Radiations

SPRING
2021

The official publication of Sigma Pi Sigma

From **College** to **Career**

SPS OUTSTANDING SERVICE AWARD

SPS awards 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.

Do you know an SPS or Sigma Pi Sigma member who has had a positive impact on an SPS chapter, a department, or the broader community?

Nominate a member today!

www.spsnational.org/awards/service

Applications are accepted on a rolling basis.

ΣΠΣ OUTSTANDING SERVICE AWARDS

ΣΠΣ is looking to award individuals who have performed meritorious service to the field of physics, to Sigma Pi Sigma, or your department.

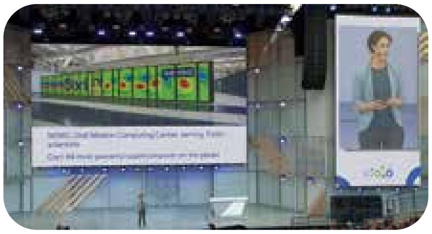
Awards can be bestowed by individual chapters.

Nominate someone today!

www.sigmapisigma.org/awards/service

Recipients receive national recognition and certificate.

Contents



ON THE COVER

Dorian C. Moore, president of Florida A&M University's SPS chapter, was one of the students recognized in the 2020 Virtual Senior Recognition Ceremony hosted by the Society of Physics Students. Image courtesy of Dorian C. Moore.

Radiations

Spring 2021
Volume 27, Issue 1

Radiations (ISSN 2160-1119) is the official publication of Sigma Pi Sigma, the physics honor society, published twice per year by the American Institute of Physics, One Physics Ellipse, College Park, MD 20740-3841. Printed in the USA. Standard postage paid at Columbus, OH. POSTMASTER: Send address changes to: Radiations Magazine, Sigma Pi Sigma, 1 Physics Ellipse, College Park, MD 20740-3841.

Sigma Pi Sigma is an organization of the American Institute of Physics. It was founded at Davidson College, Davidson, NC, December 11, 1921. Member, Association of College Honor Societies. Contact us at sigmapisigma@aip.org; telephone: (301) 209-3007; fax: (301) 209-3082.

LETTER FROM THE CENTENNIAL SIGMA PI SIGMA CONGRESS EXECUTIVE PROGRAM COMMITTEE CHAIR

Building Momentum for the Next Generation of Physicists

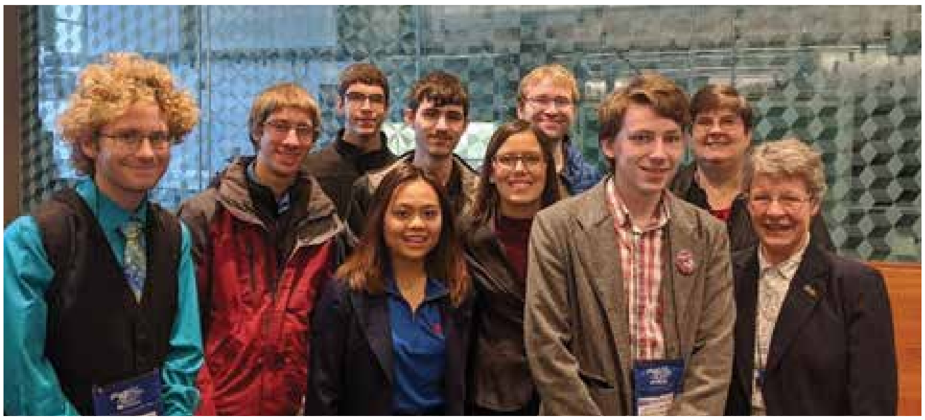
by DJ Wagner, Past President of SPS National, SPS Chapter Advisor and Professor of Physics, Grove City College

Photo courtesy of DJ Wagner.

As I look through the contents of this issue of Radiations, I think about how much has changed since my own Sigma Pi Sigma induction 30 years ago. I don't recall having access to any resources about careers in physics. Of course, the World Wide Web hadn't been invented yet, so dissemination of information was very different! Now, many physics departments offer multiple concentrations to help students tailor their studies to their chosen path, career services offices are often (or at least sometimes) better informed about the diverse careers physics majors pursue, and many excellent career resources abound, such as the Careers Toolbox and the profiles of physicists available on the SPS website. Departments, and SPS, continue to evolve to meet the changing needs and resources of each generation.

One amazing resource not available when I was a student is the Sigma Pi Sigma Congress—PhysCon. Attending conferences and getting a sense of what it means to be a professional is a valuable experience for students, and I strongly encourage all of my students to attend conferences whenever possible. The Sigma Pi Sigma Congress is unique because it is a conference designed with the physics undergraduate in mind—whether a speaker will be understandable by and accessible to undergraduate students is a key criterion of Sigma Pi Sigma Congress planning. There are also interactive workshops relevant to the undergraduate; opportunities for students to present posters on science outreach and research (in any stage and at any level of significance); a physics "phine art" contest and exhibit; fascinating tours; talks by world-class physicists; opportunities for chapters to share ideas; networking, both with peers and with professionals in the field; and much more.

My first experience with the Sigma Pi Sigma Congress was in 2004, attending with one student. As the conference wore on, I thought, "This is the best conference I have ever attended! I am bringing a busload of students to the next one!" So I did—I have brought between 20 and 33 students to each Sigma Pi Sigma Congress since then. Whether it is meeting famous speakers such as Dame Jocelyn Bell Burnell, who has graciously posed with my students at the past three congresses (see photo), getting to share research ideas with both students and professionals in the field, learning about some cutting-edge advance in the field, making connections that lead to a summer internship, job, or graduate school, or just



Members of the Grove City College Physics Club with Dame Jocelyn Bell Burnell at the 2019 Sigma Pi Sigma Congress. Photo courtesy of DJ Wagner.

finding out how many other physics students are out there who share their interests, the Sigma Pi Sigma Congress has been a valuable part of my students' educational experience.

I encourage you to help the next generation of physicists by getting involved in the upcoming Sigma Pi Sigma Congress taking place in Washington, DC, in October 2022. Please also consider attending—the conference is open to everyone, and we are hoping to attract a large number of alumni for this centennial celebration of Sigma Pi Sigma. If you are connected to an undergraduate physics program, encourage students (and faculty) to attend and do whatever you can to support their trip. If you are able, donate to help defray travel expenses: to your local chapter or your alma mater, with instructions to use the funds for Sigma Pi Sigma Congress student travel, and/or to the ΣΠΣ Centennial Campaign fund, which specifically supports student travel to the Sigma Pi Sigma Congress. This will be a fantastic event, and I hope I will see you (and the students you encouraged to attend) there! ●

DJ Wagner is a member of the College of William & Mary ΣΠΣ chapter ('91) and advisor of the Grove City College chapter. She served on the National Council for 11 years, four as SPS president, and has been a key member of the planning committees for three Sigma Pi Sigma Congresses, including the upcoming Congress in 2022.

The Grove City College Physics Club at 2019 Sigma Pi Sigma Congress.
Photo courtesy of DJ Wagner.

physcon
2022 Physics Congress

October 6-8, 2022
Washington, D.C.

Centennial Congress Plenary Speakers:

Dame S. Jocelyn Bell Burnell
Rush Holt
Sarah Hörst
Renee Horton
Julianne Pollard-Larkin

Learn more about the 2022 Congress at sigmapisigma.org/congress/2022.
Read about funding opportunities for student travel here:
sigmapisigma.org/congress/2022/awards

AIP
American Institute of Physics

The American Institute of Physics is a federation of scientific societies in the physical sciences, representing scientists, engineers, educators, and students. AIP offers authoritative information, services, and expertise in physics education and student programs, science communication, government relations, career services, statistical research in physics employment and education, industrial outreach, and history of the physical sciences. AIP publishes *Physics Today,* the most closely followed magazine of the physical sciences community, and is also home to the Society of Physics Students and the Niels Bohr Library & Archives. AIP owns AIP Publishing LLC, a scholarly publisher in the physical and related sciences. www.aip.org

Member Societies

Acoustical Society of America
American Association of Physicists in Medicine
American Association of Physics Teachers
American Astronomical Society
American Crystallographic Association
American Meteorological Society
American Physical Society
AVS Science and Technology of Materials, Interfaces, and Processing
The Optical Society
The Society of Rheology

Other Member Organizations

Sigma Pi Sigma
Society of Physics Students
Corporate Associates

Connect with Sigma Pi Sigma

LinkedIn
www.linkedin.com/groups/Sigma-Pi-Sigma-physics-honor-142619

Facebook
www.facebook.com/groups/sigmapisigma

Donate
donate.aip.org

Sigma Pi Sigma — A Departmental Legacy of Fellowship Part 4: SPS — A Society for All

by Brad R. Conrad, Director of the Society of Physics Students and Sigma Pi Sigma

Well before the 1968 creation of the Society of Physics Students from the merging of Sigma Pi Sigma (ΣΠΣ) chapters and American Institute of Physics (AIP) local student sections, physics departments from across the country knew that ΣΠΣ could do more. While ΣΠΣ was bringing together students from different class years (within individual departments) and helping to increase interactions with some alumni, not everyone could meet the high academic bar set by the honor society. As a member of the Association of College Honor Societies (ACHS), ΣΠΣ adhered to rules that standardized membership requirements for academic honors societies. Before the formation of SPS, correspondence between advisers and Marsh White, the administrative executive of ΣΠΣ, discussed ways to broaden the base of people who could benefit from the organization. For example, the Syracuse University chapter created an associate membership class for students who completed their first course in physics.[1] This general observation—that all physics students within the department had need of something like ΣΠΣ—was also observed by the leadership of AIP.

