Sciences U S A*, vol. 107, no. 27, pp. 12174–12179. https://doi.org/10.1073/pnas.1006183107

PBS 2015, 'Trove of fossils from a long-lost human ancestor is greatest find in decades', *PBS Newshour*, 10 September, viewed 29 November 2021, <http://www.pbs.org/newshour/bb/trove-fossils-long-lost-human-ancestor-greatest-find-decades/>

Pink, RC, Wicks, K, Caley, DP, Punch, EK, Jacobs, L & Carter, DPF 2011, 'Pseudogenes: pseudo-functional or key regulators in health and disease?', *RNA*, vol. 17, no. 5, pp. 792–798. https://doi.org/10.1261/rna.2658311

Poliseno, L 2012, ‘Pseudogenes: newly discovered players in human cancer’, *Science Signaling*, vol. 5, no. 242, a2002858. https://doi.org/10.1126/scisignal.2002858

Poliseno, L, Salmena, L, Zhang, J, Carver, B, Haveman, WJ & Pandolfi, PP 2010, ‘A coding-independent function of gene and pseudogene mRNAs regulates tumour biology’, *Nature*, vol. 465, pp. 1033–1038. https://doi.org/10.1038/nature09144

Potts, R & Sloan, C 2010, *What does it mean to be human?*, National Geographic, Washington, DC.

Prang, TC, Ramirez, K, Grabowski, M & Williams, SA 2021, ‘*Ardipithecus* hand provides evidence that humans and chimpanzees evolved from an ancestor with suspensory adaptations’, *Science Advances*, vol. 7, no. 9, a2474. https://doi.org/10.1126/sciadv.abf2474

Raine, J 2016, ‘The evolutionary origins of laughter are rooted more in survival than enjoyment’, *The Conversation*, 13 April, viewed 28 November 2021, <https://theconversation.com/the-evolutionary-origins-of-laughter-are-rooted-more-in-survival-than-enjoyment-57750>

Rak, Y, Ginzburg, A & Geffen, E 2007, ‘Gorilla-like anatomy on *Australopithecus afarensis* mandibles suggests *Au. afarensis* link to robust australopiths’, *Proceedings of the National Academy of Sciences U S A*, vol. 104, no. 16, pp. 6568–6572. https://doi.org/10.1073/pnas.0606454104

Ramlagan, N 2013, ‘Human evolution takes a twist with *Australopithecus sediba*’, *AAAS News*, 11 April, viewed 29 November 2021, <http://www.aaas.org/news/science-human-evolution-takes-twist-australopithecus-sediba>

Reilly, R 2015, ‘Is this the first human? Extraordinary find in a South African cave suggests man may be up to 2.8 million years old’, *Daily Mail*, 10 September, viewed 29 November 2021, <http://www.dailymail.co.uk/sciencetech/article-3228991/New-species-ancient-human-discovered-Fossilised-remains-15-bodies-unearthed-South-African-cave.html>

Rice, SA 2007, *Encyclopedia of evolution*, Checkmark Books, New York.

Richmond, BR & Strait, DS 2000, ‘Evidence that humans evolved from a knuckle-walking ancestor’, *Nature*, vol. 404, pp. 382–385. https://doi.org/10.1038/35006045

Rightmire, GP, Ponce de León, MS, Lordkipanidze, D, Margvelashvili, A & Zollikofer, CPE 2017, ‘Skull 5 from Dmanisi: descriptive anatomy, comparative studies, and evolutionary significance’, *Journal of Human Evolution*, vol. 104, pp. 50–79. https://doi.org/10.1016/j.jhevol.2017.01.005

Rincon, P 2017, ‘Primitive human “lived much more recently”’, *BBC News*, 25 April, viewed 29 November 2021, <http://www.bbc.com/news/science-environment-39710315>

Ruiz-Orera, J, Hernandez-Rodriguez, J, Chiva, C, Sabidó, E, Kondova, I, Bontrop, R, Marqués-Bonet, T & Albà, MM 2015, ‘Origins of *De Novo* genes in human and chimpanzee’, *PLoS Genetics*, vol. 11, no. 12, a1005721. DOI 10.1371/journal.pgen.1005721

Sanders, M 2018, ‘The unusual case of evolution education in South Africa’, in H Deniz & LA Borgerding (eds.), *Evolution education around the globe*, pp. 409–428. https://doi.org/10.1007/978-3-319-90939-4_22

Sarmiento, EE 2010, ‘Comment on the paleobiology and classification of *Ardipithecus ramidus*’, *Science*, vol. 328, no. 5982, a118148. https://doi.org/10.1126/science.1184148

Sarmiento, EE, Sawyer, GJ & Milner, R 2007, *The last human: a guide to twenty-two species of extinct humans*, Yale University Press, New Haven.

