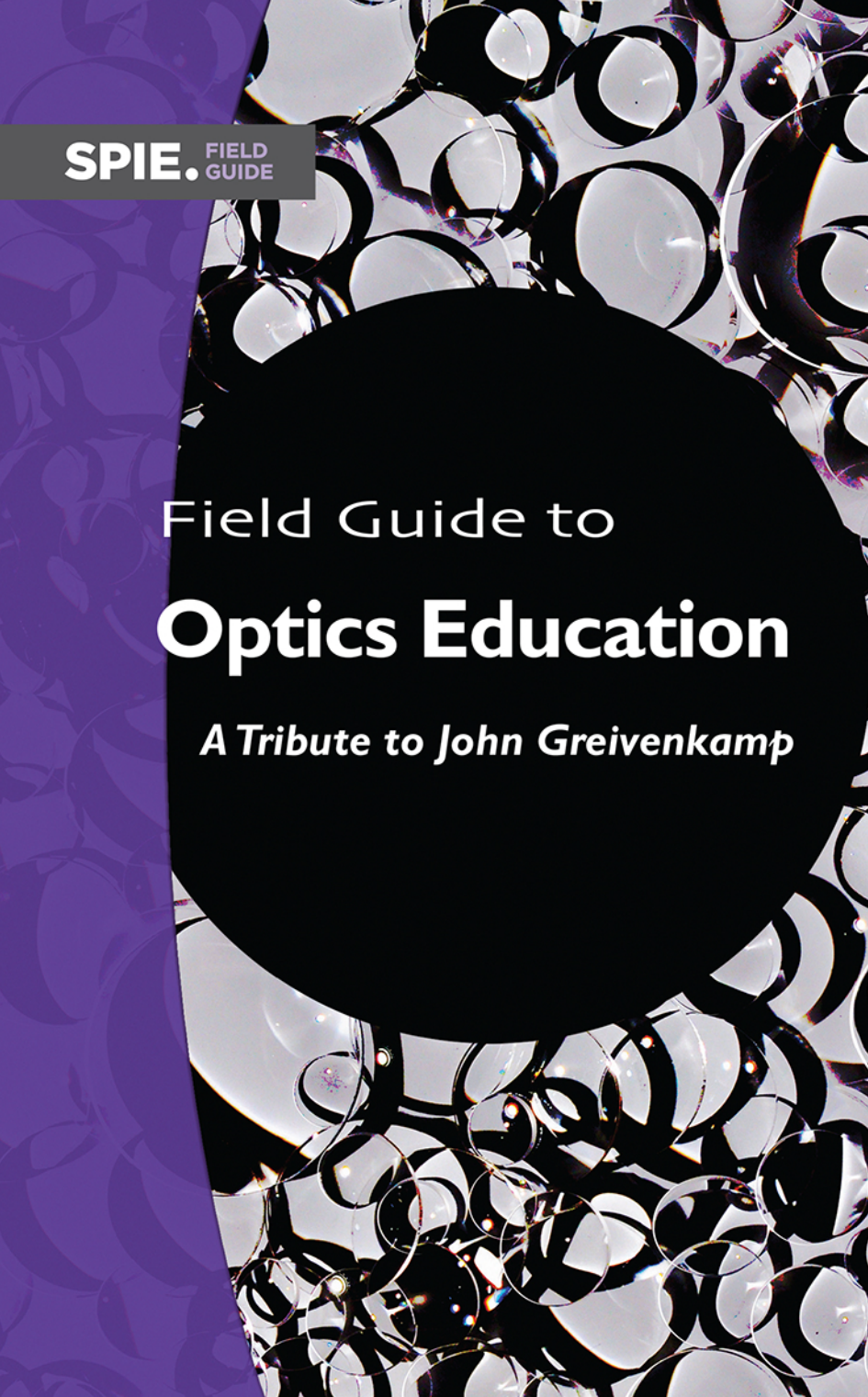
SPIE. FIELD GUIDE



Field Guide to Optics Education

A Tribute to John Greivenkamp

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Field Guide to

Optics Education: A Tribute to John Greivenkamp

SPIE Field Guides
Volume FG53

J. Scott Tyo, Series Editor
Eric Pepper, Guest Editor

SPIE PRESS
Bellingham, Washington USA

Library of Congress Control Number: 2022938951

Published by

SPIE
P.O. Box 10
Bellingham, Washington 98227-0010 USA
Phone: +1 360.676.3290
Fax: +1 360.647.1445
Email: books@spie.org
Web: http://spie.org

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About the Cover
The front cover for this *Field Guide* is inspired by SPIE's Lenses tie, designed by John Greivenkamp and SPIE staff. The image is an interpretation of a photograph of a pile of lenses, with details depicting light properties such as transparency, shadows, reflection, refraction, and dispersion.

Printed in the United States of America.

First printing 2022.
For updates to this book, visit http://spie.org and type "FG53" in the search field.

SPIE.

Introduction to the Series

2022 is a landmark year for the SPIE *Field Guide* series. It is our 19th year of publishing *Field Guides*, which now includes more than 50 volumes, and we expect another four titles to publish this year. The series was conceived, created, and shaped by Professor John Greivenkamp from the University of Arizona. John came up with the idea of a 100-page handy reference guide for scientists and engineers. He wanted these books to be the type of reference that professionals would keep in their briefcases, on their lab bench, or even on their bedside table. The format of the series is unique: spiral-bound in a 5″ by 8″ format, the book lies flat on any page while you refer to it.

John was the author of the first volume, the seminal *Field Guide to Geometrical Optics*. This book has been an astounding success, with nearly 8000 copies sold and more than 72,000 downloads from the SPIE Digital Library. It continues to be one of the strongest selling titles in the SPIE catalog, and it is the all-time best-selling technical book from SPIE Press. The subsequent several *Field Guides* were in key optical areas such as atmospheric optics, adaptive optics, lithography, and spectroscopy. As time went on, the series explored more specialized areas such as optomechanics, interferometry, and colorimetry. In 2019, John created a sub-series, the *Field Guide to Physics*, with volumes on solid state physics, quantum mechanics, and optoelectronics and photonics, and a fourth volume on electromagnetics to be published this year. All told, the series has generated more than $1.5 million in print sales and nearly 1 million downloads since eBooks were made available on the SPIE Digital Library in 2011.

John's impact on the profession through the *Field Guide* series is immense. Rival publishers speak to SPIE Press with envy over this golden nugget that we have, and this is all thanks to him. John was taken from us all too early, and to honor his contribution to the profession through this series, he is commemorated in the 2022 Field Guides.

We will miss John very much, but his legacy will go on for decades to come.

Vale John Greivenkamp!

J. Scott Tyo
Series Editor, SPIE Field Guides
Melbourne, Australia, June 2022



John Greivenkamp, 2020 SPIE President and Founding Editor of the Field Guide Series.

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Foreword

I first met John when he was a 22-year-old first-year graduate student at the Optical Sciences Center (OSC) at the University of Arizona. During his time at OSC, he took three of my classes, and I remember him as a very personable, dedicated student. When John graduated, he went to work at the Kodak Research Labs in Rochester, New York, but we kept in touch. About 10 years after he graduated, we invited John to apply for a faculty position. Luckily for us, he accepted and quickly became one of our most valuable professors.

John was a lifelong learner, who was constantly growing and evolving. He was an excellent teacher and mentor for our students and was well-known for the optics demonstrations he used to help students understand the basic concepts he discussed in class. He was an expert on the history of optics and, on his own, he created a world-class antique optics museum at OSC. John also understood the importance of professional societies and was deeply involved with both Optica and SPIE. He served as president of SPIE in 2020 and earlier, together with the SPIE staff, he created the concept of an optics Field Guide and served as the first editor of the Field Guide series from 2004 to 2020. Hence, it is very fitting that SPIE is honoring John with this special *Field Guide to Optics Education*.

Field Guides are typically written by individual experts in a specific technical area. However, as stated in the email that was sent to the contributors for this field guide, "The goal for this *Field Guide* is to present a collection of the perspectives, insights, and even secrets of individuals who throughout their professional careers have achieved great respect as teachers and mentors in optics. Contributions can range from best practices to the best lesson that you hope gets passed on to future generations to lessons learned from your own mentor and/or favorite professor. Or you might simply write about your personal philosophy/approach to the teaching of optics." I think when you read the short articles in this Field Guide you will agree with me

that the results are fantastic. I have learned something from each of them.

This Field Guide features contributions from more than 50 leading optics and photonics educators from around the world. Contributors include John's teachers, John's peers, John's students, and even students of John's students, as well as those he taught through his SPIE activities. I don't have space to mention all of the pieces included, but let me mention just a few to give you a flavor of the book.

One of my favorite pieces emphasizes the importance of a teacher being kind—you can be firm and tough, but you must be kind. Several submissions describe basic optical principles, but the descriptions are different from what we normally hear or read, showing that there are many different ways to describe the same topic. There are pieces giving guidelines for writing scientific publications, as well as how to teach. Other ones talk about the importance of understanding hardware and not just theory, which was an important part of John's teaching. There are several articles about other professors who had a large influence on the author's life—it is amazing how much a teacher can influence a student's life. There are even articles on what we have learned about teaching during the pandemic.

Lastly, let me mention that some of my favorite articles in this Field Guide describe a particular author's experiences with John. John certainly touched a lot of people and there are many great remembrances of him. I think you will enjoy this Field Guide as much as I do.

Happy reading!

James C. Wyant
June 2022

Preface

In January 2022 SPIE and the optics profession at large lost a giant of our community, Prof. John E. Greivenkamp of the Wyant College of Optical Sciences at the University of Arizona. John had a long and distinguished career in optics, but his most impactful contribution was as an educator. He directly impacted hundreds, if not thousands, of students as the instructor for the introductory geometric optics courses in the undergraduate and graduate programs at the University of Arizona, and many more through the short courses he taught through SPIE and other venues. He indirectly impacted a host of students and professionals through his *Field Guide to Geometrical Optics* book. John also served SPIE in just about every manner imaginable. In 2020 he was President of the Society. He served multiple terms as a member of the SPIE Board of Directors, and was committee chair, conference chair, and short course instructor many times over. He was always available to fulfil any duty–formal or informal–professional or personal.

While John's contributions to SPIE were myriad, his most unique and probably most enduring legacy was the creation of the *Field Guide* book series. He served as founding Series Editor until 2020, and his *Field Guide to Geometrical Optics* is the archetype of the genre. It remains to this day the most popular technical book in SPIE's catalog. SPIE has now published more than 50 Field Guides and has initiated subseries to extend coverage into other important fields such as fundamental physics. John's impact through the Field Guide series will continue for decades.

Upon learning of John's untimely passing, SPIE wanted to find an appropriate way to honor his unique and lasting legacy. An obvious choice was this *Field Guide to Optics Education: A Tribute to John Greivenkamp* because it ties together John's passions for education and service to the optics community.

In planning this Field Guide, we asked a number of educators and industry leaders, many of whom were John's

colleagues and collaborators, to reflect on the importance of education in their careers and to provide insights into their approaches to teaching and mentoring students and young professionals. We gave the contributors very few constraints, and the result was an incredibly diverse range of essays.

These essays are organized into four broad categories that reflect the varied nature of the contributions: *Perspectives; Teaching Methodologies and Paradigms; Specific Lessons;* and *Reminiscences*. We hope that you, the reader, find something in this book that takes you a step further on your own journey in optics education as a teacher, student, or both. For those of you who did not know John personally, we hope that you gain some insight into the value he placed on education. And for those of you who were lucky enough to count John among your friends and colleagues, we hope these stories bring a tear to your eye and remind you of the passion John brought to his work.

Acknowledgments

SPIE is grateful to each contributor for their inspirational stories and perspectives on such an important and timeless topic. The response to contribute on short notice was amazing.

We also thank the reviewers, Katie Schwertz, Matthew Jungwirth, and Craig Olson, for their timely and constructive feedback.

Photographs from the Museum of Optics, Wyant College of Optical Sciences were graciously provided by Ameé Hennig, Manager of Media Content at the Wyant College of Optical Sciences at the University of Arizona. We are grateful to share images from one of John's other optics passions in this text.

This book would not have happened without the support of our many sponsors. The goal was to make this title accessible to the international optics community both in print and online, and it is only possible thanks to their

generosity. This book will reach many thousands of students, teachers and mentors, and aspiring scientists and engineers thanks to: Alluxa, APOMA, Archer OpTx, Arizona Technology Council—Optics Valley, CREOL, Edmund Optics, Esco Optics, LaCroix Precision Optics, Lumedica, Montana State University, Optimax, Opto-Sigma, Precision Optical, Quartus Engineering, Spectrogon, Sydor Optics, Thorlabs, University of Rochester, Wyant College of Optical Sciences, University of Arizona, and Zygo.

And finally, this book would not have been possible without the dedication and hard work of the team at SPIE Press. Special thanks to Dara Burrows, Katie Sinclair, Gina Gabl, Carrie Binschus, and Ingrid Taylor for helping us pull off the impossible.

Thank you all!

J. Scott Tyo, *SPIE Field Guide* Series Editor
Eric Pepper, Guest Editor
Patrick Franzen, SPIE Director of Publications

Prologue 1

I often remark to my children that I have never actually had a real job in my life. After 18 years of childhood and adolescence, I went to college and then graduate school. For a couple of years in the late 1990s I pretended to enter the workforce, but one can hardly call being a researcher at the U.S. Air Force Research Lab "work." After that brief stint, I formally entered the academy, where I have taught at universities in the United States and Australia for the past 25 years. One of the most amazing things about being a professional educator is that you are actually a student. I have learned something new every time I have taught a course, and those insights and concepts have had a direct impact on the contributions I have made as a researcher. Being a student is a lifelong journey that, at least for me, has never stopped.

In 2006, I moved to the University of Arizona where I met John Greivenkamp for the first time. John and I had many opportunities to interact around education since we both taught a fall semester, compulsory, first-year course in the Optics PhD program. We discussed students, assessment, marking, content, and philosophy many times. One point about John that sticks in my mind is when he told me that, initially, he did not see himself as an "expert" in geometrical optics. However, he dedicated himself over decades to being the best possible teacher of geometrical optics that he could be. One of the specific features he brought to his teaching was the use of practical examples. When John walked to his lectures, he would always be pulling a luggage cart with a bin full of optics demonstrations that he used to help his students see the concepts they were being asked to learn.

When I left Arizona in 2015 to move to Australia, I did not necessarily think of John as one of my closest professional colleagues. However, when located on the opposite side of the world, I found myself increasingly reaching out to him for advice on leadership, service, and education, as well as for personal advice about some of the medical issues that he and I shared. John gave me, along with my colleague

Prologue 1

Andrey Alenin, the chance to write two Field Guides, and these were transformative experiences for a lifetime student. The amount of learning needed to distill a complicated topic into 300 words and a picture that fit on a single page is incredible, and it is incredibly rewarding.

In 2019, John afforded me one of the most amazing professional honors I have received when he contacted me on behalf of the selection committee to invite me to take on the role of *Field Guide* Series Editor. This was humbling, flattering, and terrifying, all at the same time. The Field Guides *are* John, and I was not sure I could live up to his expectations. Though this is not the first volume published in my term as editor, it represents an inflection point in the series where John's direct influence ends. We all get to see where we go from the foundation he built.

The importance of John to me was driven home only two weeks ago. A difficult issue arose around the publication of one of the upcoming volumes, and my immediate thought was to drop John a message to get his insight. I was saddened when I remembered I could no longer do that. I then realized that I can still ask John for advice, but that advice will no longer come in his voice, but will instead come through the wisdom he imparted on me through our 15 years of friendship. No matter how I decide to deal with the issues I face in the future, John will have contributed to those decisions.

J. Scott Tyo
Monash University
Melbourne, Australia

Prologue 2
John Greivenkamp and the SPIE Field Guides

John Greivenkamp first joined the SPIE Publications Committee in the late 1990s. He championed practical publications that helped people understand and solve real-world problems. John's acumen led to his appointment as committee chair in 1999–2000, and again from 2011–2013. I was SPIE staff Director of Publications during this period, and John and I established a rapport and friendship. We enjoyed getting together at SPIE conferences, or in Tucson or Bellingham, where we brainstormed publishing strategies and new project ideas, most often over dinner.

As I came to know John better, I saw that he derived his greatest professional satisfaction from teaching as well as service to the optics community through his numerous committee and leadership positions within OSA (now Optica) and SPIE.

The idea of the Field Guides was first suggested to me by someone affiliated with SPIE, but it was just a fuzzy concept, evoked by the field guides people use to help them identify birds, flowers, and objects in the night sky. How would it fit optical science and engineering?

John accepted the challenge, eventually forming an idea that resonated with this field guide construct. John and the SPIE staff envisioned a series of concise, portable books encapsulating key concepts, formulas, and tables in a handy reference format for use in the lab—or, indeed, in the *field*. One could easily carry these small books in a briefcase or backpack to refer to as needed. The Publications Committee gave the Field Guides a big thumbs up and appointed John as the Series Editor.

The Field Guides were never intended to be traditional textbooks or monographs. They would be short—100 or so pages, with one or two pages per subtopic, including key definitions, diagrams, and equations. They would be spiral

Prologue 2
John Greivenkamp and the SPIE Field Guides

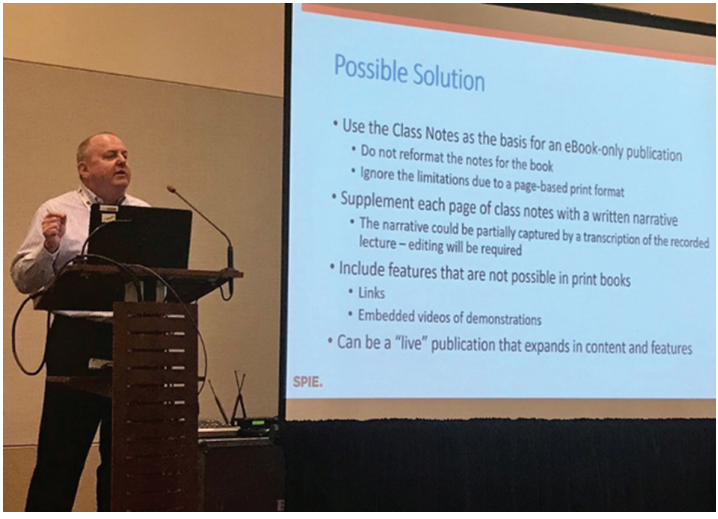
bound and compact, as well as succinct, comprehensive, and rigorously organized and edited.

SPIE book series editors choose the topics and recruit the authors. John wanted to write the first Field Guide to establish a consistent format for all future Field Guides, so he got to work on the *Field Guide to Geometrical Optics*. Once he had completed several topical entries, he began inviting authors, using the sample pages he had written and formatted as the example. The invited authors mirrored John's enthusiasm, and the series sprang to life.

Since the 2004 launch with the *Field Guide to Geometrical Optics*, SPIE has published more than 50 Field Guides. Countless engineers, scientists, students, and teachers in diverse technical fields and settings have used and benefitted from them. New Field Guides will continue to be added under the guidance of John's successor, Scott Tyo. The series remains alive and well.

John was proud of the Field Guides and always grateful for the amazing work of the authors, reviewers, and SPIE staff who created them. I know he would be pleased by this *Field Guide to Optics Education* and moved that so many educators and industry leaders he respected have participated in its creation. John would be especially glad if those who read it reap something valuable from it.

Prologue 2
John Greivenkamp and the SPIE Field Guides



John speaking on "SPIE eBooks: affordable and accessible educational resources for students, teachers, and practicing engineers," a talk we jointly presented to the Special Libraries Association in 2017.

Eric Pepper, Guest Editor
June 2022

Perspectives



Paper through antique opera glasses (photo credit: Wyant College of Optical Sciences, University of Arizona).



A.J. Welch (right) enjoys a break with colleagues and trainees at the 1995 NATO Advanced Study Institute in Erice, Sicily. Steven Jacques (left) and Jennifer Barton (second from left).

The Power of Kindness

Jennifer Barton
The University of Arizona, USA

The most important lesson I learned from my mentor was the power of kindness.

Of course, I learned lots of technical things as well: the diffusion approximation, Monte Carlo modeling, heat transport, how to align cranky old lasers, and why it is so difficult to treat port-wine stains. I also learned the professional skills that every trainee needs: how to write a manuscript, present a poster, draft a proposal, and approach scary big-name researchers at conferences.

All of the technical and professional lessons were critically important, but the real reason my mentor A.J. Welch has such a legacy is that he valued people over projects. His research was highly impactful—some of his publications have thousands of citations—but his true legacy is his dozens of trainees in leadership positions in government, academia, and industry. A.J. was unfailingly patient and kind, and that attitude was critical for his trainees' successes. If you couldn't get an assignment to work, or if you just broke an irreplaceable hand-built laser (I still cringe at that memory), he let you know that he believed in you, and that the situation would work out. His attitude led to creative thinking, hard work, and camaraderie, so that situations almost always did work out.

I've tried to take A.J.'s lesson in kindness and employ them in the lab and classroom. It's hard! Kindness can be mistaken for passivity or even weakness, but nothing is farther from the truth. Kindness is empathy with action—viewing the situation from another's perspective, discerning what the person needs, and providing it as best as possible. Kindness takes strength, compassion, and a lot of energy. Here are three thoughts on kindness:

1. *Be kind; you don't know what others are going through*. College is a challenging time under the best of circumstances, and it got harder during the pandemic. I teach a large Freshman class, and, although I never ask for personal details, students have volunteered that they missed class or assignments because they were at the bedside of a dying family member, at emergency counseling, or being evaluated after a sexual assault. To show kindness, I try to be a good communicator, avoid assumptions or judgements, and focus on learning rather than arbitrary benchmarks and schedules.
2. *Being kind doesn't mean being easy*. It is not a kindness to lower standards, or to let a trainee avoid responsibility. In the long run, this lowers self-esteem if the person realizes that they are not performing, or else it leads to a distorted view of reality if they don't come to that realization. For me, schedules may be flexible, but communication, effort, and high quality are not. It is a kindness to tell a trainee that they are not meeting expectations and to make known the consequences of their (in-)actions. This hard conversation hopefully leads to discovering the root of the problem and development of a remedy. Very rarely, the kindest thing to do may be to end the relationship.
3. *Be kind to yourself*. True kindness to others can only come when we are kind to ourselves. We all make mistakes, get affronted at a perceived slight, grow tired and take the easy path rather than the right one, and, overall, act as fallible human beings. Being kind, forgiving yourself, and yet still holding yourself accountable and striving to do better are critically important.

Learning to be kind is a journey. But the power of kindness is so strong that, even imperfectly executed, kindness leaves a legacy that lives in the trainees who are touched by it. Pay it forward!

Telling the Story of Optics

Hans Zappe
University of Freiburg, Germany

As a graduate student at UC Berkeley, many years before the beauty and diversity of optics seduced me into new scientific directions, I discovered how truly talented teachers were able to reveal the wonders of electronics, hidden amongst obtuse analog circuits or intractable transistor phenomena, and thereby nurture what would become a lifelong fascination with the challenges of engineering.

Yet my role model as a teacher was not an engineer. It was Paul Feyerabend, who would amble into a packed lecture hall, swing himself up onto a table in front, and spend the subsequent hours holding forth on the philosophy and history of science. How did he so successfully engage the attention of a hundred or more young students, who listened, enraptured, without making a peep? He told a story. Certainly, a long and complex story, with subplots and ancillary threads, but a story, nonetheless. And I am certain that every week, everyone learned something from his story.

What does this have to do with teaching optics? A lot. Optics is a field that brilliantly lends itself to being taught as a story, and it is in its telling that we can captivate and motivate our students. Let's consider an example, one that every layperson will likely imagine when we speak about optics: the simple refractive lens. The story of the lens spans time and space, and we can ease the student into the topic by looking back to see how a humble curved piece of glass has fascinated and challenged centuries of thinkers and tinkerers. We hear names like Willebrord Snell and Antonie van Leeuwenhoek, perhaps Ernst Abbe or Joseph von Fraunhofer, and arrive at our modern understanding of how a lens works. With that, the mathematical toolbox is opened, and the story continues with rules and methods: rules for quickly determining how light rays traverse a lens and methods for calculating these rules in detail.

Admittedly, this is the hard part of the story, but the attentive student will see how we got here.

That student might then think that we are now approaching the denouement, but no. One of the really appealing things about optics is that, for many of the basic concepts, she can see these for herself in real life. So, the yarn we are spinning moves to the lab, and with hardware that any undergraduate can handle, we show that the methods and rules that so clearly explained what *should* happen to a light beam as it encounters a lens actually describe what *does* happen. And at the same time, this experiment suggests that there is even more to the story than has been told, since anyone who has picked up a lens to measure it knows that those methods and rules don't explain *everything* that happens. So, the students plunge into another optics subplot and find that the story is even richer than they originally thought.

So, as teachers of optics, we can and should tell the fascinating stories of which our field consists. Because, as optical storytellers, we don't just provide tools, we provide appreciation and context, which will go much further in inspiring our students to continue weaving the tale themselves.

