

# Radiations

SPRING  
2026

*The official publication of Sigma Pi Sigma*



**Campus SHINE Lights  
the Way to Responsible  
Campus Illumination**

**An Unforgettable Experience:  
The 2025 Physics and  
Astronomy Congress**

**Unapologetically Me:  
A Journey of Self-  
Reflection**



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SPS recognizes faculty and students who exemplify an attitude of service to the discipline of physics and astronomy through actions at the local, national, or international level.

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### ON THE COVER

Julianne Pollard-Larkin, a medical physicist at MD Anderson Cancer Center, inspires students during a plenary talk at 2025 Physics and Astronomy Congress. During the meeting, she was recognized as an honorary member of Sigma Pi Sigma, the society's highest class of membership.

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# A NOTE OF GRATITUDE and Reflection

by Blane Baker, Sigma Pi Sigma President



Blane Baker opens the 2025 Physics and Astronomy Congress. Photo by SPS.

As outgoing Sigma Pi Sigma President, I want to express my sincere gratitude to each of you. Your devotion to SPS and Sigma Pi Sigma, your advocacy for the disciplines, and your commitment to fostering inclusivity and belonging motivate me each day. I am honored to be associated with passionate folks who support one another and our work in the fields of physics and astronomy. As we reflect together, I would like to celebrate a few of our successes, discuss some of the challenges ahead, and look to the future by embracing our past and committing to the ongoing work of SPS and Sigma Pi Sigma.

The 18th Physics and Astronomy Congress, held in Denver, Colorado, last October, was an extraordinary success. The meeting featured outstanding speakers who graciously shared their expertise and advice, workshop leaders who facilitated impactful sessions, and tour organizers who provided valuable and engaging experiences. Over 1,100 students, mentors, and friends participated in the 2025 Congress.

## Get Support for Inductions and Chapter Activities

Sigma Pi Sigma Chapter Project Awards of up to \$600 are awarded to chapters to support inductions or other engaging activities that include alums or promote Sigma Pi Sigma on campus or to the public. Learn more at [sigmapisigma.org/sigmapisigma/awards/chapter-project](https://sigmapisigma.org/sigmapisigma/awards/chapter-project).



## ABOUT AIP

As a 501(c)(3) non-profit, AIP is a federation that advances the success of our Member Societies and an institute that engages in research and analysis to empower positive change in the physical sciences. The mission of AIP (American Institute of Physics) is to advance, promote, and serve the physical sciences for the benefit of humanity.

## Member Societies

- Acoustical Society of America
- American Association of Physicists in Medicine
- American Association of Physics Teachers
- American Astronomical Society
- ACA: The Structural Science Society
- American Meteorological Society
- American Physical Society
- AVS: Science and Technology of Materials, Interfaces, and Processing
- Optica
- The Society of Rheology

## Other Member Organizations

- Sigma Pi Sigma
- Society of Physics Students

## Connect with Sigma Pi Sigma

 **LinkedIn**  
linkedin.com/groups/142619

 **Instagram**  
instagram.com/spsnational

 **AIP Foundation**  
foundation.aip.org

For me the high point of the congress was connecting with students and recognizing their outstanding efforts. Students, you are the reason we exist. You inspire us; you give us hope in the future of physics and astronomy. We value each of you and offer our continued support.

Beyond the success of the 2025 Congress, SPS and Sigma Pi Sigma remain vibrant and active. We see countless examples of local chapters and members embracing our core values of honor, encouragement, service, and fellowship. You devote time to helping others gain greater understanding of and appreciation for the disciplines, and you generate opportunities for service within your local communities. Many of you participate in research and disseminate your work through presentations and publications, while others share their expertise in industry roles, as teachers, and in a wide range of other careers. We appreciate all that you are doing, and we remain committed to helping you in this ongoing work.

The valuable experiences at the congress and the engagement of our chapters would not be possible without the support and devotion of a host of volunteers, Society of Physics Students (SPS) staff, and the American Institute of Physics (AIP). They work diligently to help our programs run, and they offer support in many ways. Please take opportunities to show how much we appreciate them.

While we have much to celebrate, several challenges are imminent. Confidence in physics and astronomy and other science-related fields among the general population is in decline. These reversals impact funding for science, attitudes toward science and scientists, and personal actions of citizens. Many people in society ignore the findings of science if they do not fit their political leanings or worldviews. While these trends are disappointing, SPS and Sigma Pi Sigma embrace these challenges and stand ready to serve our communities and the society at large. I can assure you that we will work tirelessly to show the value of our disciplines, uphold scientific ways of thinking, and defend evidence-based decision-making.

Other difficulties arise from budgetary constraints at colleges and universities. As a result, many physics and astronomy departments face existential threats. Current data from AIP indicate that three to four physics programs are closing each year. With persistent budget cuts, these trends are likely to continue. Advocacy for physics and astronomy programs is an important part of addressing budgetary challenges. Yes, budgets are tight, but failure to advance scientific knowledge has dire consequences for our health, welfare, and economies. Some of our recent work in the societies has focused on listening to departments facing these challenges and helping them to tell their stories. While specific outcomes are not always to our liking, we continue to provide support and empowerment during these difficult times.

Another challenge is ensuring the well-being of students and those who work with students, especially considering the stress caused by social, professional, academic, and financial pressures. While we do not offer direct services, we are committed to helping students connect with experts and sharing their recommendations on how to deal with burnout and mental-health challenges. We truly care about our members, and we want everyone to thrive.



## Be a Resource for SPS Chapters

Join the SPS and Sigma Pi Sigma Alumni Engagement Program—a database of participants willing to be speakers, panelists, tour guides, and mentors for SPS chapters. Visit [students.aip.org/alumni/become-a-mentor](https://students.aip.org/alumni/become-a-mentor).

## Letter from the Outgoing President

Looking to the future reminds me of our origins and emerging history. You are a part of an organization that values students and commits time and resources to supporting them. In 1921 Sigma Pi Sigma was founded as an honor society by a group of students at Davidson College with the support of their faculty. At one of their first meetings, student members proposed the pillars of the organization and emphasized the need for encouragement of students. In 1968 Sigma Pi Sigma joined with AIP's Student Sections to form SPS, an organization committed to serving all students interested in physics and astronomy. Today Sigma Pi Sigma remains a separate honor society within SPS.

SPS and Sigma Pi Sigma offer many exciting opportunities for current and past students. As you continue your studies or pursue other endeavors, remember that you always have a home here. You play a vital role in our long-term success. Your gifts of time and resources empower the next generations of students. Your ongoing participation contributes to our overall strength and health. Many folks continue involvement after graduation by helping to organize future congresses, working with local chapters, connecting with students via research and service, and offering workshops on a broad range of topics. Others promote science through advocacy and personal interactions. Each of us has opportunities to advance our disciplines and build a more sustainable future for humanity. We encourage you to participate in ways that empower and inspire you.

In closing, my plans are to continue volunteering once my term as president ends in June 2026. I am particularly interested in helping with future congresses and addressing the challenges experienced by departments under threat. I have enjoyed my tenure as president, but most of all, I am honored to have served and worked with you. I anticipate seeing many of you at the next congress and other SPS and Sigma Pi Sigma events. Let us strive together to make SPS and Sigma Pi Sigma the most relevant, engaged, and active organizations for students and alumni. United in mission and vision, we can accomplish all that we desire. •

## Society Notes

# The Lasting Legacy of Professor Steve Feller

*by Brad Conrad, Education And Workforce Development Manager, Office of Advanced Manufacturing, NIST, and Brittney Hauke, Journals Managing Editor, The American Ceramic Society*

**T**here are scientific leaders whose influence is measured in concepts, papers, and citations. There are also those who impact their community by championing people, education, and our best ideals—encouraging others to be a better version of themselves. Steve "Doc" Feller, a past president of Sigma Pi Sigma and longtime professor and SPS advisor at Coe College, will be remembered as both of these, and to many in our community, much more. The Worth Seagon-dollar Award winner passed away on November 19, 2025.

Over 46 years, Feller built a premiere undergraduate research program focusing on oxide glasses at Coe College in Cedar Rapids, Iowa. The pillars of  $\Sigma\Pi\Sigma$  were at the heart of his career, guiding him in everything from groundbreaking condensed matter research to being a mentor, leader, and engaged member of the physics and astronomy community.

## Scholarship

Doc earned his PhD at Brown University and began teaching at Coe in 1979. Working with fellow Coe professor Mario Affatigato and their students, Doc published nearly 140 papers on the atomic structure



*At the 2022 Sigma Pi Sigma Congress, Steve Feller (center) poses with authors Brad Conrad, past director of SPS, and Brittney Hauke, one of his former students. Photos courtesy of Hauke.*



**“Our results are used all over the world. But the most important thing, for sure, not even close, is the students.”**

**—Steve Feller**

*Steve Feller (seated, left) relaxes with colleagues and members of the class of 2017 during an event for senior physics majors.*

and physical properties of glass. Most have undergraduate authors. One of Doc’s shining achievements was including undergraduate students in every part of the research and dissemination process. Because of his efforts, hundreds of his students contributed to the field and test drove careers in research and engineering.

