A Jewel in the Crown II

ESSAYS IN HONOR OF
THE 90TH ANNIVERSARY OF
THE INSTITUTE OF OPTICS
UNIVERSITY OF ROCHESTER

Edited by Carlos R. Stroud Jr. and Gina A. Kern

A Jewel in the Crown II

Portrait of Professor Emil Wolf by Tong Wang.

A Jewel in the Crown II: Essays in Honor of the 90th Anniversary of The Institute of Optics University of Rochester

Edited by
Carlos R. Stroud Jr. and
Gina A. Kern

Meliora Press
An imprint of the University of Rochester Press

First published 2020

Meliora Press is an imprint of the
University of Rochester Press
668 Mt. Hope Avenue, Rochester, NY 14620, USA
www.urpress.com
and Boydell & Brewer Limited
PO Box 9, Woodbridge, Suffolk IP12 3DF, UK
www.boydellandbrewer.com

Vol. 1 ISBN-13: 978-1-58046-162-7
Vol. 2 ISBN-13: 978-1-58046-997-5
Vols. 1 and 2 ISBN-13: 978-1-58046-998-2

Cataloging-in-Publication Data available from the Library of Congress.

This publication is printed on acid-free paper.
Printed in the United States of America.

This volume is dedicated to the memory of Emil Wolf (1922–2018), who with Max Born wrote *The Principles of Optics*, aka the "Bible of Optics," and more than anyone else defined the field of optics in the second half of the twentieth century.

Contents

Preface

It has been fifteen years since we published the first *Jewel in the Crown* celebrating the seventy-fifth anniversary of the founding of The Institute of Optics. The seventy-five essays in that volume recounted the history of The Institute from its founding in 1929 to 2004. While there are certainly more stories to tell from that period, in this volume we concentrate for the most part on the developments of the past fifteen years. The one notable exception is an essay on the meeting of nine men in 1915 that set on its way the subsequent founding of the Optical Society of America, now called simply The Optical Society, and The Institute of Applied Optics, now simply called The Institute of Optics. The Optical Society celebrated its centennial in 2004, and as a part of that celebration published a book of historical essays: *OSA Century of Optics*, a comprehensive survey of the development of the whole field of optics in the twentieth century.[1]

The developments in The Institute for the past fifteen years are so numerous and exciting that we could easily fill another volume the size of the first one covering seventy-five years, but we have tried to restrain ourselves somewhat, realizing that we perhaps lack perspective to judge which accomplishments will stand the test of time. Instead we have limited ourselves to approximately one-third of the size of the original volume, but include more than a hundred color photographs, primarily in photographic essays called "Highlights."

The new volume is divided into seven sections. Parts I and VI describe the way in which The Institute has been driven by a charge that it was given in 1915 before its founding to serve the optics community. In 1915, the service was mostly to the few optics companies in the United States, mainly Eastman Kodak and Bausch & Lomb in Rochester. Today, with the invention of the laser and optical communication, the field has expanded enormously, and to continue to serve the vastly increased constituency The Institute has refocused its attention, beyond the two major local optics companies to the more than one hundred optics, photonics, and imaging companies in the Rochester area, to a rapidly growing constituency throughout the country and indeed the world. Happily, our original lone Institute has been joined by other optics academic programs, including those at the University of Arizona and University of Central Florida. The emphasis is increasingly on cooperative and collaborative efforts with our sister organizations around the world. This outreach is described in a series of essays in part V.

Part II focuses on the leadership and accomplishments under the directorships of Wayne Knox and Xi-Cheng Zhang and an evolving administrative staff. Part III describes the rapid growth of the undergraduate program and the new ABET-accredited degree, bachelor of science in optical engineering. It also describes the expanded master's degree program and the greatly enhanced teaching laboratories. Part IV includes several essays with overviews of major research efforts in a number of fields, including polarization, nano-optics, freeform optics, laser modification of surface morphologies of metals, efforts to preserve historic daguerreotype photographs, and more. Part VI also includes essays of remembrances, and photographs associated with the award of the 2018 Nobel Prize in Physics to Gérard Mourou and Donna Strickland for their work on developing the technique of chirped-pulse amplification that revolutionized short-pulsed high-power lasers. It also includes a photographic essay on meetings of faculty members with dignitaries around the world. Finally, part VII presents group photographs of current members of the faculty, students, and staff, as well as detailed listings of the faculty and graduates from the entire ninety-year history of The Institute as well as the companies they have founded. We hope that this combined listing will be of great utility to all who are interested in who were the people who have contributed to this remarkable enterprise.

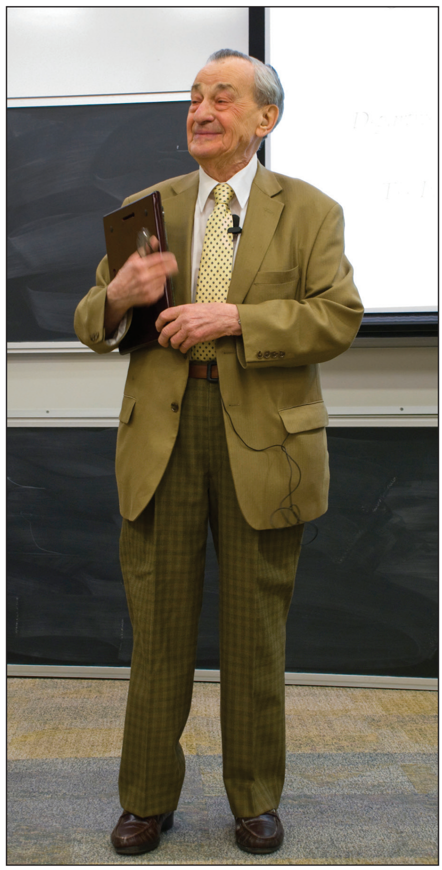
Finally, we thank the authors of all of the individual essays, others who took time to come to group photo sessions, and to Scott Carney, who as director inspired and financed this history. We could not have completed this project without the generous help of those who gathered data, shared photos, and checked facts. Heartfelt thank-you's also go to our spouses, Jim Kern and Pat Stroud, for their patience and support. And last, but not least, huge gratitude to all faculty, staff, students, and alumni of The Institute. It has been an honor to work with so many along the way, and to reap the benefits of all who put such heart and soul into growing The Institute. Meliora, indeed.

This volume is dedicated to the memory of Emil Wolf, who served on the faculty of The Institute of Optics, and the Department of Physics of the University of Rochester for almost sixty years; from 1959 until his death in June 2018. The themes of this book—academic and research excellence and service in the field of optics—epitomize his life. He was born July 31, 1922, in Prague, Czechoslovakia, to Jewish parents and was forced, along with his brother, to flee the German invasion in the spring of 1939, first to Italy, then to France, and finally in the middle of the night to escape again to England. All of this before his eighteenth birthday. In England he was able to finish his high school education and then earn a scholarship to Bristol University, where he earned his bachelor and doctoral degrees. On the recommendation of Dennis Gabor, he was offered a postdoctoral research assistantship with Max Born. With Born he began the long process of writing *Principles* *of Optics*, which is now usually called "Born and Wolf" or the "bible of optics." It is the most cited book in all of physics.

The writing of *Principles of Optics* took eight years, in the middle of which Born retired and moved back from Edinburgh to Germany. Wolf moved to the University of Manchester, but the two corresponded weekly on the progress of the book, and about their family lives. Happily, Wolf preserved the correspondence, which is being prepared for publication. During this period, Wolf continued to develop the foundations of the theory of optical coherence. It was this work that brought him to the attention of Robert Hopkins, who was then the director of The Institute. In 1959, the race was on to build the first laser, and Hopkins realized that Wolf's theory was needed to describe the output of this new optical source. On a trip to a conference in Europe, Hopkins stopped by Manchester and recruited Wolf to join the Optics faculty.

In Rochester, Wolf soon recruited Leonard Mandel and then Joseph Eberly to form the nucleus of the Rochester Quantum Optics Group. He also started the Rochester Conferences on Coherence and Quantum Optics. These conferences are held every six years, with the eleventh which was held in August 2019. These conferences have been landmarks in the development of the fields of coherence and quantum optics. Wolf authored two other important textbooks; edited the *Progress in Optics* series, which includes more than fifty volumes; and

Bruno Wolf with his dad, Emil, as Xi-Cheng Zhang unveils the oil portrait during the Optics Alumni reception at the OSA 100th anniversary celebration, Rochester, New York, October 2016.



Emil Wolf, Wilson Professor of Optical Physical, at the last Optics research colloquium he presented, on November 16, 2009, at the age of eighty-seven.

personally mentored thirty doctoral students, while publishing more than four hundred papers.

He served as president of the Optical Society of America, was named an honorary member, and, most remarkably, presented a paper at fifty consecutive annual meetings of the society. His classroom lectures, which inspired generations of students, were notable for their careful organization, with each equation numbered as it was written on the chalkboard. He once mentioned casually that he devoted approximately eight hours preparing each lecture, regardless of the number of times he had taught the course. Beyond his scholarship, he was beloved by students and fellow faculty members for the kindness and concern that he bestowed on us all. He is missed.

Gina Kern and Carlos Stroud
The University of Rochester
May 2019

Notes

1. OSA Century of Optics, ed. Paul Kelley, Govind Agrawal, Michael Bass, Jeff Hecht, and C. R. Stroud Jr. (Washington, DC: Optical Society of America, 2016).

PART I

Meliora

I. *Meliora*

Meliora is the motto of the University of Rochester. It translates to "ever better." We have chosen *Meliora* as the theme of this volume and the title of this section. In the one essay in this section, Carlos Stroud documents how from its very inception The Institute had a mission that was different from that of a usual academic department in a research university. In 1929 there was no academic department specializing in optics in the United States, so the charge for the new department was literally to define the field and provide leadership for it. The new "Institute for Applied Optics" took this charge seriously, including its national scope. The field has evolved enormously in the 104 years since the group of nine men met to plan for the founding of the university institute and the Optical Society of America. The Institute has had to indeed become ever better to meet the growing challenge. In the final section of this book the director, P. Scott Carney, carries this *Meliora* theme further to extrapolate another decade to predict how The Institute will continue to serve the optics community at the centennial of its founding. Also included in this section is a map of New York with locations of local optics and imaging companies marked. It is clear that the local optics community has grown even faster than the national optics community.

1. The Mission of The Institute

Carlos R. Stroud Jr.

Tradition of Service

The faculty and directors of The Institute of Optics have since its earliest days felt an obligation to serve and nurture the field of optics and its practitioners, not just at the University of Rochester, or among its own faculty, students, and alumni, but in the Rochester area, the United States, and particularly in recent years, throughout the world. This sense of obligation has led our faculty, former faculty members, and alumni to serve as president of the Optical Society of America eighteen times, as president of the Society of Photographic Instrumentation Engineers (SPIE) eight times. At present the Optics faculty serve as editors of three professional journals. The faculty have authored many of the standard textbooks in optics, including three that are currently among the most cited in all of physics.[1] They have served on innumerable committees advising governments on topics ranging from repairing the flawed optical system of the Hubble Space Telescope, to design of counterfeit-resistant paper currency, and laser-assisted isotope separation. One even served the president as deputy in the Office of Science and Technology Policy. The Institute has reached out to the optics industry through a professional summer school for practicing engineers to return to campus and keep their skills up to date in the rapidly developing field. It also has an Industrial Associates program in which representatives from many of the leading optics companies come to campus twice a year, to meet faculty and students, to advise regarding the needs of the industry, and to learn about the latest research. The outreach has become quite international in recent decades. Steve Jacobs put together a program to distribute to schools around the world suitcases with kits for carrying out simple optics experiments (see Essay V.19). Formal cooperative agreements have been signed with more than twenty-eight schools and universities around the world to encourage exchanges of faculty, students, and research. All of this with a full-time faculty that always has been fewer than twenty.

In this essay we will see how this strong tradition of service was built into The Institute from its inception. In the first volume of this history of The Institute of

Optics, Susan Houde-Walter described the common origins of the Optical Society of America and The Institute of Optics in a series of meetings in late 1915 and early 1916, when a group of men met in Rochester to start in motion a concerted effort to raise the level of education and research in the United States to match that existing in Europe. At that time, most precision optical instruments and optical glass were manufactured by Zeiss and Schott in Jena, Germany. Here we will explore in more detail the particular meeting that started these efforts that went a long way toward determining the path of optics development for the next century and beyond.

It had started to snow in Rochester early in the fall of 1915, but on the late afternoon of November 18 the weather was clear and nine men had no problem making their way to a little reading room in the Physics Department of the University of Rochester. The minutes of the meeting and subsequent follow-up meetings were carefully recorded, and are preserved in the Archives of the University of Rochester. In this essay we will explore three questions about this meeting:

- Why Rochester?
- Why in 1915?
- Why these nine men?

Why Rochester?

In a very real sense, consumer optics started in Rochester and was flourishing at the beginning of the last century. Bausch & Lomb had developed a vulcanized rubber eyeglass frame that was cheap and durable such that eyeglasses, which had previously been available primarily to the wealthy, were now affordable and practical for the masses. Twenty million pairs of glasses were shipped around the world from the Rochester factory in 1903. In 1900, Eastman Kodak introduced its Brownie camera, which brought photography from its role as a rich man's hobby to a central place in every family vacation and birthday party. The "Kodak Moment" entered the popular vocabulary. The need for trained employees in this new industry was great. The management of these companies also appreciated the importance of research and development to develop new products, and indeed technologies, and they were willing to invest in this R&D. These companies started their own research laboratories, but felt the need for an academic center to carry out basic research and train their employees. The Genesee Valley predated Silicon Valley by more than a half century, as the hub for a new consumer technology industry.

Why 1915?

By 1915, there were dozens of companies in Rochester involved in the new optics industry, not only suppliers for the two big companies, but also spin-off companies developing their own products. All of this activity needed academic support.[2] There was in addition a much more urgent problem: World War I had broken out in Europe, and international shipping was being disrupted. Furthermore, the entry of the United States into the war on the side of Great Britain and France against Germany was imminent. The US optics industry was severely endangered because of its dependence on the high-quality optical instruments and optical glass that had been imported from Zeiss and Schott. The problem was exacerbated by the growing importance of optical instruments to the modern military. Machining of cannons had become so precise that they could accurately hit targets more than ten miles distant, if they could be aimed precisely. Such aiming required optical range finders, binoculars, and telescopes of similar precision. Aerial warfare had achieved a major role in the war both for reconnaissance and bombing. This required bomb sights, binoculars, and telescopes for the airplanes and for antiaircraft guns. In spite of the massive mobilization during the war, including developing the first manufacturing facility for optical quality glass at Bausch & Lomb's factory on St. Paul Street in Rochester, it was clear that efforts would have to be continued after the war to develop the infrastructure to support an American optical industry. A part of this infrastructure was an academic institute of applied optics to carry out basic optics and train optical scientists and engineers. Perhaps not so obvious was the perceived need to found a national optical society and an optics journal to publish original research. There were two primary drivers for this effort in Rochester at the time. The first was C. E. K. Mees, the founding director of the Eastman Kodak Research Laboratories, who was convinced that to keep the very best scientists and engineers happily and productively working in his laboratory, he had to allow them to publish their work and to interact with other scientists with similar interests at scientific conferences. Another researcher working with Mees was Dr. Perley Nutting, who was recently hired from the optics group at the National Bureau of Standards in Washington, DC. While in Washington he led an earlier unsuccessful effort to found a national optical society. One might have thought that the meetings and journals of the American Physical Society (APS), founded a few years earlier, in 1899, would have served the needs of the optical industrial researchers. However, there was a movement among the leadership of the APS to focus the society and its publications on basic physics and to exclude applied physics. This sentiment was also common in university physics departments, so workers in applied optics needed another home. Both Eastman Kodak and Bausch & Lomb were willing to put resources behind the founding of an appropriate society and an academic department to serve the needs of industrial optics in the United States.

Why These Nine Men?

We are not left to guess at the motivations and intentions of the nine men who met in the reading room of the Physics Department of the University of Rochester on the afternoon of November 18, 1915. They quickly elected a secretary, who took careful and thorough minutes of the meeting. Those minutes, along with those of all other meetings of the Rochester Society for Applied Optics, later to become the Rochester Section of the Optical Society of America, are preserved in the Archives of the University of Rochester. The specifically stated goal is clear in the minutes of that first meeting: "The need for some organization to promote the advancement of the science of applied optics being apparent to workers in the field, a meeting was called to consider plans for the organization of such a society."

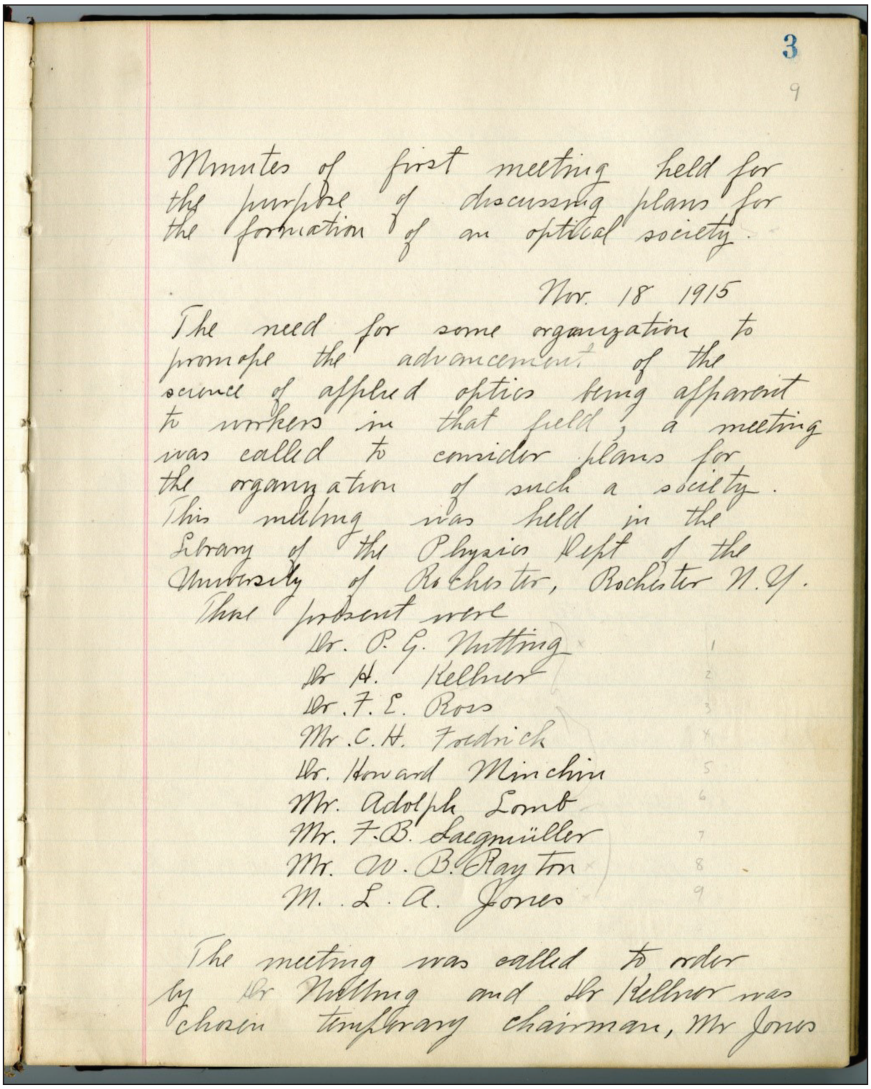
While these minutes do not make the longer-term goal of establishing an academic institute to train engineers and scientists in optics, and carried out optics research, Nutting and Mees both felt that it was essential. They convinced George Eastman and Edward Bausch, on February 6, 1918, to write a joint letter to Rush Rhees, president of the University of Rochester, urging the formation of such an institute. Eastman and Bausch offered $200,000 to set up The Institute, and $20,000 each per year to sustain it. (The letter is preserved in the Archives of the University of Rochester.)

President Rhees was preoccupied with building the new River Campus for men and was not able to follow up immediately. But once construction was commenced, Rhees put the proposal to the Board of Trustees, which approved the formation of The Institute of Applied Optics in March 1929. As is described in the seventy-fifth anniversary history of The Institute, President Rhees sailed to England to recruit the first two faculty members.

The minutes list the names of the nine men whose meeting started the whole process. Let us go through the list and see who they were, their role in optics in Rochester in 1915, and what contributions they made to seeing that their early proclaimed intent was carried out.

Dr. Perley Nutting is the first name on the list. He was elected president of the local society at that first meeting and was elected the next year to be the first president of the Optical Society of America. He was born in 1873, and received a PhD in physics from Cornell University in 1903, after which he joined the newly formed Optics Section of the National Bureau of Standards in Washington. While there, he began campaigning for a national optical society. In 1910, C. E. K. Mees, the founding director of the Eastman Kodak Research Laboratories, hired Nutting to assist in the development of a practical color photographic process. While at Kodak, Nutting authored a book entitled *Outlines in Applied Optics* in which he argued strongly for an increased academic effort in applied optics. He was a tireless campaigner for optics and an effective first president of the national society. He did not remain in Rochester to see his dream of an academic institute realized, but was hired away by Westinghouse to form its corporate research laboratory in Pittsburgh.

The second name on the list is Dr. H. Kellner. G. A. Hermann Kellner was born July 20, 1873. He studied at the Universities of Berlin and Jena, receiving a doctorate from the latter in 1899. He came to Buffalo in 1905 to join Spencer Lens Company and later moved to Rochester to become director of the Scientific



3

9

Minutes of first meeting held for the purpose of discussing plans for the formation of an optical society.

Nov. 18 1915

The need for some organization to promote the advancement of the science of applied optics being apparent to workers in that field, a meeting was called to consider plans for the organization of such a society. This meeting was held in the Library of the Physics Dept of the University of Rochester, Rochester N.Y.

Those present were

Dr. P. G. Nutting 1
Dr H. Kellner 2
Dr. F. E. Ross 3
Mr. C. H. Fredrich 4
Dr. Howard Minchin 5
Mr. Adolph Lomb 6
Mr. F. B. Laegmüller 7
Mr. W. B. Rayton 8
M. L. A. Jones 9

The meeting was called to order by Dr Nutting and Dr Kellner was chosen temporary chairman, Mr Jones

Figure 1.1. Minutes of the first meeting of the Optical Society of America

Bureau of the Bausch & Lomb Optical Co. He was not only active in the Rochester optics scene, but was the founding editor of the *Journal of the Optical Society of America.* He served as editor from 1917 to 1919, setting a very high standard that got the journal off to a good start. He remained at Bausch & Lomb until his death in 1924.

Dr. F. E. Ross is the third name on the list. A friend of Perley Nutting in graduate school in California, Ross was offered a position as an “accountant” at Eastman Kodak in 1915 at the instigation of Nutting. He actually worked on ray tracing, and was said to be particularly adept at using logarithm tables for lens design. His main love was astronomy and designing lenses for astronomical observations. He designed a lens with a wide field of view that was very successfully used in a number of observatories for surveys looking for the motion of nearby stars. We are indebted to him for the fine job he did as recording secretary of the local section in its formative years.

"Mr. C. H. Frederick" is the listing for Charles W. Frederick, who was the head of the lens design department at Eastman Kodak. He retired in 1936 and was replaced by Rudolf Kingslake, who served in that position for thirty-one years until his retirement.

Dr. Howard Daniel Minchin was assistant professor of physics at the University of Rochester, with a PhD in physics from the University of Michigan. He left UR in 1916 to become president of the Rochester School of Optometry.

Mr. Adolph Lomb, born in 1866, was the eldest son of Captain Henry Lomb, cofounder of Bausch & Lomb (B+L). He studied mathematics and physics for two years at the University of Rochester and then transferred to MIT, where he earned a bachelor's degree in mechanical engineering. He followed this with advanced studies in Paris, Berlin, and Jena. In Jena he made important contacts at Carl Zeiss Works, which would later be important in developing alliances between B+L and Zeiss. By 1916, he was on the board at B+L and very active in philanthropy to support science. He served as treasurer of the local optical society and was the first treasurer of the Optical Society of America. In this role he was instrumental in helping the society survive the Great Depression, by personally donating funds to cover the budget deficits of the society's early years. He accumulated a personal optics library that was purported to be the best collection in the country when he died. He died without a will, and his brother donated the collection to the University of Virginia at the suggestion of his good friend James C. P. Southall, professor of optometry at Columbia University, who was a graduate of Virginia.

F. B. Saegmuller was the son of George N. Saegmuller, whose optical instrument company had in 1905 joined with Bausch & Lomb to form what for a few years was called Bausch, Lomb, Saegmuller Company. Later Saegmuller helped form an alliance with Zeiss that resulted in Zeiss owning a third of the Rochester company. In 1915, the alliance was broken as a result of the war in Europe. Frank, the son, studied at the University of Virginia, then with Dr. Kellner, and later in Jena.

Wilbur B. Rayton spent his career working at Bausch & Lomb. He along with Lloyd Jones and T. R. Wilkins formed a committee that in 1926–27 planned out a curriculum for the soon to be established Institute of Optics. He was a founding member of the Optical Society of America and served as its president in 1933–34. He was an adjunct faculty member in The Institute, 1929–31.

Lloyd A. Jones, educated at the University of Nebraska, worked for several years at the Bureau of Standards before joining the Eastman Kodak research staff in 1912. He was appointed chief physicist in 1916, a position he held until he retired. He served as president of the Optical Society of America, 1930–31. In addition to serving on the planning committee for The Institute, he was an adjunct faculty member from 1929 to 1943.

More details on these fascinating and visionary men can be found in the essays by Hilda Kingslake and Susan Houde-Walter in the seventy-fifth anniversary version of *A Jewel in the Crown*. We amplify them here in order to point out that the mission of service to support the field of optics generally through education, research, and outreach was built into The Institute from the beginning, and guided its activities in 1929 just as strongly as it does now as we approach its centenary.

Figure 1.2. Liz Rogan, CEO of the Optical Society, is responsible for the oversight, strategic direction, and fiscal soundness of programs and activities of this $40 million, 150+ staff society. Photo courtesy of OSA.

Notes

1. http://www.nature.com/polopoly_fs/7.21245!/file/GoogleScholartop100.xlsx.
2. Rudolf Kingslake, *Lens Design Fundamentals* (San Diego: Academic Press, 1978).

Highlight I: Map of New York Photonics

Map highlighting upstate New York's Optics, Photonics and Imaging industries, produced annually by Rochester Regional Photonics Cluster & New York Photonics

PART II

Administration

II. Administration

The director of The Institute of Optics has played a much larger role than the usual academic department chair, with responsibilities not only to the local students and faculty, but also to the optics community more generally. During the past decade, there have been two directors to complete their terms, Wayne Knox and Xi-Cheng Zhang, and P. Scott Carney is currently serving. Gary Wicks served as associate director under Walmsley and Knox and continued to provide strong support under Zhang's directorship. In this section he reviews the principal events that occurred during Knox's and Zhang's leadership. In addition, Knox and Zhang each review one main accomplishment of their directorship. The successes that The Institute can claim are perhaps as much due to a very able staff as they are to the faculty. Gina Kern gives highlights of staff accomplishments in the past decade. Finally, we include a photographic essay showing that all is not hard work and drudgery for the directors and their families.

2. The Directorship of Wayne Knox, 2001–2011

Gary W. Wicks

Wayne Knox served as director of The Institute of Optics from the summer of 2001 to the summer of 2011, replacing former interim Institute director Ian Walmsley, who had taken a faculty position at the University of Oxford.

Wayne was recruited to The Institute directorship from his Bell Labs position as director of Advanced Photonics Research. In moving to The Institute's director position, Wayne was coming home, having grown up in Rochester and gone through The Institute of Optics undergraduate and graduate programs. After completing three terms as Institute director, he transitioned to the Hajim School Dean's Office as associate dean of education and new initiatives.

During the few years around the turn of the millennium, a third of The Institute's faculty left the university to start companies and/or take positions at other universities. Thus, the beginning of the Knox directorship presented big opportunities for growth and rebuilding. Six tenured or tenure-track faculty members were hired in the Knox years: Professors Guo, Zavislan, Fienup, Alonso, Rolland, and Vamivakas. In addition, the primary appointment of Prof. David Williams was moved to The Institute. Julie Bentley and John Marciante were added in teaching and research faculty positions, respectively. Secondary appointments for Professors Krauss and Yoon were created. Several new staff members were hired, too, including Gina Kern and Lori Russell.

Figure 2.1. Wayne H. Knox, professor of optics, and director of The Institute of Optics 2001–11

Three named faculty chairs were created, and their first occupants installed. Prof. Robert Boyd was named to the Parker Givens Chair, which was endowed in 2001 by James Wyant, PhD alumnus of The Institute (1969), University of Rochester trustee, professor at the University of Arizona, and a former student of Givens.

Figure 2.2. M. Parker Givens Chair established: Wayne Knox, Parker Givens, Robert Boyd, and James Wyant

In 2002, Prof. James Fienup was appointed as the Robert E. Hopkins Professor of Optics. Rather than the typical funding of a chair with a single gift, the funding of the Hopkins Chair was accomplished by a groundswell of hundreds of gifts from friends and colleagues, demonstrating the broad respect and appreciation of Hopkins.

In 2009, Prof. Jannick Rolland was named to the Brian Thompson Chair. The funding of the Thompson Chair was part of a generous gift from Institute friend and supporter John Bruning. The second part of the Bruning gift, combined with an initial grant from KLA Tencor, created the Robert E. Hopkins Center for Optical Design and Engineering, named in honor of the former Institute director and father of optical engineering. The opening of the Hopkins Center unveiled a suite of three laboratories; for metrology, optical design, and fabrication and finishing.

In a related optical engineering development, The Institute created a new undergraduate degree program, the BS in the field. The traditional undergraduate program, the BS in optics, still remained, serving students interested in optical physics.

Two major facility constructions occurred during the Knox directorship. The Optics teaching labs had previously been in Dewey Hall, a different location from the rest of The Institute. The teaching labs and the rest of The Institute were reunited by the completion of a $1 million project, funded by The Institute, which renovated the top floor of the Wilmot Building for a new teaching laboratory suite.

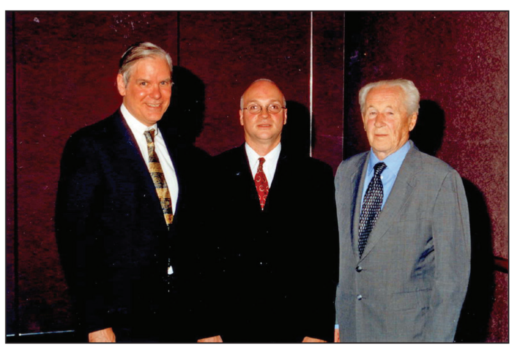


Figure 2.3. Robert E. Hopkins Chair established: James Fienup, Wayne Knox, and Brian Hopkins

The big splash of the Knox years was the Robert B. Goergen Building. This was a very large project, involving $37 million in fund-raising, design and construction, and moving in. The new building attaches to the Wilmot Building on several floors. The Institute of Optics occupies the entire Wilmot Building, the NYS Optics (Wilmot Annex) Building, and half of the Goergen Building. Biomedical Engineering occupies the other half of the Goergen Building, an arrangement that facilitates interactions of these two dynamic departments.

Figure 2.4. John H. Bruning in the Robert E. Hopkins Center.

The decade of the Knox directorship was an especially lively time for The Institute with many new hires, new facilities, and a new building. Wayne's boundless energy and enthusiasm was a good match for all the bustling activity of that time. The expansions of the infrastructure and the increased staff placed The Institute in a strong, secure position for the beginning of the twenty-first century.

Figure 2.5. Charles Munnerlyn (PhD '69) and Stephen Fantone (PhD '79), both cochairs of the fund-raising committee for a building to house optics and biomedical engineering; Tom LeBlanc, dean of the college faculty; Wayne Knox, director of The Institute of Optics; President Jackson; Richard Waugh, professor and chair of biomedical engineering; and Kevin Parker, dean of the School of Engineering and Applied Sciences, share the honors of breaking ground for the new building during fall 2011 Meliora Weekend. Photo by Deron Berkhof/University Public Relations.

3. The Construction of the Robert B. Goergen Hall for Biomedical Engineering and The Institute of Optics

Wayne H. Knox

In this short article, I review the previous homes of The Institute of Optics and discuss how the modern building was constructed. Figure 3.1 shows the original location of The Institute of Optics in its founding in the Prince Street building. Once the River Campus opened, The Institute of Optics moved in to the top floor of the Bausch & Lomb Physics Building (see fig. 3.1). In 1977, with Director Nicholas George at the helm, The Institute of Optics moved into the Space Sciences Building, which had been built in 1967 with NASA funding for the Astronomy and Geology Departments of the university. The telecommunications bubble bursting in March 2000 led to quite a flurry of activity in the field of optics. In the run-up to the bubble in the late 1990s, quite a few university faculty members had been enticed to take academic leaves of absence to start their own companies, or to join other start-ups. In The Institute of Optics, this led to a difficult situation wherein a handful of Optics faculty members had done just that, leaving as few as eleven faculty in the department. At the same time, large companies were trying to deal with the instabilities in the telecom market, and the corresponding exodus of researchers to start-up companies, with many large companies actually splitting into smaller companies as a reaction to that trend. These were the conditions that caused me to leave Bell Laboratories' Advanced Photonics Research Department, where I was director, and join The Institute of Optics in April 2001 as director and professor of optics. When I returned after seventeen years since graduating with my PhD in 1984, I found the Wilmot Building to be very much the way I remembered it. The Optics faculty strongly wanted to develop some new laboratory spaces, classrooms, and updated facilities. Coincidentally, just as I arrived, the Biomedical Engineering Department, founded in 2000, was drawing up plans for a small new building to be built in the parking lot of the Wilmot Building. With ties in the field of Biomedical Optics from my days doing research at the university, initial discussions made it

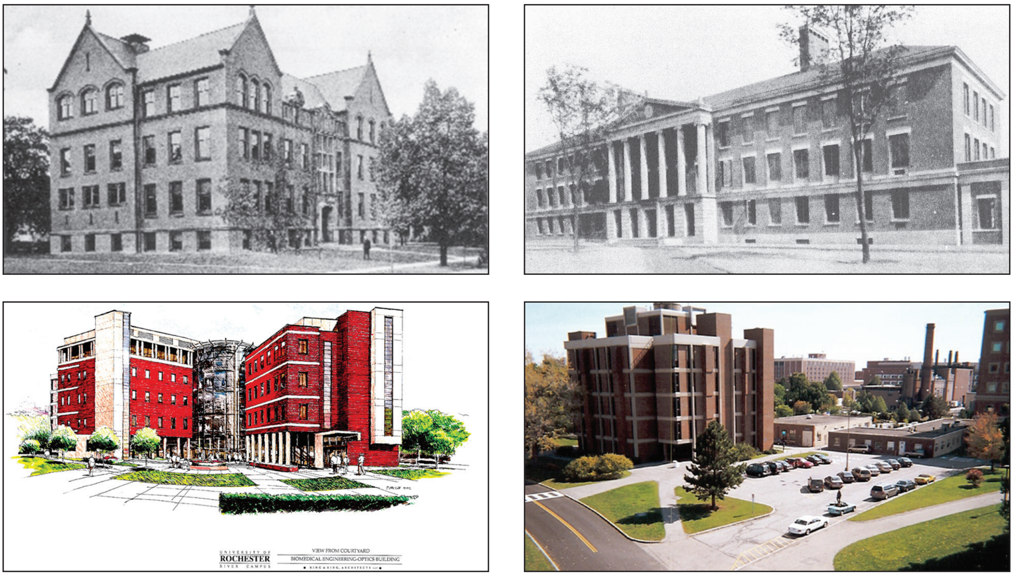


Figure 3.1. (a) The original Prince Street building through 1929; (b) the Bausch & Lomb Physics Building, the top floor of which was occupied by Optics from 1929 through 1977; (c) the Wilmot Building; (d) a 2002 concept for a new Optics–Biomedical Engineering building that was not built. The right wing was suggested for BME, and the left wing was suggested for Optics.

absolutely clear that there would be great interest in strengthening our Institute of Optics connections with the BME Department, while enhancing collaborations in the field of biomedical optics. Additional components were entrepreneurship, enhancing optical engineering, hiring new faculty to replace those lost to start-up companies, and updating teaching laboratories. But how could all of that fit into a new building? In one initial plan, a first draft design in 2002 produced a concept for an expanded wing coming off of the Wilmot Building, with a separate wing for the BME Department (see fig. 3.1). It was quickly realized that such an arrangement would not be conducive to the strong interactions needed to drive new interdisciplinary research and education, so we redesigned the building to be more integrated.

A rigorous design process was pursued, and the final design selected placed The Institute of Optics in the top two floors of a five-story building, BME in the second and third floors, with public spaces and shared classrooms featured on the first floor. But first, it was necessary to clear the space. Optics faculty were more than happy to help begin the demolition of the machine shop and old Cyclotron Buildings, leading the way for more clearing (see fig. 3.2a). A brief pause in construction activity allowed the faculty, students, and staff to pose for a construction photo (see fig. 3.2b.) Building construction proceeded (fig. 3.2c), finally finishing and opening in April 2007 to great excitement and fanfare. The building is modern and open, and has very much fulfilled our expectations.

Figure 3.2. (top) Optics faculty members start the demolition of the old machine shop building; (bottom) Optics faculty, students, and staff pose during a brief pause in construction.

Some minor problems have been dealt with, such as a few roof leaks, and the atrium lights burning out after about seven to ten years causing very difficult replacement with LED cans, and so on. Figure 3.3 shows day and night views of the building from the vantage point of the new Hajim Engineering Quad, which was just completed with the addition of the the Goergen Institute for Data Science, located in Wegmans Hall, founded at the University of Rochester in 2014.

It is now eleven years since we moved into the building, and we have seen many benefits as a result. The building has very much enabled multidisciplinary collaborations in many fields. It has helped us recruit top new faculty; establish state-of-the-art research groups; host numerous symposia, meetings, and tours; and capture the imagination of all who enter. The building even seems bright and cheerful on a dark, gray Rochester winter day (which does occasionally happen).

With so much emphasis on the new building and planning small details like the colors of the floor tiles, and the styles of the door handles and laboratory cabinets, it was possible to get lost in the details. During the design phase, our

Figure 3.3. (Day (a) and night (b) views of the Robert B. Goergen Building for Biomedical Engineering and Optics.

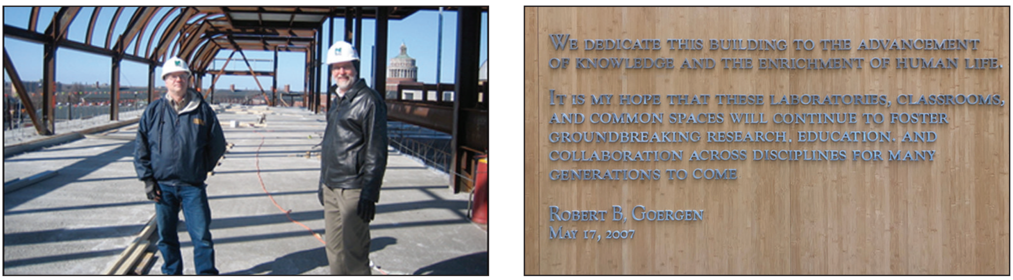


Figure 3.4. (a) Wayne Knox (left) touring the construction site with Prof. Richard Waugh, chair of the BME Department at the time; (b) the words of Robert B. Goergen on display in the Munnerlyn Atrium.

faculty, staff, and students in the Optics and BME Departments endured many sessions with the architects and project planners, and during the construction phase, I walked through the site every day with my hardhat on (see fig. 3.4), making sure that things were on track to our satisfaction. In the end, the buildings and facilities are very important, for without them, we cannot do our basic work. But the buildings would do nothing by themselves. It is the people who inhabit them and work in them. It is the new collaborations and new connections that are enhanced by the design of the building, and the revolutionary as well and evolutionary smaller advances that are imagined by those inhabitants. We can conclude that the facilities are *necessary but not sufficient for success*. We have found that indeed there is great synergy between the buildings and the faculty and students, which facilitates great results.

I look to the words of Robert B. Goergen that are attached to the Munnerlyn Atrium wall, and periodically ask whether we are fulfilling the mission that he envisioned (see fig. 3.4). Having seen, and been part of, our biomedical optics research and education expansion, as well as other advances enabled by the new facility, I think that we can confidently say that the mission is being accomplished every day, and we look forward to a bright future.

4. The Directorship of Xi-Cheng Zhang, 2012–2017

Gary W. Wicks

Xi-Cheng Zhang served as director of The Institute of Optics for five and a half years, from January 2012 to July 2017. He was hired after an international director search to replace former director Wayne Knox, who had become associate dean of education and new initiatives in UR's Hajim School of Engineering.

Prior to taking on the director position at The Institute, Xi-Cheng held an academic leadership position as the acting head of the Department of Physics, Applied Physics, and Astronomy, and founding director of the Center for Terahertz Research at Rensselaer Polytechnic Institute. He brought to The Institute of Optics an international reputation as a leader in the field of THz science and technology, especially regarding THz generation with nonlinear optical processes involving ultrafast lasers. His Rochester appointment included the M. Parker Givens Professorship.

Figure 4.1. Xi-Cheng Zhang, M. Parker Givens Professor of Optics and director of The Institute of Optics 2012–17.

Professor Zhang's directorship was characterized by further strengthening an already strong Institute, and by national and international extension of its connections and collaborations. A significant development was the expansion of the undergraduate and master's programs, which occurred under Xi-Cheng. At the beginning of Zhang's term, the numbers of students enrolled in the BS and MS programs were lower than the department's preferences. Intentional growth in these two programs was accomplished with substantial recruitment efforts.

Figure 4.2. Students Mark Ordway ('17), Jane (Zhenzhi) Xia ('16), Pedro Vallejo Ramirez ('16), Chris Marsh ('15), and Ching (huiquing) Zhu ('16) participate in STEM family night (2014).

Prior to Zhang's term, the undergraduate numbers had been fairly constant for a decade or so, at around eighty students in the program. By the completion of his term, this number had increased to two hundred. A good share of this success was due to the hiring of undergraduate coordinator Dan Smith. Similar success was achieved in the MS program, which tripled its enrollment to fifty students in 2017. The PhD program was in good shape at the beginning of the Zhang years and remained stable at around fifteen students admitted per year.

The growth in the undergraduate and master's programs produced immediate benefits. More graduates produce more impact and attention. The Industrial Associates program became more attractive to member companies, who now had access to a larger number of students. The department's finances were improved with larger student enrollment.

Significant expansion of The Institute's faculty occurred during the Zhang years. Three new hires to tenure-track positions were made: Profs. Nick Vamivakas, Jaime Cardenas, and William Renninger. Jennifer Kruschwitz was hired as assistant professor (teaching), and The Institute's intrauniversity collaborators were expanded with six new secondary faculty appointments: Jonathon Zuegel, Jake Bromage, Brian Kruschwitz, John Howell, Jennifer Hunter, and Benjamin Miller.

The Institute's Industrial Associates program experienced major growth during Zhang's directorship, in part due to Xi-Cheng's extensive international connections. Between 2015 and 2017, the number of IA member companies nearly tripled, rising to just short of fifty. A large amount of the credit for the strengthened IA program goes to its development manager, Ellen Buck.

Nine endowed graduate scholarships and three graduate student prizes were created during the Zhang years. The scholarships are named in honor of Institute faculty and alumni.

Figure 4.3. A large group of grad students attended the IODC-2014 meeting in Kona, HI. Back row: James Corsetti, Peter McCarthy, Qun Yuan, Yang Zhao, Jacob Reimers, Kyle Fuerschbach, Aaron Bauer, Eric Schiesser; front row: Margaret Dominguez, Joelle McCarthy, Anthony Visconti, Anthony Yee, Michael Theisen.

Figure 4.4. Team IA: Ellen Buck, Xi-Cheng Zhang, Brian Thompson, Jay Eastman, and Gina Kern.

Figure 4.5. Xi-Cheng Zhang, Joel Seligman, Nicholas George, Carol George, Milton Chang, and Duncan Moore during the celebration at the Professor Emeritus Nicholas George Professorship and Graduate Scholarship

Scholarships:

Nicholas George (2013)
Duncan Moore (2013)
Govind Agrawal (2014)
Xiangdong Cao (2014)
Stephen Jacobs (2015)
Stephen Fantone (2016)
Emil Wolf (2016)
Sunny Optical Technology (2017)
Carlos Stroud (2017)

Graduate Student Prizes:

James Fienup Academic Achievement Award (2016)
Gary Wicks Community Leadership Award (2016)
Per Adamson Laboratory Excellence Award (2016)

The Institute's faculty was very productive during the Zhang period, raising about $7 million of annual research funding. Nine faculty (Govind Agrawal, Miguel Alonso, Julie Bentley, Andrew Berger, Thomas Brown, John Marciante, Duncan Moore, Jannick Rolland, and Nick Vamivakas) won ten UR and Hajim School prizes during 2013–17. This is likely the highest number of teaching awards in a single department in the recent history of UR.

Two professors also transitioned to emeritus status in 2015: Kenneth Teegarden was named professor emeritus after teaching for sixty years and serving as director of The Institute from 1981 until 1987; Nicholas George served as the Marie C. Wilson and Joseph C. Wilson Professor of Electronic Imaging, professor of optics, and professor of electrical and computer engineering at the university for almost thirty-eight years. In addition, George was the founding director of the university's Center for Electronic Imaging Systems. From 1977 until 1981, he served as director of The Institute of Optics, significantly expanding the Industrial Associates program.

The Institute broadened its interactions and collaborations with other parts of the University of Rochester by extending several secondary appointments to UR faculty and scientists. Three scientists of the Laboratory for Laser Energetics received Optics faculty secondary appointments, Assoc. Prof. Jake Bromage, Assoc. Prof. Brian Kruschwitz, and Prof. Jonathon Zuegel. Secondary appointments in the Medical School were made to Asst. Prof. Jennifer Hunter (Ophthalmology) and Prof. Benjamin Miller (Dermatology).

Professor Zhang used his extensive global connections to increase the international footprint of The Institute. Nine international companies were added to the Industrial Associates program during his directorship. A large fraction of the increase in the number of MS students achieved during his directorship were international students. Several international memos of understanding were established.

At the conclusion of Director Zhang's term, The Institute was healthy and strong. All three degree programs were flourishing. The total number of faculty was thirty-five, with eighteen tenured and tenure-track faculty (fourteen full professors, two associate professors, and two assistant professors). Seven of The Institute's professorships were endowed. Three of The Institute's faculty were members of the National Academies of Science, Engineering, and Medicine. Institute faculty and alumni had served as presidents of the OSA twenty-four times and of SPIE nine times. The Institute had granted about half of all optics degrees awarded in the United States.

5. International Engagement

Xi-Cheng Zhang

As the first optics education program in the nation, The Institute has granted over 3,200 degrees in optics. The Institute of Optics has trained the critically needed scientists, engineers, and entrepreneurs in the broad field of applied optics. Throughout its history, The Institute of Optics, together with the University of Rochester, has gained a great reputation and compared favorably with top-ranked institutions and universities nationwide, with the majority of its students from domestic schools.

There have been significant numbers of non-US graduate students since the 1960s. However, there were relatively few non-US undergraduate students until the past decade. After a growth period of BS majors in optics during the telecom bubble in the 1990s, the period from 2000 through 2012 saw the number of undergraduate students at The Institute remain relatively low. A desirable student-to-faculty ratio has always been maintained, but a flat undergraduate enrollment was not desirable for such a leading institute. When I became the director in 2012, some of our faculty expressed great concern for the future alumni pool. As an Institute priority, the Optics Executive Committee (OEC), consisting of Profs. Duncan Moore, Gary Wicks, Miguel Alonso, and myself, recommended a plan to increase in the total number of BS and MS students while maintaining academic quality as the top priority. The OEC was elected by the faculty at my request to provide advice to me as the new director when I first arrived, and to provide executive administrative guidance for The Institute as a whole.

The original charge to The Institute was to stimulate and support applied optics in the United States. As research and development in optics has become much more international in the past decade or two, it is crucial that our charge should be expanded appropriately. One of our committee's recommendations was to actively recruit the top international students. After a few years' hard work, The Institute met the challenge. We increased both BS and MS student enrollment, and the percentage of international students has also increased, especially from China. As of early 2019, we have 145 undergraduates, with thirty-five students from China making up 24 percent of our undergraduate population.

Table 5.1a. The Institute of Optics: Domestic MOUs

City and State	Institution/Organization
Meadville, PA	Allegheny College
Bryn Mawr, PA	Bryn Mawr College
Hamilton, NY	Colgate University
Appleton, WI	Lawrence University
Terre Haute, IN	Rose-Hulman Institute of Technology
St. Paul, MN	Stonehill College
Easton, MA	University of St. Thomas
Middletown, CT	Wesleyan University
Cincinnati, OH	Xavier University

Table 5.1b. Research and General Agreements: International MOUs

Country	Foreign Institution/Organization
Azerbaijan	Institute of Physics of Azerbaijan National Academy of Sciences
Canada	University of Ottawa
China	Changchun Institute of Optics, Fine Mechanics and Physics
China	Huazhong University of Science and Technology
China	Jilin University
China	Kunming University of Science and Technology
China	Xi'an Institute of Optics and Precision Mechanics
China	Zhejiang University
China	Nankai University
Denmark	Technical University of Denmark
Germany	Friedrich Schiller University, Jena
Germany	Max Planck Institute for the Science of Light
Korea, Republic of	Chungnam National University
Russia	ITMO University
Russia	Lomonosov Moscow State University
Russia	Moscow Engineering Physics Institute
Singapore	Nanyang Technical University
Taiwan	National Chiao Tung University

I was excited to have the opportunity to work together with an amazing team in order to make a global impact in optics and photonics when I became the director. In addition to our esteemed, world-class faculty and the high-quality students, we had great support from Dean Rob Clark, Provost Peter Lennie, and President Joel Seligman for our outreach efforts. Our UR executive team joined me in multiple visits to meet with the leaders of prestigious international universities to establish connections and collaboration, and to help host esteemed visitors to our campus. During this period, The Institute signed many new memoranda of understanding (MOUs) and student exchange agreements with domestic schools and foreign universities, ultimately doubling the MS degree program's size.

The reputation of The Institute of Optics is very high in the United States and Europe; however, it is less well known in Asia. During my directorship, I engaged in sixty-three international trips (over six and a half years), and presented about twenty-five to thirty technical talks each year. One of my early trips was to Baku, the capital city of Azerbaijan, in 2013 where I was invited to participate in the third annual Baku International Humanities Forum. This event brings together top representatives of political, scientific, and cultural organizations, including Nobel laureates, university presidents, former heads of state, founders of multinational corporations, and leaders in natural and social sciences to hold dialogues, discussions, and exchanges of views on global issues in the interest of all humanity. I had the honor to chair the roundtable session "Converging Technologies and Outlines of the Future: Landmark Challenges of the 21st Century." This led to an MOU with the Azerbaijan National Academy of Science. I take the opportunity to make people aware of The Institute's history, faculty achievements, and educational reputation whenever I can.

One of the examples of our outreach coordination and expanding connections was a research agreement with Zhejiang University of China to engage in an international joint research center. Provost Peter Lennie and I visited the university in 2014, when we entered into the agreement. Vice Provost for Global Engagement Jane Gatewood went to Zhejiang University for a follow-up visit in 2015. As codirector of the Joint International Research Lab of Photonics, I was invited to visit the International Campus of Zhejiang University following the Westlake Photonics Symposium held in November 2016 (I have attended the three Westlake Forums held to date). Dean Xu Liu accompanied our group (which included me, Prof. Bahaa Saleh, dean of CROEL, University of Central Florida, and a retired director from the Royal Technological University of Sweden (KTH, Sweden). In two years, this impressive lab was opened on the Hangzhou main campus to welcome the first one hundred undergraduate students from international institutes, including the Imperial College London's Applied Data Science Lab, the University of Edinburgh's Biomedical Sciences, the University of Illinois Urbana-Champaign Nano, and the University of Pennsylvania's Wharton Business School. It is planned that the lab will eventually be located in the city of Haining, which has provided generous funding for the space and the building, as well as further support.

In addition to Zhejiang University, connections were made with Changchun Institute of Optics and Fine Mechanics, Xi'an Institute of Optics and Fine Mechanics, Hangzhou University of Science and Technology, and Nankai University in China; Technical University in Denmark; and Lomonosov Moscow State University and Information Technologies, Mechanics and Optics (ITMO)

Figure 5.1. Duncan Moore and Brian Thompson present Xi-Cheng Zhang with an Optics flag at the lunch celebrating achievements during his directorship, June 2017.

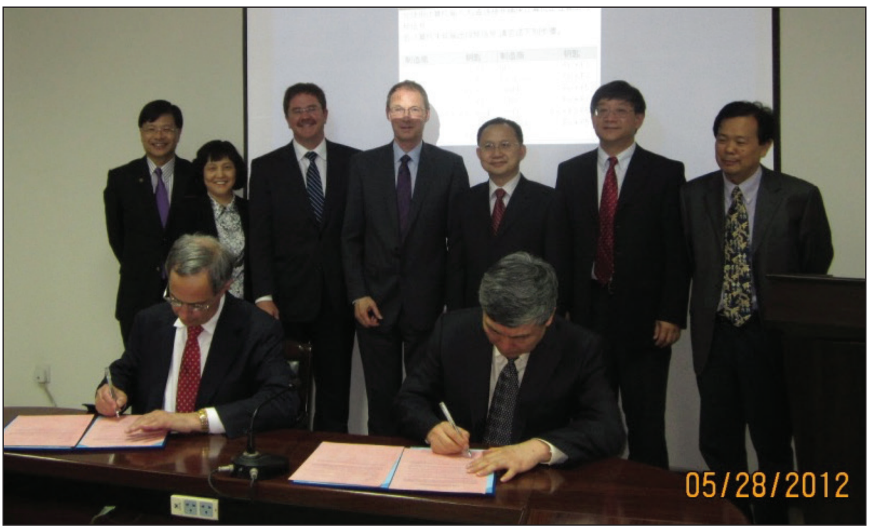


Figure 5.2. Joel Seligman signs MOU with Huazhong University of Science and Technology (HUST)–Wuhan president Penggen Li, as Rob Clark, Peter Lennie, and Xi-Cheng Zhang and other HUST administrative representatives witness the signing, May 2012.

University in St. Petersburg, Russia. We established a student exchange with ITMO University; their students came to The Institute to complete MS degrees, and UR sent students to ITMO's summer school. With Svetlana Lukishova's support, we also expanded the program from St. Petersburg to Moscow.

Another notable achievement happened on the morning of May 19, 2013, at the UR commencement. Following my nomination, and approval by the UR trustees, President Seligman awarded an honorary doctoral degree in science to Jie Zhang, president of Shanghai Jiaotong University. He was the first Chinese to receive this honor in UR's history of over 160 years. Our UR delegation visited Shanghai Jiaotong University, and some of their excellent students came to further their education at the University of Rochester.

Rob Clark joined in additional visits, including to Hong Kong and the University of Macau, where we met with president Wei Zhao. The University of Macau received $1 billion from China's central government and built an impressive campus on Hengqing Island, with over eighty new buildings. The University of Macau sends four to six undergraduate students to UR each year. Rob and I also met with some of these students. The former Chinese ambassador to the United States, was made aware of The Institute. He and his council visited Rochester twice and hosted UR delegations' visits to New York. Those activities helped us to establish a strong tie between UR and the Chinese Consulate in New York and have provided more opportunities to establish channels for additional educational and research collaborations. Invited by the Chinese Consulate, I was honored to meet Chinese premier Jiabo Wen in 2013 and Chinese president Xi Jinping in 2015 in New York City.

Many international trips featured additional visits and meetings with optics leaders such as the secretariat of the Chinese Physics Society and the presidents of Daheng Optoelectronics Company, Futurewei Technologies, and many others. Our Industrial Associates program has been growing, gaining new international members, and its participants are eager to hire both domestic and international students.

Figure 5.3. Gary W. Wicks, professor of optics, associate director (2000–2010) and interim director (2011)

I am very thankful to Prof. Gary Wicks, whose assistance to meet our objectives helped a great deal. Gary served as the interim director (2011) prior to my arrival, and as associate director (2000–2010) with Ian Walmsley and Wayne Knox. Gary was one of the OEC members elected by the faculty, and he agreed to continue serving The Institute in an administrative support role. His many contributions include managing the Optics Summer Course Series (currently in its fifty-eighth year), the teaching roster, TA scheduling, and assisting with the Industrial Associates program as needed. Gary has diligently served as a strong, key faculty member who makes crucial contributions to The Institute. A phenomenal professor who engages in innovative research, Gary is a trusted, reliable colleague who readily lends his expertise to assist the director's office.

The International Year of Light 2015 (IYL 2015) was a highlight of global engagement. Coordinated by the United Nations, IYL aimed to raise awareness of the achievements of light science and its applications, and its importance to humankind. Under the leadership of the United Nations Educational, Scientific and Cultural Organization, IYL 2015 brought together hundreds of national and international partners to organize more than 13,000 events in 147 countries. I was honored to attend and participate in the opening ceremony in Paris, along with friends and colleagues from around the world. In Rochester, our SPIE chapter students partnered with Rochester Museum and Science Center to offer "Light Weekends" as part of the celebrations. SPIE members performed many optical demonstrations with the theme of polarization to bring awareness of optics and the IYL to the Rochester community.

We have also established closer connections with our sister institutions in Arizona and Florida, taking advantage of annual meetings to gather directors to consult. We regularly work on ways to create synergistic research for our faculty and students and to investigate ways to streamline educational opportunities.

The world of optics revolutionizes many aspects of life, and our Institute, which holds an excellent national and international reputation, makes significant contributions in optics education, research, and development. Continuing to strengthen our connections and collaborations with other universities and international institutions will ensure a healthy future for our Institute to continue to provide the very

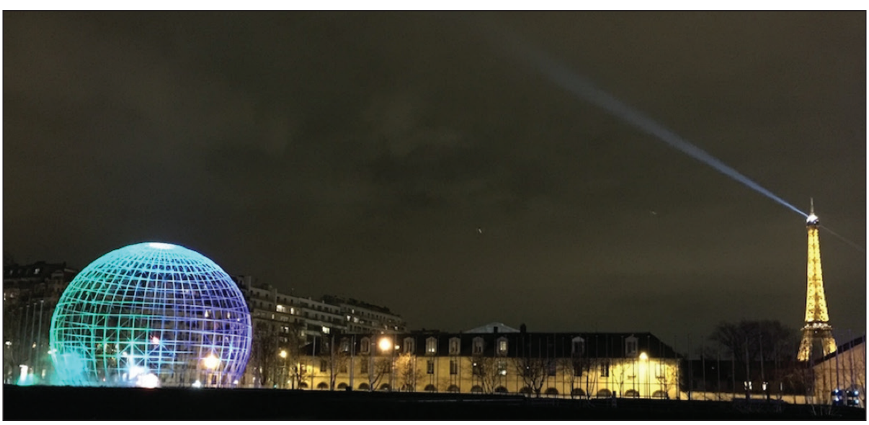


Figure 5.4. Xi-Cheng's photo from the opening ceremonies of International Year of Light in Paris, November 2015.

Figure 5.5. Directors and previous directors of The Institute of Optics (UR), the College of Optics (AZ), and CREOL (FL), at OSA FIO, October 2012. From left: Wayne Knox, Ian Walmsley, Brian Thompson, James Wyant, Bahaa Saleh, Nicholas George, Duncan Moore, Eric Van Stryland, Tom Koch, Xi-Cheng Zhang.

best scientists, engineers, and entrepreneurs in the broad field of applied optics, and pathways for our faculty and students to create a bright future for us all. Many people have worked hard to make The Institute of Optics great, and I am honored to be one of its members.

.

6. The Institute of Optics Staff

Gina A. Kern

In *A Jewel in the Crown*, Essay 71, Maria Schnitzler wrote, “Behind this great department is a great support staff. There were, and continue to be, men and women who made a lasting impression in the department, through their passion for their job, their outstanding skills, and their longevity.” Maria gave an excellent historical overview of many of The Institute’s staff members.