One Small Optics Lab Can Bring Light into the World

Ashley N. Blackwell, Atiyya Davis, and Thomas A. Searles
University of Illinois Chicago, USA

Research and education in the field of optics cannot be decoupled. In fact, the laboratory and classroom are often purposefully merged to provide hands-on experience to students through an instructional lab course or research experience. Research infrastructure and a critical mass of faculty expertise in optics can be out of reach for many institutions. However, some non–research-intensive institutions host teaching and research labs with relatively low operating costs that have a broad and profound impact on trainees.

Here, we share best practices for mentoring students in optics with the intentional inclusion of current graduate trainees. The aim of our contribution is to present food for thought from the perspective of mentees whose experiences in *small* optics labs changed their world. In addition, we honor our mentors who have changed the lives of many with research and education opportunities in optics, sometimes with little support or infrastructure.

Create space. Effective mentoring is relatable, reliable, and active. Occasionally, students fail to see the potential in themselves until someone more experienced gives them needed encouragement. Advice has more bearing when the mentor demonstrates compassion and concern towards mentee wellbeing and success. Creating a safe space for mentees could be the push needed for many to reach beyond their comfort zone. A mentor who takes the time to establish a connection with a student can provide better guidance, and occasionally the mentee advises the mentor.[1]

Be human. Be prepared to get your hands dirty, perform the heavy lifting and make mistakes. Be open to feedback from your mentees. That feedback can better the overall experience for future students. Mentors should serve as inspiration to their mentees while demonstrating that

their success is attainable. Further, students need an advocate who will be a voice for them when called upon.

The lab is for more than just research. Creating a positive lab culture can lead to student success.[2] Within labs, mentors can build community and create a physical space in which to learn from each other. Ideally, a lab can be a counterspace.[3] These are safe social spaces that offer support and enhance a sense of belonging in STEM. They can be in the form of peer-to-peer relationships, within mentor–mentee relationships, at national conferences, or the STEM departments themselves. Further, when executed thoughtfully, a lab often serves as a source for undergraduates to ask advanced students about their experiences, and for new graduate students to learn from older students as they prepare for careers. In fact, peer-to-peer mentoring in research labs is known to be as effective as traditional PI–student relationships.[2]

Research is an opportunity for all students, not just the "best." Consider choosing students who might have limited access or opportunity for research experience. Most research opportunities are restricted to students who are already academically privileged. Unfortunately, this excludes many well-deserving and qualified students who matriculate without any research experiences. Having a proficient research mentor can change the trajectory of a student's academic career. As important, research experiences can help a mentee discover their passion, which is a leading factor in student persistence for minoritized and marginalized STEM students.[4]

In conclusion, we hope that this *Field Guide* can aid in supporting all students in their pursuits of optics. We would like to honor our own mentors: Drs. A. Bak, C. S. Brown, A. Darwish, P. Delfyett, N. J. Halas, G. L. Harris, A. H. Walker, R. L. Horne, A. M. Johnson, L. Johnson, J. Kono, E. N. Lalanne, J. Leotin, K. M. Lewis, W. Lowe, J. Mendenhall, V. R. Morris, W. S. Rockward, C. Scarlett, C. E. Simien, D. T. Walton, and W. L. Wilson. We thank

Dr. L. T. Quigley for her review of this piece. TAS acknowledges support from NSF DMR No: 2047905.

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Teaching. You Mean Learning! How Online Education May Help Carve an Effective Pathway

Jannick P. Rolland
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Perhaps, in a world with rapidly growing fields of engineering and science, students need accelerated learning. How can we tailor our teaching methods to optimize students' knowledge and retention? Starting with the need to know how well we are doing, the best feedback has often been from former students reaching out to praise what they learned in a class and the way this learning impacted their professional lives. Hearing from students who strongly resisted being challenged, sometimes years later, especially brings deep encouragement as a teacher.

After taking two summer courses to learn how to put my courses online with best practices during the pandemic, I realized that online classes could be challenging for instructors (and for some students). Still, online classes have also been transformative for the majority of students. I experienced this firsthand as a student myself in these courses, where I also read many articles on teaching pedagogy and learning. A clear message was the advice to shift the focus from the content to the students themselves. That point is why online education may provide a superior path to learning:

- First, students must step up from passive on-taking of lectures to self-learning guided by the professor.
- Second, the lectures (now recorded online) are organized in smaller mini-lectures that are more digestible and can be quickly reviewed. Introverts may ask questions through online mechanisms.
- Third, the students engage in peer-to-peer learning via discussion boards and collaborative platforms. There is a saying that "You never really know something until you teach it to someone else."

- Fourth, the professor can focus on interacting with the students via online platforms and live discussions tailored to the identified challenges. Also, guest experts on specialized topics can readily engage in the classroom brought online.
- Finally, students can provide reflection memos along the way for feedback, allowing for adaptation.

I can never go back, as I see the benefit of these advanced learning methods, at least at the graduate level.

University Teaching and Research: Transferring Knowledge to the Next Generation

María J. Yzuel
Universitat Autònoma de Barcelona, Spain

Professor John Greivenkamp was an excellent model of a university professor and an inspiration for all, both professors and students.

We are teachers of optics, one the most wonderful and interesting branches of physics and in engineering. In my case, I taught in the Physics degree program, and my courses ranged from the fundamentals to the applications of optics. It is very important to students that their university professors also be researchers who can discuss with other professors, researchers, and students edge-cutting fields of research and high technologies in optics, as well as their applications. One of the most interesting aspects of our work is the supervision of PhD students, including the orientation and recommendation we can provide them as mentors to continue working in the field if they are so interested.

Optics has a very important role in developing fields such as environmental sciences, human health, and energy. Reading the 17 United Nations Sustainable Development Goals, one can identify many light-based technologies that will help the optics community reach several of these goals. This idea can also be an inspiration for our students: Photonics is a discipline, but it is also an enabling technology that is crucial for the progress of other technologies.

An extensive, ongoing discussion at universities and professional societies is whether we need more students in science and engineering, as the number has been decreasing in recent years. My answer is yes, we need very well-trained and very motivated scientists and engineers because optics is an enabling technology that provides solutions to many other fields of science and technology that are advancing the quality and comfort in our lives.

Moreover, the percentage of female students pursuing physics and engineering degrees is much smaller than the percentage for other degrees. This general concern leads to a need to identify actions that could increase the number of female students, mainly in fields like optics and photonics, and could encourage young, talented students to continue in the field after they finish their degrees or their PhD studies.

I mention here two international conferences that are excellent forums for meeting colleagues interested in optics education and for presenting innovations and activities in this field. In odd years, the Education and Training in Optics and Photonics (ETOP) Conference is held in collaboration with the major professional societies in optics and the International Commission for Optics. This conference started in 1991 and has been held in many different countries around the world. In even years, SPIE organizes the Optics Education and Outreach Conference as a track of the SPIE Optics + Photonics Symposium in San Diego, California, US.

I am finishing my writing for this piece on the International Day of Light (IDL), which is a great opportunity for outreach activities. The IDL was declared by UNESCO as a legacy of the International Year of Light and Light-based Technologies held in 2015 and is celebrated worldwide on the 16th of May. Many student chapters organize hands-on activities for students at primary and secondary schools on this day.

We need to make society aware of the importance of light and light-based technologies in our lives. By appealing to the young generation of students, we might convince them of the beauty in optics and photonics.

Optics Outreach with the International Day of Light

John M. Dudley
Université Bourgogne Franche-Comté, France

For more than ten years, a partnership of scientific societies and other organizations has worked with the United Nations Educational and Scientific Organization (UNESCO) to raise awareness of the importance of light science for sustainable development. This partnership led to the proclamation of the year 2015 as the United Nations International Year of Light,[1] and since 2018, of an International Day of Light, celebrated annually on May 16, the anniversary of first laser operation.[2] SPIE has been at the heart of these initiatives since their inception. Successive SPIE presidents, including of course John Greivenkamp, have shown tremendous support and enthusiasm that have been central to the success of these initiatives.

The International Year of Light in 2015 is recognized as amongst the most effective of any of UNESCO's international observances, with more than 13,000 activities taking place in a 12-month period, involving millions of people in more than 100 countries. The five International Day of Light celebrations to date have reached an estimated audience of over a million, with more than 2200 events taking place in 103 countries, including many developing nations and regions. It is essential to stress this latter point. Whilst outreach events are a regular feature of well-resourced institutes and universities, education initiatives with a global reach very often only take place under the umbrella of a UNESCO program.

Education is a continual-learning endeavor, and our experience with international outreach has been no exception. Many important lessons have been learned, and this *Field Guide* is an ideal place to summarize them. Probably the most important lesson is that international actions must be open to all potential partners—both geographically and thematically. This may appear obvious, but during the construction phase of these projects, some

partners expressed reluctance to embrace sectors such as art and culture; and there was sometimes surprising lack of knowledge of the needs of developing countries. Outreach activities designed in a rich western university simply may not work elsewhere. It is essential to communicate with local partners as early as possible. Including themes of arts and culture is equally important. Where outreach can make a lasting difference is in opening to communities that we do not usually interact with. Our experience has been that including themes such as art, culture, heritage, and design is an extremely effective means to attract a broader audience. Another lesson is to build on the political visibility of a UNESCO or United Nations observance to organize events that include policy and/or funding decision-makers. Although many scientists prefer to avoid interacting at a political level, doing so can lead to major long-term change.

One of the great benefits of an International Day is its place as an annual reminder of our responsibilities as scientists and science communicators to engage as widely as possible. As Carl Sagan put it 25 years ago: "We've arranged a society based on science and technology in which nobody understands anything about science and technology. And this combustible mixture of ignorance and power sooner or later is going to blow up in our faces." His message is more urgent now than ever.[3]

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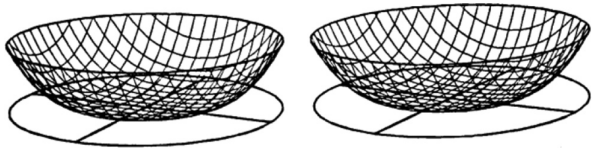
Teaching Optical Design

José Sasián
The University of Arizona, USA

Optical design is a great field that is essential for producing optical devices. At the Wyant College of Optical Sciences, we have developed a strong curriculum in optical design. We inherited and expanded the curriculum that Bob Shannon and Roland Shack put together in the early years of the college.[1]

Earlier years

Prior to the advent of personal computers, Bob emphasized the use of computers and asked students to do substantial homework in lens design.[2] Bob also engaged students with optical design projects from the industry and government agencies.



Roland Shack's stereo pair, showing the wavefront deformation for spherical aberration.

Roland's teaching was about deep optics thinking; he spoke of 'global understanding,' 'from the right perspective,' and of the 'elegance' of an analytic treatment. Roland also added an element of pleasure in his teaching by using artistic and appealing graphics and models. He had an unusual gift for motivating students.

Taking up the torch

John Greivenkamp revised and enhanced Roland Shack's course in basic geometrical optics. In particular, John did live demonstrations of optical principles with actual optical devices and produced a number of excellent teaching notes. Notably, his *Field Guide to Geometrical Optics* published by SPIE Press[3] is very well known: it has been sold by the 1000's. John's fascination for teaching and engaging with students led him to put together what is now the

John E. Greivenkamp Museum of Optics at the Wyant College of Optical Sciences.

I have had the privilege to teach Roland Shack's course in optical aberrations, which throughout the years has been enhanced in several ways, including by covering new topics. My book *Introduction to Aberrations in Optical Imaging Systems*[4] captures the heritage in this topic that Roland and several of his students, including myself, helped develop. I also have had the privilege to teach the lens design courses that Bob Shannon originated. Over the years, these courses have been successful, and many students really enjoy them. My book *Introduction to Lens Design*[5] also captures the spirit of these courses.

Enlarging the optical design curriculum

The optical design curriculum has also been enlarged. Tom Milster has been interested in diffractive optical elements and offers a course on the theory and design of such elements. Tom also taught a course on the fabrication of DOEs. With the subsequent hiring of Russ Chipman, the teaching of optical design grew to include light polarization effects and their engineering. Russ has championed 3D Jones matrices and polarization ray tracing. The book *Polarized Light and Optical Systems*,[6] authored by Russ and his former students, is an excellent resource to engage in this field. We were very fortunate to hire John Koshel, who brought to the College the teaching of optical design of illumination systems. He has edited a book, *Illumination Engineering*,[7] which outlines the fundamentals of this art. Ronguang Liang has been teaching the course Practical Optical Design, where students learn how optical design is applied to the design of actual optical systems. Yuzuru Takashima teaches the undergraduate course in lens design as well as a course on applications of optical design.

A comprehensive curriculum

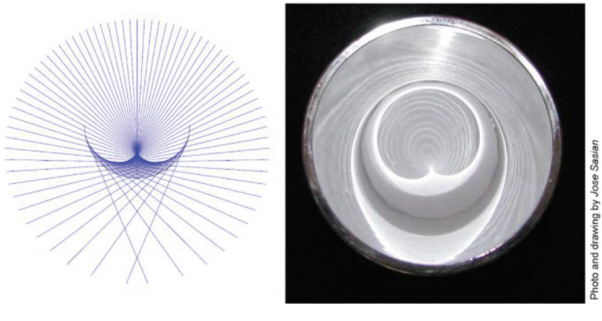
As can be appreciated, the optical design curriculum at the Wyant College is comprehensive and covers many topics of current interest. The curriculum represents a strong legacy in the effective teaching of the field. The courses are

attended by both on-campus and distance-learning students. In many cases, students further their learning of optical design by working on projects where they actually design and built optical devices.

Throughout the years, we have invited as guest speakers many experts in optical design. These experts give students excellent lectures and refreshing views about optical design: John Rogers, Dave Shafer, Mary Turner, Don Dilworth, Dick Buchroeder, Bill Cassarly, and Rich Pfisterer, to name some of the speakers—we certainly appreciate and thank them for sharing their expertise. We also give many thanks to the optical design software companies that generously provide academic licenses to use their excellent software packages for optical design.

A personal touch

Naturally, each of us, as professors, contributes with different teaching styles. One of my drives in teaching is to establish, whenever possible, an academic relationship with each student. In my view, this is helpful in engaging students to learn. Finding ways to clearly explain optical principles, demonstrating their use, and following with appropriate homework are elements of effective teaching. One example of illustrating concepts is shown below for a ray caustic forming the cardioid curve.



A ray caustic forming the cardioid curve.

One also must motivate and inspire students; for this, one's personal technical experience is helpful. Of course, being passionate about optical design is key and has a substantial impact on effective teaching. One never stops learning how to teach. There are many rewards for serving as a professor; it is a joy to pass information and training to students that will help them tackle the many challenges they will face in their professional careers.

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Education in Medical Physics as an Entry to an Academic Career in the Optics and AI of Medical Imaging

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Optics enters the education of the medical physicist through the teachings of imaging science in the formation of medical images. Such studies include understanding the physics of sources, detector systems, image reconstruction algorithms, noise reduction, image display, and image interpretation (by human or computer/AI). And many accomplishments from medical physicists are reported at the annual SPIE Medical Imaging Symposium held every February.

My involvement in medical physics education has included didactic teaching, advising students (mainly PhD graduate students but also undergraduates, medical students, and high school students), and serving as the (past) Director of our CAMPEP-approved Graduate Program in Medical Physics/Chair of the Committee on Medical Physics at the University of Chicago. My didactic lectures have covered radiography, transfer function analysis, and computer vision/AI/computer-aided diagnosis. In general, PhD students are (i) educated in the domain of study, e.g., medical physics and (ii) mentored to become independent investigators. By "advising," I actually mean a combination of advising, mentoring, and sponsoring students and researchers. Sponsoring involves recognizing and passing along opportunities to others so they can grow in their career.

Throughout my career, I have learned that communicating effectively is the key to progress, and that miscommunication is often the cause of misunderstandings leading to problems. This was also strongly stressed and taught by John Greivenkamp, as I learned during my times on the SPIE Board with him. John kept the Board and the documents of SPIE clear and proper. His knowledge of

parliamentary procedure and how to run a Board meeting were impressive, and I appreciated being taught by John.

The highlights of my day are when I am brainstorming with students, and I greatly look forward to the time when a student becomes a colleague, which I imagine was one the highlights of John's life.

Optics Informed by History and Nature

Joseph A. Shaw
Montana State University, USA

In optics, we stay current by following the newest ideas and accomplishments. However, historical optical systems offer many valuable lessons, something that drove John Greivenkamp to collect and display historical cameras, telescopes, and microscopes. I developed a similar love of classic optical systems by being exposed to them by my physicist father, who loaned me a 1950s Leica camera to use in my high school photography class. I was initially embarrassed to be the only one in the class with such an old camera, but I soon learned to focus instead on the incredible capabilities of that classic camera.

Throughout my career, I have turned to that camera and other historic cameras, lenses, and telescopes to teach about optical system design. This kind of teaching is particularly effective if our students see real historic items up close and, ideally, hold them to experience their magnificent craftsmanship. There is nothing quite like the feel of a classic camera with its mechanical shutter and metal body! It is also impressive to use classic lenses and observe first-hand how incredibly sharp some of those old lenses were (but also to see some of the limitations being removed with newer technology).



The 1950s Leica camera I used to learn photography—a beautifully designed classic camera and lens.

To me, the only source of optical ideas and stories better than history is nature. A seemingly simple rainbow, for example, can be used to teach principles of refraction, transmission, reflection, dispersion, and polarization. Plotting rays into a spherical water drop from different angles, one finds most of the rays clustering near the minimum-deviation angle, which defines the angular size of a rainbow. The same phenomenon occurs with ray tracing in hexagonal ice crystals, leading to the 22-degree halo.

The refractions and reflections that give rise to halos and rainbows also produce partial polarization. For example, two refractions and a partial reflection at the back of a water drop produce the readily identifiable color distribution in the primary rainbow, but they also polarize the light. The refractions and reflection each favor orthogonal polarization states, with the net polarization dominated by the strongly polarized reflection near the Brewster angle. By considering how the plane of refraction changes orientation for different parts of the bow, we can deduce that polarization of rainbow light is oriented tangentially to the bow.



Rainbow polarization illustrated with primary rainbow photographs recorded with (left) a linear polarizer oriented tangentially to the bow and (right) a polarizer oriented perpendicular to the bow.

By teaching optics from history and from nature, we broaden students' perspectives and help them better understand not only the optical principles we are teaching, but also how to learn from those who came before—and from the continual array of optical examples that nature parades before our eyes if we only learn to see them and learn to question what we see.

Is Optics Easy to Learn and Master?

Halina Rubinsztein-Dunlop
The University of Queensland, Australia

In rereading the *Field Guide to Geometrical Optics* by John Greivenkamp, it struck me how useful the format of the *Field Guide* series is and how usable this book is for wide audiences, including students and professionals in optics. I wish that I had an opportunity to listen to some of John's lectures in optics. So many of his former students remarked on John's fantastic abilities as a teacher. He enthused his students with the subject, evoked their curiosity in investigating complex optical systems, and prepared them to find solutions to new problems. From my own experience in physics, I know that an excellent and enthusiastic teacher with empathy and understanding for their students can give birth to a genuine and deep love of the subject that they teach. We know that many of John's students continued on to have successful careers in optics. My own experience is rather similar—I also had wonderful teachers in my undergraduate and postgraduate years, who shaped my interests in physics and directed me in choosing optics, photonics, and quantum optics as my research areas. Such teachers also influence us in how we ourselves approach teaching and research.

Throughout my teaching years, many interesting teaching methods have been developed that help students build a better understanding of the subjects we teach. I have been teaching optics, quantum physics and quantum optics, and laser physics. In all of my courses, I use an active learning method to ensure a real learning experience for my students. I should probably explain what I mean by "real learning experience." Normally, when I start any course, I choose the material on which to base the course, making sure that it will be accessible to students. Then the real work starts in trying to convey the material to the students in a way that they will be able to use it in "real life." I started teaching physical optics when I was a PhD student in Sweden. The method we used there was more or less based on the UK system of tutorials. Students would

come in small groups to ask questions about a certain part of the course, and the lecturer would answer these questions, which often involved theoretical derivations, and help to solve problems based on a particular part of the course. This type of teaching was very effective in terms of synthesizing and retaining the knowledge. Most of my pedagogic endeavours in optics and my choice of the course material was heavily based on E. Hecht's *Optics*, but when I was preparing for the lectures, I also heavily used F. L. Pedrotti, L. M. Pedrotti, and L. S. Pedrotti's *Introduction to Optics*, F. A Jenkins and H. E. White's *Fundamentals of Optics*, and M. Born and E. Wolf's *Principles of Optics*. My secret was that I also used a locally produced Swedish optics text by Ulf Ringström and Lars-Erik Selin, *Wave Optics, Acoustics and Optics*, which was used by my first lecturer in optics when I was an undergraduate student. This little book was a real pearl as far as theoretical derivations were concerned, but it also provided numerous instructive examples and exercises, especially for the topics of interference and diffraction, which are notoriously difficult. But this book was published only in Swedish and very many years ago! So, I acted as an interpreter and made the wonderful findings of this book available to my students.

I strongly believe that we learn any subject best when we must present it to others, especially to our students. What struck me when I was establishing my first experimental physics lab in Australia was when I noticed that even my extremely gifted PhD students who passed all their courses with flying colors could not apply their knowledge gained in the optics course in practical settings. How to use $\lambda/4$ or $\lambda/2$ plate, when to use a polarizing beamsplitter, how to change polarization, how to use interferometry, and what can we then expect, and what can we measure, etc. These were parts of optics that we had to go through again and practically investigate to learn their properties and their use. I am convinced that the method of active learning and peer instruction for active learning represents a good approach for giving students a larger purpose in learning the course material as well as for engaging them in

self-preparation. Education is more than just the transfer of information. We, the instructors, develop conceptual quizzes to guide students' preparation and use the conceptual questions during "instruction" time. We then let the students discuss these questions with their peers and come up with answers. We monitor the answers and evaluate whether a particular concept has been grasped. And it is only when the concept has been understood by most students that we move forward to the next concept.

Incorporating simple demonstrations and experiments into our instructions and engaging students in analyzing the results of these experiments is helpful in building a deep understanding of the presented concepts. For example, we can ask, what is interference and diffraction? Or more generally, how do we infer that light can behave like waves? How can diffraction and interference be explored using equipment students can make themselves? How can we use inexpensive and accessible materials to present the intricacies of polarization? Can we play with inexpensive polarizers, bits of sticky tape, and few pieces of glass or plastic to investigate polarization phenomena in detail?

Our experience during the recent pandemic also taught us a valuable lesson: we can achieve much more personalized instruction by using breakout rooms for highly individualized and direct learning. We can determine what it is that we can do online that we cannot not do in the classroom. Are there lessons to be learned?

No matter what learning methods we use, the most essential component is an outstanding, accessible textbook. And this is where we go back to John Greivenkamp's exemplary text *Field Guide to Geometrical Optics*. John was really a visionary in establishing this *Field Guide* series, and his own contribution to the series is a prime example of a highly desired text that is of great value for instructors and for students.

You're on Mute

Alexis Vogt
Monroe Community College, USA

"What's that? You *prefer* a Zoom lecture? To teach *optics*?" A few years ago, the word "Zoom" was unfamiliar. Today, Zoom is part of our common vernacular, and we use it as both a noun and verb. In the world of academia, discussing the benefits and disadvantages of virtual learning remains one of the most common debates. While many people share concern that virtual learning is impersonal, my experience as an educator has shown inclusive classrooms can be created even over Zoom. In my Monroe Community College *Introduction to Optics* class, which meets over Zoom on Mondays and Wednesdays, my virtual classroom is made up of students in Rochester, a precision optics apprentice in Maryland, an optics company executive in New Jersey, an optics enthusiast from California, and students from Washington State and Bahrain. Zoom has provided unprecedented access to students all over the world.

A virtual classroom provides for more diversity. Within our class we have artists, musicians, gamers, chefs, mechanics, and athletes with different genders, races, socio-economic backgrounds, veteran status, and age. What is important to every student's success is a sense of community. In our Monroe Community College Optical Systems Technology program, we not only train world-class optics technicians, but we also establish an inclusive community.

With the curriculum stored on our Monroe Community College learning management system, I can afford the time to start each class by greeting every student. Learning about each student—as a means to both take attendance and check in—takes times, but our 100% retention rate demonstrates that the time is well-spent. And end-of-semester surveys reveal that students greatly value the time devoted to learning about their classmates. In addition to learning about Snell's law, polarization, how optical fiber works, and other fundamentals of optics, we celebrate lacrosse and soccer games won, successful car

brake changes, movie recommendations, Monday night pool league wins, 50th birthdays, meals cooked, and Ramadan observances.

An inclusive community combined with the triad of knowledge, ownership, and experiential learning is what enables students, and all people, to excel. And the evidence shows that an inclusive community *can* be established over Zoom.

Resources for Effective Approaches

Stephen M. Pompea
NSF's NOIRLab, USA

John Greivenkamp played an important and outsized role in creating larger national plans and blueprints that encouraged and supported optics education at all levels. Our NSF-sponsored OSA-SPIE project for middle-school-aged students, *Hands-On Optics: Making an Impact with Light* (Pompea et al. 2005) was just one example of a project that stemmed from John's commitment to optics education at the pre-college level. John once commented to me about the amount of work involved in creating an optics lesson on color for his daughter's 4th grade class. I wasn't at all surprised, as good units take significant time. For most of us, time is in short supply. In the spirit of encouraging efficiency, here are a few tips based on my experiences in teaching optics in classrooms and in outside-of-school settings. Perhaps they will save you time and frustration, making the process more enjoyable.