Informal meetings during the early 1940s led Marsh White to formally approach Dr. Henry Barton, then AIP director, in 1948.[2] White originally proposed that ΣΠΣ join AIP as a full membership society. Realizing the importance of helping students become professional physicists and astronomers, Dr. Barton created a special committee (consisting of AIP board members) to explore the idea and report back to the Board of Directors with recommendations. Through several meetings in 1948, AIP's Policy Committee recommended that AIP should form a "special relationship" with ΣΠΣ, different from its relationships with the existing five Member Societies.[3] In response, a joint ΣΠΣ/AIP committee comprised of active members from both societies was formed to investigate "other ways in which ΣΠΣ could satisfactorily be incorporated into AIP."[3] Discussions proceeded for several years, with progress shared regularly with ΣΠΣ membership through public and confidential correspondence. Much of the conversation focused on how to best serve departments and students "to develop spirit and also the beginnings of a professional society" among students. A primary concern for ΣΠΣ was how to preserve the pursuit of excellence on which ΣΠΣ was founded.

It's important to note that ΣΠΣ's regular correspondence with departments about these developments generated a large number of suggestions and public discussion. Publicly shared feedback tended to focus on the need for departmental and Member Society interactions, technical sessions (professional development) for students, and a need to increase alumni interactions across the sciences. Above all, the need to support "all students with an interest in physics" drove the conversation. In addition, the small society's highly variable budget and financial instability hampered its ability to provide consistent student support in a shifting educational landscape. For example, early ΣΠΣ initiatives included graduate fellowships. A 1936 ΣΠΣ newsletter notes the fellowship value, $450 at the time, as less than ideal given that a $500 salary constituted comfortable living.[4] ΣΠΣ also offered emergency student loans to students experiencing financial need (repayable, as they could afford), when it was financially able.

Figure 1: (L-R) Marsh White, Vincent Parker, Walter French, Lewis Seagondollar, and Stanley Ballard at a 1965 Sigma Pi Sigma Executive Committee Meeting at Oak Ridge National Labs. Photo courtesy of Oak Ridge Institute of Nuclear Studies Inc., courtesy of AIP Emilio Segrè Visual Archives, Physics Today Collection.

The joint ΣΠΣ/AIP committee, comprised of active ΣΠΣ and AIP Member Society members, ultimately recommended that AIP and ΣΠΣ work together to establish one home for physics students. To begin this complicated and long process, the committee recommended the formation of local student sections of AIP with a governance structure based on that of ΣΠΣ. This meant that a new organization could begin to take shape even as AIP and ΣΠΣ worked out the details of the formal agreement. A core tenet of the recommendation was that two separate societies for physics students would be a disservice to both the departments and the Member Societies. The formation of AIP chapters was not without considerable discussion, as at least four different versions of the local sections were developed before a consensus was reached. Participation in ΣΠΣ was to be actively encouraged in AIP chapters, and ΣΠΣ agreed to help support individual Member Society initiatives such as AAPT meetings, AIP careers services, and *Physics Today.* In the same spirit, ΣΠΣ petitioned APS leadership to create a membership category for graduate students.[5]

The collaboration continued to develop, as is evident by Marsh White's 1947 Statistical Survey of PhD Physicists in Training.[6] Data from the creation of ΣΠΣ chapters and local sections was then used by AIP to produce reports on enrollment and employment. Similar reports are still produced today through AIP's Statistical Research Center. As a sign of good faith and a token of future collaboration, ΣΠΣ also financially supported AIP, as much as a small student society could, through a $500 donation to the building fund of AIP.[7] As the magnitude of the endeavor to create what would become SPS was not wasted on the organizations, AIP, each of its five Member Societies, and ΣΠΣ ratified the creation of the AIP local student sections.

A model constitution for the local sections was developed by AIP in conjunction with ΣΠΣ through society leaders Homer Dodge, R. C. Gibbs, F. Wheeler Loomis, and Marsh White. That model is the basis of the constitution we use today.[8] The term "local sections of AIP" was used as a temporary name to avoid any confusion around the two separate student organizations and to provide a "flexible plan" so that an agreement between ΣΠΣ and AIP could be found without rushing forward. As a first step toward a formal agreement, ΣΠΣ was accepted as an AIP Affiliate in 1951.

Conversations about how to best combine ΣΠΣ and the AIP local student sections continued through the 1950s and were driven by how to most effectively educate the growing number of future physicists, how to incorporate graduating students into Member Societies, and how to effectively govern a large chapter-based society while maintaining membership oversight. A large part of the delay between inception of the merger and full implementation came from eight years of negotiations with ACHS about how ΣΠΣ could remain a recognized honor society while sharing a constitution with a society that welcomes all. White's desire to retire after 30 years accelerated the issue, resulting in the three-year process of voting to merge the societies. In August of 1966 the AIP Governing Board gave its unanimous approval to the merger plan. The same plan went for a final vote by 200 delegates representing 90 chapters at the 1967 Physics Congress and was approved by a one-vote margin![8] While the two societies were already intertwined, delegates were concerned about oversight and maintaining the spirit of ΣΠΣ. The final agreement required AIP to provide financial support for a full-time director, a fund to support Sigma Pi Sigma in perpetuity, and conditions under which Sigma Pi Sigma could withdraw from the new organization "if things did not work well."[9] Ultimately, society leaders within ΣΠΣ, the AIP student sections, and department chairs from around the country helped to form the key concepts that would guide the formation of SPS:

1. We must do what "best serves the need of the students."[2]
2. We must form the widest possible umbrella—everyone with an interest in physics is welcome.
3. Competing societies are hurtful to both departments and future physicists and astronomers.

A key result of the 1967 Congress was that the two organizations should remain linked in purpose but held as distinct entities in character. One of the most important aspects of any organization, especially a member society, is how it chooses to acknowledge itself publicly. The emerging society made two such public declarations to convey its identity: its name and its symbol. Names were discussed at great length, even when being compared to a standard department meeting. Ultimately, the Society of Physics Students was selected as the most inclusive name. This name reflects the society's support of all physics students, no matter what they might wish to do upon graduation. Undergraduates unsure of their future, career ambitions, and even their major may be wary of joining professional organizations tied to one track, but as the adopted name implies, they can find a home in SPS.

In the same vein, one of the first actions of the newly formed 1968 Executive Committee and National Council of the Society of Physics Students and Sigma Pi Sigma was to have chapters decide on both an insignia and symbol for this new student-focused organization. Marsh White and AIP director Ed Koch requested no change to the ΣΠΣ logo but advocated for students to determine a new logo for the Society of Physics Students. One of the first actions of the newly formed National Council was to hold a student competition to determine the SPS logo and seal.

With over one quarter of all chapters submitting a design, the logo and seal were selected by vote of the Executive Committee and National Council from over 66 finalists. The SPS logo was submitted by Craig B. Shumaker of the Purdue University chapter, and the basic design for the seal was submitted by Bruce Bushman of the Seattle University chapter[10] (see Figs. 2 and 3, respectively). Each student received a $100 prize (over $700 in today's US dollars). While the insignia is used in official communications from the national organization, chapters often use the SPS logo in unique ways to express themselves and what they are passionate about: at carved pumpkin art competitions, on physics-themed T-shirts, and prominently displayed on SPS lounge walls in hundreds of configurations. Just like the symbol, SPS is whatever it needs to be to best serve its student members. To this day, the SPS logo and insignia are a reminder of the organization's commitment to student leadership and self-determination. ●

Figure 2: Earliest known use of the SPS logo, dated May 1970. Image courtesy of SPS National.

Figure 3: The student-designed seal of SPS and Sigma Pi Sigma. Image courtesy of SPS National.

References:

1. W. R. Fredrickson, Department head of University of Syracuse, Private correspondence, April 2, 1948.
2. M. White, Sigma Pi Sigma general letter to the Executive Committee, December 16, 1948.
3. *The Radiations*, 1949, vol. XIV, no. 4.
4. *The Bulletin of Sigma Pi Sigma*, May 14, 1936, vol. 5.
5. *Radiations,* 1949, vol. XIV, no. 2.
6. M. W. White, "Statistical Survey of Number of Physicists in Training," Rev. Sci. Instrum. 18, no. 4 (1947).
7. M. White, Sigma Pi Sigma general letter to chapters, January 30, 1945.
8. Executive Committee of the American Institute of Physics, April 1, 1950.
9. P. Dixon, "The History of Sigma Pi Sigma," https://www.sigmapisigma.org/sigmapisigma/about/history.
10. *Society of Physics Students Newsletter,* January 22, 1969.

Read More

This article is Part 4 in "Sigma Pi Sigma – A Departmental Legacy of Fellowship," a series highlighting the history of Sigma Pi Sigma and SPS in celebration of our upcoming Centennial on December 11, 2021. The rest of the series is available online.

- **Part I: Formation and the Early Years**
  www.sigmapisigma.org/sigmapisigma/radiations/issues/fall-2019
- **Part 2: A Phase Change in the Late 1920s**
  www.sigmapisigma.org/sigmapisigma/radiations/issues/spring-2020
- **Part 3: Developing Community (1930s & '40s)**
  www.sigmapisigma.org/sigmapisigma/radiations/issues/fall-2020

Student Conferences – Sigma Pi Sigma Supports the Next Generation of Scientific Leaders through Crucial Grants and Awards

by Brad R. Conrad, Director of the Society of Physics Students and Sigma Pi Sigma

While travel remains something most students aren't able to do much of this academic year, student presentations (whether virtual or in person) remain one of the most important professional development activities in which they can participate. Engaging in regional and national conferences provides students with a wealth of skills and experiences that will serve them throughout their careers. While presenting at conferences can be a challenging experience for many students, the professional connections they make there and the act of connecting to lifelong professional societies and their members can help students find career pathways, paid positions, and future collaborators. By sharing their physics and astronomy research and outreach, students not only participate in the scientific process but also hone their communication skills as they learn to share findings and interests with a wide audience. Such experiences allow them to practice their elevator speeches and develop an awareness of what it means to become part of the scientific community beyond their immediate research groups and academic departments. Often, students gain insights into how their research connects to other research groups or entire fields of study of which they were not aware. Science that occurs in a vacuum runs the risk of not helping to advance the field and our shared understanding of the universe.