### Leadership

Through his involvement with organizations including the American Physical Society (APS) and the American Ceramic Society, Feller helped bring together physicists from across the globe to collaborate on cutting-edge research. He played a leading role in organizing conferences and symposia, including Sigma Pi Sigma congresses. At Coe, he mentored countless student leaders, helping them develop the skills they needed to succeed. Doc was tireless in creating an environment in which students felt supported and empowered.

### Service: An Attitude and Lifestyle

One of the first things people learned on meeting Doc, besides his characteristic greeting of “Yo,” in a thick Brooklyn accent, was his passion for giving back. He was involved in many programs promoting science education, particularly to those underserved in the field. Doc believed that science should be accessible to everyone, and worked to make sure every student could engage in physics and astronomy on their terms. He built a wide base to support student travel that was highly successful—often allowing dozens of students to attend meetings—and effective at helping students connect their passion for science to the broader community, creating a strong Coe physics alumni network.

A celebrated institution, Doc’s SPS chapter received Outstanding recognition countless times. He made sure each  $\Sigma\Pi\Sigma$  induction ceremony was a community-building event, often securing renowned scientists such as Jocelyn Bell Burnell and Jim Gates to not just speak with students but build lasting connections. From shar-

ing his “world-famous” liquid nitrogen ice cream recipe to encouraging chapter support of the local community, Doc’s impact can be measured in lives changed.

### Fellowship: A Collaborative Physics and Astronomy Community

Doc was a strong believer in the importance of Fellowship, both within the academic environment and in the scientific community. He recognized that science thrives when students and researchers across many levels of experience collaborate, share knowledge, and support each other. Doc was famous for bringing his students with him to every meeting and laboratory he could.

Through his contributions to science and his tireless support of those he worked with, Feller made a lasting impact on the fields of physics and glass science. He is a model for how one can embody the values of  $\Sigma\Pi\Sigma$ —Scholarship, Leadership, Service, and Fellowship—throughout their career. His work will continue to shape the future of physics and impact generations of scientists for years to come. ●


# Sustaining the Four Pillars: Alumni Gather at the 2025 Congress


by Andrew Czeidinski, Science and Technology Policy Fellow, American Association for the Advanced of Science, and Stephanie Howell, Physics Graduate Student, University of Oregon


**T**his past October, more than 60 Sigma Pi Sigma members gathered at the 2025 Physics and Astronomy Congress to network and to reflect on the society's pillars. The keynote speech was delivered by one of Sigma Pi Sigma's newest honorary inductees, K. Renee Horton, who encouraged physicists to boldly take up space at the forefront of society by disseminating knowledge and sharing the wonder of scientific discovery. In attendance were plenary speaker Jocelyn Bell Burnell and longtime SPS donor Jack Hehn, both fellow honorary members who inspired the audience with their presence and support.

As dinner was served, participants from diverse career stages engaged in a guided exercise about the Sigma Pi Sigma pillars, touching on what they mean in practice and how they might be strengthened moving forward. Here are some notes from the activity.

 **Fellowship** is an investment in people, both students and alumni. Members emphasized supporting young scientists and suggested that regional alumni and networking events could coincide with local conferences and events to enhance community and sustain long-term connections.

 **Service** is a responsibility and a learning experience. Through service, members said, one learns the importance of teaching resilience and perseverance. Other members noted the growing need for effective science communication and support for events like the congress.

 **Honor** and scholarship are striving for excellence while uplifting others. Members linked these values to respect, integrity, honesty, and open-mindedness in their professional lives and beyond.

 **Encouragement** often comes from family, professors, and peers who reinforce one's confidence in overcoming challenges. Members emphasized the power of Sigma Pi Sigma to encourage students, noting that the members can do more to champion and support the next generation of physicists and astronomers.

Across all four pillars, Sigma Pi Sigma members expressed a shared desire for greater activation and recognized the collective impact the society can have in the community. •

If you are interested in helping grow and strengthen the Sigma Pi Sigma network, check out [students.aip.org/alumni](https://students.aip.org/alumni) to learn more.

## You Make Sigma Pi Sigma a Community

by Alejandro de la Puente, Past Director of SPS and Sigma Pi Sigma, and Rianna Ehrenreich, SPS and Sigma Pi Sigma Programs Engagement Associate

The students and professionals that join Sigma Pi Sigma form a network of those striving for excellence in the physical sciences. As much as the National Office desires to build a community, that is not something that can be forced. Community requires the sustained effort and enthusiasm of members; otherwise, we have nothing more than a mailing list.

Last year, several Sigma Pi Sigma members participated in workshops to help society leadership determine how to make engagement easier. As we spend 2026 planning and establishing these programs, we encourage you to form local alumni communities of your own. Stay in contact with your undergraduate and graduate peers, or join the Sigma

Pi Sigma LinkedIn page to find fellow members in your area. Host reunions, networking events, or even the kind of bad physics movie nights you organized as a student. The magic of SPS connections doesn't have to go away just because you've graduated.

When you feel connected to a community, you gain support, encouragement, and understanding. In a time of heightened career uncertainty, it's important to interact with people with whom you can relate. Sigma Pi Sigma is here to facilitate an alumni community, so please share your perspectives, experiences, and voice. And keep an eye out for ways to get more involved this year! •

# Meet the Newest Sigma Pi Sigma LEADERSHIP SCHOLARSHIP Recipients

## ***Raisa Rahman Richi***

A senior at Franklin and Marshall College in Pennsylvania, Raisa Rahman Richi is pursuing a double major in physics and mathematics. Her passion for physics began in childhood, when science fiction novels inspired her to pursue a research career.

Through a summer internship at Fermilab in 2024 and at CERN in 2025, Richi developed an interest in experimental particle physics. At Fermilab she used machine learning algorithms to improve neutrino reconstruction techniques, and at CERN she contributed to an energy efficiency analysis of a high-energy physics event generator.

Richi is the president of the SPS chapter at Franklin and Marshall College, leading weekly meetings, organizing research presentations, and coordinating conference participation. Next year Richi plans to pursue a PhD in physics, with hopes of becoming a research scientist at a national laboratory or a university professor. Outside of physics, she enjoys traveling, hiking, running, and playing guitar.



## ***Yurok Song***

Yurok Song is a senior physics major at Emory University interested in applying physics to living systems and medicine. He is completing an honors thesis in Ilya Nemenman's theoretical biophysics group, where he uses quantitative models to study population activity and inhibitory-excitatory dynamics in mouse auditory cortices. He has also conducted research at Stanford University on accelerating diffusion-weighted MRI using computational methods.

Yurok serves as copresident of the Emory SPS chapter, a learning assistant captain in the physics program, and an advanced EMT and division chief of operations for Emory EMS. He is committed to strengthening the physics and broader scientific and health communities through outreach, mentoring, and creating welcoming spaces for younger students. After graduation, he plans to pursue an MD/PhD in physics and pursue a career using quantitative tools to inform diagnosis, treatment, and health policy. •



Ad

# Thank You for Supporting Student Travel TO THE 2025 CONGRESS



Snapshot from the 2025 Physics and Astronomy Congress. Photos by SPS.

For many students, attending the recent Physics and Astronomy Congress wouldn't have been possible without the generous support of Sigma Pi Sigma donors. As the students convey below, your gift changes lives.

"This stipend directly enabled our SPS chapter to attend the conference, which opened an opportunity that expanded our academic perspective, strengthened our professional network, and motivated us to bring new ideas back to our campus. A major highlight was presenting in the poster session and having feedback from the broader physics community. We also had the chance to meet the SPS Executive Committee and members of Sigma Pi Sigma, which helped us better understand how to grow our chapter and better serve our members. As chapter president, one of my favorite moments was meeting and speaking with Dr. Jocelyn Bell Burnell. Without this support, our participation would not have been possible."

- Yulián Humarán, University of Puerto Rico - Mayagüez

"Attending SPSCon was one of the most valuable experiences that I have had throughout my undergraduate career. Getting the opportunity to network with other undergraduate physicists while learning about various career opportunities in academia, industry, and national labs was valuable for planning my career."

- Logan Finke, Embry-Riddle Aeronautical University

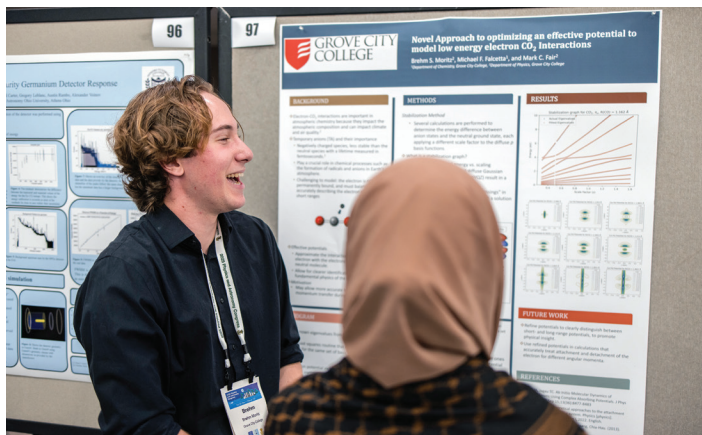
"The SPS Chapter Travel Award allowed our chapter to attend the Sigma Pi Sigma Physics and Astronomy Congress for the first time. . . . It provided invaluable insight into graduate school pathways, career opportunities, and the broader climate surrounding science today. The experience was both informative and inspiring, and we are fully committed to doing everything we can to ensure our chapter is able to attend future congresses."