During the years since publication of the timeless tome highlighting our first seventy-five years, staff have continued to work together with the faculty and students to maintain excellence. However, after decades of longevity, all of the administrative and technical staff who were here to celebrate the seventy-fifth anniversary either reached retirement or moved forward to new opportunities. In their stead, a new, diverse team of professionals has assembled to continue the strong support needed at The Institute.

Those present in 2004 who retired after decades in Optics include Joan Christian, Gayle Thompson, Noelene Votens, Betsy Benedict, Maria Schnitzler, and me. Jim DePinto, Sylvia Schattschneider, Mike Koch, and, most recently, Per Adamson continued to new positions. Brian McIntyre, a senior engineer and senior lecturer with UR since 1985, can still be found on site, managing the Nano Lab and teaching an Electron Microscopy class each spring semester. Although UR moved Brian’s home department and the management of the Nano Center under the domain of Physics in 2008, he will forever be a member of the Optics team.

In 2006, James DePinto, Optics administrator since 2001, left for a new position at the Monroe County Water Authority. A “hail fellow well met” type of guy, Jim was instrumental in helping Wayne Knox with the planning and beginning construction of the Robert B. Goergen Hall for Biomedical Engineering and Optics (BMEO) building, as well as building stronger relations with the Dean’s Office. Tragically, he and his wife Patty, a kindergarten teacher, were killed in 2011, when a drunk driver hit them as they turned onto the Lake Ontario State Parkway after a day of apple-picking.

Lori Russell joined The Institute as the third Optics administrator in 2006 and is currently the administrative staff member with the longest history in the department. Lori earned her MBA from Nazareth College and previously worked in UR Undergraduate Admissions as well as the Graduate Education Department at the School of Medicine and Dentistry at the UR Medical Center. Lori instituted regular staff meetings and modernized staff reviews and now leads innovative retreats and works continuously with faculty, staff, and HR to create an ever stronger team. She brought new levels of data analysis and assistance to The Institute's director in staff management, decision making, and strategy development, helping to enhance the academic and research reputation of The Institute and the school.

The graduate program has gone through several staff changes since our seventy-fifth anniversary. In 2007, Joan Christian retired after nineteen years at UR; she and her husband moved to West Virginia (they have since returned to upstate New York). Maria Schnitzler accepted the duties for Graduate Admissions, and Lissa Cotter was hired to handle the graduate program. Lissa left in March 2013, and Betsy Benedict took the challenge of managing the graduate program until her retirement in 2014. The Institute then hired Kari Brick. With a master's in college student personnel administration, Kari was a natural in the job and managed the program and admissions. She made a positive impact on the faculty, staff, and students, engaging in student development outings and even hosting Thanksgiving in her home for some of our international students.

Figure 6.1. Kari Brick hosting international graduate students at Thanksgiving dinner. Clockwise from top right: Kari Brick; Nataliya Khoshooniy, Russia; Yi Zhang, China; Haoyu (Arthur) Chen, China; Jaikai Lyu, China; Christopher Pietsch, Australia; Aniruddha Sonde, India.

However, in 2017, Kari advanced to a position as program director with the Gwen M. Greene Center for Career Education and Connections. Jaqueline Thomas-Bell was hired in Fall 2017 and served a few months before leaving in early 2018. Kai Davies, secretary to Chunlei Guo since 2015, was recruited as an interim coordinator and transitioned to full-time as the graduate program

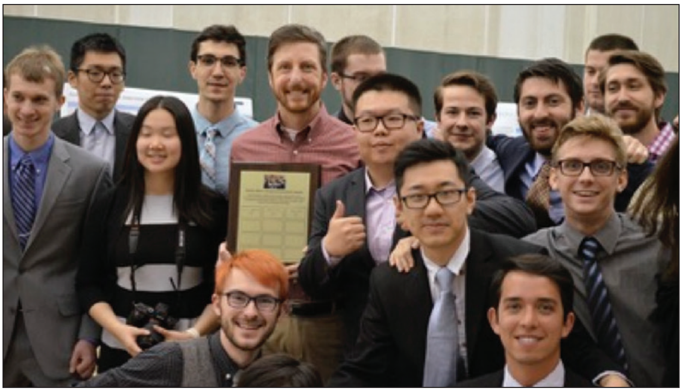


Figure 6.2. Dan Smith surrounded by Optics students as he receives the 2016 Dottie Welch Student Enrichment Award. From left, foreground: Zach Evans (tinted hair), Jiajian He (thumbs up), Zhiqi Wang, Pedro Vellejo Ramirez, Tyler Berryman; first row standing: Alex Anderson, Wanyue Song, Dan Smith, Alex Rainville, Jordan Teich, Weston Moore; last row: Haotian Jang, Ty Adair, Josh Hess, Jacob Milberger.

coordinator in 2019. Kai brings a strength and commitment to the program that is promising for the future of the department.

The undergraduate program has enjoyed the continuity of strong support. When Betsy transitioned in 2013, after twenty-three years of coordinating our undergraduates, former navy helicopter pilot Daniel Smith was hired to manage the program. Dan brought great enthusiasm, maturity, and expertise in working with young "recruits." He moved the program to new levels of success and was so good at the job that he was awarded the 2016 Dottie Welch Student Enrichment Award.

Dan left The Institute at the end of 2017 and is now working part-time with RAM Photonics. However, he also continues Time as Reported (TAR) with The Institute, helping with outreach and recruitment. Our search in 2017 yielded another strong, caring, organized, dependable, and personable coordinator; army reservist Captain Dustin Newman. It is interesting to note Dustin is our third military veteran to run this program. Bev Holloway would be proud of The Institute for hiring Dan and Dustin.

After the building of the BMEO, a major resource for the undergraduate students developed. Thanks to a generous gift from John Bruning; a grant from the KLA Tencor Foundation; and contributions from numerous companies such as AudioDev USA, Edmund Optics Corporation, Lambda Research Corporation, Newport Corporation, Optical Research Associates, Optikos Corporation, RSoft Design Group, and Zygo Corporation, the Robert E. Hopkins Center for Optical Design and Engineering officially opened on March 30, 2009. With a suite of three laboratories, each dedicated to a specific phase of the engineering process, a valuable resource was added for hands-on laboratory experience for students. Prof. Tom Brown served as its first director, followed by Prof. Jannick Rolland starting in 2012. Per Adamson was a crucial staff member for the Hopkins Center until his retirement in 2018, along with a succession of other technical staff including Martin Huarte-Espinosa and Adam Hayes. Graduate students and alumni often volunteer time and hone their skills as they partner with undergraduates engaged in learning the principles of trustworthy measurements, reliable instruments, and state-of-the-art optical design software. Currently, Mike Pomerantz, technical lab associate, is the critical staff member helping to run the Hopkins Center, with the assistance of Trevor O'Laughlin, manager of the teaching labs.

The new BMEO building also provided opportunities to host events in house. A grateful staff enjoyed easier setting up for events such as IA meetings, family nights, annual department holiday parties, and multiple academic and celebratory events that continue to occur on a regular basis. One unique event was hosted in 2012, when June 6 was proclaimed "George Fraley Day." Brian Thompson brought George to campus to gather with faculty, staff, and alumni for lunch. He was presented with the proclamation, as well as a free parking pass in the Optics "Fraley" parking space for life!

A major review of Optics staff positions, completed by HR in 2014–15, resulted in restructuring of The Institute staff and duties. The last secretarial positions were phased out, Gayle and Nolene retired after decades of service, and Adrienne Snopkowski (AS, optics, Monroe Community College; BS, finance, Rochester Institute of Technology) was hired as The Institute's first information analyst. Adrienne brought a healthy understanding of optics and finance through her education, and had worked at the Laboratory for Laser Energetics and Center for Optics Manufacturing (LLE/COM) with Steve Jacobs and Harvey Pollicove in the early 2000s. In late 2018, Tyler Jean-Mary was added as a financial program assistant to help Adrienne with the increasing P-card purchases and online bookkeeping. In early 2019, Meir Brea was added to the team as staff accountant.

Per Adamson was recruited from The Institute in Fall 2018 for an exciting opportunity at RAM Photonics. Per had started at LLE in 1996 and came to The Institute in 2007, where he worked closely with, and was mentored by, M. Parker Givens and Ken Teegarden. Parker, who kept bees for thirty years while at The Institute, passed his bees to Per. Per continued to supply The Institute with

Figure 6.3. George Fraley Day, June 6, 2012. From left: Brian McIntyre, Nicholas George, Carlos Stroud, Jim Zavislan, Gayle Thompson, Kenneth Teegarden, George Fraley (seated), Steve Jacobs, Jay Eastman, Duncan Moore, Mike Morris, Wayne Knox, Brian Thompson (seated), Per Adamson, Tom Brown, Susan Houde-Walter.

honey for many years and continued a celebration of Parker Givens's birthday each year by providing Parker's favorite Snickers ice cream bars to the entire Institute. There was also an infamous episode on a wickedly hot move-in day in 2013; Per and Dan distributed ice cream bars to incoming freshmen and families, earning Optics strong recognition and a delightful impression. In 2014, Per earned the Outstanding Staff Award. At the time, Rob Clark (then senior vice president for research and dean of Hajim SEAS, appointed provost in 2015) said, "Suffice it to say, the education that takes place in that busy beehive we know as The Institute of Optics is a far sweeter, more rewarding experience because of Per Adamson."

Figure 6.4. Per Adamson.

I retired at the end of 2018, after enjoying a total twenty-two years in Optics. As one of a total of five assistants to the director of Optics in its ninety-year history, I had the pleasure of working initially with Duncan Moore in 1986, when he first was named director of Optics. I left to raise two sons and complete my BS in applied arts and science at the Rochester Institute of Technology (RIT). In 2002, I returned and had the honor to assist Wayne Knox, Gary Wicks, Xi-Cheng Zhang, and finally, Scott Carney. In 2018, The Institute and Hajim surprised me with the Outstanding Staff Award. During the presentation at the graduation ceremony, Dean Wendi Heinzelman read the citation; "Gina has truly been the face of The Institute, the

Figure 6.5. Xi-Cheng Zhang, Gary Wicks, Duncan Moore, Gina Kern, Scott Carney, Wayne Knox, and Wendi Heinzelman gather to celebrate Gina's retirement, November 2018.

heart of the staff and the keeper of institutional memory." I was humbled and will always remain truly thankful for the years spent supporting Optics and its directors.

Tal Haring joined The Institute to assist the director in September 2018. Tal is The Institute's first strategic analyst; he holds a BS in business economics and is pursuing an MBA at Simon. Tal's position reflects the department's continuing tactical reviews and adjustment in staff development to meet the evolving needs in Optics staff support.

The advancement of the computer, Internet, and ensuing online resources impacted our society and significantly changed how we all do our jobs. Staff workload, communication, and responsibilities transitioned in myriad ways for faculty, students, and staff. From the writing of the first *Jewel*, there has been a continuing shift of duties among the departments at UR. Moving from manual, secretarial style duties to increasingly sophisticated computer processing, streamlined planning, and communications transformed the way work is performed. Many responsibilities have shifted to the department level, and staff positions undergo continual reviews and revision.

Resources and references are immediately available, yet increasingly complicated. Many departments such as Finance, ORPA, and ISO post a wealth of reference and training material, and departments provide detailed information online. In 2012, the UR composed teams of staff to create "Mastery Methods." Lori Russell and I led two of the teams working to provide templates and guidance for accounts payable, budgets, equipment and space, faculty effort reporting, faculty recruiting, summer salary processing, financial reporting, graduate enrollment, grant management, and personnel administration. These resources are included in the Hajim Dean's Intranet, another website with an abundance of resource materials, including the area where faculty complete their annual activity reports and file for reimbursement of travel expenses (which also automatically tracks the international travel for the UR annual reporting). Even the student course opinion questionnaires moved from paper based to online only in the early 2000s.

The increasing presence on the Web brought new opportunities for departments to strengthen advertising. Barbara Schirmer (MS, computer IT administration and management, Golden Gate University) succeeded Sylvia Schattschneider as Lukas Novotny's staff administrator with the nano group in 2004. Barbara also served as the Optics webmaster, updating our website to comply with the new Hajim School design formats and maintaining a strong online presence. In 2014, Lukas decided to return to Switzerland, and Barbara transitioned with him. She continues to travel out and back between her home in Rochester and ETH Zurich.

Adam Hayes (PhD, nuclear physics, RIT) joined The Institute as a senior research engineer in 2005. In addition to his work with the Center for Freeform Optics (CeFO), Adam took over as our webmaster when Barbara left. In 2018, Adam was recruited to a great opportunity at LighTopTech, a company founded by Prof. Jannick Rolland and Christina Canavesi (PhD '14, MBA Simon '15). The Arts, Science and Engineering Dean's Office strengthened IT support and increased strategic implementation of the overall web presence. It now provides web services to departments and maintain a continuity across the college.

Mike Pomerantz joined the UR in January 2016, working jointly with The Institute of Optics and Mechanical Engineering as a technical lab associate. Mike assists with the Hopkins Center, as well as CeFO (see Jannick Rolland's essay). In 2018, Mike received the RRPC Education Award for inspiring students to embrace optics, photonics, and imaging sciences and guiding them in career development.

The Industrial Associates (IA) program, instituted by Brian Thompson in 1976, has long been a strong component for The Institute, providing amazing opportunities for students to connect with companies and experience a job placement rate that is the envy of other departments. Staff members are the backbone of the program's operation, which requires strong teamwork to successfully manage the biannual spring and fall symposia and interview sessions. For many years, Gayle Thompson was the core support IA staff member, organizing the events and working with the administrator to manage corporate membership. Gayle earned the Outstanding Staff Award in 2009, reflecting her strong help with the program.

In 2007, then-Director Wayne Knox coordinated with the Center for Business Engagement for assistance with IA corporate membership development. Daniel Camenga was the first external staff member to help grow IA. When he left in 2009, Andrew Muldoon took over to identify and implement specific strategies to cultivate and solicit strategic high-value corporate partners. During this time, alumni Jay Eastman (BS '70, PhD '74) also agreed to help manage the IA program. Jay, who refers to himself as "a serial entrepreneur," founded and served in C-level positions in numerous optics companies, is a previous director of LLE, and contributes a wealth of experience, connections, and ideas. Jay has been instrumental in growing the program and garnering excellent speakers, such as Louise Slaughter in 2015.

In early 2013, the university hired Optics alumnus Scott Catlin (BS '92) as vice president for innovation and commercialization in the Office of Technology Transfer. By November, Scott's push for innovation helped transform his office with an expanded focus on technology development and commercialization and a new name of UR Ventures. Scott, who also earned a Juris Doctor (cum laude) from the University of Notre Dame, brought an even stronger partnership with Optics. Andrew Muldoon, our staff liaison with Scott's office, advanced to a new position, and Scott then appointed Melissa Smith to help Optics in 2014. Melissa had a strong focus on marketing, and with guidance from Jay and help from UR Communications, a new IA branding and media kit was developed. Melissa left in July 2015; while she had contributed greatly to marketing, the membership drive had received little attention. Additionally, Gayle Thompson's position ended in 2015, and I assumed the duties for core IA staff support. Ellen Buck became our new liaison, and her fresh enthusiasm and determination to increase membership has been a catalyst. With her focus and our teamwork with Jay Eastman, the number of IA members more than doubled in size, with a current membership of about fifty companies.

Wayne Knox had established a practice of hosting a casual evening prior to the IA symposium for all who arrived in town early, providing low-key opportunities to network with faculty and fellow optics professionals. Director Xi-Cheng Zhang took this tradition a professional step further. With the help and advice of Jay Eastman, Xi-Cheng established the Director's Advisory Council. Representatives of the strategic-level members, faculty, and guests of the director attend an afternoon program and evening reception to provide input and feedback on the academic program and develop new strategies to enhance the experience for corporate members. This quickly provided a great avenue to help with the new ABET program (see the essay by Andrew Berger). In 2016, the program branched out to feature a Company Connection Showcase, where students and company reps participate in an open forum session, with a job fair–styled setting, to meet and network. In Jay's words, our first session was a "catastrophic success," and the session format continues to provide an opportunity for staff to find ever larger spaces to accommodate the increasing number of corporate and student participants. With Lori Russell's guidance, Xi-Cheng also added the professional services of UR's conference and event staff, bringing even greater professional management skills to support the program. Some of their staff members have become "honorary" members of Optics, joining their expertise to help us create an ever more polished program.

Scott Carney, arriving in 2017, brought a dedication and new vision to enhance IA even further and moved quickly to meet the growing needs of increased membership. With his mantra of "being the tide that raises all boats," Scott invited and engaged students and faculty with an optics focus in all other UR engineering departments, as well as Physics and at Monroe Community College (MCC). Alumna Alexis Spillman Vogt (BS '01, PhD '07) heads the optics program at MCC and helps coordinate the inclusion of students from its associate's program for opportunities to move forward to professional and/or academic progression. The feedback for IA has been consistently, overwhelmingly positive, and the Rochester IA program continues to be a trailblazer.

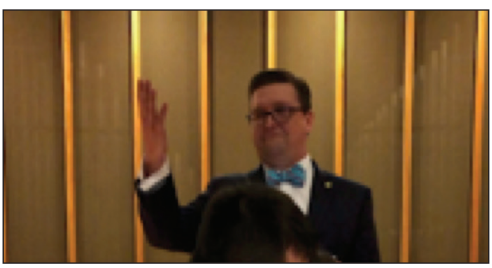
Other staff who hold honorary positions with The Institute include Duncan Moore's executive assistant Lynn Reiner and administrator Evelyn Goldman. Although their home department is technically the AIN Center, they work with Optics staff on a daily basis as they manage Duncan's research and optics engagements. Both have also provided additional staff support for The Institute as needed in a myriad of ways through the past few years. The Institute also hires several undergraduate students each academic semester and summer who work as administrative and/or lab assistants. Most are Optics students, although a few have been from other UR programs, or are family/friends of Optics personnel who are hired especially in the summer months; many return for several years. Danielle Smith, Amy Smith, and a number of faculty sons and daughters, and even a couple spouses, have provided notable support.

Figure 6.6. 2017: Adrienne Snopkowski, Kari Brick, Maria Schnitzler, Lynne (Doescher) Reiner, Lori Russell, Per Adamson, Kai Davies, Dan Smith, Gina Kern.

The Institute has been blessed with leaders who had great integrity and kept the needs, health, and commitment to excellence of The Institute as their primary focus. The Institute continues to maintain a world reputation as a leading center of education and research, being the working home for many students, faculty, and staff. It has long fostered the feeling of an "optics family." However, as we move forward with modern business practices, and employees whose long-term goals often lead them to continue to higher positions, The Institute staff has transitioned more to a professional team focus. This has provided a positive impetus for developing the administrative and technical professionals that derive inspiration from working as, and with, incredibly busy, talented people doing important work. The duties of each position are often diverse and challenging, and the staff retention rate has historically been quite strong. May The Institute continue to enjoy a talented staff that bring a variety of skills to function as a strong, loyal team. *Meliora!*

Highlight II: Directors after Hours

1. Duncan Moore is an avid Red Sox fan. His students often find unique ways to celebrate his birthday each year, and one year honored him with a Duncan Moore Red Sox bobble head! Duncan always celebrates members of his group with birthday celebrations and regularly hosts annual gatherings for alumni of his group during events such as Photonics West.



4. P. Scott Carney provides strong support and builds great camaraderie with his group members, but takes it a step beyond. Scott is a licensed officiant and has performed weddings for three of his graduate students. At the latest ceremony on February 14, 2019, he wed Jingwei Jiang to Caiqun Xu in the Interfaith Chapel on the UR's river campus. The reception was held at Rochester's Good Luck Restaurant.

2. Wayne H. Knox's alter ego, "Kimo," with his wife, Victoria "Kaiulani" Visiko, share the aloha spirit. Wayne plays and teaches a unique slack-key style of guitar, as well as ukulele, while Victoria specializes in Hawaiian dance and singing. Kimo and Kaiulani performed Hawaiian music for The Institute regularly during his term as director. They are well known as performers around Rochester and even in Hawaii,and have produced five delightful CDs of their music. Wayne also featured an ongoing Optics musical series in The Institute during his term, showcasing the talent of many Optics students as they performed concerts for the campus community.

3. Xi-Cheng Zhang and his wife, Wendy, regularly host Chinese New Year celebrations for all Chinese members of The Institute. In 2018, fifty-one students joined them to ring in the new year.

PART III

Academics

III. Academics

In this section we review developments in the academic programs over the past decade, and there have been many. Andrew Berger describes the complex process by which The Institute began offering two separate undergraduate degrees: a bachelor's degree in optics with a required thesis, and an ABET-accredited bachelor's degree in optical engineering with a senior design project. The master's degree program was also changed significantly with its own version of the core courses with a more applications-oriented approach; Jennifer Kruschwitz describes this new program. The optics teaching laboratories have greatly expanded, both in the new space on the fifth floor of Wilmot and in series of new lab courses; Per Adamson describes this development. Quantum optics, nano-optics, and quantum information have played an increasingly important role in both basic science and applications of optics. Svetlana Lukishova describes a laboratory that she developed to engage students ranging from Monroe Community College students to graduate students in these new fields. Finally, we include some of the most remarkable artistic creations of our graduate students in posters announcing their final thesis defenses.

7. ABET Accreditation of The Institute's Optical Engineering Degree

Andrew J. Berger

The BS degree in optics from The Institute of Optics has been a stamp of quality since the department's founding. Why on earth, then, did the department recently feel the need to create a second undergraduate degree in optical engineering? It wasn't as if our undergraduates were having any trouble getting industry jobs. And furthermore, why did the department take the (huge) extra step of getting the new degree accredited? After all, as a flagship undergraduate program in optics, the Rochester BS degree did not need the accreditation to bolster its credibility within academia or industry.

In the early 2000s, however, a number of forces started pushing The Institute of Optics in this unexpected direction. One nuisance was that undergraduate optics

Figure 7.1. Class of 2013: Samuel Steven, Hae Won Jung, Sarah Walters, Michael Zarella, Greg McKay, Anthony Yee, James Talerico.

majors were being excluded from awards and honors for which they had traditionally competed. Tau Beta Pi, the engineering honors society, adopted a rule requiring new inductees to have the word "engineering" in their degree titles. The Society of Women Engineers applied the same restrictions to its award offerings. Students raised these concerns to Institute director Wayne Knox—a well-chosen target, given that he had been inducted into TBP himself as an optics major.

In addition, the word "engineering" started gaining a lot more traction with Rochester students in the mid-2000s. UR alumnus Edmund Hajim made a major gift to create the Hajim School of Engineering and Applied Sciences (HSEAS). This development was paired with the hiring of a new dean of engineering and applied sciences, Robert Clark, from Duke University. The college began a targeted push to increase the percentage of engineering majors in its incoming classes. As the popularity of engineering rose, The Institute's optics degree started to suffer in comparison to the other HSEAS departments, all of which had "engineering" in their degree titles (biomedical, chemical, electrical & computer, and mechanical). When first-year students at the annual HSEAS orientation session were shown a slide listing the school's degrees, asterisks were placed next to all of the ABET-accredited degrees, making optics look like a possibly riskier path to employment. This took its toll on enrollment; at low ebb, the department graduated only seven majors in 2013.

Now, you might think that these concerns about the word "engineering" could have been fixed just by a cosmetic name change. Not so fast! New York State approval is required for any new degree names, and the state stipulated that any new degree containing the word "engineering" had to pursue ABET accreditation. ABET (Accreditation Board for Engineering and Technology) is an organization that accredits postsecondary degree programs in engineering and applied sciences. Certification indicates that there is a process in place for continuous assessment, evaluation, and revision of an educational program.

The push to pursue ABET accreditation didn't just come from New York State. Not to be ignored, there was also some friendly pressure from our peer institutions. Several undergraduate programs, including the University of Arizona's, had recently gone through the ABET accreditation process. Director Knox reported to the faculty that its counterparts were nudging him to pursue accreditation in order to show solidarity and strengthen the brand among optical engineering programs.

And so, when all was said and done, The Institute decided to create a new undergraduate degree called "optical engineering" and to get it accredited by ABET. Prof. Thomas Brown, the chair of the Optics Undergraduate Committee, led the department's first step of designing an optical engineering track and getting it approved. Compared to the existing optics degree, the new program had three new features:

- A two-semester, team-based design project was added as a capstone course.
- The standard two-cluster requirement for college degrees was reduced to "cluster plus 1" (one cluster plus a single other class in the humanities or

social sciences), in line with the college's other accredited engineering degrees.

- A breadth requirement of twelve technical-elective credits (the equivalent of three full classes) was added. These electives could be any nonintroductory course in science, technology, engineering, mathematics, or computer programming.

Rather than convert its existing optics degree into optical engineering, the department chose to retain optics as a separate degree option. This would allow interested students to pursue a senior thesis project (most likely research, but alternatively curriculum development or historical reviews) rather than the ABET-mandated team design project. The thesis was made mandatory, to parallel the optical engineering (OPE) design requirement.

Everything else about the new OPT and OPE degrees was identical: same technical elective requirement, same required core classes, and same cluster-plus-1. OPT thus became the only non-ABET degree in the college that does not require two clusters. While this was heresy to the Rochester Curriculum, it was deemed essential for the survival of the OPT degree (and thank goodness the college approved it). Undergraduates in The Institute, cursed with the inability to see ten years into the future, typically avoid as many writing classes as possible. Just think what would have befallen the OPT degree if it had retained the two-cluster requirement while the OPE degree lurked in the wings with its inviting cluster-plus-1!

After much heroic back-and-forth led by Tom Brown, the College Curriculum Committee approved the OPE degree near the end of the spring semester in 2010. This was in time for Hillary Maben (now Balonek) to be awarded the first OPE degree at graduation in May 2010. In anticipation of the degree being approved, Hillary had taken the required courses, including doing a senior design project.

Approval from New York State followed swiftly; a letter was sent to President Joel Seligman by the state on October 8, 2010, with the initial registration lasting only until September 1, 2011. As forewarned, extension beyond this date was explicitly tied to evidence that the department was working toward obtaining ABET accreditation. The die was cast.

The Institute's decision to pursue ABET accreditation came into focus at an interesting time for optical engineering programs. In 2010, a few other optical engineering programs in the country had ABET certification, including those of the University of Arizona, University of Alabama in Huntsville, Rose-Hulman Institute of Technology, and Norfolk State University. There was no distinct category for optical engineering; however, these programs were all certified under the "Other" category, an umbrella that included, for instance, sanitation engineering.

Convinced that the field of optics needed its own space, IEEE and SPIE jointly sponsored a new ABET category in the area of optical engineering. The curricular part of the accreditation effort was led by Dr. Barry Shoop from West Point. In January 2011, Institute of Optics professors Wayne Knox, Jannick Rolland,

Figure 7.2. Optics has experienced significant growth since ABET accreditation; from seven in 2013 to forty-three in 2019. Class of 2019: front row (faculty): Wayne Knox, Per Adamson, Scott Carney, Andrew Berger, Tom Brown, Jennifer Kruschwitz, Brian Kruschwitz; second row: Jaren Ashcraft, Jake Rosvold, Maximillian Bruggeman, Dylan Borruso, Dylan Beckman, Raymond Yul; third row: Katherine Donnelly, Colleen Stone, Ciara Hingston, Nicole Naselaris, Amanda Mietus, Jason Tiemer; fourth row: Kyle Daub, Evan Villafranca, Ryan Walton, Ankur Desai, Conrad Holzemer, Cristian Flores; fifth row: Xiaojing Huang, Guoxin Li, Tristan Yates, Nikita Makarov; sixth row: Yuanchao Wang, Dingzhe Zheng, Yu Hui Du, Samara Levy, Kristoffer Olsen, Jingkai Zhang. Not pictured: Cesar Adrian Cort, Jason Ewanow, Kyle Guzek, Andrew Howard, Benjamin Larson, Daniel Le, Huiyan Li, Shiyu Ma, Jack Myers, Matthew Orenstein, John Piotrowski, James Rutledge, Xiaoduo Wen, John Westerbeke, Li Zhang.

and Andrew Berger attended a first planning meeting at Photonics West.[1] After more than two years, the new category of Optical, Photonic, and Similarly Named Engineering Programs was approved at the fall 2013 ABET board of directors meeting in Baltimore. Thanks to this timing, the University of Rochester was placed in position to be the first school to apply for ABET accreditation in this new category. (The program criteria that define ABET's Optical Engineering category are provided as an appendix.)

The Hajim School had its next ABET reaccreditation visit for its other programs (ECE, ME, BME, CHE) coming up in Fall 2015. This was chosen as target time for the OPE application, since an earlier off-cycle accreditation would have required reaccreditation in 2015 anyway.

At the request of the new Institute director, Xi-Cheng Zhang, Prof. Andrew Berger stepped down as Undergraduate Committee chair and took the lead on both undergraduate recruitment and the ABET accreditation process. Berger mapped out a path with Wayne Knox (at that point the new associate dean of education for the Hajim School) and Barbara Masi, UR's new director of education innovation and assessment initiatives, who had recently worked on ABET assessment at MIT. After a sabbatical year for Berger in 2013–14, the effort began in earnest in Fall 2014.

With help from Masi, Berger implemented reviews of the undergraduate curriculum. These have since been conducted every semester since Fall 2014. They consist of a standardized form that is filled out by every instructor, called a Course Reflection Memo. This gives the instructor a chance to reflect on what needs improvement and what steps should be taken the next time the class is taught. Starting with Fall 2015, the instructor could also mention how well the revisions had worked. This creates a cycle of continuous improvement (assessment/evaluation/revision), which is the core of ABET's philosophy.

The curriculum review includes short reports from each instructor and discussion by those present. This is a chance for instructors to share information and discuss the undergraduate educational process with a bird's-eye view: for example, which topics come up in multiple classes, and which prerequisites need to be added for certain classes. Notes are taken (generally by the undergraduate coordinator) and become part of the record submitted to ABET.

ABET requires a process that is guided by a set of Program Objectives. These are aspirations for what the program's graduates will be accomplishing a few years after they have left the university. ABET also requires Student Outcomes, which are measurable accomplishments that the students have attained upon graduation. Program Objectives and Educational Outcomes were developed by the Undergraduate Committee and then discussed and voted on by the full faculty. They are revised periodically. The current ones are listed publicly, per ABET rules, on the departmental website (and are also included here as an appendix).

The ABET application itself, called a Self-Study, required a large amount of documentation. No part was generated without effort, but some elements were at least straightforward, such as syllabi for every undergraduate course, faculty CVs, a history of the department, and a summary of the findings from curriculum reviews.

More substantially, the Self-Study required assessment of the Student Outcomes. Andrew Berger created a spreadsheet that mapped the Outcomes onto the OPE classes required for the degree. Each class thus became responsible for occasional assessment of one or more Outcomes. This became part of the Course Reflection Memo that instructors submitted for curriculum reviews.

In addition, the year immediately prior to an ABET accreditation required a fine-grained snapshot of student work. For every class, three anonymized examples (good/medium/poor) of every graded written assessment (homework, quiz, exam) were acquired. This made lots of work for the instructors and their teaching assistants! Charlotte DeBossu, an undergraduate optics major working in the department front office, helped out enormously by redacting the names from the homework assignments and tests.

Lastly, the department assembled an external advisory board. For this purpose, it leveraged the Director's Advisory Council (DAC), a subset of the Industrial Associates roster. Every spring since 2015, the department's ABET team has made a presentation about the status of the undergraduate program to the DAC and has stimulated either full-room or small-group discussion, with notes taken to preserve the feedback.

Prof. James Zavislan, now serving as the new Hajim School associate dean (and yes, it has been very convenient to have Optics faculty occupying this slot continuously) worked to centralize the ABET Self-Study process for all UR engineering programs. Material common to all applications (e.g., details about the Hajim School and the University of Rochester) were generated by Hajim staff members. This allowed The Institute to focus on the most optics-centric parts. Zavislan strategically deployed high-quality box lunches at ABET meetings to maintain morale.

The Institute's Self-Study was finally completed and submitted at the end of June 2015. The department received pre–site visit feedback from ABET and addressed the organization's questions in writing in advance of the all-important site visit later that year.

On Monday, October 12, 2015, the site visit took place. The University of Rochester was visited by a team of ABET evaluators led by Prof. Frank Croft from Ohio State University. The program evaluator for optical engineering was Prof. Robert Bunch from Rose-Hulman Institute of Technology. Predictably, Professor Bunch was assigned a busy schedule on his first day: he met with the Hajim School dean, the Optics Undergraduate Committee, the senior design instructor, selected OPE juniors and seniors, the undergraduate coordinator (Dan Smith), the all-important lab guru (Per Adamson), and representative instructional faculty.

Bunch was given full access to all the materials that had been assembled, either electronically (on a dedicated laptop) or physically (course binders). With great help from Gina Kern (assistant to The Institute director), all of this was set up in the Goergen 417 conference room for Bunch to do with as he pleased. The scenario was vaguely evocative of the Rumpelstiltskin story, in which a young lady is locked in a room with hay (course binders) and required to spin it into gold (program assessment). The professor finished his work on the following day and departed cordially, without revealing whether the assessment was glowing or not.

Thankfully, the OPE proposal was indeed given a mostly positive review. The program itself earned flying colors; the requested changes focused on a few rookie mistakes. For example, we accidentally wrote our Program Objectives to describe students at the moment of graduation. We were told to revise them to reflect expectations for students who were three to five years past receiving their degrees. We also had to rewrite our Student Outcomes to ensure closer adherence to general

ABET standards. At the end of the day, the true sign of having been through the ABET accreditation process is that you no longer have to pause for ten seconds to remember the difference between an Objective and an Outcome.

We sent in our corrections and settled in to wait for ABET's decision. Finally, The Institute got the good news on August 19, 2016, when a letter was sent to President Seligman by Lawrence Jones, president of ABET: the OPE degree was accredited, retroactively to October 1, 2014. Hoorah!

Our initial accreditation lasts until September 30, 2022. A newly formed departmental ABET committee, consisting of Knox (chair), Zhang, and Berger, will oversee the next application cycle. In the meantime, the Undergraduate Committee is considering several additional changes to the curriculum, including different tracks for majors, greater distinction between OPE and OPT degrees, and a new BA in optics. There's discussion about a degree in photonic engineering, and another in optical sciences. There's even talk about The Institute helping to establish new programs in optics at other universities. Stay tuned! The commitment to the best in undergraduate optics education never rests.

Appendix

ABET's Program Criteria for Optical, Photonic, and Similarly Named Engineering Programs are as follows:

Curriculum

- The structure of the curriculum must provide both breadth and depth across the range of engineering topics implied by the title of the program.
- The curriculum must prepare students to have knowledge of and appropriate laboratory experience in: geometrical optics, physical optics, optical materials, and optical and/or photonic devices and systems.
- The curriculum must prepare students to apply principles of engineering, basic sciences, and mathematics (such as multivariable calculus, differential equations, linear algebra, complex variables, and probability and statistics) to modeling, analyzing, designing, and realizing optical and/or photonic devices and systems.

Faculty

- For primarily design courses, faculty members must be qualified by virtue of design experience as well as subject matter knowledge.

As of this writing, The Institute's Objectives and Outcomes for its optical engineering degree are as follows:

Program Objectives

- Graduates of the University of Rochester's bachelor of science degree in optical engineering will, after a few years, be assuming leadership roles in commercial and governmental jobs, or be progressing toward advanced degrees.
- Our graduates will have a track record of continued education, trainability, and adaptability within their workplaces.
- Our graduates will be valued for their innovativeness, technical proficiency, teamwork, and excellence in conveying information.
- Our graduates will have gained awareness of the many ways engineering skills are used, allowing them to select paths that align with their interests and maximize their contributions.
- Our graduates will know how to act ethically and will appreciate the relationship of engineering and science to their society, their economy, and their environment.

Student Outcomes

ABET recently revised its Outcomes; they will be in effect for the 2019–20 application cycle. They are:

1. An ability to identify, formulate, and solve complex engineering problems by applying principles of engineering, science, and mathematics.
2. An ability to apply engineering design to produce solutions that meet specified needs with consideration of public health, safety, and welfare, as well as global, cultural, social, environmental, and economic factors.
3. An ability to communicate effectively with a range of audiences.
4. An ability to recognize ethical and professional responsibilities in engineering situations and make informed judgments, which must consider the impact of engineering solutions in global, economic, environmental, and societal contexts.
5. An ability to function effectively on a team whose members together provide leadership, create a collaborative and inclusive environment, establish goals, plan tasks, and meet objectives.
6. An ability to develop and conduct appropriate experimentation, analyze and interpret data, and use engineering judgment to draw conclusions.
7. An ability to acquire and apply new knowledge as needed, using appropriate learning strategies.

Note

1. See Kathleen B. Robinson and Barry L. Shoop, "ABET accreditation for optical and photonic engineering: The why and how," *Education and Training in Optics and Photonics 2015*, https://www.osapublishing.org/abstract.cfm?uri=etop-2015-MEE01, for an article about this and other aspects of the process.

8. Optics Teaching Laboratories

Per S. Adamson

One could say that the teaching laboratories were established within The Institute of Optics when the department was formed in 1929. Back then the name of the department was The Institute of Applied Optics, and within that context the teaching laboratories had an important role of offering applied optics phenomenon and hands-on experience. The laboratory experiences at that time included such diverse topics as testing of optical systems, spectrophotometry, radiometry, polarimetry, interferometry, advanced photography, and optical shop work.[1] Some of the original equipment still exists in the teaching laboratories, such as the Pulfrich refractometer and the Hilger lens and prism-testing interferometer. Neither of these instruments is used in the day-to-day operations today, but they are an important reminder of our past. A photograph of the Hilger interferometer and Brian O'Brien, taken by Ansel Adams, can be seen on page 44 of *A Jewel in the Crown*.[2]

The first location of the teaching laboratories was on the fourth floor in the John J. Bausch–Henry Lomb Memorial Building. Expansion of research and growth of the program demanded that the teaching laboratories be moved to the second floor of Gavett Hall in the 1970s. In the early 1980s, the program was booming, and the undergraduate population increased by eightfold in the decade. The teaching laboratories would again move, this time to the fourth floor of Dewey Hall. The dean and provost of the university supported the decision to move the teaching laboratories and provided $225,000 to renovate the space in Dewey Hall. The laboratories then needed to be filled with $250,000 of updated equipment. In 1982–83, fund-raising for the teaching laboratories was organized by Christopher Dainty and Michael G. Morris, as well as the director, Kenneth J. Teegarden.[3]

One side note: The fourth floor of Dewey was a unique location for the teaching laboratories for a couple of reasons. First, it was not near an engineering or science department. It was located between the Simon Business School and the Warner School of Education, which made finding the laboratories a little difficult. Second, it was once the location of a museum collection of taxidermied animals. The museum designation can still been found above the door of the north entrance of the building.

The teaching laboratories would stay within the lime green walls of Dewey Hall until they moved to their present home on the fifth floor of the Wilmot Building in the summer of 2008. The move was made possible by the vision of the director of The Institute of Optics, Wayne Knox. Early in Wayne's tenure as the director, he noticed Per Adamson bringing equipment across the walkways from Dewey Hall to the Wilmot Building in the pouring rain. Wayne then quipped, "That is no way to treat our equipment . . . nor our employees." The plan to bring the teaching laboratories to the Wilmot Building was sprouted.

The building of Goergen Hall provided an opportunity for the teaching laboratories to become fully integrated within The Institute of Optics. The fifth floor of the Wilmot Building was vacated after professors moved their offices and laboratories to the fourth and fifth floors of the newly constructed Goergen Building. The entire Wilmot fifth floor then needed to be renovated to make best use of the space. However, this time the department would take most of the financial responsibility for the renovations of the laboratory space. Financial donations from Insight Technology and Edmund Optics also provided some of the funds necessary for this investment in the optics program. Four laboratory rooms are named for their generous contributions.

With just under $1 million and over a year of planning, the laboratories were renovated. Keeping the budget for the project under $1 million averted the necessary approval from the board of trustees. The new laboratory space included seventeen laboratories, storage space, one darkroom for wet chemical processing, as well as a lounge to encourage students to stay close to the laboratories to study. The teaching laboratories also contain the Collaboratory, which is classroom that was designed to be a space where teamwork could take place in a laboratory setting. It was decided during the planning stages that the high-temperature ovens used by Duncan Moore would stay on the fifth floor to provide a resource for undergraduate and graduate research.

In the summer of 2008, Roger Smith and Brandon Zimmerman spent their time assisting Per Adamson in moving the teaching laboratory equipment from the fourth floor of Dewey Hall to Wilmot. One last effort was implemented when the staff of The Institute of Optics spent an entire day packing equipment from the cabinets in the storage room into boxes. The move was complete and The Institute of Optics was whole once again.

Laboratory Classes

The following accounts of people and activities in the teaching laboratories cover the years from 1999 until 2018.

In the summer of 1999 Greg Pierce left The Institute of Optics to work in the private sector, as this was the time of the telecom boom and great opportunity could be had. Per Adamson, who came from the Laboratory for Laser Energetics, followed Greg's tenure as the laboratory coordinator.

Figure 8.1. Ken Teegarden with students in the Collaboratory, ca. 2008.

The teaching laboratories in the year 1999 hosted laboratory experiences for the geometrical and physical optics classes and OPT 256, which was an intensive laboratory course for seniors and master students. Summer activities included the annual summer course series and a summer scholars high school program.

In 1999, OPT 256 was taught by Kenneth Teegarden and Parker Givens. Around that time, Ken Teegarden updated the fiber optics lab to have students create a continuous-wave laser and mode-locked laser and measure their characteristics. For the mode-locked laser, Ken used saturable absorber mirrors that were created in Gary Wick's laboratory. Parker Givens would coteach OPT 256 until his second retirement in approximately 2003. Parker "retired" for the first time in 1981 and became the first professor emeritus, as the mandatory retirement age was 65. Parker would continue to be in contact with alumni and faculty of the university until his death on January 11, 2013. Improvements to the laboratory experiments were constantly being tweaked by Ken Teegarden. Ken taught OPT 256 until 2014, when the senior optical lab course OPT 256 stopped being required. At that time, the department was going through ABET accreditation, so seniors were required to take either a senior design or senior thesis track. The decision was made to not require OPT 256 based on the laboratory experiences of OPT 201, OPT 202, OPT 203, and OPT 204, as well as the senior design project. The OPT 456 laboratory course was created for master's students after OPT 256 was no longer being offered. Chunlei Guo, John Marciante, Jim Zavislan, and eventually Jennifer Kruschwitz taught the OPT 456 laboratory course.

In the 2000s, major changes started to take place. The Undergraduate Committee decided that optical laboratory experiences, which were part of the Geometrical and Physical Optics classes, were not sufficient for the students. The optics laboratories were separated into their own classes and Geometrical Optics Laboratory (OPT 197), Physical Optics Laboratory (OPT 198), and Optical

Instrumentation (OPT 199) were born. Great effort was made by Andrew Berger, Tom Brown, Jim Zavislan, and David Berg to create this new laboratory curriculum. The workload of these classes was not reflected in the one credit hour received, and complaints from the students were abundant. In the spring of 2014, a new laboratory sequencing began with the addition of a new course, Sources and Detector Laboratory (OPT 204). The students would now receive two credit hours for their labs. One unsung "hero" of this time was Bianca Jackson. Bianca, a postdoctoral research associate of Xi-Cheng Zhang, dedicated large amounts of time, outside of her research, to improve the experience for the students in OPT 204. In 2016, David Berg would leave The Institute of Optics, after ten years of teaching the Geometrical and Physical Optics laboratory classes, to spend more time on his consulting as well as teaching at Monroe Community College. Clarke Eastman would take the reins for the Geometrical (OPT 201) and Physical Optics (OPT 202) lab classes. His previous experiences included working for Corning as a senior inspection engineer. Clarke's fresh perspective and work experience was another opportunity to make changes to the laboratory experiments and in the management of laboratory classes. "Upper-level" undergraduate students were once again an integral part of teaching "lower-level" undergraduates. Instrumental Optics Laboratory (OPT 203) would continue to be taught by Jennifer Kruschwitz, who received a grant to add a colorimeter to the metrology equipment. Svetlana Lukishova would take over for Jim Zavislan to teach Sources and Detector Laboratory (OPT 204) and add her nano-optic twist to the class.

Though not officially part of the teaching laboratories, the Hopkins Center became an important facility for laboratory experiences. Three laboratory rooms were designated for the Hopkins Center. One room would contain computers with the newest software for lens design, coating design, and mathematical computations and simulations. One room would contain metrology equipment and be used nonexclusively for the optical instrumentation laboratory course. The equipment included a Zygo scanning Fizeau interferometer, a Zygo white light interferometer, an Optikos MTF bench, an Abbe refractometer, and, for a time, an AudioDev coating spectrometer. The third room would be an optical element fabrication room that would house a QED magnetorheological finishing (MRF) machine, polishing and grinding machines, as well as the associated equipment and hardware. The MRF machine, mostly used for research, was used in a beta test for the first senior design project. The students working on that project spent so much time with the machine that they gave it a name, Wanda. Traditional manufacturing practices had been offered on and off since the formation of The Institute of Optics; however, in the spring of 2016 Mike Pomerantz, an optical technician, was hired. Mike would split his time between the Mechanical Engineering Department and The Institute of Optics. Mike Pomerantz came to the University of Rochester with twenty years of experience from Optimax Systems. From 2016 forward, a more rigorous optical manufacturing class would once again be offered.

Summer Activities

Summer use of the teaching laboratories was also important in our mission of educating people in the field of optics. The number of summer activities in the teaching laboratories started to increase in the 2010s. For more than fifty years, the annual summer school program had been one of the few major activities in the teaching laboratories over the summer recess. The laboratories offered hands-on experiences for summer school attendees during the evening hours. Parker Givens would usually stay late for these night sessions until he could no longer drive at night. Students were impressed with his knowledge of up-to-date optics and hands-on skills, even though he was in his mid-eighties and his hands trembled. The professorial staffing of the laboratories would then vary and include Jim Zavislan, Tom Brown, and Nick Vamivakas. Also, altruistic graduate students would be an integral part of the summer school, for they would give up their precious summer evenings to assist in the labs for minimal salary and pizza or DiBella subs.

The Summer Scholars program was another summer activity taught by graduate students. The program was run by energetic and driven graduate students to give high school students an in-depth look at one topic in optics. John Heebner and Brian Soller ran a holography class, and Malik Mehul offered a class on the optics and electronics of laser tag.

Photon Camp was created to be a recruiting tool for new students by offering high school juniors and seniors an opportunity to learn about optics. Campers would listen to lectures from professors, have lab experiences, go on field trips, and give a tabletop presentation at the end of the week. The summer of 2013 was the inaugural year for Photon Camp, and the effort was led by Jim Zavislan, Andrew Berger, Daniel Smith, and Per Adamson. Fifteen seniors from West Irondequoit High School participated in the first year.

Figure 8.2. Photon Camp 2019.

Figure 8.3. Per Adamson has an uplifting experience with the graduating class of 2009. Top: Tom Bruno; standing: Greg Balonek, Rebecca Berman, Zachary Darling, Zachary DeSantis, Daniel Balonek, Anthony Visconti, Ezra Milby, Robert Balonek, Jonathan Brand; horizontal: Per Adamson; front: Cheonha Jeon.

The teaching laboratories have hosted a weeklong, precollege program in optics and lasers since 2015. This summer program has been a recruiting tool designed for ninth through twelfth grade students and taught by various graduate students. Some of those graduate students included Katelynn Sharma, Charles Grainger, Greg Jenkins, Kevin Liang, and Ashan Ariyawansa.

Postscript

Per Adamson left The Institute of Optics in the summer of 2018 to work for RAM Photonics, LLC, which was cofounded by John Marciante and Stojan Radic. Graduate student Trevor O'Loughlin filled in part-time as the lab coordinator. Many of the other responsibilities were transferred to Jennifer Kruschwitz.

Notes

1. T. R. Wilkins, "The Institute of Applied Optics of the University of Rochester," *Journal of the Optics Society of America* 369 (1931).
2. Carlos R. Stroud Jr., *A Jewel in the Crown: Essays in Honor of the 75th Anniversary of the University of Rochester's Institute of Optics* (Rochester, NY: Meliora Press, 2004).
3. Kenneth J. Teegarden, "The Institute of Optics Teaching Laboratories" [brochure] (Rochester, NY: University of Rochester, 1982).

9. The Last Twenty Years of Optical Design at The Institute

Julie Bentley

Courses in lens design are as old as The Institute. The first class was offered by Rudolf Kingslake in 1932, when Kingslake taught the course as an adjunct professor while working full-time at Eastman Kodak Company. Once Kingslake retired, Duncan Moore taught the class until he was tapped to be President Clinton's associate director for technology in the White House Office of Science and Technology Policy in 1997. As one of Duncan's former graduate students, I was asked to take over the class in the spring of 1998. It is interesting to note that, similar to Kingslake, for many years I taught this class as an adjunct professor while working full-time at Corning Tropel, a maker of extremely high precision lenses and lens assemblies primarily for the semiconductor industry; and as with Kingslake,

Figure 9.1. Julie Bentley in her Goergen office.

this gave the course an important connection to the real world. “There are many degrees of freedom in lens design,” says John Bruning, former president and CEO of Corning Tropel. “No single unique solution exists. Finding the best solution comes about by involving all of the parameters—and most of those that are important for the industry are not in the textbooks or the design programs.”

While almost everything about the lens design process has changed since Kingslake’s day, many of the fundamentals remain true. One of Kingslake’s mottos, for instance, was “Never design a lens you can’t build.” Ironically, in the age of computer-based lens design, that maxim has never been more important. “Far more people today are using lens design software programs because they’re relatively cheap, but fewer people actually know how to use them well,” says Bruning. “Anybody can design a lens, but very few can design lenses that can be built and are robust.” That’s a message that I still hammer home in my classes. I also believe that lens design includes an intuitive, almost aesthetic component and encourage my students to take a step back while working on their design to ask themselves, “Does it look good?”

One might question the relevance of a course that has been taught continuously at The Institute since its founding in 1932. At first glance, it may seem that this particular branch of optics is tapped out, picked over, and understood so thoroughly that no further fundamental challenges exist. The reality of modern lens design is that the task has gotten more complicated, not less, because of advances in optical design software, new materials, new manufacturing techniques, and ever more extreme demands for precision in optical components. Over the last twenty years, I’ve seen the interest in lens design steadily increase, not decrease, and the demand from industry for students with lens design experience grow.

In 1998, my first class had only five students and the class was taught every other year. By 2004, the class size had grown to thirty-two students, and it was decided that the course should be offered once a year. From 2005 to 2015, the class size continued to grow to where it peaked at over fifty students! Although OPT 444 was a graduate class designed for MS and PhD students, many undergraduate juniors and seniors (and occasionally advanced sophomores) would take the class. In 2016, it was decided that the course should be split into an undergraduate version (OPT 244) and a graduate version (OPT 444). While I continued to teach the graduate version, my former graduate student Anthony Visconti (BS ’09, MS ’13, PhD ’15) and later Institute alumni Georg Nadorff (BS ’85, MS ’87) took over the reins of the undergraduate lens design class.

One of the most interesting aspects of this class is that (in lieu of a final exam) the students are given six weeks to complete a final individual design project. The students first need to find an application and then formulate a set of specifications based on that application and then work through the design process from setup to optimization to analysis and tolerancing. Students often discover that they need to adjust their specification targets and time expectations in a manner that mirrors the realities in industry. Once they’ve completed their design, they write a

Figure 9.2. Alumni Katie Schwertz ('12), married to alumni Dan McCormick ('12), with Julie Bentley (BS '90, MS '92, PhD '96) at the presentation of the 2014 Goergen Award for Excellence in Undergraduate Teaching (photo by J. Adam Fenster/University of Rochester).

final report and give a fifteen-minute presentation to "sell" their design to their "customer" classmates. When asked about the class, Katie Schwertz (BS '08) states, "There was no undergraduate class I worked harder on my homework, or appreciated more in my career, than Julie's design course. She had a habit of putting our design solutions up on the projector for everyone to see, which is incredibly intimidating as a student! It was great preparation for the 'real world,' however, because there's no partial credit for the designs I do at work and I regularly have to present my solutions to others."

The design projects range from historical lens design forms to reverse engineering design concepts published in recent patents and papers. I try to stress the application and then use the application to drive the specifications and then—and only then—design the lens. Project examples include camera lenses (standard, wide angle, telephoto, zoom, DSLR, mirrorless, large format, and everything in between), microscope objectives, reflective telescopes, projection lenses, lithography lenses, riflescopes, and AR/VR displays. PhD students are given the opportunity to work on designs needed for their research, and often these designs are eventually built, and in some cases even become the starting point for a product/company spin-off (e.g., LighTopTech and Clerio). It's not uncommon for more creative students to come up with an off-the-wall application that several years later shows up in industry. For example, Brett Sternfield (MS '14) designed a fisheye lens to help navigate a drone for the delivery of his Chipotle! A few years later, I saw the same exact concept advertised on a TV special report—a drone was delivering a Chipotle burrito to a customer. Brett was also one of the many winners of the annual Synopsys Student Optical Design Competition:

- "The Design of a High Zoom Ratio Riflescope," David Lippman (2018)
- "Design of a Compact Telephoto Lens for Cellphone Cameras," Dylan Beckman (2018)
- "Design Study: Dual Band Solar Concentrator/Coupler," Nicholas Kochan (2017)
- "Design of a Telephoto SLR Camera Lens from Scratch," Maximillian Bruggeman (2017)
- "LWIR Multi Sensor Aerial Reconnaissance Camera," Francisco Santos (2016)
- "Wide Angle Climbing Camera," Scott Paine (2015)
- "Retrofocus 2.5x Zoom Lens for Single-Shot, Single-Lens HDR Photography and Video," Anthony Vella (2014)
- "Pushing the Envelope of Mobile Phone Imaging with Curved Sensors," Nicolas Brown (2014)
- "220 Degree Field of View Fisheye Lens for Full Frame SLR Camera," Jonathan Papa (2013)
- "Extended Depth of Field in an Intrinsically Wavefront-Encoded Biometric Iris Camera," Matthew Bergkoetter (2013)
- "Optical Passive Athermalization Using Schott Chalcogenide Glasses," Anthony Visconti (2012)
- "190° FFOV Fisheye for Autonomous Robots," Brett Sternfield (2012)
- "A High Resolution Four-Pi Steradian Panoramic Video System," Dustin Moore (2011)
- "193 nm Catadioptric Photolithography Lens for Manufacturing Semiconductor Devices," Kyle Fuerschbach (2010)
- "Telecentric Zoom Lens Design for DLP Projection," Yuhong Yao (2009)
- "Wide FOV Head Mounted Display for Virtual Reality," Xinye Lou (2008)
- "Design of a 360 Degree Panoramic Camera Lens," Manuel Guizar-Sicairos (2007)
- "All-Plastic Compact HMD Design," Yijing Fu (2006)
- "Design of a Sparse-Aperture Interferometric Telescope," Matthew Bolcar (2004)
- "Design of Backwards Compatible Blu-Ray and HD-DVD Objectives for Reading High Capacity (15 GB and 23 GB) DVDs," Chris Supranowitz (2004)

As the interest in lens design increased and I ran out of room in the semester for cool new lens design topics, I decided to create an advanced lens design class (OPT 544) in 2005 with topics in illumination, unobscured reflective design, zoom

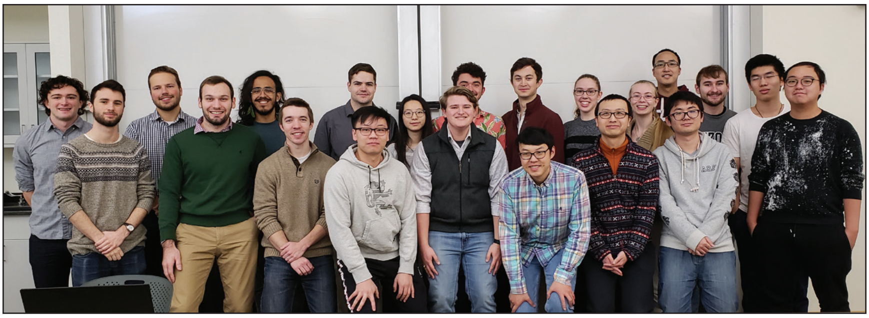


Figure 9.3. 2014 Optical Design Conference in Hawaii: Julie Bentley, James Corsetti, Anthony Yee, Duncan Moore, Rebecca Berman, Yang Zhao, Greg Schmidt.

Figure 9.4. Some students in OPT 544, Fall 2018—largest Advanced Lens Design class to date.

lens design, color correction, and tolerancing. Again, this class started with a handful of students and was taught every other year until the class size become too large (in 2008), after which it has been taught every year in the fall.

Instead of individual design projects, the students are tasked with designing a complex lens system (often a zoom lens) from scratch. The class operates very much like a research group/engineering team with biweekly meetings and reports from group members. Each year the students build on the previous year's students' work, and the result has been the development of an impressive, complex set of design tools in Matlab/Python and over fifteen papers presented at design conferences around the world.

I've used the class notes from both of these classes to write the SPIE field guide to *Lens Design* with Craig Olson in 2012 and an introductory textbook, *Designing Optics with CODE V,* with Don O'Shea in 2018. We've also recently added classes in illumination design, taught by Josh Cobb (BS '88, MS '00); system design, taught by John Bowen (PhD '91); and freeform design, taught by Jannick Rolland. So in the last twenty years, what used to be one small class in lens design has now branched into six different design classes, and continuing Kingslake's legacy the majority of these instructors are also adjuncts working full-time in industry and bringing real-world experience into the classroom. In summary, in 2019 lens design is alive and well (and thriving) at The Institute.

10. Quantum Optics Laboratory

Svetlana G. Lukishova

Approval of the National Quantum Initiative Act establishes a federal program to accelerate quantum research and development for the United States' economic and national security, which also includes training quantum engineers.

Quantum Optics, Quantum Information, and Nano-Optics Educational Laboratory Facility at The Institute of Optics: Some History

The first quantum optics, quantum information, and nano-optics research and educational laboratory facility at The Institute of Optics was built in 2005. Initial equipment for the entanglement and Bell's inequality experiment was borrowed from Lucas Novotny. Graduate student Anand Kumar Jha (now a quantum optics professor) assembled this setup. Other labs were based on my research facility on single-photon generation and characterization funded by Army Research Office (ARO) and National Science Foundation (NSF) grants.[1] In 2006, a four-credit-hour quantum optics advanced laboratory course for both undergraduate and graduate students appeared in The Institute of Optics curriculum.

A new step was started from support of Carlos Stroud, a director of the Center for Quantum Information, and two NSF educational grants of 2007–12. Wayne Knox's and Per Adamson's help, a donation from Spectra Physics, and a Kauffman foundation Initiative Award permitted further development of this facility. Now it is located in three rooms in Wilmot with a total of 587 square feet. The courses Quantum Optics (OPT 253) and Nano-Optics Laboratory (OPT 453/PHY 434) became popular among the students.[2] Some of the students of the OPT 253 class went on to become quantum optics professors (Mehul Malik, Zhimin Shi, Omar Magaña-Loaiza, and Heedeuk Shin).

Currently these courses consist of ten lectures and four six-to-fifteen-hour labs: (1) entanglement and Bell's inequalities; (2) single-photon interference (Young's double slit experiment and Mach-Zehnder interferometer) and quantum eraser;

(3) single-photon source I: confocal microscope imaging of single-emitter fluorescence; and (4) single-photon source II: Hanbury Brown and Twiss setup and photon antibunching.[3] These labs with different requirements for graduate and undergraduate levels are in constant development. For instance, the Wadsworth C. Sykes Faculty Engineering Award of the Hajim School permitted a very enthusiastic teaching assistant, Joe Choi, to build a new entanglement setup. Joe Choi as well as Anand Kumar Jha were very creative, occasionally insisting with energy and passion on including some measurements that were not previously planned. Lucas Novotny and his group, especially his postdoc Andreas Lieb, were very helpful. Luke Bissell, a PhD student, also contributed to this class.