One of the primary goals of the Society of Physics Students is to be among the first membership societies that students experience to help prepare them to enter the professional community. Within its mission statement is a commitment to help students develop into contributing members of the professional community. While traditional coursework develops an extremely important set of skills, other skills are needed for students to flourish professionally, and student travel provides a vital key to unlocking those skills for many students.

A map showing the locations from which AAPM/COMP attendees participated in the virtual meeting. Image courtesy of the meeting's website: https://aapm-comp.pathable.co/.

As Sigma Pi Sigma members, we can help students acquire these skills by supporting undergraduates in overcoming the many financial burdens associated with participating in professional conferences and meetings. Each year the Society of Physics Students offers Student Travel and Student Reporter Awards for those who wish to attend, either to present their research or to report on a national or regional conference. While amounts are limited to $300 for an in-person event (or $75 to cover a virtual registration fee), these funds are a tremendous help for students as they piece together the support needed to participate in such meetings. Often, students will carpool, bring their own food, or share rooms to be able to afford to present work that represents the result of months or years of intensive focus and research. Having judged many undergraduate poster and oral presentations, I can personally attest that many people remember their first presentation with a mix of excitement and anxiety. It is because of the support of Sigma Pi Sigma members and the American Institute of Physics that SPS is able to offer these student awards each year.

If you would like to help support student presentations at regional and national meetings, please contribute to the Sigma Pi Sigma Endowment, which supports student travel grants and community events, or to the Congress Centennial Endowment, which supports student travel to the Sigma Pi Sigma Physics

Michelle de Oliveira. Photo courtesy of Oliveira.

"*Topics ranged from hard skills such as those used in diagnostic, imaging, and therapy physics, to softer skills like residency mentor–mentee relationships, social media, and alternative educational tracks. … All and all, I had a fantastic first AAPM|COMP experience that encouraged a greater understanding of what it means to be a medical physicist, specifically in response to growing need.*"
– Michelle de Oliveira, on attending an American Association of Physicists in Medicine (AAPM) and the Canadian Organization of Medical Physicists (COMP) Conference with the support of an SPS Reporter Award.

Congress, in perpetuity. Details can be found at the AIP Foundation's Student Programs page: **aip.org/helpstudents**. ●

A panel discusses the voice of women in physics. Taken on July 22, 2020 the final day of the AAPT conference. Image courtesy of Sarah Andersen.

"After learning remotely for half a semester and moving online for my summer internship, I realized that the world was transitioning to remote practices for the next year and potentially longer. I wanted to understand the implication of this transition on national physics departments and to better understand the reasoning behind new learning practices implemented by teachers. Furthermore, being one of few female physics majors at Wake Forest University, I had a particular interest in the equity and inclusion aspects of the conference. … I believe that a teacher can completely change a student's perspective on a subject and can play a significant role in his/her chosen academic path. Overall, I found the conference to be very insightful, and I am very grateful for the experience!"

- Sarah Anderson, *on attending the American Association of Physics Teachers Summer 2020 Meeting with the support of an SPS Reporter Award.*

Fall 2020 Chapter Awards

Congratulations to the following winners of the Fall 2020 Chapter Awards. These awards are made possible in part by generous contributions from Sigma Pi Sigma alumni. For examples of past award-winning projects, visit **www.spsnational.org/awards/chapter-awards**.

Future Faces of Physics

Future Faces of Physics Awards are made to SPS chapters to support projects designed to promote physics across cultures. The goal of the Future Faces of Physics Award is to promote the recruitment and retention of people from groups historically underrepresented in physics.

Calvin University
From Every Nation – Physics Mentoring for All
Willem Hoogendam (Leader)
Jason Smolinski (Advisor)

Illinois State University
ISU Physics Tutoring Program
Brighton Coe (Leader)
Matthew Caplan (Advisor)

University of Central Florida
Amplifying Diverse Perspectives
Riley Havel (Leader)
Costas Efthimiou (Advisor)

University of the Sciences
What's So Hot with Physics
Dan Fauni (Leader)
Roberto Ramos (Advisor)

The University of Texas at Dallas
Physics HALO
Victoria Catlett (Leader)
Jason Slinker (Advisor)

Marsh W. White

Marsh W. White Awards are made to SPS chapters to support projects designed to promote interest in physics among students and the general public. The Marsh W. White Award dates back to 1975 and is named in honor of Dr. Marsh W. White for his long years of service to Sigma Pi Sigma and the community.

Cleveland State University
It's Getting Hot in Here!
Andrew Scherer (Leader)
Kiril Streletzky (Advisor)

University of Dayton
The Power of Light: Increasing Interest in Physics Through Optics
John Merkle (Leader)
Jay Mathews (Advisor)

University of Rochester
DIY Physics Demonstration Boxes
Molly Griston (Leader)
Frank Wolfs (Advisor)

University of the Sciences
The Sound of Science
Keeran Ramanathan (Leader)
Roberto Ramos (Advisor)

SPS Chapter Research

The SPS Chapter Research Award program provides calendar-year grants to support local chapter activities that are deemed imaginative and likely to contribute to the strengthening of the SPS program.

Florida Polytechnic University
Microencapsulated Thermochromic Materials for Energy Savings Applications
Daniil Ivannikov (Leader)
Sesha Srinivasan (Advisor)

Old Dominion University
Observational Astronomy
Alicia Mand (Leader)
Matthew Nerem (Advisor)

Purdue University–West Lafayette
A Rope within a Rope: Fluid Polymerization in the Liquid Rope Coiling Effect
Matthew Schulz (Leader)
Rafael Lang (Advisor)

Rhodes College

Standardization of Novel Photovoltaic Cell Characterization for Rhodes College Cubesat Program, RHOKSAT
Giuliana Hofheins (Leader)
Brent Hoffmeister (Advisor)

South Dakota State University

Ultrathin PTAA Layer and Phenylhydrazinium Iodide for Defect Passivation and Enhanced Charge Carrier Mobility in Perovskite Solar Cell
Abdullah Al Maruf (Leader)
Robert McTaggart (Advisor)

Universidad Autonoma de Ciudad Juarez

Xenon Beam to Detect Polluting Particles
Julio Lopez Ibarra (Leader)
Sergio Flores (Advisor)

University of Central Florida

Simulations of Black Hole Dynamics: From Event Horizon to AMD Ryzen
David Wright (Leader)
Costas Efthimiou (Advisor)

University of North Alabama

Speckle Imaging for Fun and Outreach
Charles Harville (Leader)
Ronald Blake (Advisor)

Sigma Pi Sigma Chapter Project

The Sigma Pi Sigma Chapter Project Award provides funding of up to $500 for chapter inductions and events.

Missouri Southern State University

Facing Forward
Joshua Numata (Leader)
Jency Sundararajan (Advisor)

University of the Sciences

Sigma Pi Sigma: Induction Ceremony
Matthew Becker (Leader)
Roberto Ramos (Advisor)

Wheaton College

Increasing and Supporting Sigma Pi Sigma Honors Inductions
Stephen McKay (Leader)
Heather Whitney (Advisor)

2019–20 SPS Outstanding Chapter Advisor

The SPS Outstanding Chapter Advisor Award is the most prestigious recognition given each year by SPS. The following SPS advisors were nominated by their students, colleagues, and departments in recognition of their dedication to furthering the mission of SPS. The winner receives a total of $5,000 for themself, their chapter, and their department. The winner was officially recognized at the Winter 2021 AAPT Meeting. The runner-up's chapter receives a $100 gift card for a pizza party and other chapter activities. Learn more at **spsnational.org/awards/outstanding-chapteradvisor**.

Image courtesy of SPS National.

Winner

Robert McTaggart, ***South Dakota State University***

Runner-Up

Ronald Kumon, ***Kettering University A & B***

Nominees

Adele Poynor, ***Allegheny College***

Alyssa Hamre, ***Bethel University***

Bjorg Larson, ***Drew University***

Cecilia Vogel, ***Augustana College***

David Newman, ***University of Alaska Fairbanks***

Jency Sundararajan, ***Missouri Southern State University***

Kristopher Bunker, ***University of Colorado at Denver***

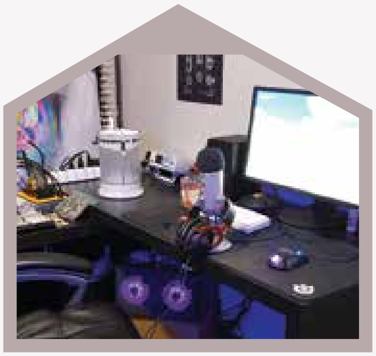
Peter Sheldon, ***Randolph College***

Work-from-Home Spaces

During the pandemic, "going to the office" has looked a little different for many people, including our members, who have been creating work-away-from-work spaces during the past year. Here are some of our favorite work-from-home setups among those submitted by members.