1. Optics education is equal parts "knowledge and wonder," as Francis Bacon so aptly described his philosophy: "For all knowledge and wonder (which is the seed of knowledge) is an impression of pleasure in itself," (Bacon & Montegu 1852).

   Knowledge ascertains how the natural world is organized and how the individual pieces work, and work together. When we study how a lens or mirror works, we are helping build investigative knowledge on refraction and reflection. Equally important, though, is the sense of wonder. This can be wonder that there are indeed laws that govern refraction and reflection, and that these laws can be determined through careful observation. There is also the wonder of observing the images created by lenses or mirrors. Equally impressive, though harder to explain, is a rainbow or halo created by complex combinations of simpler effects.

Bacon also emphasized the pleasure derived from these observations. We should remember that enjoyment is a large part of learning. Appreciating the beauty of optical phenomena is a powerful motivator for sustained learning.

2. Optics education is both an art and a science, and needs to incorporate the lessons learned and best practices from both from research studies and the experience of practitioners. The best practices for working with schools and museums are well documented in many ETOP proceedings and can save novices much aggravation and trouble. Some starting points for becoming more effective when participating in science education at the pre-college level can be found in a long review by Pompea & Russo (2020) and in several recent shorter articles (Pompea & Russo 2021a,b).
3. Working with younger learners has the most impact and can be the most rewarding. Children who are 9 or 10 years old are excited about learning science and have great investigative skills. Take advantage of that interest by providing experiments that are learning opportunities. Teach them how to do (play) science. They don't need to be spectators as they learn the rules of science.
4. Color is a particularly broad and effective teaching area. Much of optics can be explored by young children through their observations and examinations of the colors that occur in nature. A broad review of the possibilities to teach with color is given in Pompea & Carsten-Conner (2015).
5. Optical scientists and engineers are a resource to classroom teachers and museum professionals. Partnering with educators as resource agents is an effective strategy. Educators have the knowledge of pedagogy and how to teach. Optics professionals know the subject and the practical applications of optics. They also know how to obtain equipment that might be useful for simple classroom experiments.

6. Help to build interest in science among children and help them identify with science by developing their science capital. You can do this by fostering a mindset more open to exploring and enjoying STEM topics. A powerful way to achieve this is to incorporate art into STEM subjects (Conner et al. 2019). This provides an additional level of science appeal to art-interested children who may not yet identify with science or who have already had negative science experiences (Conner et al. 2017, Sullivan et al. 2017).

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Teaching Optics: A Tribute to John Greivenkamp

Zeev Zalevsky
Bar-Ilan University, Israel

Education and science are no doubt the main driving force for global equality and prosperity, and for evolving a more fruitful and successful human society. This is our mission and legacy as scientists and as educators. Specifically, optics has an ultimate importance due to its huge potential contribution to a large variety of fields such as health (e.g., bio-medical photonic sensing and treatment), vision correction, ecology (e.g., remote photonic hyperspectral sensing for detection of pollutions), clean energy (conversion of sun light into electricity and power), and many more.

The recent Covid pandemic was very helpful in accelerating the maturing of a large variety of technology platforms that are capable of assisting scientists and educators to bring their insights and knowledge to the end-users faster and farther, no matter where their geographic location might be. This was done by developing online digital platforms such as Zoom and Teams, which allow us to conduct lessons and give lectures without the need of physically traveling to remote locations that may require the delivery of the specific knowledge.

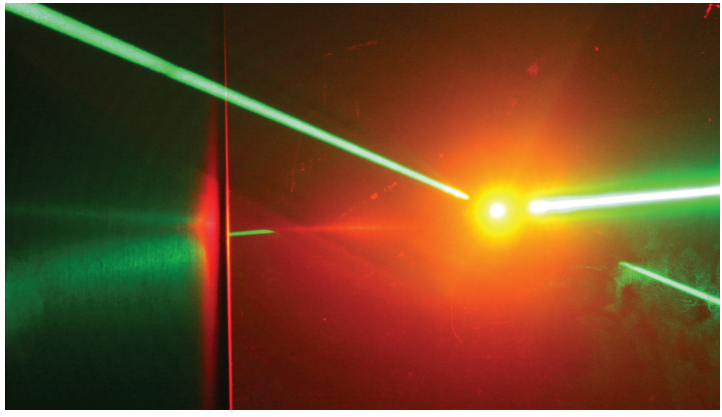
However, this technological facilitation by itself is not sufficient since being a good scientist does not ensure the capability of being a good educator or a good teacher. I personally believe that our capability of explaining our ideas to an audience that is not completely familiar with the field can significantly strengthen us as scientists—asking basic questions makes me better understand my own work.

My PhD supervisor, Prof. David Mendlovic, who is not only a good scientist, entrepreneur, and engineer, but also an excellent educator and teacher, taught me that there are no stupid questions that could be asked by students; there are only stupid answers that could be given by the teacher. Students should ask about everything, and a good educator

needs to be sufficiently patient and elaborative to be able to answer any question, no matter how basic or fundamental it might be.

Nowadays, in many institutions worldwide, the issue of improving one's teaching skill is becoming very important and is now one of the significant factors being considered in the academic promotion process of a scientist— a factor as important as one's scientific achievements and capabilities.

Having said that, I want to stress my admiration of the educative work and legacy of John Greivenkamp, who wrote the well-known *Field Guide to Geometrical Optics*. John devoted his life to promoting the important concept that photonics education should be facilitated in the best possible way to the next young generation of engineers and scientists—a generation who will continue down this path, spreading technology and, through it, improving the world we all live in.



Attracting high school students to study optics by illustrating the vibrant colors involved with laser light and the properties of its scattering. (Image captured at the lab of Prof. Zeev Zalevsky during a visit of a group of high school students.)

Balancing Perfection and Achievement: Life Lessons & Optics

Cather Simpson
The University of Auckland, New Zealand

One of my favorite things about teaching optics is the many-faceted life lessons on balancing optimization and achievement that I can slip in when I work with students at all stages, from university freshmen to postgraduates. For those who don't continue in optics, I hope these "softer" lessons help guide them to success in whatever they pursue.

Students in university lab courses often focus on understanding and applying optical principles to measure optical outcomes—to achieve the right focal point, identify the prism or lens material, steer the beam to the right place, or get the telescopic magnification right. Proper design and precise alignment are key. Doglegs illustrate how complexity can be used to simplify, meaning that students can learn how to iteratively walk a system towards alignment. They learn that the more you optimize the better your results. Perfectionists and the mechanically inclined love it; big-picture thinkers and the less patient find it frustrating. However, that thread that links the logical application of focused effort and precise adjustment to excellent results is hard for any student to miss.

In the undergrad lab, it's not so much about finding balance—the "time to stop optimizing the optics" is determined by the lab period length. For the more advanced postgraduate or postdoctorates, though, that decision becomes self-driven.

In the research settings I'm most familiar with, optics is a much more complex tool used to illuminate the behavior of physical and chemical systems. Time-resolved femtosecond absorption or Raman spectroscopy involves interlacing commercial and home-built instruments, lots of optical "tinker toys" and multiple types of linear and nonlinear optical processes.

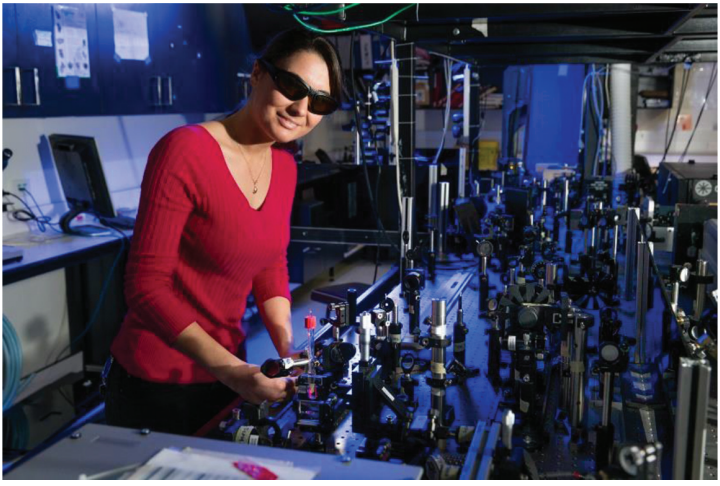
Temperature and humidity can wreak havoc on alignment from day to day, or even sometimes hour to hour. A PhD student might take a year or more to build an instrument and get it working well. However, in the end, it is still just a tool used to probe, and it is the behavior that is ultimately the focus of the research.

The data quality from such a system depends exquisitely on its optical alignment. The temptation is to keep optimizing, to squeeze out another 1% improvement, motivated by "I'll get better data." At some point, however, one must stop optimizing and measure. Identifying the right time for that is hard for many optics students.

It's a common trap to fall into, and not just for the optical perfectionist. Entire project management systems have been developed to help companies decide when to stop improving a software or hardware product and move it from research into development and production. Success in just about anything aligns with being able to confidently decide "this is good enough." I explicitly discuss these challenging times in the laser lab with students as key moments for them to develop this important life skill.

These are just two examples that show how optics provides very fertile ground for helping students succeed, to evolve into successful leaders and contributors to anything they choose to do. Optics also provides educators like me with a versatile and invaluable tool for helping my students grow and learn.

I didn't know John Greivenkamp as well as I would have liked, but his dedication to students strongly resonates with me. His contributions to education in optics and photonics and to SPIE is legendary, and I am delighted to be part of this publication in his honor.



Dr. Nina Novikova as a PhD student optimizing the femtosecond transient absorption spectroscopy system in the Photon Factory at the University of Auckland.



Undergraduate, honors, master's, and PhD students (left to right) illustrate the evolution of an optics education.

Debug Your Hardware as You Would Your Software

Kathy Creath
Optineering, USA

Back in 1979 when I started doing research for my master's thesis as a senior undergrad at the University of Rochester, I noticed two basic types of theses that students were working on: hardware and theoretical. Most of my fellow students were focusing on experiments requiring hardware. These types of projects required being able to design, build, and test electronics to get your data. Film and oscilloscopes were standard lab staples. Since I didn't really want to solder circuits together, I first chose a topic that involved a vacuum system that we could never get to work for lack of funding to buy the necessary parts to fix it. While working on that, I had my first real "aha" in an optics lab. I was told to line something up using Brewster's angle. When I rotated the polarizer and saw that Brewster's angle really did change the polarization state, I thought WOW, this stuff they're teaching really works.

Once our group realized that we weren't going to fix the vacuum, I switched topics to characterize an infrared detector. This required me to do the soldering I hadn't initially wanted to do to build an electronic amplifier and filter for biasing the detector so we could get a signal out. Compared to the other project, it turned out to be very straightforward to take data. What wasn't straight-forward was figuring out why this detector was behaving as it was. This required adapting a theoretical framework to fit the observations. When fitting the data, I did some basic programming on a large tabletop HP calculator/plotter. That was the beginning of my seeing how software was going to take over.

When I went to work on my PhD at the University of Arizona in 1982 I saw I had a choice of electronics vs. software for processing images. Seeing the complex boxes of electronics being used in the optics shop for the interferometers they were using, I thought that software was the way to go. From the modeling I did for my master's

thesis, I saw the power of computation to crunch data. As you know, I chose to work on interferometry. I poked at a lot of different topics before Professor Jim Wyant dropped a draft of a book chapter on my desk on electronic speckle-pattern interferometry. Up to this point, ESPI had required very complex electronics to get fringe patterns and "analyze" them. He asked if I thought I could do it in software. I took a look at the book chapter and said "sure." The rest (as they say) is history.

Since then, I've basically become known as an "algorithms" person. Yes, I certainly did a lot of that along the way. But when people from lots of different application areas within optics come to me as a consultant and ask for help solving a problem, the answers are usually a lot more basic than fixing an algorithm.

I have found over the past three decades that many of these projects have not had good starting points. Often, the optical system is not producing the best possible image, or the illumination is not uniform. It could also be that the camera being used hasn't been calibrated or maybe someone simply forgot to turn off the automatic gain. The algorithms assume that you're getting a one-to-one correspondence between the object and image. But so many little things can disrupt that conjugate relationship. If you don't start with a good image, you're not going to get a good measurement result. This is a basic tenet of optical metrology.

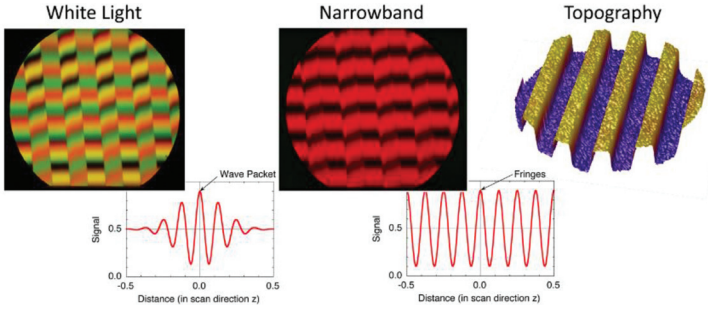
So often I find that the questions I get asked are at a very high level. However, the real question that needs to be addressed is usually at a low level. Often, it could be something as basic as setting up a way to align an optical component the same way on every system. But, what's happening instead is that there are too many degrees of freedom and you end up with every system having a different problem. Those are tough problems to tease out.

Unfortunately, this type of problem solving and finding solutions is generally not taught in the classroom. I have found that those who've worked on real-world problems have a leg-up on those who haven't. A lot of this knowledge only comes from experience doing it and by learning from fixing our mistakes. Once you've had to fix something more than once, you probably will not do it the same way again, and you'll come up with a way to do it better.

How do we train our younger optical scientists to understand these things and to learn how to learn from what they do? I advocate more hands-on training—the more of it the better. Summer jobs are great. Undergraduate senior team projects and master's theses research more clearly reflect how we work in the real world than do lectures and exams. Lectures and preparing for exams help us know what material we need to understand and where to find it, as well as the answers to specific direct questions, but actually rotating the polarizer to get Brewster's angle is what we need to be able to recognize as the fix to debug systems we are working on.

My takeaway message is to not just look at the final outcome. Dig in and figure out places where you can check your results. Intermediate measurements and calculating results using known inputs can help you understand how to improve your hardware as well as your software. *Debug your hardware as you would your software.*

Ultimately, I think we should be thinking more about the questions, and how we mentor young scientists and engineers so they can benefit from what we have learned to pass on these skills. This, I argue, is more important than memorizing answers to specific problems that will be asked on an exam.



Deep grating on silicon substrate. (left) White light fringes taken through Mirau interference microscope. (middle) Narrowband fringes taken through Mirau interference microscope [images by K. Creath]. (right) Topographic map of grating generated from interferograms (images by J. Schmit).

Optics Education: Engaging the Next Generation

Adam P. Wax
Duke University, USA

When I think back to the first time that optics caught my attention, I recall a visitor to my 3rd grade class. He described himself as a laser chemist and brought with him a He-Ne laser. He set up a few basic experiments and lit up the beam path using chalk from the blackboard eraser. It was a good demonstration, but it didn't spark my imagination until later that school year, May of 1977 to be precise, when a little-known space movie introduced laser swords. I think I probably would have been hooked on Star Wars even without the classroom laser demo, but it did make me feel a special connection.

John Greivenkamp has had a strong impact on the field of optics, but his devotion to optics education may be his greatest contribution, for which he was recognized with the 2017 SPIE Educator Award. Optics education has the unique opportunity to capture the imagination of future scientists using dazzling effects that few other science fields can offer. The hands-on demonstration should be a staple of the optics educator. Today we have incredible resources available to show optics principles. Laser pointers can put a coherent monochromatic beam in the hands of every student in the class, while modern smart phones can conduct a range of functions, serving as a microscope or generating a hologram. My favorite demo that I would do for my own students' classes used a compact disc to generate rainbow diffraction patterns, although it's getting harder and harder to find CDs these days.

As the faculty advisor of DOSC, the Duke Optical Student Chapter (joint Optica/SPIE), I have had the opportunity to help our students develop and deliver new outreach activities for K-12 students. This is an important role for the chapter for two reasons. First, it helps the young professionals in our chapter, typically PhD and master's students, develop their interest and skills in teaching.

The second reason is an even greater motivator, inspiring the next generation of optical scientists and engineers.

While our outreach has been very successful, consisting of traveling to local elementary, middle, and high schools with live optics demos, some of our best events have taken place when we open up our doors to the community. Working with the leadership of the Fitzpatrick Institute for Photonics at Duke (Prof. Tuan Vo Dinh, Director; August Burns, Manager), we have hosted several events at our center. This provides a very exciting opportunity for aspiring scientists to gain hands-on experience with optics, since many have never had the chance to see a real research lab. Our open houses for the International Year of Light and Introduce a Girl to Photonics were very well attended and may have influenced many young scientists to follow a career in optics. Although our most recently planned event, the Photonics Field Day was sidelined due to the pandemic, we hope that we will be able to open our doors again soon.



Photo credit: August Burns.

Teaching (Optical Design) Students to Learn from Their Mistakes

Julie L. Bentley
University of Rochester, USA

In optical design, optimization is a process that involves taking a starting point, defining variables, and making changes to those variables to find a new solution with improved performance. While much of this process is now automated, lens design is still part "art," as the designer often intervenes to direct the optimization to move in a certain direction using an intuition that is built up over years of trial and error. For example, is not unusual to need to scrap everything you've done for the last three days and start from scratch. Thus, it is important to allow yourself to make "mistakes" and "fail" to gain a better understanding of the design space and find a good path to a solution.

Learning, like optimization, is a highly nonlinear process. Each student has different preferences and inclinations. Allowing students to make errors helps them assimilate the information you are trying to teach according to their own learning styles. Unfortunately, most people don't see making mistakes as a good thing; however, I believe that teaching students to learn from failure is the key to a successful class. It is important to give students problems with both multiple paths to a solution and multiple paths to failure. As a teacher, you could easily give them the solution (and the fastest way to the solution), but it is much more effective to go through the solution path(s) *after* they've attempted it themselves. This lets students learn from their mistakes. You can then spend your class time building up their understanding of the problem afterwards.

Implementing this type of an approach is not easy. Many teachers are afraid to take this approach, as mistakes take time, and time is limited in classrooms, but I think the end result is well worth the time. Below are some quick tips to help if you choose this path:

- Challenge the student's concept of success by establishing up front that making mistakes isn't just

acceptable, but it is the preferred course of action in your course.

- Lead by example by not being afraid to show your students your own mistakes and how you learned from them.
- Ask the "why" questions to force your students to think deeper.
- Give them "no stakes" quizzes throughout the course where they know failure is allowed. This gives them a real-time assessment of what they know without the test results affecting their outcome in the course. It also gives you timely feedback to adjust your course content.
- And last, but not least, don't give them *everything* they need to solve the problem. One of the toughest skills of teaching lies with the holding back of information and patiently waiting for students to figure it out or ask for further help.

Thomas Edison once said, "I haven't failed; I have just found 10,000 ways that didn't work."



Julie Bentley (right) raytracing on the walls of Goergen Hall with Danielle Getz.

Education in an International Community Is a Solution: A Journey Inspired by Researchers on Different Continents

Samuel Serna Otalvaro
Bridgewater State University, USA

I first fell in love with light when I was an undergraduate student at the Universidad Nacional de Colombia in Medellín. It was my third year in Physics Engineering. I wanted to combine my passion for scientific research with giving back to marginalized communities with less access to education. Then, only 37% of youth in Colombia attended university, and 50% of these did not finish their undergraduate degrees. (In the US, 64% of youth attend university, and 56% of these complete their degrees.) Yet, Colombia is a country with one of the world's highest primary and secondary school completion, and literacy rates; people there are renowned for research, resilience, and ingenuity. I knew, from my own experience growing up in a small town just outside of Medellín, the crucial importance of outreach to inspire high school students and their families to apply to university. I also knew how important mentorship—to complete university and to imagine a future career—is to young people born and raised in a country deemed in the 1990s as one of the most violent in the world. And, as in many places around the globe, this university outreach is especially important regarding science. I have come to realize that outreach is important not only to inspire young people to believe they can become scientists. It is important to open worlds of scientific research across institutional and geographical borders. When I began scientific research as an undergraduate, I already felt lucky to work in a corner of my desk on a theoretical question because I found it fascinating. My collaborations with scientists and institutions in five countries have since revealed to me that our research, especially when done in diverse global teams, has possibilities for groundbreaking science that can also improve human life and the natural environment in the 21st century and beyond.

At the beginning of my career, the words "optics" and "photonics" had no larger meaning to me than a particular view of Maxwell's equations (and the common relation to opticians). I wondered how it is possible to have so many worldwide organizations on this apparently narrow topic.

The first insight about a possible answer came from my first optics professor: Dr. Román Castañeda. In his lectures, he combined history, literature, poetry, and science. In the very first lecture he said: "At the end of this course, you will understand how it is possible to obtain darkness by adding light." He was referring to one of the most beautiful experiments in optics, performed by an almost forgotten scientist (and priest): Francesco Maria Grimaldi. Between the Italian Plague and the decline of the city of Bologna, he described (or not?) the first observation of interference. My professor's inspiring teaching opened worlds I otherwise would not have known existed, let alone had access to or believed I had the ability to enter. The beauty of light phenomena captivated me. It inspired me to find deeper explanations and farther frontiers. I was motivated by the opportunities provided by scientific societies.

Through optics, I had the chance to travel outside my country for the first time. I attended the SPIE Optics and Photonics conference in 2010 as the president of the SPIE student chapter at my university thanks to a student travel grant. Since that eye-opening conference, I have been fortunate to work in optics research, publications, and outreach in four languages and countries: Colombia, Germany, France, and the United States.

Building my network has been a pillar for the scholarships that enabled me to continue my research. Under a European Erasmus Mundus scholarship in Optics in Science and Technology (OpSciTech), I could see the differences and common ground among optics researchers in Germany and France, and the importance of bridging these differences and commonalities for research in a field that has global possibilities and implications. My master's research in each country enabled me to define a research

topic that requires this kind of bridging in what I had since learned is a huge field with many inter- and intra-disciplinary possibilities. Integrated optics, particularly silicon photonics, attracted my attention as a key enabling technology that has the potential to dominate the circuit industry in the coming years.

I had opportunities to be trained in experimental optics by some of the finest French researchers I know, in particular, Prof. Nicolas Dubreuil, Prof. Eric Cassan, and Dr. Laurent Vivien. From them, I have learned to appreciate the importance of failing: failing at experiments, failing at grant applications, and failing at visa paperwork. There is something very noble in defeat—to learn how to lose and to learn from the loss. We obtained world-class results that overshadow all of the failures that came from them. Stubbornness, perseverance, and discipline is the message I learned and want to transfer to my students. Stand firm when the hard times come.

Since coming to the US, I have had the chance to work in one of the most prestigious universities, MIT, and to live in the rich academic environment that the US Northeast offers. Here, I reinforced my idea that our optics and photonics community is ready to face the challenges that this new century is bringing. A challenge that requires a new form of education connecting with "the Other." An education that requires fact checking and involves hands-on experiments.

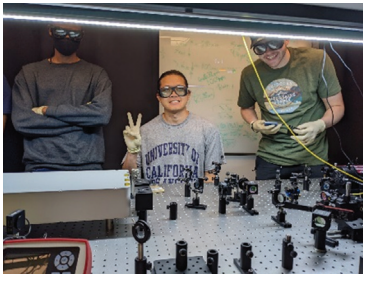
Finally, and as a proposal, I want to highlight the unique bachelors' program in Photonics and Optical Engineering I have been co-building with great colleagues at Bridgewater State University (BSU) for three years. It is the first photonics-related engineering program in a public university in Massachusetts and one of the few in the country. I invite every researcher and student to contribute to a new education model for new technologies, where everyone belongs.

Core to my teaching is also inspiring youth and adults to believe they can be scientists, including doing research in photonics. I especially focus on organizing classes where

people who have traditionally had the least access to higher education in general and science/photonics in particular. This includes people of color, immigrants, low-income students, first-generation students, women, people who have lived through war, with diverse abilities, and who identify as LGBTQ+. Usually, these students are alight with passion for science and work with me to apply to university study and/or professional work in science. Little by little we are building a small and mighty diverse cohort of scientists studying photonics at BSU with the invaluable support of the SPIE community.



Joint bootcamp in integrated photonics between BSU and MIT with grads and undergrads from both institutions. Photo taken at the BSU Photonics and Optical Engineering labs.



Technician students from the joint program between Bridgewater State University and Stonehill College in a visit to one of the Optical Parametric Oscillators in the Photonics and Optical Engineering lab.

On Hyperlinked Teaching and Learning

Bahaa Saleh
University of Central Florida, USA

During my decades of teaching various courses in engineering, physics, and optics, I have often walked into a classroom with a board filled with equations and drawings left from a previous class. Many times, I would see material identical in content to that which I intended to teach, albeit expressed with different notations and probably taught in a different context. The underlying mathematics is apparently the same, but the physical systems are different. At times, I encountered a few bright students discovering with amazement that similar principles apply to different situations; these students saw that the newly found links enrich their knowledge and abilities to address new problems. Other students were clueless and confused; similarities and congruences are not part of their learning experience.