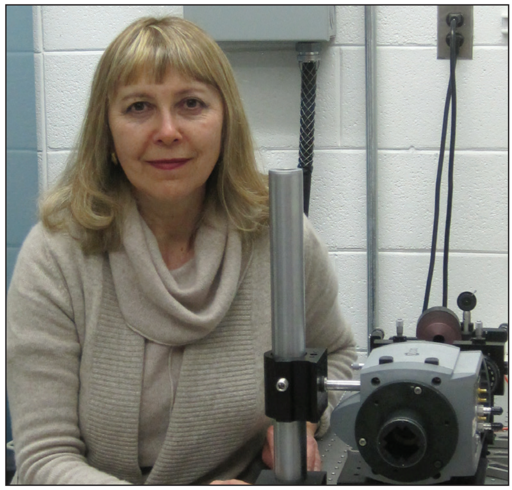


Figure 10.1. Svetlana G. Lukishova with the EM-CCD camera for single-photon experiments.

One strength of this course is the students' immersion in a real research environment, working on state-of-the-art, fragile, and expensive equipment that modern quantum optics research uses around the globe. Occasionally in the class students obtained results that were reported later at the top professional conferences or included in journal publications. This intentional blurring of the dividing line between "education" and "research" strongly boosts student interest.

Short, three-hour lab versions of the quantum labs were developed for students with diverse backgrounds. More than 560 students of the University of Rochester carried out different versions of these labs (from 2006 to Fall 2019), which were included to the following classes:

1. First-year: It became a tradition that, every year, freshmen from the OPT 101 class of Wayne Knox and later of Thomas Brown use the "quantum" facility for their ten-hour research projects.
2. Juniors and Seniors: In another class, Quantum Mechanics for Optical Devices (OPT 223), taught by Carlos Stroud, three-hour versions of entanglement and single-photon interference labs were introduced. The last lab was also included in the Sources and Detectors (OPT 204) labs.
3. Graduate class: "Quantum" projects of Optical Laboratory (OPT 456) are based on this facility.
4. Department of Physics and Astronomy: An entanglement lab at The Institute of Optics also became popular among physics students of the Advanced Laboratory (PHY 243W)

Figure 10.2. Students of Fall 2016 class OPT 253/OPT 453 on the lab lecture.

Program on the Certificate in Nanoscience and Nanoengineering

In 2015, the quantum optics, quantum information, and nano-optics lab facility became the basis for the undergraduate program on the Certificate in Nanoscience and Nanoengineering, suggested by Nick Bigelow, a director of the Integrated Nanosystems Center (URnano).[4] This program was supported by an NSF grant. From 2015 to May 2019, thirty-four students were awarded the certificate after taking two classes on nanoscience/nanotechnology, carrying out a one semester research or design project in this field, and taking a new class Nanometrology Laboratory (OPT 254/PHY 371), taught by Brian McIntyre, Semyon Papernov, and Svetlana Lukishova. This class consists of three lab modules on microscopies: (1) electron (SEM and TEM), (2) atomic force, and (3) confocal fluorescence.

Dissemination of Quantum and Nano-Optics Labs among Other Institutions

NSF grants supported teaching Monroe Community College (MCC) students in the quantum optics and nano-optics laboratory and in URnano at the University of Rochester. During a decade of NSF support, 144 MCC students with their professor Paul D'Alessandris visited the Wilmot Building for two three-hour "quantum" or "nano" labs. Brian McIntyre taught MCC students at URnano.

During Fall 2009, Ron Jodoin from the Rochester Institute of Technology spent his sabbatical in the quantum labs of The Institute of Optics. In August 2011, The Institute participated in the Immersion Program of the Advanced Laboratory Physics Association and hosted six visitors from different universities for three days.[5] During two days in October 2012, five students of Adelphi University and their professor Sean Bentley (PhD, The Institute of Optics) carried out four labs at this facility. Experience in the quantum optics labs was also shared with the University of Oklahoma–Tulsa. Several student groups (more than 250 students) from the University of Rochester, Colgate, and Alfred University visited the "quantum" facility for lab demonstrations. This facility is constantly being shown to leading experts in quantum optics.

Notes

1. S. G. Lukishova and L. J. Bissell, "Nanophotonic advances for room-temperature single-photon sources," in *Quantum Photonics: Pioneering Advances and Emerging Applications*, ed. R. W. Boyd, S. G. Lukishova, and V. N. Zadkov (Cham: Springer, 2019), 103–78.
2. http://www.optics.rochester.edu/workgroups/lukishova/QuantumOpticsLab/; S. G. Lukishova, "Quantum optics and nano-optics teaching laboratory for the undergraduate curriculum: Teaching quantum mechanics and nano-physics with photon counting instrumentation," *Proceedings of SPIE* 10452, paper 21-1, 14th International Conference on Education and Training in Optics and Photonics (ETOP), May 29–31, 2017, Hangzhou, China.
3. http://www.optics.rochester.edu/workgroups/lukishova/QuantumOpticsLab/; Lukishova, "Quantum optics and nano-optics teaching laboratory."
4. http://www.optics.rochester.edu/workgroups/lukishova/QuantumOpticsLab/; S. G. Lukishova, N. Bigelow, P. D'Alessandris, "Development of multidisciplinary nanotechnology undergraduate education program at the University of Rochester Integrated Nanosystems Center," paper 10-1, 14th International Conference on ETOP, May 29–31, 2017, Hangzhou, China.
5. http://www.optics.rochester.edu/workgroups/lukishova/QuantumOpticsLab/.

11. Preparing the MS Program for Growth and Industry Focus

Jennifer D. T. Kruschwitz

For several decades, the graduate program at The Institute of Optics required master's (MS) and PhD students to take the same core classes in physical optics (OPT 461), geometrical optics (OPT 441), and radiometry (OPT 425). These core classes had always been mathematically rigorous and centered on theoretical models. Much of the curriculum was geared to preparing the PhD students for their preliminary exam the summer after their first year. The MS program ran on a very different timeline. MS students typically only studied for one year before receiving their degree and moving on to jobs in industry. Although the MS students could handle the workload in these core classes, there was a disconnect between what they were learning and what applied concepts they needed to know when they left The Institute for the workforce. The one consolation was that class sizes were relatively small, typically fifteen MS students and fifteen PhD students. There were opportunities for all of the students to have personal attention from the professor or the teaching assistants when they needed it most.

In 2015, the MS class admitted to The Institute grew to close to forty students. This influx of new students required the faculty to reassess how they were going to continue to provide an excellent education in optics where the majority of students would graduate in nine months. Combining the two graduate student groups would limit the personal attention that could be given. This was an opportunity for the faculty to incorporate a more applied optics model in the curricula, which would be MS centric. PhD students would continue to take the traditional core courses, and The Institute would develop three new courses that would benefit the MS students on an applied front and would allow the professors and teaching assistants the ability to continue to interact with these students on a personal level. The three new courses developed were:

- Wave Optics and Imaging (OPT 463): A physical optics course that includes content on interference, diffraction, and Fourier analysis.

Figure 11.1. Professor Kruschwitz with some MS students, Spring 2019. From left, back row: Matthew Page, Brandon Walter, Trevor Oloughlin; middle: Madilyn Beckman, Nora Lane, Wesley Chiang; front: Logan "Cooper" Conran, Prof. Jennifer Kruschwitz, and Michelle Fuksa.

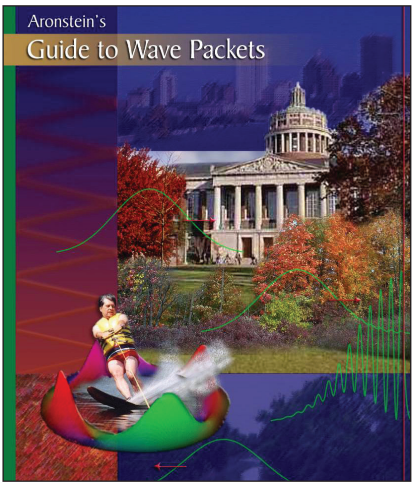
Figure 11.2. Jennifer Kruschwitz and Gary Wicks with winners of the 2016 Gary Wicks Community Leadership Award: Natalie Pastuszka and Tess Jacobs.

Fundamentals of Modern Optical Systems (OPT 443): A geometrical optics course that reviews ray optics and aberration theory, preparing students for Lens Design (OPT 444) the following spring.

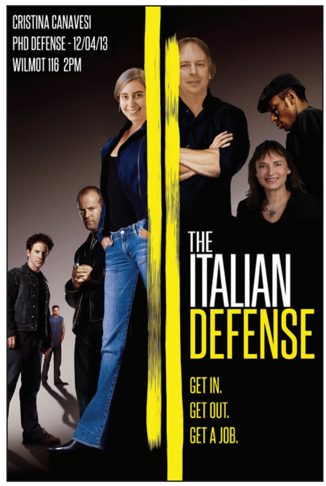
- Detection of Optical Radiation (OPT 423): A radiometry/photometry course that includes statistics of light, and operational parameters for photodetectors and many other types of detectors.

Incorporating the change required an adjustment period. As with anything, change is not easy. We have had four fall semesters of these MS-specific classes to date, and we have met certain milestones of success. Since the change, we have admitted several MS students to the PhD program after their fall semester, and every single one has turned out to be a fabulous addition to their respective research groups. OPT 443 and 463 have complementary themes throughout the semester, especially when discussing how aberrations affect an optical system. The students see how the optical transfer function is impacted by aberrations in Wave Optics while simultaneously seeing how they affect a transverse aberration ray plot or spot diagram in Modern Optical Systems. The goal for The Institute of Optics has always been to enable all of our students to be successful. This new addition to our MS graduate program has proven to deliver on that goal as well.

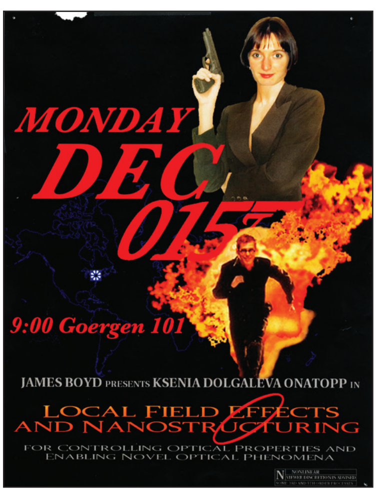
Highlight III: Graduate Defense Posters



1. Aronstein / Stroud



2. Christina Canavesi / Rolland

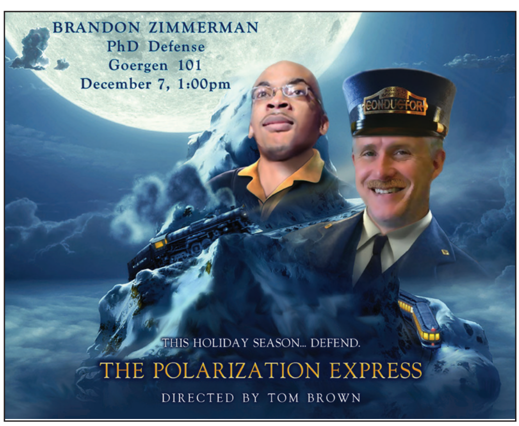


3. Ksenia Dolgaleva / Boyd

4. Kang Liu / Zhang

5. Peter McCarthy / Moore

6. Dan Savage / Knox



7. Brandon Zimmerman / Brown

PART IV

Research

Part IV. Research

In this section, we review a few of the many research accomplishments of our faculty, students, and alumni. Tom Brown reviews recent exciting progress in the understanding of optical polarization and its application in many new areas. Govind Agrawal, the author of a textbook that is among the top ten most cited in physics, describes the contributions to the field of optical communication from The Institute. Chunlei Guo describes the remarkable work done in his group using femtosecond laser pulses to modify the morphology of metallic surfaces to make them hygroscopic or hydrophilic. Jannick Rolland describes the founding and development of the Center for Freeform Optics, including contributions by Professors Fienup and Alonso. Brian McIntyre and Nickolas Vamivakas contribute two essays, one on local research progress in nano-optics in general, and the second on exciting work in saving historic daguerreotype photographs from microscopic scavengers. Research is never done in a vacuum. The various research groups have a number of visitors every week, and some give departmental colloquia, which are generally well advertised and well attended. Some colorful posters announcing those colloquia are included in a Highlight.

12. Polarization

Thomas G. Brown

Polarization encompasses the vector character of light and is an academic subject over two hundred years old. Even at the founding of The Institute of Optics, much was already understood about how to measure, control, and make use of the polarization of light in optical instruments. With the invention of the laser, as sources of polarized light became more ubiquitous, faculty at The Institute of Optics and eventually the Laboratory for Laser Energetics relied more and more heavily on polarization-based optical science and engineering.

Polarization and Coherence

When Emil Wolf died in the summer of 2018, the optics world and The Institute of Optics lost a treasure. Emil was often called the father of modern coherence theory. He spent active years long after the usual retirement age focusing in on fascinating new problems that were emerging in physical optics. By the year 2000, he had already worked a number of years toward a unified theory of coherence and polarization: in Emil's view, polarization should be described not simply in terms of a local polarization state (the traditional textbook view), but would be properly understood to include the spatial and spectral correlations between vector components that must exist in any real electromagnetic field. As he worked with students, postdoctoral scholars, and colleagues, he began to understand that the vector correlations must propagate in such a way that a quantity such as the degree of polarization and the spatial distribution of polarization states within a field will evolve and change under propagation. Many of these principles were laid out in detail in Mandel and Wolf's *Coherence and Quantum Optics*, but Emil continued to feel that students could benefit from a shorter book summarizing the principles of classical coherence theory in a way that inclusion of polarization can naturally fit. The result of this project was the 2007 publication of the *Introduction to the Theory of the Coherence and Polarization of Light*. It included work with Olga Korotkova (polarization and atmospheric turbulence), Govind Agrawal (propagation-induced polarization changes), Taco Visser, Greg Gbur, and many other former students and collaborators. Emil continued publishing in this area and, in his last ten years, proved that (at least in his mind) there remained many unanswered questions. He included some of them in the titles of his papers: "Does a light beam of very narrow bandwidth always behave as a monochromatic beam?" (with his last student, Mayukh Lahiri) and "Can a light beam be considered to be the sum of a completely polarized and a completely unpolarized beam?" (as sole author).

Meanwhile, Miguel Alonso, along with students and collaborators, was building on the mathematical foundations of both Wigner functions and ray-based wave fields to include both polarization and coherence in the radiometric description of optical systems. This work attracted collaborators across the globe who were intrigued by Alonso's ability to take a complex problem needing four (perhaps five) dimensions to properly describe, and reduce its complexity using geometrical transformations and mathematical insights. Within The Institute, Miguel Alonso's ability to illustrate his insights using real-time Mathematica computations became legendary.

Inspired by Emil's infectious interest in experimental science, the Brown group collaborated with the Franco Gori group at Roma Tre (Italy) to construct an apparatus that could provide an experimental map of the correlation function between any two vector components of the field. Dean Brown (PhD student of Thomas Brown) was able to both collaborate with Emil on a measurement of a fully correlated azimuthal beam, and extend both the measurement and theory to better understand the polarization coherence structure of an azimuthally polarized critical or Kohler illumination system. It was around 2010 that Miguel Alonso joined the effort, assisting in the theory and design of an LCD mask–based coherence measurement system that culminated in the publication "Using shadows to measure spatial coherence." The key recognition was that, within certain mathematical constraints, one could measure the 2D correlation function of a field about a particular point by using an amplitude or phase mask, along with its complement. In 2016, Katelynn Sharma and Greg Costello were able to complete an extension of this measurement to experimentally acquire the 4D polarization correlation matrix of an optical field, repeating Dean Brown's results and extending the measurement to complex, space-variant polarization coherence functions.

Even in his later years, there was little activity in coherence and polarization at The Institute that did not have Emil's influence. During Fall 2015, Miguel Alonso organized a seminar course in modern coherence theory (something Emil had taught for many years). It was held in the Physics Department, on a day each week when Emil (now over ninety years old) was on campus and available. Most weeks, Emil took the students and faculty out to lunch at his favorite restaurant. He continued to be intensely interested in their work. The work on polarization and coherence will, no doubt, continue at The Institute; however, we will continue to ask, "What would Emil say about this?" for many years to come.

Polarization in Quantum Optics

The burgeoning field of quantum information has, for the past thirty years, relied heavily on quantum optics. The groundbreaking work of Hong, Ou, and Mandel laid the foundation for studies of single-photon sources, single-photon interference, and two-particle entangled states (e.g., qubits) that rely heavily on entangled polarization states for implementation. One important path to practical, nonclassical sources is the single-photon source. Graduate student Luke Bissell, working with Svetlana Lukishova, Carlos Stroud, and Robert Boyd, demonstrated a room-temperature single-photon source based on fluorescence of dye molecules in a chiral nematic structure. Robert Boyd led several studies incorporating polarization into quantum optical schemes for angular momentum control and sorting, making use of q-plates, chiral materials, and surface plasmon polaritons.

Beginning in 2005, Joe Eberly began asking intriguing questions about classical analogs to entanglement, and whether one could create entirely classical fields that showed the essential mathematical properties of quantum entanglement. In a series of papers with his postdoctoral scholar Xiao-Feng Qian, he explored classical modes that are nonseparable combinations of polarization states and spatial modes. When cast in the language of quantum mechanics, Eberly and colleagues argued (and showed experimentally) that features (such as a violation of Bell's inequality) can be seen in classically entangled fields. As a 2015 paper stated: "[There is a] growing recognition that entanglement is not exclusively a quantum property, and does not even originate with Schrödinger's famous remark about it."

The use of polarization in better understanding the "quantumness" of a light source has become even more intriguing in recent years. Beginning in 2016, Eberly, Qian, and Vamivakas began exploring what they referred to as the "last hidden optical coherence." It had long been understood that the spin angular momentum of an optical beam was associated with its polarization, and the spatial mode with orbital angular momentum. By linking correlations between time, space, and polarization, the team was able to establish an experimentally tested equality relationship between measures of visibility, distinguishability, and spatiotemporal coherence.

As of this writing, we are seeing even more intriguing links between unconventional classical polarization states and their quantum counterparts beginning to emerge. Some of this is in work related to classical weak measurements led by Alonso, Brown, and recent PhD Anthony Vella. Other clues are found in the broad collaborations by Robert Boyd and Miguel Alonso on links between polarization (spin) and orbital angular momentum and on exploiting these links to find new ways to measure the polarization properties of single photons.

Polarization in Strong Field and Nonlinear Optics

It has long been understood that optical transitions both in atoms and solids are fundamentally polarization dependent. In the strong-field limit, the photons involved in double ionization need not have the same polarization or phase. Furthermore, the resulting electron correlation in strong-field ionization can yield potentially interesting quantum states of the subsequent electron pairs. Joe Eberly and former PhD student Xu Wang published a series of papers exploring the polarization dependence of double ionization, concluding that the polarization ellipticity can have a strong influence on the ionization probability.

In nonlinear optics, the anisotropy of materials used for frequency mixing (e.g., doubling and downconversion) and the induced anisotropy in soliton interactions can result in nontrivial, and therefore highly interesting, phenomena. In 2007, a list of the most-cited books in physics was released. The most cited was Born and Wolf's *Principles of Optics.* But also appearing prominently in the top ten were *Nonlinear Optics,* by Robert Boyd, and *Nonlinear Fiber Optics,* by Govind Agrawal. The secret was out: The references familiar to generations of Institute alumni were now appreciated throughout the world.

Unconventional Polarization States

It was the early 1990s when Dennis Hall began asking what type of laser modes would exist in a circularly symmetric distributed feedback (DFB) laser. He knew that such a laser would oscillate in the plane of the waveguide, but with an out-coupled beam that would diffract out perpendicular to the surface of the structure. So-called second order or third order DFB lasers were well known, but none emitted a clean circular beam. What was somewhat surprising was that the natural modes of oscillation of such a laser produced a beam with an optical vortex at its center and a tangential polarization distribution about the axis of the beam. Dennis dubbed these "azimuthal polarizations," and wrote an important paper entitled "Vector Beam Solutions to Maxwell's Equations," which laid out the propagation and focusing properties of an azimuthally polarized Bessel-Gauss beam. Meanwhile, Thomas Brown was taking great interest in possible applications of these beams as well as simpler ways of generating them. (Dennis and his group had found that the lithographic precision and control of the gain medium made it difficult to maintain a stable mode profile in the DFB laser.)

Brown also recognized that the homology of Maxwell's equations required that there be an equivalent solution in which the magnetic field was azimuthally polarized, leading to a beam polarization with an electric field polarized in a radial direction. He and his student Kathleen Youngworth began asking what might happen if such a beam were tightly focused using a well-corrected, high numerical aperture lens. And did there exist simple experimental arrangements to transform a Gaussian beam, such as that coming from a HeNe laser, into a radial or azimuthal polarization? Following Dennis Hall's description, they called these "cylindrical vector beams"—vector beam solutions to Maxwell's equations that followed perfect cylindrical symmetry. One of the key results in these early investigation was the realization that a focused, radially polarized beam could provide a focal field slightly smaller than predicted by scalar wave theory; more significantly, the energy density in the focal region was dominated by the polarization component along the optical axis. This, along with similar studies carried out by the Leuchs group (in Erlangen, Germany) spawned a flurry of activity in the study of descriptions of polarization.

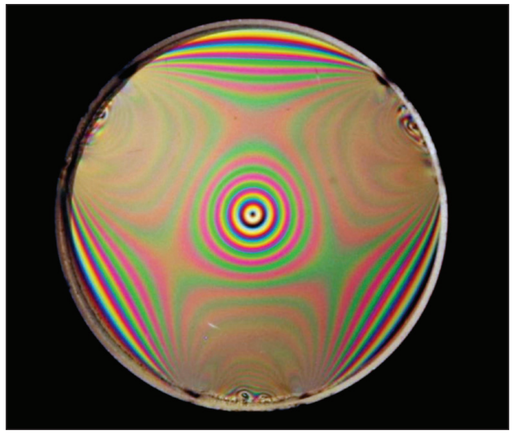


Figure 12.1. Birefringence in a stress-engineered optic from Amber Beckley's PhD thesis.

When Lukas Novotny established his world-class nano-optics laboratory at The Institute, he brought with him the knowledge that nanostructures, particularly sharp tips and noble metal nano-antenna structures, were exquisitely sensitive to the 3D polarization structure of a focal field. His work on single-molecule fluorescence microscopy, tip-enhanced Raman microscopy, and nano-antenna design took polarized light to experimental scales that had been inaccessible to previous generations. In a collaborative effort with the Brown group, Lukas was able to show that the 3D orientation of single molecules could reveal the 3D in single-molecule imaging through the creative use of polarized light.

Stress-Engineered Optics and Full Poincare Beams

It was soon clear that radial and azimuthal beams were simply two members of a much larger class of beamlike optical fields that could be created by superposition (interference) or through a space-variant transformation element. Upon the suggestion of former student Stephen Kreger and in partnership with PhD student Alexis Spilman Vogt, Thomas Brown began exploring the use of spatially inhomogeneous stress birefringence as an engineering tool to create radial and azimuthal beams from ordinary, low-coherence sources. They soon found that an ordinary window with three peripheral stress points created a remarkable spatial structure; this finding continues to yield surprising results nearly fifteen years later. Among these results was an observation predicted and analyzed by Miguel Alonso, and carried out by Amber Beckley, that a stress-engineered optic (SEO) could transform an ordinary, circularly polarized Gaussian beam into a beam whose cross section carried a stereographic map of the Poincare sphere, containing every possible fully polarized state of the field within one beam. They coined the solution a "Full Poincare Beam"—in its simplest form, the beam was a superposition of Gaussian and LaGuerre-Gauss beams having orthogonal polarizations, and therefore followed simple, analytic propagation laws in the paraxial regime.

In subsequent investigations, the SEO opened up new avenues for polarimetry—the measurement of polarization. Building on the work of Amber Beckley, MS student Roshita Ramkhalowon showed that an SEO placed in an optical system could produce a point spread function whose shape was uniquely correlated with the polarization state (specifically, the Stokes parameters) of the input field. PhD student Brandon Zimmerman was then able to take this principle, optimize it, and apply it experimentally to a Mie scattering experiment. This opened up the possibility (which Zimmerman demonstrated) of single shot Mueller matrix polarimetry using unconventional polarization states.

Polarization in Three Dimensions

The full description and understanding of polarization in three dimensions has remained a subject of active study. Because textbook treatments of degree of polarization, Stokes parameters, etc., deal implicitly with beamlike (2D) solutions, the proper definition of both coherence and polarization in three dimensions remained ambiguous and (to use Emil Wolf's favorite label) controversial. Emil himself wrote heavily on the subject, as did his former students and colleagues. As with much of his other work, Emil was chiefly concerned with the nature of a fluctuating field. Meanwhile, colleagues at The Institute and elsewhere were equally intrigued by the deterministic and beautiful structure that could be engineered into nearly deterministic fields. One of these was Robert Boyd, who coauthored a paper on the three-dimensional structure of a focused beam (a cousin to a Full Poincare Beam, produced by a so-called q-plate) that was shown to exhibit a type of Mobius strip in the polarization of the focal region. The work was later extended to more complex, knotlike field distributions linked to the topological features of the focal field.

Optical scattering (specifically Mie scattering) by small particles was another case that attracted the attention of Emil Wolf, Miguel Alonso, and Thomas Brown in separate collaborations. Emil addressed problems related to 3D stochastic descriptions, while Alonso, along with students Jon Petrucelli and Nicole Moore, began looking at the Mie scattering of nonparaxial fields using focused radial and azimuthal fields as a starting point. Brown and Youngworth looked at the scattering of axial fields from particles near a surface, and were able to map out axial field components using a confocal microscope illuminated with radially polarized light. Brown and David Biss, in work done for the semiconductor community, explored the scattering of radial and azimuthal fields from edges such as might be important in semiconductor metrology. The result was a new kind of dark-field confocal imaging that could highlight edges of a semiconductor structure in a way similar to that found in differential interference microscopy.

Polarization at the Laboratory for Laser Energetics

Polarization was an important part of the first beam line at LLE and triggered the Hoppy story made famous in the first edition of *A Jewel in the Crown*: Hopkins had spent much of the night trying to diagnose problems with the beam line, and finally yelled for someone who "knows something about polarization." At LLE, the electro-optic materials required for q-switched and actively mode-locked lasers were dependent on careful polarization engineering; indeed, the original paper by Donna Strickland and Gérard Mourou laying out the science of chirped-pulse amplification that would eventually win them the 2018 Nobel Prize described in some detail the trick of using a polarization-based system to trap a pulse in a laser cavity for a prescribed number of round trips before releasing the amplified pulse.

Twenty years later, polarization remained a focus of tremendous importance at LLE. To achieve a smooth irradiance profile within a fusion target, it was necessary to spatially scramble both the phase and the polarization of the high-energy, 355 nm wavelength, pulse in each of the beams in the Omega system (and, eventually, its successor the Omega EP). Two parallel efforts were pursued: (1) James Oliver explored and optimized a glancing angle thin film deposition of columnar films; (2) Stephen Jacobs led an effort to produce photoaligned, high-damage threshold liquid crystal materials for patterned polarization conversion in the high-energy line. Meanwhile, Brian Kruschwitz (PhD graduate and instructor at The Institute) incorporated plasma electrodes into the large-aperture Pockels cells in the beam line, thereby allowing an increased aperture and much higher damage threshold for polarization-based high-energy laser elements.

Polarization in Optics Education

Ten years ago, there was a growing recognition that the study of polarization in the optics curriculum deserved an upgrade. This has happened gradually, in the undergraduate and graduate courses and laboratories. In Andrew Berger's shepherding of the course in electromagnetic theory for undergraduates, he spends a great deal of time on understanding polarization, how it changes on reflection and through an anisotropic crystal, and the importance of polarization in optical scattering. On the graduate level, Thomas Brown introduced an MS-level course in polarization (that generally includes undergraduate juniors and seniors), and there has been a renewed interest in laboratories designed around modern polarization measurements. An example of this is the quantum optics laboratory, designed by Svetlana Lukishova, in which students use polarization-entangled states to explore violation of Bell's inequality and to study single-photon and two-photon interference.

In summary, the contributions of Institute faculty, students, and alumni to polarization science and engineering have been exciting, productive, and fruitful over the last fifteen years. The number of students making use of polarization in their dissertations and project work has increased, as have the number of faculty that include polarization in at least part of their research portfolio. What will a review of polarization at year 100 look like? We will perhaps be writing more about the creative use of polarization in integrated quantum photonics, an emerging field here at The Institute and elsewhere. We will, no doubt, be writing about spin and orbital angular momentum in engineering terms; and surely we will be amazed at the new polarization-related physics that is being uncovered each day in ultrafast laser science and engineering. But, if Eberly and Vamivakas are correct, we will no longer be searching for hidden coherences, at least for optical fields.

13. Fiber Optics and Optical Communications

Govind P. Agrawal

The advent of the Internet during the decade of 1990s impacted our society in unforeseen ways. Addiction to cell phones, social media dominated by Facebook and Twitter, video streaming by companies such as Netflix and Hulu, and on-line shopping by the masses through Amazon are some of the things that were unimaginable in the 1980s, or even in the 1990s. What is seldom realized is that the Internet revolution would not have been possible without optical fibers and the optical communication technology developed for sending vast amounts of data over them.

The history of fiber optics has been traced by Jeff Hecht in his 1999 book.[1] He recounts an event in 1951 that we can take as the beginning of fiber optics at The Institute of Optics. It so happened that Prof. A. C. S. van Heel from the Technical University of Delft in the Netherlands visited The Institute's director Brian O'Brien in October 1951. He had been trying for some time, without success, to produce bundles of glass fibers capable of transmitting an image. He tried coating glass fibers with silver (and other materials), hoping that multiple internal reflections would confine a light beam to the fiber, but this approach failed. Over a dinner in his home, O'Brien suggested to van Heel that he use a dielectric cladding with a lower refractive index on top of the glass fiber to take advantage of total internal reflection. The Dutch guest took this advice, made cladded fibers, and was successful in transmitting images. He tried to make O'Brien coauthor in a paper he published in *Nature*, but his letter didn't reach O'Brien, who had moved to Boston to join the American Optical Company. O'Brien even tried to patent his idea, but his lawyer misinterpreted the date of publication of van Heel's paper, and a patent was never filed.

In 1953, optical fibers were also being made by Narinder Singh Kapany, a graduate student of Harold Hopkins at the Imperial College in London. In fact, it was Kapany who coined the term "fiber optics" for the first time. After he graduated in 1955, Kapany joined The Institute of Optics. He did not stay very long for he was interested in exploiting optical fibers for business opportunities. Indeed, Kapany founded several companies and had a successful career. Because of his departure, The Institute did not develop a research program in fiber optics. During the 1980s, Dennis Hall worked with Thomas Brown on optical waveguides, but they were mostly interested in semiconductor waveguides. Duncan Moore's group was involved with gradient-index materials, but did not make optical fibers from them. The Institute did try to have visibility in the field of fiber optics. Donald Keck, a well-known expert on fiber optics from Corning, was appointed on a part-time basis in 1985, but he discontinued his affiliation by 1988.

I joined the faculty of The Institute of Optics in January 1989. Before arriving, I was working at AT&T Bell Laboratories on various aspects of optical communication, and my research focused both on semiconductor lasers and on optical fibers. I had published in 1986 my first book on *Semiconductor Lasers* and had just completed another book entitled *Nonlinear Fiber Optics*.[2] My plan was to establish a research group working on all aspects of optical communication, including diode lasers and optical fibers.

The first thing I noticed at The Institute was the lack of any course in the area of optical communication. The Institute of Optics offered such a graduate-level course for the first time in 1989. I was surprised by the huge interest. The course was taught regularly during the 1990s and often had more than thirty students enrolled, which was not a common situation for graduate courses. Some students came from local industry, including Kodak and Corning. I decided in 1991 to write a book on optical communication systems, based on my course notes. This book was published in 1992 by Wiley.[3] It turned out to be a wise decision in retrospect. The field of optical communication was growing rapidly, and the book was adopted as a textbook by many universities worldwide, enhancing the reputation of The Institute. *Nonlinear Fiber Optics* also attracted considerable attention and became one of the most-cited books in physics. The front cover of the first editions of both books is shown in figure 13.1.

It was important to keep the momentum growing by adding additional faculty in the area of fiber optics. Turan Erdogan joined The Institute of Optics in 1995 from Bell Labs. He established a laboratory for studying fiber-based Bragg gratings and their diverse applications. A master's degree with specialization in optical communication was added to The Institute's MS program. I organized in 1997 a conference on "Advanced Concepts in High-Speed Optical Communications," which was held at the University of Rochester during May 25–27. Corning supported the research at The Institute through joint research projects. Several international collaborations were started during this time. My group was involved with the Ecole nationale supérieure des télécommunications (ENST), located in Paris. During a visit in June 1992, I was invited to make a presentation at the Centre national d'études des télécommunications (CNET) in Lannion, France. In addition, a multiyear collaboration was set up with the University of Rennes in France that was partly funded by the US National Science Foundation. Several faculty members of The Institute of Optics visited this university in 1999. As Rennes is a sister city of Rochester, the mayor of Rennes invited us to City Hall for a welcoming celebration.

Figure 13.1. Covers of first editions of Fiber-Optic Communication Systems, a textbook first written in 1992, and Nonlinear Fiber Optics, one of the most-cited books in physics.

The field of optical communication exploded during the 1990s, soon after the telecom systems based on dense wavelength-division multiplexing (WDM) were developed. The capacity provided by such systems led to the tremendous growth of the Internet, as more and more businesses decided to set up websites. Eventually the growth became so rapid that it led to the dot.com bubble. The Institute of Optics was also affected by this boom-and-bust cycle. During the boom phase, several of my graduate students, including Clifford Headley, John Marciante, Stojan Radic, Rene Essiambre, Natasha Litchinister, and Drew Maywar, were hired by companies such as Corning and Lucent Bell Labs. Figure 13.2 shows several members of my group in the year 2000. The person on the right is Prof. Collin McKinstrie, with whom my group was collaborating at that time.

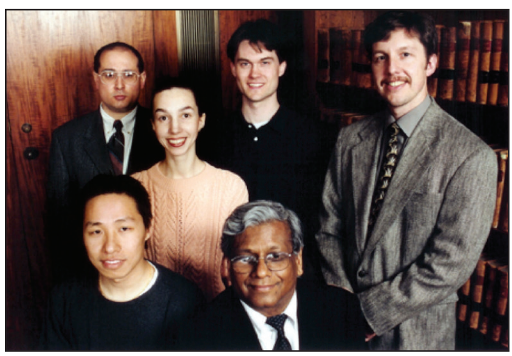


Figure 13.2. Agrawal group 2000: Back row: Fatih Yaman, Ekaterina Poutrina, Drew Maywar, Collin McKinstrie; front: Zhi M. Liao, Govind Agrawal.

During the boom phase, several faculty members left The Institute to join one of the many new companies that were being founded at a rapid pace. I was also tempted but decided to remain at The Institute. Wayne Knox was hired from Lucent Bell Labs as the new director of The Institute, just as the bubble was bursting. His job was to build up the faculty and prepare The Institute for the twenty-first century. He hired several new faculty members and convinced the administration to expand The Institute into Georgen Hall, a new building that was completed in 2007. Several Institute alumni donated large sums of money for this project to succeed.

The field of optical communication did not recover for nearly ten years. I stopped teaching the optical communication course because the number of students declined to below five. I shifted to a new area known as silicon photonics where more external funding was available. One of my PhD students, Qiang Lin, worked in this area and is currently a professor of electrical engineering at UR, with a secondary appointment in The Institute of Optics. Another student, John Marciante, left Corning after the telecom downturn and is now a faculty member at The Institute. Because of a declining enrollment in the optical communication course, I began made of silica, silicon, or other semiconductor materials. The research on optical communication started growing again after 2010 as the focus shifted to a new technique, known as spatial-division multiplexing. It makes use of new kind of fiber known as multicore fibers and may even employ multimode fibers that have been known of since the 1970s. Both Corning and Lucent Bell Labs have supported my research in this emerging area.

Both fiber optics and optical communication constitute active areas of research and teaching in 2018. I taught the course on optical communication systems in Fall 2018. My research group is investigating nonlinear optical phenomena in multimode optical fibers and collaborating with companies such as Corning and Nokia Bell Labs. In recent years, The Institute of Optics has added three new faculty members. Jaime Cardenas came in 2016 as an expert on waveguide technology, especially in silicon photonics. William Renninger became an assistant professor in 2017 as an expert on fiber lasers and ultrafast technology. Scott Carney joined us in 2017 as the new director of The Institute. With these additions, The Institute of Optics is forging ahead with its mission of being at the forefront of the research and education in optical sciences and engineering.

Notes

1. J. Hecht, *City of light: The Story of Fiber Optics* (New York: Oxford University Press, 1999).
2. G. P. Agrawal and N. K. Dutta, *Semiconductor Lasers* (New York: Van Nostrand Reinhold, 1986; 2nd ed. 1993). G. P. Agrawal, *Nonlinear Fiber Optics* (San Diego: Academic Press, 1989; 5th ed. 2013).
3. G. P. Agrawal, *Fiber-Optic Communication Systems* (Somerset, NJ: Wiley, 1992; 4th ed. 2010).

14. The History of Nanoscience in The Institute of Optics

Brian L. McIntyre and A. Nickolas Vamivakas

Looking back across the first ninety years of The Institute of Optics, it is possible to find many points of departure to begin the journey of tracing the history of nanoscience in The Institute. The breadth of the term *science*, qualified only by *nano*, speaks to the diversity of activity that the phrase captures. Because of this diversity, pinpointing an exact origin is near impossible. The best way to become oriented for the current essay can be found, in part, by consulting *A Jewel in the Crown*, Essays 21, 29, 39, 44, 48, and 58. Although only Essay 48 by Prof. Nicholas George directly, and briefly, speaks to nano-optics, the seeds from which The Institute's nanoscience endeavors grew are discussed in these earlier selections.

For the reader that decides not to look back, and forges ahead, a quote harvested from Essay 58, "Photonics" by Dennis Hall, is fitting: "Advances in optical science and engineering have always intimately been connected with advances in materials science." Dennis's observation in the first *Jewel* rings as true now as it did then. The wealth of new materials, both natural and artificial (metamaterials to use the popular jargon), are creating abundant new scientific and technological opportunities in optics and beyond. Many of the new materials are enabled by our ability to work with tools that allow us to engineer—design, fabricate, and characterize—physical structures with characteristic length scales of a few to tens of nanometers. The ability to tailor a structure's geometry and material composition at these lengths directly influences the exhibited optical, electrical, and mechanical properties. In certain instances, it even becomes necessary to consider the quantum behavior of a material's excitations in device design and development.

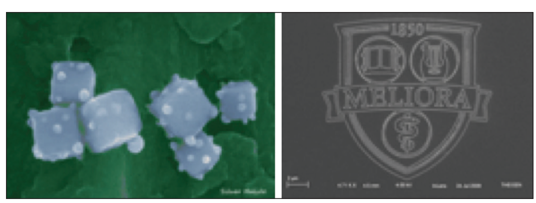


Figure 14.1. Left: silver halide taken with the scanning electron microscope (SEM); right: electron beam lithography of the UR logo.

Consideration of the previous raises a question that may be lurking in the background: how to define what constitutes *nanoscience*? Clearly it has to do with the size of an object—its wavelength spans ~ 400–700 nm. Is all visible light optics nano-optics then? We will let the reader ponder this for a bit before offering some tentative definitions.

In an attempt to provide some order in the rest of this discussion, two main themes will be pursued. The first will follow the evolution of optics-based nanoscience. The emergent subfields of nano-optics and nanophotonics will be described. The second trajectory will tell the story of non-optical nanoscience in The Institute and its eventual institutionalization in the URnano facility. Although presented as two distinct strands, the two endeavors are intertwined, as articulated by Dennis Hall's quote. URnano provides infrastructure to discover and structure materials that catalyze new opportunities in optics, and optics, through spectroscopy, supports the identification and discovery of new materials. A positive feedback loop exists where technological advances and innovation move forward hand in hand.

Nano-optics and Nanophotonics

So, what puts the *nano* in optics and photonics? Although there is no commonly agreed-upon definition, nano-optics emerged out of efforts studying electromagnetic fields, and how they interact with matter when they are concentrated into regions of space that would not be possible by using a conventional refracting or reflecting lens (due to the diffraction limit). Specific interest is on inhomogeneous and nonpropagating electromagnetic fields. A powerful way to conduct these studies involved using sharp needles of glass or metal to concentrate electromagnetic energy at their apex.[1] Viewed from this perspective, nano-optics grew out of near-field optics. The recognition that nonpropagating fields are important in nano-optics provides one way to delineate it from nanophotonics. Nanophotonics is concerned with scenarios of field concentration below the diffraction limit, but these fields may propagate. Of course, this is only a crude attempt to partition. From the words themselves—nano-optics and nanophotonics—one may be led to believe that in the latter case quantum electromagnetic field effects are important ("photon") whereas in the former QED is not. However, the usage of these terms does not respect such a quantum divide, and quantum effects are of interest in both nano-optics and nanophotonics.

Early Years—the 1980s and 1990s

Before terms such as nano-optics and nanophotonics were in vogue, there were already research activities within The Institute addressing problems that, in hindsight, would now be regarded as such. Institute research teams that were active in these efforts were the groups of Profs. Govind Agrawal, Nicholas George, Dennis Hall, and Gary Wicks. Research that engaged areas such as plasmonics, silicon photonics, integrated photonics, and optical materials were all ahead of their time. Each of the previous themes now connect in one way or another with some aspect of nano-optics and nanophotonics. Again, the essays mentioned above provide descriptions of these works. In addition to research, the educational mission of The Institute also provided foundations in this yet to emerge area. Courses during this time that may now be viewed as containing elements of nano-optics and nanophotonics include Optical Properties of Materials: Physical Optics I (OPT 421), Physical Optics II (OPT 462), Advanced Topics in Telecommunications (OPT 528), and Advanced Physical Optics (OPT 561).

The Turn of the Century (1999–2011)

Prof. Lukas Novotny was hired by The Institute in 1999 with the vision to build a research program around a research area he termed *nano-optics*. With near-field optics at its core, Lukas formed the Nano-Optics Group and put The Institute on the map as an early leader in this then-nascent optics discipline. One of the present authors (N.V.) first became aware of nano-optics when he was a PhD student studying Lukas's book appropriately titled *Principles of Nano-optics*.[2] The book grew out of a course (Nano-optics, OPT 592) taught to many generations of undergraduate and graduate students.

The Nano-Optics Group made a number of research achievements. In collaboration with Todd Krauss, professor of chemistry and optics, a near-field microscope was utilized to perform Raman scattering measurements on individual carbon nanotubes (a nanometer diameter, micron-long, rolled-up sheet of carbon atoms).[3] Thinking about near-field optics led to a new understanding of antennae in the optical part of the electromagnetic spectrum when scaled to the nanoscale. This discovery has been critical in nano-optics and nanophotonics. Another achievement was to quantify the influence of the electromagnetic environment on the excited-state lifetime of a two-level system. In this experiment, the metal tip of a near-field microscope was gradually brought into the vicinity (as close as ~ 1 nm) of the two-level system, and its influence on light emission dynamics was recorded. It was discovered that depending on the exact nanoscale position of the tip, the light emission could be enhanced or suppressed. This latter experiment also provides an example of the earlier remark that quantum optics is irrevocably linked with nano-optics and not just nanophotonics.

During this period, the Nano-Optics Group had many students, too many to list, and was also frequented by many scientific visitors. Among these guests was the father of near-field optics, Prof. Dieter Pohl. How does one get the father of near-field optics around Rochester? Of course, you would use the "nano-car." Figure 14.2 has Lukas in the driver's seat, and Dieter as the passenger.

Another staple of the Nano-Optics Group was Lukas's famed espresso machine, purchased with his first paycheck as a postdoc at the Pacific-Northwest Laboratory, and still in operation at The Institute. That machine fueled many late nights of nano-optics research. And last but not least, synonymous with the Nano-Optics Group throughout its history in The Institute was Barbara Schirmer, the group's longtime administrator.

Figure 14.2. Lukas Novotny (right) and Dieter Pohl (left) in the "nanocar."

To the Present Day (2011–2018)

As The Institute continues to grow into the twenty-first century, a central theme in its research mission remains nano-optics and nanophotonics. In 2011, two new faculty were hired, one of the authors (N.V.) and former Institute PhD student Qiang Lin, both of whom are working on these topics. Nick's group is particularly focused on the opportunities for quantum science and technology afforded by nano-optics and nanophotonics.

Qiang Lin is also interested in similar issues with an added emphasis on the mechanical properties of nanophotonic devices. A new area also to emerge during this time takes its inspiration from the early work of Arthur Ashkin on optical tweezers. Ashkin was recognized with the 2018 Nobel Prize in Physics for his efforts. In this new frontier of nano-optics, tightly focused lasers levitate nanoparticles (see fig. 14.3) and simultaneously control their dynamics.[4] These experiments, reimagined by Lukas Novotny and collaborators, are also a major research area in Nick's group. As of this writing, it looks like these levitated optomechanical systems may provide a pathway to room-temperature, table-top, mesoscale quantum mechanics. Imagine quantum superpositions and entanglement of objects nearly the size of a speck of dust!

Not only have new faculty hires expanded the scope of nano-optics and nanophotonics research in The Institute, existing faculty have also grown their programs into this research space. For example, Svetlana Lukishova has been making devices incorporating single-photon emitters into both liquid crystal dielectric cavities and metallic plasmonic cavities. Tom Brown has been studying nanoscale polarization and how to use this property of light to make subdiffraction limited metrology measurements.

In 2015, The Institute hired Prof. Jaime Cardenas, adding expertise in the areas of silicon photonics and nanophotonics. Jaime is providing a bridge between The Institute and the American Institute for Manufacturing Photonics (AIM Photonics) as well as novel approaches to active integrated nanophotonic devices. In 2017, Prof. Will Renninger joined The Institute. Will is also interested in the mechanical resonance of nanophotonic devices, but instead of using device geometry as the handle on vibration frequencies, he is focusing on the material's intrinsic phonons. In the context of nanophotonics, these material excitations provide a number of approaches to signal control as well as possibly acting to transfer quantum information on a chip.

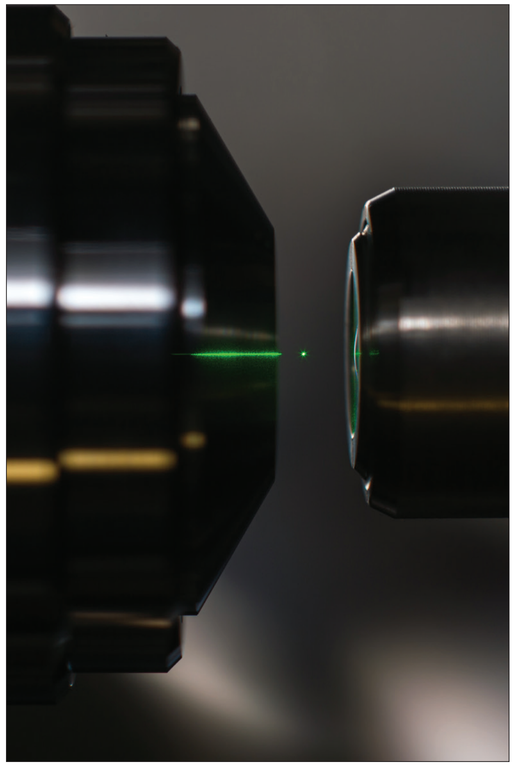


Figure 14.3. A nanoparticle (green dot) levitated in a free-space optical trap (Photo by J. Adam Fenster/University of Rochester).

As always, the increase in research activity in nano-optics and nanophotonics has been accompanied by a growth in course offerings. Current courses in The Institute that touch on nano-optics and nanophotonics are Chemical Bonds: From molecules to matter (OPT 429), Nanophotonics and Nanomechanical Devices (OPT464), and Waveguides and Optoelectronic Devices (OPT468). There is also a lab course Quantum and Nano-optics Lab (OPT 253/453). Another exciting development, spearheaded by Svetlana, has been a certificate in nanoscience for undergraduates. To receive the certificate, a student must complete certain elective courses, take the lab class, and carry out an independent research project within a faculty member's lab.

What is next for nanoscience at the Institue? It is likely that in addition to continuing to uncover new understanding in the interaction of light and matter, nano-optics and nanophotonics will play a major role in quantum science and technology. I encourage the reader to consult *Jewel in the Crown* Essay 74 on quantum optical engineering for perspective on this burgeoning field.

History of the University of Rochester Nanosystems Center (URnano)

In 1985, a scanning electron microscope (SEM) was purchased as part of the materials effort associated with the multi-investigator Center for Advanced Technology (CAT). Brian McIntyre was hired (by Duncan Moore) as the engineer in charge of training students to use this rather specialized piece of equipment that was generally new to the University of Rochester. He also oversaw operations of the lab, located on the fifth floor of Wilmot.

Figure 14.4. From left: Will Renninger, Nick Vamivakas, Jaime Cardenas.

During the following decade, many students were trained to operate the microscope and many research projects were undertaken. Some of the graduate students involved during these years included Susan Houde-Walter, Mike Houk, Jim Zavislan, Tom Brown, John Bowen, Mike Cumbo, Alan Evans, Dean Faklis, Ed Gobbi, Niels Haun, Doug Kindred, Brian Olmsted, among many others. Brian's expertise in both high-resolution imaging and micro/nano chemical analysis proved instrumental to the progress of The Institute during these years. The industry magazine *Research and Development* got wind of a project involving electron beam lithography using a Macintosh computer and published a cover article about the work.

Around 1995, a new SEM was purchased with MRI funds from the NSF, spearheaded by Susan, then a faculty member. This being a higher-resolution tool and the fifth floor of Wilmot no longer a stable enough environment, it was installed in the Wilmot annex on the quiet end of the hallway. Lots of microscopy happened in the annex. During this time, Brian also took over the operations of The Institute's computing facility and network design, taking care of the VAX 11/750 and moving the department into the distributed UNIX computer age with Appletalk and ethernet connectivity. Around 1995, Brian obtained a transmission electron microscope (TEM) from the Xerox Palo Alto Research Center. This was a very high resolution microscope and a great find for The Institute. Moving it involved many hours of careful packaging and unpackaging until it was fully installed for use on the second floor of Wilmot.

Speaking of the VAX 11/750, you may have heard of a legend concerning a VAX-in-a-Box . . . the story is true. The computer was purchased, and with the rapidly changing computer technology of the day, another computer was installed that made the first computer obsolete before it was ever installed.

Soon many other departments became aware of the capabilities within The Institute, and there began a steady increase in research workload for the microscopes for non-optics-related projects. As such, The Institute turned over control of what became known as the "Microscopy Lab" to the Engineering Dean's Office. This arrangement continued until about 2007 with various steering committees overseeing the operation of both electron microscopes.

Around 2003, Lukas Novotny and Brian decided to start teaching a hands-on course in nano-metrology techniques. The first year proved instructive in that Brian did most of the teaching, so from 2004 forward Brian was the sole instructor. It became a course in microscopy and microscopy techniques. The format of the course was to present background information for about two-thirds of the semester, with labs to back up the lectures. The last third of the course was set up to provide lab time for completing a project proposed by the students about midterm. After proposals were reviewed and accepted, students were turned loose to demonstrate proficiencies, including at least six separate microscopy techniques learned in class. This has proven to be a good model for teaching skills, and students upon completion of the class can realistically call themselves "microscopists" before the rest of the world. Each year the students have a poster presentation showing their experimental designs and results, and perhaps more importantly, they create a website to present their projects that also serves as a project archive. Many requests for use of class results have been facilitated by Brian over the years; you may see some in publications and books on a variety of topics.[5]

Around 2007, Wayne Knox, then director of The Institute, had a vision of nanoscience becoming one of the growth areas in optics and optical engineering. He brought many other faculty members into the process of setting up a new facility that would encompass both the Microscopy Lab and a new fabrication facility including a cleanroom for nanotechnologies. The new faculty included Ching Tang, Nick Bigelow, Lukas Novotny, Phillipe Fauchet, Hong Yang, Tom Brown, and a few others. Federal funds were obtained, and the university began to put together their ideas and desires. Sadly, the Great Recession ensued and everything was put on hold. Brian also had to take some time off for a serioius illness. In any case, the University of Rochester Integrated Nanosystems Center (URinc) was back-burnered for a while. In 2009, things picked back up and siting for the cleanroom was initiated. The committee looked at renovating half of the Wilmot annex, but the cost and the visual aesthetics would not allow this site to proceed. Fortunately, Goergen Hall had just been completed, and the plans included moving the existing Microscopy Lab and the Novotny research labs into its basement, ostensibly because it was a "low vibration" environment. Well, this didn't turn out to be the case because all of Goergen Hall's mechanical systems were built out on the same slab that continued through the basement labs, thus propagating vibrations, which meant that the existing labs had to stay put. This nonusable space was then repurposed for the cleanroom, which had much lower specifications for vibration. Over the next couple of years, the space was gutted and reconfigured for a 2,000-square-foot class 1000 cleanroom. It was populated with tools and equipment in 2009–10 and became fully functional in 2011. URinc was also decommissioned as the facility acronym because it looked too much like a corporation name; it was replaced with

URnano, which seemed to fit. Since then, over six hundred individuals from many on-campus departments and a variety of non-UR-affiliated companies and schools have been trained here to do work in the nanosciences. Current technologies available include optical lithography (laserwriter, aligner), deposition (sputtering, evaporation, ALD/CVD), etch (wet, plasma), thermal processing, 2D material growth (graphene, hBN, TMDCs), metrology, microscopy (SEM, TEM, STEM, AFM, uIR), optical thin film analysis, and XPS.

From the grand opening celebration in August 2011: "The Nanosystems Center offers unprecedented capabilities in nanoscience research that will build on our historic strengths, encourage the development of new technologies, and facilitate collaborations with industry" (Joel Seligman, university president).

Collaboration with industry has been a URnano goal from its inception, and was a major reason US Representative Louise Slaughter worked hard to secure $4.4 million in federal funding to help launch the center. "I'm particularly excited because I know that this lab will create jobs, not only in the lab itself, but also in new companies catalyzed by the research taking place in the lab," Slaughter said on the day URnano officially opened its doors.

URnano management has consisted of the director, Nick Bigelow, and operations manager, Brian McIntyre. Jim McGrath came on board as the associate director in 2016. Financial oversight was performed initially by Sondra Anderson and Connie Hendricks and later on by Rachel Eberly and Bill Burrows in Physics. Lab staff included Brian, Alex Mann, Jim Mitchell, Hatice (Nursah) Kokbudak, and Ralph Wiegandt. Over the years, undergraduate students have assisted in URnano-related activities, including Rachel Perlman, Jaren Ashcraft, and Donnell Jackson.

Notes

1. Lukas Novotny, "The History of Near-Field Optics," Progress in Optics 50 (2007): 137; D. W. Pohl, "Optics at the Nanometre Scale," Philosophical Transactions of the Royal Society of London, Series A, Mathematical Physical and Engineering Sciences (2004): 701–18.
2. Lukas Novotny and Bert Hecht, Principles of Nano-Optics (Cambridge: Cambridge University Press, 2012).
3. Achim Hartschuh, Hermeneglido N. Pedrosa, Lukas Novotny, and Todd D. Krauss, "Simultaneous Fluorescence and Raman Scattering from Single Carbon Nanotubes," Science 301 (5638) (2003): 1354–56.
4. Nick Vamivakas, Mishkat Bhattacharya, and Peter Barker, "Levitated Optomechanics," Optics and Photonics News 27 (7) (2016): 42–49.
5. The Electron Microscopy Facility Archival Area for Classroom Activity can be found online at http://www2.optics.rochester.edu/workgroups/cml/classB.html, accessed March 20, 2020.

15. From Black to Superhydrophobic: Research on Laser-Matter Interactions at The Institute and Beyond

Chunlei Guo

When I first joined The Institute in September 2001, my research interest lay in very fundamental physics and optics research. At the time, I was mostly involved in understanding fundamental interactions of femtosecond laser pulses with matter. My initial research focused on two directions: one was to study how atoms and molecules respond to strong laser fields, while the other was on laser interactions with metals. Years later, the fundamental nature of my research in atoms and molecules remain unchanged, but my work on metals took a very unexpected turn.

In the early 2000s, the study of femtosecond lasers interacting with materials seemed to stagnate.

Many people were excited about micromachining using femtosecond lasers to make microstructures with high precision. These research activities were supported by the prevailing theory at the time—i.e., femtosecond laser pulses were so short that when an intense pulse was applied to a material, all the pulse energy would be used for material ablation and virtually no energy deposited into the material. With this prevailing theory, people also argued that femtosecond laser ablation was very efficient since little heat was involved. This theory seemed to agree with the micromachining results people obtained using femtosecond lasers. Therefore, there was a sense that the theories were in place and there was not much to be done to further improve our understanding of femtosecond laser material interactions. However, one surprising fact was that the prevailing theory was never fully tested experimentally. Nevertheless, it was not considered to be a significant issue; since the theory was very reasonable, few thought there was need for experimental validation.

The lack of direct experimental support to the prevailing theory was also due to significant experimental challenges. To measure how much pulse energy is deposited into a metal during laser ablation, one would need to rely on subtracting the reflection from the incident beam energy. This would work well if the metal surface is smooth and reflects like a mirror. However, for intense laser ablation, the metal surface will be damaged and diffuse light. Since it was nearly impossible to effectively collect all the diffused light, no one would have bothered to study this energy absorption issue experimentally as the theory simply made sense. Unfortunately, as I will discuss below, the prevailing theory was not as robust as it sounded.

In the first few years after I arrived at Rochester, I was joined by Anatoliy Vorobyev, a very passionate and experienced researcher who had studied longer pulsed laser phenomena but not femtosecond lasers. Anatoliy and I started to look into this femtosecond laser energy deposition problem, and we decided to build a laser calorimeter that could allow us to make direct measurements. It took a great amount of work to get this calorimeter built and with it, we performed the first calorimetry studies in femtosecond laser interactions. What we found was quite astonishing; instead of seeing little pulse energy deposited into the metal following femtosecond laser irradiation, we found a significant amount of energy stayed in the irradiated samples under certain experimental conditions. Although these results were very significant fundamentally, they were quickly overshadowed by some more applied findings that followed. That was in 2005, and it was the start of an era in which we found many interesting things from plain metals.

With the insight gained from studying the energy deposition, we realized that we could dramatically increase the absorption of metals following femtosecond laser irradiation. As a result, we created the so-called black metal around 2005–6, when we could turn a shiny piece of metal pitch-black as seen in figure 15.1. Not only did it appear black, but the surface had also a near-perfect broadband absorption across UV, visible, and near IR. Obviously, the black metal will be useful whenever light collection is needed, such as making better thermal sensors and detectors. Unlike black paint or coating, the enhanced absorption from our black metal came from a range of morphological micro- and nano-scale structures formed by femtosecond laser irradiation. These structures are very tiny so that the metal surface is still smooth to the touch, but can be seen under high-power microscopes. This is unique because the blackened surface is still part of the metal and retains the same metallic properties. When our invention somehow became public knowledge, the phone calls came in from businesses, fellow scientists, and people from all walks of life. As a scientist, it was an interesting experience to relate my research to the general public. But at the same time, it was also quite distracting. Little did I know that this was just the beginning of our research reaching people far beyond the academic community.