Your fellow Sigma Pi Sigma members are interested in news about you.
Submit items about civic activities, academic activities, honors, promotions, and career changes:
www.sigmapisigma.org/sigmapisigma/radiations/member-news

Kendra Redmond
Kendra Redmond Stories
Inducted at Carthage College Sigma Pi Sigma chapter, 2007.



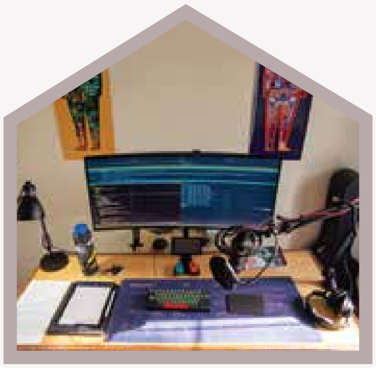
Cale Gray
Ford Motor Company
Inducted at Kettering University Sigma Pi Sigma chapter, 2018.

Webster Smith
Johns Hopkins University Applied Physics Laboratory
Inducted at Clark University Sigma Pi Sigma chapter, 1978.

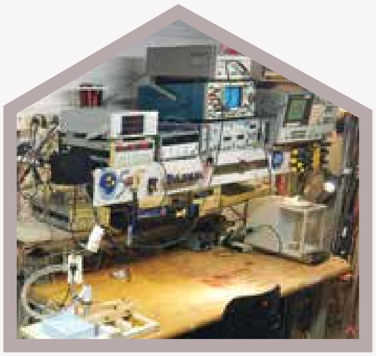
Fred Wilson
Angelo State University
Inducted at University of Kansas Sigma Pi Sigma chapter, 1960.

James Overduin
Towson University
Inducted at Towson University Sigma Pi Sigma chapter, 2009.

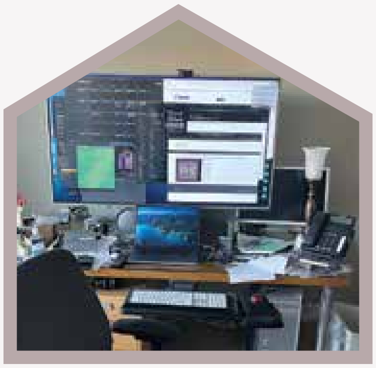
John W. Dooley
Retired, Millersville University
Inducted at Wabash College Sigma Pi Sigma chapter, 1963.



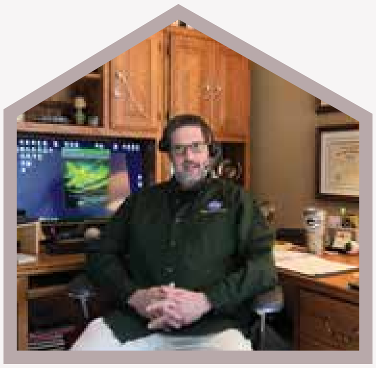
John Evans
University of Maryland
Inducted at University of Maryland Sigma Pi Sigma chapter, 2018.



Steven Garrett
Retired
Inducted at University of California Los Angeles Sigma Pi Sigma chapter, 1966.



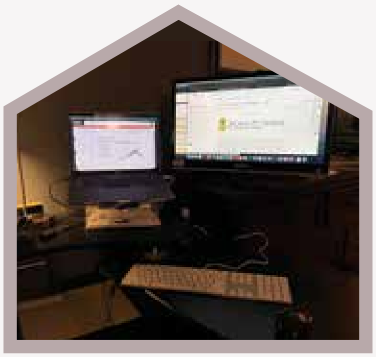
Ken Danti
Danti Labs
Inducted at Colorado School of Mines Sigma Pi Sigma chapter, 1978.



Lawrence D. Huebner
NASA
Inducted at Ripon College Sigma Pi Sigma chapter, 1981.

Ronny Nguyen
Cardiff University
Inducted at University of New Hampshire Sigma Pi Sigma chapter, 2018.

Robert Managan
Lawrence Livermore National Lab
Inducted at Rice University Sigma Pi Sigma chapter, 1977.



William Limestall
Illinois Institute of Technology
Inducted at Illinois Institute of Technology Sigma Pi Sigma chapter, 2017.

Googlers on Physics

Google's Mountain View, California headquarters. Source: Google.

Four Google employees who graduated with a physics major share their thoughts with *Radiations*.

Responses have been edited for length and clarity.

Casey Feinstein

Senior Engineering Manager, Nest Hardware Engineering – Optics, Cameras, and New Technology, Google

My teams are responsible for designing and building Nest camera hardware, optics, and illumination systems, and for investigating and developing new technologies for Nest products.

Sandeep Giri

Technical Project Manager, Infrastructure for Machine Learning & AI, Google Cloud

I am part of the organization within Google that builds datacenter hardware & software that powers all of Google's products and services. My project specifically focuses on building infrastructure to enable machine learning and artificial intelligence. I am the cross-functional project manager, bringing together multiple technologies from concept to production.

Bill Huggins

Research Scientist, Quantum AI – Algorithms, Google

I'm one of the people responsible for exploring different ways that we could use Google's quantum computers (either today's or tomorrow's). This can look like building the software to manage the data from an experiment or perform a calculation. It also involves a lot more talking, reading, and writing than you might expect.

Julian Kelly

Senior Staff Research Scientist, Quantum AI – Hardware, Google

I lead a team responsible for building the hardware electronics and software control system of a quantum computer. I am also one of the leads of Quantum AI; we are responsible for determining and leading the overall effort's research and development agenda.

To learn more about Sandeep Giri, check out "Such Great Heights" in the Spring 2019 issue of Radiations at www.spsnational.org/sigmapisigma/radiations/spring/2019/such-great-heights-sandeep-giri.

What skills did you develop as a physics student that have served you especially well in this role?

Feinstein: Physics gave me a broad base to understand new technologies, or those that require an understanding of the fundamentals of more than one engineering discipline. Quickly evaluating a proposed new technology often involves mechanical, electrical, thermal, and materials science questions. Having a basic understanding of each domain is very helpful in a research and development environment.

Giri: I have built products that span many industries: smart watch, solar, head-mounted display, flow battery, stratospheric balloon, and currently data center hardware. Each one of these products was very multidisciplinary, with mechanical, electrical, thermal, manufacturing, operations, software, test, and end-application components, among others. This requires me to be able to pick up the inner workings of any new product type and multiple domains in a short period of time. Physics taught me to understand the fundamentals of how anything works and also fostered deep curiosity, which is one of the driving forces behind me building a variety of products.

Huggins: One of the most important skills is knowing how to make a good approximation. So many things in physics are difficult to calculate exactly, but as a student I started to learn how to cut the right corners to get an answer that was good enough—for example, replacing a function with the first few terms in its Taylor series expansion. When I'm trying to understand the behavior of a quantum algorithm, the exact same mathematical tricks can be useful.

Kelly: Our entire field exists on the promise of turning physics experiments into practical technology, so we are constantly immersed in physics problems. My physics background has given me the skill set to take complex problems and break them into simpler ones that can be reasoned out. Additionally, by having had exposure to a breadth of physics concepts, I am more easily able to communicate with team members in different roles to understand the set of challenges in our field.

What are one to two key skills outside of the traditional physics skill set that have been instrumental in your success and that you wish your education could have provided?

Feinstein: Some of the tools of engineering disciplines—for example, mechanical CAD or geometric dimensioning and tolerancing (GD&T) skills—were things that I had to pick up on the job. They are extremely useful as tools for communicating and collaborating with engineering teams and are even more critical when separated by language and time zone differences that are common in a global technology supply chain.

Giri: If I were to speak to my 18-year-old self, I would say, invest in becoming a better writer. Communication in any form—papers, presentations, email, project updates—requires one to be a strong writer. Writing can also enable one to become a seasoned speaker. My role requires verbal communication in 20 to 25 meetings each week. Learning the basics of engineering design as an undergraduate would have also been beneficial, as this is something that touches all industries.

Huggins: I've been shocked at how much of my time has been spent writing and how crucial it has been that I write well. Writing has been fundamental to communicating clearly with the larger academic world through research papers. It's also been important on a day-to-day level, as I write emails and notes to keep my colleagues up to date on what I'm working on. Even when I'm just trying to clarify an idea for myself, I've come around to seeing how useful it is to write things down in clear language. I wish that I'd had more formal training in writing and that I had been taught to see it as an important tool rather than a mostly irrelevant nod to a liberal arts education.

Kelly: In my experience, technical skill is only one core component of achieving success. Soft skills such as communication, leadership, and teamwork are absolutely instrumental, as almost all modern challenges require teams of people working collaboratively. Although these skills can't be easily taught in classes, they can be acquired through mentorships or through firsthand experience working with others.

What is one message for change that you'd share with the physics department at your alma mater?

Feinstein: I'm grateful for the quality of the education I received, but the cost was daunting. My parents paid as much as they could, I worked three jobs, and even with grants and scholarships I left school with significant student loan debt. In retrospect the education was well worth the cost, but at the time it influenced decisions about work versus graduate school and what kinds of jobs I would consider.

Giri: Provide students with more opportunities around learning teamwork, leadership, influencing without authority, and negotiation. Traditionally, these have been wrongly characterized as "soft skills," but my personal observation has been that these are essential skills for flourishing in any employment sector. Thus far, I have helped hire 100-plus folks in my career, and those who were good at the aforementioned skills grew and thrived at a tremendous pace. Physics departments have to come up with creative solutions to boost these skills in students prior to graduation.

Huggins: I wish that the department had placed more emphasis on the value of teaching undergraduate students. I was fortunate enough to have had very dedicated professors for some classes, but it's unfortunate that teaching is often seen as an obstacle to research rather than an end in its own right.