- *Angel Fraire Estrada, University of Tennessee Chattanooga*



"This congress gave me the opportunity to meet outstanding scientists who have experienced the struggles I have faced as an undergraduate. Attending Dr. Renee Horton's plenary talk helped me realize that I should focus on professional development opportunities I am truly passionate about and make time for myself so that I can thrive rather than survive through my physics career."

-*Blake Schuetz, Embry-Riddle Aeronautical University*



"The SPS Physics and Astronomy Congress was an impactful experience. . . . I feel more secure knowing that there are other people interested in the same research as me but also fighting to keep science in the forefront."

- *Andrew Elder, University of Tennessee Chattanooga*



"We had four students attend, and all four students presented research that they had done at our school. It was a great opportunity for all of us to present our work in a safe and thriving physics environment. . . . Without the travel grant, our students would not have been able to attend."

- *Naomi Wagner, Oglethorpe University*

## Supporting Students

Student travel to Physics and Astronomy Congresses is supported by the SPS Student Success Fund. This fund enhances the academic and professional development of physics and astronomy students through targeted support. It provides financial assistance for student travel to conferences, internships for hands-on experience, and scholarships to ease educational costs. The fund also fosters community by supporting regional events that connect aspiring physicists. You can learn more about donating to this fund and the Alumni Engagement and Sigma Pi Sigma fund at [aip.org/foundation/student-programs](http://aip.org/foundation/student-programs).

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# TWO DECADES

## of Connecting Students and Physicists

*by Gina Watkiss, Science Educator, The Heritage School, and Sheri Nakai, Retired Gifted Ed Educator, Adopt-a-Physicist Moderators*

**T**he Adopt-a-Physicist program connects physics alumni with high school physics classes through online discussion boards for three-week interactive sessions. Students post questions, and their "adopted" physicists answer in detail, with pictures, links, and challenging questions for students to consider. The program, which is celebrating its 20th anniversary, is run by Sigma Pi Sigma in collaboration with the American Association of Physics Teachers (AAPT) and the digital library ComPADRE.

Don Lincoln, a senior scientist at Fermilab, has participated every year since the program's inception. "I grew up in a world in which there were no scientist role models, and it wouldn't have been all that hard for me to follow a path that didn't involve science," he says. Over the years, Lincoln has spoken with hundreds of enthusiastic students through the discussion boards. "Some of them have chosen to study physics in college," he says. "I hope that some of my correspondents will themselves one day be Adopt-a-Physicist mentors."

Gina Watkiss's classes at The Heritage School in Georgia have participated in Adopt-a-Physicist for more than 10 years, and they have adopted Lincoln

multiple times. During those sessions, her students are always thrilled to see him featured in the school library's issue of *Scientific American* and NOVA programs on TV, she says.

For a few weeks each year, Adopt-a-Physicist "links my classroom directly to the real world of physicists," says Matthew Anticole, a physics teacher at Norwin High School in Pennsylvania. "My STEM-centric students have impactful conversations with folks they aspire to become," he says. "My STEM-adverse students, on the other hand, discover that physicists are actually just normal (and usually pretty funny) people who do cool and important things with physics."

Through the program, students are exposed to the brilliance and humanity of scientists, says Alden Marchman, another teacher at The Heritage School. "A question about dark matter, pulsars, or space-time can quickly turn into a conversation about a favorite baseball team or a treasured recipe," he says.

During one session, Tom Hogan of Quantum Design intrigued students with his latest side project, building replica lightsabers modeled after the hilts you see in the Star Wars films. Another time, Jason Kooi, a research physicist at the U.S. Naval Research

Laboratory, captured students with these opening lines, "Physics has been a passion of mine for many years. As a kid under the influence of such notable scientists as Dr. Egon Spengler (Ghostbusters) and Donatello (Teenage Mutant Ninja Turtles), I would spend hours tinkering with anything I could get my hands on."

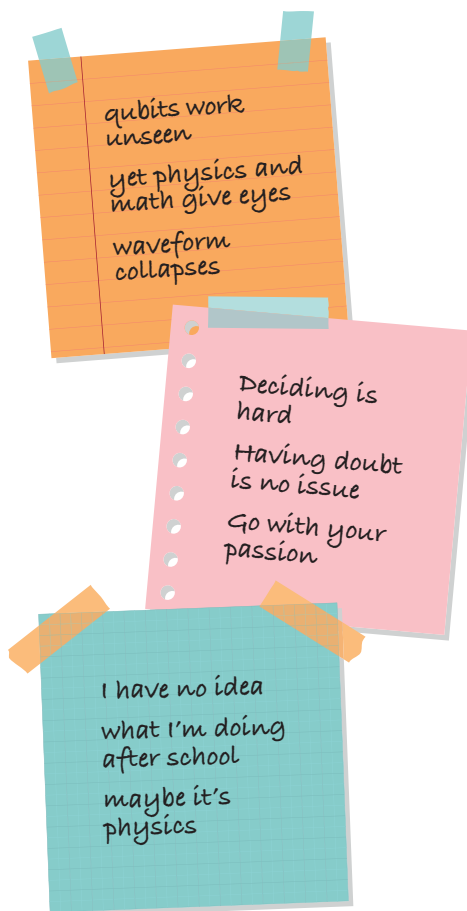
Lisa Sitek, a science teacher at Burlington High School in Vermont and a 14-year veteran of the program, says interacting with physicists gives her students a broader sense of what it means to be a physicist. "The Adopt-a-Physicist program allows students, who often think the only job in physics is in a lab, to meet real people using physics in interesting jobs that they could see themselves doing one day," she says. "The program helps take away the mystery of physics and answers the question, 'When would I ever use physics?'"

Teachers also appreciate that their students are exposed to physics and astronomy topics beyond what is covered in introductory textbooks. Ami DuBois, a research physicist at the U.S. Naval Research Laboratory, introduced students to plasma in her 2022 forum. That prompted a student to reply, "We normally only study the three main types of matter, so to learn about the 4th is really cool! Lightning and neon lights are the only two other forms of plasma that I know about, but I would love to learn about some other examples!"

The impact of these interactions is evident in feedback from students. "I learned about the similarities and differences be-

tween going toward a more engineering-based path or a research-based path in college and as a career," says one student from Norwin High School. "Physics not only teaches about how the universe works but teaches your brain how to think in different ways," says another student, reflecting on what they learned from their experience.

At the end of each Adopt-a-Physicist session, Anticole's students express their experiences in Haiku (and Haiku-ish) form.



**"The program helps take away the mystery of physics and answers the question, 'When would I ever use physics?'"**

**-Lisa Sitek**

Helena Richie, a former student of Anticole's, is now a doctoral candidate in physics. She's come full circle, now participating in the program as a physicist. As a high school student, an Adopt-a-Physicist conversation played a pivotal role in her decision to pursue astrophysics.

"I had a love for astronomy throughout my life, but somewhere along the way, I had picked up the idea that it wasn't a realistic career path for me," she says. Surely there were only a few people who could make a living studying the universe, she thought.

"The main thing that participating in Adopt-a-Physicist helped me learn is that being an astronomer is a 'real' career path," she says. Hearing that it was a path she could pursue directly from an astronomer was really important, she notes.

Physicists and astronomers of all specialties, education levels, and career types are invited to interact with students through Adopt-a-Physicist. You too can influence how students perceive a career in physics or astronomy—and whether they think they're capable of achieving one. •

One of teacher Lisa Sitek's favorite physicists to adopt was Kenneth Ford, a participating physicist for 18 years. In 2024, at 98 years old, he responded to a student's question about childhood idols with this reply:

- *Two of the giants of the field with whom I had the chance to work were John Wheeler and Enrico Fermi. Wheeler, who coined the term 'black hole,' transformed Einstein's theory of general relativity into a tool of experimental physics. Fermi explained the phenomenon of beta decay and laid the groundwork for much of modern particle physics.*
- *I never met Einstein, although we lived in Princeton at the same time. Since I drove around Princeton's streets at night, sometimes too fast, I did worry that my lasting claim to fame might be bringing Einstein's life to an untimely end.*
- *Idolize is not a term I would use. Respect and admiration seem better. These giants are human with human frailties complementing their brilliance. And mostly, they are very likable people.*

Sadly, Ford passed away on December 5, 2025, at age 99. He will be greatly missed in upcoming Adopt-a-Physicist forums.

## Learn More

Learn more and register at [adoptaphysicist.org](https://adoptaphysicist.org).