Schaffner, S 2018, *Human chimp genome similarity*, The BioLogos Forum, viewed 30 November 2021, <https://discourse.biologos.org/t/human-chimp-genome-similarity/38409/116>

Schlinger, HD 1996, ‘How the human got its spots: a critical analysis of the just so stories of evolutionary psychology’, *Skeptic*, vol. 4, pp. 68–76.

Schloss, JP 1998, ‘Evolutionary accounts of altruism & the problem of goodness by design’, in WA Dembski (ed.), *Mere creation: science, faith & intelligent design*, InterVarsity Press, Downers Grove, pp. 237–261.

Schloss, JP 2002, ‘Emerging accounts of altruism: “love creation’s final law”?’, in SG Post, LG Underwood, JP Schloss & WB Hurlbut (eds.), *Altruism and altruistic love: science, philosophy, & religion in dialogue*, Oxford University Press, Oxford, pp. 212–242.

Schmid, RE 2009, 'World's oldest human-linked skeleton found', *NBC News*, 01 October, viewed 12 June 2016, <http://www.nbcnews.com/id/33110809/ns/technology_and_science-science/t/worlds-oldest-human-linked-skeleton-found/>

Schmid, P, Churchill, SE, Nalla, S, Weissen, E, Carlson, KJ, De Ruiter, DJ & Berger, LR 2013, 'Mosaic morphology in the thorax of *Australopithecus sediba*', *Science*, vol. 340, no. 6129, a1234598. https://doi.org/10.1126/science.1234598

Schwartz, JH & Tattersall, I 2015, 'Defining the genus *Homo*', *Science*, vol. 349, no. 6251, pp. 931–932. https://doi.org/10.1126/science.aac6182

Seaman, J & Buggs, R 2020, 'FluentDNA: nucleotide visualization of whole genomes, annotations, and alignments', *Frontiers in Genetics*, vol. 11, a292. https://doi.org/10.3389/fgene.2020.00292

Shermer, M 2016a, 'Did this extinct human species commit homicide?', *Scientific American*, viewed 29 November 2021, <http://www.scientificamerican.com/article/did-this-extinct-human-species-commit-homicide1/>

Shermer, M 2016b, '*Homo naledi* and human nature', *Scientific American*, viewed 29 November 2021, <http://blogs.scientificamerican.com/guest-blog/homo-naledi-and-human-nature/>

Shreeve, J 2009, 'Oldest skeleton of human ancestor found', *National Geographic*, 01 October, viewed 29 November 2021, <http://news.nationalgeographic.com/news/2009/10/091001-oldest-human-skeleton-ardi-missing-link-chimps-ardipithecus-ramidus.html>

Shultz, S, Nelson, E & Dunbar, RIM 2012, 'Hominin cognitive evolution: identifying patterns and processes in the fossil and archaeological record', *Philosophical Transactions of The Royal Society B*, vol. 367, no. 1599, pp. 2130–2140. https://doi.org/10.1098/rstb.2012.0115

Skell, PS 2005, 'Why do we invoke Darwin?', *The Scientist*, p. 19, 10, viewed 30 November 2021, <https://www.the-scientist.com/opinion-old/why-do-we-invoke-darwin-48438>

Smith, SE 2020a, 'Is evolutionary psychology possible?', *Biological Theory*, vol. 15, pp. 39–49. https://doi.org/10.1007/s13752-019-00336-4

Smith, SL 2020b, 'Texas is not a human evolution desert! Presenting human evolution to the public through museum displays', *Evolution: Education and Outreach*, vol. 13, a3. https://doi.org/10.1186/s12052-020-00117-9

Smithsonian Museum of Natural History 2010, *Genetics*, SI.edu, viewed 30 November 2021, <https://humanorigins.si.edu/evidence/genetics>

Snowdon, CT 2001, 'From primate communication to human language', in FBM De Waal (ed.), *Tree of origin: what primate behavior can tell us about human social evolution*, Harvard University Press, Cambridge, pp. 193–227.