The course-based, one-instructor-per-course educational system can be too compartmentalized and may be even fragmented. Admittedly, alternatives have their own difficulties. When faculty infrequently share their experience with different courses and are busy delving into the depths of the subjects of their own courses, and not worrying about the general objectives of the program, the courses become much like the atoms of a cold gas, colliding infrequently and incoherently. How do we create the interconnections, bonds, and "hyperlinks" that establish greater coherence in the educational program? Change is rarely successful when directed from above or established by committees. However, it can be initiated by individual instructors inspired to inject into their courses links or "hyperlinks" that offer a dose of integration with other courses and that possibly help provide the students with an integrated knowledge of the field.

I was privileged to lead the group that designed and implemented the undergraduate program in optics and photonics at CREOL about 10 years ago. Armed with knowledge about the contents of various courses and labs of the program, and having co-authored a comprehensive optics textbook, I was in a good position to practice what I preach in the course I teach: Imaging and Display.

Image science and engineering is, by its very nature, integrated with core topics in the optics program. Optical imaging is inherently linked to geometric and physical optics and is based on an understanding of optical propagation, diffraction, interference, and polarization. Additionally, since imaging is presented from the perspective of systems, with inputs, outputs, and transfer functions, it also uses concepts and tools from courses in signals and systems, and circuit analysis. Some of these courses are taken by students concurrently, so students might often hear the same story more than once in the same semester, but perhaps from a different perspective and using different notations.

In an imaging course, students learn two-dimensional Fourier analysis in terms of spatial variables, often while still learning or digesting one-dimensional Fourier transform and the notion of spectrum, with time as the underlying variable. Also, since digital image processing is based on discrete variables, another challenge is translating the continuous-variable vocabulary, engraved by multiple mathematics courses, like calculus and differential equations, into a world of MATLAB®-based computing and a view of processes and systems such as cellular automata. This requires teaching by analogy.

Analogy, similarity, correspondence, and equivalence are notions that can be used effectively to communicate, retain, and recall knowledge. They require the creation of myriad "hyperlinks" between courses. I have, whenever appropriate, emphasized the universality of certain concepts or methods and the multiplicity of their applications. This should help the student gain a perspective on the significance of the

material learned in one course in relation to other courses, and their scope of applicability within the overall field.

Knowledge confluence—the coming together of several seemingly independent topics to solve one problem—brings the student great joy for their learning experience. Courses such as imaging offer ample opportunity for the students to pool knowledge from diverse courses to see, describe, or design complete systems, which is essential for building student confidence in utilizing their knowledge. While this is typically accomplished in the capstone senior design project, I require students in my class to write reports about complete imaging systems, explaining how knowledge from the course, and other courses, pertains to various aspects of the system.

While knowledge confluence can indeed come from practice and hands-on experience in the lab, and Field Guides, I believe that instructors should inject "hyperlinks" into their courses with connections to the material in previous, concurrent, and subsequent courses, with the ultimate goal of presenting the student with an integrated learning experience.

The Importance of Students' Cross-Cultural Mobility

Małgorzata Kujawińska
Warsaw University of Technology, Poland

Education in general and higher education, in particular, is the backbone of any society. Its main goal is to provide in-depth knowledge and understanding of the world to advance students to new frontiers of knowledge. Science and technology higher education focuses on providing healthy, knowledgeable representation in research, industry, and commerce, but it also should create sighted, intelligent, and courageous leaders in politics and administration.

Universities and especially educators/researchers should help to discover the innate qualities of individual students and develop these qualities through suitable training by showing good practices and providing wise mentorship. However, one might ask whether deep science and technology support and knowledge transfer in a single university is sufficient to develop all of the intellectual skills required in a future professional life—or is sufficient to create an international awareness with a full understanding of freedom, justice, and equality, which are so needed in today's world.

My answer to this question is NO.

To properly gain a deep understanding of the surrounding world and other nations, students should be exposed to other students and research teams from universities and countries besides their own. A student's mobility experiences assist in the development of

- cross-cultural awareness and better understanding of other people (to develop empathy),
- adaptability and tolerance,
- open-mindedness, and
- a better understanding of complex global issues.

Multicultural experience is also a great asset that helps in finding a dream job. After completing internships abroad, candidates are perceived by recruiters as active, determined, and independent people ready to take on challenges and show flexibility and willingness towards new situations under demanding circumstances. Internships abroad are also the best way to acquire international adaptability and cross-cultural sensitivity and self-confidence while learning how to effectively share ideas, doubts, or fears.

The friendships and networks created during studies abroad, internships, or other collaborative activities among students (e.g., those through SPIE, OSA, or IEEE student chapters) often last throughout the professional lives of the involved individuals.

This was confirmed by my own experience leading at Warsaw University of Technology (WUT), Poland, for the European Erasmus Mundus Masters "Optics in Science and Technology, OpSciTech." OpSciTech was run by five prestigious European universities, namely, Institute d'Optique (France), Imperial College (UK), Delft Technical University (The Netherland), Fredrich Schiller University in Jena (Germany), and WUT. More than 100 master's level students from 15 countries completed OpSciTech during the years 2006–2012 (see the photo on the next page). Many of them now hold important positions in research institutions, industry, and administration in Europe and their own countries. Most of them keep in touch and continue to co-operate with both their former classmates and with us, their teachers. From my perspective, OpSciTech was a great learning opportunity for the recruited foreign students, their Polish, French, German, Dutch, and English colleagues, as well as the staff and co-operating Universities.

My advice to all students is to make an effort to use the multiple opportunities that arise during their studies to open up to the world through (partial or full) studies abroad, internships, or other collaborative international activities with other students. Internationalization of your

education will not only bring new scientific and technological experiences, but it will also facilitate the promotion of the 'international features' that are desired in the global economy, such as openness and sensitivity to intercultural differences, foreign language skills, flexibility of thinking, and tolerance and respect for others.



Graduation gathering of the first cohort of OpSciTech Erasmus Mundus Masters.

The Importance of Hands-On Learning

James C. Wyant
The University of Arizona, USA

There are many ways to learn technical material. We read books, papers, and notes and watch videos. Sometimes the professor presents demos in class. And we work homework problems, which, in my opinion is essential for obtaining a good understanding of the concepts presented.

But, as a student, I needed to do an experiment to really understand a subject. Doing a lab experiment on a particular topic always helped me grasp the topic much better than just reading textbook material. There are students, however, who do not like taking labs and some professors who do not like teaching them. It can take the professor a long time to set up a lab experiment, especially if they have trouble finding all of the equipment needed, or if the equipment must be repaired before it can be used. Labs can also be expensive.

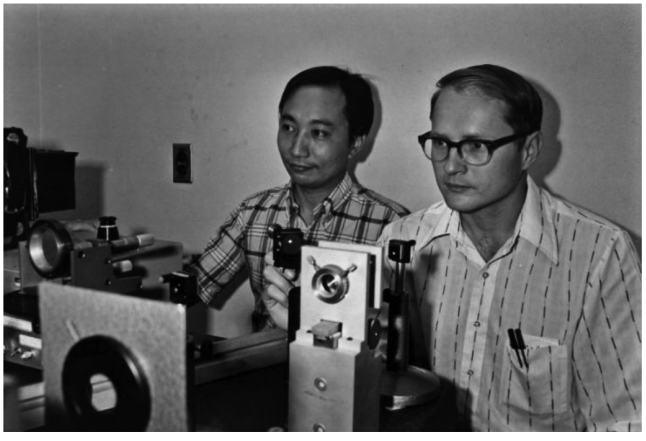
If lab classes are so much trouble, why bother with them? The answer is very simple—if taught properly, labs can be fun, and students may understand the material much more easily doing a hands-on experiment that illustrates the concepts being taught compared to learning the material in a lecture setting. By tilting a mirror or moving a lens (or other optical components) and observing what happens, students can learn so much. Additionally, students gain an appreciation for the beauty of optics.

For these reasons, every optics class I taught at The University of Arizona had an associated lab. For most of my classes, the lab was not mandatory but highly recommended, and almost all of the local students took advantage of the opportunity. When I graded the final exam, I could usually tell which students had not taken the lab—in most cases they did not seem to understand the material as well as the students who had taken the lab.

Lab reports can take a lot of time to write, so I required the students to write only one lab report at the end of the

semester; students were not told which lab would require a report until a week before the report was due. Consequently, it was essential that they kept an up-to-date lab book with the results of all experiments performed throughout the semester. I also required the students to complete the lab book during the lab time when they were doing the experiment. I found that, if they waited until after leaving the lab to make entries in their lab book, they might not remember the details well enough, and they may even realize that additional measurements should have been taken.

I strongly believe that lab courses are essential for understanding the concepts of optics. If I remember correctly, John Greivenkamp took three labs from me: Interference and Diffraction, Holography, and Optical Testing. I am quite sure that John felt as if he learned a lot of optics from these lab courses and that he enjoyed the labs—especially the Holography Lab, where he spent extra time making additional holograms.



James Wyant (right) demonstrating coherent optics principles to graduate student Poohsan Tamura, 1976 (photo courtesy of Poohsan Tamura, taken by George Kew).

Teaching Methodologies and Paradigms



Binoculars (photo credit: Wyant College of Optical Sciences, University of Arizona).

Teaching Laser Engineering to Undergraduates: A Practical Approach

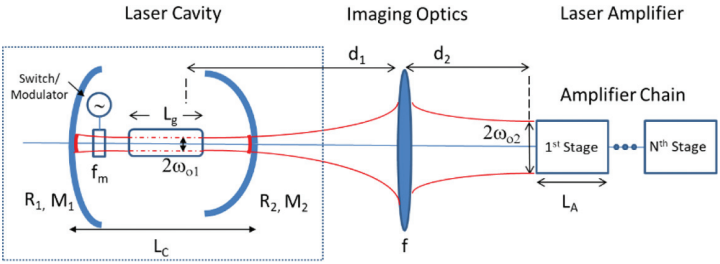
Peter J. Delfyett
University of Central Florida, USA

Teaching a course on lasers can be quite challenging, especially at the undergraduate level. There are many very different topics in optics that are integrated to realize coherent stimulated emission from an optical resonator. In most teaching scenarios, each of the subtopics, e.g., energy states in atoms, fundamental concepts in physical optics, the Fabry–Pérot cavity, Gaussian beams, coupled rate equations leading to gain saturation for an oscillator and/or amplifier, and the different regimes of operation (cw, q-switched, mode-locked), are discussed in a somewhat independent fashion. For example, the ordering of the physics of the gain medium and the development of cavity optics/Gaussian beams can be easily interchanged. In this modality, I have found that students find it difficult to integrate the knowledge to understand the interrelationships between these topics to realize a working laser system. It is in this context that we share our experience with others.

Motivated by Prof. Greivenkamp's *Field Guide to Geometrical Optics*, I have found that I obtain greater teaching success if the course is taught by introducing a schematic of a 'working laser system' on day 1, and then using this 'canonical master oscillator-power amplifier laser system' as a roadmap for where and how each of the independent topics of a laser course fit in. In addition, we develop a set of "working equations" based only on the physical parameters that an engineer would have in the real world, e.g., mirror reflectivity and radii of curvature, energy level diagram and level lifetimes, spontaneous emission line shape, etc., that completely describe the laser output in any of its operational regimes. Thus, as one teaches about the individual components/concepts that make up a laser, the student can immediately see how this knowledge fits into the 'canonical system'. At the end of the semester, students have a set of approximately 50 working equations that rely

only on the physical parameters described above, which enables them to completely predict the output performance characteristics of the laser, operating in any of the conventional operating regimes. Most importantly, since the students gain the expertise of analyzing and predicting the output of a generic laser system, by exercising the process in reverse, i.e., selecting a desired output operating condition, they can construct a design to achieve this goal.

A schematic of the canonical laser system is shown below. Each of the components (cavity, gain, output coupling optics, amplifier configuration, operational mode, etc.) can be easily modified in the teaching process to provide emphasis on different possible configurations, without leading to a loss in generality.



Design, Fab, and Test

Glenn Boreman
University of North Carolina at Charlotte, USA

I first met John when we were in graduate school together at The University of Arizona. Over the years, we interacted many times. He was a dedicated educator, with a lasting legacy of the students he taught.

The observation I offer is that, in my training of PhD students, I've found it useful for their professional development to incorporate three aspects into their research project: design, fabrication, and testing. These were often fondly referred to by my students as the "three legs of the stool." For most students, one of these areas will be their "comfort zone." Some are naturally computational folks, some like cleanroom work, and some are most comfortable with lab measurements. But it is important that a computational electromagnetics person understand that the sidewalls of a waveguide are not smooth and are not always vertical. Once they have fabricated devices and examined them, they understand that. A fabrication person needs to understand the assumptions involved in predicting the device performance, and how their fabrication process either satisfies or violates them. Also, they need to appreciate how their device layout affects what can be conveniently measured. And, to me, the "proof of the pudding" is in the experimental measurement of device performance. This is where we close the loop on the design.

There are always discrepancies between the predicted and measured characteristics, and their comparison is where the majority of the learning takes place. It is always satisfying to be able to plot the predictions and the measurements on the same graph without having to resort to a logarithmic scale. The design-fab-test loop is typically executed several times until the predictions match up well with the results. I have found that this paradigm prepares students well and gives them a well-rounded perspective.

Fab
Test
Design
Signal (μV)
Antenna Length (μm)

What Do Holiday Lights and Solar Panels Have in Common?

Fatima Toor
University of Iowa, USA





Semiconductor light-emitting diodes (LEDs), which make up both holiday lights and solar photovoltaic panels, have p–n junctions.

Recently, in my semiconductor devices lecture, a junior/senior-level, undergraduate electrical engineering course I teach every spring, I started the lecture by asking students what holiday lights and solar panels have in common? The answer was *p–n* junction diodes. We were starting to study a chapter on semiconductor junctions, namely, *p–n* junctions, which make up both LEDs and solar cells. In a *p–n* junction device, a *p*-doped semiconductor is put in contact with an *n*-doped semiconductor. At the metallurgical *p–n* junction, diffusion of carriers occurs, and a built-in electric field is induced. This built-in electric field can then be manipulated by external stimuli to the *p–n* junction, such as electric potential (in LEDs) and sunlight photons (in solar cells). I think the question at the beginning of the lecture definitely piqued my students' interest, and once I shared the answer, I overheard a few ah-ha's from the students.

My favorite part of teaching is connecting hard sciences to items we use in our daily life. My favorite teachers were also those who could explain to me the science behind the things around us. While I really enjoyed the technical rigor of an engineering educational career because it was intellectually challenging, to me the fact that engineering



Interior of St. Vitus Cathedral, Prague, Czech Republic, where sunlight shines through stained-glass windows loaded with plasmonic metal nanoparticles.

was really applied science made it fun—especially the science of light, which helped me understand why the sky is blue (Rayleigh scattering of blue light), why we see colors (reflection), how cosmetics are designed using optical science (diffused scattering), and how ancient architects developed color in glass, also known as stained glass, using metal nanoparticles (plasmonics).

One of my favorite professors of nonlinear optics in graduate school at Princeton always taught some of the most complex principles of optics via simple, everyday examples, which made me enjoy his lectures a lot. For my PhD qualifying exam, the optics questions, designed by said professor, were in fact on (i) explaining the science behind the famous Lycurgus cup (localized surface plasmon resonance excitation), and (ii) the reason for the reddish color of the sky at sunset (Rayleigh scattering). I hope that I can inspire optical science research and exploration in my students by making connections to everyday life examples as I teach them about unfamiliar concepts.

Teaching Wave Mechanics with a Modern Digital Toolkit

Andrew Forbes
University of the Witwatersrand, South Africa

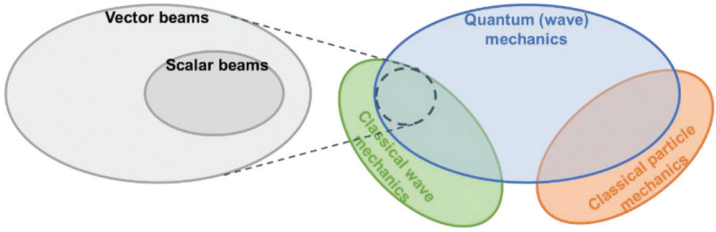
At my university in South Africa, which surely is typical of many universities in the developing world, our optics undergraduate laboratory exercises are more or less confined to double-slit interference, some imaging, and a little Fourier optics. Quantum optics experiments do not exist in the sense that we think of this topic today, with quantum experiments inspired by advances a century ago, mostly 'particle' based. Entanglement is very much a topic of the textbook. Yet in my own research laboratory, we routinely create and control high-dimensional photonic entangled states, performing state-of-the-art quantum optics experiments. Why does it take such a long time for the advances in research to reach the teaching laboratories? At least in the developing world, one reason is equipment, and the skills required to implement an experiment, particularly of a quantum nature. Recently, we have tried to rectify this problem by, on the one hand, introducing a modern digital toolkit for modern optical experiments, and, on the other hand, exploiting the fact that quantum mechanics is a wave theory, like optics, and thus 'wave mechanics,' classical and quantum, can be taught with the same principles and the same toolkit. I would even go so far as to suggest that we teach a wave mechanics course that is a blend of optics and quantum mechanics.

In a drive towards inexpensive, fast, and digital, we have introduced digital micro-mirror devices (DMDs) to our repertoire of optical tools for teaching and research alike, offering best practices to get started with DMDs,[1] to accelerate the uptake. What can you do with such digital tools in the optical laboratory? Well, first you can digitize the traditional double-slit experiment, bringing an element of computation, digital control, and automation to the experiment—not to mention more entertainment and versatility in execution; e.g., the slits, as images displayed

on the device, can be dynamically changed in all parameters such as size, geometry, separation, and so on, giving the students flexibility to explore and truly "experiment." Furthermore, the tools allow one to generalize the traditional interference experiment to fringes in other geometries and other degrees of freedom,[2] such as radial and azimuthal fringes, and fringes in the polarization structure of light, as well as in the orbital angular momentum of light, highlighting that fringes are not restricted to intensity. The same tools can be used to digitally propagate light, digitally spatial filter light, and thus to demonstrate Fourier optics with a modern flavor.[3]

The aforementioned experiments are traditionally taught as part of a course on wave optics, resting largely on the superposition principle of waves. It is well known that the equation of motion for quantum states has a form analogous to that in paraxial optics, and recently the parallels have deepened, with a realization that many quantum principles can be demonstrated with classical light,[4] including entanglement.[5] Recently, we exploited this to produce a do-it-yourself teaching kit[6] that allows the user to demonstrate Bell violations, quantum state tomography, density matrices, and so on, all with 3D-printed components and conventional laser light, e.g., from inexpensive laser pointers. This has proven instrumental in visualizing and working through 'quantum' measurements, and 'quantum' data, except without any 'quantum' complexity in the experiment itself. Here the objective is to make the theory come alive, to work with real data, but at the expense of not realizing a true quantum experiment. Where time and resources are tight, as they often are in large undergraduate classes, this approach has its place.

In our university, we are in the process of switching experiments over to this approach and have used our digital toolkit to great effect in teaching, as well as in outreach to local schools, inspiring the next generation by showcasing that optics is modern and alive.



There is a classical particle mechanics and classical wave mechanics, but only one quantum mechanics. Both optics and quantum mechanics can be taught in the overlapping region where the superposition principle holds supreme. Vector beams, with inhomogeneous polarization states, can be used to mimic entangled states.

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Tips, Tricks, and Tactics for Terrific Teaching

William Wolfe
The University of Arizona, USA

It is a pleasure to pass on some tips and techniques that I have garnered over many years of teaching optics. At the Wyant College of Optical Sciences, I taught only graduate students and never had a class larger than 20.

My first suggestion is to never teach a class larger than 20. That allows you to get to know the students and allows them to participate without restraint. You may have to argue with the Dean, but there is always a next semester.

My second suggestion is to work out problems in class. Assign one and several classes later attack it in class. Make sure you have considered all of the solutions and approaches first. This can even be done with the more-theoretical classes, like diffraction theory or quantum optics (although I never had to).

My third suggestion is to give oral exams, especially to graduate students. These exams prepare them for their real oral exams. They are also a means to learn how much a student really knows. You cannot filibuster during an oral. When you give oral exams, you must rely on the honor system so that you can ask everyone the same questions. Take notes as you get the oral answers. This has the advantage for students that, a few hours after the last question is posed, the results are known. I have done this, and it works!

My fourth suggestion is to introduce humor. Although optics is a fascinating subject, a joke or witticism now and then helps the medicine go down.

Finally, introduce mnemonics of some sort where you can. I discussed "seven deadly noises" and introduced the mantra "think of everything" in my radiometry class.

Thank you, John, for all your help with ancient instruments.

The Art of Insight in Optical Science and Engineering

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Optical Systems Group LLC, USA

Perhaps the most common reason undergraduate students decide to major in science and engineering is that they like to understand how "things" work. In this section, I give a brief overview of an instructional methodology—the art of insight—which brings a more conceptual and intuitive approach to the educational process to directly address this interest.

To illustrate, I use the example of the wave equation in physical optics for the propagation of the electric field amplitude E_y:

$$\frac{\partial^2 E_y}{\partial t^2} = v_\phi^2 \frac{\partial^2 E_y}{\partial z^2}$$

In the conventional approach, this equation is presented to students and immediately followed by common methods of solving for E_y: product solutions, numerical solutions, and so forth. The student who is motivated by surviving a difficult class will, of course, learn these methods; the student also motivated by curiosity, however, would like to know more: What does the equation itself mean? Yes, it describes waves, but can we be more specific?

An instructor familiar with teaching the art of insight will, at that point, introduce an analogy: Instead of E_y, think of a stretched string with a vibrating amplitude y. What does the wave equation mean in that case? The answer is straightforward: The acceleration ($\partial^2 y/\partial t^2$) of any point on the string depends on the phase velocity v_ϕ of the wave and the local curvature ($\partial^2 y/\partial z^2$) of the string at that point. That is, the faster the wave passes, the greater the acceleration; at the same time, an initial condition of amplitude (not wavefront) curvature is required for a wave to propagate.

Further questions from the curious student are then inevitable, such as: What does the phase velocity depend on? Comparing electromagnetic wave propagation in vacuum with that in glass, for example, the frequency ω (and "acceleration" $\partial^2 E_y/\partial t^2 \sim \omega^2$) remain the same; in addition, the wavelength λ in glass is shorter, giving more curvature ($\sim 1/\lambda^2$).

The wave equation then tells us that, if the curvature in glass is higher, the phase velocity must be slower to maintain the same ω—with the refractive index *n* describing how much slower via $v_\phi = c/n$ for the speed of light in vacuum equal to *c*. The concept of refractive index is thus essential for understanding not only the static picture of Snell's law of refraction, but also the dynamics of wave propagation.

And like all good analogies, the string-optics analogy can be carried too far. After all, if an elastic medium such as a string is required for mechanical waves, what medium (or "aether") is required for electromagnetic waves? It actually took the optics and physics communities quite a bit of time to answer this question, with the interferometric experiments of Michelson and Morley showing that there is no aether, and that electromagnetic waves self-propagate.

And so, with the inquiry-based motivation of looking for a first-order intuitive understanding of the wave equation, we have discovered a powerful teaching and learning methodology—i.e., the art of insight, or distilling a problem down to its physical essence—that quickly led us in multiple directions, covering a deep conceptual overview of how some optical "things" work.

For more details on this topic and many others, two excellent references are: (1) F. S. Crawford, Jr., *Waves*, McGraw-Hill (1968) and (2) S. Mahajan, *The Art of Insight in Science and Engineering*, MIT Press (2014).

There is More to Teaching Optics and Photonics Than Science and Engineering

Anne-Sophie Poulin-Girard
Université Laval, Canada

Sometimes, gaining technical skills is not the only, nor the main, goal of education and training in optics and photonics. As educators, we can pursue a variety of goals to help our students become the next generation of scientists and engineers, and science notions are not always the main character of our training efforts. Making sure students would gain technical knowledge was certainly not the only goal of the Photonics Games committees, who have welcomed more than 2500 high school students since the activity was created 14 years ago.

In 2008, with a group of friends from my SPIE student chapter, we created the Photonics Games. SPIE student members are great educators, creating countless outreach activities, reaching out to kids and the general public around the world. Held once a year over one or two days, the concept behind the Photonics Games is very simple: in teams of four, high school students compete in various optics and photonics challenges.

When we created this activity, we decided on two goals we wanted to reach. The first one was quite standard: increase awareness about the science of light amongst young people and improve their knowledge in the field. The second goal was more ambitious in my opinion. We chose to leverage the fact that STEMs are seen as complicated topics in order to increase the self-confidence of teenage students from underprivileged areas by creating a positive experience in a STEM context. We designed six challenges that each call on different aptitudes: artistic sense, knowledge and memory, physical coordination, 3D visualisation, social interactions and teamwork, and mathematical and logical reasoning. A student who doesn't have much knowledge of optics might be very good at 3D visualization and would perform on the optical mini-golf course. Since each team was accompanied by a university student volunteer, it was

a great opportunity to put the participants in contact with potential role models—an opportunity they might not have had in their normal surroundings. The volunteers also made sure the spirits were high all day long, no matter what the outcome of the challenges was.