# Campus SHINE Lights

## *the Way to Responsible Campus Illumination*

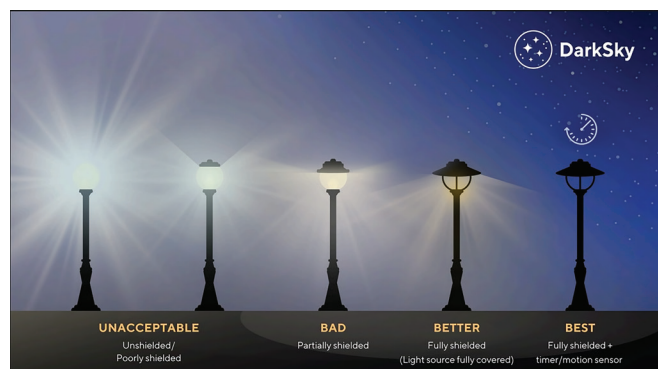
by Kendra Redmond, Editor

**O**n clear nights, a few of my college classmates and I used to load the Physics and Astronomy Department's telescopes into a car and drive out behind one of the fire stations. There we'd set up the tripods and telescopes, wait for them to acclimate to the temperature, and work on our observing projects.

Although the fire station was just a few miles down the road, it was far darker than anywhere on campus, where streetlamps lined roads and walkways, spotlights illuminated signs and sculptures, and stadium lights blazed to the heavens.

Our campus, like many others, made liberal use of light. That made it safer, right?

Research shows that while adding more light *can* make outdoor areas safer, indiscriminate lighting actually reduces visibility by introducing glare. And dispelling darkness has other negative consequences—disrupting sleep patterns, harming ecosystems,



**“Not being able to see the stars is not the problem—it is a symptom of the problem. The real problem is the harm caused by bad lighting, and the waste of resources.”**

—Vayujeet Gokhale, Truman State University

increasing energy costs, and limiting the human experience of the night sky. Smart lighting choices and simple shields can alleviate much of the problem, if people are willing to take action.

As *Radiations* readers know, students often drive change. That recognition is at the heart of Campus SHINE: Safe and Healthy Illumination for the Nighttime Environment, an American Astronomical Society initiative that promotes responsible, thoughtful campus lighting. The initiative challenges students to lead collaborative efforts on campus to address this straightforward yet persistent problem.

A Campus SHINE Guide, developed by experts in astronomy, lighting design, environmental science, and sustainability, details a roadmap for change inspired by successful efforts at Truman State University, the University of Alabama at Birmingham, Smith College, and other institutions.

Sigma Pi Sigma chapters—which bring together alumni, faculty members, and current students—are well positioned to spearhead this effort on their campus. To learn more and get started, download the guide and check out success stories at [CampusShine.org](http://CampusShine.org).

### Get Support from SPS

Implementing Campus SHINE requires assessing existing campus lighting, exploring the impact of alternative lighting options, conducting outreach, and bringing together experts, students, and faculty members. Sigma Pi Sigma Project Awards, SPS Chapter Research Awards, and SPS Marsh W. White Awards can help!

- Sigma Pi Sigma Chapter Project Awards of up to \$600 are made to chapters for activities that engage alumni or expand the recognition of Sigma Pi Sigma.
- SPS Chapter Research Awards of up to \$2,000 are made to chapters for physics or astronomy research projects conducted by the chapter.
- SPS Marsh W. White Awards of up to \$600 are made to chapters for activities that promote interest in physics and astronomy among students and the general public.

Get the details at [students.aip.org/awards](http://students.aip.org/awards).

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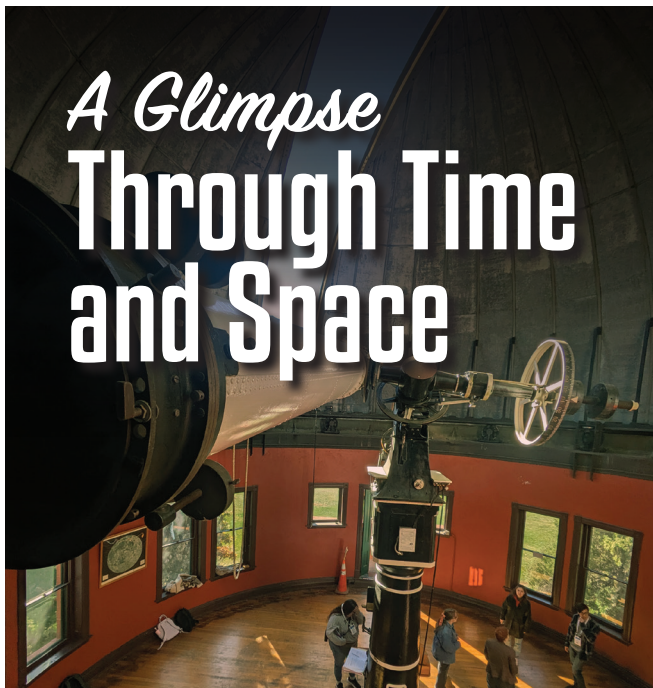
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# An Unforgettable Experience:

## *The 2025 Physics and Astronomy Congress*

Last October, more than 1,100 physics students, faculty members, and alumni gathered in Denver, Colorado, for an exciting three days of tours, plenary talks, workshops, science, and art. The Physics and Astronomy Congress is a unique meeting aimed at undergraduates and takes place just once every three years. We invite you to relive or experience the highlights for the first time through student pieces in the next few issues of *Radiations* and the *SPS Observer*.



by Olivia Nippe-Jeakins, SPS Reporter, George Washington University

The morning was crisp and bright as about 15 of us chatted on the small tour bus. We were still a bit drowsy, the exhaustion from the previous day's travels not quite lifted, but an undercurrent of excitement kept us awake. This was the first official day of SPSCon, and we were starting with a bang: a tour of the Chamberlin Observatory, a 19th-century facility maintained by the University of Denver (DU). It's home to a massive 20-inch refracting telescope, one of few still operational in the US.

Upon first glance, the observatory didn't appear extraordinary. It's not particularly tall or imposing. But entering felt

*A view of the Chamberlin Observatory's refracting telescope from the top of the scaffolding, looking down. Photos courtesy of Olivia Nippe-Jeakins.*

like stepping back in time, as though we were walking into an old schoolhouse. Research posters plastered the walls, interspersed with black-and-white portraits of important-looking historical figures. The school-like atmosphere soon made sense, as we realized we actually were standing in a classroom—albeit a classroom unlike any other I've seen. The room wrapped around a massive, central column, the chairs arranged so that both sides of the room could see a whiteboard and screen. We took our seats.

Denver University professor Jennifer Hoffman, director of the observatory, gave us a warm welcome and walked us through the history of the observatory. It was absolutely fascinating to hear about construction during the era of horse-drawn carriages.

Upstairs, the sight of the telescope left us speechless. It is 26 feet long and sits atop a column that stretches all the way down to the bedrock below. Dr. Hoffman walked to a thick rope dangling from the ceiling and gave it a tug. To our amazement, she was manually opening a slice of the dome. The ceiling above us slowly rotated out of the telescope's way, and Dr. Hoffman adjusted the telescope's orientation, gently swinging it down so we could examine it more closely. It was far too bright for observation, but climbing the scaffolding and peering through the lens was an unforgettable experience.

Ultimately, this tour underscored the importance of understanding and honoring the contributions of those who came before us, allowing their achievements to inspire and propel the work we do today. We owe a tremendous debt to the early pioneers whose curiosity and persistence laid the foundation for our understanding of the world. ●

# Reflections on the SPSCon Plenary Workshop

by Shoshana Shapiro and Jaden Hubbard, SPS Reporters, SUNY New Paltz

**N**ear the end of the first day of SPSCon, hundreds of undergrads filed into a ballroom for a plenary workshop. We were told to sit at tables based on zones, and our group ended up sitting with a group of students from Yale University.

We expected our experiences as physics students to be completely different. The Yale students were from a well-funded, well-known university with a large physics department, while we came from a small state school with limited resources. But when we began discussing the first question, "How would you describe the current atmosphere in your chapter or department?" the similarities surprised us.

SUNY New Paltz is small, supportive, and close-knit. Professors form strong relationships with their students. Research opportunities tend to be informal and accessible. The Yale students also had a strong community with motivated students eager to do research. But they felt more distant from the faculty. We discovered that all of us wanted stronger connections and a more collaborative atmosphere.

When asked, "What are the biggest issues facing physics and astronomy majors today?," our table immediately agreed: the rise of anti-intellectualism. We talked about how skepticism toward science has risen in the public sphere, making it harder for people to trust experts, be curious, and value critical thinking. Misinformation spreads quickly, while outreach can't keep up. This cultural shift affects funding, science communication, and public support.

Eventually we rotated to new tables, and I was joined by students from other small departments across the country. We bonded over familiar struggles: limited course offerings and small faculties. Together, we reflected on the question, "How do we get people excited about physics?" We agreed that excitement would come from making people feel welcome, interested, and included.