Spoor, F, Wood, B & Zonneveld, F 1994, 'Implications of early hominid labyrinthine morphology for evolution of human bipedal locomotion', *Nature*, vol. 369, pp. 645–648. https://doi.org/10.1038/369645a0

Stedman, HH, Kozyak, BW, Nelson, A, Thesier, DM, Su, LT, Low, DW, Bridges, CR, Shrager, JB, Minugh-Purvis, N & Mitchell, MA 2004, 'Myosin gene mutation correlates with anatomical changes in the human lineage', *Nature*, vol. 428, pp. 415–418. https://doi.org/10.1038/nature02358

Stitz, M, Chaparro, C, Lu, Z, Olzog, VJ, Weinberg, CE, Blom, J, Goesmann, A, Grunau, C & Grevelding, CG 2021, 'Satellite-like W-elements: repetitive, transcribed, and putative mobile genetic factors with potential roles for biology and evolution of *Schistosoma mansoni*', *Genome Biology and Evolution*, vol. 13, no. 10, a204. https://doi.org/10.1093/gbe/evab204

Stringer, C 2015, 'Human evolution: the many mysteries of *Homo naledi*', *eLife*, vol. 4, a10627. https://doi.org/10.7554/eLife.10627

Suntsova, MV & Buzdin, AA 2020, 'Differences between human and chimpanzee genomes and their implications in gene expression, protein functions and biochemical properties of the two species', *BMC Genomics*, vol. 21, no. 7, a535. https://doi.org/10.1186/s12864-020-06962-8

Tallis, R 2011, *Aping mankind: Neuromania, Darwinitis, and the misrepresentation of humanity*, Acumen Publishing, Durham.

Toth, N & Schick, K 2015, 'Overview of paleolithic archaeology', in W Henke & I Tattersall (eds.), *Handbook of paleoanthropology: principles, methods, and approaches*, 2nd edn, Springer, Heidelberg, pp. 2441–2464.

Troskie, RL, Faulkner, GJ & Cheetham, SW 2021, 'Processed pseudogenes: a substrate for evolutionary innovation', *BioEssays*, vol. 43, no. 11, a2100186. https://doi.org/10.1002/bies.202100186

Turner, A & O'Regan, H 2015, 'Zoogeography: primate and early Hominin distribution and migration patterns', in W Henke & I Tattersall (eds.), *Handbook of paleoanthropology: principles, methods, and approaches*, 2nd edn, Springer, Heidelberg, pp. 623–642.

University of Colorado Anschutz Medical Campus 2015, 'Ancient ancestor of humans with tiny brain discovered', *ScienceDaily*, 10 September, viewed 29 November 2021, <https://www.sciencedaily.com/releases/2015/09/150910084610.htm>

University of Michigan News Service 2000, *New study suggests Big Bang theory of human evolution*, UMich.edu, viewed 29 November 2021, <http://www.umich.edu/~newsinfo/Releases/2000/Jan00/r011000b.html>

University of the Witwatersrand 2015, 'The hand and foot of *Homo naledi*', *ScienceDaily*, 06 October, 2015, viewed 29 November 2021, <http://www.sciencedaily.com/releases/2015/10/151006123631.htm>

University of the Witwatersrand 2017, '*Homo naledi*'s surprisingly young age opens up more questions on where we come from', *ScienceDaily*, 09 May, viewed 29 November 2021, <https://www.sciencedaily.com/releases/2017/05/170509083554.htm>

University of Toronto 2007, 'Humans and chimps differ at level of gene splicing', *Science Daily*, 15 November, viewed 27 November 2021, <https://www.sciencedaily.com/releases/2007/11/071114151513.htm>

Val, A 2016, 'Deliberate body disposal by hominins in the Dinaledi Chamber, Cradle of Humankind, South Africa?', *Journal of Human Evolution*, vol. 96, pp. 145–148. https://doi.org/10.1016/j.jhevol.2016.02.004