After the black metal work, Anatoliy and I were determined to push the black metal technology one step further. The black metal absorbs different colors of light undistinguishingly; we were thinking about producing a surface that would selectively absorb certain colors but reflect other colors. In that case, the metal surface would appear to be a certain color. A year later, this became a reality; we produced the so-called colored metals. At that point, we could turn shiny metals not just

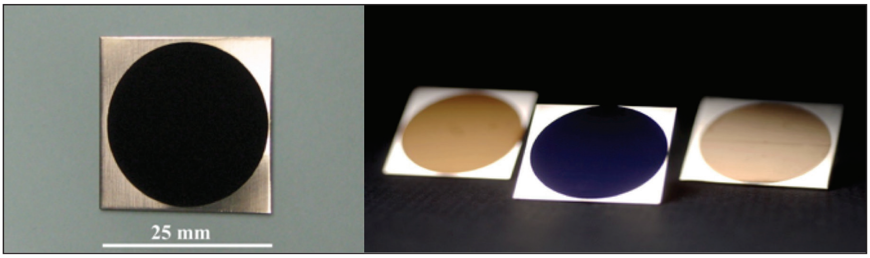


Figure 15.1. From left: aluminum turned black, aluminum turned a gold color, titanium turned to blue, platinum turned gold.

black, but also different colors all through laser surface structuring. As shown in figure 15.1, we turned aluminum and platinum gold, and titanium blue. Shortly after our discovery, it was interesting to see that a *New York Times* article called this work “a feat of optical alchemy.” The article went on to discuss possibilities of creating colorful jewelries.

After studying light absorption, Anatoliy and I went on to study light emission from the black metal. At the time, the United States and many other countries around the world were phasing out incandescent light bulbs. There was no dispute about the low efficiency from incandescent lamps. However, one limiting factor often overlooked was that the tungsten filament, being made of a metal, has very low emittance because of its low absorbance. However, there was really nothing people could do to change this at the time because the emittance is determined by the intrinsic property of tungsten. Anatoliy and I started to discuss if we could change the emittance of the tungsten filament with our black metal technology. Experiments were tried; we fired a femtosecond laser beam directly through the glass envelope of a light bulb and blackened a part of the filament. After the blackening, the light bulb was turned back on. Lo and behold, the blackened part of the filament glowed much brighter—indeed, twice as bright! As the law had been passed and nothing could really rescue the incandescent bulbs, I could deeply feel the public emotions toward the tungsten bulb. Prompted by our discovery, the *New York Times* ran two separate articles on this topic: “Can Incandescent Bulbs Compete on Efficiency?” and “Incandescent Bulbs Return to the Cutting Edge.”

After much study on photons, we turned our attention to water. The question Anatoliy and I had was if our surfaces would have different wetting properties. In the next few years, we created a number of laser processing techniques that turn a wide range of regular materials, including metals, semiconductors, dielectrics, and even biological materials, superhydrophilic and superwicking. Compared to other hydrophilic materials, the hydrophilicity we created is extremely strong. Water or other liquids, as soon as they touch the bottom of a vertically standing treated surface, will defy gravity and sprint uphill at a high velocity (several centimeters per second). One potential use of this technology is for liquid cooling, particularly in microelectronics as heating is a major issue. After we turned silicon superwicking,

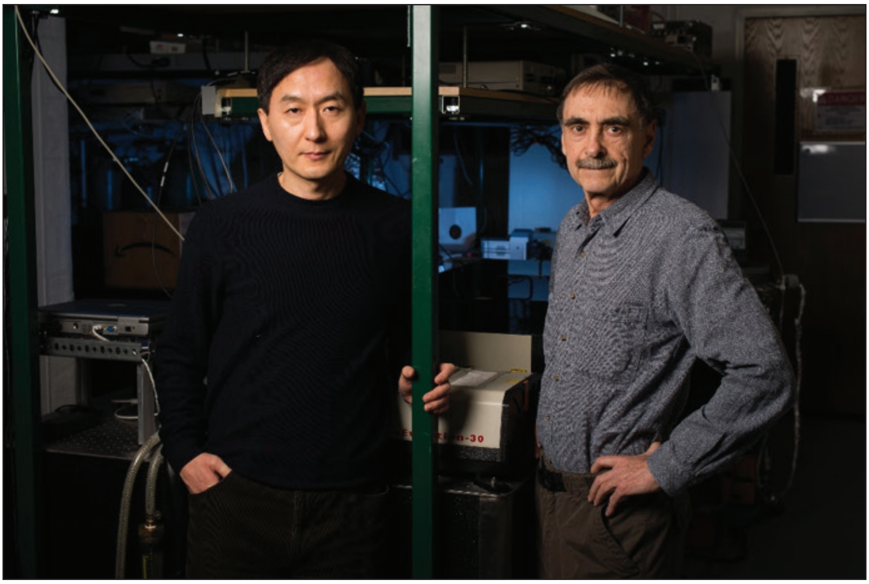


Figure 15.2. Senior scientist Anatoliy Vorobyev and Professor Chunlei Guo stand in front of their lasers. Photo by Adam Fenster/University of Rochester.

this potential application was immediately discussed in yet another *Times* article entitled "For Cooler Chips, Follow the Grooves."

After the superhydrophilic work, we turned to the counterpart technology—i.e. creating a superhydrophobic surface with femtosecond lasers. A few years later, we produced a multifunctional surface that is both black and super water repellent. In fact, the superhydrophobic surface we created repels water with such a vigor that water droplets bounce off like Ping-Pong balls. One interesting fact is that most scientific discoveries in physics are driven by pursuing high tech. But in contrast, our work in creating superhydrophobic surfaces was actually driven by an ongoing project we have working with the Bill & Melinda Gates Foundation. For this project, we planned to develop a self-cleaning surface to address global sanitation needs. Today, our Gates Foundation project has entered a new phase with a close collaboration with Changchun Institute of Optics, Fine Mechanics, and Physics (CIOMP) in China.

My collaboration with CIOMP started in 2016. CIOMP is the first optical institution in China, in a similar position as our Institute in the United States. Given the positions that each institute holds, giving birth to the academic study of optics in their respective countries, CIOMP and the University of Rochester had been keen to establish a close collaborative tie. In fact, several rounds of high-level institutional meetings and visits were carried out by the administrators from both sides. From the Rochester side, this included Provost Peter Lennie, the then-Dean of Hajim School Robert Clark, and Vice Provost Jane Gatewood of Global Engagement. With

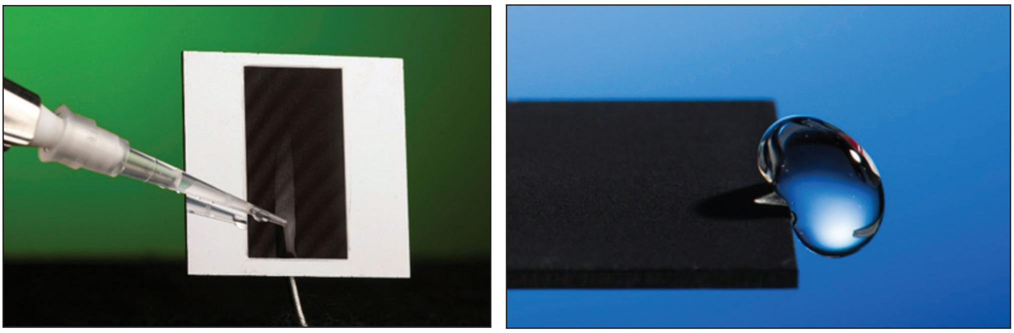


Figure 15.3 and 15.4. Laser-treated surfaces become both pitch-black and (left) superhydrophilic: a water droplet sprints upward against gravity on a superhydrophillic surface; (right) superhydrophobic: a water droplet is repelled off a superhydrophobic surface. Photo by J. Adam Fenster/University of Rochester.

CIOMP, an institutional MOU was signed by Provost Lennie and a departmental exchange MOU was signed by The Institute director, Xi-Cheng Zhang. In 2015 and 2016, the CIOMP leadership again visited UR and discussed building a more concrete collaboration. With strong support from Director Zhang and the current dean of the Hajim School Wendi Heinzelman, a close collaboration was established between my lab at The Institute and a newly established Photonics Lab at CIOMP. I have been able to oversee the design and growth of this new lab. Merely two years later, starting from a completely empty space and a couple of part-time staff helpers, the new CIOMP Photonics Lab has rapidly grown into a team of about sixty members housed in a 30,000-square-foot state-of-the-art modern research building. The lab research covers areas of laser-matter interactions, high-order nonlinear optics, materials and devices, and nanophotonics. Many of my Rochester lab members have also contributed to the close interactions with the CIOMP lab, including Subhash Singh, Mohamed Elkabbash, Jihua Zhang, KwangJin Lee, and Kai Davies. The CIOMP lab also provided summer intern opportunities to a number of Rochester graduate and undergraduate students, including Bo Lai, Cong Cong, Xiaoyun Li, and Huiyan Li. Not only did the CIOMP lab make great strides in building its team, scientific research, and infrastructures, but it also built these on a firm ground in inclusiveness and diversity. Today, over half of the CIOMP lab staff members are foreign nationals, and more excitingly, our student body consists of more than 50 percent females, a ratio rarely seen anywhere in the world for a STEM program. Apparently, my Rochester and CIOMP labs have plenty to learn from each other. More importantly, the current ongoing Gates Foundation project funds the two labs working side by side to scale up our functionalized materials and bring them to real-world sanitation applications.

16. The Freeform Optics Revolution

Jannick P. Rolland

Short Biography and Notes

Jannick Rolland received a master's in optical engineering from The Institute of Optics in Orsay, France, and a PhD in optical science from the University of Arizona. She joined The Institute of Optics at the University of Rochester in January 1209 under the directorship of Wayne Knox (BS '79, PhD '84).

Rolland's thirteen-year professional academic path prior to joining UR had led from assistant professor to full professor at the Center for Research and Education in Optics and Lasers (CREOL) at the University of Central Florida.

On April 19, 2009, Rolland was endowed as the Brian J. Thompson Professor of Optical Engineering at UR, a humbling moment in her scientific career. John Bruning, former CEO of Corning Tropel and a lifelong friend to UR and The Institute, honored Brian Thompson's achievements with the creation of this chaired professorship. Jannick was appointed director of the R. E. Hopkins Center in July 2012 when Xi-Cheng Zhang took office as director. Rolland is grateful for having been part of these various sanctuaries of optics spanning France to the Wild West, to the Far South and finally to the Great North.

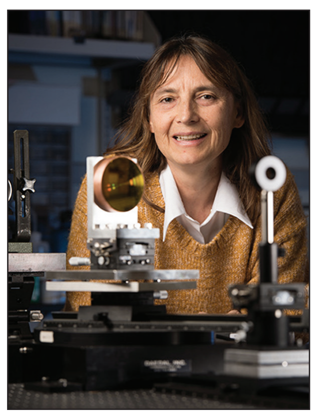


Figure 16.1. Jannick Rolland, Brian J. Thompson Professor of Optical Engineering. Photo by J. Adam Fenster/University of Rochester.

Rolland's entry into Optics at The Institute of Optics in France was through a path less traveled. She was admitted to the *grandes ecoles*, the "agreed-upon" elite schools in France, having declined an offer from the Institut Universitaire de Technologie (IUT) Measures Physiques in Orsay, France. After a long three weeks spent in Grande Ecole Carneau in Paris, she decided to reconsider and approached the IUT in person. The connection through her optics professor, Jacques Serres, at the

Figure 16.2. Thompson/Rolland group at chair installation.

IUT Measures Physiques combined with her love for mathematics led her to apply to The Institute of Optics in Orsay two years later. Her admittance was unpopular with a couple of professors, even though she was a valedictorian. However, Michel Cagnet, astronomer and directeur des etudes at The Institute of Optics in Orsay, known for cowriting the *Atlas of Optical Phenomena*, admitted her following an oral exam and an interview. This opportunity seeded her career as an optical engineer.

Rolland's move to the United States in her early twenties stemmed from her intuition that moving deeper out of her comfort zone (first experienced with admission against the will of a couple of faculty), together with learning how to communicate fluently in English, would be critical skills to learn in either of the two professions she still considered: optics or professional dancing. It would require further development of the adaptation gene, which Rolland thinks turned out to be essential along her path. Wouldn't it be nice to satisfy that quest while doing optics and dancing? Rolland applied to the College of Optical Sciences at the University of Arizona, originally driven to explore her interests in space optics and dancing—and met with an inevitable culture shock. She graduated in 1990 with her PhD in optics with a focus on medical imaging, working with Prof. Harry Barrett as her adviser.

Rochester, New York—a Magnet for Optics

Rolland's move to Rochester, New York, in 2009 was guided by her strong drive to accelerate the emergence and impact of two technologies: a biomedical optics technology, *Gabor domain optical coherence tomography (GD-OCM),* and *freeform optics.* Rolland invented GD-OCM around 1996, which achieves high-definition volumetric subsurface optical sectioning at the cellular level together with nanometer-class thickness estimation. The magnet in Rochester for Rolland was the rich optics industry ecosystem that grew out of the success of Kodak, as well as a medical school across the street from The Institute of Optics, which is highly ranked in research innovations. A NYSTAR Foundation career award (i.e., an approximately $1 million joint investment between the State of New York and the University of Rochester) seeded Rolland's rapid progress with her team in these two fields of research. One led to the start-up LighTopTech (www.lightoptech.com), incorporated in May 2013 with cofounder Cristina Canavesi, Rolland's first PhD graduate at The Institute, and the other to the Center for Freeform Optics (CeFO), awarded a grant by the National Science Foundation on August 1, 2013, for five years, and renewed September 1, 2018, for five more.

Optical Design, a Legacy at The Institute of Optics in Rochester

The Institute of Optics at the University of Rochester has a long legacy of teaching optical system design. Rudolf and Hilda Kingslake joined the university in 1929 at the founding of The Institute of Optics, followed by Robert E. Hopkins (MS '39, PhD '45) in the early years of The Institute. Rudolf Kingslake is regarded as the father of lens design, and his book *Lens Design Fundamentals*, along with Conrady's contributions to the field (published in Part I of the book), have served as references to lens designers for approaching a century.[1]

Since 1998, Julie Bentley (BS '90, PhD '95) has been teaching the foundations of optical system design to both undergraduate and graduate students at The Institute. These foundations have focused (in large part) on rotational symmetric systems. First published in 2012, Bentley's *SPIE Field Guide to Lens Design* is expected to support the education in foundations of optical system design for generations of students to come.[2]

While optical system design was popular from 1930 to 1960, with the invention of the laser, the field of optical system design slowly took a plunge until recent years. Attracting students to study this field of engineering became a challenge as the laser quickly became a hot topic in both its further developments and exploding applications. Pioneers in laser engineering Gérard Moreau, professor at The Institute of Optics in the 1980s, and Donna Stickland (PhD '89) won the Nobel Prize in Physics in 2018.

As all comes in cycles, "lens" designer, a profession that may have been thought to be coming to the brink of extinction in the twenty-first century, is now one of the most in-demand specialty fields among broadly trained optical engineers and is attracting strong young talent to this field.

Reflection on the Birth of Freeform Optics in Rolland's Laboratory

The intersection of our passions appears to be key in sustaining the drive in research. Rolland will now highlight an early connection to freeform optics.

In 1990, after graduating from the University of Arizona, Rolland took another path less traveled and joined the Department of Computer Science at the University of North Carolina to design head-worn displays for medical visualization. She had just graduated with her PhD in optics and spent the next six years as the only optical engineer working with computer scientists leading research in Augmented and Virtual Reality. It was simultaneously an amazingly challenging and exciting time.

Perhaps it was serendipity, but another group at UNC, the Vision Group, was conducting research in 3D shape perception, which fascinated Rolland to the point that, after one and a half years doing optical system design, she decided to diversify her efforts and agreed to lead the Vision Group. This period seeded her curiosity in the mathematical definitions and perception of complex shapes we call today freeform optics. Rolland first pursued her interest in optical metrology of freeform optics a few years after joining CREOL at the UCF in 1996.[3] In 2005, Rolland started working on optical design with freeform surfaces, which rapidly pointed to the opportunity and challenge ahead.[4]

Nodal Aberration Theory Seeded the Development of Freeform Optics Aberrations: Birth of the Center for Freeform Optics (CeFO)

Between 1978 and 1980, driven by the needs of the astronomical community, nodal aberration theory (NAT) was invented at the University of Arizona by Roland Shack, and Kevin Thompson developed NAT up to the fifth order.[5] NAT expands the conventional aberration theory of H. H. Hopkins to rotationally nonsymmetric systems, and was specifically targeted to account for misalignment-induced aberrations.

Rolland (Jannick) started working with Thompson (Kevin) in 2006, partnering in science and in life. Jannick and Kevin collaborated in applying NAT to understand the optical aberrations of off-axis optical systems as well as misaligned systems. When Jannick joined The Institute of Optics in 2009, Kevin was working for ORA-Synopsys, but he also joined The Institute as a visiting scientist. On August 20, 2009, Kevin and Jannick were married at the Eastman House among family and friends, including the late Emil Wolf and his wife, Marlies, who lit up our Institute for many years.

Joining The Institute of Optics at the University of Rochester in 2009 fast-tracked Jannick and Kevin into the future, as they were already working with Rochester-based companies in freeform optical manufacturing. What may have been specified as a smooth freeform surface in design was manufactured, in fact, as a diffraction grating. The tool artifacts, expressed as fine lines created during diamond turning referred as midspatial frequencies (MSF), were severe. Two

NSF program directors, Dr. John Zavada (PhD '71, New York University) and Dominique Dagenais (MS '76), recognized the innovation in freeform optics and awarded Rolland, as principal investigator, and Thompson, as co-PI, a GOALI grant (2010–13). This was conceived in partnership with Optical Research Associates (ORA), a division of Synopsys since 2010, as the lead company on the topic of freeform optics that seeded the early work in this field at The Institute. Also, the II-VI Foundation funded Rolland through the block-gift program from 2010 to 2020 on projects related to freeform optics.

In 2010, Thompson and Rolland, working with Fuerschbach (PhD '14), realized the far-reaching importance and role that NAT may have in understanding the aberration theory of freeform optics essential in the design of freeform optical systems.[6]

Between October 30 and November 1, 2011, fifty-four experts in optical design, optical fabrication, and testing from academia, industry, and governments labs, national and international, gathered in Washington, DC, for the first Optical Society of America (OSA) incubator meeting, a new type of meeting Rolland led while serving on the OSA board of directors in 2010–13. Freeform Optics was the topic of the inaugural meeting.[7]

The Center for Freeform Optics

At the beginning of the twenty-first century, something highly unexpected took place: the "Freeform Revolution."[8] Here the word is chosen from the perspective of a technology that is over one hundred years old: the freeform optical surface. The fabrication of high-precision freeform surfaces required for imaging applications was practically enabled only in the last two decades, both by optical design tools and by optical testing. This revolution will forever change these industries and the customers they serve.

A freeform surface is an optical surface that *requires* a third independent axis (C-axis in diamond-turning terminology) during the fabrication process to create an optical surface whose surface shape lacks translational or rotational symmetry about axes normal to the mean plane. In the recent past, the denomination *freeform* was (erroneously, from a design point of view) given to surface shapes, such as toroidal surfaces and off-axis conics, that break rotational symmetry.

In fabrication, an off-axis conic made without first creating the parent optics, is considered a freeform surface by fabricators. In design, however, this surface shape does not have the degrees of freedom required to correct the optical aberrations of 3D folded systems and as such falls short of being considered a freeform surface.

The community of research engineers and scientists expressing an interest in freeform optics grew rapidly in the first ten years, which led Rolland and a team of collaborators across the Departments of Optics and Mechanical Engineering as well as the Laboratory for Laser Energetics to propose a Center for Freeform Optics to the National Science Foundation.

CeFO was awarded a grant by the NSF on August 1, 2013, with the headquarter in Rochester (focused on design and metrology) and a site partner at the University of North Carolina at Charlotte (focused on optical and optomechanical manufacturing). Rolland (Optics) has led CeFO since 2013 with Associate Director John Lambropoulos (Mechanical Engineering). At UNC-Charlotte, the center was served by Angela Davies (Optics) (2013–15), with Associate Director Christopher Evans (Mechanical Engineering), followed by Matthew Davies (Mechanical Engineering) (2015–18) and Associate Director Thomas Suleski (Optics), who took the directorship in 2018 with Associate Director Konstantinos Falaggis (Mechanical Engineering). The partnership between Optics and Mechanical Engineering is central to CeFO and has enabled concurrent engineering that is essential to advancing the technology-readiness level of freeform optics. Other faculty partners of The Institute in the center from 2009 to 2019 include Profs. James Fienup and Miguel Alonso, whose research in freeform optics is featured later in this chapter.

The vision of the Center for Freeform Optics is that compact, affordable, and performant optical systems will permeate precision technologies of the future. Its mission is to advance research and education in the science, engineering, and applications of systems based on freeform optics through a dedicated, continuing industrial partnership based on shared value.

A major interdisciplinary research program emerged with, on the academic side, twenty-one faculty members and thirty-four students comprising 40 percent underrepresented minorities and a majority of women. On the corporate and government side, seven pioneers (Air Force Research Lab, Ball Aerospace and Technologies, Optipro Systems, PolymerPlus, Rochester Precision Optics, SCHOTT North America, and Zygo) joined CeFO to enable its launch, with support from the National Science Foundation.

From 2013 to 2019, a total of twenty-six members partnered with CeFO (the seven pioneers as well as Aperture Optical Systems, ARRI, Collins Aerospace, Corning, Eminess Technologies, Facebook Reality Labs, Google, Jabil Optics, JPL, LightPath Technologies, L-3 Communications, Microsoft, Nikon Research Corporation of America, OptoAlignment Technologies, PerkinElmer, Poco Graphite, Synopsys, Thales, and Zeiss). Also, NASA has been supporting selected students with fellowships to advance freeform optics for space science.

An expansion into the curriculum was soon initiated by Rolland in Fall 2016, with a new course in Freeform Optics that spans from historical highlights to hands-on optical system design with freeform surfaces. In January 2019, Aaron Bauer (PhD ’16) joined Rolland to coteach the course and facilitate hands-on workshops using CODE V optical design software. One of the longest-lasting effects of CeFO is the development of a new generation of young scientists broadly educated in freeform optics. The students, ranging from undergraduates to masters to PhDs to postdocs, represent a broad spectrum of backgrounds. Importantly, the constant contact with industry as well as CeFO faculty represents a new model of learning for all students involved in the center, where industry itself is the third partner in the student-teacher intellectual relationship.

Freeform optics is poised to permeate all precision technologies of the future, and perhaps a lot sooner than we ever anticipated.

Figure 16.3. The Center for Freeform Optics (CeFO), December 2019. Front row: program director Andre Marshall (red tie), Wendi Heinzelman (burgundy jacket), next to Jannick Rolland (director, black jacket) and John Lambropoulos (associate director, black sweater); third row: UNC-Charlotte director Thomas Suleski (brown jacket); back row: Matthew Davies, 2015–18 UNC-Charlotte site director (red tie).

Freeform Optical Design: Jannick Rolland and Kevin Thompson

A foundation in optical system design, whether the system leverages rotationally symmetric or sections of rotationally symmetric surfaces, or freeform surfaces, is to start the design process with TABLE 1, a short name for Table of Specifications that solely requires first-order computations. The term TABLE 1 was cast by ORA, led by Robert S. Hilbert (BS ’62) (MS ’64) as president from 1991 to 2008, a lifetime partner to The Institute. Kevin Thompson (PhD ’80, University of Arizona) led the ORA Engineering Group as vice president of engineering and shared these best practices with students. ORA was one of a handful of companies to advance the development of optical design software from mainframes to the personal computer.

Early on at The Institute and elsewhere, the research effort focused on the mathematical surface descriptions of freeform optics.[9] The research also started to investigate methods of optical system design with freeform surfaces. The first freeform imager, Pathfinder 1, a F/1.9 long-wave infrared imager, was designed at The Institute, fabricated at II-VI Infrared, and tested at The Institute.[10] To point to its size, Rolland referred to Pathfinder 1 as “pamplemousse,” the French counterpart to “grapefruit,” to communicate intuitively the approximate volume of the system.

At Rochester, Jannick and Kevin with graduate student Fuerschbach focused their next efforts on the derivation of aberration theory for freeform optics, and with graduate students Bauer (PhD ’16), Eric Schiesser (PhD ’19), Jonathan Papa (PhD ~’20), Nicholas Takaki (PhD ~’21) on design methods.[11] In Rolland’s group—graduate students Jianing Yao (PhD ’16), Di Xu (PhD ~’20), and Romita Chaudhuri (PhD ~’21)—has significantly advanced the metrology of freeform optics.[12]

In the second phase of CeFO (2018–23), we are applying the existing and emerging methods to a wide range of optical systems addressing the various needs from space optics to microscopy. We are steadily advancing high-precision manufacturing of freeform optics across a diversity of materials. On the roadmap are plans to advance the precision manufacturing of diamond-turning-based methods as well as volume manufacturing through high-precision molding and replication. High-precision metrology of freeform optics is probably one of the toughest challenges. Various approaches are being developed in parallel, and the layout of a metrology roadmap for both existing and emerging methods is being developed to detail a pathway to advance the technology-readiness level of freeform optics necessary to permeate various markets.

Figure 16.4. Miguel Alonso, professor of optics.

Mathematics of Midspatial Frequencies: Miguel Alonso

The group of Miguel A. Alonso (PhD '96) began in 2016 a project with the goal of giving a simple and intuitive description to MSF errors and their effect on the performance of optical systems. Participants in this research included Alonso as well as graduate students Kevin Liang (PhD '20) and Wenhua He (MS '18), as well as two external collaborators: Gregory W. Forbes (a former professor at The Institute of Optics) and Thomas Suleski (UNC-Charlotte). The idea was to combine ray and wave optical theory with elements of basis representations, probability, statistics, and geometry to arrive at simple rules of thumb that not only give quantitative predictions but also (and perhaps more importantly) an intuitive picture of the effects.

One of the main thrusts of this project was to define new quantities that provide a link between the probabilistic nature of surface errors and standard optical performance metrics. This began with a study of the Strehl ratio by Alonso and Forbes, which was later extended by Liang and Alonso to the description of more general image-quality measures such as the optical transfer function (OTF) and its link to MSF through the definition of a new quantity, the pupil-difference probability density (PDPD).[13] This description was used to study the MSF structure resulting from turning and milling processes, and even simple aberrations.[14] In combination with simple geometry, this approach led to simple closed-form accurate estimates of the OTF. These results were validated against more numerically intensive simulations in collaborative work with Suleski and his PhD student Hamidreza Aryan.[15]

A second thrust of this work was to understand and evaluate the accuracy of a standard perturbative approximation used in the study of optical systems with

MSF errors. The effects of aberrations and other errors on the wave-optical performance of a system are particularly easy to model when those errors are assumed to be placed at the exit pupil of the system or a plane conjugate to it, since then they can be accounted for by a phase over the field at the pupil, from which the point spread function (PSF) is obtained through simple Fourier transformation. However, typically, the phase errors caused by surface deviations such as MSF are not at a plane conjugate to the pupil but at several different planes along the system. The standard approximation is then to drag these errors to the pupil along the system's nominal rays, so that a Fourier transformation can be used to estimate the PSF. Liang, Forbes, and Alonso provided a careful study of the validity of this approximation and found simple and intuitive rules of thumb for what level of error it introduces.[16] As a side product, their work on this topic gave rise to a new complete orthonormal basis set (an alternative to the Zernike and Q polynomials) for the study of phase errors.

Phase Retrieval for Freeform Metrology: James R. Fienup

In a number of different disciplines, one wishes to know the wavefront of an optical field, which is directly related to the phase of the field, despite making only measurements of the intensity of the field, referred to as the problem of phase retrieval. Application areas include, for example, coherent X-ray diffractive imaging (crystallography without requiring crystallization of the sample) and image reconstruction for optical astronomy and microscopy. A third application area is for wavefront sensing.[17] In 1990, we were able to determine the phase aberrations of the Hubble Space Telescope from measured intensity images of stars taken with the telescope; knowledge of the aberrations allowed optical engineers to make correction optics that were installed into Hubble that have since given us the wonderful pictures of the cosmos that have inspired us all. Based on that experience, NASA and its contractors built the James Webb Space Telescope (JWST), which totally relies on phase retrieval in order to operate, with its primary mirror consisting of eighteen separate segments, to be accurately aligned in space. For more details on the JWST, see Essay V.20 by David Aronstein.

We decided to apply related techniques for the difficult task of the Center for Freeform Optics to develop approaches to accurate optical metrology on freeform surfaces being manufactured.

Aaron Michalko (PhD '20) and his adviser, Prof. James R. Fienup, the Robert E. Hopkins Professor of Optics (since 2002), began work on this project in the fall of 2015. They employed a particular phase-retrieval approach called transverse translation diverse phase retrieval (TTDPR) (or ptychography). As illustrated with the cartoon (fig. 16.6), it involves illuminating one part of the freeform surface at a time, and collecting a splotch of light reflected to the plane of a detector array. The illumination beam is scanned over the surface with overlapping illumination patterns, and the resulting collection of splotches of light goes into a nonlinear optimization algorithm that determines which one optical surface is consistent with producing all those splotches of light. This approach uses an absolute minimum of optics, which makes it potentially much less expensive than other metrology approaches, and it minimizes the need to characterize the system's optics. Since no reference beam is involved as in interferometry, it should be relatively tolerant to vibrations and does not suffer from retrace errors.

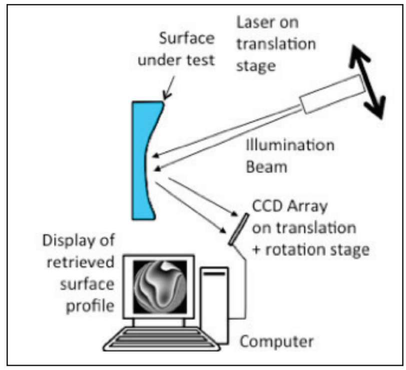


Figure 16.5. Illustration of the phase-retrieval approach called transverse translation diverse phase retrieval (TTDPR), or ptychography.

Investigation into this technique has been performed both in simulation and in the laboratory. Through simulations, the algorithm has been shown to work with soft-edged illumination beams as well as in the presence of large aberrations, which are expected when testing nonspherical optics.[18] In the lab, the method was verified against standard metrology and tested on a freeform surface. This technology could be an enabler for wider use of freeform optics.

Notes

1. Rudolf Kingslake, Lens Design Fundamentals (San Diego: Academic Press, 1978).
2. J. Bentley, SPIE Field Guide to Lens Design (Bellingham, WA: SPIE Press, 2012).
3. W. Zou, K. P. Thompson, and J. P. Rolland, "Differential Shack-Hartmann Curvature Sensor: Local Principal Curvature Measurements," Journal of the Optical Society of America A 25 (9) (2008): 2331–37.
4. O. Cakmakci, B. Moore, H. Foroosh, and J. P. Rolland, "Optical Local Shape Description for Rotationally Non-symmetric Optical Surface Design and Analysis," Optics Express 16 (3) (2008): 1583–89.
5. K. P. Thompson, "Description of the Third-Order Optical Aberrations of Near-Circular Pupil Optical Systems without Symmetry," Journal of the Optical Socieity of America A 22 (2005): 1389–1401; K. P. Thompson, "The Multi-nodal 5th Order Optical Aberrations of Optical Systems without Rotational Symmetry (Part 3): The Astigmatic Aberrations," Journal of the Optical Society of America A 28 (2011): 821–36.

Figure 16.6. Professor James R. Fienup drives phase retrieval in more ways than one.

6. K. Fuerschbach, J. P. Rolland, and K. P. Thompson, "A New Family of Optical Systems Employing φ-Polynomial Surfaces," Optics Express 19 (22) (2011): 21919–28; K. Fuerschbach, J. P. Rolland, and K. P. Thompson, "Extending Nodal Aberration Theory to Include Mount-Induced Aberrations with Application to Freeform Surfaces," Optics Express 20 (18) (2012): 20139–55.
7. K. P. Thompson, P. Benitez, and J. P. Rolland, "Freeform Optical Surfaces: Report from OSA's First Incubator Meeting," Optics and Photonics News 23 (9) (September 2012): 33–37.
8. K. P. Thompson and J. P. Rolland, "Freeform Optical Surfaces: A Revolution in Imaging Optical Design," Optics and Photonics News 23 (6) (June 2012): 30–37.
9. Cakmakci, et al., "Optical Local Shape Description"; I. Kaya, K. P. Thompson, and J. P. Rolland, "Edge Clustered Fitting Grids for ϕ-Polynomial Characterization of Freeform Optical Surfaces," Optics Express 19 (27) (2011): 26962–74; G. W. Forbes, "Characterizing the Shape of Freeform Optics," Optics Express 3 (3) (2012): 2483–99.
10. K. Fuerschbach, K. P. Thompson, G. E. Davis, and J. P. Rolland, "Assembly of a Freeform Off-Axis Optical System Employing Three φ-Polynomial, Zernike Mirrors," Optics Letters 39 (10) (2014): 2896–99.
11. Fuerschbach, Rolland, and Thompson, "Extending Nodal Aberration Theory"; K. Fuerschbach, J. P. Rolland, and K. P. Thompson, "Theory of Aberration Fields for General Optical Systems with Freeform Surfaces," Optics Express 22 (22) (2014): 26585–606; A. Bauer, J. P. Rolland, and K. P. Thompson, "Ray-Based Optical Design Tool for Freeform Optics: Coma Full-Field Display," Optics Express 24 (1) (2016): 459–72; A. Bauer, E. M. Schiesser, and J. P. Rolland, "Starting Geometry Creation and Design Method for Freeform Optics," Nature Communications 9 (2018): 1756; J. C. Papa, J. M. Howard, and J. P. Rolland, "Starting Point Designs for Freeform Four-Mirror Systems," Optical Engineering Special Issue on Advanced Design Methods 57 (10) (2018): 1705; N. Takaki, A. Bauer, and J. P. Rolland, "On-the-Fly Surface Manufacturability Constraints for Freeform Optical Design Enabled by Orthogonal Polynomials," Optics Express 27 (5) (2019): 6129–46.
12. J. Yao, A. Anderson, and J. P. Rolland, "Point-Cloud Noncontact Metrology of Freeform Optical Surfaces," Optics Express 26 (8) (2018): 10242–65; D. Xu, J. D. Owen, J. C. Papa, J. Reimers, T. J. Suleski, J. R. Troutman, M. A. Davies, K. P. Thompson, and J. P. Rolland, "Design, Fabrication, and Testing of Convex Reflective Diffraction Gratings," Optics Express 25 (13) (2017): 15252–67; R. Chaudhuri, J. C. Papa, and J. P. Rolland, "System Design of a Reconfigurable Null Test Using a Spatial Light Modulator for Freeform Metrology," Optics Letters 44 (8) (2019): 2000–2003.
13. M. A. Alonso and G. W. Forbes, "Strehl Ratio as the Fourier Transform of a Probability Density of Error Differences," Optics Letters 41 (2016): 3735–38; K. Liang and M. A. Alonso, "Understanding the Effects of Groove Structures on the MTF," Optics Express 25 (2017): 18827–41; K. Liang and M. A. Alonso, "Effects of Defocus and Other Quadratic Errors on OTF," Optics Letters 42 (2017): 5254–57.
14. Liang and Alonso, "Understanding the Effects of Groove Structures"; Liang and Alonso, "Effects of Defocus."

15. H. Aryan, K. Liang, M. A. Alonso, and T. J. Suleski, "Predictive Models for the Strehl Ratio of Diamond-Machined Optics," Applied Optics 58 (2019): 3272–76.
16. K. Liang, G. W. Forbes, and M. A. Alonso, "Validity of the Perturbation Model for the Propagation of MSF Structure in 2D," Optics Express 27 (2019): 3390–3408.
17. G. R. Brady, M. Guizar-Sicairos, and J. R. Fienup, "Optical Wavefront Measurement Using Phase Retrieval with Transverse Translation Diversity," Optics Express 17 (2009): 624–39.
18. A. M. Michalko and J. R. Fienup, "Transverse Translation Diverse Phase Retrieval Using Soft-Edged Illumination," Optics Letters 43 (2018): 1331–34; A. M. Michalko and J. R. Fienup, "Verification of Transverse Translation Diverse Phase Retrieval for Concave Optical Metrology," *Optics Letters* 19 (2018): 4827–30.

17. Rescuing the Daguerreotype

Brian L. McIntyre and A. Nickolas Vamivakas

The University of Rochester received an NSF grant in 2010 to research the science and conservation of the daguerreotype, in collaboration with the George Eastman Museum. The extensive study collections of the museum provided source materials for research, and the University of Rochester Integrated Nanosystems Center (URnano) carried out the research, primarily relying on its state-of-the-art SEM and TEM instruments. Detailed analysis of more than fifty daguerreotypes by SEM and TEM has provided an unparalleled resource of the nanostructure of the daguerreotype and documentation of its deterioration pathways.

This research revealed for the first time the complex nano-scale physicochemical phenomena of the first medium of photography. Extensive use of URnano's focus ion beam (FIB) cross section setup for thin-section preparation and lift-out for TEM analysis has provided the basis to explain both the process and its deterioration.

The daguerreotype was introduced by Louis-Jacques-Mandé Daguerre in 1839. The process entails a highly polished silver plate (silver clad copper), photo-sensitization by iodine vapors, exposure in camera to effect the silver-halide photoreduction reaction, which forms a latent image, and then development of the nanometer grains of silver into light scattering particles on the order of 1–10 microns by a mercury vapor atmosphere. The diffuse scattering of the particles contrasts with the specular reflection of the polished silver, producing a high-resolution, high-dynamic range black-and-white direct positive image. The daguerreotype was the first photographic image process and a world-changing technology, both culturally and scientifically. It was superseded by far more efficient and replicable processes using negatives and paper prints by 1860. The native resolution of the direct positive mercury developed silver particle image has never been improved upon. A well-made daguerreotype from 1850 has an approximate resolution equivalent to 25 MP.

URnano's use of the FIB and nanoprobe has allowed detailed characterization of the image formation, comparative analysis of different daguerreotype makers'

Figure 17.1. Unidentified man. George Eastman Museum Study collection; 6th plate [2.75” x 3.25”], ca. 1850.

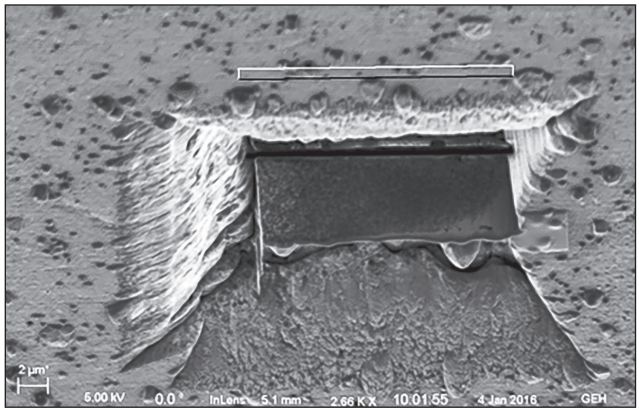


Figure 17.2. Preparation of a thin section in daguerreotype surface; 15 µm x 5 µm.

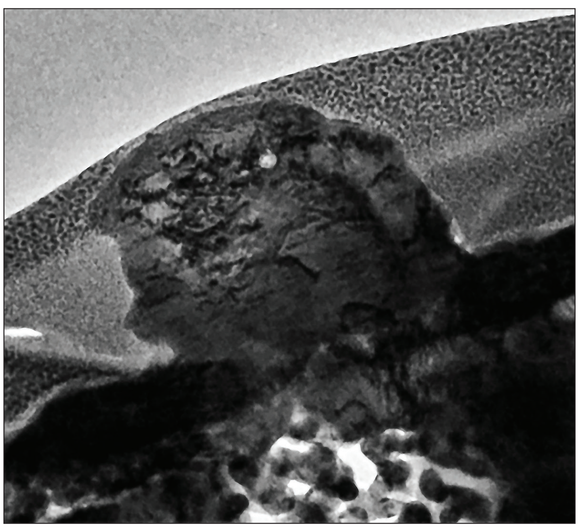


Figure 17.3. HR TEM image of an image particle at 50,000 x magnification. The full structure of the image surface is revealed. The surrounding matrix is platinum to protect the surface from ion beam damage, and the encompassed particle shows density differences of the silver-mercury-gold complexes that are formed in this iteration of the daguerreotype process. It also reveals the dynamics of mass transfer and formation of Kirkendall voids that research has documented in the image formation.

Figure 17.4. Daguerreotype from 1850; red circle shows area analyzed.

methods, and most importantly, better understanding of the deterioration mechanisms of the highly reactive metals at the nanoscale.

Thin-section preparations in the SEM chamber by FIB and nanoprobe lift-out for TEM analysis by imaging and energy dispersive X-ray analysis (EDS) has revealed many details of the daguerreotype process at the nanoscale.

A profoundly significant component of the research done at URnano with daguerreotypes has entailed the documentation and description of a susceptibility of the silver-gold-mercury nanostructure to engage with bio-organisms that contact the surface. In the presence of atmospheric moisture, the conditions are ideal for a nano-scale bio-metallic propagation, which has yet to be fully described. In this research, nearly all daguerreotypes researched manifested this phenomenon. This has grave implications for daguerreotype collections around the world, and as a result, a derivative of this research has led to the development of microclimate enclosures and storage systems that can maintain low humidity, or ideally sustain an oxygen-free argon atmosphere.

Figure 17.5 shows the biologically driven growth that reduces the nanometallic metal surface complexes and incorporates them at the molecular level into a dynamic growth pattern. The nanoparticles are being ingested. Numerous FIB analyses show that this mechanism engages metals from the subsurface and

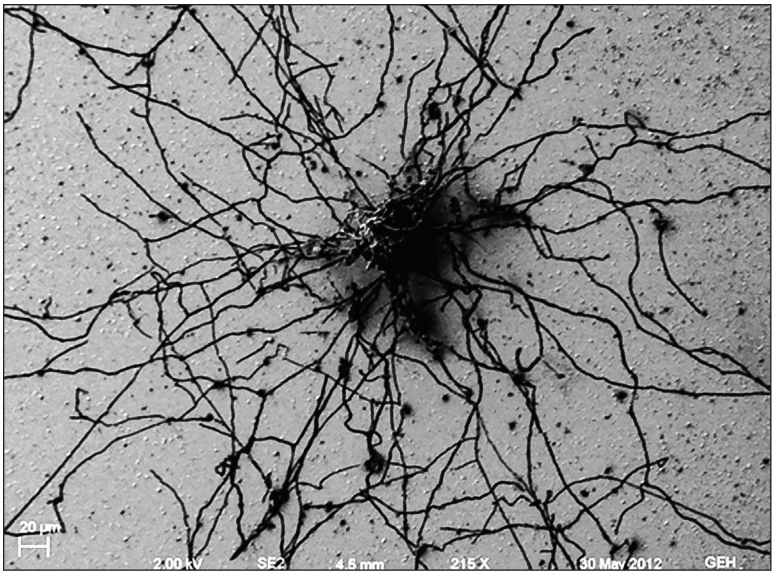
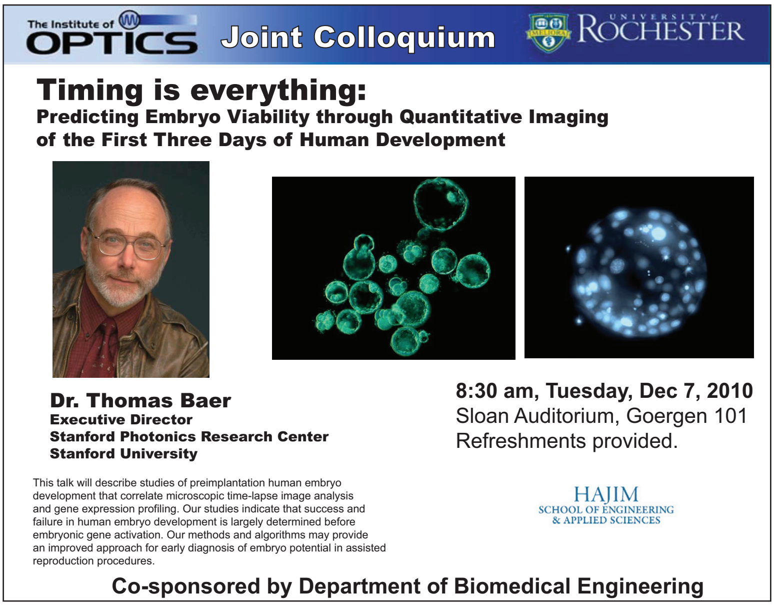


Figure 17.5. Electromicrographs of the biological infestation.

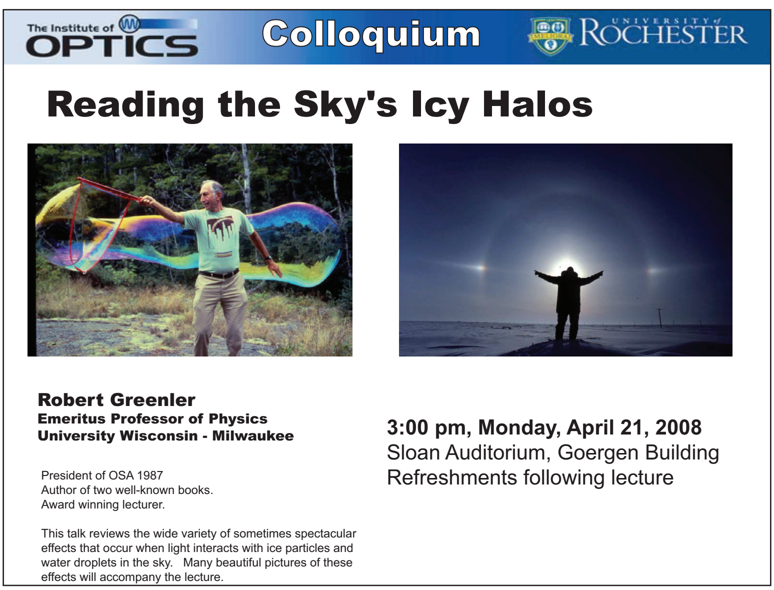
disrupts the surface structure. The original biological form becomes increasingly a metallic pseudomorph over time.

This extensive work at URnano has benefited the daguerreotype and its conservation, as well as increasing the capacity of the center through skill development, engagement of students in the NSF Research Experiences for Undergraduates (REU) program in summer internships, and full exploitation of UR's powerful electron microscopy suite. More of this research is available at http://rochester.edu/college/nod/, and additional material will be added in the near future.

Highlight IV: Colloquia Posters

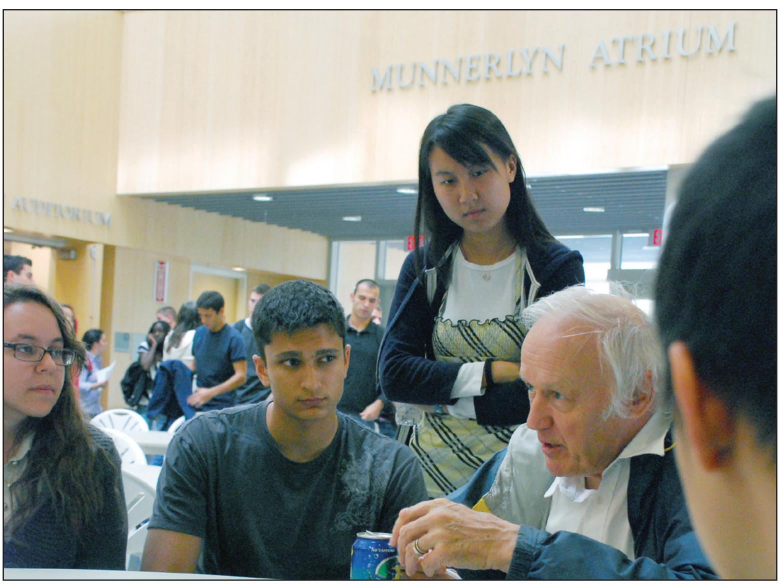


1. Thomas Baer.

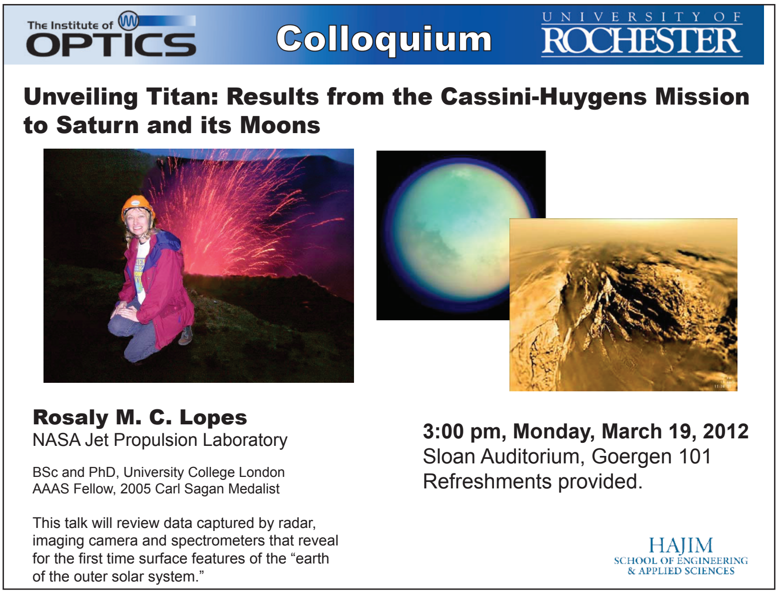


2. Robert Greenler.

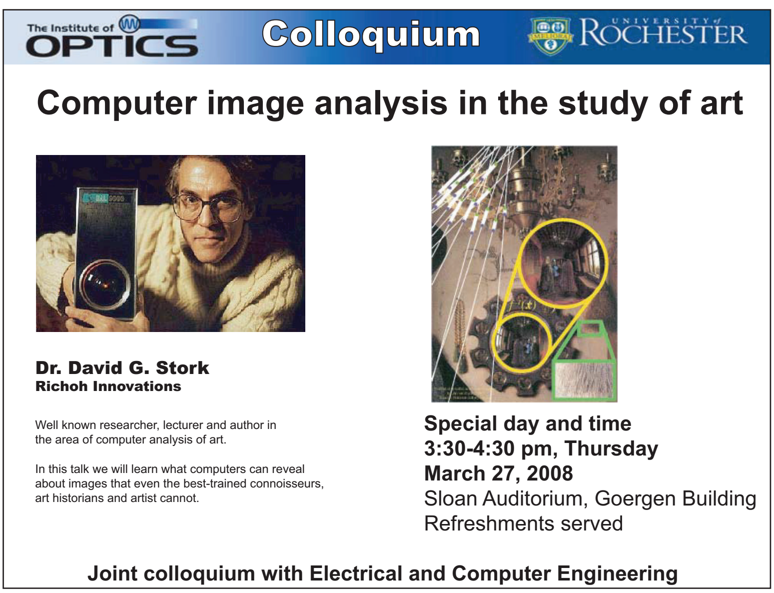
3. Susan Houde-Walter.



4. Anthony J. Leggett with students.



5. Rosaly Lopes.



6. David Stork.

PART V

Outreach

Part V. Outreach

As we have described from the beginning, The Institute feels an obligation to serve the optics community on campus, in the Rochester area, nationally, and indeed worldwide. This outreach is described here in a series of essays showing the remarkable extent of these outreach activities. Duncan Moore begins by describing the entrepreneurial activities of the students, faculty, and alumni in starting more than two hundred companies and the way that this is enhanced by the TEAM program. Tanya Kosc, alumna and scientist in the Laboratory of Laser Energetics, describes the wonderful Optics Suitcase program started by Steve Jacobs, which has delivered basic optics experiment kits to schoolchildren all over the world. Another alumnus, David Aronstein, reviews the numerous contributions made by the faculty, students, and alumni to the design and construction of the James Webb Space Telescope, which is scheduled for launch next year. Tom Brown contributes an essay describing the founding of a huge new national photonics center in Rochester, the American Institute for Manufacturing Photonics, or *AIM Photonics*. Mike Campbell, the director of the Laboratory for Laser Energetics, describes the important synergistic relation between LLE and The Institute. Finally, we have another Outreach photographic essay showing that life at The Institute is not all homework and long hours in the lab and classroom.

18. Optics and Entrepreneurship

Duncan T. Moore

With contributions from Mrs. Leslie Jacobs, Dr. Jessica DeGroote Nelson, Mr. Ken Marshall, Dr. Jack Kelly, Dr. John Soures, Ms. Leslie Gregg, and Dr. Eileen Korenic. Entrepreneurship is in the culture at The Institute of Optics. Since 1946, over 140 graduates, faculty, and staff have started at least 236 companies. Nearly fifty graduates have started more than one company, with one launching a total of eight.

From classes and lab work to built-in mentors and exposure to industry professionals, an education here equips future business owners to make their mark in a highly competitive environment after graduation. In fact, while the Kauffman Foundation reports that the average age of entrepreneurs at the time they founded their companies is thirty-nine, and MIT puts that age at forty-two for successful entrepreneurs, the average age for Institute of Optics students is thirty-four for BS graduates and thirty-nine for MS and PhD graduates.

They have a strategic advantage. To start with, they come from a rigorous program with a rich history that includes former director Robert E. Hopkins's world-renowned reputation as an innovator in the field of lens and optical system design. They are taught by leading experts in the field. And they come to understand that what you know and what you don't know are equally important guideposts when searching for a solution using continuously changing technology.

In the 1980s, The Institute of Optics recognized its need for a stronger role in economic development once it was clear Eastman Kodak Company's troubles were not temporary; therefore, it charted an equally challenging yet more interdisciplinary course for students. That evolution laid the foundation for what The Institute continues to offer students today—requisite experience in the field, a pragmatic understanding of how to meet market needs with new technology at an affordable price, opportunities to define their career long before graduation, and the knowledge of how to start a business that has real leverage.

Becoming an entrepreneur before graduation has never been an anomaly.

When I came to The Institute of Optics as a PhD student, I wanted to be a professor or director of research. After listening to others talk about starting companies,

Figure 18.1. Duncan T. Moore, vice provost for entrepreneurship, Rudolf and Hilda Kingslake Professor of Optical Engineering, and director of the Institute of Optics, 1987–94.

and with the encouragement of a research colleague, I decided to start a business using technology I had developed in my research lab. Gradient Lens Corporation became the manufacturer of the Hawkeye boroscope.

Several companies have been started by students in the Senior Design course alone. The course pairs students with customers from multiple backgrounds including start-up companies, large corporations, and individuals who need solutions to difficult problems. In some cases, the customers actually believe a solution is impossible. Potential solutions arise through teamwork and a curriculum that covers professional ethics, report writing, customer meetings, design reviews, risk assessments, presentations, and more. The course also includes information about intellectual property rights, underscoring that students are given what they need to know before they walk out the door. That was a benefit to three students who submitted a preliminary design study for a San Francisco–based start-up two years ago. The start-up was developing an instrument to quickly diagnose traumatic brain injury, to be used in real time on a football field, for example. Weeks later the students were on a plane to California to meet with venture capitalists. The start-up wound up filing a patent and naming the students as coinventors.

The Institute prepares students by example as much as through study. Faculty routinely serve as consultants and commercialize their work. According to the most recent statistics available, digital records show a total of 175 patents have been issued to Institute faculty members, with coinventors, since 1987.

Hands-on opportunities for experience abound in faculty-led research laboratories, as well as in the connections and collaborations fostered between students, alumni, and people from industry. Research contracts, many of which come through alumni, are a mutually beneficial enterprise. Start-ups with limited resources sponsor projects to gain access to university resources they wouldn't be able to afford otherwise, while students become heavily involved with state-of-the-art research and frequently land jobs with the start-ups as a result. Grants funded through the Center for Emerging & Innovative Sciences match scientists and faculty, and by extension students, with companies with similar research interests.

Students have access to valuable resources such as the Simon Business School, and to the off-campus UR Student Incubator at NextCorps. As the region's only state- and federally designated business incubator, it has housed three optics start-ups. Entrepreneurs there interact with mentors and other local entrepreneurs, and are able to use the First Prototype Lab with 3D printers and other tools without

Figure 18.2. OVITZ Company. From left; Pedro Vallejo-Ramirez ('16), Joung Yoon (Felix) Kim ('14), Samuel Steven ('13), graduate student Aizhong Zhang, Len Zheleznyak ('05, MS '06), and Nicolas Brown ('16). (Photo by J. Adam Fenster/ University of Rochester).

paying any fees or giving up any equity. Even after earning their degree, graduates can pay $100 a month, up to one year, to continue having the same benefits. A cofounder of one optics start-up credits technical preparation at The Institute for the successful submission of research proposals, which have garnered more than $1.5 million in federal funding within the company's first five years of operation.

Networking starts early and is at the core of much of what we do. Aside from organizing social events at Photonics West and other major conferences, The Institute hosts student chapters of OSA and SPIE, both of which help students stay relevant with industry news and connected with successful entrepreneurs. A weekly Colloquium Series brings in speakers from companies and universities (about one-third of them alumni) to meet with students and faculty and talk about topics ranging from recent professional achievements to current challenges in the field.

The Industrial Associates (IA) program, a semiannual four-day event to increase student and faculty engagement with industry, featuring student lectures. In the Master's Students Showcase, MS students present their educational background, work experience, and career goals, and PhD graduate students give research talks. It's a time when companies can get a head start on recruitment, with three hours on the second day devoted to a company connection showcase, which provides a job fair opportunity. The final two days are composed of employment interviews. Many of the member companies were either started by alumni or encouraged by employees who are alumni to join IA. The first day of IA includes a Director's Advisory Council meeting of strategic members and faculty who gather to answer such questions as: What are the new hot topic areas we should be concerned about? How prepared are our students? Where can we improve? As of 2018, forty-five companies are members of the program, including Apple, Microsoft, and Oculus.

Almost no one receives an undergraduate diploma without a job already lined up, and internships seed future entrepreneurs as early as the summer between freshman and sophomore year. In addition to exposure to real-world employment situations (experience critically important for future job interviews), students learn about how jobs get quoted, how risk is managed, and the importance of maintaining and cultivating relationships with customers. In the last three years, the Gwen M. Greene Career and Internship Center has doubled the size of its staff, allowing a more precise focus on finding the right placements—whether for an internship or for that first key job at the boost phase of a student's career.

Another source of assistance comes from the Paul F. Forman Engineering Excellence Award, a $1 million endowment that supports two students at the master's level who have a passionate interest in optics and entrepreneurship.

With The Institute's influence and advocacy, students are easily inspired to make an impact in an industry with incredibly diverse, nearly limitless application areas.

The term "serial entrepreneur" does not resonate with one graduate, however, who is on his fourth start-up and has forty-six US patents and more pending. Instead, he thrives on new challenges every day, a drive that he says stems from a culture at The Institute that motivates in countless subtle ways.

To that end, being a successful entrepreneur isn't only about making money; it's also about the excitement that comes when someone is willing to pay for something you've invented. It's also about remembering where you came from. It's nice when successful entrepreneurs give back to the institution that helped make them successful. Indeed, the building of the Robert B. Goergen Hall for Biomedical Engineering and Optics received significant funding from such alumni. Additionally, many students benefit from fellowships underwritten by alumni who want to contribute to the success of future generations of optics leaders.

The Technical Entrepreneurship and Management (TEAM) MS Degree

The history of the master of science in technical entrepreneurship and management program dates back to my early coursework offered in the 1980s. In 1988, I began teaching a graduate course about technical entrepreneurship in which both Simon Business School and Hajim School of Engineering and Applied Sciences students were permitted to register for the same class. This was a very unique concept and course at the time, and most faculty of the two schools were not accepting of the course and its academic merits. The course was offered again the following year and was taught by Jay Eastman and then was not offered again for more than a decade.

In 2001, when I returned from my work in Washington, DC, I proposed the technical entrepreneurship course once again to the deans of the Simon and Hajim Schools. By this time, both deans were very enthusiastic and supportive regarding the course. The course was offered again in 2002 and enrolled students not only from the Optics Department, but also from various engineering departments and School of Medicine and Dentistry students.

The history of alumni from the graduate technical entrepreneurship course was undertaken in 2013. The research found that twenty-five alumni who had taken the course in 1988 and 1989 had gone on to start seventeen unique companies. Only one of the seventeen was based on the plan written in the class. This is to be expected as we teach the principles of entrepreneurship.