I left the workshop feeling more grounded as a scientist and more connected to the broader physics community. Hearing students from such different institutions speak passionately about the same issues was a reminder that no matter the size or resources of our departments, we're all working toward the same goal of making science accessible and welcoming. That shared purpose is what I carried with me long after I left the room. •



The SPS crew from SUNY New Paltz, including reporters Shoshana Shapiro (left) and Jaden Hubbard (second from right), commemorates SPSCon. Photo courtesy of the SPS reporters.

# Come for the Merch. Stay for the Opportunities



SPS reporters (L-R) Ella Luking, Savannah Russell, and Aubyn Sallee enjoy the second day of the SPSCon expo.

by Aubyn Sallee, Savannah Russell, and Ella Luking, SPS Reporters, Rhodes College

Let's be honest—when it comes to any college career or graduate school fair, recruiters have mastered the art of drawing students in with everything from stress balls and pens to candy and branded sticky notes. But keeping them there? Oftentimes, that's a different story.

This challenge, however, was overcome by the 2025 SPSCon Career Expo and Grad School Fair. Occurring each day of the three-day conference, the Expo offered attendees a vibrant hub of discovery and career exploration. The free goodies were just the icing on the cake!

One of the major draws was the dozen or more professional societies and

outreach organizations. Many of these groups, such as the American Association of Physics Teachers, the National Society of Hispanic Physicists, and the Shadow the Scientists program, represented specialized, physics-centered communities rarely found at standard university career fairs.

A standout outreach organization was the Little Shop of Physics, a science engagement program based at Colorado State University's College of Natural Sciences. The group's booth featured over a dozen hands-on demonstrations, including a photoelectric effect salad spinner. It was a fun and inspiring break from the formal atmosphere of the event.

As for graduate program offerings, there were an astounding 45 schools and specialty booths. On the university side, representatives were excited to share information with undergraduate students standing shoulder to shoulder, waiting to hear what each school had to offer. Whether speaking with Georgia Tech or the Max Planck School of Photonics, each conversation was a fantastic opportunity to find potential connections and advisors.

Bianca Hassan, a student at Davidson College, told us that the prospect of choosing a graduate school sometimes seems daunting. She advises SPS members who attend the next SPSCon to visit each booth and "block everyone else out to see what they have in store at their universities."

The Expo also featured a section of potential employers, which grabbed our attention. At the Lockheed Martin booth, we had the opportunity to connect with recruiters one-on-one about space-related careers. For those into manufacturing and engineering, ThorLabs and other top employers offered advice on the job market, and their representatives helped to put faces to large corporations.

All of us had a great time at the SPSCon Career Expo and Grad School Fair; there was so much to learn and take away! Other physics students seemed to agree with us. "If you're a physicist, you will definitely find your people here," said Mason Chadwick, a student at the University of Maine. Talking to other schools for the first time, he said, "feels inspiring and motivating for the future." •



The Little Shop of Physics booth features fun science demonstrations. Photos courtesy of the SPS reporters.

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 AIP



# Unapologetically Me:

## *A Journey of Self-Reflection*

by Lily Stetson, Grace Mostek, and Samantha Chiang, SPS Members, Kettering University

**O**n the last day of the congress, my friends and I collapsed onto our hotel beds and talked. We talked about life in a long, meandering conversation, about where we're from and where we're going—a couple of murmuring voices trading fragments of their souls as the digital clock ticked upward into the dead of the night.

Sometimes things align in ways you don't expect, and there's no telling when you'll experience an encounter that will change you. The day before I left for the

congress, I was in a job interview. The manager looked at me and said that I needed to figure out what came next because it seemed I didn't want to be there. He was right.

It was the second day of the congress when I attended a workshop by Dr. Renee Horton called "Unapologetically Me" in this big ballroom. I remember watching as people began to fill this grandiose room while Dr. Horton and her friends distributed her book *Reframe Your Picture: From Surviving to Thriving*. It was a workbook

centered around building a life you want, turning just passing the days into living them. Throughout the entire workbook, her own story was sprinkled as a guiding presence.

I remember the way the lights caught on her face as she looked into the crowd and told us what she'd lived through, the good and the bad. I remember the way she spoke when she talked about her childhood love of science, of her parents' divorce, her own divorce, and other big experiences in her life. One of the things she



(L-R) Authors Grace Mostek, Lily Stetson, and Samantha Chiang pose with Renee Horton and their SPS Advisor, Ronald Kumon, at the 2025 SPS Congress. Photo courtesy of the SPS reporters.

emphasized over and over again was how important community is, for both her and the audience. It was almost subconscious, the way my eyes flicked across the table, taking in the two friends who had come with me from halfway across the country and through two years of college.

A contemplative silence would descend upon the room whenever Dr. Horton directed us to work on a section, or so it felt to me. My two friends and I sat around a table, necks craned over the book as our pens flew. No one spoke, just the sounds of scribbling on paper. One section was on recognizing survival mode, another on stagnation and overcoming it. We put plans in place,

acknowledged what we needed to let go of, and made a list of the things that truly made us want to live our lives, not just pass through them.

I type all this with her book sitting next to me, thumbing through the pages with one hand while admiring the eager, rushed scrawl filling so many of them from that day of the congress. Most of the pages are still empty, but slowly the words have been accumulating.

The rest of the conference was a blur, but no less wonderful. Other fantastic speakers and events made for a genuinely great experience, culminating in a three-hour party where my friends and I danced, laughed, and brought the truly

memorable experience to a close. I was sad to see it end.

Then, later that night, we started talking about it all, the big and the small. We talked about our goals and hopes for the future. We shared things we had never told each other before. It was such a fitting way to end the congress, sharing fragments of our souls. Three hours of high-intensity fun, and then more hours still of quiet contemplation with people I cared about.

The introduction of Dr. Horton's book ends with a bold-faced line I'd like to share. **"Community, it is not about proximity or traditional labels, but about love, shared experiences and mutual respect."** •

# JACK HEHN

## Honored with Worth Seagondollar Award

by Korena Di Roma Howley, Contributing Editor

Over a six-decade career serving the physical science community, Jack Hehn has remained deeply engaged with students and faculty as both an educator and an association leader. It's a career that's been built, he says, on collaboration, service, and enduring professional relationships.

"The most important factor in my career, almost without a doubt, has been the outstanding people I've had the privilege to work with," he says.

As a young student in Texas, Hehn had an interest in biology and planned to become an oceanographer. But influential teachers and mentors offered encourage-

ment in physics, as well as experiences with early computing that deepened his passion for the field.

At the University of Texas in the 1970s, Hehn met physics professor Robert Beck Clark, who introduced Hehn to the American Association of Physics Teachers and became the most significant mentor of his career.

***"The most important factor in my career, almost without a doubt, has been the outstanding people I've had the privilege to work with." –Jack Hehn***

*Jack Hehn and Jocelyn Bell Burnell pause for a photo at the 2025 Physics and Astronomy Congress. The Worth Seagondollar medal hangs around Hehn's neck.*



After finishing his bachelor's degree, Hehn taught physics, math, engineering, and one of the first computer science courses in the state. Meanwhile, Clark had established a master's program for physics teachers at Texas A&M University, and Hehn spent summers working toward his degree. He then went on to complete his PhD at the University of North Texas, where he helped to build an innovative physics instructional center.

Later, he transitioned into association leadership, serving at AAPT, the National Science Foundation, and as director of Education at the American Institute of Physics, where he helped launch or grow several major initiatives: the digital library ComPADRE, the Physics and Astronomy Faculty Teaching Institute, the PhysTEC program to strengthen physics teacher preparation, the revitalized SPS Congress, and the SPS intern and reporter programs.

For these and other achievements, Hehn was named the recipient of the Worth Seagondollar Service Award, given in recognition of an exemplary level of commitment and service to the Society of Physics Students and Sigma Pi Sigma. His award citation reads, in part,

• *His impact on this organization is measured by the number of students who continued on in physics and astronomy and the vibrancy of the countless student club events that occurred during his tenure. ...Jack Hehn continues to serve the physics and astronomy societies with distinction and a never ending passion. Jack is among the best of us and the best of this society.*

Hehn also became an honorary Sigma Pi Sigma member, the society's highest class of membership. Both honors were announced at the 2025 SPS Congress in Denver, Colorado.

"I was overwhelmed," Hehn says. He recalls being acquainted with Seagondollar, a Manhattan Project physicist and former president of Sigma Pi Sigma, and once hearing him speak to a rapt audience

of 700. "To have known him and to receive the award—it's a big emotional difference and a real pleasure."

When considering what advice he might pass along to students, Hehn speaks again of relationships. "I've been really, really lucky because of the people that I've worked with," he says.

For students, he stresses the importance of perseverance, collaboration, department leadership roles, internships, and society membership. Overall, he says, students should immerse themselves in the world of physics and astronomy.