Kelly: Nearly all physics work today requires some element of software. I never actually had formal software training, but it is one of the most important aspects of my day-to-day work. Not only should the basics be a requirement for physics degrees, but we should also teach code hygiene (version control, readability, etc.), as these are requirements for efficiency and collaboration. ●

The Employment Landscape for New Physics Degree Recipients

by Patrick J. Mulvey, Research Manager, and Anne Marie Porter, Survey Scientist, Statistical Research Center of the American Institute of Physics

The career paths of physics degree recipients vary greatly, influenced by personal circumstances, interests, degree(s), and economics. This article explores the initial postdegree outcomes of physics degree recipients at the bachelor's, master's, and PhD levels. The data come from surveys of physics graduates from the classes of 2017 and 2018 conducted by the Statistical Research Center (SRC) of the American Institute of Physics (AIP). The data was collected from new graduates in the winter following the academic year in which they received their degree.

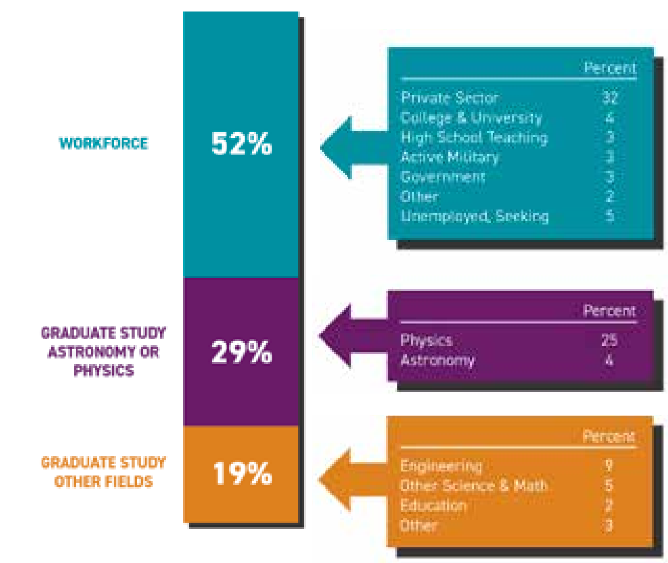


Figure 1: Status of physics bachelors one year after degree, classes of 2017 and 2018 combined. Two percent of respondents indicated they had left the US to pursue employment or graduate study and are not included in the figure. All figures are courtesy of the American Institute of Physics, Statistical Research Center.

PHYSICS BACHELORS

The number of students receiving physics bachelor's degrees from US institutions has been increasing for over two decades, reaching almost 9,200 in 2019.

New physics bachelors follow one of two initial postdegree paths: they enter the workforce or enroll in graduate school. For the classes of 2017 and 2018, about half (48%) indicated they were enrolled in a graduate program in the winter following the year they received their degree. Of these, the majority were studying physics or astronomy (Fig. 1).

The other half (52%) of new physics bachelors were employed in the workforce or seeking employment. They held positions in a variety of economic sectors, with the private sector employing by far the largest proportion (67%). Within the private sector, physics bachelors were most commonly working in engineering (38%) and computer or information systems (26%). About a fifth were working in non-STEM positions, although the majority were regularly called upon to solve technical problems. Very few respondents (3%) indicated that they were working in physics or astronomy. About a third of the employed physics bachelors indicated they were planning to enroll in a graduate program in the future.

EXITING PHYSICS MASTERS

Exiting masters refers to those who earn a master's degree from a US physics department and leave that department to enter the workforce or pursue another graduate degree elsewhere. Physics departments in the US conferred about 900 physics master's degrees in 2019.

Class of 2017 and 2018 survey data showed that US citizens with exiting master's degrees generally tended to follow a different postdegree path than non-US citizens (Fig. 2). The majority of those with US citizenship entered the workforce or remained in positions they held prior to receiving their degrees. The most common outcome for non-US citizens was continuing graduate study at another department or institution.

Regardless of citizenship, the majority of those continuing their graduate studies were enrolled in a physics or astronomy program at another US institution. The most commonly cited "Other Field" of graduate study was engineering.

Similar to the physics bachelors, over half (57%) of the employed exiting masters were working in the private sector. The next largest employment sector was two- and four-year colleges and universities (20%). Eight percent of the physics masters were working as high school teachers, of whom almost all indicated that they were teaching STEM subjects.

Physics masters secured employment in a diverse set of fields, confirming the notion that physicists have the skills and training to work in many areas of the economy (Fig. 3). Almost equal proportions of exiting physics masters were employed in the fields of “physics or astronomy” or “engineering,” comprising over half of those in the workforce. Six percent indicated they were working in a non-STEM field, most commonly finance. Many (12%) of the new physics masters in the workforce hoped to return to graduate school in the future.

PHYSICS DOCTORATES

During the 2018–19 academic year, US physics departments conferred about 1,900 physics PhDs. Although this number is relatively unchanged from the previous year, the number has risen 75% since a recent low in 2004. New physics PhD recipients generally enter a postdoctoral fellowship (postdoc), work in a potentially permanent position, or accept a nonpostdoctoral temporary position (Fig. 4). For most of the last two decades, the most prevalent employment outcome has been a postdoc, but this is no longer true. In the physics PhD class of 2018, an almost equal portion of PhDs accepted a postdoc as accepted a potentially permanent position.

Again, the class of 2017 and 2018 results reflect differences between US citizens and non-US citizens. A considerably greater proportion of non-US citizens than US citizens accepted postdocs, 51% vs. 40%, respectively. The reverse is true for potentially permanent positions, with 47% of the US citizens and 35% of the non-US citizens accepting such a position.

Of those who accepted a potentially permanent position, the majority (74%) were employed in the private sector by companies ranging from the smallest startups to the largest corporations. Those in

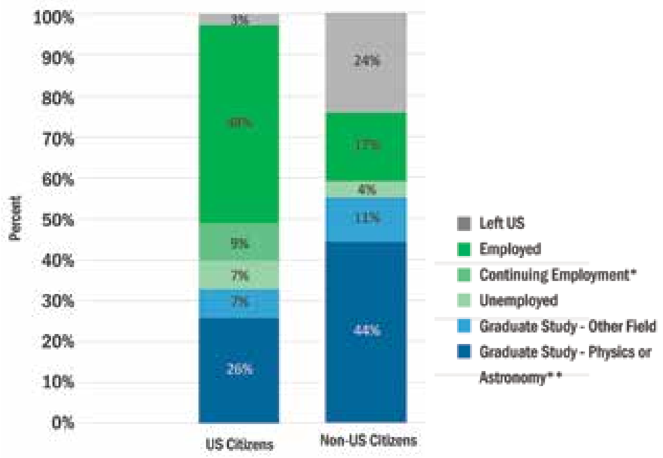


Figure 2: Status of exiting physics masters by citizenship one year after degree. Data shown is for the classes of 2016, 2017, and 2018 combined. This figure is based on the responses of 265 non-US citizens and 500 US citizens.
*Continuing Employment: employed with the same employer for more than a year prior to earning master’s degree.
**Graduate Study - Physics or Astronomy: enrolled at a different institution than where master’s degree was obtained.

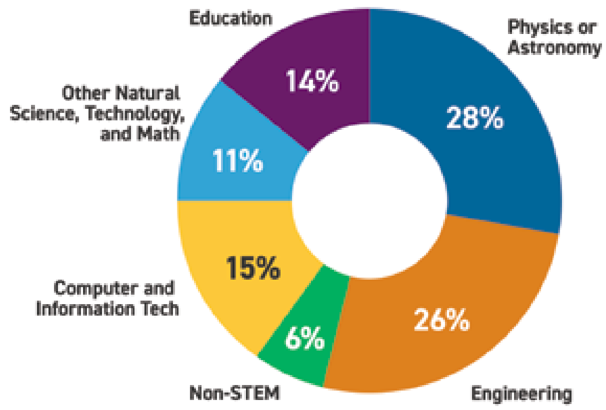


Figure 3: Field of employment for new physics masters one year after degree. Data is from the classes of 2016, 2017, and 2018 combined. Figure includes physics masters employed in the US, including those who were employed part time (7%) and masters continuing in positions they held while pursuing their degrees (16%). Figure is based on 331 individuals.

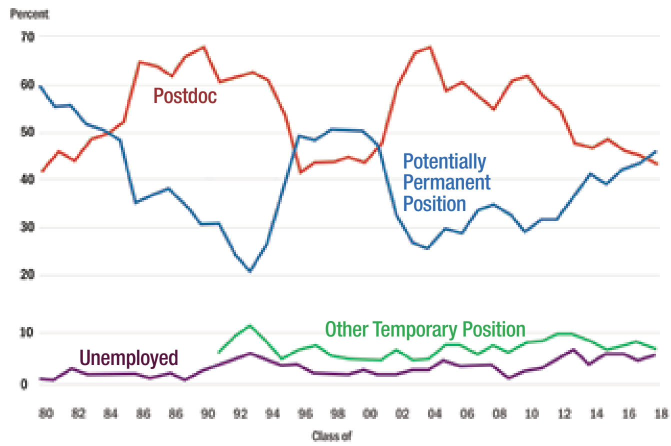


Figure 4: Initial employment of physics PhDs, 1980–2018. Data is limited to PhDs who earned their degrees from a US university and remained in the United States.