Vansickle, C, Cofran, ZD, Garcia-Martinez, D, Williams, SA, Churchill, SE, Berger, LR & Hawks, J 2016, 'Primitive pelvic features in a new species of *Homo*', in *The 85th Annual Meeting of the American Association of Physical Anthropologists*, viewed 29 November 2021, <http://meeting.physanth.org/program/2016/session39/vansickle-2016-primitive-pelvic-features-in-a-new-species-of-homo.html>

Varki, A, Geschwind, DH & Eichler, EE 2008, 'Human uniqueness: genome interactions with environment, behaviour and culture', *Nature Reviews Genetics*, vol. 9, pp. 749–763. https://doi.org/10.1038/nrg2428

Venema, D 2018, 'Human chimp genome similarity', *The BioLogos Forum*, viewed 30 November 2021, <https://discourse.biologos.org/t/human-chimp-genome-similarity/38409/118>

Verrengia, JB 2004, 'Missing link found in gene mutation?', *NBC News*, 24 March, viewed 30 November 2021, <https://www.nbcnews.com/id/wbna4593822>

Viegas, J 2009, '"Ardi," Oldest human ancestor, unveiled', *Seeker*, 01 October, viewed 12 June 2016, <http://www.seeker.com/ardi-oldest-human-ancestor-unveiled-1766073270.html. This was article originally posted at Discovery Channel News at http://news.discovery.com/history/ardi-human-ancestor.html>

Wade, N 2006, 'An evolutionary theory of right and wrong', *New York Times*, 31 October, viewed 30 November 2021, <http://www.nytimes.com/2006/10/31/health/psychology/31book.html>

Wade, N 2011, 'New fossils may redraw human ancestry', *New York Times*, 08 September, viewed 29 November 2021, <http://www.nytimes.com/2011/09/09/science/09fossils.html>

Walker, A & Shipman, P 1996, *Wisdom of the bones: in search of human origins*, Alfred Knopf, New York.

Warren, M 2018, 'Diverse genome study upends understanding of how language evolved', *Nature News & Comment*, 02 August, viewed 05 July 2023, <https://www.nature.com/articles/d41586-018-05859-7>

White, R 2003, *Prehistoric art: the symbolic journey of humankind*, Harry N Abrams, New York.

White, T 2013, 'Five's a crowd in our family tree', *Current Biology*, vol. 23, no. 3, pp. 112–115. https://doi.org/10.1016/j.cub.2012.12.001

White, TD, Asfaw, B, Beyene, Y, Haile-Selassie, Y, Lovejoy, CO, Suwa, G & Woldegabriel, G 2009, '*Ardipithecus ramidus* and the paleobiology of early Hominids', *Science*, vol. 326, no. 5949, pp. 75–86. https://doi.org/10.1126/science.1175802

Wilford, JN 2001a, 'On the trail of a few more ancestors', *New York Times*, viewed 10 July 2016, <http://www.nytimes.com/2001/04/08/world/on-the-trail-of-a-few-more-ancestors.html>

Wilford, JN 2001b, 'Fossils may be earliest human link', *New York Times*, viewed 10 July 2016, <http://www.nytimes.com/2001/07/12/world/fossils-may-be-earliest-human-link.html>

Wilford, JN 2010, 'Scientists challenge "breakthrough" on fossil skeleton', *New York Times*, 27 May, viewed 12 June 2016, <http://www.nytimes.com/2010/05/28/science/28fossil.html>

Wilford, JN 2012, 'Some prehumans feasted on bark instead of grasses', *New York Times*, 27 June, viewed 29 November 2021, <http://www.nytimes.com/2012/06/28/science/australopithecus-sediba-preferred-forest-foods-fossil-teeth-suggest.html>

Wolpoff, MH, Senut, B, Pickford, M & Hawks, J 2002, '*Sahelanthropus* or "*Sahelpithecus*?"', *Nature*, vol. 419, pp. 581–582. https://doi.org/10.1038/419581a

Wong, K 2012, 'First of our kind', *Scientific American*, viewed 29 November 2021, <http://www.scientificamerican.com/article/first-of-our-kind-2012-12-07/>