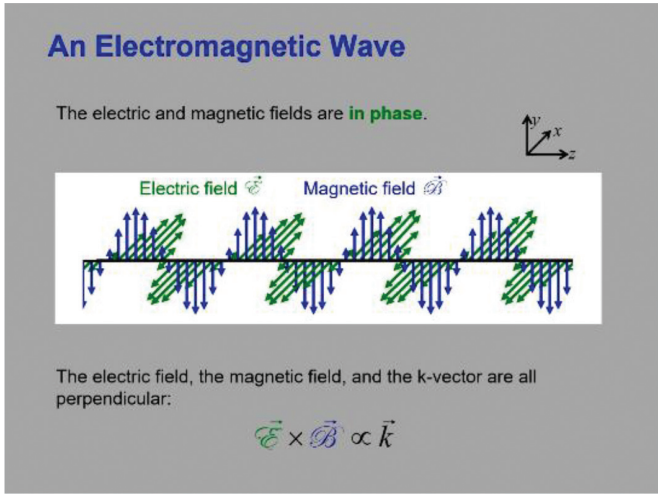
To maximize the occurrence of STEM-related successful situations during the activity, we had a medal ceremony at the end of the day, which is logical as the Photonics Games are inspired by nothing less than the Olympic Games. There were never real medals, but we decided to present the top three teams of each challenge and give fun science-related gifts to the winners. We also encouraged cheering and expressions of joy, which can become quite loud in the presence of 200 high school students and 70 university volunteers.

I have participated in the organization of several editions of the Photonics Games, and the initiative is still thriving to this day. Over the years, high school teachers have told us countless heartwarming stories about their students in the Photonics Games retrospective surveys or during informal conversations. The activity contributed to students becoming more serious towards their studies, a reduction in student absenteeism, an increase in self-confidence, and young people considering technical career paths for the first time. And I cannot recall any teacher who talked about how the Photonics Games significantly impacted their students' ability to perform optics and photonics theoretical calculations. That was simply not the main goal.

Re-inventing the Lecture

Rick Trebino
Georgia Institute of Technology, USA

The class lecture hasn't changed in 5000 years, continuing to comprise a pitifully dull talking head mumbling before a bleak blackboard. Having completely sat out the ongoing spectacular technological revolution, the class lecture remains inherently dull and often exacerbated by inadequate teacher knowledge and communication skills. Worse, lecture preparation is time-consuming, and lecture notes are not amenable to being shared. So, as with books before Gutenberg, the task of preparing lectures must currently be performed independently and hence massively redundantly by every teacher in the world. Lectures absorb *tens of billions* of human hours annually.



A snapshot of a slide. In addition to animations, the wave also actually propagates across the page.

So, it's time to re-invent the class lecture. If lectures were actually exciting, students would pay attention, not because they fear a low grade, but because they'd want to. Alas, it's impossible for a talking head to effectively convey this excitement. Teenagers easily remember minute

details of popular movies seen years earlier but often can't recall key ideas from the previous day's math class.

As a result, I've created visually exciting, elegant, high-tech PowerPoint lectures, packed with colorful gifs, animations, images, and diagrams. Then, during the pandemic, I carefully wrote entertaining scripts for, narrated, and meticulously audio-edited them, yielding near-professional videos of entire Modern Physics and Optics courses (see frog.gatech.edu).

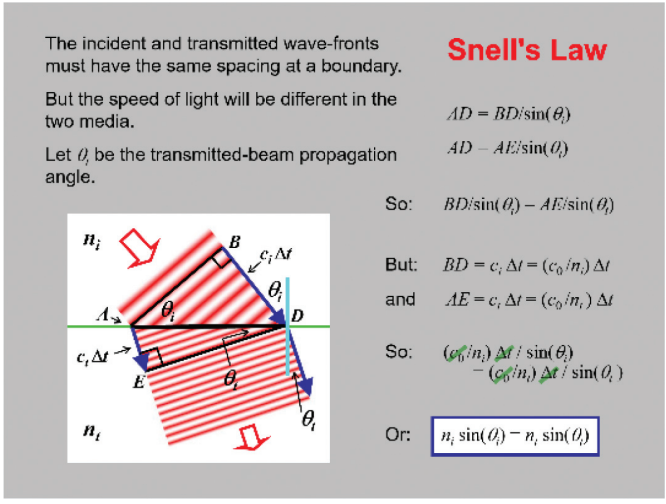


While still works in progress (I'm still learning the relevant skills), they're vastly superior to live lectures. As downloadable movies, they can be watched anytime and many times, greatly reducing student anxiety. Also, they can be shared with the world, solving the redundant-effort problem.

These videos also immediately solved one pesky problem: the ubiquitous exponential decay of college class attendance over the semester. In my optics course, because they could do so anytime, nearly all the students reported watching 100% of the lectures. Also, grades were spectacular, mostly A's for the first time in a course of mine.

Now, of course, we can't expect teachers to have all of the skills or time to create such lectures. But we don't need to. We only need *one*. Or, better, one *team* of teachers. Perhaps the Gates or similar foundation would provide grants of,

say, $200,000 per team per course. Creation of, say, 50 high-school and 200 college courses, each at two different levels, would cost $100M, a small fraction of the $2B spent reducing class size in a previous failed attempt to improve student performance.



This derivation involves multiple animations for the text, diagram, and equations.

Implementation of this proposed approach will do for lectures what Gutenberg did for books. Teachers could then spend their newly available time, say, acquiring more knowledge and working with students.

As the entire world acquires Internet access, such lectures could bring quality education to even the poorest schools. Indeed, this effort could inspire other foundations and companies to provide Internet access to the one third of the world that currently lacks it. Finally, in countries hostile to the education of girls, girls could self-educate by privately watching such lectures. PowerPoint can translate narrated lectures into 60 languages.

In conclusion, I believe that this transformation is long overdue and will reap benefits currently unimagined.

From Ray Geometrical to Wave Diffraction Imaging

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The University of Arizona, USA

It is quite common to start the study of geometrical optics with Fermat's principle and derive its laws of rectilinear propagation, refraction, and reflection from it in 2D. Then, using the paraxial or the small-angle approximation of the rays, launch into the imaging equations for refraction and reflection. Sometimes, instead of deriving the equations for reflection independently, they are obtained from those of refraction by giving a value of -1 for the refractive index and replacing the angle of refraction with a minus value as the angle of reflection. As soon as these equations are established, the fact that they have been obtained in the small-angle approximation is forgotten. Has anyone who has obtained the image of an object by a graphical construction wondered if the rays used in the construction actually make small angles? In fact, the small-angle approximation is never quantified, except that it is imposed by replacing the sines and tangents of the angles, however large, by the angles (in radians). Even the curved refracting and/or reflecting surfaces are replaced by their paraxial counterparts in the name of *tangent planes*. The image of an object obtained in this manner is called a Gaussian image. Unfortunately, when done in this manner, Gauss, who introduced the *paraxial* or *Gaussian* approximation, does not get credit for how he came up with the idea of his approximation.

Rays do not travel only in a plane. Hence, it is important to consider propagation of skew rays and derive the laws of geometrical optics in 3D.[1,2] When this is done, we realize that, to trace a ray exactly from one point to another on an imaging surface, the transverse coordinates of the surface point depend on the direction cosines of the ray and the distance between the two. However, the distance itself depends on the coordinates of the incident point. Hence, the two equations are coupled and must be solved simultaneously. The ray is refracted or reflected according to the law of refraction or reflection. In an imaging system

consisting of multiple refracting and/or reflecting surfaces, where a ray originates at a point in the object plane, coupled equations are solved when the ray leaves one surface and meets another, finally reaching the image plane. The refracted and reflected rays lie in the plane of incidence, i.e., the plane containing the incident ray and the normal to the refracting or reflecting surface at the point of incidence. In the small-angle approximation, projections of a *skew ray* in two orthogonal planes propagate independently of each other. A ray in the tangential plane, for example, remains in that plane after refraction or reflection. Because of the rotational symmetry of an imaging system, the consequence is that we need to trace rays only in one of these planes. It is a common practice to trace rays in the tangential plane of an imaging system. Because the sine of an angle is replaced by the angle itself, which is a *first-order approximation*, ray tracing in this approximation is called *first-order optics*, and the process of determining the image in this manner, regardless of the magnitude of the angles and sizes, is called *Gaussian optics*.

Gaussian imaging is used to determine the image location and its size in terms of the object location and its size. It depends only on the vertex radius of curvature of a surface. Thus, the Gaussian image formed by a conic surface of some vertex radius of curvature is the same as that formed by a spherical surface of the same radius of curvature. How does the difference in the two surfaces manifest itself? While the two Gaussian images are the same, their actual images and qualities are not. In Gaussian optics, the image is aberration free; in reality, that is generally not the case. The rays from a point object incident on an optical system do not all pass through its Gaussian image point. Their distribution is called a *spot diagram*, and their separations in the image plane from the Gaussian image point are called *transverse ray aberrations*. The spherical wavefront incident from the point object is not refracted by it as a spherical wavefront. The deviations of the wavefront along the exact rays from a spherical surface with its center of

curvature at the Gaussian image point and passing through the center of the exit pupil of the imaging system are called *wave aberrations*. Such deviations are different for spherical and paraboloidal refracting surfaces. A lens designer designs an optical imaging system with multiple surfaces to control the aberrations to required tolerances over a certain field of view of an object.

For a rotationally symmetric imaging system, the aberrations at a point (r, θ) on its pupil for the imaging of a point object at a height h from its optical axis depend on the integral powers of three *rotational invariants*: h^2, r^2, and $hr\cos\theta$.[1] The order of such aberrations is even. This is how the fourth-order, or primary, or *Seidel* wave aberrations r^4, $hr^3\cos\theta$, $h^2r^2\cos^2\theta$, h^2r^2, and $h^3r\cos\theta$ come about. These are spherical aberration, coma, astigmatism, field curvature, and distortion, respectively. The higher-order aberrations can be similarly written. Since the ray aberrations represent the gradients of the wave aberrations, their order is one less than that of a corresponding wave aberration. Thus, Seidel ray aberrations, for example, are of the third order. If the image is observed in a plane that is displaced along the optical axis from the Gaussian image plane, a defocus wave aberration varying as r^2 is introduced. Moreover, if the aberration is considered with respect to a point in the Gaussian image plane other than the Gaussian image point, a wavefront tilt aberration varying as $r\cos\theta$ is introduced. These are referred to as classical aberrations. A wave aberration of a certain order can be combined with those of lower orders to minimize its variance across the pupil. These aberrations are called *balanced aberrations* and are represented by *Zernike polynomials*. These polynomials are orthogonal to each other across a circular pupil. A wave aberration can also be balanced so that the variance of the corresponding ray aberrations, or the spot size, is minimized. However, such wave aberrations are not orthogonal to each other, but their gradients are.

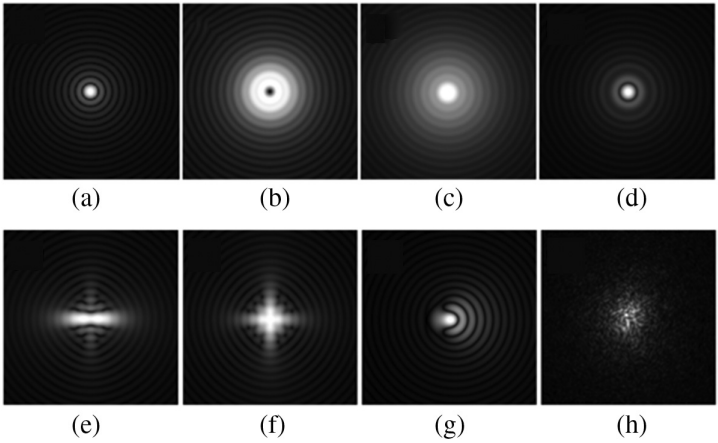
In principle, a system can be designed to yield the image of a point object to be small to some prescribed tolerance.

Even if the rays transmitted by the system intersect at the Gaussian image point, the observed image, instead of being a point, is a light distribution, called the *Airy pattern*.[1,3] Owing to the circular symmetry of the pupil, the pattern consists of a bright circular spot, called the *Airy disc*, surrounded by alternating dark and bright circular diffraction rings of decreasing brightness. The Airy disc contains 83.8% of the total amount of light. Its radius is $1.22\lambda F$, where λ is the wavelength of light, and F is the focal ratio (distance between the pupil and image planes divided by diameter of the pupil) of the image-forming light cone. The Airy pattern also represents the squared modulus of the Fourier transform of the uniform distribution of light across the circular pupil because of the diffraction of light. The brightest point lies at the Gaussian image point. This point is where the center of the pattern lies and is equidistant from the points on the spherical wavefront; it is also where Huygens' secondary wavelets interfere constructively. When aberrations are present in a system, the points on the wavefront exiting from its pupil are not equidistant from the center of the pattern, and secondary wavelets interfere partially destructively, thus resulting in a reduction of the brightness at this point. When the defocus wave aberration, varying as r^2, is an integral number of waves, secondary wavelets interfere destructively at the center, and the irradiance reduces to zero.

For small aberrations, the relative brightness at the center, called the *Strehl ratio*, is given approximately by $\exp(-\sigma^2_\Phi)$, where σ^2_Φ is the variance of the phase aberration.[1,3] The fabrication tolerance for a single mirror for a Strehl ratio of 0.8, for example, is approximately $\lambda/30$ (where we have doubled the surface error to obtain the wavefront error because of reflection of light). The irradiance distribution of the image of a point object is called the *point-spread function*, and its Fourier transform is called the *optical transfer function* (OTF).[3] The OTF is a complex function, and the integral of its real part yields the Strehl ratio. Its modulus is called the *modulation transfer function* (MTF).

In the presence of aberrations, whereas the spot diagram grows linearly in size, the distribution of light in the observed image changes without such increase, as shown in the figure.[3] Although the spot diagram does not represent the true distribution of light in the image, lens designers use it as a convenient tool in the early stages of a design. As the spot diagram becomes small in the range of the Airy disc, they resort to diffraction calculations of the image to ascertain the image quality. Two commonly used image quality criteria are the fraction of light on a pixel in the image plane and the MTF of the system.

While ray geometrical optics determines the location and size of the image of an object, its quality is determined by wave diffraction optics, and the aberrations provide a bridge between the two. It is suggested that, in a course on geometrical optics, the paraxial approximation be derived from 3D ray tracing and the Airy pattern be discussed at least at an elementary level, including how it is impacted by aberrations.



Aberrated PSF: (a) Airy pattern, (b) defocus, (c) spherical, (d) balanced spherical, (e) astigmatism, (f) balanced astigmatism, (g) coma, and (h) random aberration.

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2. M. V. Klein and T. E. Furtak, *Optics*, John Wiley & Sons (1988).
3. V. N. Mahajan, *Optical Imaging and Aberrations, Part II: Wave Diffraction Optics*, SPIE Press (2001); 2nd ed. (2011) [doi: 10.1117/3.898443].

Teaching Optics Outside the Discipline

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Classes for our graduate students and undergraduate majors give a comprehensive background in optics, photonics, and lasers. We have specialty courses developed by scholars, and these core lecture courses are complemented by extensive laboratory experiences. However, what about a single course for science and engineering majors, or incumbent workers, who will only take one course in optics?

The good news is that there are good textbooks available that that cover the major topics of importance. The sad news is that there is no way to cover that material in a one-semester, three-credit-hour lecture course with no accompanying laboratory experience. The situation is further complicated by the reality that some students have strong physics backgrounds while others have an engineering background. This, in practice, means minimal derivations and maximal applications and practice. Since there is no lab associated with this course, I always bring a bag of "touchy-feelies" to the lectures: lenses, mirrors, gratings, polarizers, birefringent crystals, laser pointers, and a bit of optical fiber. Specific components are shared with students for their inspection according to the subject of the lecture.

My approach is to do a brief review of simple ray optics, the laws of reflection and refraction, and Snell's law at the level of physics for science and engineering majors. Even one-time students of optics should have knowledge of how to ray trace a simple two-element lens system. Thusly equipped students can also explore total internal reflection and basic propagation in an optical fiber and the role of fiber cladding.

After this introduction, I move on to physical optics, starting with Maxwell's equations for linear, isotropic media with no free current or charge. We then do a derivation of the wave equation. I require that the students be able to demonstrate that the wave equation is linear

using harmonic functions in sinusoidal and exponential forms. This math review prepares the students (who have mixed math skills) for the superposition principle, interference, polarization, diffraction, understanding a bit about optical properties of materials, and basic laser operations. The vector field nature of light must be included even though many of the topics above are treated as scalars. One must also understand how optical fields propagate, how they transmit energy, and the relationship of irradiance to the electric field of the electromagnetic wave.

The above paragraph is in effect the syllabus of the course. For optics and photonics majors, this material is covered by the many courses and accompanying laboratories. Thus, the emphasis is to look for synergy in the various topics. The classic example of this is emphasizing that many topics and applications of optics require the careful tracking and/or calculation of phase differences among beams where the superposition of waves is invoked. Examples include interferometry and diffraction (which, after all, is the self-interference of waves.) Polarization is inherently a vector property but is easily taught in terms of orthogonal vectors whose components are treated as scalars along each axis, where the resultant vector is determined by the relative phase of the two components.

There is inherent conflict regarding what is derived and what is stated. For example, we derive the results for diffraction from a slit and from Young's double slit, with emphasis on which terms in the relative phases can be discarded and which must be included. This is easy to then generalize to rectangular and circular apertures.

Homework is assigned to students so they can discover the inverse relation between the scale of the aperture size and the scale of the resulting pattern. Quiz and exam questions are written that give answers without complex calculations. Other problems allow the students to discover that the peak on an axis field depends on the square of the area of the aperture, independent of the aperture shape. This, in

turn, demonstrates that the peak on axis irradiance depends on the area squared.

Most students in this class have seen Fourier transforms, but few are proficient. I simply point out that calculating the far-field pattern is exactly of the form of a Fourier transformation, and that a lens performs Fourier transform as it images a source at the lens focus. The result is that an optical telescope produces an irradiance at the focal plane that is proportional to the fourth power of the objective lens radius. A lab to show this would be great! The next-best option is to give crafted homework problems that demonstrate this effect. After students solve these problems, it is easier to convince them that the amount of light collected is proportional to the area of the objective, and the area of the diffraction-limited image is proportional to the inverse of the square of the aperture radius, thus giving the irradiance at focus, which is proportional to the fourth power of the objective radius.

In summary, a single-course survey of optics needs a small amount of (but essential) derivations. Tie the lecture topics to the touchy-feely samples that student can play with, and give homework problems that are crafted to teach the key concepts in practical applications.

In my bag of optical samples used in the class is a pair of late 18^{th} century binoculars given to me by Professor John Greivenkamp. It is among my favorite optical instruments!

Tissue Optics: Student Lab in the Kitchen with First Aid Kit and Smartphone

Valery V. Tuchin
Saratov State University, Russian Federation

Introduction

Because tissue optics is one of the main disciplines at the Department of Optics and Biophotonics of Saratov State University, we prioritize the acquisition of primary knowledge and practical skills by first-year bachelor students studying optical and biophysical phenomena in living objects. The discipline "Introduction to Specialty" is based on the courses of school physics, biology, chemistry, mathematics, and computer science, as well as general physics and mathematics courses given to students during the first and second semesters. During two semesters, students prepare written reports and short presentations for public defense of their projects, which include laboratory work.

Laboratory work

Students receive assignments to perform laboratory work at home, in their kitchen using animal tissues from the refrigerator, kitchen utensils for sample preparation, optical clearing agents (OCAs) from the home first aid kit, and their smartphone. A typical topic of laboratory work is the control of the optical properties of tissue when exposed to an OCA. In agreement with the professor, the student chooses the type of animal (chicken, pig, bull, sheep, etc.) and tissue (skin, muscle, heart, liver, kidney, sclera, dura mater, cartilage, tendon, etc.), and an OCA (glycerol, glucose, fructose, sucrose, or vape—a mixture of glycerol and propylene glycol).

Student use improvised means to assemble experimental setups for recording images of a tissue sample in transmitted or reflected light. For about an hour, using a smartphone, student register several dozen images of a sample placed in an OCA. Next, for the selected points (or small areas) of the image, using available software, students plot the dependence of the brightness of the

selected image pixels on the time duration of the sample soaking in the OCA. Such an analysis can be carried out separately for the red (R), green (G) and blue (B) components of white light and thus obtain information about the properties of the tissue from different depths.

Theory

Attenuation of a light beam of intensity I_0 and wavelength λ in a tissue layer of thickness l can be described by the Beer–Bouguer–Lambert law:[1]

$$I(\lambda) = I_0 \exp(-\mu_e l)$$

where

$$\mu_e = \mu_a + \mu_s$$

is the light-beam attenuation coefficient (1/cm), μ_a is the absorption coefficient (1/cm), and μ_s is the scattering coefficient (1/cm).

For many tissues, attenuation due to scattering is much stronger than that due to absorption. Therefore, to increase tissue optical transmittance $T(\lambda)$, one can decrease the scattering coefficient

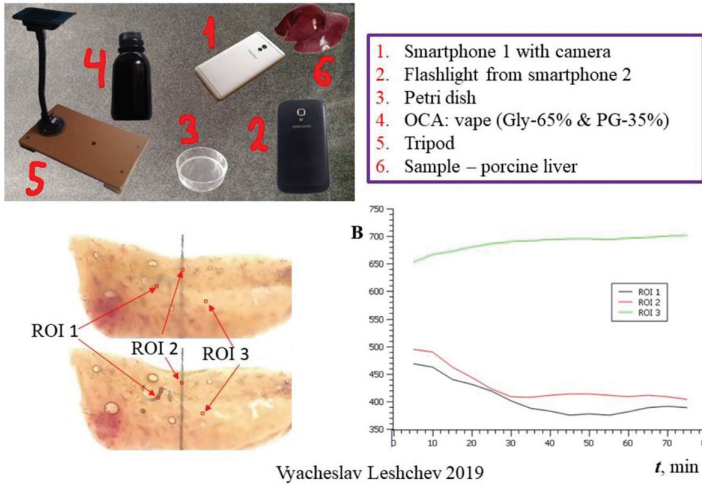
$$\mu_s \infty (m-1)^2$$

where $m = n_s/n_0$ is the relative index of refraction of tissue scatterers n_s and the ground medium n_0. Tissue fibers and cell organelles are scatterers of light as their index of refraction n_s is higher than that of the ground medium n_0 formed by cytoplasm and interstitial fluid. When an OCA with refractive index n_a higher than that of the ground medium n_0 diffuses in a tissue, the refractive index of the ground medium increases with time. This diffusion means that $n_0 \rightarrow n_s$, $m \rightarrow 1$, and $\mu_s \rightarrow 0$; thus, optical transmittance $T(\lambda) \rightarrow 1$.

Example of student work

Fragments of the report of one of the laboratory works are presented in the figure on the next page. At the bottom left, two digital images of a tissue sample are seen, obtained in

the transmission mode—before (top) and after (bottom) the action of the OCA. Three regions of interest (ROIs) are identified in the characteristic regions of the sample, above item 5 (ROI 1) and the black line (ROI 2) drawn on the sample substrate, and in the area free of light-absorbing elements (ROI 3). It can be clearly seen that the sample becomes more transparent upon optical clearing due to a decrease in light scattering. Therefore, as seen in the bottom right panel, the brightness of the image in the absorber-free region of ROI 3 increases over time from 650 to 700 units. In the areas of ROI 1 and ROI 2 (item 5 and the black line), absorption decreases because nonscattered light is blocked by absorbing elements. In this case, the black line and item 5 imitate the presence of a light-absorbing tumor, which was not visible at the start of the experiment but then appeared with good contrast.



A fragment of a report on laboratory work performed by a student for a 0.5-mm thick porcine liver tissue that was optically cleared with an OCA: a vape containing 65% glycerol and 35% propylene glycol. The images obtained with the camera of smartphone 1 were processed using Adobe® Photoshop® and SciDAVis software.

Conclusion

Many years of experience conducting these classes have shown that university students in their first year of study, who have only high school courses in physics, mathematics, computer science, chemistry, and biology, are quite capable of doing an experiment at home on the optics of dispersed media of natural origin, which include biological tissues.

Reference

1. V. V. Tuchin, *Tissue Optics: Light Scattering Methods and Instruments for Medical Diagnostics*, 3rd ed., SPIE Press, p. 988 (2015) [doi: 10.1117/3.1003040].