In 2005, the University of Rochester was one of the partners of the Workforce Innovation in Regional Economic Development (WIRED) grants. Utilizing this grant we proposed offering a master's program about technology commercialization. Using the curriculum and faculty already in place at the University of Texas, Austin, an executive program was launched. It was taught on alternating Fridays and Saturdays via synchronous telecommunications. Only three students enrolled the first year of the program. For the second year, a great deal of investment and effort was made to increase enrollment. However, at the start of the second year, only two students had enrolled. After the second class graduated, the agreement with UT and WIRED was abandoned.

Provost Rob Clark was installed as dean of the Hajim School of Engineering in 2008. Shortly after his arrival, he proposed launching a degree program similar to one at Duke University called the Master of Engineering Management (MEM) program. But instead of housing the program in the school of engineering as it was at Duke, he suggested the program be administered by the Center for Entrepreneurship. As vice provost for entrepreneurship, I worked with both the Simon Business School dean at that time (Mark Zupan) and Dean Clark to come to an agreement that the new degree program be jointly conferred by both schools and that half of the curriculum would be taught by Simon faculty and half by Hajim faculty.

Once this agreement was reached, a working committee was formed to begin the process of mapping the program curriculum and drafting the New York State Department of Education proposal. The proposal was completed and submitted June 4, 2009, and in record-breaking time received approval June 10, 2009. The first class of only four students was enrolled in Fall 2009. The TEAM program today has close to fifty students registered.

The most recent development for the TEAM program was the stewardship of the Paul F. Forman Graduate Fellowship Endowment Fund. Paul was a 1956 alum of The Institute of Optics and was one of the three founders of the Zygo Corporation. In 2016, Barbara Marks, Paul's widow, established the fund in his honor to help support graduate students interested in studying optics and entrepreneurship. The first Forman Fellowship was awarded in 2017, and there were two recipients for the 2018–19 academic year.

The TEAM program at the University of Rochester offers students the opportunity to immerse themselves in a technical concentration of their choice while receiving a strong foundation in entrepreneurial management. TEAM was designed for students with an undergraduate degree in engineering, science, or mathematics who wish to pursue a master's-level technical education in combination with business, entrepreneurial management, and leadership courses. Students accepted into the TEAM program may choose any technical concentration, such as optics, energy and the environment, computer science, data science, biomedical engineering, chemical engineering, electrical and computer engineering, materials sciences, or mechanical engineering. We have also partnered with the School of Medicine and Dentistry to offer a TEAM program in which students there take technical classes in the field of biomanufacturing and therapeutic development.

Students simultaneously take courses at the Simon Business School and the Hajim School of Engineering. Students can complete the TEAM program in as little as two academic semesters. A part-time schedule and three-semester track are available for students working full-time or interested in extending their time to degree to include research and/or internship experience.

The specially designed core curriculum of the TEAM program consists of five entrepreneurially focused business courses developed and offered by the Simon Business School, three graduate-level engineering courses offered by the Hajim School of Engineering, and either an additional technical or entrepreneurship elective. A required practicum accompanied by a written business plan and oral presentation ensures students have practical experience, while graduate-level technical courses of the student's choosing serve to extend the student's science and engineering background.

The TEAM curriculum strives to create well-rounded, business-savvy engineers and scientists who are prepared to be entrepreneurs who can take on both the technical and business challenges of any industry in a global economy. We often use the equation: innovation = invention × marketing opportunity. We want students to be able to understand that if either invention or market opportunity equal zero, there can be no innovation.

The core TEAM courses were designed to provide students with the knowledge required to effectively innovate, lead, and strategically manage in industry and potentially launch their own venture. The five courses include Economics, Marketing and Strategy Primer for Entrepreneurs (TEM 401), Accounting and Finance Primer for Entrepreneurs (TEM 402), Screening Technical Opportunities (TEM 440), General Management of New Ventures (TEM 411), and Product Development and Technical Management (TEM 441).

With over 180 alumni, the program has had impressive program diversity and student-placement success. Over the past ten years, we have had representation from thirty-five different countries, including Sudan, Nepal, Bahrain, Egypt, and Italy. Additionally, the male-to-female ratio year over year has hovered around 60:40, which is uncharacteristically high when compared to other engineering fields. Our graduates have found success professionally postgraduation. We have maintained a consistent 90 percent placement rate among students within six months of graduation. This percentage increases to 95 percent when accounting for US alumni only.

I hope the program will continue to grow in size and diversity. The program is also seeking other academic units that are interested in creating similar programs, such as the Eastman Dental School or other School of Medicine and Dentistry departments, much like the TEAM Biomanufacturing and Therapeutic Development version.

19. Stephen Jacobs and the Optics Suitcase

Tonya Z. Kosc

The Optics Outreach Innovator

Occasionally children encounter a science fair project that projects vibrant streaks of light that grab their attention and point toward an exciting lifelong path of learning and discovery. Such were the captivating colors in Steve Jacobs's middle-school spectroscopy project that set him on his path to a remarkable career in optics. The brilliant colors, in orderly array, probably appealed to Steve's innate desire for clarity, focus, and organization. Optics represented a "clean" science, as opposed to the "dirty" sciences like chemistry and biology, and immediately captured his interest. This initial fascination with color led to a lifelong course of research into laser glass, frequency conversion crystals, liquid crystals, polymer cholesteric liquid crystal flakes, near-surface interactions in grinding and polishing, and magneto-rheological finishing. Finally coming back full circle, Steve developed the Optics Suitcase in his endeavor to inspire young scientific minds with the colors of optics that had started it all for him.

Steve loved to share science, and educational outreach was one of his greatest passions. He was a rare scientist who not only realized that the general public, and youth in particular, must be engaged in science, but took action to address this need. Perhaps it was a latent memory of his science fair project that led to the development of the Optics Suitcase, a middle-school outreach program designed to answer the question "Where does color come from?" This new tool for science outreach was developed in 1999, in conjunction with the Rochester Section of the Optical Society of America. It provides a visual and tangible science experience for youth and exposure to possible careers in STEM. The outreach program is based on demonstrations and a forty-five-minute, in-class presentation designed for children ages nine to thirteen.

Science is supposed to be fun, and the keys to achieving this are interesting demonstrations, interactive participation, and take-home packets. Steve paid attention to every aspect of the presentation and included a detailed instruction guide so that any teacher or parent without a science background could still use an Optics Suitcase. The event starts with icebreakers, and the first one explores the science of chemical heating pads. The second icebreaker, with the silly name of "Happy and Sad Balls," investigates properties of vulcanized rubber. Note that these demonstrations are not optics based, because the case is being made for *science*, not just optics. Optics is finally introduced with the comparison of a silicon wafer and a silica lens. While individuals get to participate in the icebreakers, an entire group is brought in on the action with the Theme Packets. Each child receives three little baggies with materials to actively explore the concepts of diffraction, polarization, and selective reflection as the presenter explains them. Steve knew that excitement would wane after the Optics Suitcase is packed up. He figured that even if the children forget the science, they can take the Theme Packets home to share with parents, siblings, and friends. While the Optics Suitcase is meant to be reusable, the Theme Packets are specifically designed to be handed out.

Steve used a combination of friends, colleagues, industry contacts, and various organizations to support the program, and he solicited donations to ensure that the suitcase could be distributed free of cost. One only needed to write a letter requesting the suitcase and commit to providing a report once the first demonstration was completed. Demand quickly outpaced supply for the Optics Suitcase, which was being assembled by an army of students and dedicated employees. Steve carefully considered geography when deciding whose request could be granted. He focused on extending the reach of the Optics Suitcase, and he declined requests if another suitcase could be found in the same town or region.

A Memorandum of Understanding was signed with the Optical Society of America in approximately 2013, whereby OSA agreed to purchase a specific number of suitcases and distribute them to student chapters. The increased volume required additional resources. Since 2016, the Rochester company Masline Electronics has been producing and shipping the Optics Suitcase at cost. Given Steve's meticulous records, we know that the first Optics Suitcase was sent to Bob Basor at Coherent, Inc. (Auburn, CA), and the first suitcase to be shipped internationally (#9 overall) went to Nobel laureate Dr. Donna Strickland, Steve's former LLE colleague at the University of Waterloo (Canada)! The first suitcase to leave the continent (#29) was sent to Karen Emanuel at the Photonics Institute in Eveleigh, Australia. As of 2018, over 1,000 Optics Suitcase*s* have been shipped. They are found in forty-one states, in sixty-six countries and on six continents.

Two years after I gave a historical overview of the Optics Suitcase at a symposium honoring Steve's life and work during the OSA Frontiers in Optics 2016 conference, I was taken aback by an unexpected conversation at the 2018 SPIE Laser Damage conference. In the course of describing Steve's role in liquid crystal optics development, I was stopped midsentence by a professor and entrepreneur from Vilnius, Lithuania, who immediately recognized Steve's name. He had attended that OSA symposium two years earlier and had been very moved by Steve's educational outreach. Not realizing I had given that particular talk, he excitedly described his intention to order one of those suitcases to outfit the outreach "bus" that he dreams will one day visit schools across his country. The Optics Suitcase has become a fitting legacy for someone who was so completely devoted to sharing his love of optics with all ages and all geographies.

The Optical Materials Guru

Throughout his career, Steve demonstrated the rare ability to recognize key optics and photonics technologies with the potential to solve practical problems, target these areas for research, and transfer the knowledge and experience obtained beyond the walls of the research laboratory. His research was all conducted at the Laboratory for Laser Energetics, where Steve's work spanned four decades. While Steve achieved expertise and renown in many and varied fields of optical science, he also became a beloved mentor, adviser, and friend to countless students and colleagues, ensuring that his work would be carried on and disseminated.

Steve's first significant career accomplishment came with the development of the athermal phosphate laser glass, LHG8, installed on Omega. The standard silicate laser glasses available at that time (1974) could not withstand the intensity of the 100 ps pulses required for exploding pusher targets on Omega. Steve's charter was to develop a new glass with high gain, low nonlinear index of refraction and low thermal index. Dr. John Soures recalled that Steve began talking with glass scientists at Hoya and gained their trust, becoming perhaps the only person in whom the Japanese scientists confided. He cultivated a working relationship with Dr. Tetsuro Itsumitani and developed a lifelong friendship. Together, they developed a phosphate laser glass that, upon irradiation with intense xenon flashlamps, underwent a change in index of refraction whose effect was canceled by the thermal expansion of the glass. This property allows the Omega laser to be continuously aligned, an important attribute that allows for the relatively short shot cycle of forty-five minutes. (For reference, the laser at the National Ignition Facility (NIF) laser can be fired a maximum of twice per day.) Some members of the fusion laser community feel that this was Steve's crowning achievement—accomplished in his thirties and on his first big project out of graduate school. Without Steve, there very well might not be phosphate laser glass.

Steve was tasked with a second critical project during the building of the Omega laser—the procurement of large-aperture (≥ 100 mm) birefringent optics for the Omega system. Because it was not physically or financially feasible to obtain the hundreds of optical-quality 100 mm calcite optics for the waveplates and polarizers required, he turned to liquid crystals (LCs), a novel birefringent technology employed in information displays. Having read a paper in *Scientific American* written by James L. Fergason, the inventor of the twisted nematic liquid crystal display device, about these strange birefringent LCs, Steve boldly set out to build LC polarizers and hired chemist Ken Marshall, a former colleague of Jim Fergason, to bring the technology to LLE. They built and installed the first set of LC optics in Omega, and immediately, they were confronted with disaster. Over 60 percent of the LC optics was damaged after the first laser shot, and Steve, who received the news over the phone while away at a conference, thought his career was over. Uncowed by this setback and given an opportunity to rectify the problem, Steve traced the induced laser damage back to extrinsic particulate contamination introduced during manufacturing. After three years of research in LC materials selection and manufacturing process refinement, LC optics were produced that met all performance benchmarks, including laser damage resistance. These LC devices have been in continuous operation in Omega for over two decades; many of the original devices remain in operation today. Steve's leadership and determination resulted in *Research and Development Magazine* awarding the LLE its first R&D 100 Award in 1989 for developing a liquid crystal circular polarizer/isolator device.

Not content with this success, Steve wanted to improve the technology further and turned to polymer LCs, liquid crystalline materials that are solid at room temperature. He sought to develop a solid film with the same unique optical properties of the fluid LCs. If successful, the amount of glass used in the LC devices could be reduced by at least 50 percent, and LC optics could potentially be made vacuum compatible. This concept led in another research direction based on polymer cholesteric LC flakes, with ultimate application in particle displays (think E-Ink in the Kindle). Research slowed after the dot-com bubble burst and funding dried up, but to this day the LLE is working to develop polymer or glassy LCs for applications on Omega and the NIF at the Lawrence Livermore National Laboratory.

Steve Jacobs was a visionary and a risk taker, despite what his calm, organized demeanor might have suggested. He had the vision to spot the potential of magnetorheological finishing (MRF), an unusual technology seemingly straight out of a science fiction novel, that had been developed in a distant country struggling to emerge from the ashes of the Soviet Union. Steve not only recognized MRF's potential but, together with investor Lowell Mintz, took an enormous risk to bring both the technology and its inventor, William Kordonsky, from Belarus to the LLE. This risk paid off handsomely; it revolutionized optical finishing and spawned QED Technologies in 1996 (see Essay 60 by Don Golini). MRF enabled deterministic subaperture polishing in manufacturing of high-precision aspheric optical surfaces and is now a key enabler for exciting new technologies such as freeform optics. In 2001, Steve and his team received a second R&D 100 Award, naming the Q22-Y MRF system as one of the top 100 technical research development products nationwide for that year.

The Treasured Mentor and Friend

Steve Jacobs was a highly respected scientist, but to many he was a boss, a mentor, and most of all, a friend. His work was his hobby, which meant that even while on

Figure 19.1. The Optics Suitcase.

Figure 19.2. Prof. Stephen Jacobs explaining the difference between silicon and fused silica, the difference oxygen makes, and how optical properties change.

Figure 19.3. Sharing the Optics Suitcase with a young class of students.

vacation, he would inevitably be working. Steve and his wife, Leslie, would go on vacation, and Leslie did not want Steve to think about the lab during these times—but he couldn't help it. Leslie Gregg, his technician, once got a phone call from him with the opening words, "Leslie [his wife] is in a shop, so I don't have much time. How is everything going in the Lab?" Though Steve was always in the lab working on something, if anyone—student, staff, fellow researcher—had a question or needed help, he immediately gave that person his undivided attention until the matter was resolved.

Steve's character is captured in an email exchange described by one of his graduate students, Dr. Eileen Korenic: "After I had graduated from The Institute of Optics and was working as an optical physicist in industry, after less than a year, I realized I really missed the academic world and wanted to get back to teaching. I wanted some advice about making a switch after the short time and emailed Steve after not having contacted him in a while. My subject heading was "Question out of the blue." Steve responded right away with great advice about personal and

Figure 19.4. Sharing the Optics Suitcase with students in Haiti.

Figure 19.5. Prof. Stephen Jacobs with his OPT 443 class: 1 Ed Fess, 2 Professor Jacobs, 3 Hillary Maben, 4 James Feeks, 5 Hannah Miller, 6 Teddy Lambropoulos, 7 Kramer Harrison, 8 Dan Brennan, 9 Jacob Reimers, 10 Joseph Lomando, 11 Hae Won Jung, 12 Yang Zhao, 13 Kaitlin Wozniak, 14 Anthony Yee, 15 Allison Browar, 16 Eric Schiessen, 17 Amanda Pendleton, 18 Alex Maltsev, 19 Mike Kaplun.

professional choices, but I noticed he changed the subject of the email to "Question out of the red, green and blue"—a lovely reference to the liquid crystal color display work we had done, but also a fitting metaphor to the thoroughness of his advice covering more areas than I had at first considered."

Eileen is but one example; Steve was a bright guiding light for many. He was the kind of mentor and friend that most people could only wish for: patient, caring, honest, generous, nurturing, innovative, and extremely smart and hardworking. As a colleague, he valued work and science, but as a friend, he knew they could always be put on hold for family and personal issues. He was approachable not only personally, but intellectually—he strived to present problems and topics in a way that everyone could grasp. If he didn't know an answer, he would find someone who did know or could help you find out. Perhaps that is why we take comfort in the many ways he is still with us. A tour of the Omega laser at the Laboratory for Laser Energetics, a walk past a QED Inc. MRF machine, the excited faces of ten-year-olds exploring color—all underscore the effectiveness and endurance of Steve's vision and career. The legacy of Stephen D. Jacobs will continue to touch science, industry, and education for years to come.

20. Contributions by The Institute of Optics to NASA's James Webb Space Telescope

David L. Aronstein

The James Webb Space Telescope (JWST) will be the successor to the Hubble Space Telescope and the premier astronomical observatory of the 2020s. It is an infrared telescope with a 6.5 m–diameter primary mirror. It is scheduled to be launched into space on an Ariane 5 rocket from French Guiana in 2021, and it will orbit the second Lagrange point ("L2") formed from the gravitational fields of the Sun and Earth.

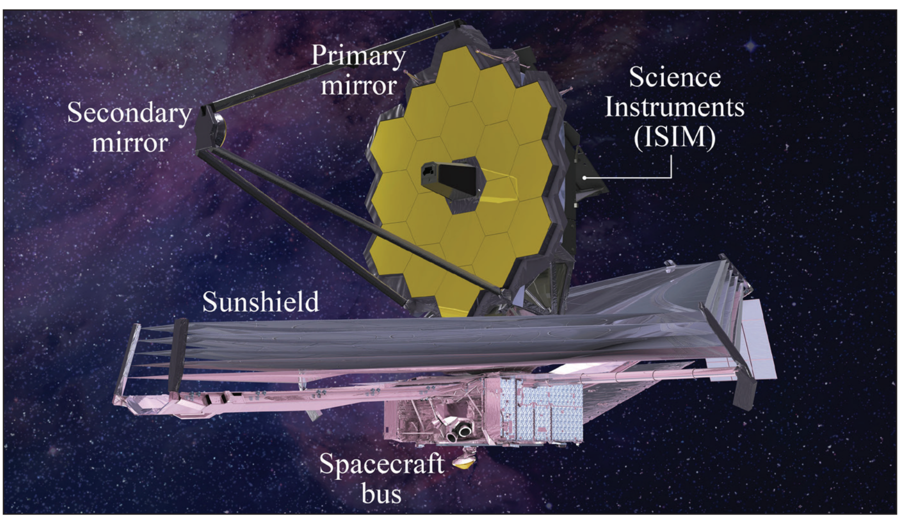


Figure 20.1. An artist's conception of the James Webb Space Telescope, showing the primary and secondary mirrors of the optical telescope element (OTE), the integrated science instrument module (ISIM), the five-layer sunshield, and the spacecraft bus. Photo courtesy of Northrop Grumman, contributed to the JWST photo album on flickr.com, with text labels added by D. Aronstein.

It is perhaps fitting that the next premier astronomical observatory has been enabled by graduates and members of the premier educational institution for optics. Since NASA began work on the JWST in 1996, many hundreds of people have been involved in the design, fabrication, assembly, and testing of its components, instruments, and subsystems. We have identified forty-three people from The Institute of Optics family who have contributed; in this essay, we describe their contributions in the context of the stages of development of JWST.

The James Webb Space Telescope was named in honor of James E. Webb, who served in the 1960s as the second administrator of NASA. The observatory's telescope (called the optical telescope element, or OTE) has a primary mirror consisting of eighteen hexagonal segments that are made of a beryllium substrate and coated with gold. The telescope's primary, secondary, and tertiary mirrors are arranged in a design form called the three-mirror anastigmat. Different portions of JWST's field of view are relayed to the fine guidance sensor (FGS) and to four imaging and spectroscopy science instruments (SIs):

- The near-infrared camera (NIRCam) forms separate shortwave (0.6–2.3 μm) and longwave (2.4–5.0 μm) infrared images of the same field of view.
- The near-infrared spectrograph (NIRSpec) has a microshutter array that allows for one hundred different spectra in the field of view to be measured simultaneously.
- The near-infrared imager and slitless spectrograph (NIRISS) operates at wavelengths of 0.6–5.0 μm, complements NIRCam and NIRSpec with low- and medium-resolution slitless spectroscopy, and shares an optical bench with the FGS.
- The mid-infrared instrument (MIRI) operates at wavelengths of 5.0–28 μm and has imaging and spectroscopic capabilities as well as two types of coronagraphs.

The SIs, mounted in their supporting structure, are collectively called the integrated science instrument module (ISIM). The full optical train of the observatory, consisting of the OTE followed by the ISIM, is called OTIS, an acronym mashup of "OTE + ISIM."

The James Webb Space Telescope is being led by NASA's Goddard Space Flight Center (GSFC) in Greenbelt, Maryland. The prime contractor is Northrop Grumman Corp. in Redondo Beach, California. The subcontractor for the observatory optics is Ball Aerospace & Technologies Corp. in Boulder, Colorado.

A division of Harris Corp. in Rochester (which, during the lifetime of JWST, began as Kodak Federal Systems, then became part of ITT Industries, which was later spun off to be ITT Exelis, then Exelis Inc., before becoming part of Harris!) is in charge of the full-optical-train testing of the observatory, discussed more below.

Lee Feinberg (BS '87) is the OTE manager, and Joe Howard (PhD '00) is the lead optical designer. Other Institute of Optics graduates serving on the observatory team, providing management and engineering for JWST, include Gary Golnik (MS '76) and Kim Mehalick (BS '85). J. Howard, Blair Unger (PhD '10), and Garrett West (MS '14) developed analysis tools for optical performance verification and performed simulations of on-orbit optical commissioning scenarios. The sole Institute of Optics contributor at the prime contractor, Northrop Grumman, is Rich Gong (BS '84).

A foundation of NASA's technical standards (its so-called GOLD Rules) for preparing missions is to "test as you fly, and fly as you test"—test the full mission hardware on the ground in spacelike conditions, and launch without modifications what was tested. The JWST represents a challenge to a strict interpretation of this rule, since it was infeasible to create a football-field-sized test chamber that could put the full observatory through its paces in a cryogenically cooled and air-evacuated (together called cryogenic/vacuum, or cryo-vac) environment. From the point of view of evaluating the optical train, the testing plan for JWST became a two-step process: a high-precision test of the JWST science instruments (ISIM), followed by a less precise test of the entire optical train for the observatory (OTIS). These two steps were separate test campaigns, the ISIM-level and OTIS-level verifications, respectively.

Since the science instruments were tested independently of the telescope (OTE) in the ISIM-level test, a suitable illumination system was needed to test the optical performance of the SIs in as flightlike a way as possible. This source, called the OTE Simulator (OSIM), uses a 1.5 m spherical mirror and relays point sources to the object surface of the SIs; it was developed by Ball Aerospace & Technologies Corp. Development of OSIM and engineering of the observatory optics involved contributions by Jim Baer (MS '78), John Fleming (BS '85), Rob von Handorf (MS '82), Kathleen Youngworth (PhD '03), and Richie Youngworth (PhD '02). The OSIM was set up in NASA GSFC's cryogenic/vacuum Space Environment Simulator (SES) chamber and was tested and calibrated in 2012 and 2013, with contributions on the NASA side by David Kubalak (MS '93).

The science instruments (in ISIM), illuminated by OSIM, were tested in the NASA GSFC SES chamber in three test campaigns, in 2013, 2014, and 2015. The first test was a risk-reduction test with the goal to ensure success of the subsequent ISIM tests. Cryogenic/vacuum testing was run 24/7, with three work shifts a day and a large staff on hand at all times to monitor the test facility and SES chamber, oversee the implementation of the testing procedure, problem-solve issues when they arose, approve changes to the test plan, do a first analysis ("Quick Look") of image data, and so forth. After each test campaign, ISIM team members then took a deeper dive into the data and used the analysis results to verify ISIM-level requirements and to gather the information needed to feed forward to the OTIS team. ISIM-level testing was the longest-duration cryogenic-vacuum testing performed by NASA. ISIM-level testing involved contributions by David Aronstein (PhD '02), Renee Gracey (BS '90), J. Howard, Alden Jurling (PhD '15), D. Kubalak, K. Mehalick, R. von Handorff, G. West, and Tom Zielinski (PhD '11).

The full JWST observatory optical train, the OTIS, was tested at the Johnson Space Center (JSC) in Houston, Texas; "Pathfinder" tests—two optical and one thermal—were performed in 2015 and 2016, and the actual cryogenic/vacuum test was in 2017. JSC's Chamber A, a ninety-foot-tall facility originally used for testing the Apollo spacecraft in the 1960s, was substantially renovated, including the addition of a liquid helium shroud and compressor and the upgrade of the liquid nitrogen compressor. The ground-support equipment as well as the planning and operation of the OTIS tests were provided by Harris Corp. Institute of Optics alumni from this team included Becky Borrelli (PhD '12), Joe Cosentino (MS '15), David Fischer (PhD '02), Josh Johnson (PhD '03), Kevin Lyons (BS '80), Mike Melocchi (PhD '03), Cormic Merle (BS '91), David Strafford (MS '96), Mark Waldman (MS '78), Conrad Wells (MS '91), Alan Wertheimer (PhD '74), Tony Whitman (MS '88), and Michael Zarella (BS '13).

A critical optical test of the alignment state and control process of the primary-mirror segments during OTIS-level testing involved the use of the Center of Curvature Optical Assembly (COCOA) and Center of Curvature Interferometer, which succeeded with contributions by J. Cosentino, C. Wells, and T. Whitman.

OTIS-level testing was the most complex cryogenic-vacuum testing performed by NASA. L. Feinberg was the OTIS test codirector, and C. Wells was the deputy test director. OTIS had a similar 24/7 operation schedule and had people in similar roles to the ISIM-level testing. On-site contributors during the OTIS testing included D. Aronstein, Matt Bergkoetter (PhD '17), J. Cosentino, L. Feinberg, R. Gracey, J. Howard, A. Jurling, K. Mehalick, Scott Paine (PhD candidate), R. von Handorff, M. Waldman, C. Wells, G. West, T. Whitman, M. Zarella, and T. Zielinski. After the test, Greg Brady (PhD '09) was involved with data review and analysis.

Beyond the technical complexity of the ISIM- and OTIS-level tests, there were some remarkable, extenuating circumstances during ground testing, including the first ISIM test being interrupted by the sixteen-day federal government shutdown of October 2013. There were even times when it seemed that nature itself was trying to slow our progress toward learning more of its secrets with such an exquisite observatory: The third ISIM test happened during the January 2016 blizzard (dubbed "Snowzilla"). The team of scientists and engineers testing ISIM were hunkered down at GSFC, sleeping on cots and sleeping bags set up in offices and taking turns using the one shower available in the building. During OTIS-level testing, Hurricane Harvey dumped over forty inches of rain on JSC. Many people couldn't safely travel to JSC due to flooded roads and had to support the tests from their hotel rooms; the on-site crew worked under plastic sheeting (because of roof leaks) and slept in sleeping bags. Businesses were closed and supply trucks were not coming to Houston; L. Feinberg led the heroic effort of arranging for liquid nitrogen to be delivered to the center during the hurricane so that cryo-vac testing could continue.

One of the enabling technologies for JWST is image-based wavefront sensing and control (WFSC); here, *wavefront sensing* is a process to evaluate the OTE +

Figure 20.2. Some of The Institute of Optics alumni participating in the OTIS-level testing in Houston, Texas. From left: Renee Gracey, Matthew Bergkoetter, Tom Zielinski, Scott Paine, Alden Jurling, Kim Mehalick, Lee Feinberg, Mark Waldman, Joe Howard, Garrett West. Photo courtesy of Mark Waldman, with some Photoshop surgery performed by Sophia Desyngs, fiverr.com user sophia_desyngs.

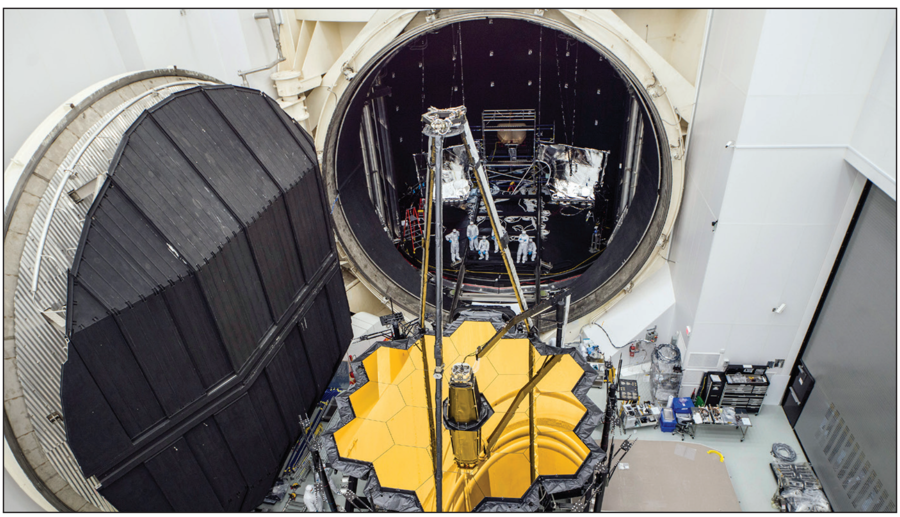


Figure 20.3. The OTIS in front of Chamber A at the Johnson Space Center in Houston, at the end of OTIS-level testing. Photo courtesy of Chris Gunn/NASA, contributed to the JWST photo album on flickr.com.

Science Instrument's wavefront error, using a set of intentionally defocused images that are recorded at the SI's image detector, and *control* closes the loop and determines how to adjust the primary-mirror segments and the secondary mirror to optimize performance. This technology addresses the need for a way to align the OTE's mirrors initially on orbit, after a bumpy launch and journey into space, and then for periodic adjustment of the OTE's mirrors during the scientific operation of the observatory. Ball Aerospace built a 1/6-scale testbed telescope to prove out WFSC technologies, developed the on-orbit commissioning procedure for aligning the telescope, and will be in charge of the actual commissioning; Jim Oschmann (BS '82) was involved in Ball's WFSC contributions.

Although WFSC was initially envisioned for use only with testing field points in NIRCam on orbit, as systems engineering and on-orbit commissioning simulations matured, it became clear that most of the SIs would need to be part of on-orbit WFSC in order to avoid alignment states where the OTE could meet imaging requirements at the few field points used for calibration but then be out of specification at the edges of the observatory field of view. Then, in an effort to simplify testing and reduce costs, the decision was made to use WFSC for the ISIM-level and OTIS-level ground testing too. Institute of Optics alumni involved with developing the WFSC algorithms for JWST and using these algorithms to perform ISIM-level and OTIS-level tests on JWST and/or those expected to be involved with on-orbit WFSC work after launch include D. Aronstein, M. Bergkoetter, G. Brady, A. Jurling, Rick Lyon (MS '87), and T. Zielinski.

Wavefront-sensing computer algorithms were developed and applied to NASA missions during the diagnosis of why the Hubble Space Telescope had unacceptably aberrated images after launch; this Hubble Aberration Recovery Program team included Jim Fienup (professor), R. Lyon, and Joseph Marron (PhD '86). The success of wavefront sensing during the diagnosis and quantification of the Hubble primary-mirror aberrations gave NASA the confidence to make this technique central to on-orbit alignment of JWST. After joining The Institute of Optics faculty in 2002, Professor Fienup and his research group have served in the role of wavefront-sensing risk reduction, researching ways to make the JWST WFSC process more robust, accurate, and successful. Many research papers and PhD theses from the Fienup group have documented important contributions toward this risk-reduction goal, and Institute of Optics personnel contributing to this body of work include Matthew Bolcar (PhD '09), A. Jurling, D. Moore, S. Paine, Joseph Tang (PhD candidate), Sam Thurman (PhD '03), and T. Zielinski. Some of these students were able to participate in the JWST cryo-vac testing: D. Moore, who participated in ISIM-level testing, applied his work in transverse-translation diversity phase retrieval to wavefront sensing of the coronagraphic optical train of the NIRCam longwave channel, and S. Paine served as one of the wavefront-sensing data analysts during OTIS-level testing.

Frequent technical reviews by peers and external experts are another key aspect of NASA's GOLD Rules, and JWST had a regularly convened product integrity team

(PIT) that assessed progress and plans for the telescope and optics. The PIT was chaired by Duncan Moore (PhD '74 and professor) and also included J. Fienup, Greg Forbes (former professor), and Jim Wyant (PhD '69).

After JWST, the next planned large observatory is currently called the Wide Field Infrared Survey Telescope (WFIRST). WFIRST is being managed by NASA GSFC, Harris Corp.'s Rochester team has won the contract to provide the optical telescope assembly, and NASA's Jet Propulsion Laboratory is responsible for the observatory's coronagraphic instrument. Looking further into the future, NASA is already formulating plans for subsequent space telescopes with capabilities and scientific goals beyond Hubble, JWST, and WFIRST; the current missions being explored include the Large Ultraviolet/Optical/Infrared (LUVOIR) Surveyor, the Origins Space Telescope (OST), and the Habitable Exoplanet Observatory (HabEx). Someday when the stories of WFIRST and its successors can be told, there will no doubt be many from The Institute of Optics family who will have helped ensure their success, perhaps including many named herein.

Note

Note from the author: I thank Lee Feinberg, Jim Fienup, and Mark Waldman for their careful reading of and feedback on this essay. Joe Sullivan (Ball Aerospace & Technologies Corp.) provided information on OSIM and its testing. Eric Berger (Space City Weather, Houston, Texas) helped fact-check the impact of Hurricane Harvey on JSC. I attempted to contact everyone mentioned in this essay, and several people kindly gave their time to help look for other alumni and to answer my questions. For their efforts in "alumni finding," my thanks also go to Gina Jones (PhD '05) and to two people with no Institute of Optics ties—Charlie Atkinson (Northrop Grumman Corp.) and John Kincade (Zygo/AMETEK Ultra Precision Technologies). The James Webb Space Telescope has been under development for more than twenty years, and employee migration and institutional memory present serious challenges to having a complete list of JWST-contributing Institute alumni. My deepest apologies for anyone who was not included but should have been.

21. AIM Photonics and The Institute of Optics

Thomas G. Brown

Figure 21.1. Thomas Brown (PhD '87), professor of optics. Photo by J. Adam Fenster/University of Rochester.

Integrated photonics describes the science and technology of light-based integrated circuits that are analogous to and structurally similar to integrated circuits in electronic technologies. In most implementations, a waveguide functions as the photonic wire by confining light (often in a subwavelength cross section) and directing it to various optical circuit elements: couplers, resonators, modulators, and detectors. Modern developments have also begun adding plasmonic elements, photonic crystals, 2D materials, and acoustic-optic materials to the list of active elements.

The Institute of Optics has played an important role in the history of integrated photonics. In the 1980s and early '90s, Dennis Hall and his students attacked a variety of fundamental questions related to optical waveguides, resonators, and the materials that comprise them. Among the most significant efforts (although not recognized at the time) was the proposal that waveguides fabricated in and on silicon wafers could open the door to integrated optical circuits that would leverage the extensive infrastructure already in rapid development for electronic integrated circuits. Hall's view proved prophetic: beginning in the late 1990s an international push toward the development and eventual standardization of silicon-based photonics gained momentum. By 2005, a number of companies and universities around the country had begun investing in research and development of optical circuits in silicon. These included IBM, Intel, MIT, Cornell, Corning, Cisco, among others. A number of Institute graduates were influential in these efforts, including Sean Anderson (Cisco), Alan Evans (Corning), Alex Gaeta (Cornell), and Kevin Sullivan (Intel).

Figure 21.2. Vice President Joe Biden announces that the federal government will provide $110 million in funding for an institute for photonics in the Rochester area during a news conference at Canal Ponds business park in Greece, New York, July 27, 2015. Photo by J. Adam Fenster/University of Rochester.

By 2010, it had become clear that, while the tools of the electronics industry could be leveraged for photonic circuit design and manufacture, the problem of connecting those circuits to the outside world remained a difficult problem. There was a significant need to automate the design process so that engineers could establish manufacturable designs before submitting to an expensive foundry. But there was an even more challenging problem: according to some analyses, up to 80 percent of the cost of a photonic circuit was taken up in the process of test, assembly, and packaging (TAP). The packaging for photonic integrated circuits differs in many respects from that for electronics. The most expensive and difficult part of the process is achieving optical I/O that provides consistent connections with loss sufficient for the application, including both the injection of input light into the photonic integrated circuit (PIC) and the collection of output light from the PIC into a fiber or fiber array. In short, there was a need for a new initiative built around the manufacturing of photonic integrated circuits, one that would seek low-cost and reliable packaging solutions for silicon photonics.

In July 2015, Vice President Joe Biden traveled to Rochester to announce, with great fanfare, the establishment of a new manufacturing initiative in photonics.

Part of the national network of manufacturing innovation, the initiative, dubbed the American Institute for Manufacturing Photonics (AIM Photonics), was a joint effort that would combine an existing foundry based at SUNY Polytechnic Institute with teams from the University of Rochester, MIT, Columbia, the University of Arizona, and the University of California, Santa Barbara. Institute graduates were central to the organization: Nick Usechak (USAF) became the government chief technology officer, while Alan Evans coordinated Corning's activities. The organizers of AIM Photonics immediately moved to launch a multiproject wafer and assembly (MPWA) program. This would be tightly integrated with a electronic/photonic design automation program in order to allow members and outside users access to the design tools necessary to carry out reliable prototyping and move as quickly as possible to manufacturing relevant designs and processes.

Figure 21.3. James R. Zavislan (BS '81, PhD '88), associate professor of optics, biomedical engineering, ophthalmology, Center for Visual Science; associate dean of education and new development; Mercer Brugler Distinguished Teaching Professor (2018–21).

While initially centered around a silicon photonics foundry in Albany, the effort announced plans for a new facility for test, assembly, and packaging in Rochester. The total federal and New York State investment was expected to be $360 million, with an additional $200+ million contributed from other states and member companies. The story of how such a center ended up in Rochester, and the circuitous political discussions that enabled it, must wait for the 100th anniversary of The Institute. During the proposal preparation, Robert Clark (then dean of the Hajim School of Engineering) asked Duncan Moore to head a UR-based team to participate in the proposal writing. A variety of UR-based initiatives were proposed by the team; the two that emerged were a TAP effort led by Tom Brown along with a UR Medical Center–based photonic sensors effort led by Ben Miller, professor of dermatology and optics. In addition, Jim Zavislan played a vital role in proposal preparation, coordinating administrative oversight and maintaining communication with the UR administration and government relations offices.

SUNY Polytechnic University (part of the SUNY system) was the lead organization; however, its activities were mostly based in Albany, and it became important to have a strong presence in Rochester to coordinate and organize activities in preparation for the new facility. To accomplish this, Tom Brown formed a team with two RIT-based groups that had expertise in packaging, photonic testing, and silicon photonic designs. The team later added new Institute professor Jaime Cardenas, an expert in the design and testing of photonic integrated circuits.

Meanwhile, Ben Miller formed a PIC sensors team that combined efforts from UCSB and MIT along with companies such as GE, Orthoclinical Diagnostics (a Rochester-based company and former Kodak subsidiary), and IBM.

The funding for AIM Photonics also included an MIT-led education and workforce development program that involved an Institute project led by Director

Xi-Cheng Zhang and implemented by Jaime Cardenas, Tom Brown, and Jim Zavislan. Cardenas has worked very closely with Prof. Stefan Preble of RIT to establish an RIT-UR collaboration in photonics education for The Institute summer school as well as the AIM Photonics EdX distance learning program.

Figure 21.4. Jaime Cardenas, assistant professor of optics.

The TAP facility, now close to operational, encompasses the fourth and fifth floors of the building currently owned and occupied by On Semiconductor, across the street from Eastman Kodak Research Laboratories on Lake Avenue. It includes a clean area (20,000 square feet) with accompanying office, laboratory, and utility space. It comprises a full suite of production-grade electronic and photonic packaging equipment, including a surface-mount technology line and supporting technology (e.g., commercial platers, equipment for PCB production), photonic assembly equipment (a custom designed ficonTEC CL-1500 fiber and die attach system, fiber inspection and preparation systems), a die bonder, wafer processing equipment (dicer), metrology tools (optical backscatter, X-ray imaging, acoustic microscope, digital [VIS] microscope, SEM/FIB, SWIR microscope, ellipsometer, bump metrology), photolithographic patterning, high-speed photonic test equipment (tunable lasers at all telecommunication bands, optical preamplifiers, device parameter analyzers, swept wavelength insertion loss system, swept wavelength polarization dependent responsivity system, digital component analyzer, microwave network analyzer, optical transmitters, and modulation analyzers). At the time of this writing, the facility is complete and much of the equipment is in the process of installation.

In many respects, the establishment of AIM Photonics (along with its counterpart facilities in Europe and the Pacific Rim), the increasing use of silicon photonics in commercial products, and the heightened need for high-quality photonic systems in research has validated Dennis Hall's original vision. There is, however, a missing piece that Dennis identified as early as 1981: silicon does not readily or efficiently emit light, and there is therefore no truly integrated solution that includes a light source in silicon. Despite research efforts and many premature announcements of success in silicon light emission, this remains an unmet need. A PIC cannot function without a photon, and the current state of the art requires other materials, placed within or alongside the silicon, to provide light. Although many circuits function perfectly well with an external light source, emerging quantum information systems will require an integrated source of the type that Dennis envisioned. We expect that a decade from now, at our 100th anniversary, we will be writing much more about integrated sources in quantum systems and the contributions of faculty, students, and alumni of The Institute of Optics.

22. The Institute of Optics and the Laboratory for Laser Energetics: A Dynamic Duo

E. Michael Campbell

As a former associate director for laser programs at Lawrence Livermore National Laboratory, I've long experienced the benefits of strong collaborations with the dual UR optics and lasers powerhouses: The Institute of Optics (IO) and the Laboratory for Laser Energetics (LLE). It is a distinct pleasure and honor now to find myself as director of one of these (LLE) and to have this opportunity to comment on the occasion of the ninetieth anniversary of The Institute by contributing a few words to this update of Carlos Stroud's *A Jewel in the Crown.*

Several contributors to the original volume (Hercher, Forsyth, Mourou, Eberly, Thompson, Moore, Harter, and Knox) have already pointed out the mutually beneficial nature of the interactions between IO and LLE. In fact, LLE would probably not exist today if it were not for the strong optics science and technology base provided by The Institute and the Rochester region. I'll limit my remarks here to four areas: connections, the Nobel, facilities, and transitions.

The strong personal connections to The Institute (that helped lead to the creation of LLE) have continued to flourish over the subsequent years. Testaments to this assertion include the following: (a) three of the LLE operating divisions are led by Institute of Optics graduates: Jonathan D. Zuegel (Laser Development and Engineering Division), Samuel F. Morse (Omega Laser Facility Division), Steven J. Stagnitto (Administrative Division); (b) many of the current and past leaders in laser, optical, and materials science and technology in key positions within LLE were also graduates of The Institute of Optics: Jason Puth, Amy Rigatti, James Oliver, Jay Eastman (former LLE director), John Kelly (retired), Steven Jacobs (deceased), and many more; and (c) a continuing stream of exceptionally strong IO graduate students carry out their graduate research at LLE.

The year 2018 marked the fifty-eighth anniversary of the invention of the laser. The year was also the eighty-ninth anniversary of The Institute of Optics and the forty-eighth anniversary of LLE. The dynamic optics "amplifier" provided by these

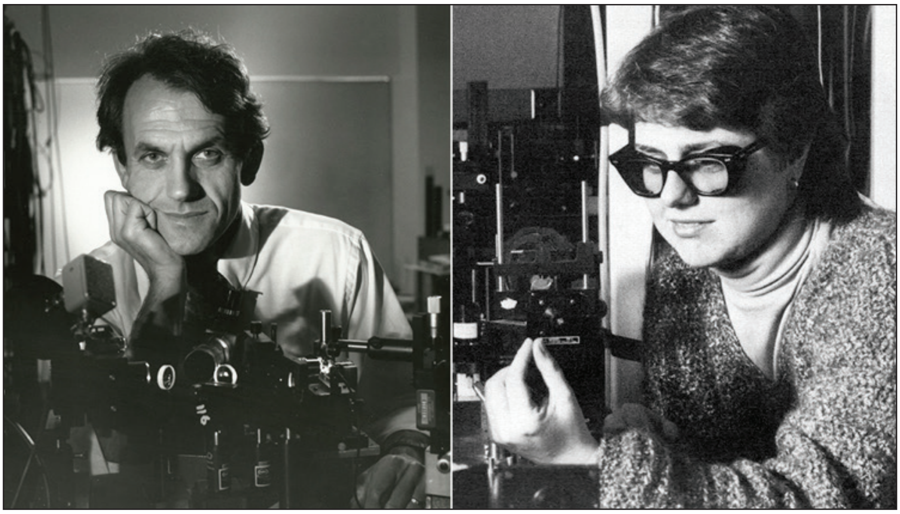


Figure 22.1. Gérard Mourou (left), photographed in Rochester in 1987, and Donna Strickland (PhD '89), seen aligning an optical fiber in her lab in Rochester in 1985. The pair will share half of the 2018 Nobel Prize in Physics "for their method of generating high-intensity, ultra-short optical pulses." University of Rochester photos; caption from Lindsey Valich.

two institutions within the University of Rochester is best exemplified by the 2018 awarding of the Nobel Prize in Physics to Donna Strickland and Gérard Mourou for their invention of chirped-pulse amplification (CPA) techniques for lasers. Donna Strickland, who received her doctorate in optics from Rochester in 1989 and is now a professor at the University of Waterloo in Ontario, and Gérard Mourou, a former engineering professor and scientist at LLE and currently a professor at the École polytechnique in France, were recognized for their work to develop lasers as a high-powered tool that ultimately opened the door to new and numerous medical, scientific, and commercial applications. CPA, the basis of Strickland's PhD dissertation at Rochester, made it possible to generate ultrashort laser pulses using conventional Nd:glass lasers. Strickland is only the third woman to receive the prize in physics, joining Marie Curie (1903) and Maria Goeppert-Mayer (1963), and the only one educated in the United States. The research leading to the Nobel Prize was conducted at LLE, and the laboratory where CPA was first demonstrated is still in use.

CPA is the enabling technology for the development of petawatt lasers that are now of exceptional interest in the investigation of high-energy-density science. A 2017 report titled "Opportunities in Intense Ultrafast Lasers—Reaching for the Brightest Light" by the National Academies of Science, Engineering, and Medicine concluded that the United States is losing ground in a second laser revolution of highly intense ultrafast lasers that have broad applications in manufacturing, medicine, and national security. The report recommended a broad network to support science, applications, and technology of these lasers.

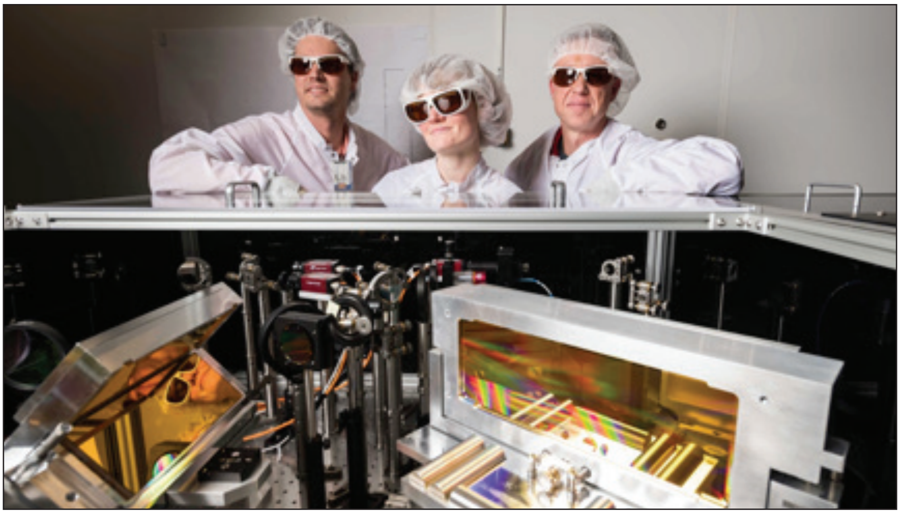


Figure 22.2. Dustin Froula, senior scientist and assistant professor of physics; his PhD student Sara Bucht; and Jake Bromage, senior scientist and associate professor of optics, use CPA in their research to develop the next generation of high-power lasers and to better understand the fundamentals of high-energy-density physics.

To this day, CPA remains the state-of-the-art technique for generating the highest-power lasers in the world. It enables cost-effective, high-power lasers that are used ubiquitously in universities and industries around the world and produces laser intensities that accelerate relativistic particle beams for scientific, medical, and industrial applications. Ultrahigh-intensity lasers based on CPA generate new high-energy photon sources, including X-rays and gamma rays that can probe dense matter and even nuclear structures. CPA is the foundation for producing laser pulses that probe atomic and solid-state dynamics, opening such new fields as femtochemistry and attosecond science. Industry has adapted the technique for a range of laser materials-processing techniques, including machining of brittle materials such as the cover glass used in smart phones.

Building on the success of CPA, LLE took a major step in the future development of high-energy-density science with the addition of the high-energy petawatt laser Omega EP to the Omega Laser Facility in 2008. Since 1979, the Omega Facility, comprising the sixty-beam Omega laser and the four-beam Omega EP, has served as a major national and international research center and users facility for inertial fusion and high-energy-density science. High-energy-density science is the foundational science for how the universe works. It includes studies of stellar and planetary evolution, dynamic compression of matter, fusion ignition, and exotic chemistry and new states of matter. The thousands of laser shots provided by the facility each year provide experimental high-energy-density science opportunities for hundreds of scientists from fifty-five universities and thirty-five centers and national laboratories from twenty-one nations. The University of Rochester is ideally placed to lead this new frontier in science and has now established a Center for Matter at Extreme Energy Density.

Transitions: In all aspects of life, we are always the beneficiaries of those who came before us. In keeping with this thought, I note the recent retirement of my predecessor, Prof. Robert L. McCrory, as director of the laboratory on October 1, 2017. Under his leadership, during the last thirty-five years, the lab has grown to become the largest single research facility at the university. It has also established itself as an important partner to the national laboratories: Lawrence Livermore National Laboratory, Sandia National Laboratories, Los Alamos National Laboratory, Massachusetts Institute of Technology Plasma Science and Fusion Center, Naval Research Laboratory, and Princeton Plasma Physics Lab. The LLE has provided an academic home to more than five hundred PhD candidates, including more than two hundred from outside the university, as well as offered research opportunities to generations of undergraduates and many high school students.

With the death of Steven Jacobs in 2015, the laboratory lost one of its major leaders in optical materials development. After a national search, we were fortunate to bring Stavros Demos (formerly of LLNL) to LLE in 2016. Stavros was recently named a fellow of the Optical Society of America for pioneering and sustained contributions to the understanding of dynamic behaviors and improved performance in optical materials for high-power lasers.

Highlight V. The Institute after Hours

1. The UR Student Chapter of the Society of Photographic Instrumentation Engineers (SPIE) is one of the largest student chapters with about eighty members (students and alumni). The UR chapter hosts many outreach activities and runs a summer student colloquium series. In this photo from 2015, volunteers from UR's SPIE Student Chapter; three guests from St. Petersburg, Russia; and Thomas Battley, executive director at New York Photonics, organize and install twenty photo banners depicting the Beauty of Optics at the Greater Rochester International Airport. From left: Maria Borovkova, Gustavo Gandara Montano, Fabrizio Buccheri, Xing Fan, Thomas Battley, Sam Birsa, Aizhong Zhang, Evgenii Strepitov, Leonid Lialiushkin.

I know your notes are torn and ragged
And quantum makes your hair turn grey
But lift your head and smile at trouble
'Cause you'll have your degree some day

Go to sleep you quantum scholars
Let the eigenstates go on by
Can't you hear the photons clicking?
That's an optics lullaby
Some days you try to 'be the photon'
And then, some days you search the 'net
But if you could just match up the pupils
There would be nothing to vignette

Go to sleep you optics scholars
Let the waves drift slowly by
Can't you hear the laser humming?
That's an optics lullaby

I know professors cause you trouble
They cause trouble everywhere
But when you graduate to heaven
There won't be no professors there

Go to sleep you optics scholars
Let the rays drift slowly by
Can't you hear the laser humming?
That's an optics lullaby

(lyrics by T. Brown, set to the tune of
Guthrie's Hobo Lullaby)

2a. The annual Optics Senior Roast features an opportunity for students and faculty to poke gentle fun at one another in a way that honors their academic journey. In this photo from 2009, Prof. Thomas Brown roasts the students with his version of an Optics Lullaby.

2b. Cheon Jeon, Jack Chang, and Brandon Zimmerman enjoy the fun with Professor Brown.

3. The UR Optical Society of America student chapter is a preprofessional organization and an academic club for all students with an interest in optics and optical engineering. Chapter meetings feature networking, outreach, and social activities that range from hosting elevator pitches and business card workshops, to organizing events including the Photon Cup, laser shows at Strasenburgh Planetarium, engineering socials, outreach demos to local schools, and more. This photo shows (from left) Ellen Buck, Kari Brick, Nick Cochan, Jane Xia, Ray Lopez Rios, and Per Adamson making holograms at the optics booth during OSA Frontiers in Optics 2016.

4. In 2011, the Photon Cup was established as a friendly soccer match between The Institute of Optics and the Physics and Astronomy Department. The trophy goes home each year to the victorious department, but every participant is a winner! From left: Pedro Vellejo Ramirez, Sarah Walters, Jacob Reimers playing in the 2014 Photon Cup. Photo by Dustin Moore.

5a. Optics features numerous conference opportunities where optics professionals, faculty, and students gather for growth and fun. In 2016, special celebrations were held as OSA celebrated its 100th anniversary. At the 2016 FiO in Rochester, an alumni reception was hosted by UR, Arizona, and CREOL, with support from OSA. Susan Houde-Walter, Jia Qiao, Jannick Rolland, Julie Bentley, and Wendi Heinzelman gather for a fun shot in the photo booth.

5b. Ian Walmsley and Steve Fantone being photobombed by Liz Rogan and Monique Rodriquez.

6. All work and no play . . . is not the Optics way! Each fall Institute of Optics faculty, staff, alumni, family, and friends gather for an annual picnic—and in recent years, a run. Sabrina Villanueva, Amanda Mietus, and Nicole Naselaris lead the way at this Optics 5K.

7. Many students find happiness ever after at The Institute. One example shown here is Hillary Maben and Greg Balonek, who were married July 26, 2014. From left: James Corsetti ('10, MS '13, PhD '17), Zach Maben, Robert Balonek ('09), Hillary Maben ('10, MS '14), Greg Balonek ('09, MS '14), Daniel Balonek ('09, MS '14), Sid Sampat, and PhD/MD candidate Daniel Savage ('10, MS '15, PhD '18).

PART VI

Meliora for the New Millennium

Part VI. *Meliora* for the New Millennium

1. Donna Strickland receiving the news of her Nobel Prize.

2. University of Waterloo president Feridun Hamdullahpur, 2018 Nobel Prize laureate Donna Strickland, and University of Rochester president Richard Feldman at the Stockholm ceremony awarding the 2018 Nobel Prize in Physics.

This section follows up on the *Meliora* theme of part 1 by celebrating the magnificent achievement of alumna Donna Strickland and former faculty member Gérard Mourou in sharing the 2018 Nobel Prize in Physics. Donna's award for her dissertation research for her PhD in optics while working under the supervision of Mourou at the Laboratory for Laser Energetics was only the third Physics award to a woman in the history of Nobel Prizes. A number of short reminiscences by people who worked with her during her student days make up Essay VI.23. A second by the current director, P. Scott Carney, goes out on a limb to predict where the process of amelioration that we have described in previous essays will take us in our centennial year, 2029.

3. From left: University president Richard Feldman, Donna Strickland (PhD '89), and U.S. Representative Joe Morelle celebrate at the university's annual commencement dinner. Morelle made a statement on the House of Representatives floor recognizing Donna Strickland, Gérard Mourou, and the University of Rochester's Laboratory for Laser Energetics for their 2018 Nobel Prize in Physics. The statement was inserted in the Congressional Record, and a framed version was personally presented to Strickland at the event during commencement weekend.

23. Nobel Prize Reflections: Gérard Mourou and Donna Strickland

See Leang Chin, Joseph H. Eberly, Conger Gabel, Wayne H. Knox, and Robin S. Marjoribanks

We got to know Gérard Mourou and Donna Strickland through different paths, which eventually merged in Rochester and then diverged.

See Leang Chin first met Gérard Mourou in 1970. See Leang finished his PhD degree in 1969 from the Physics Department of the University of Waterloo (where Donna Strickland is now a faculty member). He was hired as a postdoc in the Physics Department of Laval University in Quebec City, Canada. Gérard arrived at Laval University in 1970 to engage in laser physics research with Madam Marguerite Marie Roberge in lieu of French military service. His laboratory was right next to that of See Leang. The two of them often discussed laser physics in the corridor in front of their labs—in particular, Gérard's experimental measurement of the then-ultrafast relaxation time (pico-second) in dye molecules. In the summer of 1971, Gérard and his wife Marcelle left Laval University and returned to France. They had rented an apartment till September 1971 and were looking to sublet. See Leang had just married May that summer and was looking for an apartment; thus they sublet their apartment to the Chins. Back in Paris, Gérard wrote his doctoral thesis using much of the results he obtained at Laval University. Since then, See Leang has encountered Gérard often at various conferences.

At the end of 1987, when See Leang was nearly halfway through his sabbatical leave in the laboratory of Paul Corkum and John Alcock in the National Research Council of Canada in Ottawa, he received a phone call from Gérard. Essentially, Gérard wanted to invite See Leang to Rochester to make use of his newly invented T^3-laser, which gave out 1 ps, 1 TW pulses. At that time, it was the most powerful table-top laser in the world. See Leang hesitated. A day later, a phone call came again from Rochester. This time, it was Joseph H. Eberly at the other end. Joe was very persuasive. Finally, See Leang agreed to go to Rochester as soon as possible. The Chin family arrived in Rochester in early 1988 in the middle of a big snowstorm.

The first thing See Leang did in Rochester was to decide which experiment to do using the T^3-laser. There was some intense discussion with Joe in his office. Finally, they agreed with See Leang's suggestion to try some experiments on multiphoton and/or tunnel ionization of atoms. Gérard also agreed. At that time, See Leang had successfully performed some experiments and published a few papers on tunnel ionization of atoms using a powerful CO_2 laser at both Laval University and INRS-Énergie, in Varennes (near Montreal). Those were the first experimental observations of tunnel ionization in the twenty years since Keldysh published his famous theoretical paper on strong-field ionization of atoms. See Leang did not really know what to expect in the experiments using the new powerful tool in Rochester, though he had measured up to Xe^{6+} using the CO_2 laser in Canada. He went to the Laboratory for Laser Energetics (LLE). Donna and a new graduate student, Steve Augst, had been shooting the T^3-laser pulses into a vacuum system for quite a while, trying to obtain some relativistic radiation at the second harmonic of the pump laser. See Leang was not familiar with the idea of that experiment. He was told that Donna had to finish doing some interaction experiment using the T^3-laser (at 1 μm wavelength) she had successfully built. The content of the laser alone was not sufficient for a PhD thesis. See Leang explained to Donna what he and Joe would suggest she do, and Donna agreed.

See Leang asked some questions about the performance of the vacuum system. The best pressure in the vacuum system was of the order of 10^{-5} Torr. See Leang believed that the vacuum system needed to be cleaned thoroughly. He suggested that Donna and Steve clean up the system and install a time-of-flight mass spectrometer. The two agreed and followed See Leang's instructions. They dismantled the whole vacuum system including the diffusion pump and cleaned all the pieces using the recipe suggested by See Leang. After reassembling the vacuum system and installing a time-of-flight mass spectrometer, the vacuum could go down to 10^{-7} Torr. Donna and Steve fired the laser into the vacuum chamber in which Xe gas was leaked. Bang! The first shot gave them a spectacular result, which See Leang did not expect. All the eight electrons from the whole outer electronic shell of Xe were stripped off. A clear mass spectrum showing ion peaks of up to Xe^{8+} was obtained. Furthermore, if one looked closely, tiny ion peaks of up to Xe^{12+} could be seen. It was about 9 p.m. Outside, it was cold and wet. See Leang got very excited and called Joe at home to invite him to come immediately to see the exciting (and historic) result. Even though Joe was (and still is) a theoretician, he sensed and understood the importance of the observation. He immediately jumped into his car and came to the laboratory. The rest was history. Donna and Steve kept on doing more experiments on tunnel ionization. Finally, she wrote up her PhD thesis.