Wong, K 2015, 'Mysterious new human species emerges from heap of fossils', *Scientific American*, viewed 29 November 2021, <http://www.scientificamerican.com/article/mysterious-new-human-species-emerges-from-heap-of-fossils/>

Wong, K 2016, 'Debate erupts over strange new human species', *Scientific American*, viewed 29 November 2021, <http://www.scientificamerican.com/article/debate-erupts-over-strange-new-human-species/>

Wood, B 2011, 'Did early *Homo* migrate "out of" or "in to" Africa?', *Proceedings of the National Academy of Sciences*, vol. 108, no. 26, pp. 10375–10376. https://doi.org/10.1073/pnas.1107724108

Wood, B & Collard, M 1999, 'The human genus', *Science*, vol. 284, no. 5411, pp. 65–71. https://doi.org/10.1126/science.284.5411.65

Wood, B & Grabowski, M 2015, 'Macroevolution in and around the Hominin clade', in S Emanuele & N Gontier (eds.), *Macroevolution: explanation, interpretation and evidence*, Springer-Verlag, Heidelberg, pp. 347–376.

Wood, B & Harrison, T 2011, 'The evolutionary context of the first hominins', *Nature*, vol. 470, pp. 347–352. https://doi.org/10.1038/nature09709

Wood, BA 1992, 'Evolution of the australopithecines', in S Jones, R Martin & D Pilbeam (eds.), *The Cambridge encyclopedia of human evolution*, Cambridge University Press, Cambridge, pp. 231–240.

Wuketits, FM 2015, 'Charles Darwin, paleoanthropology, and the modern synthesis', in W Henke & I Tattersall (eds.), *Handbook of paleoanthropology: principles, methods, and approaches*, 2nd edn, Springer, Heidelberg, pp. 97–125.

Yirka, B 2020, *Study of partial left femur suggests Sahelanthropus tchadensis was not a hominin after all*, Phys.org, viewed 26 November 2020, <https://phys.org/news/2020-11-partial-left-femur-sahelanthropus-tchadensis.html>

Yong, E 2012, 'ENCODE: the rough guide to the human genome', *Discover Magazine*, viewed 30 November 2021, <https://www.discovermagazine.com/the-sciences/encode-the-rough-guide-to-the-human-genome>

Yong, E 2015, '6 tiny cavers, 15 odd skeletons, and 1 amazing new species of ancient human', *The Atlantic*, 10 September, viewed 29 November 2021, <http://www.theatlantic.com/science/archive/2015/09/homo-naledi-rising-star-cave-hominin/404362/>

Zimmer, C 2005, *Smithsonian intimate guide to human origins*, Madison Books, Toronto.

Zimmer, C 2010, 'Yet another missing link', *Slate*, viewed 29 November 2021, <http://www.slate.com/articles/health_and_science/science/2010/04/yet_another_missing_link.single.html>

Chapter 10

Birney, DS 1969, *Modern astronomy*, Allyn and Bacon, Boston.

Burnett, C 2013, 'The twelfth-century renaissance', in DC Lindberg & MH Shank (eds.), *Cambridge history of science: volume 2, medieval science*, Cambridge University Press, Cambridge, pp. 365–384.

Cormack, LB 2009, 'That medieval Christians taught that the earth was flat', in RL Numbers (ed.), *Galileo goes to jail: and other myths about science and religion*, Harvard University Press, Cambridge.

Coyne, J 2013, *Did Christianity (and other religions) promote the rise of science?*, viewed 10 February 2021, <https://whyevolutionistrue.wordpress.com/2013/10/18/did-christianity-and-other-religions-promote-the-rise-of-science>

Danielson, DR 2001, *The book of the cosmos: imagining the universe from Heraclitus to Hawking*, Basic Books, Cambridge.

Draper, JW 1874, *History of the conflict between religion and science*, D. Appleton, New York.

Eastwood, BS 2013, 'Early-medieval cosmology, astronomy, and mathematics', in DC Lindberg & MH Shank (eds.), *Cambridge history of science: volume 2, medieval science*, Cambridge University Press, Cambridge.