The Importance of Learning Both the Great Potential of Optics and the Significant Practical Challenges of Meeting It

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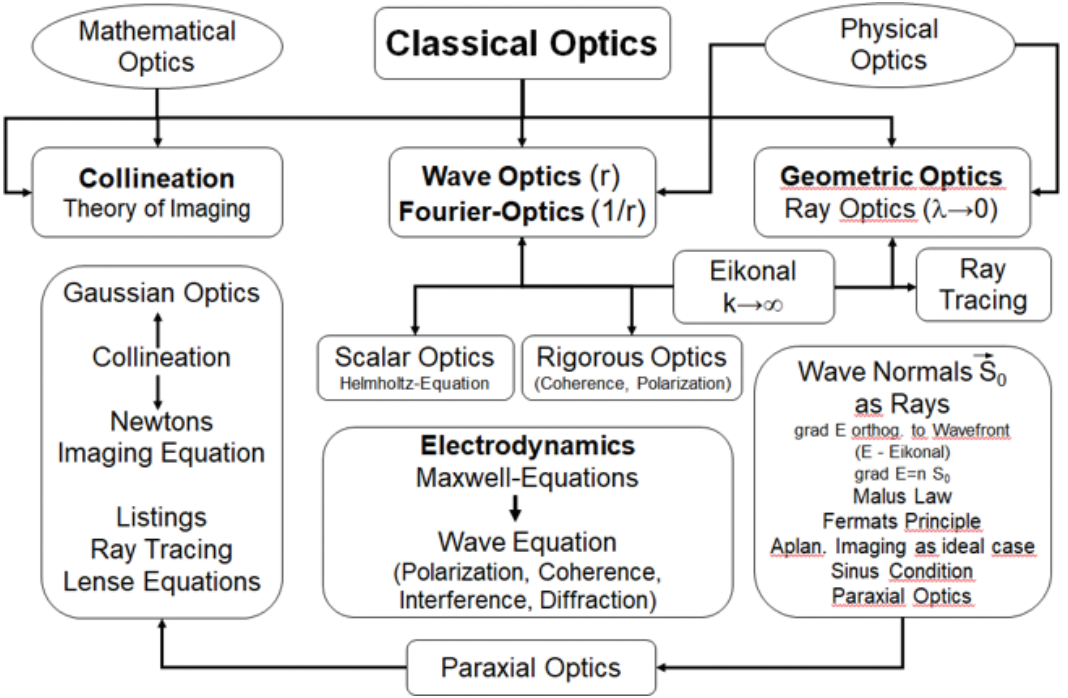
Remembering my university time at the Friedrich-Schiller University in Jena, Germany, I can only conclude that I had wonderful teachers. My area of study was physics, but I specialized in optics. This was mainly motivated by my fascination for holography so I made wrote my diploma thesis on Coherence Optics. One of the lectures that I was required to hear at the time was Optical Imaging. This lecture was given by Christian Hofmann, a manager from ZEISS and a visiting professor at the universities in Jena and Ilmenau.

I cannot remember any other lecture that was as unique in its speed and its depth as well. But two other peculiarities about Hofmann's lecture shaped me in the long term and significantly influenced my attitude towards teaching optics. At any moment during his lecture, a student could interrupt him and ask questions. He would immediately stop his flow of words and his extremely fast writing on the black board and start to give another lecture off the cuff. We all then sat on our benches with open mouths, ears and eyes trying to follow his deep excursions into, for example, the wide field of electrodynamics. The other peculiarity was the way he taught us both the great potential and the challenges of designing optical systems with a high level of imaging quality. Thus, he did not start by writing Maxwell equations on the black board and deriving from them the features of light. He started by asking the question: What do we expect from an ideal optical imaging? The way he tried to answer that question became an excursion into the realm of Gaussian or paraxial optics—a purely mathematical response based on linear transformations and collineation. What we learned from it gave insight into what we can expect from optical imaging in the most ideal case and what the challenges are in designing a system that at least approximately fulfills the properties of an ideal system.

This was, admittedly, a very dry start, which, however, opened up the view to what must be done in order to achieve a high level of imaging quality. The answers came later when geometrical optics, wave optics, aberration theory, photometry, and Fourier optics were extensively examined.

When I implemented a similar approach to my lectures at the Bremen and Stuttgart universities, the student response was at first ambivalent. My precursors had preferred a more classical or intuitive way of teaching. However, with time, and as the lectures progressed, the students and assistants understood the advantages of this approach and grew to appreciate not only the potential of optical imaging but also the challenges to achieving them.

In the flowchart on the next page, I have tried to visualize the interconnections of the different models for presenting and understanding the features of an optical imaging. I am convinced that there is always room to make a presentation even better. In any case, the biggest gift for me as a teacher of optics is seeing the glow in my students' eyes and feeling their hunger to hear more when I talk about the great fascination of optics, as well as its significant challenges.



An attempt to visualize the interconnections and main peculiarities of different models for presenting classical optics.

Specific Lessons



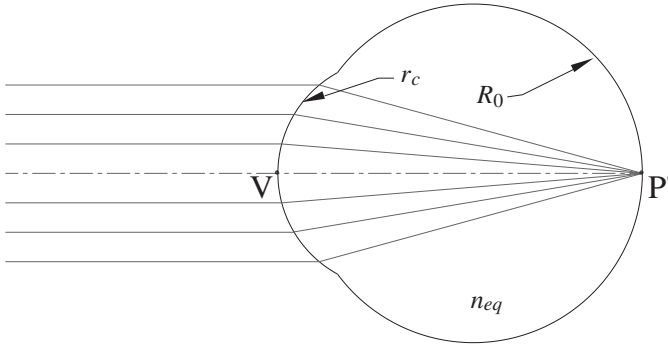
John Greivenkamp with an antique telescope (photo credit: Wyant College of Optical Sciences, University of Arizona).

Could Our Eye Be a Single Sphere?

Yobani Mejía
Universidad Nacional de Colombia, Colombia

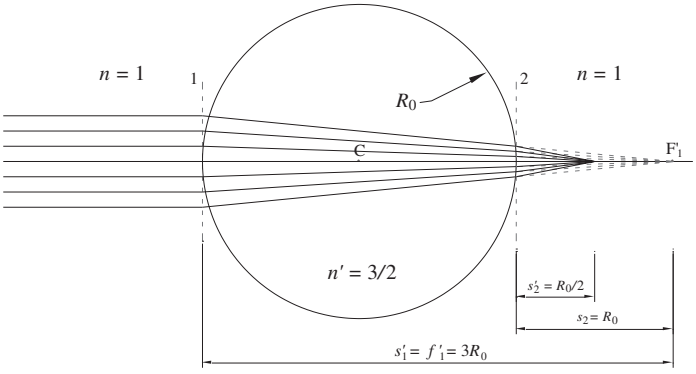
When I teach the Gaussian formula for a single spherical surface, $n'/s' - n/s = (n' - n)/R$, I like to mention two examples: the human eye and the refractive sphere.

In a first approximation, within the paraxial region, a reduced schematic eye estimates the image in the retina. It is composed of two parts: the rear part is a spherical surface of radius R_0, and the frontal part is also a spherical surface of radius $r_c < R_0$, as shown in the figure below. The medium bounded by these surfaces has an equivalent refractive index $n_{eq} \approx 4/3$.[1] With regard to the shape of this eye model, I ask students whether it is possible to have an eye as a single sphere.



Reduced schematic human eye.

Then, after some discussion, I pose the problem of the refraction of light at a glass sphere of radius R_0 and index 3/2 when it is immersed in air with index 1.0. First, I ask the students to sketch the refracting rays coming from the infinite. Some of them draw the point where the rays converge inside the sphere, and others draw it outside the sphere, but no one draws it in the second vertex. From the Gaussian formula, at each surface, it is found that the point at which all the rays converge is outside (at $R_0/2$) the second vertex, as shown in the figure below.



Refraction of a parallel beam at a sphere.

Finally, I ask them what we need to change in the schematic eye to have an eye like a single sphere, in order for a parallel incident beam to converge at the second vertex. The solution implies a change in the refractive index n'. From the Gaussian formula, with $s = -\infty$, and $s' = 2R_0$, the answer is $n' = 2$.

When I talk about this with eye specialists (optometrists, ophthalmologists), they are surprised, and tell me that they had never thought about it. In some way, the human eye must have the current shape because, in our bodies, the refractive index of fluids like the aqueous humor and vitreous humor are close to that of water.

This simple exercise allows students to understand that the general geometry of the human eye can be explained with the Gaussian formula.

Reference

1. D. Atchison and G. Smith, *Optics of the Human Eye*, Butterworth-Heinemann (2000).

Teaching Optics by Analogy and Association

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Analogy and association help students to gain a systematic and unified understanding of seemingly different subjects and physical phenomena in optics.

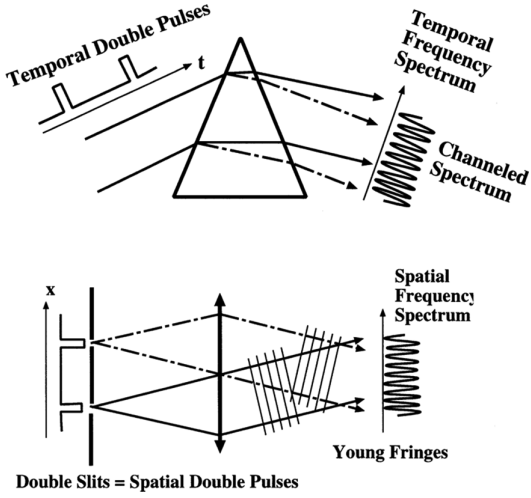
The wave equation,

$$\nabla^2 u(\mathbf{r}, t) = (1/c^2)[\partial^2 u(\mathbf{r}, t)/\partial t^2]$$

has space–time symmetry. Its general solution can be expressed by superposition of elementary plane waves:

$$\exp[i(\mathbf{k} \cdot \mathbf{r} - \omega t)] = \exp(i\mathbf{k} \cdot \mathbf{r}) \exp(-i\omega t)$$

which have two-fold symmetries between the variables in space (**k**, **r**) and time (ω, *t*), as well as between those in the signal domain (**r**, *t*) and the frequency domain (**k**, ω). This permits an interchange of the roles played by the variables and thereby serves as the origin of analogy.



In this example of space–time analogy, Fizeau's channeled spectral fringes, generated by double time pulses in the temporal spectrum domain, are explained in association

with Young's fringes, generated by double slits in the spatial spectrum domain, which is more familiar to students.

Viewing the lower figure, it should be easy for students to imagine that Young's fringes would become holographic fringes if one of the double slits were replaced by an aperture with its transmittance representing an object. By analogy, the students would be able to understand the principle of time holography—in which one of the double pulses is replaced by a waveform representing a temporal object—without much difficulty.

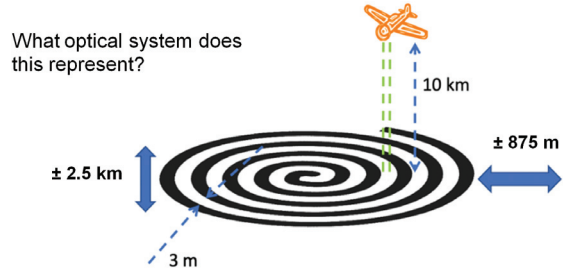
When learning interferometry, students can gain a unified understanding of the principles of temporal and spatial heterodyne techniques by noting their formal analogy.

Analogy is not only of interest per se, but suggests to students that, if there is a principle that works with a time variable, there is a similar principle that works with a space variable, and vice versa. Understanding this will help students increase their capacity for invention.

Six Myopic Engineers and the ?? System

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Imagine you're in a plane, 10 km above the ground, and flying at an extremely high velocity. The plane will travel 12.5 million km, and throughout the flight, it must maintain its height with an error of only ±1.5 m. This plane has a very specific flight path or track that it must fly over. The width of the plane is only a couple of meters, and it must stay centered over the track, which is of a slightly smaller width. As if this wasn't challenging enough, the track below is moving both horizontally by ±875 m and vertically by ±2.5 km, as the plane flies. What optical system do you think this represents? If you haven't guessed by now, maybe this last clue will help. The flight path is not straight but a spiral.



This is how I start teaching the course Optical Engineering.[1] I always begin the very first lecture with the following statement, "I am going to present an analogy to an optical system. This is a system that you have all used, and many of you probably own."* I then ask students to guess the optical system represented by the analogy,[2] which, as you have seen, describes a plane flying in a flight path with very tight specifications.

Everyone loves a puzzle, so this is a great way to start any class, but the reason that it takes students time to get the answer to this particular question is that most of them

*This used to be true when I started teaching this course in 2005!

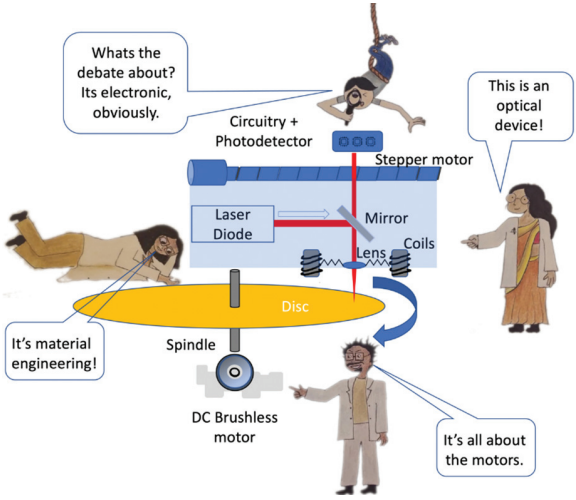
don't think of the CD pickup as an optical device. To be fair, I teach the course in the Department of Electrical Engineering. Most of the students are training to be electrical engineers, and the others are from departments such as Mechanical Engineering, Engineering Physics, Engineering Design, etc. For many students, their last encounter with optics would have been in high school. Whatever the reason, not surprisingly, most students classify the CD player as an electronic device. And that is another reason I love using this example—because that classification isn't wrong; the CD pickup is an electronic device. (Who am I to argue with Wikipedia?[3])

The ensuing discussion always reminds me of the story of the Six Blind Men and the Elephant.[**,***] Some students will insist that the CD player is an electronic device with some optics in it, and others will argue the reverse; the few mechanical engineers in the class, who probably never thought about the innards of this system before, start to wonder aloud about all the nifty little mechanical devices and motors in it. The class has just started, and a healthy discussion is already in progress, which sets the tone for the entire course. This is a good way to begin any class, but the great thing about teaching optics is that there is no dearth of examples of devices that students have used, or optical phenomena they have personally witnessed, that can kickstart such conversations. In addition, the CD pickup very quickly conveys to students the idea that "optical" systems are rarely purely optical. Most students electing to take this course probably already understand that optical systems are quite interdisciplinary. This particular example reinforces the importance of this diversity in a very elegant way. And isn't that the power of optics? Optics is used in so many systems today—and

[**]The full poem, called "The Blind Men and the Elephant" by John Godfrey Saxe (1816–1887) can be accessed at https://www.extension.iastate.edu/4h/files/page/files/The%20Blind%20Men%20and%20the%20Elephant.pdf.

[***]The scientists in the figure "Six Myopic Engineers and the CD Player" were drawn by my daughter, Sumitra Bhattacharya.

we're not talking about the obvious ones like cameras and microscopes. From easing our lives by giving us the ability to flick channels from the comfort of our armchair to the small but life-saving pulse oximeter, optics is quietly revolutionizing the world. I end that first class by telling students that this course will equip them to speak the language of optics and allow them to be part of this revolution.



Six myopic engineers and the CD player.

The first CD players were sold in 1982. And while some labs or fabrication facilities still insist on using only CDs as storage devices (no pen drives allowed!), and music CDs sold more than expected in 2021, it's probably time to change this example. I think the smart phone will be a wonderful system to use. I just need to find an analogy as impressive as the CD–airplane one. Any suggestions?

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1. https://nptel.ac.in/courses/108106161
2. https://www.repairfaq.org/sam/cdfaq.htm
   Note: While the main idea of the analogy is taken from this reference, I've modified the numbers using a linear conversion scale. In the end, the exact numbers used are not that important, except to highlight what a difficult task this is.
3. https://en.wikipedia.org/wiki/CD_player

Bent Seesaw

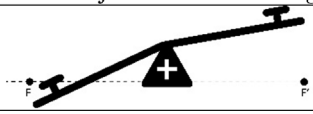
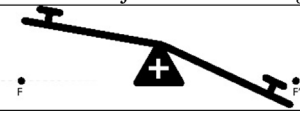
Jim Schwiegerling
The University of Arizona, USA

John taught geometrical optics to multiple generations of graduate students. For several of those years, I taught the undergraduate version of his course. We had many discussions regarding teaching the material. While we could never agree on the correct way of writing the imaging equation, we did agree that the students who struggled with the material seem to struggle with the most fundamental concepts. Lacking the proper foundation meant that these students were lost with more advanced concepts. Many of our discussions were coming up with easy visualizations for this fundamental material. One of John's favorites was the bent seesaw.

The bent seesaw is a visualization to illustrate the object and image locations. While these relationships are easily determined from the imaging equation, students may have difficulty visually analyzing a system, especially when the object or image is virtual. For positive-powered lenses, the seesaw is bent such that, when the left side is horizontal, the right side is bent toward, the ground as shown below.

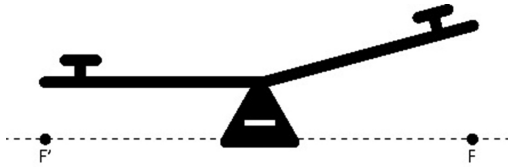


The planks of the seesaw schematically represent the upper marginal ray before and after the lens. The lens serves as the fulcrum of the seesaw. The optical axis lies along the ground plane, with the front and rear focal points placed as shown. In this particular case, the left plank is horizontal, so the object is located at infinity. The right plank is bent downward, passing through the rear focal point.

Real Object / Real Image	Object at F / Image at ∞
	
Real Object / Virtual Image	**Virtual Object / Real Image**
	

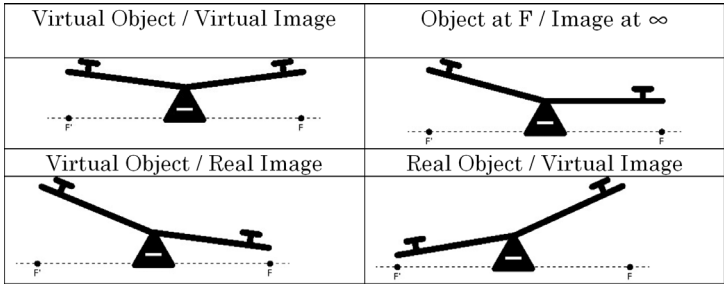
As the seesaw tips through different angles, the object and image locations follow from the orientations of the left and right planks. When the left plank is tilted downward, the object is real. If the right plank is tilted downward, the image is real. If the object is to the left of the front focal point, the real image is to the right of the rear focal point. If the object is to the right of the front focal point, the virtual image is to the left of the front focal point. From these illustrations, the various object/image relationships are easily visualized for a positive-powered lens.

For a lens with negative power, the seesaw simply needs to be bent in the opposite direction. When the left plank is horizontal, the right plank is now bent upward to appear as if it is angled toward the rear focal point (which is now on the left side).



Tilting the seesaw now gives the various combinations of object and image relationships. As the left plank moves up, denoting a virtual object, the right plank moves down, giving a virtual image. When the left plank appears to pass through F, the right plank is horizontal. Further raising the left plank now tilts the right plank downward to give a

real image. Tilting the left plank downward means that a real object is formed with a virtual image to its right.

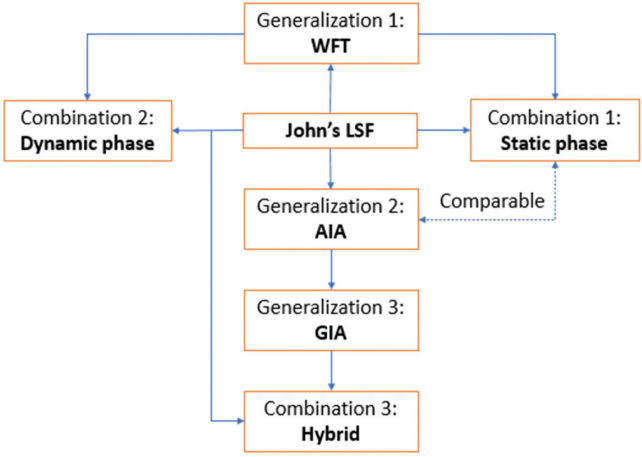


As I take over John's class in the Fall of 2022, I only hope that I can match his dedication and enthusiasm. His efforts will be continued.

Phase Measurement: Simplicity, Beauty, and Uncertainty

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In 1997, Kemao started his PhD study on phase measurement for precision engineering. He initially knew of Dr. John Greivenkamp's work through his 1984 paper.[1] (Kemao finally met John at the SPIE Optics + Photonics Conference in San Diego in 2014.) This paper used least-squares fitting (LSF) for phase estimation from phase-shifted fringe patterns with random and known phase shifts. The simplicity and beauty of this three-page article make it a classic work. The idea to use LSF influenced Kemao's work implicitly and explicitly. Some of his related works are depicted in the flowchart and described in the text as three generalizations and three combinations.



Some related works on phase measurement.

Generalization 1: Kemao proposed using the windowed Fourier transform (WFT) for fringe pattern analysis such as phase extraction and denoising. It was later found that the WFT is a maximum-likelihood estimator, and it turned out to be a LSF in a very general sense.[2]

Generalization 2 vs Combination 1: In John's work, the phase shifts need to be known. Wang and Han proposed the advanced iterative algorithm (AIA), which essentially used LSF alternatively for phase estimation and phase shift estimation until converged, and thus was applicable for unknown phase shifts.[3] Later, Kemao et al. combined WFT with John's LSF to achieve the same goal, where the WFT and the LSF were responsible for phase-shift estimation and phase extraction, respectively.[4] In general, the phase is static since phase shifting is involved.

Combination 2: The WFT and the LSF were combined again, in a slightly different way, to extract a dynamic phase from a sequence of fringe patterns in a frame-wise manner, where the WFT and the LSF were responsible for phase denoising and phase extraction, respectively. A unique feature of this method is that neither phase shifting nor a carrier was needed during this process.[5]

Generalization 3 and Combination 3: The AIA's convergence and accuracy are uncertain when various error sources are present. Yuchi Chen (the second author), in his 4 years of PhD study starting from 2018, worked on this problem. The convergence was confirmed through thousands of simulations; the error sources were handled by the proposed general iterative algorithm (GIA),[6] and more interestingly, the phase-shifting algorithms for known and unknown phase shifts were integrated as a hybrid solution.[7] We had the goal of making the GIA a simple and beautiful framework, and indeed we accomplished this. However, we still need to see how it works in other applications, which is a new uncertainty for us to address.

The pursuit of simplicity and beauty and the emergence of uncertainty has been consistently encouraging researchers to move forward. John was one of these researchers.

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Writing a Good Scientific Paper

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Learning to write a high-quality paper benefits both the writer and the reader, and is thus a useful part of graduate-level education in science and engineering. Fortunately, you do not have to be a good writer to write a good science paper, but you do have to be a careful writer. Typically, writing for a peer-reviewed journal requires learning and executing a specific formula for presenting scientific work, with the goal that readers will judge it by the quality of the science rather than the quality of the writing. That formula begins with the structure of the paper, and most papers follow the "IMRaD" format: Introduction, Method (materials, experiment, theory, design, model), Results and Discussion, Conclusions.

Introduction: What is the paper about, and why should the reader care? To answers these questions, the introduction should cover the scope, novelty, and significance of the work. Writing from the general to the specific, establish a territory (what is the field of the work, why is this field important, what has already been done?), then establish a niche (indicate a gap, raise a question, or challenge prior work in this territory—pose the research questions), and finally occupy that niche (outline the purpose and announce the present research). Avoid unnecessary background (things you can assume the intended audience already knows) and avoid exaggerating the importance of your work.

Method: Describe how the results were generated, with sufficient detail (including citations) so that another in the field can validate your conclusions. Internal validity means that the conclusions drawn are supported by the results presented. External validity refers to the degree that the conclusions can be generalized (rather than being applicable only to the narrow confines of this one work). Avoid including results in the method section, extraneous detail, or treating the method as a chronological history of events.

Results and Discussion: Present the results, organized to make them as accessible as possible to the reader, clearly indicating what is new to this work. Evidence does not explain itself. The purpose of the discussion section is to explain the results and show how they help to answer the research questions posed in the introduction. This discussion generally passes through the stages of summarizing the results, discussing whether results are expected or unexpected, comparing these results to previous work, interpreting and explaining the results (often by comparison to a theory or model), and hypothesizing about their generality. Avoid presenting results that are never discussed, discussing results that are not presented, ignoring results that do not support the conclusions, or drawing conclusions from results without providing sound logical arguments to back them up.

Conclusions: Provide a very brief summary of the results and discussion, showing how each research question posed in the introduction has been addressed, then explain how the work is significant. The goal here is to provide the most general claims that can be supported by the evidence. The conclusion should concisely provide the key message(s) the author wishes to convey. Avoid repeating the abstract, repeating background information from the introduction, introducing new evidence or new arguments not found in the results and discussion, repeating the arguments made in the results and discussion, or failing to address all of the research questions set out in the introduction.

There are, of course many other considerations in writing a good scientific paper, but the most important one is to be reader-focused. Think always about serving the needs of the reader. Only then will your paper go beyond that and serve your needs as well.

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Exciplexes and Excimers and the Importance of Calling Them by Their Proper Names

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Research on electronically excited supermolecules *exciplexes* and *excimers* and their applications continue to fill the pages of scientific and technical journals and books, especially those dealing with laser systems, including those published by SPIE. One cannot help but notice some confusion and inconsistency in the nomenclature of these excited supermolecules. Unfortunately, *excimer* has become the generic term used to broadly describe these excited supermolecules, especially in technical publications in optics and related fields. The error and confusion arise primarily from sloppiness and a lack of understanding of the roots of these terms and thus their true meaning.