"It's a remarkably small community, and you will see people that you meet over and over again for many years," he says. "The friends you make and work with really inflect your career for the rest of your life. And that's the real reward." •

## About Worth Seagondollar

After working as a graduate student at Los Alamos on the Manhattan Project, nuclear physicist L. Worth Seagondollar was a professor for more than 40 years. He served as president of Sigma Pi Sigma from 1962 to 1967, overseeing the merger between the honor society and the American Institute of Physics that created SPS.

Jack Hehn (left) on an outing with the 2025 SPS summer interns. Photos courtesy of SPS.



# The Medical Dosimetrist and Graduate Program Director

by Korena Di Roma Howley, Contributing Editor

**G**rowing up in Kenya, Jacky Nyamwanda aspired to be a doctor. Then, on a premed track at Smith College, she took a required physics course and found it to be an even better fit for her strengths.

"I just loved it so much more," she says. "I always liked it in high school as well. But I never imagined it was something I would use in a career. Back then, studying physics meant going to work for NASA."

Nyamwanda credits her instructors, as well as the all-female environment at Smith, with her decision to choose a path forward in physics. "Women in STEM are sometimes intimidated in a co-ed class," she says. "But I had so much freedom."

Though Nyamwanda knew she could stay on a premed path with a physics major, her mind was made up. She still wanted to be in health care, but she would no longer be going to medical school.

After graduation, Nyamwanda worked on DNA sequencing as a lab assistant in the Department of Molecular and Cellular Biology at Harvard University. But after a couple of years, she found she was still thinking of a career in health care.

One day in 2001, Nyamwanda noticed an ad for a medical dosimetrist in the Boston Globe. The preference was for a physics major interested in health care. "And I thought, that is me," she says. Nyamwanda applied and began on-the-job training at Massachusetts General Hospital, where she continues to practice as a part-time dosimetrist today. Finding the ad while sitting on her stoop that day was, she says, "very fortuitous."

Medical dosimetrists work with radiation oncologists to calculate the precise path of radiation beams as part of a cancer treatment plan. The challenge is to map a trajectory for the beam that targets a tumor without exceeding the radiation dosage limit for nearby organs. Dosimetrists are part of a team that

includes medical physicists, whose main role is one of quality assurance—checking that equipment is functioning properly and that calculations made by dosimetrists are correct. They may also develop new treatment techniques. And while medical physicists must go through a residency, dosimetrists complete specialized certificate programs and clinical training.

For Nyamwanda, it's rewarding to create treatment plans that help to prolong lives and ease pain. "Every day, I'm impacting someone's life," she says.

In addition to her clinical practice, Nyamwanda serves as the graduate program director for medical dosimetry at Boston's Suffolk University. In this multipronged role, Nyamwanda is able to teach what she practices, conduct research, and work with students in the clinic. She's also involved in outreach, helping to spread the word about dosimetry. It's a field that's growing as the Baby Boomer generation ages, but it's currently also experiencing a shortage of candidates, Nyamwanda says.

"It's very hidden, both literally and figuratively," she says, noting that radiation departments are often located in the basement of medical centers. But, she adds, word about the field is getting out.

For those interested in medical dosimetry, Nyamwanda says it's essential to love physics and have an interest in helping people. It's also important to have analytical and problem-solving skills, creativity, the ability to think in three dimensions—and a lot of patience. She recommends shadowing a professional or completing an internship in order to fully understand what's required of the job. This is important whether considering a career in dosimetry or education.

"You have to really enjoy what you're doing," she says. "I love the job even when things get stressful. I've never had a bad day of work at the clinic." •

# The Laws of Reflection, Refraction, and Relative Amplitudes

## Derived from Boundary Conditions of Maxwell's Equations

by Dwight E. Neuenschwander, Professor Emeritus, Southern Nazarene University

The laws of reflection and refraction in geometrical optics, and the relative amplitudes of the incident, reflected, and refracted waves, follow as deductive consequences of boundary conditions that emerge from Maxwell's equations.<sup>1</sup>

When electric and magnetic fields encounter matter, the molecules typically become polarized—or if they were already polarized, their dipole moments are enhanced. These induced electric and magnetic dipole moments produce additional electric and magnetic fields of their own. Taking these polarization effects into account, the Maxwell equations that relate charges and currents to the fields can be written in terms of the electric field  $\mathbf{D}$  due only to free (excess) charges of density  $\rho_o$  and the magnetic field  $\mathbf{H}$  due only to free currents of density  $\mathbf{j}_o$ :

$$\nabla \cdot \mathbf{D} = \rho_o \quad (1)$$

$$\nabla \times \mathbf{H} = \mathbf{j}_o + \frac{\partial \mathbf{D}}{\partial t}. \quad (2)$$

The Maxwell equations with no source terms are conveniently written in terms of the total electric field  $\mathbf{E}$  and the total magnetic field  $\mathbf{B}$ :

$$\nabla \cdot \mathbf{B} = 0 \quad (3)$$

$$\nabla \times \mathbf{E} = -\frac{\partial \mathbf{B}}{\partial t}. \quad (4)$$

The source-free and total fields are related to each other through parameters that encode the effects of polarization,<sup>2</sup> in the so-called constitutive relations, which in homogeneous and isotropic media<sup>3</sup> take the form

$$\mathbf{D} = \epsilon \mathbf{E}, \quad (5)$$

where  $\epsilon$  is the material's permittivity, and

$$\mathbf{H} = \frac{\mathbf{B}}{\mu}, \quad (6)$$

where  $\mu$  is the material's permeability. If the medium contains no matter at all—a vacuum—the permittivity of free space is  $\epsilon_o = 8.85 \times 10^{-12}$  F/m, with permeability  $\mu_o = 4\pi \times 10^{-7}$  H/m. Significantly,

$$\mu_o \epsilon_o = \frac{1}{c^2}, \quad (7)$$

where  $c$  denotes the speed of light in vacuum,  $c = 3 \times 10^8$  m/s. Equations for electromagnetic waves in matter readily follow from Maxwell's equations. For instance, taking the curl of Eq. (2) and using a vector identity yields

$$\nabla(\nabla \cdot \mathbf{H}) - \nabla^2 \mathbf{H} = (\nabla \times \mathbf{j}_o) - \frac{\partial}{\partial t}(\nabla \times \mathbf{D}). \quad (8)$$

You can use Eqs. (3) and (6), eliminate the first term, and use Eqs. (4) and (5) to turn Eq. (8) into the inhomogeneous wave equation for  $\mathbf{H}$ ,

$$\nabla^2 \mathbf{H} - \mu \epsilon \frac{\partial^2 \mathbf{H}}{\partial t^2} = -(\nabla \times \mathbf{j}_o), \quad (9)$$

showing the magnetic wave's speed to be  $1/\sqrt{\mu\epsilon}$ . A similar wave equation can be derived for  $\mathbf{D}$  by taking the curl of Eq. (4), then using the constitutive relations and the other Maxwell equations to derive

$$\nabla^2 \mathbf{D} - \mu \epsilon \frac{\partial^2 \mathbf{D}}{\partial t^2} = \nabla \rho_o + \mu \epsilon \frac{\partial \mathbf{j}_o}{\partial t}. \quad (10)$$

Comparing Eqs. (9) and (10), we can see that electromagnetic waves in a medium travel at the speed

$$v = \frac{1}{\sqrt{\mu\epsilon}}. \quad (11)$$

Since the index of refraction  $n$  may be defined as  $n = c/v$ , it follows from Eq. (11) that

$$n = c \sqrt{\mu\epsilon}. \quad (12)$$

These are input facts for describing electric and magnetic fields in a material medium. Now we need the boundary conditions to see the effects on the fields when they pass from one medium into another.

### Maxwell's Boundary Conditions

Consider two homogeneous, isotropic, nonconducting media that are in contact. Whatever the shape of the contact boundary, any infinitesimal section of it may be considered a plane. In what follows we assume that no free charges and no free currents exist on the boundary, so that  $\rho_o = 0$  and  $\mathbf{j}_o = 0$  there. In source-free regions, the integral versions of Eqs. (1)-(4) read

$$\oint \mathbf{D} \cdot \hat{\mathbf{n}} \, dA = 0 \quad (13)$$

$$\oint_C \mathbf{H} \cdot d\mathbf{r} = \frac{d}{dt} \int_S \mathbf{D} \cdot \hat{\mathbf{n}} \, dA \quad (14)$$

$$\oint \mathbf{B} \cdot \hat{\mathbf{n}} \, dA = 0 \quad (15)$$

$$\oint_C \mathbf{E} \cdot d\mathbf{r} = -\frac{d}{dt} \int_S \mathbf{B} \cdot \hat{\mathbf{n}} \, dA. \quad (16)$$

Equations (13) and (15) apply to any closed surface; in Eqs. (14) and (16)  $S$  is any nonclosed surface that has closed path  $C$  for its boundary.

Imagine a small, closed Gaussian surface, a wee little box that straddles the boundary between the two media.