In fact, those were the first interaction results coming out of the new CPA laser. Another Canadian group from INRS-Énergie also came to Rochester to use the laser to do laser-plasma interaction experiments. One of the researchers was Jean-Claude Kieffer. After that, the CPA became very popular in many research laboratories around the world.

After Gérard moved to Michigan, SLC occasionally went to his new laboratory with his students and postdocs to carry out high laser field experiments using his Ti-sapphire laser at 800 nm. Later, with the advice of Gérard and Jeff Squier, SLC built up his versatile three-beam 2 TW Ti-sapphire laser at Laval University. In 1995, Gérard came to Laval to participate in a workshop organized by SLC. He told his story of accidentally damaging a series of optical components in his laboratory by his femtosecond laser pulses. He advised SLC to do more studies in this direction. SLC agreed. The field of femtosecond laser filamentation was thus born.

In 2005, Laval University honored Gérard with an honorary DSc degree. In 2010, SLC and Jean-Claude organized an international symposium at Laval University to celebrate the twenty-fifth anniversary of the invention of the CPA laser. Gérard and Donna were both honored at the symposium.

—See Leang Chin, Center for Optics, Photonics and Laser (COPL), Laval University, Quebec City; and Joseph H. Eberly, Deparment of Physics and Astronomy and The Institute of Optics, University of Rochester

I appreciate the opportunity to recall our time with Gérard and to think back on that time in my life.

The late 1970s and early ’80s were an exciting time at The Institute of Optics and at LLE. The Institute had just expanded into the Wilmot Building, and LLE was pushing hard to see if laser-driven thermonuclear fusion could be achieved. I was fortunate to have formed a working partnership with Gérard. Together, we supervised several PhD students and published half a dozen papers. We were inspired by a group of top-notch graduate students—John Agostinelli, George Harvey, Jim Kafka, and Janis Valdmanis—working on a variety of laser system topics: ultrafast optical pulse shaping, synchronization of pulses from mode-locked lasers, synchronous amplification of subpicosecond pulses, subpicosecond electro-optic sampling. Given the resources at The Institute and LLE, we could rapidly explore new opportunities and concepts.

My main recollection of Gérard during this time was his passion and enthusiasm. Gérard had a new idea (if not two or three) every day. He had a sense of humor and there was always a twinkle in his eye. One day toward the end of my active years at The Institute, I remember talking to Gérard about his new idea of chirped-pulse amplification. He was exuberant! He was especially excited about how this idea would make possible a “Table Top Terawatt” laser system. I recall thinking what a marvelous, simple, and elegant idea. Gérard went on to consider all the amazing opportunities this idea would open up.

I must confess that Gérard was way ahead on me. But now, thirty-five years later, here we are. Hats off and congratulations to Gérard and Donna for their outstanding Nobel achievement.

—Conger W. Gabel

In the year 1983, I was a PhD student doing my research at the Laboratory for Laser Energetics under the supervision of Gérard A. Mourou. I had actually been working at LLE with Wolf Seka starting in 1976 as an undergraduate even before Gérard was there, so I was, by definition, the first member of Gérard's research group. As I was finishing my PhD research and writing my thesis, I had job interviews at IBM, Hughes Laboratories, and Bell Labs. Gérard had come up with the concept of chirped-pulse amplification, from his readings about radar technology. He had the initial idea to build up a pilot demonstration system, with the thought that perhaps he could use the technique to build a laser system that could develop the same peak power as the entire Omega laser, but much smaller, perhaps the size of a table top. He came up with the name T-cubed ($T^{3)}$, for Table Top Terawatt laser. The name stuck for many years.

Anyway, he applied for an internal project approval to build the first system, and when it was approved, he came to me and said, "Wayne, the project was approved—and you can build the first T-cubed system!" I replied, "Sorry, I am accepting a postdoc position at Bell Labs, and you'll have to find somebody else to build it." Fortunately, a new PhD candidate had just joined the group and, as a second-year PhD student, accepted the project. As we now know, Gérard Mourou and Donna Strickland won the Nobel Prize in Physics for the work, and the award is well deserved. This work has had a very significant influence on the world, advancing the frontiers of high-power short-pulse lasers. One area of particular interest to me in my research is compact high-power femtosecond fiber lasers that we use for femtosecond micromachining. An important application was developed in the field of ophthalmology for blade-free cutting of corneal flaps for LASIK ablation surgery. The CPA concept made possible very compact high-power femtosecond fiber lasers that are about the size of a toaster. In my research, we have adapted this to a new kind of vision-correction procedure wherein localized refractive index corrections are written directly into the cornea with a compact CPA laser. My start-up company, Clerio Vision Inc., is now commercializing this technology, with a license to UR patents.

I have been asked if I regret my decision to turn Gérard down and go to Bell Labs for a postdoc position. My answer is: not at all! I can't imagine having done anything different . . . kudos to Gérard and Donna.

—Wayne H. Knox, professor of optics, physics,
materials science, and vision science

I've often wondered about the nature of creativity in science. Among artists, some in my family, success and fame seem clear: talent only gets you so far without inspiration, and inspiration gets you nowhere without talent. In a popular notion of scientists, people like Einstein and Feynman have set the image of success—of being a force complete unto oneself. But the fact of the matter is that in much of science success is down to the holistic nature of one's team.

Around the invention of the CPA technique, what I remember from the time is that Gérard had somehow hung on to a flashlamp-pumped amplifier that he had used in his PhD research, and it made its way into the T-cubed laser—I'll bet it came with him from France in his suitcase. And recently I read an interview that pointed out that Donna talked about the lasers in her lab at Waterloo with the same affection people normally reserve for their pets. Perhaps that's right—pets sometimes wreck your best clothes, much like the time that Donna smelled something funny, and caught her 5W argon-ion laser cutting a hole across the front of her knitted-wool sweater. Speaking as someone who tried to buy a laser rod from a magazine at age ten, these stories give me the feeling of having found my people. It makes me believe that the same excitement, shared, must have played into the teamwork that Donna, Gérard, and Patrick Maine grew into a new science with worldwide impact.

Among people who know Gérard, it's enough simply to say, "This is going to be fantastic!" with a French accent, and people will recognize who you mean. And it's easy for me to recollect Donna saying, "I'd have to give that some thought." Map and steering wheel; vision and path; conception and realization—the lines aren't quite that simple, and hard work after midnight grows all of it. In the end, teams work best when everyone does what they're good at.

—Robin S. Marjoribanks, University of Toronto

24. The Institute of Optics 2029

P. Scott Carney

Figure 24.1. P. Scott Carney, director and professor of The Institute of Optics.

Ten years isn't all that far off, not an unimaginable future. I'm not really expecting macroscopic teleportation or world peace, though both would be nice. Ten years ago, in 2009, I was on sabbatical in the Netherlands. Governments were still pouring water on the embers of the global economy. The Institute, just a few years in its new building, stood as an imagined green glow across the ocean from me like my own East Egg, a place of promise and history and infinite potential. In retrospect, the state in which I find the world and The Institute in 2019 seems like a straight-line extrapolation from that time. And yet I cannot frame or forecast the state of The Institute in 2029 with any confidence. I can only tell you what I believe will drive us, and the means by which we will understand our place in the world.

In reading this text, this extraordinary history of The Institute, this lovingly crafted masterwork of Carlos Stroud and Gina Kern, I hope you join me is seeing that we have never been about endpoints, never really about destinations. The Institute is a place of beginnings, of launches, of extraordinary optimism and a leap into the fray. To borrow from Jim Zavislan, we are the first responders of engineering; we run toward problems. We have again and again risen to meet needs: the needs of the growing optics industry in Rochester in the 1930s, the needs of the national defense in the 1940s and ’50s, the challenges in basic science presented by the laser in the 1960s, ’70s, and ’80s, the workforce needs of the telecom boom, the need for advances in medical optics, and the race to realize the promise of nano-optics. We have adapted and grown step by step with a field we have defined and created to meet needs: ouroboros wrapped around one of Jaime Cardenas’s microring resonators, creating and destroying ourselves, always brand-new, always imprinted with our history.

We have led the field through service. Today I count among my faculty four current journal editors-in-chief: Tom Brown at the *Journal of Modern Optics*, Govind Agrawal at *Advances in Optics and Photonics*, Xi-Cheng Zhang at *Optics Letters*, and yours truly at the *Journal of the Optical Society of America A*, a position I am proud to share with a previous editor and current member of my faculty, Jim Fienup. Miguel Alonso drove the creation and served as founding chair of *Spotlight on Optics*. Joe Eberly became the founding editor at *Optics Express*, leading the way on modern academic publishing. He also served as president of the OSA as did Duncan Moore. Indeed, counting up faculty, current and former, and alumni from all degrees, we conservatively come to thirty-five presidents of our major professional societies. The number of editors and associate editors among current and former faculty and alumni is dizzying. We meet needs by serving. This is the lasting hallmark of The Institute of Optics. I am confident that 2029 will see Institute faculty, then as now, devoting long hours and untold energy to serve our students, our colleagues, our community, and our discipline. We lead by serving. We serve by leading.

Of this era, I suspect a future director in 2029 may write that, led by Nick Vamivakas, we launched the age of quantum technologies. Or perhaps that Jannick Rolland paved the way to otherwise unforeseen freeform display, imaging, and sensing optical platforms. Or that Andrew Berger forged the critical diagnostic technologies needed to address maladies of age or malnutrition. Or that Wayne Knox brought perfect vision to the world with ultrafast lasers. Or that Chunlei Guo changed forever manufacturing with nanopatterned surfaces. Or all of these, impulse to run toward the needs of our community, to fill gaps in our understanding, to invent life-changing technologies, to train a workforce for exponentially expanding opportunities.

In 2029, as in 2019, we will embrace our heritage as stewards of the discipline. Academia is a funny place to make a living. We serve two masters: our students and our discipline. In a growing and dynamic field, as is optics, it is easy to forget that there are two masters, because the service of one is so easily also the service of the other. To serve our discipline we have a duty to archive, to explicate, and to disseminate the truths and intuitions, the insights and tools, the history, and the uncertainties of a field that abounds in all of these. Having felt the boundaries of knowledge and know-how, it is incumbent on us to push—to push as our forebears pushed—toward new discoveries, new inventions, and most importantly, new unknowns and new challenges. We have an obligation to open new horizons as horizons were made open to us. We answer this call with research, research like that of John Marciante, capturing astonishing new levels of power in optical fibers. And none of this means much without handing all of it to a new generation of PhDs and scholars, imparting these advances to graduates at all levels to take out into a world ready for new discoveries and inventions, to safeguard the progress we've made. In parallel to these obligations to our discipline, we are obliged to these students to set them up for success as scholars, as professionals, and as functioning members of our society. We do that through world-class instruction from experts like Julie Bentley, who spends countless hours mentoring students through real and challenging designs. We must offer our students an education that is solid and foundational and inspires a wild creativity and desire to change the world. Alumni of The Institute should be well prepared and straining at the bit. They should burst from the gate at graduation like an apocalyptic stampede, charging out across the world and shining the light of optics into every dark corner. For us at The Institute, reconciling our duty to our discipline and our duty to our students is blessedly easy: we teach them optics and let them go.

And so we come to what I believe is the fundamental, existential question for The Institute: What is optics? We hang this one like an innocent passing remark from the banners in our front hall. Maybe it's Jen Kruschwitz building a reflective coating a few molecules at a time. Maybe it's David Williams capturing the living, working retina. Maybe it's Bob Boyd taking a photon for a leisurely walk. What is optics? Oh, it's all sorts of things involving electromagnetics and lenses, and quantum mechanics, and lasers, spectroscopy, and semiconductors, and lots of other stuff too. But the quiet, subtle message, showing just around the edges of that banner, is that we define optics. And this has been the magic of The Institute. We define optics. But we have been so successful at this that we are not the only ones who seek to define the field today, and we will certainly be joined by others in 2029. As our colleagues, our brothers and sisters, help make yesterday's vision become today's reality, grow the field and make standard the academic bone fides of degrees and departments and colleges of optics, they too have a voice in the content and direction of the discipline. As 2029 approaches, we will learn a new set of skills. We will not just lead, we will listen to our many partners and we will lead with them. We will embrace the mantle of stewardship of a discipline that now comprises many voices and many institutions. We have stood long enough on the vanguard, defining and defending this discipline. In 2029, we will participate in a community of scholars and researchers who will define, together with us, what optics is.

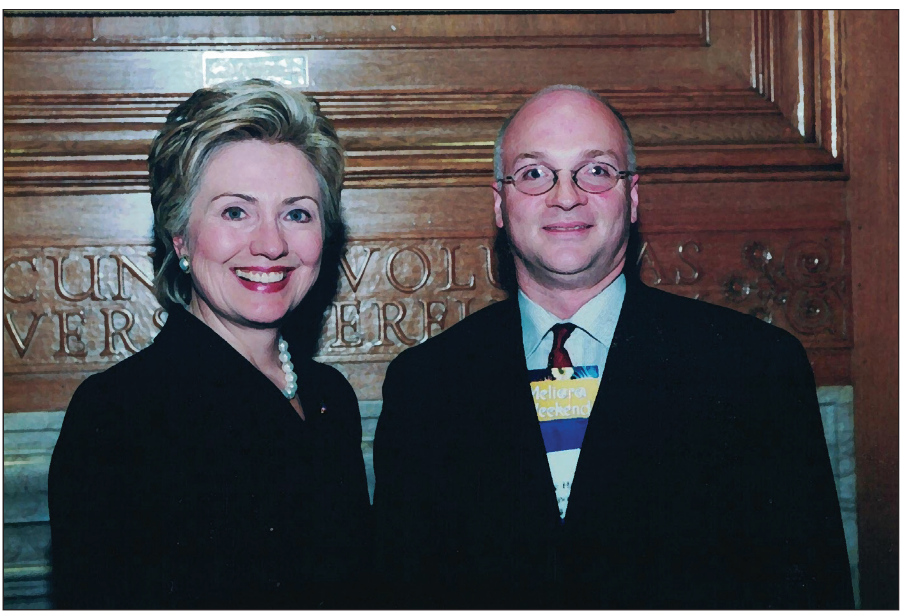
How will The Institute of Optics of 2029 differ from The Institute of Applied Optics founded a century earlier? It will not stand alone. The greatest success of The Institute is a growing field of colleagues at strong institutions around the country offering degrees in optics serving students and growing the discipline, inventing and discovering what lies just beyond the current frontiers and subsuming new territory. The success of The Institute is the success of the discipline. As we continue to build our scientific community, our industry, and our body of scholarship, come 2029 it will be commonplace that a high school student will tell her mother, "I'm thinking of majoring in physics or engineering, but most likely optics." And her mother will know exactly what that student means, because she has received so many information packets on optics programs around the country and the parents of the friends of her daughter have proudly declared that their child is off to major in optics, excited to study solitons and nonlinear optics with the world-renowned Will Renninger. The Institute in 2029 will be filled with people who feel the momentum of our history and look forward to the next hundred years.

Highlight VI. Presidents, Emperors, and Optics Leadership

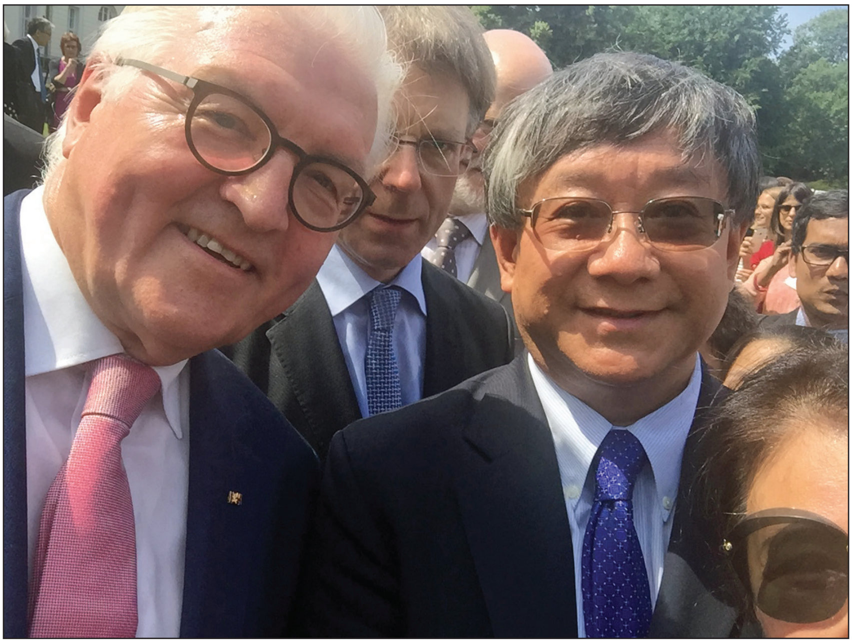
1. Carlos Stroud with Louise Slaughter at the Fall 2015 Industrial Associates meeting.

2. His Holiness the Fourteenth Dalai Lama presenting the third-place award to University of Rochester students in the 2015 Tibetan Innovation Challenge.

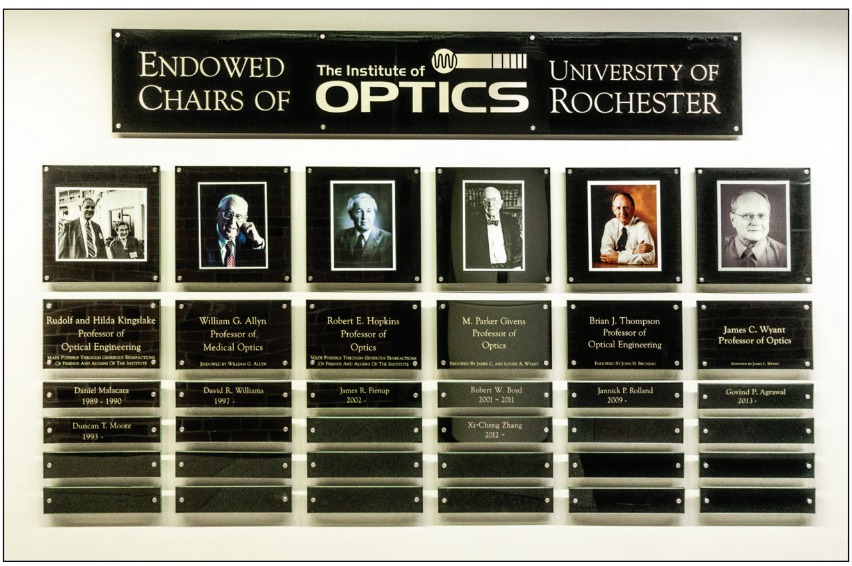
3. Emperor Akihito and Empress Michiko greet Duncan Moore after the toast he presented at the International Council for Science Meeting, October 2017.



4. Wayne Knox with Senator Hillary Clinton, Meliora 2003.



5. German president Frank-Walter Steinmeier with Xi-Cheng Zhang, the 2018 Alexander von Humboldt Prize winner (taken during reception at the German Presidential Palace).



6. Institute of Optics endowed professorships display (to be added to the display: the Nicholas George Professorship in Optics).

PART VII

People of The Institute

25. Faculty, Staff, and Students: A Photographic Essay

Figure 25.1. Faculty of The Institute of Optics, 2018. First row: Govind Agrawal, Duncan Moore, Jaime Cardenas, Svetlana Lukishova; second row: Chunlei Guo, Wayne Knox, Jennifer Kruschwitz, Carlos Stroud, Jannick Rolland; third row: Xi-Cheng Zhang, Georg Nadorff, Gary Wicks, John Marciante; fourth row: Jake Bromage, James Fienup, William Renninger, Thomas Brown, Nickolas Vamivakas; fifth row: P. Scott Carney, Joseph Eberly, James Zavislan, Andrew Berger; not pictured: Miguel Alonso, Julie Bentley, Robert Boyd, Thomas Foster, Jennifer Hunter, Krystel Huxlin, Todd Krauss, Brian Kruschwitz, Qiang Lin, Benjamin Miller, David Williams, Guenyoung Yoon, Jonathan Zuegel. Adjunct faculty: John Bowen, Dale Buralli, Josh Cobb, Clark Eastman, Brian McIntyre, Jessica Nelson, James Oliver, Greg Savich, Anthony Visconti.

Figure 25.2. Staff of The Institute of Optics, 2018; front row: Adrienne Snopkowski, Lynn Reiner, Lori Russell; middle: Evelyn Goldman, Per Adamson, Gina Kern, Cecilia Chapa; back: Dustin Newman, Kai Davies, Tal Haring.

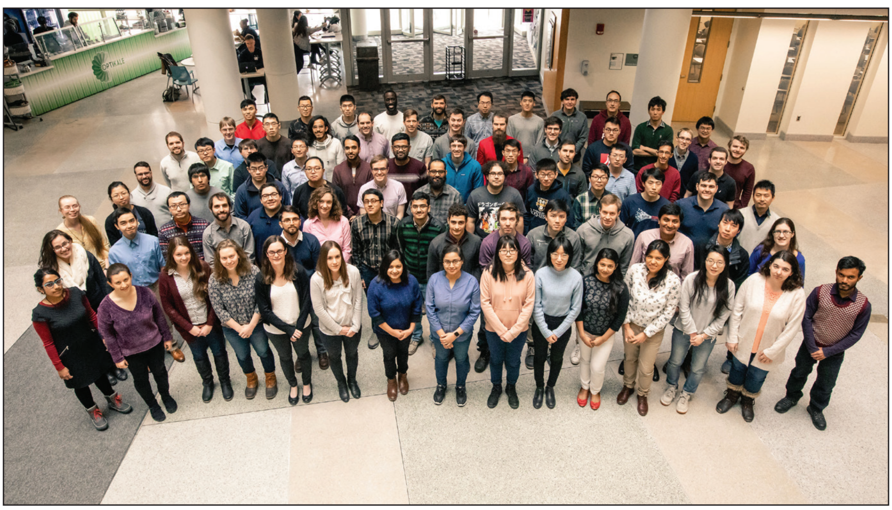


Figure 25.3. Some of the graduate students of The Institute of Optics (April 2019).

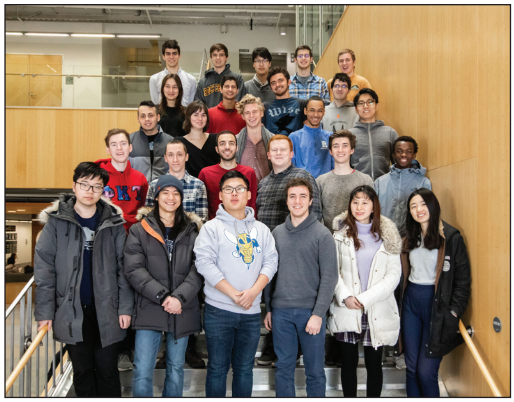


Figure 25.4. Some of the undergraduate students of The Institute of Optics (April 2019).

Figure 25.5. Members of The Institute of Optics gathered in the Munnerlyn Atrium of Goergen Hall (April 2019).

Table 25.1. 2018 UR Faculty of The Institute of Optics

<table>
<tr><th colspan="2">Tenured Full Professors (15)</th><th colspan="2">Secondary Appointments (12)</th></tr>
<tr><td>Govind Agrawal</td><td>Wayne Knox</td><td>Nick Bigelow</td><td>Todd Krauss</td></tr>
<tr><td>Miguel Alonso</td><td>Duncan Moore</td><td>Jake Bromage</td><td>Brian Kruschwitz</td></tr>
<tr><td>Andrew Berger</td><td>Jannick Rolland</td><td>Joseph Eberly</td><td>Qiang Lin</td></tr>
<tr><td>Robert Boyd</td><td>Carlos Stroud</td><td>Tom Foster</td><td>Ben Miller</td></tr>
<tr><td>Thomas Brown</td><td>Gary Wicks</td><td>Jennifer Hunter</td><td>Goonyoung Yoon</td></tr>
<tr><td>P. Scott Carney</td><td>David Williams</td><td>Krystel Huxlin</td><td>Jonathan Zuegel</td></tr>
<tr><td>James Fienup</td><td>Xi-Cheng Zhang</td><td></td><td></td></tr>
<tr><td>Chunlei Guo</td><td></td><td></td><td></td></tr>
<tr><th colspan="2">Tenured Associate Professors (2)</th><th>Sr. Scientist</th><th>Lecturer</th></tr>
<tr><td>Nickolas Vamivakas</td><td>James Zavislan</td><td>Svetlana Lukishova</td><td>Brian McIntyre</td></tr>
<tr><th colspan="2">Tenure-Track Assistant Professors (2)</th><th colspan="2">Adjunct Faculty (9)</th></tr>
<tr><td>Jamie Cardenas</td><td>William Renninger</td><td>John Bowen</td><td>Georg Nadorff</td></tr>
<tr><th colspan="2">Associate Professors (non-TT) (2)</th><td>Dale Buralli</td><td>Jessica D. Nelson</td></tr>
<tr><td>Julie Bentley</td><td>John Marciante</td><td>Josh Cobb</td><td>Greg Savich</td></tr>
<tr><th colspan="2">Assistant Professor (non-TT) (1)</th><td>Clarke Eastman</td><td>Anthony Visconti</td></tr>
<tr><td>Jennifer Kruschwitz</td><td></td><td>Svetlana Lukishova</td><td></td></tr>
<tr><td></td><td></td><th colspan="2">AIN Center (2)</th></tr>
<tr><td></td><td></td><td>Randall Hems (AIN)</td><td>Filipp Ignatovich (AIN)</td></tr>
</table>

26. Companies Founded by Institute of Optics Alumni and Professors

Name	Name of Company	Start Date
Aikens, David	Savvy Optics	2007
	Dema Bekz Corp.	1989
Amarel, John	Amarel Precision	1980
Anderson, James	Tropel (with R. Hopkins and J. Evans)	1953
	Optics Technology, Inc. (with J. Buzawa)	1986
Arnon, Oded	Arnon Optical Engineering	mid-1980s
Atkinson, III, Leland G.	Gradient Lens Corp. (with D. Moore)	1980
Bado, Philippe	Medox electro-optics	1987
	MXR (Medox Research)	1989
	Clark-MXR	1992
	Translume	2001
Bechtold, Michael	Optipro Systems (president)	1982
Berg, David	Oren Sage Technology	2006
Blough, C. Gary	Photon Gear, Inc. (with J. Bowen and D. Faklis)	2000
Bowen, John	Photon Gear, Inc. (with G. Blough and D. Faklis)	2000
Boyd, Robert	KBN Optics, LLC	2009
Bristow, Thomas	Chapman Instruments (president and founder)	1989
Brophy, Christopher	Optical Engineering Services	2008
Brukilacchio, Thomas	Concepts in Electrooptics (CEO)	1990
	Innovations in Optics	1993
	Vipera Systems	1996
Buzawa, (Michael) John	Optics Technology, Inc. (with J. Anderson)	1986
Caldwell, J. Brian	Caldwell Photographic, Inc.	2001
	Optical Data Solutions	1988

(continued)

Name	Name of Company	Start Date
Carellas, Peter	Xcitex	1999
Carney, P. Scott	Diagnostic Photonics, Inc.	2008
Chan, Richard "Rick" Henri	Super Stealth Mode	2017
Costich, Verne	Design Optics	
Cotton, Christopher	ASE Optics	1994
	Lumetrics	2003
	ASE Instruments	2002
	ASE Properties	2002
	Rochester Regional Photonics Cluster	2000
Creath, Katherine	Optineering	1995
Cumbo, Michael	OCR	1993
	Sandia Electro-Optics Corporation	2013
	Eta Diagnostics, Inc. (ETAD)	2013
DeBell, Gary	MLD Technologies	1997
	DiMaxx Technologies	1997
Diehl, Damon	DIEHL Research Grant Services	2011
Duquette, Philip	Premier Pastry	1989
Eastman, Jay M.	Lucid	1992
	Optel	1981
	Vital Motion, Inc.	1991
	Optel Systems	2014
Erdogan, Turan	Semrock	2000
Evans, John (Jack)	Tropel (with R. Hopkins and J. Anderson)	1953
	Velmex	1967
Faklis, Dean	Rochester Photonics Corp.	1989
	Ascribe, Inc.	1997
	Perluma	1997
	Photon Gear, Inc. (with J. Bowen and G. Blough)	2000
	LightGage, Inc. (with J. Marron)	2001
Fantone, Stephen D.	Optikos	1982
Fargnoli, Joseph	RITRE (Rochester Innovation and Technology Research Enterprise)	2009
Farmiga, Nestor	Khiram Prototype Works	2009
Fischer, Robert E	OPTICS 1, Inc.	1987
Flint, Douglas	Holometrix	1987
	Azimuth	1991

(continued)

Name	Name of Company	Start Date
Forbes, Gregory	R&D Technology, Australia	1993
Forkey, Richard	Precision Optics Corporation (CEO)	1982
Forman, Paul	Zygo	1970
Forsyth, James	Hampshire Instruments	1985
Freese, Robert P.	Alphatronix	1987
	Acclivity, Inc.	1998
	Bright View Technologies	2001
	Ometric	2004
Gabel, Conger W.	Hardy Gabel Group, LLC	2000
	George, Gabel & Conners (GG&C) Imaging Systems (with N. George and Gary Conners)	2004
Gaeta, Alexander	PicoLuz, LLC	2009
Gardner, Leo	Optical Data Solutions	1988
George, Nicholas	George, Gabel & Conners (GG&C) Imaging Systems (with C. Gabel and Gary Conners)	2004
Goldstein, David	Elgeet Optical	1946
	D.O. Industries, Inc.	1972
	NAVITAR	1993
Golini, Donald	QED Technologies	1997
Gortych, Joseph	Opticus IP Law	2000
Granger, Edward M.	Ontario Beach Systems, LLC	1999
	IQ Colour, LLC	2003
	Delta E Instruments	2008
	XYZ Color Science	2010
Greenwald, Roger	NJK & Associates, Inc.	2007
Harris, Thomas I.	Optical Research Associates	1963
Hearn, Gregory	SCIOPT Enterprises	1981
Hennings, David	Sunrise Technologies	1986
	Newstar Lasers	1994
	Cooltouch Corp	1996
	Pulsar, Inc.	1998
Hercher, Michael M.	Coherent Optics	1964/65
	OPTRA, Inc.	1980
Hesterman, Jacob	Invicro	2008
Hopkins, Robert Earl	Tropel (with J. Evans and J. Anderson)	1953
	Optizon	1982
Horwitz, Bruce A	TechRoadmap, Inc.	2000

(continued)

Name	Name of Company	Start Date
Houde-Walter, Susan N.	LaserMax	1989
Houk, Michael	Bristol Instruments, Inc.	2005
Howard, James	Telic Optics	1986
Hudyma, Russell	Paragon Optics, Inc.	1994
	Hyperion Development (with M. Thomas)	2004
Jain, Anil	Optivision	1985
	Computer Vision Research Laboratory	1984
Kapany, Narinder Singh	Optics Technology, Inc.	1960
	Sikh Foundation (nonprofit)	1967
	Kaptron, Inc.	1973
	K2 Optronics	2000
Kim, Felix	Ovitz	2013
Kim, Joseph	Rainbow Research Optics, Inc.	1995
	Tecport Optics	1997
Klimasewski, Robert	Burleigh Instruments, Inc.	1972
Knox, Wayne	Clerio Vision	2014
Ko, Michael	Vitex, LLC	2003
Koliopoulos, Chris L.	WYKO	1983
	Phase Shift Technology	1987
Kowarz, Marek	MicroAdventure Technologies	2011
Kramer, Charles J.	Holotek	
Kruschwitz (Traylor), Jennifer	JK Consulting	1998
Kumler, James (Jay)	Coastal Optical Systems	1991
	JENOPTIK Optical Systems, LLC	2002
Lahcanski, Tomi	Torox Vision	2012
Last, Jay T.	Fairchild Semiconductors	1957
	Amelco Corporation	1961
	The Archaeological Conservancy (nonprofit)	1989
Lees, David	DEBL Associates	1994
Leiner, Dennis C.	Lighthouse Imaging Corp	1984
Lou, Xinye	North Ocean Photonics	
Malyak, Phillip	Dragon Fire, Inc.	2002
Mandra, Robert	RSM Advisors	2012

(continued)

Name	Name of Company	Start Date
Manian, Bala	Digital Optics Corp.	1980
	Lumisys	1987
	Molecular Dynamics	1987
	Biometric Imaging	1993
	Quantum Dot Corp.	1998
	SurroMed Corporation	2000
	ReaMetrix, Inc.	2003
	India Innovation Fund	
Marron, Andrea	Studio 28 Couture	2007
	Ragtrades, Inc.	2013
Marron, Joseph C.	LightGage, Inc. (with D. Faklis)	2001
McGuire, Kevin	Tailored Lighting	1989
	UV Technologies, LLC	2010
McKinley, Harry R.	McKinley Optics (president)	1967
Miceli, Joseph	Sweet Technology, Inc.	2001
	Sweetproperty, LLC	2003
	Banyon Finance	2004
	Seneca Property, LLC	2005
Moore, Duncan T.	Gradient Lens Corp. (with L. Atkinson)	1980
Moran, John	Velocity Screenprint & Embroidery	1996
	Glas Apparel & Film	1995
	Blue Wave Marketing and Promotions	1991
Morris, G. Michael	Rochester Photonics Corp.	1989
	Apollo Optical Systems (CEO)	1989
Morrison, Robert	Coherent Investments	2006
	Forward Steps Foundations	2006
	Clear Crossing	2006
	Realizing Aptitudes	2008
Munnerlyn, Charles R.	VISX	1987
	Ical	1979
Munro, James	Munro Design & Technologies, LLC	2007
Murnan, Andrew S.	Genawave, Inc.	1993
Neumann, Gad(i)	Negevtech	1991
Nir, Shlomo	Controp Precision Technology Ltd	2000
Noyes, Gary R.	Gary Noyes Lens Design	1998
Oron, Moshe	Kilo Lambda	2001
Osada, Hidenori	OPI (Osada Photonics Int) Corporation	2008
Palvino, Mark	MPX Wireless	1999

(continued)

Name	Name of Company	Start Date
Pansari, Ankur	Artillery Games, Inc.	2012
	Favo, LLC	2006
	Treosoft	2002
Papademetriou, Stephanos	Selva Medical, Inc.	2003
	Irillant, Inc.	2007
	Oramic	2005
	Eve Biomedical	2011
	IntraVu, Inc.	2015
	neuroFit, Inc.	2016
Pavia, Michael	Sydor Instruments	2004
Pfisterer, Richard N.	Photon Engineering	1997
Plotsker, Vadim	Oasys Technologies	2004
Potter, Robert J.	RJ Potter Company	1990
Procino, Wesley	AutoVision	1997
Pugliese McMackin, Lenore Jo	InView Technology Corp.	2009
Remijan, Paul	Micro-Optics, Inc.	1997
	Fathom Imaging, Inc.	1997
Renaud, Blaise	OptWare CH	1989
Rimmer, Matt	Scientific Calculations	1963
Rinehart, Thomas	Alphatronix	1997
Ruda, Mitchell	Ruda & Associates	1994
	Cardinal Optics, Inc.	2000
Ruff, Bruce J.	Bruce Ruff Optical Engineering	
Sankey, N. Darius	Zone Ventures	
Shafer, David	David Shafer Optical Designs	1980
Sheehy, Christy	C. Light Technologies	2019
Sinclair, Douglas C.	Sinclair Optics	1976
Smith, Douglas	Plymouth Grating Laboratory	2004
Smith, Linda	Ceres Technology Advisors	2006
	Tego	2005
Spencer, Gordon H.	Scientific Calculations	1963
Sprague, Robert A.	Gyricon LLC	2000
Stern, Ronald	Telic Optics	1986
	New England Optical Systems	2008
Stoltzmann, David E.	Optical Engineering of Minnesota	1989
Stone, Thomas W.	Wavefront Research, Inc.	1993
Sweetser, John	Think Optics	

(continued)

Name	Name of Company	Start Date
Sydor, Stefan	Sydor Optics	1972
Thomas, Michael	SPICA Technologies, Inc.	1990
	Genesee Valley Transportation	1990
	Hyperion Development (with R. Hudyma)	2004
Tinker, Flemming	Flemming Tinker, LLC	2005
	Aperture Optical Sciences, Inc.	2010
Tocci, Michael	Contrast Optical Design & Engineering, Inc.	2005
Truax, Bruce E.	Diffraction Limited Design, LLC	1993
Unger, Blair	BLU Optics	2008
Vayser, Alexander	Invuity	2004
	Medvision, Inc.	1992
	Parallax Devices, LLC	2004
Vizgaitis, Jay	OPTX Imaging Systems, LLC	2014
Vock, Curtis	Think Village	2006
	PhatRat Technology	1994
	Golf Age Technologies	1995
	SeeUV	1994
	Headmouse	1995
	OptiEnz	2008
Waldman, Mark	Healthy Gigs	2014
	Three Freedoms International	1998
Walsh, Ken	Optizon	1982
Weller-Brophy, Laura	FluoroLogic, Inc.	2008
Williamson, Steven	Picometrix	1992
Wohl, Michael	Prism Manufacturing, Inc.	1992
	BWMedia, Inc.	1996
	Greenspace	2008
	Art of Peace Foundation	2008
	Climate Hedge Investments	2013
Wyant, James C.	WYKO	1983
	4D Technology	2002
Zavislan, James	Lucid, Inc.	1992
Zweig, David	Zarbeco	2001

27. Professors of The Institute of Optics

Name	Dates
Agrawal, Govind P.	1989–
Ahrenkiel, Richard K.	1973–77
Alley, Carroll O.	1962–63
Alonso, Miguel A.	2003–
Altman, Joseph H.	1969–98
Balasubramanian, N.	1973–75
Baldini, Giancarlo	1960–64
Baumeister, Philip W.	1959–79
Bentley, Julie L.	2000–
Berg, David	2006–16
Berger, Andrew J.	2000–
Berry, William	1929–33
Bigelow, Nicholas P.	2001–
Blakney, Robert M.	1959–66
Bowen, John	2018–
Boyd, Robert W.	1977–
Boynton, Robert M.	1955–72
Brody, Edward M.	1970–81
Bromage, Jake	2015–
Brown, John L.	1975–78
Brown, Thomas G.	1987–
Buralli, Dale A.	2002–
Campbell, J. Stuart	1935–40
Cardenas, Jaime	2016–
Carney, P. Scott	2017–
Carpenter, Vance J.	1956–62
Clark, Herbert A.	1938–43
Clarke, Frank J.	1964–65
Cobb, Josh	2018–

Name	Dates
Collins, Francis A.	1964–67
Covell, William D.	1940–42
Creuzberg, Martin	1967–71
Critchfield, Charles L.	1940–41
Dai, Jainming	2012–15
Dainty, John Christopher	1979–85
Davy, L. Nevil	1987–94
Dewey, Jane	1929–30
Dexter, David	1953–61
Di Francia, Giuliano T.	1953–54
Dray, Richard C.	1942–43
Dunham, Theodore	1953–57
Dunn, Paul	1971–81
Dutton, David B.	1954–63, 1975–78
Eastman, Clarke	2016–
Eastman, Jay M.	1979–98, 2011–
Eberly, Joseph H.	1979–
Edgerton, Robert F.	1962–63
Ellis, Jonathan	2011–17
Erdogan, Turan	1992–2004
Evans, John W.	1943–65
Evans, John Cushing	1946–49
Ewald, William P.	1956–65
Eyer, James A.	1959–66
Fairbanks, Floyd C.	1929–30
Fang, Sheng-Heng	1961–62
Fassin, Gustave	1930–40

(continued)

Name	Dates
Fauchet, Philippe M.	1994–2012
Fienup, James R.	2002–
Finkelstein, Nisson	1958–59
Forbes, Gregory W.	1985–94
Forsyth, James M.	1969–85
Foster, Thomas H.	2002–
Fox, David	1958–59
French, Robert W.	1943–46
Fumi, Fausto	1957–58
Gabel, Conger W.	1975–88
Garbuny, Max	1969–70
George, Nicholas	1978–2015
Givens, M. Parker	1948–2013
Gold, Albert	1962–70
Goldblatt, Norman R.	1967–69
Gough, Peter T.	1975–77
Greenwood, Gilbert	1929–30
Guo, Chunlei	2001–
Hall, Dennis G.	1981–2002
Hamilton, John F.	1969–88
Harrison, Patrick G.	1964–68
Hercher, Michael M.	1965–75
Heurtley, John C.	1968–74
Holmgren, Douglas E.	1985–88
Hood, J. Douglas	1929–30
Hopkins, Robert E.	1943–2009
Houde-Walter, Susan N.	1987–2005
Hyde, W. Lewis	1963–68
Howell, John	2015–
Hunter, Jennifer	2017–
Huxlin, Krystel	2018–
Illingworth, Robert	1961–63
Ingelstam, Erik	1960–61
Jacobs, Stephen D.	1988–2015
Jones, Lloyd A.	1929–43
Kapany, N. S.	1956–57
Kay, David B.	1975–78
Kaye, Rachel	1960–61

Name	Dates
Keck, Robert	1985–88
Kingslake, Rudolf	1929–2003
Knox, Wayne H.	2000–
Knox, Robert S.	1960–61
Kristianpoller, Norbert N.	1961–63
Kruschwitz, Brian	2015–
Kruschwitz, Jennifer Traylor	2007–
Kurtz, Henry	1930–32, 1935–36
Lea, Michael C.	1980–87
Lin, Qiang	2011–
Lisle, Claudine	1964–65
Loewen, Erwin	1988–98
Lowry, Earl M.	1929–30
Lubin, Moshe J.	1971–81
Luckiesh, M.	1930–31
Lukishova, Svetlana	2006–
MacAdam, David L.	1977–96
Mandel, Leonard	1978–2000
Marchand, Eric	1980–94
Marciante, John R.	2001–
Martin, L. C.	1936–38
McIntyre, Brian	2004–
Mees, C. E. Kenneth	1929–43
Miller, Benjamin	2016–
Miller, Christine E.	1994–96
Milne, Gordon G.	1948–66
Moore, Duncan T.	1974–
Morris, G. Michael	1980–2002
Moss, F. K.	1930–31
Mourou, Gerard	1979–94
Murlin, John R.	1929–32
Murty, Mantravado V. R. K.	1959–64
Nadorff, Georg	2019–
Nakai, Yoshio	1959–61
Nelson, Jessica DeGroote	2010–
Nitchie, Charles	1934–35
Novotny, Lukas	1999–2011

(continued)

Name	Dates
O'Brien, Brian	1930–55
Oliver, James B.	1998–
Panizza, E. Hora	1965–68
Paul, Frederick W.	1948–50
Pegis, Richard J.	1961–62
Perrin, Fred	1958–61
Peskin, James C.	1959–77
Petry, Ernest	1929–36
Polster, Harry D.	1948–54
Raymer, Michael G.	1979–94
Rayton, Wilbur B.	1929–31
Renninger, William	2017–
Rogers, John R.	1985–94
Rolland, Jannick	2009–
Sands, Peter J.	1967–70
Santamaria, Javier	1975–77
Savedoff, Malcolm P.	1958–59
Sayanagi, Kazuo	1966–67
Savich, Greg	2015–
Sceats, Mark G.	1977–81
Schertler, Donald J.	1996–2002
Sedgwick, H. Jobe	1930–34
Seka, Wolf	1994–
Sherman, George C.	1970–77
Siegmund, Walter P.	1953–55
Sinclair, Douglas C.	1965–67, 1970–79
Smith, Douglas	1989–92, 1999–2002
Smith, Warren	1988–94
Snaveley, Benjamin B.	1970–7

Name	Dates
Spitalnik, Steven	1979–81
Staehle, Henry C.	1940–41
Stewart, Harold S.	1943–46, 1959–62
Stone, Bryan D.	1994–2000
Stone, Thomas W.	1997–94
Stossel, Brian J.	1996–2000
Stroud, Carlos R., Jr.	1969–
Taylor, A. Maurice	1929–34
Teegarden, Kenneth J.	1955–2018
Thompson, Brian J.	1968–
Tutihasi, Simpei	1956–58
Tuttle, Fordyce	1940–62
Unvala, Hoshang A.	1966–68
Uydess, Ian L.	1977–78
Vamivakas, A. Nickolas	2011–
Visconti, Anthony	2017–
Walmsley, Ian A.	1988–
Wang, Shen-ge	1994–2000
Wever, Grace	1980–81
Wicks, Gary W.	1987–
Wilder, Herbert E.	1929–39
Wilkins, T. Russell	1929–39
Williams, David R.	1988–
Wolf, Emil	1978–2018
Yonezawa, Seiji	1968–70
Yoon, Geunyoung	2008–
Zavislan, James M.	2001–
Zhang, Xi-Cheng	2012–
Zuegel, Jonathan	2015–

28. Alumni of The Institute of Optics through 2019

Name	Degree and date
Abel, Irving R.	BS ’45
Acchione, Lawrence John	MS ’71
Achziger, Josh M.	BS ’92
Adair, Ty	BS ’16
Adamo, Daniel Right	BS ’75
Adams, James Edward	MS ’83
Adams, Marc Spencer	MS ’00
Adams, Margaret M. Brant	BS ’48
Adelsberger, Kathleen Elizabeth	BS ’05, MS ’06, PhD ’14
Agbayani, Sheldon A	BS ’15
Agliata, Thomas Peter	MS ’69
Agnello, Samuel Matteo	MS ’19
Agostinelli, John Alfonse	MS ’77, PhD ’81
Aguilera, Nancy	BS ’18
Aikens, David Mikal	BS ’83, MS ’84
Albasio, Marco Cosma	BS ’86, MS ’90
Albert, Daniel G.	BS ’86
Albright, Dan Steven	MS ’93
Alderfer Hokula, Shannon C	BS ’11
Aldrich, Robert Earle	BS ’85
Alexander, Lindsey Marie	MS ’04
Al Ibrahim, Redha Hussein M.	BS ’18
Allard, Peter Michael	BS ’90
Allardyce-Bowler, Karen A.	BS ’82, MS ’85
Allen, Amy Christine	BS ’83
Allen, Arthur W.	BS ’33
Allen, Bradley Stuart	BS ’96
Allen, George A.	BS ’91
Allen, Matthew Mark	BS ’97
Allgeier, Michael Edward	BS ’72
Allyn, Elizabeth Stacy	BS ’85
Allyn, William Gibbons	BS ’34
Aloise, James Robert	BS ’84
Alonso, Miguel	PhD ’97
Alte, Elizabeth D.	BS ’68
Altebrando, Joseph Michael	BS ’79
Altfather, Kenneth William	MS ’79
Altman, Richard M.	BS ’50, MS ’58
Altmann, Griffith E.	BS ’90, MS ’91
Amarel, John Anthony	BS ’69
Ambrose, Joseph George	MS ’87
Ames, Gregory Holt	BS ’82, MS ’82
Anderegg, Jane Louise	MS ’87
Anderson, Alexander Quentin	BS ’16
Anderson, Neil	PhD ’07
Anderson, Sean P.	PhD ’11

(continued)

Name	Degree and date
Andre, Richard R.	BS ’96, MS ’97
Andursky, Mark Ernest	BS ’44
Angeley, David G.	BS ’85, MS ’86
Ansley, David A.	BS ’62
Antikainen, Aku Johannes	MS ’17
Antipa, Nicholas Alexander	MS ’09
Anzellotti, Jay Frank	BS ’92
Appel, James Joseph	BS ’67
Aquilina, Thomas James	MS ’77
Arabos, Vasilios Nicholas	BS ’86
Arackellian, Kevork Garabed	BS ’84, MS ’86
Arai, Takeo	BS ’85
Arecchi, Arcangelo V.	MS ’72
Argaman, Ephraim	MS ’74
Armstrong, J. Joseph	BS ’91, MS ’92
Armstrong, Katherine	BS ’18
Armstrong, Scott	PhD ’78
Armstrong, Thomas M.	BS ’75
Arndt, Joseph Henry	MS ’67
Arnold, Bruce Young	MS ’74
Arnon, Oded Ohanna	PhD ’79
Aronson, Casper J.	BS ’38, MS ’39
Aronson, David Jay	BS ’82
Aronstein, David L.	MS ’97, PhD ’02
Arrigali, Vincent Richard	BS ’82, MS ’84
Asack, Scott Michael	BS ’93
Ashcraft, Jaren	BS ’19
Ashok, Madhu Andrea	BS ’15
Atkinson, Leland	PhD ’86
Atlas, David Scott	BS ’79, MS ’82
Attanasio, Daniel V.	MS ’91

Name	Degree and date
Aude, Carl William	BS ’91
Aude Biermann, Lois Ann	BS ’87, MS ’88
Austin, Nathaniel Sean	BS ’09
Averion-Mahloch, Timothy James	MS ’88
Aviado, Carlos Guevara	BS ’79
Ax, Cathleen Marie	BS ’87
Ayers, Wendell Gale	MS ’66
Badar, Timothy Gerard	MS ’90
Bader, Todd Richard	PhD ’70
Bae, Janghwan	MS ’15
Baer, James W.	MS ’78
Baer, Jennifer Michelle	BS ’03
Baker, Catherine Mary	BS ’88
Baker, William L.	BS ’56
Baldwin, Christopher	MS ’84
Baldwin, Kevin Charles	BS ’90, MS ’91
Balkus, Francis	BS ’87
Ball, Gary Alan	BS ’85, MS ’87
Balla, Prannay	MS ’17
Balois, Maria Vanessa Cases	MS ’10
Balonek, Daniel Joseph	BS ’09, MS ’13
Balonek, Gregory James	BS ’09, MS ’14
Balonek, Robert Michael	BS ’09
Bampoe, Sidney Addo	BS ’01
Bancroft, Deborah Lea	BS ’94
Banerjee, Somnath	MS ’94
Baraban, Edward Dean	MS ’91
Baraban, Edward Dean	BS ’89, MS ’91
Baran, Timothy Michael	PhD ’13
Barber, Kenneth James	BS ’98
Barber, Paul R.	BS ’89
Barker, William Henry	BS ’05

(continued)

Name	Degree and date
Barlow, Bertram Lee	MS ’66
Barnard, James	MS ’84
Barnell, Mark D.	BS ’87
Barnes Castrovinci, Cynthia D.	BS ’70
Barrett, Robert Paul	BS ’81
Bartlett, Christopher Dana	BS ’90
Bassingthwaite, Jason Dean	BS ’92
Bastian, Robert H.	BS ’64
Bates, Robert	MS ’71
Battistoni, Donald Stuart	BS ’91
Bauco, Anthony Sebastian	MS ’97
Bauer, Aaron Michael	PhD ’16
Bauer, Gretchen Anne	BS ’10
Baughman, James Jason	MS ’08
Baughman, Richard Allan	MS ’90
Baum, Richard Charles	MS ’73
Baum, Seth Daniel	BS ’03
Baumgardner, John Dwane	PhD ’70
Baumgartner, Peter John	BS ’84
Baveja, Prashant Pankaj	MS ’09, PhD ’12
Baxter, Jerome Roger	BS ’73
Beach, Robert Applegate	BS ’44
Beal Fleming, Madeleine	PhD ’91
Beams, Ryan	PhD ’14
Bebb, H. Barry	PhD ’66
Bebb, William H.	MS ’58
Becherer, Richard J.	PhD ’72
Beck, Alisa Ann	BS ’95
Beck, David Paul	BS ’92, MS ’95
Beck, Mark Kevin	BS ’85, PhD ’92
Becker, Alex	BS ’54
Beckhard, Alan Francois	BS ’89
Beckley, Amber Michelle	PhD ’12
Beckman, Dylan	BS ’19
Beckman, Madilyn Murphy	BS ’18

Name	Degree and date
Bedard, Sharon Anne	BS ’85
Beel, William E.	BS ’34
Begis, Jacob	BS ’15
Benbow, James Samuel	BS ’86
Benda, John Anthony	MS ’84
Bender, Holly A.	BS ’05, MS ’06
Benecke, Glenn Joseph	MS ’91
Benford, James R.	BS ’35
Bennett, Brian Eugene	BS ’79
Bennett, Brian Plato	BS ’08
Bennett, Harold F.	MS ’61
Bennett, Timothy John	MS ’87
Bennett, Victor Paul	PhD ’74
Bennink, Ryan Scott	PhD ’04
Bentley, Joel	MS ’12
Bentley, Julie Lynn	BS ’90, MS ’92, PhD ’96
Bentley, Sean James	PhD ’04
Berfanger, David Martin	MS ’93, PhD ’00
Berg, David Matthew	MS ’83
Berger, Dennis Ray	MS ’90
Bergkoetter, Matthew Dennis	MS ’10, PhD ’17
Bergmann, Cedric O.	BS ’32
Bergstedt, Robert Alan	MS ’87
Berkley Irwin, Heather Elizabeth	BS ’06
Berkoff, Timothy Alexander	BS ’88
Berlinghieri, Joel Carl	BS ’03
Berman, Joann	BS ’75
Berman, Rebecca Elizabeth	BS ’09, PhD ’18
Bernhardt, Myron	BS ’40
Bernstein, Jessica Michelle	BS ’17
Berryman, Tyler J.	BS ’16
Berthold, Christof Wilhelm	BS ’87, MS ’89

(continued)

Name	Degree and date
Betzold, Amber Carol	MS ’17
Beversluis, Michael	PhD ’06
Bevin, Avery A.	BS ’88
Bhargava, Swati	MS ’15
Bhullar, Pushpinder Singh	MS ’71
Bi, Runyu	BS ’15
Bickel, Edward E.	BS ’39
Bickel, Nathan Peter	BS ’98, MS ’99
Bieber, Amy Erica	PhD ’96, MS ’06
Biermann, Mark L.	BS ’84, MS ’89, PhD ’91
Bietry, Joseph Raymond	BS ’80
Bigelow, Chad Eric	PhD ’05
Bigelow, Matthew	PhD ’04
Bilker, Lawrence Adam	BS ’91
Billow, Nicholas William	BS ’84
Bingham, Adam Lee	BS ’03
Bingham, William J.	BS ’34
Birdsall, Todd David	BS ’85
Birnkrant, Dashiell Adam	BS ’01, MS ’02
Birsa, Samuel James	MS ’16
Bishop, Amy Lynn	BS ’08
Biss, David Paul	PhD ’05
Bissell, Luke	PhD ’12
Bjornland, Sarah	BS ’17
Blakney, Robert Marsh	PhD ’55
Blalock, Todd Franklin	BS ’89
Blasenheim, Barry Joel	BS ’88
Blaszak, David Daniel	BS ’88
Bliek, David Cade	MS ’67
Bliss Mahnke, Barbara E.	BS ’86
Blitz, Dara Brandon	MS ’93
Bloomquist, William M.	MS ’70
Blough, Christian Gary	MS ’87, PhD ’92

Name	Degree and date
Blum, James Daniel	BS ’74
Blum, Thomas W.	BS ’65, MS ’67
Blumer, James William	BS ’48
Blumer, Robert Vernon	BS ’91
Bocchiaro, Joseph, III	BS ’81
Bode, Shane Elizabeth	BS ’96
Bodell, Sarah Yvonne	BS ’17, MS ’18
Bodington, Dare Edward	BS ’15, MS ’17
Bohache, James Joseph	PhD ’79
Bolak, Dogan Halil	BS ’83
Boland, Daniel Martin	BS ’00, MS ’03
Bolcar, Matthew Ryan	PhD ’09
Boldosser, Patrick Earl	BS ’93
Boles, John Ashleigh	BS ’74, MS ’76
Bond, Christopher Joseph	BS ’87
Boothroyd, Michael John	MS ’97
Bordyn, Brett Alan	BS ’92, MS ’93
Boreman, Glenn David	BS ’78
Borovkova, Mariia	MS ’16
Borrelli, John A.	BS ’87
Borruso, Dylan	BS ’19
Bortz, John Chapman	MS ’81, PhD ’84
Bos, Joseph John	MS ’08
Bothner Harkin, Jane Marie	BS ’87
Boucher, Richard Henry	PhD ’81
Bouk, Theodore F.	MS ’92
Boule, John Richard, III	BS ’12
Bourke, Peter W.	BS ’79
Bouzid, Ahmed	BS ’85, MS ’87
Bowen, John Paul	PhD ’91
Bowers, Mark Whitman	PhD ’98

(continued)

Name	Degree and date
Bowes, Elizabeth D.	BS ’93
Bozarth, Michael	MS ’15
Bracikowski, Christopher	BS ’86
Bradfield, Philip L.	MS ’82, PhD ’90
Bradley, Eric Martin	BS ’80, MS ’82
Brady, Doreen Kathryn	MS ’92
Brady, Gregory Robert	PhD ’09
Bragg, Edward B.	BS ’78
Brames, Bryan J.	PhD ’85
Brand, Jonathan Frieman	BS ’09
Brandkamp, Warren F.	MS ’73
Brandt, Michael Bernard	MS ’84
Braunstein, Ronald B.	MS ’81
Bray, Clarence P.	BS ’62
Breidenthal, Robert Stephen	BS ’71
Brennan, Daniel Ryan	MS ’14
Brennan, Derek Donald	BS ’89
Brennan, Joseph S.	BS ’43
Brewis, Graham	MS ’84
Bridges, Robert Emmett	PhD ’95
Briguglio, John	BS ’87
Brinkman, Jeffrey C.	BS ’89
Britton, William C.	BS ’48
Brodeur, David L.	BS ’85
Bromage, Jake	PhD ’99
Brooks, Daniel Robert	PhD ’18
Brophy, Chris P.	MS ’84, PhD ’84
Brost, Eric Edward	MS ’12
Brown, Benjamin Lee	PhD ’06
Brown, David Lee	BS ’87, MS ’96
Brown, Dean Patterson	PhD ’10
Brown, Matthew Deming	BS ’79
Brown, Michael John	PhD ’14
Brown, Nicolas Scott	BS ’15

Name	Degree and date
Brown, Thomas Gordon	PhD ’87
Brown, Walter R. J	MS ’49
Brownlee, Lauren	BS ’16
Bruggeman, Maximillian	BS ’19
Bruguier Ingen, Brooke Danen	PhD ’11
Brukilacchio, Thomas John	BS ’82, MS ’84
Bruno, Thomas Matthew	BS ’09
Brunsman, Michael Daniel	BS ’18
Bryant, Kyle Robert	BS ’98
Bryars, Brett Joseph	MS ’87
Bubnoski, David Paul	MS ’89
Buccheri, Fabrizio	PhD ’16
Buch, Shaival Vipul	MS ’13, PhD ’18
Buchanan, William B.	BS ’57
Buchar, Wayne Alan	MS ’82
Buchroeder, Richard A.	MS ’68
Buckland, Eric Lawrence	PhD ’97
Bugenhagen, Jeffrey Allen	BS ’88
Bui, Thu-Huong	BS ’92
Bunis, Jenifer Lynn	BS ’86
Bunzey, David A.	MS ’92
Buralli, Dale Alan	PhD ’91
Buran, James Michael	BS ’70, MS ’73
Burckel, William Paul	PhD ’74
Burdick, Nathan Erich	MS ’07
Burke, Paul Darryl	BS ’93
Burkwit, Mary Irene	BS ’91
Burner, Alpheus W.	MS ’76
Burrage, Robert R.	BS ’30
Bussard, Anne Dresden	MS ’80
Bussjager, Rebecca Jane	BS ’90
Buzawa, Michael John	BS ’52, MS ’54
Byler, Chad	MS ’14
Byrd, Ronald Eugene	MS ’72

(continued)