The precision required in science in the accurate naming of objects in the natural world underscores the need for rational scientific nomenclature. As a system of names or terms, or the rules for forming these terms, rational scientific nomenclature has always been instrumental in the development of scientific fields. It facilitates the reproducibility of experimental results, which is a central pillar of the scientific method. Standard scientific nomenclature also ensures that everyone is reading from the same page. This explains why today we have internationally adopted codes of nomenclature governing specific scientific disciplines ranging from biology to chemistry to physics to astronomy. For biology, we have the Linnaeus system of binomial nomenclature for biological species. For chemistry, we have the International Union of Pure and Applied Chemistry nomenclature for chemical elements and compounds, as well as for uniform definitions and description of chemical principles. For physics, we have the Système Internationale (International System) (SI), otherwise known as the metric system for measurements of physical quantities and their definitions. For astronomy, we have the International Union of Astronomy nomenclature for official names and designations of astronomical

objects, as well as for uniform definitions for astronomical principles.

I believe the time has come to open a discussion on the adoption of the proper nomenclature for electronically excited supermolecules in publications in optics and related fields. What better place to initiate this discussion than SPIE's *Field Guide to Education of Optics*: *A Tribute to John Greivenkamp*, a book with a focus on optics education? Were he alive today, I believe that Prof. Greivenkamp would be in support of this proposal. Accounts by people who knew him personally attest to his vehement argument over specific language and wording in scientific writing in general and the Field Guide series in particular. Given the extensive applications of ultraviolet lasers (see the table) made possible by these excited supermolecules, this publication offers a potential opportunity to begin this discussion. Some of these ultraviolet laser-based applications include deep-UV lithography, optical microscopy, and micromachining, to mention but a few.

Examples of exciplex and excimer lasers in use in optical technologies.

Laser type	Excited-state complex	Characteristic spectrum	Emission wavelength (nm)
F_2	Excimer	UV	157
ArF	Exciplex	UV	193
KrF	Exciplex	UV	248
XeCl	Exciplex	UV	308

In chemistry, the word *complex* is used to describe an association of molecules. Just as a molecule is an association of atoms, a complex is an association of molecules, and the word *supermolecule* may be appropriately used when the association energies are relatively large. A dimer is a diatomic molecule in which the two constituent atoms are identical. The association of an electronically excited

molecule *M** with a ground-state molecule *N* leads to an exciplex (*exci*ted comp*lex*) if $N \neq M$, or leads to an excimer (*exci*ted di*mer*) if $N = M$:

$$M^* + N \rightleftharpoons (MN)^* \quad \text{(exciplex)}$$
$$M^* + M \rightleftharpoons (MM)^* (\text{or } M_2^*) \quad \text{(excimer)}$$

The term *exciplex* is therefore the recommended general term for all electronically excited complexes, while *excimer* is a special case of exciplex when the excited and ground state species are identical. A laser in which the lasing species of the excited-state complex is a dimer, such as F_2, is correctly called an excimer laser, while that in which the lasing species of the excited-state complex comprises two heteroatoms, such as ArF, KrF, or XeCl, is appropriately called an *exciplex laser*. The lasing mechanisms of these systems have been described in the literature.[1–5]

Finally, accuracy in scientific and technical publications in optics and related fields should not only be about the actual experimental results; it should also include the use of the proper nomenclature of the involved electronically excited supermolecules—be they exciplexes or excimers. This will prevent unnecessary confusion and inconsistency.

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Advances in 3D Human Face Imaging and Automated Facial Expression Analysis

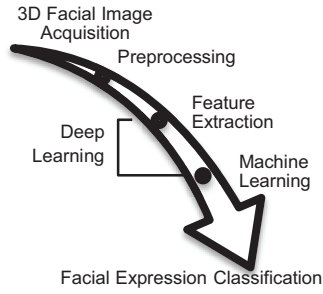
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Ubiquitous to interpersonal communication and more universal than language, human facial expressions have been a source of intrigue since the time of Darwin. Widespread applications in psychology, medicine, education, marketing, security, human–computer interactions, and more have motivated decades of research in automated facial imaging and facial expression analysis (FEA). Among many promising methods, FEA using constituent action units (AUs) has gained attention. Advances in modern sensing offer rich 2D and 3D facial imaging data that are amenable to automated FEA. Recent advances in sensing and machine learning (ML), and specifically deep learning (DL) methods, offer advantages in processing 3D imaging data. Thus, sensing and analysis of 3D expressions has emerged as an active multidisciplinary area for optical and digital information processing education and research.



Stereophotogrammetry is the use of multiple photographic imaging measurements to estimate the 3D coordinate points of an object, such as a face. Modern 3D stereophotogrammetric imaging systems represent the facial surface with near–ground-truth dense point clouds. These point clouds often undergo preprocessing steps such as 3D image registration and normalization followed by feature extraction from the 3D point cloud data. In a traditional ML pipeline, feature engineering is performed to compute geometric features (such as 3D curvature features) and spatial features (such as geodesic distances between facial landmarks). The features are subsequently input into ML models, such as *k*-nearest neighbor or support vector machines, for learning and classification. By contrast, DL models learn feature extraction and classification steps directly from the data. Different types of DL

models require different input representations for the 3D facial data. Common representations include 3D occupancy grids for models such as 3D convolutional neural networks (CNNs), 3D meshes for graphical CNNs, and raw point clouds for PointNets.



Teaching 3D FEA occurs best through hands-on experiments that apply theory to solve real problems. Advances in imaging technology, processing power, and storage capability have opened the doors for experiential learning opportunities in sensing and processing of 3D data. There remain many exciting open research areas for students and researchers. Powerful ML/DL methods have proved promising for robust AU-based analysis of neutral, happy, sad, and surprised expressions. However, expressions of fear and anger, with confounding subtle and co-occurring AUs, remain challenging. Current state-of-the-art 3D imaging and FEA methods still have a long way to go before they are ready to address the challenges of real-world applications such as automated expression analysis in autism intervention. Furthermore, due to large-scale variations in 3D data, existing methods fail to generalize to subjects outside of the training set. Overcoming these exciting challenges will be the next frontier to expanding 3D FEA beyond the laboratory and into real-world applications.

Notes on Photonic Concepts and Ideas vs. Algebra

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Photonics is a fascinating subject, principally because it is the only branch of physics that we can see! There are also countless useful equations, which tend to dominate the teaching process. However, the fact that we can see light is a powerful tool in teaching, understanding, and using photonics. Among the phenomena we can see and use, we have scattering of light and diffraction, focusing of light, and reflection and refraction. Let's spend a little time exploring a few examples. We also need a few kit pieces to illustrate concepts. A laser pointer can be used for much more than putting a dot on a projector screen, and a magnifying glass is also a very good contributor.

In a homogeneous medium, light obligingly travels in a straight line. Usually, the air we breathe is homogeneous enough to make the point—although even shining your laser pointer through a darkened room illustrates that we can, after all, see scattered light, which tells us where the laser beam is traveling. This is a very useful accidental tool by which to visualize light rays and trace the path they take.

The same tool—the laser pointer—also obligingly illustrates refraction at media interfaces, diffraction gratings, and the impact of a variety of diffracting media, for example, some thinly woven cloth; there's some in every household. You'll very easily see the impact of spacing on direction. Stretch some partially transparent cloth—your shirt or blouse, for example—and see how the diffraction angle changes as the tension increases and/or changes direction.

Refraction is a little more evasive—simply because you're really looking for a change in the direction of a light beam as it reaches an interface. However, a little imagination soon gives some straightforward examples. Even a pane of glass can give some insight when light is incident at an angle to the glass surface then that angle changes by the

amount by which the beam moves—including incident perpendicular to the surface when the beam doesn't change direction at all!

These are but a few examples of how the essential concepts of optics—reflection, diffraction, and refraction—can be readily demonstrated using everyday equipment. It also helps all concerned to see and expect the results of an illumination source on the object you see and the light reflected or scattered from it. The general idea is to raise awareness among all concerned of the simple observation that the sometimes apparently complex concepts of optics are in the everyday environment. See the light!!!

The see-to-teach-and-use factors:
See:

- Light travels in straight lines except for scatter and refraction.
- Scatter can be seen in even slightly dusty, but otherwise transparent, media.
- Refraction can be seen, too.
- Color and color changes—combinations of material and illumination—can be perceived.

What's needed as tools?

- a visible laser
- dust to create scatter
- vapor from which to scatter to see light beams
- a focused torch or similar light source

A Classical Approach to Teaching Light–Matter Interaction

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One of the authors (EVS) had a teacher in his third year of college who said that the most important problem in physics was the simple-harmonic oscillator (SHO). As the years have gone by, the truth of his statement has continued to be reinforced. Teaching a course on the interaction of light with matter can be greatly facilitated by spending considerable time teaching aspects of the damped, driven SHO. Modeling matter as "electrons on springs" provides remarkable insight into absorption and refraction in atomic/molecular/semiconductor/dielectric materials:

$$m\frac{\partial^2\vec{r}(t)}{\partial t^2}+\Gamma m\frac{\partial\vec{r}(t)}{\partial t}+m\omega_0^2\vec{r}(t)=-e\vec{E}(t),\ \text{with solution}$$

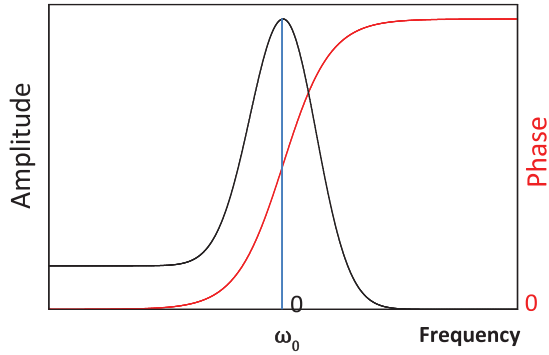
$$\vec{r}(\omega)=-\frac{e}{m}\frac{\vec{E}(\omega)}{\omega_0^2-\omega^2-i\omega\Gamma}$$

When teaching a course in this area, it is useful to include in the first lecture a computer simulation of the solution of the SHO equation of motion. Rather than focusing on the temporal growth of the oscillator versus time after a harmonic force is turned on (e.g., turning on a laser), we show several aspects of the steady-state solution while varying the frequency of the driving force. This shows the amplitude and phase with respect to that of the driving force of oscillation going through resonance. Using this model for electron displacement (or nuclear displacement for vibrations) allows for calculation of the polarization $\vec{P}(\omega)=-Ne\vec{r}(\omega)$ with the electron density N, giving the optical susceptibility:

$$\chi(\omega)=\frac{Ne^2}{\epsilon_0 m}\frac{1}{\omega_0^2-\omega^2-i\omega\Gamma}=\frac{\omega_p^2}{\omega_0^2-\omega^2-i\omega\Gamma}$$

Along with the relationship $\epsilon(\omega)=1+\chi(\omega)$ this allows for discussion in some detail of the complex Lorentz optical susceptibility, absorption and refraction, 2-level atoms and

optical transitions, Lorentzian line shapes, polarization, metals and Drude theory, vibrations, plasma frequency, and the dielectric function from which we can calculate the transmission, reflection, and absorption of some sample material. Some key points about $\chi(\omega)$ are (see figure):



1. The maximum amplitude is in resonance at $\omega \approx \omega_0$ and is purely imaginary.
2. At resonance, the phase difference between **E** and **r** is 90 deg.
3. At high frequencies ($\omega \gg \omega_0$), the amplitude of $\chi(\omega)$ goes to 0.
4. At low frequencies ($\omega \ll \omega_0$), a finite real amplitude of ω_p^2/ω_0^2 is obtained.

Once this model has been discussed for bound (Lorentz) and free (Drude) electrons, we extend it to vibrations in molecules and phonons in crystals, which are again closely related to the SHO. The model even extends to the modes of cavities (e.g., to describe the density of states in semiconductors/dielectrics) and thus black-body radiation. And this model can be easily extended to nonlinear optics by adding a small term in the restoring force that is proportional to a higher-order of **r**, e.g., $\mathbf{r}^2$.

These models allow for discussion of other concepts, such as local field correction factors, Kramers–Kronig relations, Sellmeier equations, etc. It is remarkable that so much of

light–matter interaction can be described without the need for quantum mechanics. Although many of these approaches can occasionally be found in condensed matter or spectroscopy texts, there are a few textbooks on light–matter interaction that follow this approach, notably Hopf and Stegeman,[1] Wooten,[2] and Fox.[3]

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Laboratory Courses as the Foundation / Pillars of Optomechnical Engineering

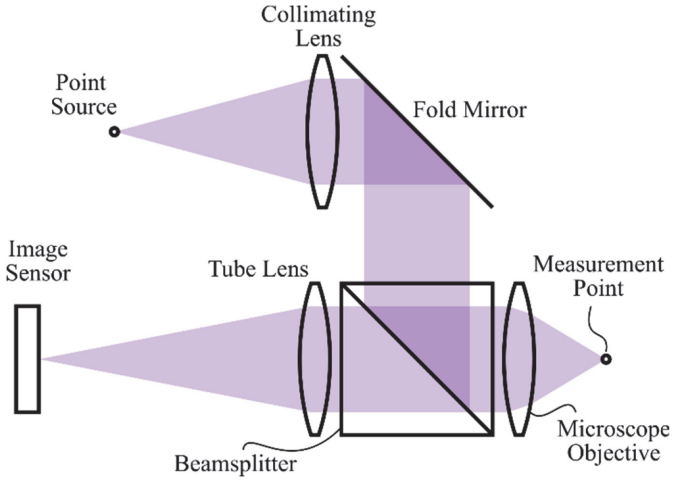
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Learning practical concepts requires getting outside one's comfort zones. Often, learning by doing, such as in laboratory classes, can cement concepts that are first introduced in lecture courses. However, a concept need not necessarily be taught in a lecture first or from first principles. Rather, the application of concept often necessitates understanding broad concepts that are related and can only be fully understood by *doing*. Two examples of this are learning in laboratory classes and learning cross-disciplines such as optomechanical engineering.

In laboratory classes, building and aligning a simple Michelson interferometer or point source microscope using benchtop components can take hours. Those hours are not lost, rather they are used to understand mounting the optics, or the painstaking process of alignment, or the sensitivity of one degree of freedom over another. It may seem frustrating at first, but these are skills that are only fully realized by physically performing them. Similarly, immersing oneself in a new disciple can be painstaking at first. But learning and understanding a few key concepts can build a foundation for future success.

Laboratory Courses as the Foundation

Laboratory courses require more resources to educate students effectively, from equipment, software, and space to instructors, and time. Building a relatively simple optical device, a point source microscope (PSM), can be used to impart many optical concepts and can be accomplished with generic, off-the-shelf components and several key laboratory devices.



The first step in building a PSM is beam collimation from a simple fiber source. This can be accomplished with a shear plate, which also demonstrates interference. The focus through the beam is found by placing a mirror at the measurement point, demonstrating retroreflection.

The reflected beam through the beamsplitter can then be collimated again with the shear plate by correctly aligning the mirror to the measurement point. Lastly, a tube lens is aligned to achieve the smallest focal point.

This can be easily expanded or modified for other concepts. Adding a mirror on the beamsplitter and removing the tube lens changes this to an interferometer. And each of these systems can be reinforced via first-principles calculations and then modeling and analysis can be performed with optical design software!

Pillars of Optomechanical Engineering

Summarizing another discipline, mechanical engineering, such that optical engineers and scientists can utilize key information, is a difficult endeavor. Nomenclature, variable notation, and common abbreviations are some of the issues faced when crossing disciplines. For example, the acronym TIR to many in the optics industry is total

internal reflection. But TIR can also readily refer to total indicator runout for lens centering, metrology, and manufacturing. Understanding the language across disciplines is the first step to branching out to new fields.

For optomechanical engineering, many concepts are required to truly master the discipline. However, many of those concepts can be distilled into three different concepts that form the pillars of optomechanical engineering and affect optical and mechanical components alike.

Everything is a spring. No component has infinite material stiffness, and geometry can affect the compliance, even for supposedly large, rigid bodies.

$$\Delta L = \frac{F}{k}$$

ΔL: displacement
F: applied force
k: stiffness

Everything is a thermometer. Every component has property changes (dimensional, optical, etc.) as a function of temperature.

$$\Delta L = \alpha L \Delta T$$

α: thermal expansion coefficient
L: length
ΔT: temperature change

$\frac{dn}{dT}$ Refractive index changes as temperature changes.

Whatever happens mechanically will be imprinted on an optical wavefront. Optomechanical Engineering is the discipline of understanding and mitigating the impact of mechanical effects on optical systems.

Reminiscences



Desert Flower, Sphere and Antique Optics Equipment (photo credit: Wyant College of Optical Sciences, University of Arizona).

Education in Optics—John's Way

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I came to know Prof. John E. Greivenkamp 30 years ago through his paper on interferometric fringe analysis for aspheric surface measurement, when he was affiliated with the Eastman Kodak Company. During those days, I was also involved in developing an automatic aspheric surface measurement system based on interferometric fringe analysis. John's ideas helped me a lot in my understanding of interferometric fringe analysis.

I then met John at the Optical Sciences Center of the University of Arizona in the early 2000s. He was happy to share his ideas on optical surface testing using interferometric methods, Shack–Hartmann sensors, etc., with me. Later, in several optical conferences, I observed John as an energetic force, fully engaged at all times. By then, he had already established himself as a successful educator. I was elected as a SPIE Board member in 2011, when I had a chance to witness an entirely different dimension of John's activities. By then, John had already completed many hours as an SPIE Board member and authored several SPIE journal articles and books, including the first of the popular *SPIE Field Guides*, for which he served as Series Editor.



John at the Spark Museum of Electrical Invention, Bellingham, Washington, during a 2014 SPIE Board meeting.

Later, in 2012, I invited John to the Utsunomiya University Center of Optical Research and Education (CORE). CORE was founded by me in 2007 with the purpose of promoting education and research in the field of optics. My vision was to develop CORE into a global center for optics education and research. The College of Optical Sciences (OSC) in Tucson, Arizona was our model, and the Dean of the OSC at that time, Prof. James C. Wyant, fully understood our mission and supported our activities. During John's stay at CORE, he delivered several lectures on optical measurement and the history of optics.

The most impressive of John's lectures that I remember was "The History of Telescopes and Binoculars," which he gave at the Utsunomiya Girls' High School. Most of the audience was high school girls who had no prior knowledge of optics. John started, "How do lenses work?" and then continued with the story of the invention of the telescope early in the 17th century, including an interesting incident on a telescope patent.[1] The story John narrated was the following: In the early 1700s, it was believed that chromatic aberration was very fundamental in its origin and could not be corrected. A Barrister in London named Chester Moor Hall had then thought of a solution: the achromatic doublet. In 1733 he commissioned two different opticians, Edward Scarlett and James Mann, to make one lens element each. By chance, both opticians subcontracted the work to the same man, George Bass. Chester Moor Hall then continued to keep his invention a secret. Around 1750, George Bass told John Dollond about the achromatic lens he had made, or at least the fact that different glasses have different dispersing powers. Dollond then began a series of experiments using different types of glass. Dollond's son, Peter, saw the potential commercial advantages and patented the invention in 1758 once they succeeded in making test lenses. Chester Moor Hall twice attempted to challenge the patent. He lost his case on the grounds that, 'the person who should be profited by an invention is the one who benefits the public by it, not the one who keeps it locked in his desk drawer.'

This was a landmark decision in patent law that remains in place to this day. Dollond went on to become the dominant manufacturer of telescopes in the late 1700s and early 1800s. In fact, the name *Dollond* became a synonym for *telescope*.

John also emphasized how difficult it was to make binoculars at that time. Toward the end of his lecture, he presented his collection of antique optics, including telescopes, microscopes, binoculars, etc., which are currently displayed in the Museum of Optics at the OSC. His lecture was so impressive that the girls pounded John with many questions and became involved in an active conversation, which is very unusual for Japanese girls. "What is light?" was one of the most serious questions raised, and John answered, "It is a very good question. Um.... Um.... A kind of wave, sometimes a particle."

John's lectures were always prepared with the ingredients necessary to stimulate a student's interest. He strongly believed that, once students' interest is piqued, there after they will continue to grow and explore unknown territories in optics with much ease. This was John's approach toward optical education, which I too practiced in my teaching profession and found to be extremely successful. John lived a life that reflected his commitment to optics and education; his life story is a model for many optical enthusiasts to follow.

Reference

1. F. Watson, *Stargazer: The Life and Times of the Telescope*, Da Capo Press (2005).

A Shared Passion for Optics Education: John Greivenkamp and Harrison Barrett

Kyle Myers
Puente Solutions, LLC, USA

John Greivenkamp was a passionate educator, recognized for his outstanding teaching by SPIE awarding him the 2017 SPIE María J. Yzuel Educator Award. John and I were mentored by another passionate educator, arguably one of the best in optical sciences, Dr. Harrison H. Barrett of the University of Arizona's College of Optical Science. Harry's impact on imaging science was largely due to his dedication to teaching and his mentoring of graduate students. His teaching extended far beyond the classroom, too. His questions at the microphone during a conference were known for being mini-tutorials that brought clarity and depth to the discussion. His many lectures at conferences and institutions around the world built a far-reaching community of imaging science enthusiasts. During his years at the University of Arizona, Harry taught more than 20 different courses and was the advisor for over 75 graduate students. When students would ask him whether they should work in industry, national labs, or academia, Harry would quickly tell them that it depends on how they personally measure success—as for himself, he kept score by the number of dissertations produced in his group, not by money.

Below are some of the lessons John and I learned from Harry Barrett regarding how to be an outstanding teacher, mentor, and influencer in imaging and optical sciences:

1. Keep teaching fresh. Harry brought great enthusiasm to each course he taught and put considerable effort into his preparations for each class. Regardless of the number of times he taught the material, he insisted on generating new teaching notes for each class to ensure that his presentations were fresh.
2. Be rigorous and strive for clarity. Harry brought rigor to all the courses he taught and the research he led. His books paid incredible attention to detail both in his

efforts to be comprehensive regarding the topics he covered as well as attention to minute aspects of notation. Harry was a master of theoretical information transfer, i.e., the science of determining what information is transferred through an imaging system. He was also a master of practical information transfer, meaning the practice of developing presentations, course materials, and publications that successfully transferred information to his audience.

3. Be inclusive. Harry's research group was one of the first to include women and other under-represented students. He was intentional in the way he shared his diverse, international network of colleagues and collaborators with us, too. Attending a conference with Harry was an invigorating experience, as he included his students in wide circles of scientific conversation and networking.
4. Students deserve second chances (and sometimes one or two more!) as well as the support to turn those defeats into success. I observed many students who, after experiencing failure with prelims or lack of success in working with an advisor, were offered not only a second chance by Harry, but also Harry's personal time spent helping to prepare the student for that next prelim round or research experience. The lifeline he offered to so many made the difference between their dropping out vs. going on to successful careers in optical science.
5. Give back. Harry and his wife Cathy generously established the Harrison H. and Catherine C. Barrett Endowed Chair in Optical Sciences for Cancer Imaging as a mechanism for supporting a faculty member with interests in cancer imaging. There were other ways in which Harry supported students, post-docs, and professional societies through generous donations. John Greivenkamp's own generosity in gifting scholarship funds and his optical instrument museum to the College of Optical Sciences are similarly inspiring and will have a lasting impact on future faculty and students at the University of Arizona.

Harry Barrett had great passion for his life's work as a researcher and educator. He was also a deep lover of life and adventure outside of work, traveling around the world and trekking across England, around Ireland, and up past Everest base camp with Cathy. He gave us a very real and alive example of living life to the fullest in and out of the lab. I see many, many parallels in John's love of optics, of the University of Arizona and SPIE, of students, of travel, and of his family. He learned from one of the masters!

Chamblant Lenses, Astigmatism, and Cylindrical Lenses

Vasudevan Lakshminarayanan
University of Waterloo, Canada

A few years ago, John Greivenkamp and I collaborated on a small project. The project directly incorporated geometric optics and optics history and dealt with visual optics, all three areas of great interest to John. An ophthalmologist in Pennsylvania, who is also a historian, contacted me about a pair of spectacles which consisted of Chamblant lenses and wanted to study the optical properties of the lenses.

The Chamblant lens consists of two joined lenses and is named after a French optician, Marie-Nicolas-Joseph Chamblant (1772–1841). The lens had originally been developed by Pierre Galland (1757–1837), and it appears that Chamblant fabricated the lens and both of them received a patent for "mirrored glasses and heliophlogic and optical instruments made from a new system that destroys spherical aberrations and can be used for heating apartments and the melting of metals, etc."[1] An English architect, Thomas Stedman Whitwell (1784–1840), studied this lens and concluded that, "The most highly advantageous result of this new system of dioptrics is the complete destruction of the aberrations which arise from the sphericity of the lenses of the old system, and by which the images of objects are so very considerably deformed."[2]

An ophthalmologist sent me a spectacle pair that had Chamblant lenses (see 1st figure), and I procured biconvex lenses (reading spectacles) from a retail store. Basic measurements were made (such as power, curvature, etc.). Since I did not have a Fizeau interferometer, I sent them to John, who readily agreed to make other measurements. Based on our measurements, we concluded that the two lenses making up the Chamblant lens were of excellent optical quality, with better performance than mass-produced modern lenses, and the Chamblant lens was a cross-cylinder lens.

The discovery of ocular astigmatism opened up a whole new need for cylindrical lenses, but astigmatism was not routinely corrected until the late 19th century. In 1825 George Bidell Airy first described his own astigmatism and its correction by cylindrical lenses. In fact, it was Airy who named the condition *astigmatism*, a term suggested by his colleague William Whewell in 1846. It should be noted that Thomas Young had described his own astigmatism in 1801 but did not suggest a cylindrical lens to correct it; he recommended tilting a spherical lens. The first cylindrical lenses for spectacles prescription were developed in 1828 by John McAllister in Philadelphia. A brief timeline is shown in the table.