Let the box's surfaces parallel to the boundary have area  $A$ . Let the box sides that connect the surfaces above and below the boundary have height  $h$ , which will go to zero, leaving the two parallel surfaces skimming the boundary on either side of it (Fig. 1). Equation (13) applied to this closed surface implies the normal component of  $\mathbf{D}$  is continuous,  $(D_{n1} - D_{n2})A = 0$ , or  $\Delta D_n = 0$  for short. Similarly,  $\Delta B_n = 0$  from Eq. (15).

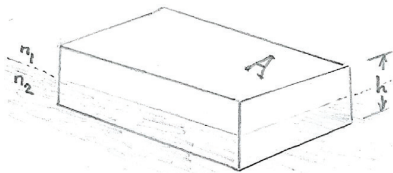


Figure 1. A Gaussian closed box used to derive  $\Delta D_n = 0$  and  $\Delta B_n = 0$ .

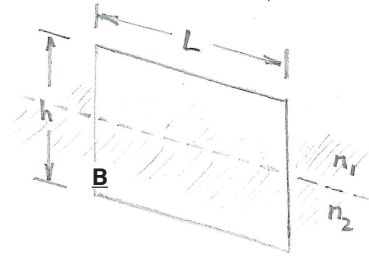


Figure 2. A closed path used to derive  $\Delta E_t = 0$  and  $\Delta H_t = 0$ .

Consider next a small rectangular contour  $C$  in Eq. (16). Let two sides of  $C$  have length  $L$  and be parallel to the boundary, one side above and one side below. Let the other two sides of  $C$  have length  $h$ , which will go to zero, leaving the two sides of length  $L$  skimming the boundary on either side (Fig. 2). Equation (16) applied to this situation implies the tangential component of  $\mathbf{E}$  is continuous,  $(E_{t2} - E_{t1})L = 0$ , or  $\Delta E_t = 0$  for short. Similarly, Eq. (14) yields  $\Delta H_t = 0$ . To summarize, Maxwell's equations for these situations require

$$\Delta D_n = 0, \quad (17)$$

$$\Delta E_t = 0, \quad (18)$$

$$\Delta B_n = 0, \quad (19)$$

$$\Delta H_t = 0. \quad (20)$$

Now let the boundary of contact between the two media be designated as the  $xy$  plane, with the positive  $z$ -axis in medium 1. Let the refractive indices of the two media be  $n_1 = c\sqrt{\mu_1\epsilon_1}$  for  $z > 0$  and  $n_2 = c\sqrt{\mu_2\epsilon_2}$  for  $z < 0$ . Consider a plane wave in medium 1 approaching the boundary with its corresponding ray, making the angle  $\theta$  relative to the  $+z$ -axis (Fig. 3). Some of the energy carried by the electromagnetic wave will be reflected, and some energy will be refracted.<sup>4</sup> As shown in Fig. 4, let the reflected ray leave the boundary at angle  $\theta^*$  from the normal, while the ray of the refracted wave enters medium 2 at the angle  $\theta'$  as measured from the normal line.

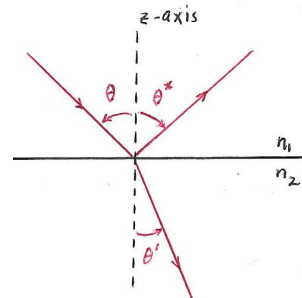


Figure 3. The angles made by the incoming ( $\theta$ ), reflected ( $\theta^*$ ), and refracted ( $\theta'$ ) rays, relative to the normal of the boundary surface.

With a wave-number vector  $\mathbf{k}$  describing the direction of propagation, let an incident harmonic wave be expressed as

$$\mathbf{E}_{inc}(\mathbf{r}, t) = \mathbf{E} e^{i(\mathbf{k}\cdot\mathbf{r} - \omega t)}, \quad (21)$$

the reflected wave as

$$\mathbf{E}_{refl}(\mathbf{r}, t) = \mathbf{E}^* e^{i(\mathbf{k}^*\cdot\mathbf{r} - \omega^* t)}, \quad (22)$$

and the refracted wave as

$$\mathbf{E}_{refr}(\mathbf{r}, t) = \mathbf{E}' e^{i(\mathbf{k}'\cdot\mathbf{r} - \omega' t)}. \quad (23)$$

For any of these fields, Eq. (4) requires, for their respective  $\mathbf{k}$  and  $\omega$ ,

$$\mathbf{k} \times \mathbf{E} = \omega \mathbf{B}, \quad (24)$$

while Eqs. (1) and (3) give  $\mathbf{k} \cdot \mathbf{D} = 0$  and  $\mathbf{k} \cdot \mathbf{B} = 0$ , respectively. We see, therefore, that the propagation vector  $\mathbf{k}$ , the electric field, and the magnetic field are mutually perpendicular. This fact along with  $v = \omega/k$  and Eqs. (24) and (12) imply, for each of the three waves,

$$|\mathbf{B}| = \sqrt{\mu\epsilon} |\mathbf{E}| = \frac{n}{c} |\mathbf{E}|. \quad (25)$$

Since we assume that no free charges or currents reside on the boundary surface between media 1 and 2, the normal and tangential component of the electric and magnetic fields must be continuous at  $z = 0$  at any time and at any location on the boundary. Therefore, at the boundary, the phases of the incident, reflected, and refracted waves must be equal:

$$e^{i(\mathbf{k}\cdot\mathbf{r} - \omega t)} = e^{i(\mathbf{k}^*\cdot\mathbf{r} - \omega^* t)} = e^{i(\mathbf{k}'\cdot\mathbf{r} - \omega' t)}. \quad (26)$$

Requiring Eq. (26) to hold for any time  $t$  means

$$\omega = \omega^* = \omega', \quad (27)$$

so classical electrodynamics predicts that the reflected and refracted waves will emerge from the boundary interaction with unchanged frequencies, which seems validated in everyday life— if our mirror is made of uncolored glass, then our reflection comes back to us with the same color as the light incident on it. (This classical electrodynamics background illustrates the significance of the Compton effect.<sup>5</sup>) Using Eq. (27) in Eq. (26) implies that, for each wave with its respective parameters,  $\omega = vk = ck/n$ , so that

$$\frac{k}{n} = \frac{k^*}{n^*} = \frac{k'}{n'}, \quad (28)$$

where  $n_1 = n = n^*$  and  $n_2 = n'$ . Also, in the boundary surface where  $z = 0$ , where the  $\mathbf{r}$  vectors depend only on  $x$  and  $y$ , the continuity of the field components in homogeneous, isotropic media implies

$$\mathbf{k} \cdot \mathbf{r} = \mathbf{k}^* \cdot \mathbf{r} = \mathbf{k}' \cdot \mathbf{r}, \quad (29)$$

which implies

$$k \sin \theta = k^* \sin \theta^* = k' \sin \theta'. \quad (30)$$

Examine the left equality of Eq. (30),

$$k \sin \theta = k^* \sin \theta^*. \quad (31)$$

Since the incident and reflected wave are in the same medium so that  $n = n^*$ , Eq. (28) gives  $k = k^*$ , and Eq. (31) thereby requires

$$\theta = \theta^*, \quad (32)$$

the law of reflection. From the right equality of Eq. (30) we have

$$k \sin \theta = k' \sin \theta'. \quad (33)$$

Recalling  $k = n\omega/c$  and Eq. (27), Eq. (33) becomes

$$n \sin \theta = n' \sin \theta', \quad (34)$$

the law of refraction, Snell's law.

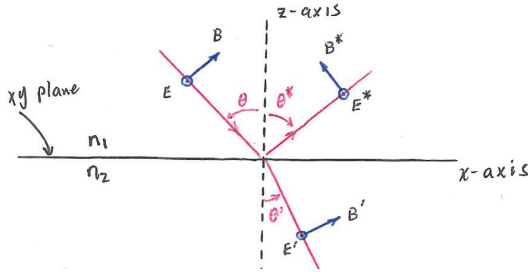
We might say that Eq. (26) is the kinematic part of the boundary conditions in Maxwell's equations, because the laws of reflection and refraction describe the directions of the reflected and refracted rays relative to the incident ray. The dynamic part of the boundary conditions will tell us the amplitudes of the reflected and refracted waves relative to the incident one, which determines where the energy goes, since the energy carried by a wave is proportional to the square of its amplitude. These results are called the Fresnel equations.

## The Fresnel Equations

Since electromagnetic radiation consists of transverse waves, the electric and magnetic fields can be polarized into two sets of orthogonal modes. Therefore, we consider two independent polarization states incident on the boundary:

- (1) The incident  $\mathbf{E}$  comes into the boundary tangent to the  $xy$  plane, with  $\mathbf{B}$  in the  $xz$  plane; and
- (2) The incident  $\mathbf{B}$  comes into the boundary tangent to the  $xy$  plane and  $\mathbf{E}$  lies in the  $xz$  plane.

**Case 1:**  $\mathbf{E}$  tangent to the  $xy$  boundary plane,  $\mathbf{B}$  parallel to the  $xz$  plane



**Figure 4.** Case 1 polarization:  $\mathbf{E}$  tangent to the  $xy$  boundary plane,  $\mathbf{B}$  parallel to the  $xz$  plane.