Elsdon-Baker, F & Lightman, BV 2020, *Identity in a secular age: science, religion, and public perception*s, University of Pittsburgh Press, Pittsburgh.

Fantoli, A 2003, *Galileo: for Copernicanism and for the Church*, Vatican Observatory Publications, Vatican City.

Fantoli, A 2005, 'The disputed injunction and its role in Galileo's trial', in E McMullin (ed.), *The church and Galileo*, University of Notre Dame Press, Notre Dame.

Finocchiaro, MA 2008, *The essential Galileo*, Hackett Publishing, Indianapolis.

Finocchiaro, MA 2009, 'That Galileo was imprisoned and tortured for advocating Copernicanism', in RL Numbers (ed.), *Galileo goes to jail: and other myths about science and religion*, Harvard University Press, Cambridge.

Finocchiaro, MA 2014, *The Routledge guidebook to Galileo's dialogue*, Routledge, New York.

Fix, JD 2011, *Astronomy: journey to the cosmic frontier*, McGraw Hill, New York.

Galilei, G 2012, *Selected writings: Galileo Galilei*, trans. WR Shea & M Davie, Oxford University Press, Oxford.

Graney, CM 2015, *Setting aside all authority: Giovanni Battista Riccioli and the science against Copernicus in the age of Galileo*, University of Notre Dame Press, Notre Dame.

Grant, E 1984, 'Science and the medieval university', in JM Kittelson & PJ Transue (eds.), *Rebirth, reform and resilience: Universities in transition 1300–1700*, Ohio State University Press, Columbus.

Harrison, P 2006, 'The Bible and the emergence of modern science', *Science and Christian Belief*, vol. 18, no. 2, 115–132.

Heilbron, JL 2010, *Galileo*, Oxford University Press, Oxford.

Kaiser, CB 2007, 'Science-fostering belief – then and now', *Perspectives on Science and Christian Faith*, vol. 59, pp. 171–181.

Keas, M 2019b, 'Atheism's myth of a Christian dark ages is unbelievable', *Evolution News & Science Today*, viewed 04 May 2022, <https://evolutionnews.org/2019/01/atheisms-myth-of-a-christian-dark-ages-is-unbelievable/>

Keas, M 2020, 'The biggest myth so far in *Cosmos* 3.0: Baruch Spinoza as science hero', *Evolution News & Science Today*, viewed 04 May 2022, <https://evolutionnews.org/2020/03/the-biggest-myth-so-far-in-cosmos-3-0-baruch-spinoza-as-science-hero/>

Keas, MN 2019a, *Unbelievable: 7 myths about the history and future of science and religion*, ISI Books, Wilmington.

Keas, MN 2021, ‘Evaluating warfare myths about science and Christianity and how these myths promote scientism’, *Religions*, vol. 12, no. 2, a132. https://doi.org/10.3390/rel12020132

Kepler, J 1952, *Epitome of Copernican astronomy*, transl. CG Wallis, Encyclopedia Britannica, Chicago.

Klinghoffer, D 2019, *Gonzalez*: *worlds like this are hard to come by*, viewed 18 February 2021, <https://evolutionnews.org/2019/04/gonzalez-worlds-like-this-are-hard-to-come-by>

Laird, WR 2013, ‘Change and motion’, in DC Lindberg & MH Shank (eds.), *Cambridge history of science: volume 2*, *medieval science*, Cambridge University Press, Cambridge.

Lewis, CS 1970, ‘Dogma and the universe’, in *God in the dock: essays on theology and ethics*, Eerdmans, Grand Rapids.

Lindberg, DC 2003, ‘The medieval church encounters the classical tradition: Saint Augustine, Roger Bacon, and the handmaiden metaphor’, in DC Lindberg & RL Numbers (eds.), *When science & Christianity meet*, University of Chicago Press, Chicago.

Lindberg, DC & Tachau, KH 2013, ‘The science of light and color, seeing and knowing’, in DC Lindberg & MH Shank (eds.), *Cambridge history of science: volume 2*, *medieval science*, Cambridge University Press, Cambridge.

Mayer, TF 2015, *The Roman inquisition: trying Galileo*, University of Pennsylvania Press, Philadelphia.