In a cross-cylinder, the cylinder axes of the two lenses are perpendicular to each other. In fact, George Stokes (1849) developed a cross-cylinder lens to correct his own astigmatism. The Stokes lens is a variable-power astigmatic lens comprising, in its standard version, two pure cylindrical lenses of equal but contrary power that rotate in opposite directions. The Jackson cross-cylinder is used in modern-day clinical practice to refine refractive correction.

Our results from the Chamblant lens project can be summarized as follows:

- Chamblant lenses show a small amount of residual astigmatism/cylinder with a smaller amount of coma. The residual cylinder is likely a result of the two surface cylinders having very slightly different radii. The tiny amount of coma was likely due to the two cylinders not being exactly at 90 deg.
- Chamblant lenses have about 5 wavelengths of residual cylinder (about 0.04 D), which not is clinically significant.
- The wavefront data showed no sign of spherical aberration correction. In fact, it is not practical to correct spherical aberration (SA) with spectacles. While you could correct SA for a straight-ahead gaze by adding an r^4 shape to the lens, as soon as the eyes

look even slightly to the side, significant coma will result. This is why even today we do not correct SA with spectacle lenses. SA correction with contact lenses can be used because the lens is "fixed" on the eye and the eye always looks through the same part of the contact lens. In general, a spectacle lens has an r^2 shape. When the eye's gaze moves away from straight ahead, prism results. The line of sight is deviated but by the same amount in both eyes. There could be an issue if the prescriptions for the two eyes were wildly different.

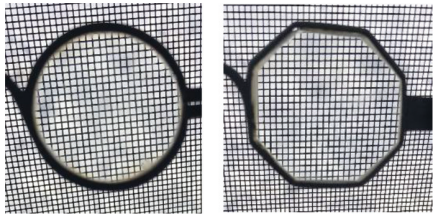
- There is no chromatic aberration correction.
- Spherical lenses have even slightly less residual cylinder.
- Clinically, Chamblant and spherical lenses are identical, and the user would see no visual difference (see 2nd figure).

Spherical aberration certainly exists in spherical lenses but, even in the early 1800s, it appears that grinding techniques were good enough to make it clinically insignificant; a spherical lens was about equal to a Chamblant lens in terms of quality—both were equivalent to a modern mass-produced reading lens. Chamblant lenses do nothing that spherical lenses do not do. We can think of absolutely no reason to make lenses that way. History has also proven this—the technology died almost instantly. So why should we study technical dead-ends? Knowledge of what worked and what didn't work gives insight into (and provides caveats to) further development of new technologies and therefore should be a part of science and engineering education.

This project incorporates John's varied interests in geometrical optics, visual optics, and optics history and provides a small example of his intellectual curiosity.



Spectacles with Chamblant lenses.



Imaging with (left) a spherical biconvex lens and (right) a Chamblant lens.

A brief timeline.

1722	Earliest mention of cylindrical lenses by John Marshall
1801	Young describes ocular astigmatism in his own eye.
1804	Galland sends a dissertation to the Athénée, a learned society, about "Heliophlogie," concerning the heating effects of lenses and mirrors described a new lens design later fabricated by Chamblant.
1813	Galland/Chamblant receive French patent for the "Chamblant" lens.
1815/ 1816	First mention of the use of these lenses in spectacles by Whitwell, in *Repertory of Arts, Manufactures, and Agriculture* (1816)
1824/ 1828(?)	Spectacles to correct astigmatism are developed by John McAllister.

1825	George Bidell Airy describes his astigmatism and correction with cylindrical lenses.
1846	Airy names the ocular condition as astigmatism.
1849	George Stokes develops a variable power astigmatic lens using cross-cylinders for astigmatism correction.
1887	Edward Jackson devices the cross-cylinder for subjective refraction, mainly in the cylinder axis and power refinement.

References

1. French patent, Arch. dep. des Deux-Sèvres, Fn-a 1513, Pierre Galland, Marie-Nicolas Chamblant, Patent of invention, Notice of the system of optics and heliophlogy, s.d. See also: Lamy, J. *Pratiques plurielles de la science: Pierre Galland de Cherveux, géomètre au début du XIXe siècle* (2012) Retrieved from https://journals.openedition.org/abpo/2328.
2. S. Whitwell, "Description of lenses of a square form stated to possess very considerable advantages over spherical ones," in *The Repertory of Arts, Manufactures, and Agriculture* Vol. XXVIII second series (1816) [In Number CLXIII of December, 1815 (pp. 13–19) London: Wyatt.]

Remembering John Greivenkamp

Larry C. Andrews
University of Central Florida, USA

I believe it was during the 1980s that I became a member of SPIE. There were only a handful of attendees at the first SPIE Orlando Conference I attended. Times have really changed since then.

I learned about SPIE's book publishing program during the mid-1990s from meetings I had with Eric Pepper, then the Director of Publications. He encouraged me to consider SPIE Press as my publisher if I had any ideas for writing a book, which I did. Later I worked with Tim Lamkins, then SPIE Press Manager, in the same capacity. During several discussions with Tim about writing a second edition of one of my books with coauthor and longtime friend Ron Phillips, Tim mentioned a new book series that SPIE Press was planning to launch. The series would be called *Field Guides*, and John Greivenkamp was to serve as the Series Editor.

Tim introduced me to John at one of the SPIE Symposia in 2002. The three of us sat around a table for some time, while John described in great detail his vision for the Field Guides. These were to be handy reference booklets of around 100 pages or so on a major field of optical science, with concise explanations of a particular topic provided in 1–2 pages. The books would have a spiral binding so that they could open and lie flat on a table for viewing without closing by themselves, as most textbooks tend to do.

John was a Professor at the James C. Wyant College of Optical Sciences at the University of Arizona. A project like this is something one might expect from a natural and seasoned educator like John. After listening to his enthusiastic vision of the *Field Guide* Series and hearing his suggestion that I write one in my area of expertise, I walked away knowing that I would write such a Field Guide.

John and I finished our Field Guides in roughly the same timeframe, and both were published in 2004 as the first and second in the Series. John's book was FG01 *Geometrical Optics* and mine was FG02 *Atmospheric Optics*. John later approved two more Field Guides that I wanted to write: FG18 *Special Functions* (2011) and FG22 *Probability, Random Processes, and Data Analysis* (2012), the latter with my coauthor Ron Phillips. John also accepted a second edition of my *Field Guide to Atmospheric Optics* (FG41), published in 2019.

My advice to new members of SPIE is to consider what knowledge you can pass along to your colleagues in the form of research papers and/or books. I've heard from many people over the years that "I can't write a book" or "I don't have enough time for that." **You can always make the time if you want**. Many of us have something to contribute to our particular area of expertise that will be useful to others. Don't be afraid to try—you might surprise yourself.

I didn't know John very well, having met him only a couple of times over the years. We lived on opposite sides of the country so our paths didn't cross very often. Nonetheless, I know that John Greivenkamp as Series Editor of the Field Guides provided a tremendous service to SPIE with this endeavor and an important and useful resource for the optical sciences community to enjoy for many years.

Getting the Word Out

Daniel Vukobratovich
Raytheon Missile Systems, USA

Providing an interchange of technical information within the optical engineering community is one of the most important functions of SPIE. In the early days, this interchange consisted of technical meetings and timely publication of the *Proceedings of SPIE*, the famous "yellow books." Later, the *SPIE Press Field Guide* series, with John Greivenkamp as Series Editor, became another highly accessible source of information.

A personal example shows the role of SPIE in spreading technical information. Thermal stress in bonded doublet lenses arising from the different thermal coefficients of expansions in dissimilar glass types often leads to fracture. Unfortunately, analyzing the thermal stress is difficult. Stress singularities at the element edges make computer-based finite-element analysis inaccurate.

An alternative analytical method sometimes attempted was to use classical "bonded plate" theory, usually without success. While working as a consultant on the design of an optical system employing many bonded doublets, I found a number of mathematical errors in the bonded plate solution. Once these errors were corrected, the solution worked well in predicting thermal stress. Later, I mentioned this to Paul Yoder, my good friend, co-author, and former head of the SPIE Publications Committee. Paul's immediate response was: "and you have not published?" I had signed a proprietary agreement when consulting, but this had long since expired.

So, in 2015 Paul Yoder and I published a joint paper on this topic: P. R. Yoder and D. Vukobratovich, "Shear stresses in cemented and bonded optics due to temperature changes," *Proc. SPIE* **9573**, 95730J (2015). The paper presentation was well received, and, as we had hoped, it served to inspire further analysis of the problem, with a paper published by other workers in the field just a few years

later. Our article is widely used and is a good example of the Society "getting out the word."



*Photograph of a bonded doublet fractured by thermal stress [P. R. Yoder, Jr. and D. Vukobratovich, "Shear stresses in cemented and bonded optics due to temperature changes," Proc. SPIE **9573**, 95730J (2015)].*

Optics at ICTP: Bringing Light to Students from the Developing World

Joseph Niemela
The Abdus Salam ICTP-UNESCO, Italy

It is a great honor to contribute to this SPIE Field Guide as a tribute to John Greivenkamp, whom I always admired for his ability to chair difficult meetings that would have sent others scurrying away, and for getting to the point quickly and often (not, unfortunately, like what is about to happen here).

First: A little known fact is that I started out as a graduate student in optics but was lured away early-on to a low-temperature group with the promise of a trip to Europe. I was "easy," I know. Ironically, while I eventually moved to Europe and the International Centre for Theoretical Physics (ICTP-UNESCO) in Trieste Italy, I also ended up being lured back into the wonderful world of international optics, largely due to people like John Greivenkamp and one particularly persuasive person at SPIE who also introduced me to The Clancy Brothers…

In Trieste, in fact, I have had the good fortune to work closely with major optics organizations within our Trieste System Optical Sciences and Applications (TSOSA) board. TSOSA provides critical advice, oversight, and support for ICTP-UNESCO's many programs in optics education and training, and in particular the annual ICTP Winter College on Optics, which brings together many students and young researchers each year from dozens of countries in the developing world. The students learn about new trends in optics, but, just as importantly, can network with both lecturers and peers, and obtain a reprieve from often-discouraging scientific isolation. As a number of the countries represented in the College invariably have strained or no diplomatic relations, it also serves to support diplomacy through science. This isn't the sort of diplomacy practiced by foreign service professionals; rather, it is related to the building of mutual respect that comes from the close engagement of scientists and/or students from different countries, religions, and cultures in a common discovery process. The same concept applies at CERN, which

was built on the premise of uniting the continent of Europe after it was torn apart by two world wars, and SESAME, which aims to unite the Middle East: SESAME scientists from different countries that are sometimes in conflict work together on a common goal and with a common passion—coming to a better understanding of one another not from the sharing of knowledge, but from the creation of it together.

Concerning the ICTP Optics Colleges, it is difficult to imagine a similarly *concentrated* collection of nationalities, where just about *everyone* is from someplace else. The students learn together, socialize together, and stay in contact through social media groups for years. And some fraction of them later will take leadership positions in their countries. This year, the College is being held entirely online for the first time, and it has been (it is going on as I write this) a fantastic learning experience. While personal relationships and understanding naturally face a larger impedance mismatch, it is abundantly evident that knowledge flows surprisingly easily over the fiber optic cables that connect us.

To help ignite the interest of younger students in science, the UNESCO Active Learning in Optics and Photonics program has reached well over 1000 physics teachers from over 60 developing countries to provide pedagogical updating on the teaching of optics and photonics in the first years of undergraduate and high school levels. The aim is to provide a better *conceptual* understanding of how light works using inquiry-based or active-learning techniques. The program has received generous base funding from SPIE for many years, and further support from other optics organizations including Optica and ICO.

Finally, at the early career professional level, the SPIE-ICTP Anchor Research program in Trieste has helped many highly selected young researchers from developing countries accelerate their career journeys, starting in Trieste. A few have used the experience to prepare successful grant applications for setting up low-cost, high-impact laboratories in universities where none had existed before. They all are self-starters and incredibly inspirational.



The ICTP Winter College on Optics: Applications of Optics and Photonics in Food Science, 2019.

Guided-Wave Photonics

Bishnu P. Pal
Mahindra University, India

The field of guided-wave photonics (GWP) examines the phenomena associated with the confinement of light in composite structures comprising two dielectrics having distinct refractive indices. GWP has been the driving force behind landmark developments such as high-speed, long-range optical fiber communication (OFC) systems and photonic integrated circuits (PICs) for signal processing at optical frequencies. Optical fibers and photonic components have, unquestionably, revolutionized how we communicate and access information today.

My first encounter with this fascinating area was as a Royal Norwegian CSIR (NTNF) post-doctoral associate (1975–77) with the Electro-optics Group (ELAB) headed by Professor Kjell Bløtekjaer at the Norwegian University of Science and Technology, Trondheim (then called NTH). It was a pleasant coincidence that both Kjell and I had both been involved in research on electron transport in semiconductors and had decided to move on to this emerging S&T field around the same time. Since then, I have been indeed fortunate to have witnessed the tremendous growth of GWP and to have been a part of that growth.

There is a lesson here-sometimes, we are too committed to our field of study during, say, graduate school and become wary of stepping out of our comfort zones. However, from personal experience, I can attest to the fact that the rigor of graduate school goes a long way towards developing the ability to comprehend new concepts and empowers young researchers to switch to new fields and make remarkable strides therein. The bandwidth of knowledge and dissemination then can grow much broader for an educator, which eventually yields rich dividends. I never regretted this switch over! One of my primary tasks while at NTH was to characterize the index profiles of newly fabricated, high-silica, low-loss fibers.

I returned to India in the Fall of 1977 to join the Indian Institute of Technology (IIT) Delhi's Fiber Optics Group, which was led by a former SPIE Educator Award recipient, Professor Ajoy Ghatak, who was keen on starting a new laboratory for fiber optics. This was a great opportunity for building a new research laboratory from scratch. Our first efforts were to characterize telecom-grade optical fibers and, in the fall of 1980, succeeded in launching an IDP (Interdisciplinary) MTech teaching program in optoelectronics and optical communication jointly with EE faculty, who also developed the dedicated laboratory for communication aspects in their department.

The program ran successfully, with equal credits provided by each participating team, and became an excellent model for programs run jointly between multiple academic departments. Within a few years from its inception, it became one of the most sought-after MTech programs at IIT Delhi. We were possibly one of the first programs in the world to start a full-fledged masters' level interdisciplinary program.

From 1982–83, as an Alexander von Humboldt Fellow at the Fraunhofer-Institut für Physikalische Messtechnik (IPM) in Freiburg, Germany, I co-authored with my host, Prof. Ralph Kersten, a paper that proposed a collection of cutting-edge (at that time) topics along with experiments in the area of optical waveguides as a pedagogy. The paper was published in *IEEE Transaction in Education* **E-28**, 46 (1985). At the time, there was a general shortage of technical prowess among those trained in photonics (in India), and our collective goal was to empower graduating students to become successful professionals and to join a global talent pool, serving in both industry as well as in academia and national research laboratories.

Today, our alumni hold key positions in multinational organizations such as Facebook, Google, Infinera, Cisco, Bell Labs/Lucent Technology, NASA, Sterlite Optical Technologies India, Bhabha Atomic Research Centre (BARC), and the Indian Space Research Organization

(ISRO), to name a few. The Fiber Optics Lab at IIT Delhi also significantly expanded over the years under the mentorships of other colleagues.

Since then, GWP has made rapid strides during the last 50 years, so much so that data/signal transmission at 200–400 Gbps is now a reality, enabling overall transmission of Tbps per fiber cable. The emergence of critical scientific advances and exciting real-world applications provide boundless opportunities for educators and students in this field. I wish the community the very best in the years to come.

Reminiscences

Rajpal Sirohi
Alabama A&M University, USA

It is a privilege to write a short note on my experiences studying and teaching optics, to be included in this Field Guide. I had known Prof. Greivenkamp for more than 20 years through his research before I met him. In May of 2017, I received his invitation to author a physics Field Guide on any one of a variety of topics. I chose the topic of general optics and prepared material that included geometrical optics, physical optics, and quantum optics. Part of a lengthy review of the manuscript is quoted here: "The book is simply trying to cover too much material. It is trying to pack Born and Wolf, Goodman, Greivenkamp's *Field Guide to Geometrical Optics*, Saleh and Teich, and more into a 100-ish page overview of optics. As previously outlined, the FG Series is not structured for this use." During the preparation of the Field Guide, Professor Greivenkamp and I had email correspondence to clarify expectations. My regret is that, despite his advice and guidance, I could not translate the contents into the form expected of a Field Guide.

I recount here some of my experiences learning and teaching optics in India. I learned optics in the 1960s by studying *Principles of Optics* (Born & Wolf) and *Interferometry* (Candler), and I did raytracing through an optical system using a hand-operated Facit machine, which required the visualization and creation of a mental picture of what the equations represented. Setting up a Michelson or Twyman–Green interferometer to obtain a white-light fringe pattern required both skill and patience, although this was easy using Newton's ring experiment. *Principles of Optics* did not have separate geometrical and physical optics sections, and did not cover quantum optics. Later, I used books like *Fundamentals of Optics* (Jenkins & White) and *Geometrical and Physical Optics* (Longhurst), which had separate geometrical and physical optics sections. Now there are books devoted to geometrical optics and others devoted to physical optics.

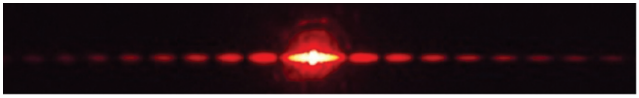
My learning experience was not optimal, which perhaps is reflected in my instruction style. I always placed emphasis on understanding the basics, and then on applying the knowledge thus gained for solving problems. Promoting entrepreneurship was never even considered.

Demonstration of some of the concepts and results became possible after the arrival of the He-Ne laser. Due to this laser, new topics evolved that would become full-fledged courses for degree programs in Optics. These new courses were, e.g., Holography and Hologram Interferometry, Optical Data Processing, Electro-optics, Speckle Metrology, and Fourier Optics. There was a renewed interest in optics, which became the science and technology that was driving innovation, and which continues to do so, although now it is considerably supported by software.

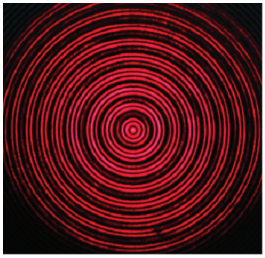
Additionally, with the He-Ne laser it became easier to demonstrate diffraction from various objects, particularly from a pinhole forming an Airy pattern. It was very easy to show the bright spot at the back of a round object when illuminated by a spherical or plane wave, the famous Arago spot (or Poisson spot or Fresnel spot). Also, to show that the diffraction patterns of a slit and a wire look similar is quite illuminating. I wrote a book entitled *A Course of Experiments with the He-Ne Laser*, which has a set of experiments that I conducted. This book became very popular in India.

Although a π phase change on reflection from a denser medium is aptly demonstrated in Newton's ring experiment when the surfaces are clean, I used Fresnel mirror interference to demonstrate the same. Most inspiring was to see the self-imaging phenomenon, in which a coarse grating is imaged by diffraction. I have used the He-Ne laser extensively in my classes to demonstrate interference and diffraction phenomena (see the photos on the next page).

The first photograph shows a diffraction pattern of human hair; the hair is plucked and held in the beam of a He-Ne laser. The second photograph shows a moiré pattern of a circular grating and its self-image in convergent light.



Diffraction pattern of a human hair.



Moiré pattern of a circular grating and its self-image in convergent light.

Mine has been a very satisfying journey, supported by my teachers, students, and colleagues. I am grateful to all of them.

Appendix: Reviewer Memories

Remembering John Greivenkamp

S. Craig Olson
L3 Harris Technologies Inc., USA

While I knew John Greivenkamp a relatively short time compared to many of those represented in this volume, I quickly learned to appreciate his dedication to SPIE and to education at large. John was heavily responsible for my own involvement with SPIE, especially in publications and governance. His own experience spanned industry as well as academia; thus, he understood all too well the balancing act at which SPIE excels. To me, his career and teaching legacy infuse every facet of the optics and photonics community, which this Field Guide clearly demonstrates.

John was not always in agreement with "accepted" wisdom, nor with "how things are done." He was, however, insightful with his reasoning, and he always approached the need for change with justifiable data and welcomed discussion. I witnessed many committee meetings during which John argued a nuanced topic on bylaws or membership yet maintained friendly professionalism. What came across during those conversations was the fact that John cared about *issues* and not *agendas*.

I have been on the receiving end of his disagreeing—but never disagreeable—nature during his decidedly non-anonymous peer review of the *Field Guide to Lens Design*, co-written with Julie Bentley. John, as always, crafted a teachable moment out of a mundane conflict in aberration theory notation and nomenclature, which ultimately led to a better publication. I am known among my own engineering colleagues for my warning: "When you came into work today, did you think you would learn anything new?" Such a mindset perfectly channels John's energy and dedication and defines his approach to science, publication, and education.

We do, as an optical community, most certainly miss John —his dedication to teaching, his love of optics history, his long devotion to SPIE, and his willingness to just *help*. Most of all, however, we will simply miss a friend.

Tribute to John Greivenkamp: A Respect for the Fundamentals

Katie Schwertz
Edmund Optics, USA

John and his Optical Design and Instrumentation classes at the University of Arizona had a reputation for straightforward demos and experiments that connected theory to reality. Paraxial optics and Gaussian reduction aren't exactly flashy, but they set the foundation of understanding for a plethora of more complex concepts in optics and photonics. I always respected that John reveled in the fundamentals and simple explanations regarding optical concepts. John instilled this foundational knowledge in so many people working today in our field.

The foundation that John set that personally impacted me the greatest was the *Field Guide* series. It's a perfect example of John's passion for fundamentals. Who doesn't have a copy of the *Field Guide to Geometrical Optics* on their desk? How many times have we all had to look up an equation we learned in our first optics class but just can't quite remember that factor of 2? Shortly after I graduated from the University of Arizona, Jim Burge and I published the *Field Guide to Optomechanical Design and Analysis*. While writing the content, the guidance was always to keep everything short, simple, and straightforward. The intent of the first book has permeated through the rest of them, creating an indispensable set of basic references for the practicing optical engineer. Publishing a field guide opened so many doors for me, and I am grateful that John made that opportunity possible.

The Power of a Brief Exchange

Matthew Jungwirth
CyberOptics Corporation, USA

For a bit of context, I attended the University of Arizona for my PhD in optical sciences so I had John for a professor. In fact, my first memory of John was from my very first day of graduate school. John's class, Introduction to Geometric Optics, was famously at 8 in the morning. (Perhaps I should say infamously since 8 am is a rather early time for a sleep-deprived grad student.) Anyway, just as class began, John looked at us all and said, "This is the first class for most of you, so let me just say, 'Welcome to grad school.'" And away we went.

My favorite memory about John, though, was in my second year at Arizona. I was a teaching assistant on a late undergrad course on radiometry for (then) Prof. Michael Descour. I had finished grading the first exam and was planning to assign grades based on the distribution (as John does); i.e., make a histogram of all the scores and hand out the A's, B's, and C's based on the breakpoints in the distribution. As you might surmise, this activity has a thick thread of art involved since the chosen bin size has a meaningful effect on the grade assignments. Thus, I wanted to check with the boss (Descour) to ensure buy-in on my method.

While waiting, John happened to walk by on the way to his office. We briefly exchanged pleasantries and he asked what I was up to:

Me: "I'm assigning grades to an exam for radiometry. I wanted to check that Prof. Descour agreed with my distribution."
John: "Oh, you are giving grades as I do in Opti 502 (his course in geometrical optics)?"
Me: "Yes, I am. It seems Descour is busy right now. Would you be able to take a look, Prof. Greivenkamp?"
John: "Absolutely. And you can call me 'John.'"

At this point, I performed the briefest of double takes. Did a well-respected professor just ask me to call him by his given name? I was slightly aghast. But, then it dawned on me: John respected me. It seemed he now saw me not just as some grad student but as a burgeoning optical scientist. No, I had not crossed the proverbial Rubicon yet, I still had the qualifying exam and that fussy dissertation to write after all, but I felt that I was now knee deep in that storied river and thus well into my journey to the big leagues in science.

So, thank you, John, for being one of the first professionals to show me that I was on the right track.

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Optics Education: A Tribute to John Greivenkamp

The past two decades have seen significant innovation in teaching methods for science, technology, engineering, and mathematics (STEM) fields. This innovation has been driven by development of new educational technologies and methods that were accelerated in 2020 and 2021 by the explosion of remote teaching due to COVID-19. The teaching of optics, being a highly specialized STEM field, has much in common with other areas, but has its own unique challenges. This volume explores individual experiences with the development of methods and their application to the teaching of optics, especially in higher education. The volume is dedicated to the memory of Professor John Greivenkamp, who passed away in early 2022 and was among the best known and most passionate educators of optics in the world.

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Series Editor

SPIE.
P.O. Box 10
Bellingham, WA 98227-0010
ISBN: 9781510653214
SPIE Vol. No.: FG53

ISBN 978-1-5106-5321-4
9 781510 653214 90000

www.spie.org/press/fieldguides