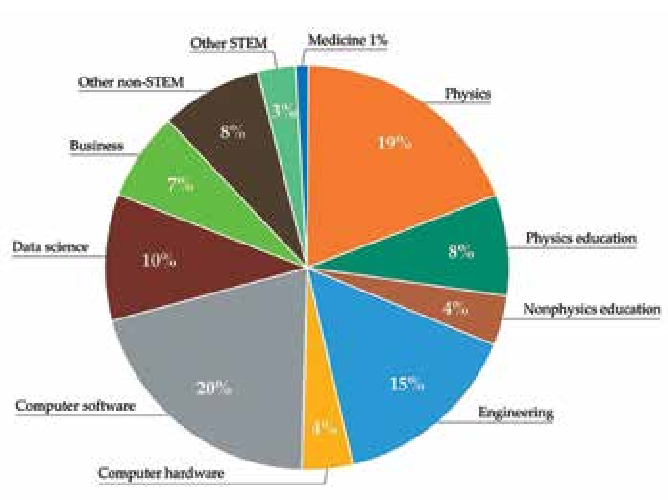


Figure 5: Field of employment for physics PhDs in potentially permanent positions. Data is from classes of 2017 and 2018 combined.

potentially permanent positions were working in a variety of fields, with physics, computer software, engineering, and data science comprising two-thirds of the fields of employment (Fig. 5).

Less than 10% of the positions new PhDs held were in non-postdoc temporary positions. These were primarily (70%) in academia and came with titles of visiting professor, guest lecturer, or research scientist.

WHAT DOES THE FUTURE HOLD?

While the graduates of 2017 and 2018 entered a strong and growing economy, the economic realities of today are somewhat different. Recessions in the US are nothing new and typically occur at least every 10 years or so. Data show that new degree recipients who enter the work force during a recession, regardless of degree field or degree level, encounter a challenging job market.

Regardless of when the economy recovers, there are some things we know are true now and will be in the future. Private sector employers will need to fill positions, government research labs will continue to need staff, and schools and universities will need to continue to hire faculty. Physics degree recipients are adept at learning and problem solving and have strong mathematical and analytical skills, making them attractive to a variety of employers even in the midst of a recession. ●

A Note about Postdocs

Postdoctoral fellowships are temporary, mentored research positions that provide new PhDs with an opportunity to improve their research skills and publish findings. They are typically two-year positions and are frequently renewable. The majority of postdocs (~75% historically) are in a university setting, with most of the remaining positions at government labs. Although these positions provide valuable experience and are almost a prerequisite for PhDs seeking an academic position, they are not a necessary step for many career paths.

Because so many new PhDs accept a postdoc that ultimately do not work in a faculty position, the SRC asked mid-career physicists whether they would again take a postdoc if they had an opportunity to do it over.[1] Not surprisingly, 91% of the physicists working in academia indicated that they would repeat taking a postdoc. The majority of PhDs working in the government or the private sector indicated the same—88% and 72%, respectively.

A Note about Mid-Career Outcomes for Physics PhDs

The data in this article addresses initial postdegree outcomes. Most people change jobs over the course of their careers—some many times. A resource from the National Science Foundation using data from its Doctorate Recipients Survey provides information on the proportion of mid-career physicists working in different employment sectors. In 2013, about half of physics PhDs who had earned their degree 10–14 years earlier were working in the private sector (51%), with fewer PhDs working in academia (43%) or government (6%).[2]

Learn More

Who's Hiring Physics Bachelors?

https://www.aip.org/statistics/whos-hiring-physics-bachelors
Employers that recently hired physics bachelors to fill science and engineering positions are listed by state.

Who's Hiring Physics PhDs?

www.aip.org/statistics/whos-hiring-physics-phds
This resource lists employers that hired new physics PhDs into potentially permanent positions by field. It includes job titles, salaries, and skills used.

Data on Starting Salaries

https://www.aip.org/statistics/data/employment/salaries
This section of the SRC website provides the starting salary ranges for new physics degree recipients by sector of employment.

PhD Plus 10 Study

www.aip.org/statistics/phd-plus-10
This series of reports explores the employment of mid-career physics PhDs.

Physics Faculty Salary Calculator

www.aip.org/statistics/salary-calculator
Explore faculty salaries for physicists by institution type, degree, job title, tenure status, gender, and location.

References

1. R. Czuko and G. Anderson, *Common Careers of Physicists in the Private Sector* (College Park, MD: American Institute of Physics, 2015), Table 2.2.
2. "Science, Engineering, and Health Doctorates in the Workforce, 1993–2013," National Science Board. https://www.nsf.gov/nsb/sei/infographic2/#main.

The Evolution of Physics Education:

How Undergraduate Departments Are Transforming

by Laurie E. McNeil, Bernard Gray Distinguished Professor, Department of Physics and Astronomy, University of North Carolina at Chapel Hill

Laurie E. McNeil. Photo by Steve Benka.

What do you remember about your physics education? Lectures on quantum mechanics? Long nights struggling with homework? Any mention of physics careers? Classmates who looked a lot like you? If you went back to your old physics department, you might find that everything is much the same as you remember. But depending on the department (and when you graduated), you might find the scene a bit different.

Who is studying physics now?

Things are looking up for our discipline. The number of physics bachelor's degrees awarded each year has never been higher—9,193 in the class of 2019.[1] This is up from a modern-day low of 3,646 graduates in 1999, the nadir of a decade-long trend that, had it continued, would have led to *zero* physics graduates by about 2016. The "market share" for physics is up as well, with physics graduates representing 0.46 percent of all bachelor's recipients, up from 0.3 percent in 1999.

The gender balance has changed too. In 2019, 24 percent of all physics graduates were female (about the same as in 1999), compared to 5 percent in 1966. Physics programs remain largely white, however—in 2019 only 4 percent of physics graduates were Black and 10 percent were Latinx, compared to 14 percent and 22 percent, respectively, of the college-age population.[2] The physics community as a whole has a lot of work yet to do on diversity and inclusion.

How has teaching changed?

If what you remember about your physics classes is lectures (stimulating or otherwise) and homework (impossible or otherwise), you have lots of company. Most of us were taught by pedagogical autodidacts who had no information other than their own experience about what works (and what does not) in the physics classroom. But that is changing (not fast enough!) with the rise of physics education research (PER) as a subdiscipline in the physics community. Physicists who do PER use rigorous scientific methods to study how people learn physics and how physics education can be improved.[3]

The findings from PER are many and varied, but if one had to draw a single conclusion from the body of research, it would be this: Interactive engagement works better than traditional lecture instruction. Students learn more by discussion and experimentation in the classroom than they do by listening to lectures, or in the words of the late Professor Lillian McDermott from the University of Washington, "Teaching by telling is an ineffective mode of instruction."

One way to measure this is to compare students' gain in understanding of physics ideas through a "concept inventory," a set of multiple-choice questions that explore students' understanding of basic concepts such as Newton's third law. For example, a question might ask which vehicle exerts more force on the other when a large truck and small compact car collide. Students complete an inventory at the beginning and end of a physics course, and the degree to which their understanding has changed (expressed as a fraction of the possible shift toward the correct answers) is recorded as the "normalized gain."

Before taking a first course in Newtonian mechanics, 75 to 80 percent of students say that the truck exerts more force on the car than the car does on the truck. After traditional lecture instruction, about 65 percent give the same answer! But interactive engagement makes a difference. Classes taught using these methods are much more likely to achieve large gains in understanding of Newtonian mechanics than are classes taught using traditional lectures (see Fig. 1).

These kinds of findings have convinced an increasing number of physics faculty members to change the way they teach. Some departments have undertaken large-scale transformations of introductory physics instruction. Gary Gladding, who led the effort at the University of Illinois at Urbana-Champaign, likened it to "parallel parking an aircraft carrier" because of its scale—over 3,000 students each semester. I led my own department's similar effort, which at

1. Statistics referenced in this article were obtained from the American Institute of Physics (AIP) Statistical Research Center, https://www.aip.org/statistics.

2. The American Physical Society (APS) and the American Association of Physics Teachers (AAPT), among others, support the STEP-UP project (https://engage.aps.org/stepup/about/overview) to enlist high school physics teachers to engage and inspire young women to study physics. AIP supports the TEAM-UP Project (Task Force to Elevate African American Representation in Undergraduate Physics & Astronomy, https://www.aip.org/diversity-initiatives/team-up-task-force) to address the persistent underrepresentation of Blacks in physics. Partial funding for TEAM-UP is provided by the Research Corporation for Science Advancement.

3. Both APS and AAPT have topical groups on PER, and in 1999 APS issued a statement (https://www.aps.org/policy/statements/99_2.cfm) that PER "has advanced our understanding of student learning in physics and has resulted in significant improvements in the methodology of teaching." The prestigious *Physical Review* family of journals has one devoted to PER (https://journals.aps.org/prper/) that published 99 research articles in 2019.

around 1,100 students per semester was more like parking a frigate. In other departments the changes have been more modest, instigated by one or two faculty members.[4]

What do these new physics classes look like?

There are many ways to implement interactive engagement, but I can give you a flavor by describing the introductory classes at my own institution.

Before coming to class, the students complete a warm-up assignment that may involve reading from the textbook or watching a video before answering questions online. They then attend a lecture in which a faculty member spends most of the time posing questions to the class. Students discuss each question with their neighbors (a technique sometimes called think-pair-share) and then use a personal response device (a "clicker") to give their answers. If most answers are incorrect, the instructor goes over the idea in more detail and addresses the misconceptions that the students' answers reveal before asking them to respond again. Once most of the students have grasped the concept, the instructor moves on.