McMullin, E 2005, ‘The Church’s ban on Copernicanism, 1616’, in E McMullin (ed.), *The church and Galileo*, University of Notre Dame Press, Notre Dame, pp. 180–181.

Mitchel, OM 1860, *Popular astronomy*, Phinney, Blakeman & Mason, New York.

Nadler, S 2019, *Who tried to kill Spinoza?*, viewed 12 January 2021, <https://jewishreviewofbooks.com/articles/4991/who-tried-to-kill-spinoza>

Nadler, S 2020, *Baruch Spinoza*, viewed 12 January 2021, <https://plato.stanford.edu/entries/spinoza>

Nye, B 2010, *Bill Nye speaks at the 2010 AHA conference: Part 3/3*, viewed 05 February 2021, <https://www.youtube.com/watch?v=S4dZWbFs8T0>

Peterman, A 2014, ‘Spinoza on physical science’, *Philosophy Compass*, vol. 9, no. 3, pp. 214–223. https://doi.org/10.1111/phc3.12115

Rosen, E 1965, *Kepler’s conversation with Galileo’s sidereal messenger*, trans. with an introduction and notes by E Rosen, Johnson Reprint, New York.

Rothman, A 2011, ‘From cosmos to confession: Kepler and the connection between astronomical and religious truth’, in PJ Boner (ed.), *Change and continuity in early modern cosmology*, Springer, Dordrecht.

Russell, JB 1991, *Inventing the flat earth: Columbus and modern historians*, Praeger, New York.

Schliesser, E 2014, *Spinoza and the philosophy of science: mathematics*, *motion*, *and being*, viewed 12 January 2021, <https://www.oxfordhandbooks.com/view/10.1093/oxfordhb/9780195335828.001.0001/oxfordhb-9780195335828-e-020>

Schneider, SE & Arny, TT 2018, *Pathways to astronomy*, McGraw Hill, New York.

Shea, WR & Artigas, M 2003, *Galileo in Rome: the rise and fall of a troublesome genius*, Oxford University Press, Oxford.

Smith, AM 2014, *From sight to light: the passage from ancient to modern optics*, University Of Chicago Press, Chicago.

Steele, JD 1869, *A fourteen weeks course in descriptive astronomy*, AS Barnes & Co., New York.

Tyson, ND 2010, foreword to JO Bennett et al., 2010, *The cosmic perspective*, Addison-Wesley, Boston.

Tyson, ND 2016, *Tweet*, viewed 01 February 2021, <https://twitter.com/neiltyson/status/692939759593865216>

Index

Science and Faith in Dialogue presents a cogent, compelling case for concordance between science and theism. Based on scientific and natural theological perspectives, two pillars of natural theology are revisited: the Cosmological Argument and the Argument from Design. Modern science provides undeniable evidence and objective support for these classical arguments to infer a rationally justifiable endorsement of theism as being concordant with reason and science – nature is seen as operating orderly on comprehensible, rational, consistent laws, in line with the conviction that God is Creator. The naturalistic explanations for the existence of the universe and sentient life are contested by showing that philosophical arguments against the Cosmological Argument and the Argument from Design are weak and that naturalistic theories purporting to provide satisfactory explanations are insufficient. The book illuminates this basic thesis by exploring fascinating natural scientific findings and their implications for global views.

◆

This *Science and Faith in Dialogue* indeed, and liberatingly so, counts as an unusually meritorious book. I have no hesitation in ranking it among the most paramount books of the current Science and Faith dialogue spectrum. The editors' and authors' gigantic scientific attainments along with their emphatical, sophisticated academic acumen hold immeasurable value for scholars who aspire to think zealously, conscientiously, and ingeniously apropos the positive affirmations of theism that rank prerequisite within the context of the science–faith dialogue. It is putting forward a consistency with a stupendous volume of scientific touchstones as it jockeys to be a *tour de force* or even better, *pièce de résistance* and triumph, as an indeterminately *phenomenal grandeur.*

Dr Johan A. van Rooyen, Department of Systematic & Historical Theology, Faculty of Theology & Religion, University of Pretoria, Pretoria, South Africa

AOSIS
aosis.co.za

Open access at
https://doi.org/10.4102/
aosis.2022.BK334

9 781779 952066

ISBN: 978-1-77995-206-6