The boundary condition  $\Delta E_t = 0$  implies

$$E + E^* = E'. \quad (35)$$

The boundary condition  $\Delta H_t = 0$  along with  $\mathbf{H} = \mathbf{B}/\mu$  and  $\theta = \theta^*$  yields

$$\frac{1}{\mu_1} (B - B^*) \cos \theta = \frac{1}{\mu_2} B' \cos \theta'. \quad (36)$$

By virtue of Eq. (25), this may be written

$$\frac{n}{\mu_1} (E - E^*) \cos \theta = \frac{n'}{\mu_2} E' \cos \theta'. \quad (37)$$

Equations (35) and (37) are two equations in two unknowns for  $E^*/E$  and  $E'/E$ . After a bit of algebra, this pair of equations gives the first set of Fresnel equations:

$$\frac{E^*}{E} = \frac{\frac{n}{\mu_1} \cos \theta - \frac{n'}{\mu_2} \cos \theta'}{\frac{n}{\mu_1} \cos \theta + \frac{n'}{\mu_2} \cos \theta'} \quad (38a)$$

and

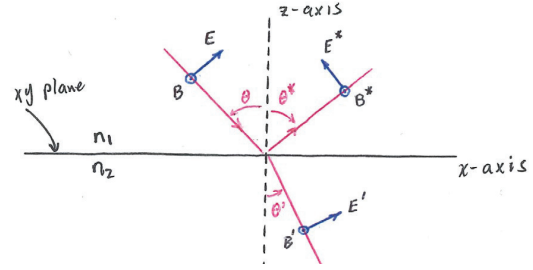
$$\frac{E'}{E} = \frac{2 \frac{n}{\mu_1} \cos \theta}{\frac{n}{\mu_1} \cos \theta + \frac{n'}{\mu_2} \cos \theta'}. \quad (38b)$$

If  $\mu_1 \approx \mu_2$  (which is typical for nonmagnetized material), then these Fresnel equations for Case 1 ( $\mathbf{E}$  tangent to the boundary) simplify to

$$\frac{E^*}{E} = \frac{n \cos \theta - n' \cos \theta'}{n \cos \theta + n' \cos \theta'} \quad (39a)$$

$$\frac{E'}{E} = \frac{2n \cos \theta}{n \cos \theta + n' \cos \theta'}. \quad (39b)$$

**Case 2:**  $\mathbf{B}$  tangent to the  $xy$  boundary surface,  $\mathbf{E}$  parallel to the  $xz$  plane



**Figure 5.** Case 2 polarization:  $\mathbf{B}$  tangent to the  $xy$  boundary plane,  $\mathbf{E}$  parallel to the  $xz$  plane.

The boundary condition  $\Delta H_t = 0$  gives

$$H + H^* = H'. \quad (40)$$

Using  $H = B/\mu = nE/c\mu$  and assuming  $\mu_1 = \mu_2$  turns Eq. (40) into

$$n(E + E^*) = n'E'. \quad (41)$$

The boundary condition  $\Delta E_t = 0$  implies

$$(E - E^*) \cos \theta = E' \cos \theta'. \quad (42)$$

Now Eqs. (41) and (42) are two equations in two unknowns for  $E^*/E$  and  $E'/E$ . Solving Eq. (41) for  $E'$  and inserting the result into Eq. (42) gives

$$E - E^* = \frac{n \cos \theta'}{n' \cos \theta} (E + E^*). \quad (43)$$

Using Snell's law, Eq. (34), to rewrite  $n/n'$  in terms of sine functions, and with the trig identity  $\sin \alpha \cos \alpha = \frac{1}{2} \sin(2\alpha)$ , Eq. (43) may be written

$$E - E^* = \frac{\sin(2\theta')}{\sin(2\theta)} (E + E^*) \quad (44)$$

or

$$\frac{E^*}{E} = \frac{\sin(2\theta) - \sin(2\theta')}{\sin(2\theta) + \sin(2\theta')}. \quad (45)$$

With the assistance of the trig identities

$$\sin \alpha - \sin \beta = 2 \cos \left( \frac{\alpha + \beta}{2} \right) \sin \left( \frac{\alpha - \beta}{2} \right) \quad (46)$$

and

$$\sin \alpha + \sin \beta = 2 \sin \left( \frac{\alpha + \beta}{2} \right) \cos \left( \frac{\alpha - \beta}{2} \right), \quad (47)$$

Eq. (45) becomes

$$\frac{E^*}{E} = \frac{\tan(\theta - \theta')}{\tan(\theta + \theta')}. \quad (48)$$

Now return to Eq. (41) and use Snell's law to write it as

$$E' = \frac{\sin \theta'}{\sin \theta} (E + E^*). \quad (49)$$

Insert  $E^*$  from Eq. (48) to derive, with the help of the trig identity

$$\tan \alpha + \tan \beta = \frac{\sin(\alpha + \beta)}{\cos \alpha \cos \beta}, \quad (50)$$

the result

$$\frac{E'}{E} = \frac{2 \cos \theta \sin \theta'}{\sin(\theta + \theta') \cos(\theta - \theta')}. \quad (51)$$

Equations (48) and (51) are the Fresnel equations for Case 2 (**B** tangent to the boundary).

### Alternative Derivations

Since we have four applicable boundary conditions, Eqs. (17)-(20), you may ask why we used only half of them—the continuity of the tangential components—in deriving both sets of Fresnel equations. The answer is that the Fresnel equations can alternatively be derived, producing identical or equivalent results, using other pairs of the four boundary condition equations. For instance, let us return to Case 2 and recall Eq. (42) for continuity in the tangential component of **E**, repeated here as

$$E - E^* = \frac{\cos \theta'}{\cos \theta} E'. \quad (52)$$

Instead of using continuity in the tangential component of **H**, let us use continuity in the normal component of **D**. The boundary condition  $\Delta D_n = 0$  along with **D** =  $\epsilon \mathbf{E}$  gives

$$\epsilon_1 (E + E^*) \sin \theta = \epsilon_2 E' \sin \theta' \quad (53)$$

or

$$E + E^* = \frac{\epsilon_2 \sin \theta'}{\epsilon_1 \sin \theta} E'. \quad (54)$$

Referring back to Snell's law, Eq. (34), and  $n = c \sqrt{\mu \epsilon}$ , Eq. (12), it follows that

$$\frac{\mu_1 \epsilon_1}{\mu_2 \epsilon_2} = \left( \frac{\sin \theta'}{\sin \theta} \right)^2, \quad (55)$$

and assuming  $\mu_1 = \mu_2$ , Eq. (55) turns Eq. (54) into

$$E + E^* = \frac{\sin \theta}{\sin \theta'} E'. \quad (56)$$

Now Eqs. (52) and (56) are two equations in two unknowns for  $E^*/E$  and  $E'/E$ . After some more algebra that includes use of trig identities, we find

$$\frac{E^*}{E} = \frac{\tan(\theta - \theta')}{\tan(\theta + \theta')} \quad (57)$$

and

$$\frac{E'}{E} = \frac{2 \sin \theta' \cos \theta}{\sin(\theta + \theta') \cos(\theta - \theta')}, \quad (58)$$

as before. The boundary conditions are quite robust!

### References

1. See David Griffith, *Introduction to Electrodynamics*, 2nd ed. (Prentice-Hall, 1989), Ch. 4 for a discussion of electric polarization, Ch. 6 for magnetic polarization, and Ch. 7 for a detailed discussion.
2. See David Griffith, *Introduction to Electrodynamics*, 2nd ed. (Prentice-Hall, 1989), Ch. 4 for a discussion of electric polarization, and Ch. 6 for magnetic polarization.
3. If the medium is not homogeneous, then  $\epsilon$  and  $\mu$  will vary with position; if the medium is not isotropic, then the permittivity and permeability coefficients become components of second-rank tensors.
4. Attenuation may be neglected since we examine the amplitudes at the surface; only when the wave has penetrated some distance into a medium will attenuation, if present, be measurable.
5. The Compton effect, which uses special relativity and quantum mechanics to model the collision between a photon and free particle of mass  $m$  that is initially stationary, shows a shift in the light's wavelength (and thus its frequency) from  $\lambda$  to  $\lambda'$  according to  $\lambda' - \lambda = \frac{h}{mc} (1 - \cos \theta)$ , where  $h$  is Planck's constant,  $c$  the speed of light in vacuum, and  $\theta$  the angle of the outgoing photon relative to the incoming one. Because  $h/c$  is so very small, the mass  $m$  must also be very small (e.g., an electron) for  $\lambda' - \lambda$  to be appreciable. The light that bounces off the mirror is "Compton-scattering" off the entire mirror, whose shiny surface consists of electrons bound to their atoms. Thus,  $\lambda' - \lambda \approx 0$  and the Compton effect goes over to the classical limit. The Compton effect (Arthur H. Compton, *Phys. Rev.* **22**, p. 411, 1923) was one of the crucial predictions confirmed by experiment that compelled the physics community to take relativity and quantum mechanics seriously.

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