The next meeting takes place in a classroom with round tables that seat nine students each. Here they work in groups of three on pencil-and-paper tutorial activities, guided-inquiry laboratory experiments, and cooperative group problem-solving, all designed based on findings from PER. The instructor circulates as the students work, answering questions and engaging in Socratic dialog. In this way students spend the vast majority of class time actively engaged in thinking about and discussing physics, challenging each other's understanding and explaining things to each other. Afterward they cement their understanding individually by solving conventional homework problems.

Similar techniques are applied in upper-division classes for physics majors, which have smaller enrollments. Here, students learn about topics in advance, then spend most of the class time applying what they've learned by working through carefully designed activities and discussing ideas with each other rather than listening to the instructor. The information transfer takes place individually, but the information application (which is much more difficult) takes place with guidance and assistance from the instructor and from peers. This works just as well for learning about quantum-mechanical orbital momentum operators as it does for learning Newton's second law.

How is content evolving?

The "standard curriculum" (classical mechanics, electricity and magnetism, quantum mechanics, and thermodynamics) is alive and well in virtually every undergraduate physics department, but increasingly departments seek to broaden physics education and attract more majors by providing interdisciplinary tracks within the major. Such tracks might focus on biophysics, astrophysics, computational physics, or even business and entrepreneurship (colloquially known as "phys/biz").

The importance of acquiring computational skills is widely recognized, and in some departments this is woven throughout the curriculum by incorporating computational exercises in most or all classes. Groups such as the Partnership for the Integration of Computation into Undergraduate Physics[5] (PICUP) foster this by holding workshops and sharing instructional materials and exercises. Physics laboratory skills (beyond that Milliken oil drop experiment that gave us all headaches) are also emphasized with the help of groups like the Advanced Laboratory Physics Association[6] (ALPhA), which fosters communication and engagement among the instructors of advanced physics laboratories. There is even an APS prize for excellence in advanced laboratory instruction![7]

These trends accord well with the recommendations from a report prepared by a team from APS and AAPT entitled "Phys21: Preparing Physics Students for 21st-Century Careers."[8] That group (which I co-led with Paula Heron of the University of Washington) assembled information about what knowledge and skills employers of physicists are seeking today and how physics departments can help their students acquire them. The report describes broad agreement among employers about the need for physics-specific knowledge (well covered in the traditional curriculum), scientific and technical skills (including coding, data analytics, and instrumentation, as well as the ability to solve ill-posed problems), communications skills (for all types of audiences), and professional and workplace skills (such as working in diverse teams, project management, and knowledge of career opportunities and job seeking). I suspect that this list includes many things needed to do a job effectively, but most of them have not been a part of the traditional physics curriculum. That's changing now as physics departments increasingly recognize that not all of their graduates will become physics professors and instead must be well prepared for the careers they will actually pursue.

Many physics departments are also recognizing their role in preparing high school physics teachers. Physics is among the hardest disciplines to find teachers for—only 47 percent of high school physics classes are taught by someone with a physics degree. At the same time, enrollment in physics in US high schools is growing. Because today's college physics students were yesterday's high school physics students, many physics departments (including my own) have created programs to prepare their majors to become high school teachers, an effort to ensure that incoming students are taught by instructors who know physics well and have enthusiasm for the subject.[9] A few states (such as New York and Utah) are producing enough new physics teachers to meet as much as 65 percent of their need each year, but over half of the states are still meeting 20 percent or less of their need. There is considerable room for improvement.

What can we expect in the future?

Certainly the trends of wider adoption of interactive engagement pedagogy, interdisciplinary education, intentional career training, and teacher preparation by physics departments are likely to continue. The

4. In many cases those faculty members were inspired by attending the New Faculty Workshop (https://www.aapt.org/Conferences/newfaculty/nfw.cfm), sponsored by APS, AAPT, AIP, the American Astronomical Society (AAS), and the National Science Foundation (NSF). Faculty members in their first few years of teaching learn about findings from PER and how to use them in their classrooms. About 2,600 faculty members from 85 percent of US institutions that offer physics degrees have attended since the workshop began in 1996, and it now reaches about 35 percent of all new tenure-track physics and astronomy faculty members.

5. https://www.compadre.org/PICUP/.

6. https://advlab.org/.

7. https://www.aps.org/programs/honors/prizes/lab.cfm.

8. https://www.compadre.org/jtupp/report.cfm.

9. APS and AAPT have been especially active in this regard by organizing the Physics Teacher Education Coalition (PhysTEC) (https://www.phystec.org/) "to promote and improve the education of future physics teachers." Over 300 institutions have joined PhysTEC, and if each college or university in the US were to produce one more teacher each year, the shortage would be eliminated.

10. Joshua Von Korff, Benjamin Archibeque, K. Alison Gomez, Tyrel Heckendorf, Sarah B. McKagan, Eleanor C. Sayer, Edward W. Schenk, Chase Shepherd, and Lane Sorell, "Secondary Analysis of Teaching Methods in Introductory Physics: A 50k-Student Study," *Am. J. Phys.* 84 (2016): 969.

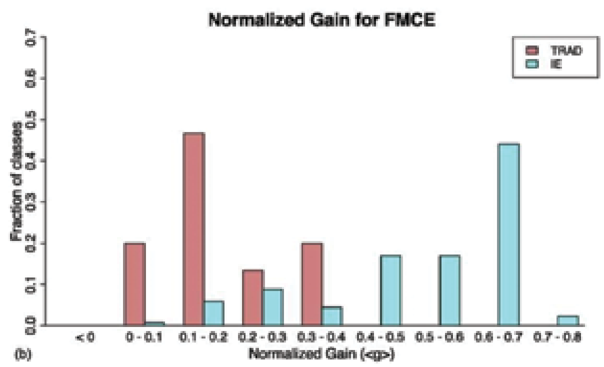
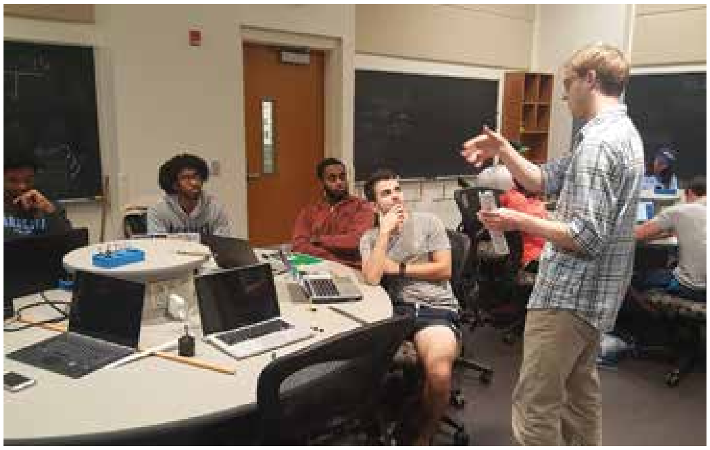


Figure 1: Comparison of results of the Force and Motion Conceptual Evaluation (FMCE) for classes taught by traditional and interactive engagement methods, taken from an analysis by Van Korff et al.[10] of the results of the FMCE from about 150 college physics classes (around 14,000 students) at institutions across the country.

next challenges will come from the need to prepare physics students for new kinds of careers that are only beginning to emerge. The current emphasis on quantum computing suggests the need for a "quantum workforce" with lab skills (particularly optics and photonics), as well as engineering and collaborative coding skills, which physics programs can certainly provide. Data science is another emerging area and includes not only dealing with "big data" in scientific contexts but also applying data analytics to business decision-making. Physicists often work with big data sets that require sophisticated statistical analysis—think of the discovery of the Higgs boson at CERN. There is now even an APS Topical Group on Data Science that focuses on big data, machine learning, and artificial intelligence.

No doubt there will be other trends we can't predict, and physicists will rise to those challenges as well. After all, as Rush Holt, physicist and former member of the US House of Representatives, is said to have remarked, "Physicists are omnicompetent." ●



Teaching assistant Ben Kaiser (standing) discusses a torque activity with a student group during an introductory physics course at University of North Carolina at Chapel Hill. Photo by Shane Brogan.

Physics Departments at Small Colleges Are Under Pressure —
Here's How to Fight Back

by Matthew Write, Associate Professor, Department Chair, Physics, Adelphi University

Matthew Wright. Photo courtesy of SPS National.

As a lower-level physics student, I remember having one of those ideas that was both exciting and wildly naïve—I wanted to build a probe that would look for life on Europa. I even had a cute, hand-drawn schematic of a lander, a depth sounder, and fish under the ice. I walked into two separate physics professors' offices on a random afternoon and started talking about how I thought this would be an interesting research project. I ultimately focused on something else, but I fondly remember how I was able to interact with and connect to the faculty at a small college. The professors I approached took my idea seriously and helped me think about my ideas more deeply.

This was one of my motivating factors for actively pursuing a faculty job at a primarily undergraduate institution (PUI), where I knew I could provide students with opportunities to receive enhanced mentorship and conduct undergraduate research, as well as give students the time to develop at their own pace. I wanted to be there for my lower-level students in the exact same way that my professors were there for me.

Colleges and universities have been under continuing pressure to make operations more efficient, increase revenue, and keep tuition low. This process has been accelerated by million-dollar losses in revenue due to the effects of COVID-19. Institutions are also facing reduced revenue from the coming enrollment cliff in 2026, as discussed in the recent Chronicle of Higher Education article, "The Demographic Cliff: 5 Findings From New Projections of High-School Graduates." The result is that revenue due to tuition is likely going to be at low levels for the next 10 years.