Name	Degree and date
Caccuitto, Michael J.	BS ’91
Cai, Xiaowei	BS ’12
Cairns, Brian	MS ’89, PhD ’92
Calarco, David B.	BS ’88
Caldwell, James Brian	PhD ’89
Caley, Wendell J.	MS ’59
Calvert, Lance Kenneth	MS ’03
Cameron, Bruce Alan	MS ’75
Campbell, Charles J.	MS ’52
Campbell, Shawn Richard	BS ’00
Canal, Nezih	BS ’82
Canavesi, Cristina	PhD ’14
Candey, Robert Mark	BS ’81
Cannaday, Ashley Elizabeth	PhD ’17
Canning, David James	BS ’95
Cannon, Bruce	MS ’87
Cannon, John Spencer	MS ’94
Canoglu, Annick Marie Noelle	MS ’01
Cappiello, Gregory Grant	BS ’84
Carbone, Frank A.	BS ’88
Cardimona, David Anthony	PhD ’84
Carellas, Peter Theodore	BS ’83, MS ’89
Carlough, Warren A.	BS ’58
Carlson, Thomas E.	MS ’88
Carman, P. Douglas	MS ’51
Carniglia, Charles K.	PhD ’71
Caro, Michael Thomas	BS ’94
Carollo II, Jerome Thomas	MS ’76
Carosella, John Henry	MS ’69
Carpenter, Vance J.	BS ’49, MS ’50
Carr, Kevin Francis	BS ’82
Carson, Alexander J.	MS ’18
Carter, James Allen	BS ’81
Carter, Thomas Edward	BS ’94
Cartwright, Steven Lee	PhD ’82

Name	Degree and date
Caruso, Angelo Thomas	MS ’91
Cary, Donald Shumway	BS ’46
Casaverde, Pablo	BS ’98, MS ’99
Castellani, Robert Joseph	BS ’88
Castle, William Palmer	BS ’86
Catlin, Scott John	BS ’92
Cavalcanti, Marcelo Bailly	MS ’99
Caya, Timothy J.	MS ’98
Centanni, Paul	BS ’91
Centurelli, Joseph Liguori	BS ’15, MS ’16
Cerami, Loren	BS ’02
Cha, Myoungsik	MS ’90
Chadwick, David Paul	MS ’75
Chakmakjian, Stephen Harry	MS ’85, PhD ’91
Chakraborty, Chitraleema	PhD ’18
Chambers, David E.	BS ’84
Chambers, Victor John	BS ’00
Chan, Eric Kin	BS ’90, MS ’91
Chan, Francis	BS ’79
Chan, Richard Henri	BS ’79
Chan, Richard Lee	BS ’89
Chan, Yali Ellen	MS ’77
Chan, Yim Oi	BS ’93
Chancy, Carl Henri	BS ’06
Chang, Chun-Hung	BS ’09
Chang, Isabella Diana	BS ’86, MS ’88
Chang, Nien-An Nia	MS ’03, PhD ’09
Chang, Thomas Fong-Jen	MS ’91
Chang, Wendi	BS ’11
Chao, Shui L.	PhD ’74
Chao, Yvonne Y.	BS ’90
Chapnik, Philip David	MS ’84
Charles, Kevin James	MS ’00

(continued)

Name	Degree and date
Chen, Gih-Horng	MS ’74, PhD ’77
Chen, Haoyu	MS ’17
Chen, Jack Hung-Ti	BS ’03
Chen, Jennifer Lynn	BS ’04
Chen, Jonathan Lee	BS ’06
Chen, Min	MS ’97
Chen, Pan-Fey Fay	BS ’85
Chen, Shengtong	BS ’14
Chen, Xi	MS ’02, PhD ’07
Chen, Yeyue	BS ’16
Chen, Zhongjie	MS ’15
Cheng, Shengtong	BS ’14
Cheng, Waikin Andrew	BS ’87
Cheng, Yuh-Jen	MS ’90
Chernosky, Mark Steven	BS ’92
Chesley, Carl H.	BS ’62
Chess, Stephen Adam	BS ’18
Chi, Wanli	PhD ’04
Chiang, Hungwei	MS ’16
Chiang, Wesley	MS ’19
Chiapperi, Joseph Michael	BS ’89
Chipper, Robert Brian	BS ’86
Chirra, Ramalinga Reddy	MS ’65
Chisholm, James Joseph	MS ’65
Chiu, John Chu-Tin	BS ’90
Cho, Doo Jin	MS ’87, PhD ’90
Choate, Albert George	BS ’69
Choi, Joseph Sung-Hwoon	MS ’13, PhD ’16
Chou, Chien	MS ’76
Chou, Robert Yuan Ying	MS ’18
Chrien, Thomas G.	BS ’84, MS ’86
Christensen, Daniel Jordan	MS ’08, PhD ’14
Christensen, Eric L.	PhD ’12

Name	Degree and date
Christidis, Georgios	MS ’14
Christo, Douglas John	BS ’71
Chu, An-Shyang	BS ’85
Chu, Hanh Tran	BS ’80, MS ’83
Chu, Kaiqin	MS ’05, PhD ’10
Chuang, Shih-Chin	MS ’89
Chung, Ji Hoon	BS ’93
Ciafre, Derec Blaine	BS ’07, MS ’08
Cicchiello, James M.	BS ’88, MS ’92
Cirucci, Nicholas Mark	BS ’15, MS ’16
Citron-Becker, Mary E.	MS ’72, PhD ’77
Clapper, Franklin R.	BS ’44, MS ’48
Clark, Edward L.	MS ’60
Clark, Guy Peter	MS ’68
Clark, Melvin Desmond	MS ’48
Clark, Michael James	BS ’89
Clark, Peter Parkhill	BS ’71
Clark, Stephen Paul	BS ’87, MS ’88
Clarkson, Andrew Ream	BS ’88
Clatterbuck, Timothy Jon	MS ’90
Close, Richard Norcross	BS ’43
Cobb, Joshua Monroe	BS ’88, MS ’00
Coblitz, David B.	MS ’72
Cochran, Eugene Rowland	BS ’83
Cocola, Anthony John	BS ’01
Coe, John Scott	BS ’86
Coelho, Roland	MS ’55
Cohen, John David	BS ’90
Cohen, Jonathan Aaron	BS ’90
Cohen, Simon Joel	BS ’88, MS ’89

(continued)

Name	Degree and date
Cohn, Brian David	BS ’80, MS ’82
Colelli, James John	BS ’87
Coleman, Edward Paul	MS ’92
Coleman, James Michael	BS ’89
Colliss, Glenn Richard	MS ’83
Compertore, David Christopher	BS ’87
Cong, Zhilin	BS ’12
Conley Smith II, Roger Allen	BS ’09
Conolly, Christopher Jason	MS ’93
Conran, Logan Cooper	MS ’19
Consentino, Albert Benedict	BS ’02, MS ’11
Constantinou, Paul	MS ’00
Conte, Pellegrino M.	BS ’18
Conturie, Yves Gilles	PhD ’83
Cook, Amy Arden	BS ’92
Cook, William Wade	PhD ’04
Cordi, Anthony Joseph	BS ’84
Corless, John Douglas	MS ’92, PhD ’97
Cornejo-Rodriguez, A. A.	MS ’68
Cornell, James Dixon	BS ’92, MS ’94
Corser Mann, Eileen Marie	BS ’87, MS ’89
Corsetti, James	BS ’10, MS ’13, PhD ‘17
Cort, Cesar Adrian	BS ’19
Cortesi Kramer, Rebecca Lynn	BS ’05, MS ’06
Corum, Curtis Andrew	MS ’94
Cosentino, Joseph Alfred	BS ’14, MS ’15
Coskun, Mustafa	BS ’02, MS ’03
Costanza, Luke Howard	BS ’08
Costanzo, Christopher Ralph	BS ’83
Costich, Verne R.	PhD ’65

Name	Degree and date
Coston, Scott Douglas	PhD ’92
Cotton, Christopher Thomas	BS ’86, MS ’90
Cottrell, Thomas H. E.	PhD ’68
Cottrell, William Jude	BS ’00, MS ’04, PhD ’09
Coult, David G.	BS ’74
Coulter, John K.	MS ’60
Courtney, Rebecca Amy	BS ’85
Coyoc Escudero, Johana Gabriela	BS ’17
Crawford, Mary Kate	PhD ’00
Craytor, Russell E.	BS ’35
Creath, Katherine	BS ’80
Creatura, Lawrence Robert	BS ’87
Cree, David A.	MS ’63
Creighton, Daniel Canavan	BS ’87
Crewdson, Ernest	BS ’45
Crichton, John F.	MS ’71
Critchlow, James Albert	MS ’76
Crocker, Susan Linda	MS ’80
Croglio, Nicholas J.	BS ’92
Cuffney, Robert Howard	MS ’87
Cui, Liping	MS ’08, PhD ’11
Culver, Thomas Richard	BS ’89
Cumbo, Michael J.	MS ’90, PhD ’93
Cummings, Christopher Matthew	BS ’95
Cummings, Jessica Lee	BS ’05
Cuneo, Peter	MS ’76
Curley, Carole Lynn	BS ’87
Dady Wind, Joella	BS ’90
Dai, Minchuan	BS ’94
Daigle, Marc Thomas	MS ’82
Daley, Michael Carr	BS ’89
D’Amato, Dante P.	BS ’85
Dame, Barry T.	MS ’65

(continued)

Name	Degree and date
Daneshkhah, Shahin	BS ’95
D’Angelo, Lawrence Michael	BS ’86
Daniel, Brian Adam	PhD ’12
Danielson, George Edward	MS ’67
Danko, Joseph John	MS ’79
Danshkhah, Shahin P.	BS ’95
Darling, Zachary James	BS ’09, MS ’10
Darrow, Douglas Jason	BS ’85
Dass, Sasha K.	BS ’91
Daub, Kyle	BS ’19
Daum, Michael Mace	BS ’83
David, Stuart Roger	BS ’90
Davidson Chazen, Barbara Sue	BS ’88, MS ’89
Davis, Arthur John	BS ’96, MS ’00
Davis, James Glenn	MS ’89
Davis, John R.	MS ’40
Davis, John Stephen	MS ’73
Davis, William V.	PhD ’93
Day, Pierce B.	BS ’48, MS ’53
De Araujo, Luis Eduardo E.	PhD ’01
de Asla, Richard Joseph	BS ’91
Deaver, Dawne Marie	MS ’96
De Baun, Barbara Ann	MS ’92
DeBell, Gary William	MS ’70, PhD ’72
Debossu, Charlotte Alice	BS ’17
DeCaro, Joel Dennis	MS ’90
De Castro, Michelle Ann	BS ’00
DeCew, Alan Edward	BS ’68
Deever, Walter Thomas	MS ’74, PhD ’78
DeGroote Nelson, Jessica	BS ’02, MS ’04, PhD ’07
De Jager, Sarah Anne	BS ’97, MS ’98

Name	Degree and date
Dejong, Christian Dean	BS ’86, MS ’87
De La Cruz Guti, Manuel	PhD ’07
Delano, Erwin	MS ’56, PhD ’66
Delarosa, John Gonzalo	MS ’82
Delgado, Alvin	BS ’86
De Long, John S.	MS ’07
De Long, John S., Jr.	MS ’07
Delorenzo, Michael Lawrence	BS ’03
DeLuca, Patricia M.	MS ’87
DeMarco, Michael Andrew	BS ’87
Demas, Jeffrey Dakin	BS ’11
DeMeijere, Hermina	PhD ’78
Demilo, Charles Angelo	BS ’87
Demogines, Alexander	MS ’03
Deng, Yang	BS ’18
Deng, Yujun	MS ’02, PhD ’06
Denton, Arthur	BS ’36
Depalma, James John	BS ’55, MS ’57
DeRosa, Ryan Thomas	BS ’06
De Rose, Christopher Todd	BS ’01
Desai, Ankur	BS ’19
De Saboia Silva, Rodrigo	BS ’94
Desantis, Zachary James	BS ’09, PhD ’17
De Smitt, Steven Mitchel	BS ’79, MS ’82
DeSterke, Carel Martijn	PhD ’88
Deuro, Justin	BS ’10
Deutsch, Bradley	PhD ’12
Deutschbein, John S.	BS ’81
Devaney, Anthony J.	PhD ’71
Devoe, Catherine Ellen	BS ’84
Devries, Gary Michael	BS ’04, MS ’09
Dewa, Paul Gerard	BS ’85

(continued)

Name	Degree and date
Dey, Thomas W.	MS ’77
Diamond, James Steven	BS ’86
Diana, John Robert	BS ’88
Dianetti, Joseph C.	BS ’44
Diblasi, Robert Harter	BS ’11
Dickinson, Caitlin Emily	BS ’02
Diehl, Damon Wayne	PhD ’04
Diehl, Timothy	BS ’10
Dietz, Jonathan R.	BS ’18
Difabio, Joseph John	BS ’16
Dil, Jan Gerard	MS ’74, PhD ’76
Dimmler, Wolfgang Michael	BS ’82, MS ’84
Ding, Lei	BS ’18
Ding, Li	MS ’04, PhD ’09
Dionne, Andrew Robert	BS ’03
Dir, Gary Arden	BS ’68, MS ’80
Discher, Wendell V.	MS ’51
Ditchman, Christopher James	MS ’04
Divitt, Shawn Mark	MS ’12, PhD ’16
Dixon Canham, Sharon	BS ’87
Do, Phuong Huu	MS ’04
Doane, Marshall G.	BS ’59, MS ’61
Doares, Andrew Robert	MS ’16
Doh, Lucius Seokhwan	BS ’89, MS ’90
Doherty, Victor J.	MS ’77
Dolgaleva, Ksenia	PhD ’09
Domey, Jacques	MS ’72
Donaher, John Casey	BS ’88
Donahue, Joseph Michael	PhD ’70
Donenfeld, Nathan M.	MS ’79
Donnelly, Katherine	BS ’19
Donner, Janet Teresa	BS ’94, MS ’98

Name	Degree and date
Doran, Robert Edward	MS ’73
Dorn, Meghan Leigh	MS ’15
Doty, James Louis	MS ’73
Dougherty, Gregory Paul	BS ’83
Dowd, Betsy K.	MS ’85
Downie, John David	BS ’83
Doyle, David A.	BS ’03, MS ’04
Doyle, Jeffrey William	MS ’83
Driscoll, David Carl	MS ’95
Druckenmiller, Daniel Hanford	BS ’90
Drummond, Iain James	BS ’92
Du, Tu Chieu	BS ’90
Du, Xiaoyu	PhD ’18
Du, Yu Hui	BS ’19
Dube, Brandon	BS ’18
Dube, George	BS ’64, MS ’69, PhD ’72
Dublin, Mark Howard	BS ’69
Du Bois, Antolin	BS ’90
Duckett, George Edward, III	BS ’93
Dudley, Eric Feine	BS ’05
DuFresne de Virel, Francois P.	MS ’81
Dugan, John Patrick	MS ’82
Dugan, Nancy Tara	BS ’89
Duling, Irl Noel, III	PhD ’85
Dulnikowski, Christine	BS ’90
Dumas, Paul Robert	BS ’90, MS ’92
Dumont, Frank J.	BS ’66, MS ’69
Dunbar, Thomas Alan	MS ’84
Dunham, David Norton	BS ’95
Dunn, Kaitlin Jennifer	MS ’19
Dunn, Thomas James	MS ’89, PhD ’94
Dupuis, Michael L.	BS ’16, MS ’17
Duquette, Philip John	BS ’86

(continued)

Name	Degree and date
Durbin, John Alan	MS ’72
Durnin, James Eugene	PhD ’87
Dvorin, Martin	MS ’66
Dwyer, Carol Annette	BS ’90
Dymale, Raymond C.	MS ’75
Dyn, Mordechai	MS ’72
Dziel, Andrew M.	BS ’90
Dziura, Thaddeus Gerard	PhD ’87
Earman, Allen Massie	MS ’87
Eastman, Clarke Kimberly	MS ’91
Eastman, Jay M.	BS ’70, PhD ’74
Eby, John E.	PhD ’60
Economou, Peter	BS ’82
Edgerton, Robert Frank	PhD ’63
Edick, Keith Allen	BS ’97
Edwards, Elizabeth F.	BS ’88
Edwards, Oliver Jackson	MS ’72
Effenberger, Frank Joseph	MS ’89
Eggers, Stephen	BS ’09
Eggleston, John N.	BS ’30
Ehlert, John Carl	MS ’89
Ehmann, Christine E.	BS ’89
Ehrlich, Daniel Jacob	PhD ’78
Elby, Stuart David	BS ’82
Elefante, David Graham	BS ’95
Elgin, Laura Elaine	BS ’04
Elkins, William Patrick	BS ’80
Elliott, Theodore F.	BS ’36
Ellis, Kenneth Scott	BS ’89
Emery, James	BS ’18, MS ’19
Emilsson, Borje Erik Ingolf	MS ’81
Emmons, Robert Milton	PhD ’92
Eng, Ron	BS ’85
Engler, Steven David	BS ’88
English, Ronald Edward	PhD ’88
Engstrom, Brian Lee	BS ’87

Name	Degree and date
Entin, Amy	BS ’16
Erckert, Samuel D.	BS ’30
Erdmann, Reinhard Kurt	PhD ’04
Erdogan, Turan	PhD ’92
Erickson, Phillip John	MS ’86
Eron, Randell Paul	BS ’90
Ertur, Elka Bedia	BS ’89
Espinoza, Evan Marco	BS ’16
Estes, Cameron B.	BS ’38
Etter, David F.	MS ’84
Evans, Alan Frank	PhD ’92
Evans, John Cushing	BS ’39, MS ’49
Evans, Preston G.	BS ’32
Evans, Samuel Irving	MS ’17
Evans, Zachary James	BS ’16, MS ’17
Everett, Jonathan Edward	BS ’91
Eversole, Daniel Steven	BS ’04
Ewanow, Jason	BS ’19
Eyer, James A.	PhD ’57
Fabrizzio, Robert Philip	MS ’99
Faduski, Charles Edward	BS ’89
Failor, Douglas Lloyd	BS ’78
Faklis, Dean	MS ’86, PhD ’90
Fales, Gregory Francis	BS ’00
Fan, Xing	MS ’16
Fang, Kejia	MS ’12, PhD ’16
Fann, Chun-Hao	MS ’19
Fanning, Andrew W.	BS ’91
Fantone, Dennis William	MS ’12
Fantone, Stephen D.	PhD ’79
Fantone, Stephen Joseph	MS ’17
Fargnoli, Joseph D.	MS ’96
Farley, Cathleen	BS ’87
Farmiga, Nestor O.	MS ’93

(continued)

Name	Degree and date
Farr, Keith Bryan	PhD ’94
Farrell, Timothy Richard	BS ’80
Farriss, Wesley Elton	MS ’18
Fath, Jack M.	MS ’68
Faust, Jessica Ann	MS ’94
Federico, Richard Joseph	BS ’79
Fedison, Joe Thomas	BS ’87
Feeks, James Anthony	MS ’15, PhD ’18
Fehniger, Michael James	MS ’71
Feifke, Benjamin Roy	BS ’15
Feinberg, Lee Daniel	BS ’87
Feinberg, Richard	BS ’33
Feldman, Paul T.	BS ’57
Felkel, Eric Matthew	BS ’97
Feng, Guanping	MS ’17
Ferguson, Gerald D.	MS ’69
Fernald, Mark Robert	MS ’76
Ferri, John Marshall	BS ’91, MS ’93
Feth Dunn, Susan Eileen	BS ’87, MS ’90
Fettig, Doug James	MS ’07
Fiala, Peter Joseph	BS ’16
Fields, David Brittain	BS ’91
Finck, David Laurence	BS ’85
Fink, Joshua Ross	BS ’04
Finlan, J. Michael	MS ’81
Finn, Colby Lorraine Kummerow	BS ’07
Finn, Mary M.	BS ’83
Fintel, William Vernon	MS ’84
Fischer, David Gerard	PhD ’96
Fischer, David Joel	PhD ’02
Fischer, Robert E.	BS ’65, MS ’67
Fisher, Andrew S.	BS ’11, MS ’12
Fitzgerald, Daniel James	BS ’02

Name	Degree and date
Fitzgerald, Gregory John	BS ’94, MS ’95
Fladd, David R.	BS ’91
Flattery Freedenberg, Candace J.	BS ’88
Fleisher, Philip	BS ’10
Fleming, John Chamberlain	BS ’85
Flint, Douglas Bradford	BS ’73, MS ’75
Flint, Shannon Elizabeth	BS ’96
Florence, Louis A.	MS ’02
Flores, Cristian	BS ’19
Flores-Hernandez, Ricardo B.	MS ’77
Florkowski, Alan Stanley	BS ’76
Fonte, William G.	BS ’85
Ford, Joseph Earl	MS ’87
Forkey, Richard E.	BS ’65
Forlenza, Kathleen Helen	BS ’89
Forman, Bruce Scott	BS ’80
Forman, Paul Frederick	BS ’56
Forman, Warren R.	BS ’87
Formicola, Salvatore M.	MS ’83
Forsyth, James Morton	BS ’64, PhD ’69
Fortmiller, Louis J.	BS ’38
Foster, Richard Burgess	BS ’45
Fouere, Jean-Claude	MS ’73
Fox, Allen Maurice	BS ’87
Fox, Richard Warren	BS ’80
Franda, Charles Arthur	BS ’84
Franks, David	BS ’94
Frantz, Amy Elizabeth	MS ’15
Frantz, Christopher John	BS ’88
Freedberg, David Marc	BS ’89
Freedman, Lori Ellen	BS ’85
Freese, Robert Paul	PhD ’80
Freling, Ryan Edward	BS ’94
Frels, Robert Henry	BS ’49

(continued)

Name	Degree and date
French, Hobert Ward	PhD ’45
Freymann, John Matthew	BS ’88
Friberg, Ari Tapio	PhD ’81
Frieden, B. Roy	PhD ’66
Friedman, Douglas Scott	BS ’86
Friedman, Marc David	BS ’84, MS ’85
Friend, John Elmer	BS ’85
Frissora, Paula Nave	BS ’85
Frith, Robert Ward	BS ’84
Froggatt, Mark Earl	PhD ’01
Frosch, Ira Charles	MS ’92
Frosino, Robert James	BS ’71
Fry, James Alexander	BS ’89
Fu, Yijing	PhD ’12
Fuerschbach, Kyle Henry	PhD ’14
Fujimura, William S.	BS ’59
Fuksa, Michelle Rae	MS ’19
Fuller, Joseph B. C.	MS ’70
Gabel, Conger W.	PhD ’75
Gacusan Kwiatkowski, Lillian	BS ’85
Gaeta, Alexander Luis	BS ’83, MS ’85, PhD ’91
Gaeta, Zagorka Dacic	PhD ’95
Gaidash, Andrei	MS ’15
Galime, Michael Paul	BS ’02
Gallagher, John Everett	PhD ’70
Gallipeau, Robert Bernard	BS ’49
Gallousis, Gregory Moschetti	BS ’88
Galuppo, Christopher Brian	BS ’97
Gamliel, Avshalom	PhD ’91
Gandia, Shaun Marie	BS ’91
Gansen, Eric John	MS ’98
Gao, Boshen	PhD ’17
Gao, Shenghan	BS ’17, MS ’19
Gao, Yifeng	MS ’17
Gardner, Craig Morris	BS ’88, MS ’90

Name	Degree and date
Gardner, Leland Vincent	BS ’52
Gardner, Leo Russell	MS ’84, PhD ’89
Garner, Michael Scott	BS ’84
Gasal, Nermina	BS ’99
Gasper, John	MS ’72
Gaumer, William Bruce	MS ’76
Gauthier, Daniel Joseph	BS ’82, MS ’83, PhD ’89
Gauthier, Vicky Marie	MS ’87
Gaynor, Edwin Stowell	BS ’79
Ge, Gary Ruian	BS ’16
Gee, Alan E.	MS ’49
Gehr, Russell Jeffrey	MS ’92, PhD ’97
Gehring, George	PhD ’12
Gelber, Robert Milton	BS ’67, MS ’68
Gemp, Kevin Robert	BS ’04
Geng, Ying “Melissa”	PhD ’12
Gengenbach, Richard Louis	BS ’90
Genin Brethen, Denise M.	BS ’84
Gerber, Ronald Evan	BS ’90, MS ’92
Gerchman, Mark Craig	MS ’78
German, Howard Lee	BS ’40
Ghilai, Shay	MS ’76
Gianola, Lawrence James	BS ’84
Gibney, Kyle James	BS ’07
Gibson, H. L.	MS ’40
Gienke, E. L.	BS ’33
Gifford, Dawn Katherine	PhD ’03
Gilkeson, David C.	BS ’48
Gill, Charles Lewis	BS ’49
Gillis, Earle W.	MS ’87
Gilman, Scott	BS ’88
Ginn, D. A.	MS ’72
Ginsberg, Robert Herman	MS ’51
Glass, Charles Joseph	MS ’56

(continued)

Name	Degree and date
Glass, Thomas R.	MS ’85
Glassman, Ann Toby	MS ’72
Glazowski, Christopher, Edward	PhD ’11
Glik, Eliezer	BS ’14
Goad, Joseph H.	MS ’68
Gobbi, Edward Francis	BS ’88, MS ’91
Godina, Adrian Christain	BS ’86, MS ’87
Goetz, William Erwin	BS ’50, MS ’53
Gold, Albert	PhD ’60
Goldenberg, Jill Forer	BS ’82, MS ’84
Golding, Douglas Joseph	BS ’89, MS ’91
Goldmunz, Michel	BS ’78, MS ’79
Goldstein, David G.	BS ’38
Golini, Donald	BS ’86
Golini, Tracey Elizabeth	BS ’88, MS ’95
Golnik, Gary	MS ’76
Golob, Laurence Perry	BS ’88
Gomba, George Andrew	BS ’81
Gondarenko, Alexander A	BS ’04
Gong, Richard	BS ’84
Gonsiorowski, Thomas	MS ’82
Gontard, Denys Georges	MS ’76
Goodfellow, Kenneth Matthew	PhD ’17
Goodridge, Stephen Franklyn	BS ’08, MS ’09
Goodridge, William Welles	BS ’63
Goodwin, David Bruce	BS ’85
Goosey, William Thomas	BS ’73, MS ’75
Gordon, Clinton Renard	MS ’83
Gordon, Ronald L.	PhD ’98

Name	Degree and date
Gordon, Thomas E.	BS ’86, MS ’87
Goren, Evan Matthew	BS ’03
Gortych, Joseph	MS ’86
Govier, Jeremy John	BS ’97
Gowin, Klemens Richardo	BS ’18
Grabarz, Robert Henry	BS ’89
Gracey, Renee Marie	BS ’90
Graham, Bruce M.	BS ’87
Graney, Daniel Robert	BS ’18
Granger, Edward Maurice	BS ’57, MS ’69, PhD ’75
Grant, Duane Earl	MS ’58
Gray, Charles B.	BS ’48
Gray, Daniel Curtis	BS ’02, MS ’03, PhD ’07
Gray, Howard Robert	PhD ’79
Gray, Robert Charles	BS ’44
Gray, Robert W.	MS ’11, PhD ’15
Greenbaum, Aaron Russell	BS ’17, MS ’18
Greenberg, David Andrew	BS ’87
Greenberg, Michael Robert	MS ’84
Greene, Pamela Lori	MS ’94, PhD ’00
Greener, William John	MS ’76
Greenfield, Martin	BS ’74, MS ’75, PhD ’79
Greenland, Alan Richard	BS ’85, MS ’87
Greenlee, William Gordon	BS ’88
Greenwald, Roger Jeffrey	MS ’75
Gregg, Patrick Clayton	BS ’11
Gregoire, Matthew John	BS ’99
Gregorka, Lisa	BS ’76, MS ’78
Gregory, Donna Louise	MS ’90
Gregory, G. Groot	MS ’87

(continued)

Name	Degree and date
Greninger, Charles Edward	PhD ’72
Gressler, William John	BS ’88
Grice, Warren Paul	PhD ’98
Griffin, Gordon Ross	BS ’53
Griffith, John D.	MS ’89
Griffith, Peter Brant	BS ’86
Grimm, Joel Glenn	BS ’86
Grindel, Mark Oliver	BS ’91
Griswold, Mack D.	BS ’34
Gross, Mason A.	MS ’87
Grove, Steven L.	MS ’89
Gruber, Leonard Steven	MS ’71
Grudus, James Walter	BS ’84
Gruhlke, Russell Wayne	PhD ’87
Grum, Franc	BS ’58, MS ’62
Gruneisen, Mark Tyree	MS ’82, PhD ’89
Gruttadauria, Jaime	BS ’09
Gu, Yichen	BS ’18
Guan, Weihua	MS ’05, PhD ’09
Guardalben, Mark J.	BS ’83, MS ’91
Guarnieri, Salvatore	BS ’04
Guerin, William G.	MS ’82
Guimaraes, Marcelo	MS ’02
Guizar Sicairos, Manuel	MS ’08, PhD ’10
Gum, Steven James	BS ’81
Gur, Joshua	PhD ’79
Gutierrez, Alina Louise	MS ’91
Gutterman Crocker, Pamela Renee	BS ’86
Guzek, Kyle	BS ’19
Guzman, Stephanie Elizabeth	MS ’17
Gwyn, Rodney Thomas	MS ’72
Haag, John Eric	MS ’93
Haas, Benjamin Loren	BS ’96

Name	Degree and date
Haddad, Steve	MS ’18
Haddock, Joshua Naaman	BS ’98
Hagen Clar, Colleen Renee	BS ’96
Hager, Stephen Christopher	MS ’13
Hagerott, Edward Carl	MS ’65
Haggans, Charles Wesley	MS ’88
Hahn, Michael Steven	BS ’92
Hahn, Robert Edward	BS ’66, MS ’68
Hahn, Walter Gordon	BS ’88
Haines, Jesse Hilton	MS ’57
Hajek, Pavel	MS ’95
Hake, Brian Patrick	BS ’81
Halbleib, William F.	MS ’57
Hale, Alexander Lon	BS ’87
Hall, Christopher Allen	MS ’04
Hall, John M.	BS ’89
Hallerman, Gregory Robert	BS ’90
Halnon, Theodore Raymond	MS ’18
Hamaguchi, Roy I.	MS ’71
Hammond, Alan R.	MS ’87
Han, Jiashi	BS ’16, MS ’18
Han, Jinyu	BS ’17
Han, Shuyuan	MS ’12
Han, Songfeng	PhD ’18
Han, Xiaoxing	PhD ’12
Hand, Douglas Robert	BS ’90
Hansen, George Keith	MS ’74
Hansotte, Eric James	MS ’92
Haque, Riaz Raihan	MS ’13
Harding, Harvard K.	MS ’97
Harding, Kevin	MS ’78
Hardy, James Alan	PhD ’79
Hark, Peter A.	BS ’97
Harkrider, Curtis Jason	PhD ’00
Harmon, Kim Marie	BS ’82
Harms Lorei, Sherry J.	MS ’87

(continued)

Name	Degree and date
Harper, David Carson	BS ’40
Harris, James Stuart	MS ’66
Harris, Matt John	MS ’86
Harris, Oswaldo	MS ’67
Harris, Thomas I.	MS ’58
Harris, Thomas J.	MS ’60
Harrison, Douglas Henry	MS ’69, PhD ’74
Harrison, Kramer Daniel	MS ’14
Hart, George Guymer	BS ’48
Hart, Jacob H.	MS ’19
Hart, James C.	BS ’35
Harter, Donald James	MS ’79, PhD ’82
Hartnett, Stephanie Marie	BS ’95
Hartzell, Andrew Keith	MS ’90
Harvey, George Treide	PhD ’81
Harvey, James Edward	BS ’39
Harvitt, Daniel Marc	BS ’87
Hasenauer, David Michael	BS ’81
Hashim, Ali	BS ’18
Hasman Vincent, Katherine Nadanne	BS ’08, MS ’09
Hassett, Jeremy David	BS ’16, MS ’18
Hassler, Richard Allen	BS ’87, MS ’89
Hatch, Marcus Richardson	BS ’72, MS ’73
Hathaway, Floyd M.	BS ’31
Hauer, Allan A.	PhD ’77
Haun, Niels	MS ’88, PhD ’93
Hawthorne, Jeff A.	MS ’90
Hay, Bryan Scott	BS ’58
Hayashi, Masayasu	BS ’17
Hayes, Jeanine Lynn	BS ’92
Hayes, Jennifer Carol	BS ’03

Name	Degree and date
Hayford, Michael John	BS ’78, MS ’79
He, Jiajian	BS ’16
He, Wenhua	MS ’18
Head, Stephen Thomas	PhD ’18
Headley, Clifford Everill	PhD ’95
Heaney, Alan Douglas	PhD ’00
Hearn, Gregory K.	BS ’72
Hebb, Ralph Milton	BS ’82
Hebert, Eric Stephen	BS ’18
Hecht, Avron S.	MS ’75
Heebner, John E.	MS ’98, PhD ’03
Heimer, Richard Jacob	BS ’56
Heiney, Allan Joseph	BS ’78, MS ’81
Heiniger, Adam Taylor	PhD ’14
Heins, Alan M.	PhD ’13
Heinz, Jonathan R.	BS ’18
Hemmat, Michael Keyan	BS ’05
Hendrick, Wyatt Lee	BS ’91
Hendrix, Karen Denise	BS ’79, MS ’81
Hendry, Michael	MS ’90
Henkart, Max Maximilien	BS ’12
Hennings, David Robert	MS ’82
Henty, Richard Ruby	BS ’46
Her, Michael	BS ’12
Hercher, Michael McCarthy	BS ’56, PhD ’64
Herloski, Robert Paul	BS ’78, MS ’80
Hernandez, John Peter	PhD ’67
Herrera, Oscar Dario	BS ’08
Heslink, Nathan Gerrit	BS ’99
Hess, Joshua Francis	BS ’16
Hesterman, Jacob	BS ’02
Heydenburg, Thomas	MS ’84

(continued)

Name	Degree and date
Heysel, Harrison Frederick	BS ’82
Hickey, Neil David	MS ’81
Hilbert, Robert S.	BS ’62, MS ’64
Hildebrandt, Michael	BS ’99
Hildreth, Leland E.	BS ’33
Hileman, Dane Earl	BS ’87
Hill, Andrew Vernon	MS ’93
Hill, Elizabeth	BS ’03
Hillman, Lloyd William	PhD ’84
Hills, Robert	BS ’44
Hilton, David James	BS ’97, MS ’99
Hines, Kevin Patrick	MS ’90
Hingston, Ciara	BS ’19
Hinrichs, Keith Marshall	BS ’92, MS ’94
Hirs, John	BS ’83, MS ’86
Hirsch, Jeffrey David	BS ’86
Hirsch, Peter W.	MS ’87
Hixson, Stephen Joseph	BS ’82
Ho, Pin-Chin	MS ’71
Hoadley, H. Orlo	BS ’35
Hoch, Carlyle Cristian	BS ’89
Hochberg, Eric B.	BS ’76
Hocheder, Stephen E.	BS ’84
Hochheimer, Bernard F.	MS ’53
Hochmuth, Damian Joseph	BS ’84
Hodgdon, Michael Scott	BS ’84
Hoesterey, Howard Frederick	BS ’49
Hofer, Heidi Jean	PhD ’03
Hoffman, Brittany Nicole	MS ’16
Hoffman, J. Nelson	BS ’55
Hoffman, Kendra Jean	MS ’96
Hoffman-Kim, Diane	BS ’88
Hoke, Charles H.	BS ’45
Hoke, William B.	BS ’87

Name	Degree and date
Hokula, Shannon C.	BS ’11
Holland, Joseph Enrique	MS ’18
Holland, William R.	PhD ’85
Holmes, Dale Arthur	MS ’69
Holmes, Frederick	MS ’32
Holmes, John Frederick	BS ’85
Holmes, Robert Lane	BS ’93
Holsten Gardner, Wanda S.	MS ’84
Holzemer, Conrad	BS ’19
Homan, Russell Jerome	BS ’91
Hoose, Joel	BS ’17
Hoose, John F.	MS ’79
Hopkins, Robert E.	MS ’39, PhD ’45
Hopler, Mark Dennis	MS ’88
Hoppe, Michael James	BS ’90, MS ’92
Horbatuck, Suzanne M.	BS ’86, MS ’88, PhD ’96
Horwitz, Bruce Alan	PhD ’76
Horwitz, Larry	MS ’75
Hossain, Muntashir	BS ’00
Hotaling, Eric James	MS ’82
Houck, Robert B.	BS ’43
Houde-Walter, Susan N.	MS ’83, PhD ’87
Houghton Olson, Jennifer Kelly	BS ’92, MS ’95
Houk, Michael Tad	PhD ’90
Houston, Caroline Louise	MS ’15
Hovorka, Richard Russell	MS ’97
Howard, Andrew	BS ’19
Howard, James William	BS ’78, MS ’80
Howard, Joseph Michael	MS ’97, PhD ’00
Howe, Dennis G.	MS ’68, PhD ’76
Howe, Donald J.	BS ’45

(continued)

Name	Degree and date
Howe, Harlan George, Jr.	BS ’57
Howe, Russell James	BS ’08, MS ’14
Howes, Walton L.	BS ’48
Hoyt, Zachary Michael	BS ’04
Hrycin, Anna Louise	BS ’79, MS ’86
Hsu, Ta-Chen	BS ’04
Hsu, Yuling	BS ’93, MS ’00
Hu, Ching Yee	BS ’97
Hu, Hui Lin	BS ’87
Hu, Shaodan	MS ’18
Huang, Danlu	BS ’15
Huang, David Szu-Chi	BS ’91, MS ’93
Huang, Felicia Fa-Niang	MS ’87
Huang, Ruiting	MS ’15
Huang, Xiaojing	BS ’18
Huang, Yanqiao	MS ’06
Hubel, Paul Matthew	BS ’86
Huber, Paul Wesley	BS ’91
Hubert, Charles Rankin, Jr.	MS ’91
Hudak, Robert J.	BS ’39
Hudson, Richard D., Jr.	BS ’45, MS ’48
Hudyma, Russell Montgomery	BS ’87, MS ’88
Huffman, Andromeda L.	MS ’15
Huggett, George R.	PhD ’64
Hughart, Bradford D.	BS ’87
Hughes, Patricia Mara	MS ’87
Humbel, William D.	MS ’85
Hung, Ching	MS ’46
Hungerford, Chanse Dylan	PhD ’17
Hunter Hochmuth, Diane	BS ’86
Hurge, Junior Anthony	BS ’10
Hurley, William	BS ’10
Hurlock, Ava Xanthe	BS ’18
Husson, Christopher J.	MS ’70
Hussong, Harold E.	BS ’35
Hutcheson, Mark F.	BS ’90
Hutchings, Franklyn	BS ’35
Hutchins, Jamie Martin	BS ’92
Hutchinson Davis, Nancy	MS ’52
Hwang, Taek Yong	PhD ’12
Iacchetta, Alexander Salvatore	BS ’11
Iaconis, Christopher	PhD ’99
Ignatovich, Filipp Vladimirovich	PhD ’07
Ikeda, Mitsuo	PhD ’62
Impellizzeri, Craig W.	BS ’85
Ingalls, Arthur Lee	BS ’32
Ingalls, Moria Anne	BS ’99
Inman, Jill-Marie	PhD ’96
Intintoli, Alfred J.	BS ’82
Ireland, Robert Joseph	MS ’85
Irving, Bruce	MS ’78
Isberg, Thomas A.	PhD ’90
Isenberg, John Frederick	MS ’78
Iskenderian, Aram, Jr.	BS ’82
Ivanov, Trevor William	BS ’15, MS ’16
Ivansky, Adam	MS ’14
Jackson, Frederic H.	BS ’54
Jackson, John David	BS ’04, MS ’05
Jackson, Patrice Donnell	BS ’14
Jacobs, Arturo A.	MS ’87
Jacobs, Donald H.	MS ’42
Jacobs, Richard David	BS ’77, MS ’80
Jacobs, Stephen David	BS ’70, PhD ’76
Jacobs, Tess Samantha	BS ’15, MS ’16
Jaeger, Arthur R.	BS ’45
Jain, Ajaykumar R.	BS ’92

(continued)

Name	Degree and date
Jain, Anil Kumar	PhD ’73
James, Daniel F. V.	PhD ’92
James, Nicholas David	BS ’07
James, Richard Allen	BS ’83
Jaminet, Keith Stephen	BS ’87
Janchaysang, Suwatwong	MS ’01
Janeczko, Donald J.	MS ’72
Jani, Parthiv N.	BS ’02
Janisiewicz, Philip Julian	BS ’99
Jarvis, Constance Louise	BS ’86
Jarvis, James Gordon	MS ’54
Jasinski, David W.	MS ’83
Jean, James Nelson	MS ’49
Jehanno Canoglu, Annick	MS ’01
Jenkins, Matthew E.	BS ’02, MS ’04
Jensen, Arthur Edward	MS ’71
Jensen, Peter A.	BS ’53
Jentoft-Nilsen, Kristi Lynette	BS ’87
Jeon, Cheonha	BS ’09
Jha, Anand Kumar	PhD ’10
Ji, Qiuzhi	MS ’18
Jiang, Haotian	BS ’16
Jiang, Jingwei	BS ’15
Jiang, Wei	MS ’10, PhD ’16
Jin, Boya	MS ’17
Jin, Michael Sungchun	BS ’86, MS ’88
Jin, Qi	MS ’17
John, Puthenpurackal K.	MS ’67
Johnson Fraatz, Kerry Megan	BS ’00
Johnson, Aaron Jude	BS ’93
Johnson, Carleton Krefting	BS ’00
Johnson, Frank W.	BS ’38
Johnson, Frederick G.	PhD ’94
Johnson, Glen Walden	PhD ’80
Johnson, John R.	BS ’35

Name	Degree and date
Johnson, Joshua Hans	PhD ’03
Johnson, Ralph Barry	MS ’72
Johnson, William Todd	MS ’85
Jolley, Morgan Lane	BS ’08
Jones, Andrew Ellicott	PhD ’92
Jones, Gina Christine	PhD ’05
Jones, Mark Edward	BS ’90
Jones, Michael Roy	MS ’94
Jones, Peter A.	MS ’77
Jones, Rebecca Henson	MS ’91, PhD ’95
Jordan, David Charles	MS ’78
Judge, Jennifer Christine	BS ’91
Jung, Hae Won	BS ’13, MS ’16
Jungquist, Robert Kent	MS ’83
Jurling, Alden Scott	PhD ’15
Kaczmarek, Crystal Lee	BS ’90
Kadamus, Christopher James	BS ’98
Kadesch, Robert Rudstone	MS ’49
Kafka, James D.	BS ’77, PhD ’84
Kahan, Lloyd Richard	BS ’87
Kaiman, Michael	BS ’10
Kalaycioglu, Hamit	MS ’89
Kalb, Adam Christopher	BS ’06, MS ’13
Kalenak, David Steven	BS ’88, MS ’90
Kalk, Franklin Dean	PhD ’81
Kamanecka Curtin, Katherine Mary	BS ’90
Kamga, Francois Mkankam	PhD ’80
Kaminski, Tracie Ann	BS ’88
Kane, Paul James	MS ’85
Kanesaka, Tomoki	MS ’02
Kang, Lanbing	MS ’14
Kanwisher, John W.	BS ’47
Kao, Pai-Fong	BS ’10

(continued)

Name	Degree and date
Kaplan, Aaron Michael	BS ’06, MS ’09
Kaplan, Michael Lawrence	BS ’85, MS ’87
Karim, Adil M.	MS ’97
Karlik Snow Gaulin, Linda	BS ’84
Karmali, Murad M.	BS ’89
Karo, Tom	BS ’11
Karp, Chris Kester	BS ’88
Kasperczyk, Mark Stanley	MS ’12
Kastner, Scott Robert	BS ’86
Kaufman, Gregory	BS ’96
Kauranen, Martti O.	PhD ’92
Kavanagh, Suzanne	BS ’91
Kay, David Blair	MS ’73, PhD ’76
Kay, Jason David	BS ’04
Kaylor, Brant M.	BS ’02
Kazunas, Peter Dennis	MS ’10
Keil, Thomas Howard	PhD ’65
Keim, Robert E.	MS ’57
Keller, Fanny	MS ’12
Keller, Jenna Lynne	MS ’09
Kellogg, Robert Charles	BS ’83, MS ’86
Kelly, Conor	MS ’04
Kelly, Donald H.	BS ’44
Kelly, John Henry	MS ’77, PhD ’80
Kelly, Joseph Matthew	BS ’18
Kelsey, John Fredrik	MS ’89
Kendall, Don Leslie	MS ’58
Kenific, Kevin Joseph	BS ’05
Kennedy, Roger Paul	BS ’86
Kenner, Shawn Harrison	BS ’07
Kent, Henry Haskell	BS ’03, MS ’04
Kent, Julia	BS ’16
Kenward, Paul L.	BS ’83

Name	Degree and date
Kerner, Katherine Rose	MS ’04
Kerr, Howard S.	MS ’52
Kessler, Marsha Ann	BS ’86
Kessler, Terrance Jude	BS ’82, MS ’84
Ketchel, Brian Patrick	BS ’89
Khan, Obaidullah Khalid	MS ’18
Khare, Kedar Bhalchandra	MS ’01, PhD ’04
Kibler, Nelson Paul	MS ’94
Kienholz, Donald Frank	MS ’70
Kiikka, Craig Donald	BS ’83, MS ’85
Kilaru, Johnathan Vasu	BS ’87
Killius, James Stephen	MS ’85
Kilpatrick, Hugh	MS ’66
Kim, Daniel Tchoonghyon	BS ’17
Kim, David	BS ’15
Kim, Joseph Moksik	BS ’91
Kim, Joung Yoon	BS ’14
Kim, Peter	BS ’15
Kim, Tong Ku	BS ’90
Kim, Wooyoun	BS ’18
Kimmel, Ronald K.	MS ’70
Kindred, Douglas Scott	PhD ’91
Kiner, Manuel L.	BS ’53
King, Allen	MS ’33
King, Matthew Kevin	BS ’04
King, Oliver Simon	BS ’85, MS ’87
King, Thomas A. J.	BS ’50, MS ’55
Kingsland, David O.	MS ’71
Kingsley, Colin Glennon	MS ’14
Kingston, Amanda Christine	BS ’06, MS ’08
Kinzer, David Jerome	MS ’83
Kircher, James Robert	BS ’84
Kirschner, Roger S.	BS ’80

(continued)

Name	Degree and date
Kissel, Robert Peter	BS ’85
Kitzke, Benjamin Kyle	BS ’97
Klaus, Jeffrey Thomas	MS ’91
Klees, Kevin J.	MS ’87
Klein, Benjamin Paul	BS ’90
Klein, Robert Stephen	BS ’68
Kleinstiver Person, Kimberly Sue	BS ’94
Klemm, Robert E.	BS ’51
Klimas, Aleksandra Elizabeth	MS ’12
Klimasewski, Robert George	BS ’66, MS ’67
Knapp, Haley Nicole	BS ’18
Knoetgen Tausanovitch, Jeanette R.	BS ’85
Knoll, Henry A.	BS ’44
Knowlton, Robert Curtis	MS ’71
Knox, Keith Thomas	BS ’70, PhD ’75
Knox, Robert S.	PhD ’58
Knox, Wayne Harvey	BS ’79, PhD ’84
Ko, Michael Seok	BS ’91
Kobilansky, Anna	BS ’93, MS ’95
Koch, Charles Louis	BS ’89
Koch, Donald A.	BS ’48, MS ’53
Koch, Karl William, III	PhD ’90
Kochan, Nicholas	BS ’17
Koehler, Bernd Guenther	MS ’88
Koehler, Elka Ertur	BS ’89
Koester, Charles John	PhD ’55
Kogan, Feliks	BS ’07
Kohin, Margaret	BS ’83
Kohnke, Glenn Eric	BS ’89, MS ’90, PhD ’95
Koliopoulos, Chris	BS ’74
Kominsky, Daniel Schiro	MS ’99

Name	Degree and date
Kondysar, James Neil	BS ’87
Kondziela, Jeffrey	BS ’87
Koomen, Martin J.	BS ’40, MS ’43
Kopacz, Stanley Philip	MS ’89
Korenic, Eileen Mary	PhD ’97
Korka, James E.	BS ’68, MS ’70
Kornhauser, Michael Arthur	BS ’07, MS ’09
Korones, Herbert D.	MS ’61
Korwan, Daniel R.	BS ’88
Korwan, David John	BS ’81, MS ’83
Kosc, Tanya Z.	MS ’97, PhD ’03
Koshel, Richard John	BS ’88, PhD ’97
Kosik Williams, Ellen M.	MS ’01, PhD ’04
Kosky, Nicole Dinkla	BS ’92
Kostuk, Raymond Kenneth	MS ’77
Kotchick, Keith Michael	BS ’93, MS ’94
Kotmel, Robert	BS ’86
Kouthoofd, Barbara Jane	BS ’85
Kowarz, Marek W.	PhD ’95
Krakauer, Bruce William	MS ’85
Kramer, Charles John	MS ’72, PhD ’76
Kramer, Mark Allen	PhD ’86
Krameri, Rebecca Cortes	BS ’05, MS ’06
Kraus, Thomas Laurence	BS ’05, MS ’07
Krause, Donald R.	MS ’82
Kreger, Stephen Todd	PhD ’97
Kretschmann, Hanno M.	MS ’95
Krill, Daniel Martin	BS ’87, MS ’90

(continued)

Name	Degree and date
Krisl, M. Eric	PhD ’79
Kristoff, Jessica M.	BS ’04
Krolak, Leo J.	BS ’49, MS ’52
Krolicki, Thaddeus D.	MS ’49
Kruschwitz, Brian Erik	PhD ’98
Kruschwitz, Jennifer D. T.	BS ’89, MS ’95
Kruse, Andrew Wyatt	BS ’16
Kubacki, Emily A.	BS ’91
Kubalak, David Albert	BS ’91, MS ’93
Kulawiec, Andrew William	MS ’91, PhD ’94
Kulleen, Seemant Prem	BS ’98
Kulpinski, Robert W.	MS ’86
Kumar, Abhishek	MS ’11
Kumler, James Joseph	MS ’87
Kumpan, Steven Andrew	BS ’71, MS ’71
Kunick, Joseph Marshall	BS ’91
Kunz, Joseph F.	BS ’50
Kuo, Shihjong	PhD ’91
Kupfer Roberts, Sharon	BS ’87
Kurdi, Bulent N.	PhD ’89
Kuriacose, Christina A.	BS ’11
Kurkhill, James Victor	BS ’83
Kurtz, Andrew Frederick	BS ’84, MS ’86
Kutner, Brian	BS ’99
Kuwa, Tomiei	BS ’98
Kuyk, Kevin Francis	BS ’18
Kuyucu, Omer Gokhan	BS ’95
Kvamme, Damon Floyd	MS ’88
Kwak, Sun-Young John	BS ’94, MS ’96
Kwarta, Brian J.	BS ’83, MS ’85
Kwasniewski, Eric Mura	BS ’17

Name	Degree and date
Kwiatkowski, Joseph Michael	BS ’01
Kwiatkowski, Stephen	MS ’85
Lafortune, Kai Nicholas	PhD ’02
Lahcanski, Tomi	MS ’82
Laikin, Milton	MS ’57
Laine, Jonathan David	BS ’05
Laird, Ronald Ernest	BS ’88
Lam, Jane Chit	BS ’90
Lambert, William E.	BS ’50
Lamberts, Robert Lewis	PhD ’69
Lambrecht, Raymond T.	BS ’60
Lambropoulos, Theodore John	MS ’14
Lamkins, Timothy Wayne	MS ’97
Lancia, Dianne Renee	MS ’08
Landau, George J.	BS ’55
Landau, Igor	BS ’94, MS ’95
Landau, Mayer Amitai	MS ’05, PhD ’10
Landowne, Gary S.	BS ’82
Landry, Joseph Edmond	BS ’90
Lane, Nora Catherine	BS ’18, MS ’19
Langanke, Kristen Lynn	MS ’96
Langley, Frank P.	BS ’44
Lapin, Zachary Jordan	MS ’12
Larkin, Eric Walter	BS ’78
Larson, Alice A.	MS ’57
Larson, Benjamin	BS ’19
Lasche, James Baltzell	MS ’93, PhD ’98
Last, Jay T.	BS ’51
Lathan, Susan Joan	BS ’85, MS ’88
Latimer, David G.	BS ’95
Latta, Milton Russell	MS ’69
Lau, Bryan	BS ’06
Lauroesch, Thomas J.	MS ’51

(continued)

Name	Degree and date
Laverty Allen, Denise Suzanne	MS ’92
Law, Joanne Yu Man	PhD ’98
Lawn, Stephen J.	BS ’92
Lawrence, Robert E.	MS ’60
Lawson, Walter R.	MS ’68
Le, Daniel	BS ’19
Le, Jerry Long	BS ’96
LeBaron Michels, Jennifer Ann	BS ’88
Lebel Kahn, Cynthia F.	BS ’79
Lee, Augustine H.	BS ’94
Lee, Danny Dao-Yen	MS ’73
Lee, David Junho	BS ’04
Lee, Esther	BS ’02
Lee, Jae Cheul	MS ’87, PhD ’90
Lee, Je Choon	BS ’94
Lee, Joe Hung	BS ’02, MS ’03
Lee, John J.	MS ’80
Lee, Mindy	MS ’05, PhD ’08
Lee, Sang Hun	BS ’96
Lee, Tammy Kee-Wai	MS ’06, PhD ’14
Lee, William	BS ’84
Lee, Wing Yee	MS ’74
Lee, Woo Chang	BS ’86
Lees, David Eric Berman	MS ’74, PhD ’79
Lefkowitz, Lester A.	MS ’72
Lehman, Richard F.	MS ’71
Lehmbeck, Donald R.	MS ’66
Lehrer, Alan Schachar	BS ’06
Leidig, Carl F.	BS ’85, MS ’87
Leidner, Jordan Palmer	PhD ’15
Leighten, Edward H.	BS ’43
Leiner, Dennis Craig	BS ’75, MS ’77

Name	Degree and date
Lennert, Jason Michael	BS ’08
Lennert, Lianne Carole	BS ’78
Lenney, James Patrick	BS ’87
Leslie, Lisa Suzanne	PhD ’12
Leslie Culbert, Diane	MS ’87
Lesniak, Mark Philip	BS ’00
Lesoine, John Frederick	PhD ’10
Lettieri, Thomas R.	MS ’76, PhD ’78
Leung, Chin Man	BS ’89, MS ’90
Leung, Paul	BS ’12
Leung, Thomas Chung Yee	MS ’78
Levene, Michael John	BS ’92
Levin, James P.	MS ’74
Levine, Bruce Martin	PhD ’86
Levine, Michael Alan	BS ’89
Levy, Samara	BS ’19
Levy, Sanford H.	BS ’33
Lewandowski, Lisa Marie	BS ’80
Lewis, Alan Edward	BS ’81, MS ’82
Lewis, Carlton P.	BS ’34
Li, Dillen	BS ’10
Li, Fai	BS ’91
Li, Guoxin	BS ’19
Li, Huiyan	BS ’19
Li, Tianyu	BS ’14
Li, Wenjun	MS ’93
Li, Xinran	BS ’17
Li, Yiang	BS ’05
Li, Yunqi	BS ’17, MS ’18
Li, Zheng-Wu	MS ’84, PhD ’89
Li, Zihao	MS ’19
Li, Zilong	BS ’18
Lialiushkin, Leonid Sergeevich	MS ’16

(continued)

Name	Degree and date
Liang, Yaoyue	MS ’18
Liao, Zhi Jing	BS ’03
Liao, Zhi Ming	BS ’95, MS ’96, PhD ’01
Liapis, Andreas	MS ’07, PhD ’15
Lichtenstein, Terri Lee	BS ’79, MS ’80
Lidfeldt, Alfred L.	BS ’40
Liem, Han-Gie	PhD ’68
Ligtenberg Gerstenberger, Julie Kay	MS ’91
Lilevjen, Katherine Beth	BS ’04
Lin, Qiang	MS ’03, PhD ’07
Lin, Wincheng	BS ’02
Lin, Ying	MS ’91
Lindacher, Joseph M.	BS ’89
Linden, Joseph J.	BS ’17, MS ’18
Ling, Jingwei	MS ’18
Ling, Maurice	BS ’90
Liodice, Christopher M.	BS ’99
Liou, Lisa Wan-I	MS ’92, PhD ’96
Lipinski, Albert J.	BS ’49
Lippman, David Henry	BS ’18
Litten, Walter	BS ’36
Little, Alan Derek	BS ’86, MS ’88
Litynski, Daniel Mitchell	MS ’71
Liu, Jianzhao	MS ’18
Liu, Kang	PhD ’18
Liu, Rong	BS ’04
Liu, Weidi	BS ’18
Liu, Xiang	BS ’14
Lo, Koon Kai	MS ’90
Loce, Robert P.	MS ’87
Loj, Katherine	BS ’87

Name	Degree and date
Lomer, Lloyd R.	MS ’67
Lompado, Arthur	BS ’88
London, Mortimer A.	BS ’37
Loomis Hunter, Vivian Dean	BS ’86
Lopez, Ali G.	MS ’93
Lopez-Rios, Raymond Fabricio	BS ’17
Lorenzo, Josie S.	MS ’18
Lou, Xinye	PhD ’13
Lovejoy, David Howard	BS ’87
Lovullo, Nicholas	BS ’14
Lu, Fei	MS ’02, PhD ’06
Lu, Meng	MS ’08
Lu, Ngoc Quang	BS ’91
Luck, William Samuel, Jr.	MS ’03
Lui, Cynthia Yee-Har	BS ’99
Lukowski, Thomas Ian	MS ’79
Lunstead, Mark Owen	BS ’86
Lurier, Jeanette	MS ’85
Lutter, Matthew Charles	BS ’98
Lutz, Eric Matthew	BS ’83
Lynn, Stephen Cester	BS ’82
Lyon, Richard Gary	MS ’87
Lyon Voci, Laurie Marie	BS ’83, MS ’85
Lyons, Kevin Patrick	BS ’80
Lyu, Jiakai	MS ’18
Lyubarsky, Alexander	BS ’10
Ma, Shiyu	BS ’19
Maas, Bryan	BS ’16, MS ’17
Maben Balonek, Hillary	BS ’10, MS ’14
MacArtor, Trudy	BS ’81
MacGowan, Charlotte	BS ’87
Machado, David Edison	BS ’92
MacKay, Douglas	MS ’62
Macnally, Sara	BS ’17

(continued)

Name	Degree and date
Macneil, James Michael	BS ’14, MS ’17
Madsen, David Dale	MS ’92
Maeda, Riki	MS ’85
Magenya, Barry Adino	BS ’2018
Magill, Lincoln Clark	BS ’48
Magna-Contreras, Diane Ruby	BS ’18
Magocs, Stephen	BS ’82
Magruder, Adam Stuart	MS ’08
Maher, Jason Robert	BS ’07, PhD ’13
Mahloch, Timothy J	MS ’88
Maier, Dennis Allan	MS ’71
Maier, Robert L.	BS ’64, MS ’66
Maislin, Seth Adam	BS ’90, MS ’92
Maiten, Jessica Ann	BS ’92, MS ’94
Mak, Oscar Sy	BS ’99
Makarov, Nikita	BS ’19
Maki, Jeffery John	PhD ’92
Malacara, Daniel	MS ’63, PhD ’65
Malacara, Zacarias	MS ’78
Malach, Joseph Daniel	BS ’96
Malcuit Stone, Michelle S.	PhD ’87
Malik, Amjad Iqbal	BS ’84
Malik, Mehul	MS ’09, PhD ’13
Mallalieu, Kim Ingrid	MS ’83
Mallalieu, Mark Richard	PhD ’94
Malyak, Phillip Herbert	PhD ’85
Mandra, Robert Steven	BS ’87, MS ’93
Manian (Balasubramanian), Bala S.	MS ’69
Manly, David Randall	BS ’15, MS ’16

Name	Degree and date
Mann, Eileen Marie	BS ’87, MS ’89
Mann, Gregory David	BS ’89
Mannello, Richard	BS ’79
Manning, Richard Irvine, Jr.	MS ’83
Mantravadi, Murty V. R.	PhD ’59
Marasco, Peter Louis	BS ’91
Marciante, John Robert	MS ’92, PhD ’97
Margaretten, Elias J.	BS ’33
Margolies, Jeffrey Matthew	BS ’94
Margolis, Samuel Phillips	MS ’17
Marino, Alberto Manuel	MS ’02, PhD ’07
Markason, David Joseph	BS ’86
Markman, Howard Philip	MS ’72
Marks, Jerold S.	BS ’44
Marleau, William J.	BS ’98
Marquart, Michael E.	BS ’88
Marron, Andrea Leigh	BS ’08
Marron, Joseph Charles	BS ’81, MS ’83, PhD ’86
Marsh, Graham Andrew	MS ’09
Marshall, Henry S.	BS ’34
Martin, Andrew Loughlin	MS ’84
Martin, John David	MS ’88
Martin, William Charles	MS ’72
Martin Cusack, Deidre E.	BS ’87
Martinez, Diego	BS ’18
Martino, Anthony Joseph	PhD ’90
Martins, Jill Maria	BS ’05
Martuscello, Karen Leigh	BS ’11, MS ’12
Masella, Benjamin D.	PhD ’13
Maslek, James Michael	BS ’15
Mason, Kenneth	MS ’85
Mason, Steven Eric	BS ’83, MS ’87
Mastandrea, Andrew A.	BS ’80

(continued)

Name	Degree and date
Masters Sandruck, Julie Christine	BS ’94, MS ’00
Mastriani, Paul J.	BS ’95
Mathur, Anant	MS ’05
Matson, Robert David	BS ’84
Matter, George H.	BS ’49
Mauldin, Lemuel Edward	MS ’69
Maxwell, Bruce Beardsley	BS ’84
Mayer, Pamela Ann	BS ’85
Maywar, Drew Nelson	BS ’92, MS ’97, PhD ’01
Mazurowski, Joseph C.	BS ’81
McCabe, George Howard	BS ’86
McCabe, Jill Marie	BS ’88
McCarthy, Matthew E.	BS ’88
McCarthy, Michael Patrick	BS ’87
McCarthy, Patrick L.	BS ’88
McCarthy, Peter William	BS ’08, PhD ’15
McClain, Sean Thomas	MS ’88
McCormick, Daniel Wayne	BS ’08
McDonald, Peter Hughes	BS ’87
McDonnell, Michael Martin	MS ’76
McFarlane, David L.	BS ’85
McGhee, Patrick J.	BS ’05, MS ’06
McGuire, Kevin P.	BS ’83, MS ’85
McHugh, Thomas James	BS ’74
McHugh, Timothy Francis	BS ’93
McIntyre, Kevin J.	BS ’88, MS ’90, PhD ’98
McKay, Gregory Neal	BS ’13
McKay, Kenneth Larkin	BS ’79
McKay, Kenneth Matthew	BS ’09
McKeever, Christopher Michael	BS ’96
McKenney, Dean Brinton	MS ’66

Name	Degree and date
McKeon DiLella, Amanda L.	BS ’93, MS ’94
McKinley, Harry Ralph	BS ’58
McKusick, Wayne L.	BS ’40
McLauchlin, John Scott	BS ’86
McLaughlin, Paul Oliver	MS ’78, PhD ’83
McMackin, Ian M.	PhD ’89
McMahon, Matthew	BS ’93
McMahon, Shaun	BS ’91
McMichael, Ryan	BS ’10, MS ’11
McMichael, Ryan Everett	BS ’94
McMinn, Theodore Samuel	MS ’81
McMurdy, John William	BS ’02, MS ’03
McNamara, Andrew John	BS ’05
McNeil, Brian	BS ’95
McNenny, Patrick J. Shelby	BS ’83
McQueen, Alexander M.	MS ’87
McShane, Thomas	BS ’99
McSwain, Berah D.	BS ’56, MS ’62
McTiernan, Michael	BS ’85
McVernon, William H.	MS ’73
McVicker, David Bryan	BS ’83
Meiners, William Michael	BS ’89
Meiron, Josef	PhD ’54
Mellberg Nessmiller, Laura	BS ’91, MS ’93
Mello, Michael	MS ’88
Melnik, Maksim	MS ’15
Melocchi, Michael Leo	BS ’97, MS ’01, PhD ’03
Mendenhall, Valerie Rochelle	MS ’89
Mendes, Geraldo Ferreira	MS ’81
Mendleson, Alton	BS ’86
Mercado, Alvaro G.	MS ’90

(continued)

Name	Degree and date
Merdsoy, Urhan S.	BS ’42
Meredith, William A.	BS ’89
Merle, Cormic Kevin	BS ’91
Mersereau, Keith	BS ’84, MS ’86
Merwin, Kenneth Stacey	MS ’92
Methvin Mehalick, Kimberly Irene	BS ’85
Metro, Brian John	BS ’06
Metzger, Robert John	BS ’85
Meyer, Jon	MS ’99
Meyer, Kathleen S.	BS ’83
Meyers, Mark M.	MS ’93
Meyzonnette, Jean Louis	MS ’72, PhD ’75
Miceli, Joseph James	PhD ’83
Michaels, Elise M. Raffan	BS ’91
Michaels, Richard J.	BS ’82
Michaels, Robert L.	BS ’91
Michalko, Aaron Michael	BS ’14
Michaloski, Paul Francis	BS ’84, MS ’86
Michalski, James Edward	BS ’86
Michel, Edwine	BS ’04, MS ’05
Michniewicz, Mark Anthony	MS ’91
Micklas, Mary Elizabeth	BS ’90
Mietus, Amanda	BS ’19
Mihaylova, Dilyana Stefanova	MS ’15
Mikhail, Ra’Ef	BS ’10
Milberger, Jacob J.	BS ’16
Milby, Ezra Mark	BS ’09
Mileski, John F.	MS ’89
Mille, Kevin W.	BS ’04
Miller, Brian Robert	MS ’87
Miller, Bruce Eliot	BS ’79, MS ’81
Miller, Donald Thomas	PhD ’96
Miller, Edward J.	BS ’85, MS ’87, PhD ’92
Miller, Gary A	MS ’01, PhD ’06
Miller, Hannah M.	MS ’14
Miller, Jennifer L.	MS ’87
Miller, Michael Owen	BS ’94
Miller, Norma	BS ’38, MS ’61
Miller, Paul Olof	BS ’90
Miller, Theodore L.	BS ’62, MS ’76
Miller, Thomas James	BS ’86
Milligan, Frank G.	BS ’61, MS ’64
Mills, James Patrick	PhD ’85
Mills, Roger Howard	BS ’83
Milne, Gordon Gladstone	PhD ’50
Milowic, Christopher Yves	BS ’82
Mimmack, William E.	PhD ’73
Minkler, Marcus W.	BS ’45, MS ’49
Minott, Peter O.	MS ’61
Mirhosseini Nir, Seyed Mohammad	MS ’13, PhD ’16
Missig, Michael David	BS ’92, MS ’94
Mitchell, Karin Elean	BS ’87
Miyamoto, Kenro	PhD ’61
Modavis, Robert Adam	BS ’81, MS ’83, PhD ’91
Moi, Michael C.	BS ’98
Molander, William A.	PhD ’83
Monacelli, Brian	MS ’01
Montano, Gustavo Gandara	PhD ’19
Montgomery, Edward Anthony	MS ’70
Montifiore, Nicholas	BS ’17
Montroll, Andrew Hugh	BS ’80, MS ’81
Moon, Jeffrey Pierce	BS ’96

(continued)

Name	Degree and date
Moore, Charles E.	MS ’78
Moore, David Richard	MS ’75
Moore, Duncan Thomas	MS ’71, PhD ’74
Moore, Dustin Bradley	PhD ’16
Moore, Eric Daniel	MS ’01
Moore, Gregory Charles	BS ’92
Moore, Matthew	MS ’04
Moore, Maureen Louise	MS ’87
Moore, Nicole J.	PhD ’09
Moore, Robert Charles	MS ’72
Moore, Sean Alan	BS ’98
Moore, Thomas Richard	PhD ’93
Moore, Weston Joel	BS ’16
Moore Sullivan, Karen Louise	BS ’90, MS ’91, PhD ’98
Moorhusen, Robert W.	MS ’70
Morales, Angel	BS ’16, MS ’18
Moran, John Paul	BS ’89
Morante, Robert J.	MS ’74
Morelli Czajka Reilly, Taryn Anne	BS ’93, MS ’95
Morgan, Jessica I.	MS ’05, PhD ’08
Morgen, Daniel Benjamin	BS ’16
Moriarty, Kenneth J.	BS ’87
Morien, Steven Bruce	BS ’88
Morrison, Jeffrey Scott	BS ’90
Morrison, Robert Vincent	BS ’88, MS ’89
Morse, Kara Denise	BS ’15
Morse, Samuel F.	BS ’83
Mortzheim, Kristofer	BS ’99
Moskun, Eric Michael	MS ’01
Moss, Tuckerman	MS ’60
Mostrom, Richard N.	MS ’67
Mott, Andrew G.	BS ’87
Motz, Teresa Marie	MS ’84

Name	Degree and date
Mount, Susan Beth	BS ’90
Mounts, Darryl Ian	BS ’79, MS ’81
Moy, Alexander William	BS ’03
Mrdjen, Peter	MS ’72
Mulkey, Daniel Dalton	MS ’16
Mullen, Siobhan Marie	BS ’83
Mullens, Cynthia Jo	MS ’88
Mulley, Joseph Richard	BS ’05
Mullis, Ronald Dennis	BS ’74
Munnerlyn, Charles R.	PhD ’69
Munro, James Fredric	MS ’90
Munroe, James L.	BS ’64
Murnan, Andrew Joseph	BS ’96, MS ’03
Murnane, Michael R.	BS ’91
Murphy, Paul Edward	BS ’95, PhD ’01
Murphy, Robert Joseph	MS ’78
Murray, Richard Paul	MS ’78
Murty, Mantravado V. R. K.	PhD ’59
Muthukrishnan, Ashok	MS ’98, PhD ’02
Myers, Jack	BS ’19
Myers, Mark Thomas	MS ’89
Nadeau, Mary	BS ’82, MS ’84
Nadorff, Georg	BS ’85, MS ’87
Nagasako, Elna Mieko	PhD ’01
Najmi, Ashar	BS ’77
Nakagawa, Kazunari	MS ’87
Nakamura, Akira	MS ’87
Naradikian, Markar Souren	BS ’00, MS ’04
Naselaris, Nicole	BS ’19
Nash, Daniel R.	BS ’88
Nasir, Amir R.	BS ’91
Naso, Mark William	BS ’90

(continued)

Name	Degree and date
Nass, Colin Evan	BS ’84
Natrella, Vincent Kevin	BS ’81
Naughton, Denis Patrick	MS ’86
Nauriyal, Juniyali	MS ’18
Naus, David Alan	MS ’67
Nebolsine, Peter Eugene	PhD ’72
Nees, John A.	MS ’85
Neff, Brian Wayne	BS ’84
Neiser, Jason Daniel	PhD ’06
Nelson, David Vern	MS ’13
Nelson, Robert Lorne	PhD ’99
Nelson, Roy Dale	MS ’76
Ness, Colin	BS ’84
Netti, Sheila Lavarn	BS ’82
Neumann, Gad	PhD ’70
Neumer, Arthur	BS ’39
Neves, Fernando Bocater	MS ’77
Newcomb, Walter C.	BS ’40, MS ’42
Newell, Raymond F.	BS ’51
Neyhart, James H.	MS ’62
Ng, Baldwin Siu-Yan	BS ’91, MS ’93
Ng, William	BS ’94
Ng Oey, Linda N.	BS ’87
Nguyen, Quang Anh	MS ’83
Nguyen, Thanh T.	BS ’01
Ni, Yun Hui (Ken)	BS ’17, MS ’18
Niazi, Zakariya Abdul Robert	BS ’12
Nichols, Craig P.	BS ’87
Nie, Zhaoyu	BS ’17
Niedzielski, Peter Andrew	BS ’92
Niedzwiecki, Colleen M.	BS ’87
Nihira, Hideomi	PhD ’10
Nikolov, Daniel Kirchov	MS ’16
Nilsen, Kristin	BS ’87
Nir, Shlomo	MS ’78

Name	Degree and date
Niu, Yifan	MS ’18
Noblett, Patricia M.	MS ’90
Noel, Michael W.	MS ’91, PhD ’96
Noethen, Mark	MS ’85
Noll, Thomas John	BS ’86
Nord, Donald Dale	MS ’69
Norris, Michelle Leanne	BS ’11
Norton, Scott Michael	MS ’92, PhD ’98
Norton, Wayne G.	BS ’41
Noske, Elaine Jane	MS ’89
Noyes, Gary R.	BS ’65, MS ’67
Nutting, Perley Gilman, Jr.	MS ’38
Nyyssonen, Diana	PhD ’75
Obear, Jeffrey Allan	BS ’84
Oberheuser, Joseph Henry	MS ’68
O’Brien, Brian	BS ’44
O’Brien, Justin Richard	BS ’87
Ochs, Michael Gerard	BS ’89
O’Connell, John M.	MS ’57
O’Donnell, Kevin Arthur	PhD ’83
O’Donohue, Stephen Daniel	BS ’03, MS ’04
Oey, Daniel Wihanan	BS ’90
Ogien, Jonas Alexandre Simon	MS ’14
O’Grady, Edward John	BS ’48
Ogunsola, Oludotun Oladipo	BS ’11
Oh, Je Sun	BS ’11
Oinen, Donald Edwin	MS ’70
Oka, Keita	BS ’07, MS ’08
Oka, Michio	MS ’85
Okay, Kemalat Fatma	BS ’88
O’Keefe, Kevin C.	MS ’82
Oles, Catherine E.	MS ’03
Oles, David	BS ’14

(continued)

Name	Degree and date
Oliver, Brian James	MS ’94
Oliver, James Brian	BS ’92, MS ’97, PhD ’12
Olmstead, Ty Richard	MS ’93
Olmsted, Brian Lewis	MS ’87, PhD ’93
Olofsson, Lars Magnus	MS ’90, PhD ’93
Olson, James	MS ’90
Olson, Kristoffer Comiskey	BS ’19
Olson, Michael James	MS ’11
Olson, Stephen Craig	MS ’95, PhD ’99
Ommundsen Askin, Sherry Ann	BS ’89
O’Neil, Burton D.	MS ’71
O’Neill, Leo James	MS ’72
O’Neill, Mark Brian	BS ’88, MS ’93
O’Neill, Patrick K.	MS ’57
Onisk, Cynthia Rae	BS ’94
Orband, Daniel George	BS ’93
Orden, Alexander	BS ’37
Ordway, Mark Gary	BS ’17, MS ’18
Oren, Igal	MS ’72
Orenstein, Matthew	BS ’19
Ori, Yuichiro	MS ’94
Oron, Moshe	PhD ’76
Orser, W. D.	BS ’34
Osada, Hidenori	MS ’75
Osborn, John	MS ’84
Osborn, Leroy N.	BS ’74
Osborn, Robert Ray	MS ’88
Oschmann, Jacobus Marinus	BS ’82
Osgood, Jeffery Steven	MS ’81
O’Shea, Kevin Paul	BS ’94
Ossman, Kenneth R.	MS ’82
O’Sullivan, Jennifer Ivy	BS ’00, MS ’04
Oughstun, Kurt E.	MS ’74, PhD ’79
Overstreet, Michael Robert	MS ’87
Ozawa, Motoki	MS ’88
Pack, Thomas John	MS ’90
Packer, Donald	MS ’35
Padnos, Stephen Herschel	BS ’84, MS ’86
Pagano, Robert J.	BS ’85, MS ’87
Page, Erik Alexander	BS ’16, MS ’17
Page, Matthew M.	BS ’18, MS ’19
Page, Taylor	BS ’17, MS ’18
Pajoohi, Tara Sohaila	BS ’04
Pakyz, Joseph Francis	BS ’84
Pal, Parama	MS ’09, PhD ’10
Palit, Robin	BS ’03
Palvino, Mark Lawrence	BS ’85
Pamplin, Daniel Hockaday	MS ’14
Pan, Dong	MS ’06
Pan, Feng	MS ’15
Panchal, Dharmesh Gopal	MS ’94
Pancy, Benjamin Michael	MS ’10
Pancy, Kit Michelle	MS ’10
Pansari, Ankur Gopiram	BS ’04
Pantano, Joseph Francis	BS ’90
Papa, Jonathan Christian	BS ’14
Papademetriou, Stephanos	BS ’86, MS ’87, PhD ’94
Pappert, Richard A.	BS ’52
Paradysz, Louis Frank	MS ’66
Parisis, John Chris	BS ’85

(continued)

Name	Degree and date
Park, Jeong	BS ’98, MS ’02
Parke, James	BS ’04
Parker, Donald J.	BS ’50
Parker, Harry Lawrence	MS ’79
Parker, Jeffrey Robert	BS ’87
Parker, Jonathan Scott	PhD ’90
Parker Seidner, Jodi	BS ’87
Parks, Vernon L.	MS ’32
Park Schue, Mi-Young	BS ’03, MS ’04
Paruchuru, Vijay Krishna	MS ’08
Pascale, Michael John	BS ’90
Pasciak Keegan, Susan Marie	BS ’80, MS ’81
Pasquale, Bert Alan	BS ’91
Passalugo, James Robert	BS ’98
Pastuszka, Natalie	BS ’15, MS ’16
Patel, Divya C.	BS ’88
Patel, Falgun Dinesh	BS ’95
Patel, Paras	MS ’99
Patel, Vinodray N.	MS ’73
Patience, Jennifer Lynn	MS ’94
Patton, William R.	BS ’42
Pavia, Michael	BS ’87
Pawluckie, William M.	MS ’94
Payumo, Vernon Ian	BS ’88
Peastrel, Mark	MS ’80
Pedrazzani, Janet R.	MS ’01, PhD ’10
Pedulla Marangola, Lesley Ann	BS ’92
Peer, Aaron Steven	BS ’98, MS ’99, PhD ’04
Pehta, Arnold J.	BS ’43
Pei, Edward	BS ’14
Peistrup, Clifford F.	MS ’54
Pendleton, Amanda Kay	MS ’14
Peng, Song	PhD ’96

Name	Degree and date
Pentico, Clark Allan	MS ’92
Pentolino, Samuel Gabriel	BS ’93
Percevault, Elizabeth Edwards	BS ’88
Percevault, Mark S.	BS ’87
Pereira, Suresh Newel	MS ’96
Perez, Marc James	BS ’06
Perkins, Richard F.	BS ’36
Perlin, Jay Elliot	BS ’83
Perman-Shea, Rachelle Marie	BS ’91
Perrella, Gavin Camillo	BS ’12, MS ’13
Perricelli Muscato, Ann Michelle	BS ’92
Perry, David Joseph	BS ’82
Perry, Stanford	MS ’59
Persky, Stacey Ilise	BS ’92
Person, Steven Michael	PhD ’14
Pessot, Maurice A.	MS ’83, PhD ’89
Pete, Alexander Joseph	BS ’93
Peters, Philip Matthew	PhD ’99
Petersen, Travis Scott	MS ’15, PhD ’17
Peterson, Kevin R.	BS ’86
Petrozzo, Ronald A.	BS ’83, MS ’89
Pettenski, Rebecca Maria	BS ’15
Pfenning, Michael John	BS ’91
Pfisterer, Richard Nicholas	BS ’79, MS ’80
Phillips, Paul Scott	BS ’81
Phillips, Sheldon	BS ’48
Piciacchio-Tudryn, Dawn Jacqueline	BS ’89
Pierce, Gregory W.	MS ’96
Pietsch, Christopher Mark	MS ’18
Pike, Charles Dean	MS ’76
Pike, H. Alan	PhD ’72
Pike, John N.	PhD ’58

(continued)

Name	Degree and date
Pilston, Robert George	BS '51
Pinyan, Christopher	MS '91
Piotrowski, John Joseph	BS '18
Piredda, Giovanni	PhD '08
Pirog, John Thomas	BS '17
Pisarski, Alexander John	BS '07
Placella, Michael Joseph	BS '80
Plaessmann, Henry George	BS '89
Plano, Mary Anne	MS '84
Plansinis, Brent William	PhD '17
Plescia, Joseph Roy	BS '94
Pline Furey, Laurie Kay	BS '82
Plotsker, Vadim	BS '89
Plympton, Richard Joseph	BS '87
Polster, Alan Armand	MS '68
Polster, Harry D.	PhD '46
Pomykai, Michael Richard	BS '91
Poon, Phillip Kin-Hung	MS '08
Popelka, Susan Renee	MS '77
Popli, Sanjeev K.	BS '88
Porat, Tamar	MS '92
Poremba, Geoffrey James	BS '91
Porter, Jason	BS '97, MS '99, PhD '04
Porter, Melbourne J.	BS '32
Portilla, Sixto Emil	BS '87
Portisch, Kuang-Chang	BS '91
Potter, Robert J.	PhD '60
Poutrina, Ekaterina	MS '03, PhD '05
Powers, Jeffrey B.	MS '91
Powers, Steven James	BS '14
Powers, Thomas Foster	BS '77, MS '83
Pradhan, Apurba Prasad	MS '02
Prakash, Rohit	MS '17
Prelewitz, David Floyd	MS '85, PhD '93
Price, Edgar E.	BS '40

Name	Degree and date
Price, William H.	MS '55
Price, William P.	MS '49
Prichard, Mark S.	MS '85
Prince, Brian Francis	BS '86
Prister, Charles	BS '53
Pritts, James E.	BS '71
Procino, Wesley John	BS '89
Proctor, Douglas E.	BS '93
Progler, Christopher John	BS '86, MS '87
Pugliese McMackin, Lenore	MS '86, PhD '91
Pulhamus, Derek Joseph	BS '07, MS '08
Purcell, Robert Emmett	BS '74
Purdy, Edmund James	BS '87
Purrazzella, Joseph John	BS '83
Puth, Jason Charles	MS '01
Putnam, Nicole Marie	BS '03
Putnam, Thomas E.	BS '47, MS '50
Puzyrev, Danila	MS '17
Qi, Rui	MS '18
Qian, Wei	BS '04
Qian, Yingxing	BS '15
Qiu, Liangyu	MS '16
Quick, Henry E.	BS '35
Quijano, Michael A	BS '04
Quinn, Daniel Michael	BS '03
Rabedeau, Melbourne E.	MS '60
Rabin, Mark David	BS '98
Rabinowitz, Jordan	BS '18, MS '19
Rachfal, Jay	MS '87
Radesi, Felix John	BS '90
Radic, Stojan D.	MS '93, PhD '95
Radkowski, Edward Joseph	MS '67
Radunsky, Aleksandr S.	BS '00, PhD '13

(continued)

Name	Degree and date
Ragg, Wolfram	MS ’92
Raguin, Daniel Henri	PhD ’93
Rainville, Alexander Ward	BS ’16
Rajappan, K. Vimaladevi	MS ’63
Rama, Jason Eric	BS ’00
Ram Kum, Sabesan	PhD ’12
Ramamurti, J.	PhD ’67
Ramkhalawon, Roshita Devi	MS ’12
Ramon, Shmuel J.	MS ’72
Ramos-Izquierdo, Luis A.	MS ’85
Rao, Mamidi Madhusudana	MS ’63
Raptis, Panagiotis	MS ’99
Rastogi, Abhinav	MS ’14
Raymond, Brion Swigert	BS ’92
Raymondo, Philip Joseph	MS ’73
Rea, Everett James	BS ’77
Reardon, Joseph D.	BS ’40
Reaves, Matthew Tyler	MS ’09
Reddersen, Brad Rawson	MS ’74
Reed, David Ronald	BS ’90
Reed, Timothy	BS ’82, MS ’85
Rees, James D., Jr.	BS ’57, MS ’65
Reese, Owein Gordon	BS ’02
Refermat, Stanley J.	MS ’67
Regelman, Jeffrey Alan	MS ’85
Regensburger, Paul J.	PhD ’67
Reid, Ellen Margaret	MS ’91
Reid, Sean	BS ’16
Reilly, Terrence H.	PhD ’69
Relin, Michelle Lynn	BS ’16
Remijan, Paul Walter	PhD ’79
Ren, Jun	MS ’97
Renaud, Blaise	MS ’72, PhD ’77
Rentoumis, George M.	BS ’43
Rentz, Stephen Paul	BS ’87

Name	Degree and date
Reven, Shawn Courtney	BS ’88
Rice, Kevin Eric	BS ’97, MS ’98
Rich, Lisa Renee	BS ’90
Rifelli, Richard E.	BS ’74, MS ’77
Rigatti, Amy L.	BS ’90, MS ’96
Riggs, John Benjamin, III	BS ’89
Rimmer, Matthew P.	BS ’56, MS ’61
Rinehart, Thomas Alan	PhD ’82
Rippel, Charles Willard, Jr.	BS ’50
Risinger, Bradley Russ	MS ’87
Rivers, Robert Royce	BS ’66
Riviere, Michel Claude	MS ’81
Roberts, Benjamin C.	BS ’97
Roberts, Eric Drexel	BS ’85
Roberts, Gregory Lin	BS ’17
Roberts, Harrison Kevin	BS ’89
Roberts, Thomas Edward	BS ’85
Roberts, William Thomas	BS ’92
Roberts-Levine, Evelyn Ann	BS ’88
Robinson, Theodore P.	MS ’80
Robles, David Clinton	MS ’94
Roche, Margot Kathryn	BS ’90
Rodenburg, Brandon Vernon	PhD ’15
Rodney, Paul James	PhD ’98
Rogala, Eric Walter	BS ’90, MS ’92
Rogers, Harry L., III	MS ’48
Rogers, Howard F.	BS ’36
Roland, Nicholas	MS ’01
Rolleston, Robert John	MS ’83, PhD ’88
Romano, Joseph Francis	BS ’01
Ropri, Omer Salman	BS ’10, MS ’14
Rosborough, Robert S.	BS ’45

(continued)

Name	Degree and date
Roseman, Steven Arthur	BS ’79
Rosen, Arthur N.	PhD ’68
Rosenbluth, Alan Edward	BS ’76, PhD ’83
Rosenstein, Jack E.	BS ’74
Rost, Martin Roger	BS ’82
Rosvold, Jake	BS ’19
Rothacker, Markus	BS ’18
Rothschild, Mordekhay	PhD ’79
Rouke, Jennifer Lynn	PhD ’01
Rouse, Andrew R.	BS ’93
Royall, William Ellsworth	BS ’74
Roychoudhuri, Chandrasekhar	PhD ’73
Roychowdhury, Hema	PhD ’06
Ruben, Paul Lewis	BS ’59, MS ’63
Rubinoff, Greg Ben	BS ’91
Ruda, Mitchell Curtis	MS ’73
Rudder, Scott Lee	BS ’88
Rueckwald, Eric Ronald	MS ’97
Ruff, Bruce J.	BS ’60, MS ’67
Rupert, Jeffrey Wayne	MS ’86
Rusin, William George	MS ’05
Russell, Charles Herbert	MS ’81
Russo, Michael James	BS ’90, MS ’91
Rustmann Atwood, Jenny T.	MS ’00
Rutins, Guntis Janis	BS ’16
Rutledge, James	BS ’19
Ryan, Andrew Thomas	PhD ’97
Ryan, Kenneth James	BS ’90
Ryan-Howard, Danette P.	BS ’77, MS ’80, PhD ’83
Saaf, Lennart Arnold	PhD ’92
Saager, Rolf B.	BS ’98, PhD ’08
Saba, Michael Anthony	BS ’86
Sabharwal, Yashvinder Singh	BS ’92

Name	Degree and date
Sabia, Yi	MS ’03
Saccketti, Nicholas Bert	BS ’77
Sachkouskaya, Olga	MS ’18
Safavi, Syed Kaiwan	BS ’89
Sales, Tasso Melo	PhD ’98
Salisbury, Francis Cedric	BS ’00, MS ’02
Salvage, Robert Taverner	MS ’80
Samios, Gregory Speros	BS ’85, MS ’87
Sampath, Deepak Prakash	BS ’97
Samuels, Joan Ellen	MS ’89
Samuels, Stephen J.	BS ’74
Sanca Zelazny, Amy Louise	BS ’83
Sanchez, Joseph	BS ’78
Sandruck, Scott Alan	BS ’94
Sangmeister, Karen Mary	BS ’76
Sankey, Norris D.	PhD ’93
Sano, Koichi	MS ’99
Sanson, Mark C.	MS ’98
Santos, Francisco Javier	MS ’16
Santwani, Sheila M.	BS ’91
Sarama, Scott Daniel	BS ’91, MS ’93
Sargent, Lisa Ann	MS ’83
Satchithanandam, Kumar	BS ’79
Sato, Akira	MS ’92
Sauer, Carolyn Louise	MS ’76
Sauer, Ryan Walter	BS ’18
Saunders, Rene	BS ’90
Sauther, Eric Joseph	BS ’99
Savage, Daniel Edward	BS ’10, MS ’15, PhD ’18
Savan, Mark	BS ’86, MS ’87
Savich, Gregory Robert	BS ’06, PhD ’15
Savidis, Nickolaos	BS ’07
Saxe, Douglas M.	MS ’62

(continued)

Name	Degree and date
Saxer, Christopher Eric	PhD ’98
Sayer, Gregory Stephen	BS ’90
Schaad, Ian Russell	BS ’93, MS ’94
Schaub, Charles L.	BS ’84, MS ’86
Schaub, Michael Patrick	BS ’86
Scheffel, Laurie A.	MS ’90
Schertler, Donald John	PhD ’93
Schiesser, Eric Michael	BS ’12
Schiff, Roy Kenneth	BS ’93
Schilling, Arthur	BS ’33
Schilling, Lynn L.	MS ’91
Schlauch, John Edwin	BS ’49
Schmackpfeffer, Kyle Thomas	BS ’88
Schmidt, Greg Richard	BS ’01, PhD ’09
Schnable, George K.	BS ’44
Schneckenburger, Wayne	MS ’87
Schneider, Laura	BS ’02, MS ’04
Schneider Miciuda, Gail Catherine	BS ’88
Schoenly, Joshua E.	PhD ’12
Scholl, Luke Charles	BS ’07
Schott, Peter Allen	BS ’95
Schottmiller, Gerard J.	BS ’49
Schrauth, Samuel Edward	BS ’06
Schuberg, Darren Elliott	BS ’90
Schubert, William Hunter	MS ’15
Schuda, Felix Joseph	PhD ’74
Schultz, Justin Thomas	MS ’13, PhD ’16
Schultz, Robert Jeffrey	MS ’07
Schultz Kraft, Kathrine Leigh	BS ’03
Schulz, Patricia M.	BS ’91
Schuma, Richard F.	MS ’59
Schwartz, Joan E.	MS ’89
Schwartz, John M.	MS ’60

Name	Degree and date
Schwartz, Richard A.	BS ’63, MS ’66
Schwarz, Richard Alan	MS ’91
Schweinsberg, Aaron M.	PhD ’13
Schwertz McCormick, Katie Marie	BS ’08
Schweyen, John Charles	MS ’81
Schwiegerling, James Theodore	BS ’90, MS ’91
Sczupak, Robert John	BS ’91
Seachman, Ned Jay	MS ’73
Seeley, Ryan	MS ’04
Segler, Dana J.	BS ’94
Seiden, Harold Norman	MS ’83
Seitz Vent, Debra Sue	BS ’89
Selent, William Parker	BS ’90
Seligson, Joel Leo	PhD ’81
Seo, Katsuhiro	MS ’94
Seppala, Lynn G.	PhD ’74
Sesko, David William	MS ’84
Sexton, John W.	BS ’52
Shaffer, James Paul	PhD ’99
Shaffer, Stephen Lawrence	MS ’84
Shank, Steven Marc	PhD ’93
Shanks, David Alan	BS ’84
Shannon, Robert R.	BS ’54
Sharma, Anchal	MS ’16
Sharma, Neelima	BS ’89
Sharma, Robin	PhD ’15
Sharma Bauer, Katelynn Asha	BS ’12, MS ’14, PhD ’17
Shea, James John	MS ’91
Sheehy, Christy Kathleen	BS ’07, MS ’10
Sherman, Bennett	MS ’47
Sherman, James Patrick	MS ’97
Sherwood, William Theodore	BS ’40
Shi, Zhimin	MS ’09, PhD ’11

(continued)

Name	Degree and date
Shieh, Mun Houng	BS ’90
Shih, I-Fu	MS ’77
Shimizu, Jeffrey	BS ’86, MS ’87
Shin, Heedeuk	PhD ’11
Shipley, Jeffrey Clay	BS ’95
Shipp, Dustin Wade	PhD ’14
Shirley, Lyle Gordon	PhD ’88
Shmoys, Dmitry B.	BS ’00
Shoemaker, Arthur H.	MS ’65
Sholtis, Jonathan Andrew	BS ’06
Shome, Krishanu	PhD ’13
Short, Darren John	BS ’88
Short, Svetlana Zonis	BS ’81, MS ’87
Shramko Rich, Ellen A.	BS ’82
Shroff, Ashutosh	MS ’04
Shu, Chi	MS ’18
Shuker, Reuben	MS ’69
Shukes, Scott	BS ’91
Shulman, Seth D.	MS ’88
Shum, Frank T.	MS ’91
Shuman, Arnold D.	MS ’71
Shuman, Timothy Michael	MS ’99
Shurkus, Albert Adam	BS ’40
Sicard Dagenais, Dominique Marie	MS ’77
Sickler, Jason William	BS ’00
Sidor, Daniel Evan	PhD ’17
Siegmund, Walter P.	BS ’46
Siemens-Wapni, William	MS ’65
Siew, Ronian Hanweng	BS ’97, MS ’99
Sigg, Christina	MS ’88
Silva, Francis Xavier	BS ’85
Silver, Rebecca	BS ’18
Silverstein, Barry D.	BS ’84
Silvestro, John Michael	BS ’88

Name	Degree and date
Simbal, John Joseph	MS ’79
Simon, Ralph J.	MS ’76
Simons, David Robert	BS ’84, MS ’86
Simonsen, Michael Paul	BS ’18
Simpson, George R.	BS ’53
Simpson Martin, Sarah	BS ’87
Sinclair, Douglas C.	PhD ’64
Sinensky Rosenfeld, Amy Lynn	BS ’89
Singel, Diane Veronica	BS ’96
Siryk, Walter John	BS ’90
Sizer II, Theodore	MS ’80, PhD ’86
Skeldon, Mark Daniel	MS ’83, PhD ’88
Skeps, Michael Joseph	MS ’70
Slater, Jonathan Travis	MS ’18
Slaymaker, Philip Arthur	PhD ’79
Sleeman, John K.	BS ’61
Sloan, Thomas R.	BS ’65, MS ’67
Smartt, Raymond Newton	MS ’71
Smith, Abbott M.	BS ’55, MS ’57, PhD ’61
Smith, Christopher Alan	BS ’82
Smith, Corey Michael	BS ’97
Smith, Dallas Carl	MS ’13
Smith, David Charles	BS ’77, MS ’78
Smith, David D.	BS ’90
Smith, F. Dowswell	PhD ’51
Smith, Howard M.	BS ’60, PhD ’65
Smith, Katherine Morgan	BS ’17, MS ’18
Smith, Linda Ann	BS ’89
Smith, Michael David	BS ’84
Smith, Nicholas Brandon	BS ’08

(continued)

Name	Degree and date
Smith, Richard Cameron	MS ’13
Smith, Robert Edward	PhD ’94
Smith, Robert James	MS ’83
Smith, Roger Allen	BS ’09
Smith, Scott Thomas	BS ’90
Smith, Steven Lloyd	MS ’96
Smith, Thomas W.	BS ’68
Smith, Warren J.	BS ’44
Smith, Zachary James	BS ’02, PhD ’09
Smoyer, Claude Benzing	BS ’59, MS ’65
Smucz, Joseph Simon	BS ’87
Snouffer, Richard Kent	BS ’66, MS ’68
Snow, Kenneth A.	MS ’67
Snyder, John R.	BS ’44
Snyder, Michael Arthur	MS ’75
Snyder, Shane	BS ’96
Sokach, Stephen John	BS ’87
Solis Baumgartner, Karolyn M.	BS ’84
Soller, Brian Joseph	PhD ’02
Solomon, Jeffrey Mark	BS ’88
Sommargren, Gary E.	PhD ’72
Sommer, Andrew Ryan	BS ’01
Sonde, Aniruddha Ramak	MS ’18
Sonderman, John B.	BS ’40
Song, Wanyue	BS ’16, MS ’19
Sonstroem, Jaime	MS ’83
Sosa, Brandon Antonio	BS ’11
Soufleris, Mitchell	BS ’18
Sowder, Andrew Gene	BS ’90
Spaker, Kurt D.	BS ’94
Spaulding, Duncan Christopher	MS ’14
Spaulding, Kevin Edward	MS ’88, PhD ’92

Name	Degree and date
Spencer, Gordon H.	BS ’57, PhD ’63
Spencer, Harvey M.	BS ’74
Spencer, Kathleen E.	BS ’05
Spencer, Sam Weston	MS ’13
Spencer, William T.	PhD ’63
Spilatro, Michael A.	MS ’12
Spilman, Joseph Robert	BS ’03
Spilman Vogt, Alexis K.	BS ’00, PhD ’08
Sprague, Robert Arthur	BS ’67, PhD ’71
Squier, Jeffrey Alan	PhD ’93
Srour, Donna Louise	MS ’90
Staffa, Jeremy Christian	BS ’18, MS ’19
Stagaman Goddard, Joan	PhD ’85
Stagaman, Gregory Joseph	PhD ’88
Stagnitto, Steven James	BS ’98
Staloff, Daniel Max	BS ’05, MS ’06
Stamnes, Jakob Johan	PhD ’75
Stamper, Brian Lee	BS ’94
Stanley, Matthew George	BS ’98
Stanley, Patricia M	MS ’90
Stansbury, Frederick Charles	BS ’71
Stark, Gregory Leith	MS ’75
Stark, Richard A.	MS ’70
Starkweather, Gary Keith	MS ’66
Stateler, Jack G.	MS ’49
Statt, Bryan D.	BS ’90
Staudenmaier, W.	BS ’52
Staver, Phillip Randall	MS ’91
Stavlo, Addison Rebekka	MS ’15
Steckroat, Thomas Fredrick	MS ’94
Steele, Paul B.	BS ’81
Steele, Richard Kenneth	BS ’63
Stegall, David Brian	PhD ’01

(continued)

Name	Degree and date
Steijn, Kirk William	BS '81
Steinberg, Gary Allen	MS '87
Steinberg, Jennifer Ivy	MS '04
Stelick, Scott Jason	BS '93
Stenton, William Conrad	MS '70
Stentz, Andrew John	MS '92, PhD '95
Stern, Ronald David	BS '81, MS '83
Sternfield, Brett Aaron	MS '14
Sterrett, Robert M.	MS '62
Steven, Samuel James	BS '13
Stevens, Colleen	MS '96
Stevens, James Spencer	MS '95
Stevens, William Tyler	MS '90
Stewart Morse, Susan A.	BS '88
Stoll, Robert A.	MS '00
Stoltzmann, David Eugene	MS '72
Stone, Bryan D.	BS '85, MS '89, PhD '92
Stone, Colleen	BS '19
Stone, Thomas W.	BS '79, MS '83, PhD '86
Storm, Michael James	PhD '10
Storne, Eric Michael	BS '86
Stossel, Bryan Joseph	PhD '95
Strafford, David Tvasta N.	MS '96
Strandberg, Brian A.	BS '03, MS '04
Strang Ferrin, Deborah Marie	BS '85
Strasser, Arden C.	BS '84
Straw, Kimball	BS '69, MS '74
Strebel, Gustave	BS '36
Strepitov, Evgenii	MS '16
Strickland, Donald Wayne	MS '81
Strickland, Donna Theo	PhD '89
Stromski, Steven Michael	BS '00
Stuadenmaier, William G.	BS '52
Stuart, Brian Dermot	BS '89
Stuart, Howard Roy	PhD '98
Stubbe, John A.	MS '69
Stuehler Cha, Alexandra Nicole	BS '95
Stulak, John Joseph	MS '78
Stull, Corey William	BS '93
Stutz, Glenn Edward	BS '81
Sucha, Gregg Douglas	MS '85, PhD '92
Sudol, Ronald Joseph	MS '77, PhD '81
Suhan, John Michael	BS '87
Sulai, Yusufu Njoni Bamaxam	PhD '14
Sullivan, Kevin Gerard	BS '89, MS '90, PhD '94
Sullivan, Robert Charles	BS '87
Sullivan, Sean Patrick	BS '10
Sullo, Nancy J.	BS '82, MS '83
Summa, Mark Anthony	BS '90
Sun, Keung	MS '91
Sun, Lei	PhD '11
Sun, Xuan	PhD '17
Sung, Po-Er	MS '05
Supranowitz, Christopher Michael	BS '05, MS '06
Surovcik Walkush, Lisa S.	BS '89
Suter, Walter J.	BS '34
Sutherland, Donald Raymond	BS '54
Sutton, Allen McDonald	BS '44
Swain, David M	MS '74
Swaminathan, K.	MS '64
Swayne, James Alan	MS '88
Sweeney, Ann Mary	BS '87
Sweeney, Kevin	MS '15
Sweetser, John Nelson	PhD '94
Sweredoski, Brent Raymond	BS '87
Swim, Cynthia R.	BS '86

(continued)

Name	Degree and date
Swyler, Karl Joseph	PhD ’73
Sykora, Daniel	PhD ’03
Sylvia, Scott Edward	BS ’84
Synborski, Charles Edward	MS ’78
Sze, Yu-Kwok	MS ’67
Szukala, James Allan	BS ’87
Ta, Oscar C.	BS ’18
Taber, Afshin	BS ’90
Tabor Pease, Paula	MS ’82
Taggart, Christopher Scott	BS ’82
Taillie, Joseph Paul	MS ’83
Talerico, James Joseph	BS ’13
Tamaddon, Houman Sanavi	BS ’95
Tan, Zheng	BS ’18
Tanis, Todd Robert	BS ’92
Tardiff, Matthew Robert	BS ’01
Taskett, John M.	BS ’79
Tatarek, Michael John	BS ’81
Tatian, Berge	BS ’51
Taychert, Edward L.	BS ’79
Taylor, Brittany Nicole	MS ’16
Taylor, Christopher D.	BS ’80
Taylor, Leonard J.	BS ’87
Tchejeyan, Sarkis K.	MS ’62
Teich, Jordan Tyler	BS ’16
Temple, Russell A.	BS ’51
Tesar, Joseph Scott	MS ’90
Thayer, Martha Hewes	BS ’65
Theilmann, Rebecca Jean	MS ’94
Theisen, Michael John	PhD ’15
Thibodeau, Kristopher Paul	BS ’87
Thoeming, Asher James	BS ’14
Thomas, Jeffrey George	BS ’80
Thomas, Michael D.	BS ’83
Thomas, Michael John	BS ’89
Thomas, Woodlief, Jr.	MS ’58
Thompson, Daniel Stephen	MS ’99
Thorburn, Eugene K.	BS ’50

Name	Degree and date
Thorp, Keith Alan	BS ’88
Thorson, Michael Lawrence	BS ’90
Thurer Wolk, Carol Ellen	BS ’87
Thurman, Samuel Trent	BS ’96, MS ’96, PhD ’03
Tiana, Carlo Lavinio	MS ’90
Tiemann, Valerie Rochelle	MS ’89
Tiemer, Jason	BS ’19
Tienvieri, Clair Theodore	BS ’87
Tietz, George Edward	MS ’74
Tindle, Ernest R.	MS ’59
Tinker, Flemming	BS ’89
Tinkham, Kameron Jennie	BS ’17, MS ’18
Tippie Watnik, Abbie Ellen	MS ’10, PhD ’12
Tirone, Stephen Thomas	BS ’87
Tisdale, David Ryan	MS ’09
Tixi, Marco	BS ’89
Tocci, Michael David	BS ’90
Todd, Henry Swan	MS ’68
Tomkinson, Todd Harding	MS ’93
Tompkin, Christina	MS ’88
Tompkin, Wayne Robert	PhD ’90
Toohig, Timothy E.	MS ’53
Toomey, Christopher Andrew	BS ’85
Toomey, Thomas John	BS ’83
Torpey, Matthew J.	MS ’93
Tourjee, David H.	MS ’06
Tracy, Mark David	BS ’87
Traina, Marissa Jane	BS ’16
Trainer, Michael N.	MS ’77
Traskiewicz-Webb, Patricia Ann	BS ’86
Trindale, D. C.	MS ’68
Triou, Scott David	BS ’87
Triplett, Roger L.	MS ’81
Truax, Bruce Edward	BS ’77, MS ’78
Trubko, Raisa	BS ’10

(continued)

Name	Degree and date
Trueswell Tedrow, Melissa M.	BS ’87
Trumper, Isaac Lowery	BS ’15
Tsang, Lisa Yin	BS ’06
Tsao, Chih-Hsuan	BS ’18, MS ’19
Tsufura, Lisa Mayumi	BS ’84
Tu, John H.	MS ’07
Tupper, J. L.	BS ’33
Turgut, Suleyman	BS ’92
Turkay, Zahit Mehmet	MS ’45
Turner, Nicholas	BS ’02
Turner, Richard M.	BS ’87, MS ’89
Tyler, Glenn A.	MS ’74, PhD ’78
Ufford, Curtis J.	MS ’72
Ugolini, Virginia Jeannette Dent	BS ’84, MS ’88
Ullom, James R.	MS ’51
Underhill, John Richard	BS ’81
Unger, Blair L.	PhD ’10
Updike, Todd Fulton	BS ’83, MS ’85
Urbach, John C.	PhD ’62
U Ren Cortes, Alfred Barry	PhD ’04
Usechak, Nicholas Gardner	MS ’03, PhD ’06
Utano, Richard Anthony	BS ’83
Uy, Kevin Joseph	BS ’87
Vaklyes, David Whitbeck	MS ’79
Valdmanis, Janis Atis	PhD ’84
Valentine, Paul Dewey	BS ’87
Vallejo Ramirez, Pedro Pablo	BS ’16
Vandenberg, Donald E.	BS ’78
Vandepoel, Alison Lorraine	BS ’87
VanDerlofske, John Felix	BS ’90
Van Kerkhove, Alan Paul	MS ’71
VanKerkhove, Steve	BS ’89
Van Leeuwen, Michael Francis	PhD ’98
Van Lieu, Neil Russell	BS ’90
VanOrden, Lynn L.	BS ’61
Van Ven Roy, Jesse Jacob	BS ’00
Varriano, John Anthony	PhD ’93
Varshneya, Rupal	BS ’05, MS ’06
Vasanthakumar, Gurram R.	MS ’72
Vastagh, Richard E.	BS ’84
Vaughn, Brendan	BS ’02, MS ’03
Vaughn, Mark Douglas	MS ’93
Vayser, Alex	BS ’89
Veit, Morris C.	BS ’34
Velazquez, Belimar	BS ’92
Vella, Anthony	PhD ’18
Venable, Dennis Lee	BS ’78, MS ’82, PhD ’89
Vento, Robert J.	BS ’87
Verdoni, Luigi Pollara	BS ’00
Vermilya, Edgar B.	BS ’33
Vernold, Cynthia Louise	BS ’87
Vickery, Daniel S.	BS ’04
Victor, Jesse Ryan	BS ’05
Vigneaux, David Alan	BS ’03
Vijayakumar, Surendar	MS ’19
Villafranca, Evan	BS ’19
Virojanapa, Jeffrey J	BS ’04
Visconti, Anthony Joseph	BS ’09, MS ’13, PhD ’15
Vizgaitis, Jay Nicholas	BS ’98
Vo, Sophie	MS ’09
Vock, Curtis Alan	BS ’86, MS ’87
Vogel, David Adam	BS ’87
Vogel, Deborah Jane	BS ’83
Voggenthaler, John A.	BS ’56
Vogler, Scott Gerald	BS ’91, MS ’98
Volatile, Heather Anne	BS ’87

(continued)

Name	Degree and date
Volkmer, James Louis	MS ’76
Vollmer, David W.	MS ’69
Vollmer, Steven Wayne	BS ’08, MS ’09
Volonino, Louis Leonard	BS ’79
Vonhandorf, Robert John	MS ’82
Vornehm Joseph E.	PhD ’14
Vrakas, John Carl	MS ’02
Wacks, Martin Paul	BS ’80
Wagner, Brenda Sue	BS ’88
Wagner, Julianne Rachel	BS ’96
Waidelich, John Albert	BS ’49
Waido, Richard P.	MS ’73
Wald, Andrew Eric	BS ’86, MS ’87
Waldman, Mark	MS ’78
Wall, Stephen Doub	MS ’72
Wallace, James Kent	MS ’93
Wallace, John Darrow	MS ’83
Wallace, Nelson William	MS ’77
Walmsley, Ian Alexander	PhD ’86
Walsh, Kenneth Francis	BS ’71
Walsh, Richard J.	MS ’70
Walter, Brandon Wayne	MS ’19
Walters, Sarah Eileen	BS ’13
Walton, Ryan	BS ’19
Walton, Samuel Forman	BS ’48
Wamsley, Charles Christopher	PhD ’99
Wang, Anna Sansan	BS ’89
Wang, Chang	MS ’16
Wang, David	BS ’85, MS ’87, PhD ’92
Wang, Guanyao	BS ’16
Wang, Ligang	MS ’01
Wang, Perry	BS ’18
Wang, Shen-Ge	PhD ’87
Wang, Yuanchao	BS ’19
Wang, Zhiqi	BS ’16

Name	Degree and date
Wang, Zichan	BS ’17
Wang Charlton, Ingrid	BS ’85
Wapniarski, William J.	MS ’66
Warner, Frederick John	MS ’94
Warner Walsh, Nita S.	BS ’88
Warren, Carlton D.	BS ’36
Warren, David Wheeler	MS ’77
Warren, Franklin A.	BS ’34
Warzak, Frank J., Jr.	MS ’57
Washington, Carl D.	MS ’84
Waters, Peter Matthew	MS ’86
Watkins, Todd Allan	BS ’84
Watson, Edward Alan	PhD ’91
Watson, Jonathan T.	BS ’02, MS ’03
Watson, Lee Harold	BS ’92
Watson, Stephen Matthew	BS ’18
Waxer, Leon Jeffrey	PhD ’99
Weaver, Daniel W.	MS ’93
Weber, Aaron Benjamin	BS ’97
Weber, William Louis	BS ’78
Weeks, Richard F.	PhD ’59
Weeks, Wendy Theresa	BS ’02
Wegner, Matthew John	MS ’92
Wehr Mathews, Kristina Maria	BS ’91
Wei, Ran	MS ’19
Weibezahl, Thomas	BS ’79
Weil, Herschel	BS ’43
Weinberg, Brian Scott	BS ’88
Weinberg, Edith Bloom	BS ’44
Weiner, Bruce Alan	BS ’84
Weiner, David	MS ’87
Weinstein, Jacob D.	BS ’33
Weinstock, Mark Jason	BS ’88
Weisler, Raymond H.	BS ’41
Weisman, Andrew David	BS ’89
Weiss, James P	PhD ’40
Weiss, Richard Scott	BS ’88

(continued)

Name	Degree and date
Weiss, Sharon Marie	BS ’99, MS ’01, PhD ’05
Weiss, Stephanie Chen	BS ’95, MS ’99
Weissman Gingold, Rachel June	BS ’86
Welch, Jeffrey Peter	BS ’84
Welch, Robert Michael	BS ’88
Weldon, John Parker	BS ’86
Weller, Scott Wayne	MS ’84
Weller-Brophy, Laura Ann	BS ’80, MS ’84, PhD ’87
Wells, Conrad	BS ’89, MS ’91
Wen, Xiaoduo	BS ’19
Wernick, Miles Nathaniel	PhD ’90
Wersinger, Ralph E.	BS ’35
Wertheimer, Alan Lee	BS ’68, PhD ’74
Weslander Quaid, Michele Ruth	MS ’94
Wesler, John E.	MS ’54
Wesley, Alex D.	BS ’10, MS ’11
Wessel, Jeffrey Warren	BS ’73
West, Cedric F.	BS ’35
West, Garrett J.	BS ’12, MS ’14
West, James Andrew	MS ’91, PhD ’98
Westcott, Mark Ranney	BS ’70
Westerbeke, John	BS ’19
Weston, Frederick C.	BS ’34
Westover, Sandra	BS ’15
Wetherell, William B.	BS ’58, MS ’61
Whalen, Michael Robert	BS ’89
Wheeler, Benjamin Scott	MS ’97
Whitcomb, Kevin Joseph	MS ’95
White, James Robert	MS ’73

Name	Degree and date
White, Sean Michael	BS ’08
White, Walter W.	MS ’62
White, Warren Travis	MS ’72
Whitfield, Charles Hemming	BS ’75, MS ’76
Whitford, Paul Henry	BS ’86
Whitman, Tony L.	MS ’88
Whitney, Fred	MS ’83
Whitney, Theodore Robert	BS ’42
Whitney Jones, Joy G.	BS ’45
Whittaker, Gary L.	MS ’67
Widen, Kenneth Charles	MS ’85
Wieder, Harold	BS ’50, MS ’58
Wierman, Kurt Warren	BS ’83
Wiggins, Grayson L.	MS ’18
Wike, Charles Kenneth	MS ’87
Wilder, Mark Andrew	BS ’85
Wildy, Marc Harrison	BS ’87
Wilhauck, Thomas P.	MS ’69
Wilk, Stephen Richard	MS ’84
Wilkens, Peter John	BS ’88
Wilkins, Michelle L.	BS ’83
Wilklow, Ronald Andrew	BS ’83
Willard, Berton C.	BS ’62, MS ’65
Williams, Christopher	MS ’92
Williams, Daniel James Lawler	MS ’14, PhD ’16
Williams, David Laning	BS ’36
Williams, Joseph C.	BS ’34
Williams, Kaia Joseph	BS ’18
Williams, Kenneth Edgar	MS ’73
Williams Goodwin, Elizabeth Suzanne	BS ’03
Williamson, Thomas John	BS ’88
Willis, Paula Christine	MS ’85
Willis, Theodore Charles	MS ’78
Willstatter, Lindsey	BS ’16

(continued)

Name	Degree and date
Wilson McColgan, Michele Marie	BS ’90
Wilson, Brian C.	BS ’93
Wilson, John Paul	BS ’07, MS ’08
Wilson, Rebecca Anne	PhD ’12
Wilson, Richard James	BS ’42
Wilson Saik, Debra Lynn	BS ’94
Winder, Amy Alison	BS ’85, MS ’87
Wing, Albert B.	MS ’52
Winiarski, Paul Robert	BS ’86
Winn Wendell, Megan Carol	BS ’09
Wischhusen, Lisa	BS ’80
Wittman, Mark Douglas	MS ’91
Witulski Becker, Eleanor	BS ’54
Wohl, Michael Craig	BS ’88
Wojcik, Walter J.	MS ’68
Wolfe, Thomas Frederick	MS ’87
Wolff, Frederick Joseph	BS ’41
Wolff, Roger George	BS ’94
Wolfson, Maxwell David	BS ’18
Wong, David	BS ’90
Wong, Jennan	BS ’86
Wong, Michael K.	BS ’91
Wong, Minchuan	BS ’94
Wong, Victor Chow	PhD ’96
Wong, Vincent Kwok Huei	PhD ’05
Woo, Seungbum	BS ’95, MS ’97
Wood, James Kirkham	BS ’14
Wood, James L.	BS ’43
Woodruff, Robert W.	PhD ’54
Woody, Loren Michael	BS ’75
Wooley, Charles Benjamin	PhD ’89
Wortman, David Lee	MS ’88
Wright, Robert James	BS ’14, MS ’15
Wrobel, Sandrine	MS ’90

Name	Degree and date
Wu, Rucong	BS ’96
Wyant, James	MS ’67, PhD ’69
Wyatt, Christopher L.	BS ’87
Wyatt, Suzanne K.	MS ’90
Xia, Zhengzhi	BS ’17
Xiang, Lian-Qin	MS ’81
Xiao, Yuzhe	MS ’12, PhD ’14
Xu, Di	MS ’14
Xu, Ke	BS ’14
Xu, Lingbo	BS ’17
Xu, Lisen	MS ’11, PhD ’13
Xu, Zhou	BS ’16, MS ’18
Yadav, Rahul	PhD ’13
Yaman, Fatih	PhD ’06
Yan, Jiahan	MS ’14
Yan, Weizhen	MS ’01, PhD ’07
Yang, Bin	MS ’09
Yang, Chau-Shyang	BS ’00
Yang, Dongmin	MS ’06
Yang, Jessie H.	MS ’72
Yang, Michael Mann-Kuo	BS ’89
Yang, Yubai	BS ’18
Yang, Yue-Nian	MS ’87
Yao, Haomin	MS ’10, PhD ’16
Yao, Jiacheng	MS ’19
Yao, Jianing	PhD ’16
Yao, Weichen	BS ’18
Yao, Yuhong	MS ’11, PhD ’15
Yarussi, Richard Anthony	MS ’94
Yates, Tristan	BS ’19
Yau, David Wai Tai	MS ’73
Ye, Chao	MS ’19

(continued)

Name	Degree and date
Yeazell, John Anthony	PhD ’89
Yee, Anthony Jan	BS ’13, MS ’16, PhD ’19
Yin, Lianghong	PhD ’10
Yoder, Lars A.	BS ’91
Yoon, Changsik	MS ’14
Youman, Roy Latcher	BS ’87
Young, Matt	BS ’62, PhD ’67
Young, Moira Anne	BS ’99
Young, Theodore R.	BS ’49
Youngman, Bruce Alden	BS ’86
Youngworth, Kathleen S.	PhD ’03
Youngworth, Richard Neil	PhD ’02
Yu, Di	MS ’15
Yu, Jenny	BS ’88
Yu, Ming	MS ’91, MS ’94, PhD ’96
Yu, Raymond	BS ’19
Yue, Bobby Ken	BS ’87
Yugawa, Koji Joseph	MS ’95
Zaidi, Shoaib Hasan	BS ’90
Zainul, Mohamed Ajaaz	MS ’94
Zampolin, Ronald Frank	BS ’87, MS ’89
Zang, Zirui	BS ’17
Zarella, Michael David	BS ’13
Zavattero, Paul F.	MS ’12
Zavislan, James	BS ’81, PhD ’88
Zawacki, David T.	MS ’74
Zellers, Brian Keith	BS ’83, MS ’85
Zerom, Petros	PhD ’13
Zhang, Aizhong	PhD ’17
Zhang, Da	BS ’15
Zhang, Eugene Jun	BS ’91, MS ’93

Name	Degree and date
Zhang, Jingkai	BS ’19
Zhang, Li	BS ’19
Zhang, Shurui	MS ’18
Zhang, Xuefeng	MS ’09
Zhang, Yanqi	MS ’18
Zhang, Yi	MS ’17
Zhao, Jiapeng	MS ’15
Zhao, Yang	MS ’13, PhD ’18
Zheleznyak, Leonard Alexander	BS ’05, MS ’06, PhD ’14
Zheng, Chumeng	MS ’16
Zheng, Dingzhe	BS ’19
Zhong, Fenghe	MS ’17
Zhu, Huiqing	BS ’16, MS ’17
Zhu, Zhaoming	MS ’01, PhD ’04
Zhu, Zhengsheng	BS ’15
Zielinski, Thomas	PhD ’11
Zimmer, Debra Ann	BS ’86
Zimmerman, Brandon Gregory	BS ’09, MS ’12, PhD ’16
Zimmerman, Donald Roger	MS ’87
Zino, Joseph Dominic	BS ’74, MS ’77
Zinter, J. Robert	BS ’85, MS ’87
Zmek, William Paul	MS ’87
Zoeller, Steven G.	BS ’84
Zoref, Jonathan Lawrence	BS ’94
Zubritsky, Elizabeth Ann	BS ’88
Zuegel, Jonathan D.	PhD ’96
Zurita Sanchez, Jorge Roberto	PhD ’05
Zweig, David Alan	BS ’83, MS ’86
Zyra, Wayne E.	MS ’71

Index