Since I started working as a professor in 2012, the minimum number of seats in a given class has gone from six to ten at my university.* Classes that had no problem running in 2012 are now in jeopardy of not being offered. According to a recent AIP report, “Size of Undergraduate Physics and Astronomy Programs,” the average number of bachelor’s degrees awarded in a given program is 6.1. This roughly indicates how many students can be found in a typical upper-level physics class such as quantum mechanics. With that number it’s possible to understand why more and more upper-level classes will not be offered because of low enrollment.

Lowering the number of physics courses that can run in a particular year can have a direct effect on the operations of a department. In some cases, departments will be required to consolidate their courses from being offered every year to every other year. In other cases, faculty will be required to teach required courses as tutorials or independent studies to ensure that students graduate on time. While this technically solves the problem for the students, it does so at great strain to the faculty. It often requires faculty to teach higher-level classes for free or at heavy discounts, while still maintaining a full load of lower-level courses and service classes. This hidden overtime is a substantial burden for physics faculty at PUIs and can take time away from recruiting new students, developing new programs, and mentoring students to keep retention high.

In terms of dollars and cents, the added expenses of funding upper-level teaching labs and extra faculty may make it appear favorable to discontinue physics departments altogether. Historically, physics is often one of those departments that may disappear when times are rough, as was discussed in the 2013 *Inside Higher Ed* article “Small Ain’t All.” As a physics chair the fact that a couple of bad years in a row could spell disaster for a department is always in the back of my mind. The thing I find most distressing is that a good department with moderate enrollment numbers may not be allowed to try to recover from sudden enrollment declines due to COVID-19, the enrollment cliff, changes in student interests, or faculty turnover.

But there is hope out there. Here are some ideas for fighting back:

- **Develop career-focused pathways.**
Our department is working with regional businesses and Brookhaven National Lab to develop career-focused pathways that we can market to incoming high school students.

- **Develop pre-engineering pathways.**
We are working with regional universities that have world-class engineering programs to develop degree pathways from an undergraduate degree in physics to graduate degrees in physics, materials science, or engineering.

- **Do outreach relentlessly.**
We are working with our admissions office to scale up our Lab for Kids outreach event, which was named one of *INSIGHT Into Diversity* magazine’s 2020 Inspiring Programs in STEM, so that it can be done remotely and with multiple schools. Every student reached is a win for the community.

- **Promote diversity.**
National programs led by physics professional societies, such as STEP-UP and TEAM-UP, are helping departments attract students from diverse backgrounds. Our students came to the faculty asking to develop diversity-themed events and discussions. We encouraged them! Our department has created a department-level task force of students, staff, and faculty to work on such topics. We participated in the TEAM-UP workshop this January.

It’s hard to look at the smaller classes caused by COVID-19 without concern. But this is a necessary market correction—the price of college is way out of hand across the board. It will force the community to rethink and reevaluate how we do business. We need to continue to evolve and grow with the times to keep up. ●

* Adelphi University has recently developed a tiered approach to class minimums. The cap for 100 and 200 levels is 12, whereas the cap for 400-level classes is eight.

Effective Practices for Physics Programs

by Jim Borgardt, Sigma Pi Sigma President

This is a challenging time in higher education, and physics departments are not immune, with many reporting varying degrees of stress. COVID-19 has only exacerbated these already difficult situations.

This situation prompted the American Physical Society to develop the Toolkit for Departments Under Threat (ep3guide.org/toolkit). This project was fast-tracked to be available for programs needing immediate guidance in defending themselves against challenges, and we welcome your input and feedback at ep3guide.org/toolkit-feedback/ as we work to make the site more useful to such programs.

EP3 Effective Practices for Physics Programs

Guidance in the Toolkit was sourced from over 50 interviews with administrators and physics faculty, generally chairs, representing physics departments under various levels of threat. While many thematic patterns emerged, one lesson is that each department represents a unique ecosystem. There is no silver bullet. However, we believe there are opportunities to improve one’s standing within university administrations and to positively influence decision-making.

The Supercomputer Specialist

Debbie Bard

Group Lead for the Data Science Engagement Group, National Energy Research Scientific Computing Center (NERSC) at Lawrence Berkeley National Lab

The National Energy Research Scientific Computing Center (NERSC) is the high-performance computing (HPC) and data center for the US Department of Energy (DOE) Office of Science. We operate research supercomputers used by scientists working across the range of DOE research areas—including particle physics, genome analysis, materials science, climate science, and fusion research.

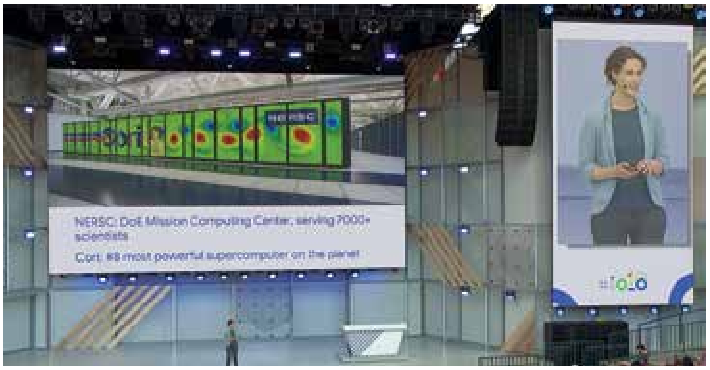
I lead the Data Science Engagement Group at NERSC. My team works specifically with scientists from experimental and observational facilities that need supercomputing-scale resources to perform their data analysis and simulations. We ensure that NERSC supports the tools, technologies, and software these scientists need to do their science, and we work closely with them to make sure they are able to use our resources effectively.

My job involves interacting with a huge range of science teams from a lot of different science areas, and there is often a language or jargon barrier. A large part of my job is translating what the scientists need to do and communicating that to our systems engineers. At the same time, I have to translate our hardware and software capabilities back to the scientists so they can structure their workflows to take advantage of what we can offer. The job also involves troubleshooting, which can be frustrating. Cutting-edge hardware rarely works as expected out of the box, and it can take a while to understand the hardware and work with our vendors to get all the bugs smoothed out. The problem-solving skills I learned as a physicist are really helpful here.

I'm a huge science enthusiast, so my favorite part of the job is learning about all the cool research being done by the DOE. It's exciting to be able to support that research and enable new discoveries through our supercomputers. I'm also excited by the possibilities of applying new computing architectures to science problems. Working at one of the nation's flagship supercomputing centers means I get to play with some of the most powerful and advanced computers on the planet, and I really enjoy figuring out how we can use these technological developments to advance science.

Physics can take you in a lot of different directions! My career spans research in particle physics, cosmology, machine learning, and supercomputing. Originally from the UK, I earned an MS in physics with French at Nottingham University and my PhD in experimental particle physics at Edinburgh University. I worked at Imperial College London and SLAC National Accelerator Laboratory before joining NERSC.

If you're an aspiring physicist, keep your mind open about what you want to do next—there are a lot of interesting options open to you. And take as many classes in computing as you can! Science today depends almost entirely on sophisticated hardware and software to run theoretical simulations and data analysis. Computing skills can take you between many different domains in science and in industry. ●



Debbie Bard delivers a talk on advances in machine learning and implications for cosmology research at Google I/O, Google's developer conference. A video of the talk is available at https://youtu.be/t81QhHaMS7w. Photo courtesy of Debbie Bard.

Lawrence Berkeley National Lab director Michael Witherell (far left) and Debbie Bard (right) share NERSC highlights with a visiting congressional delegation in 2019. Shown are (left to right) Witherell, US Rep. Bill Foster (D-IL 11th District), US Representative Jerry McNerney (D-CA 9th District), and Bard. Photo by Thor Swift, LBNL.

A Motorcycle or Bicycle as a Gyroscope (Sort of)

by Dwight E. Neuenschwander, Southern Nazarene University

I was attending the national flat-track motorcycle races several years ago in Oklahoma City, watching the competitors run their qualifying laps, racing the clock individually to determine their positions at the start of the upcoming race. Coming out of the final turn and heading into the home stretch at 80 mph, the Triumph motorcycle ridden by great flat-tracker Don Castro suddenly went into a "speed wobble," which immediately grew in amplitude and threw Castro over the handlebars.

In flat-track racing the riders speed around a half-mile oval dirt track, hitting speeds of around 100 mph. The motorcycles are not the road-racing sports bikes that, on paved tracks, will round a corner at 150 mph, leaning at angles approaching 90 degrees; flat-trackers are stripped-down roaring heavy cruisers like Harley-Davidsons and Kawasaki Vulcans. To get through the turns at speed on dirt, the riders maintain a controlled power slide (Fig. 1).

Figure 1: Jared Mees and his Indian Scout FTR 750 motorcycle in a controlled power slide during a flat-track race. Photo courtesy of David Hoenig, Flat Trak Fotos.

In everyday riding the angle of the machine's lean from vertical and the angle turned by the front wheel are related, the front wheel turning in the same direction as the lean. In coming out of a normal turn those two angles approach zero together. Although oscillations can occur, if they do they are normally easily corrected by the rider. In a power slide the angles have opposite signs. To go into a dirt-track power slide for a left turn, upon entering the curve you throw your weight deliberately to the left while turning the handlebars hard to the right (see Fig. 1) and use the throttle to control the slide through the rear wheel's angular velocity. In coming out of the power slide to head down the straightaway, under some circumstances oscillations in the lean angle can amplify with astonishing rapidity into the dreaded "speed wobble." In Don Castro's case, he knew how to fall—wearing full leathers, gloves, boots and a sturdy helmet, he slid on his back, head first down the straightaway directly in front of the grandstands, with both hands on his helmet, seeming to enjoy his slide while his motorcycle tumbled after him. When they both stopped, Castro got up, dusted himself off, and pushed his bike back to the pits. Later that afternoon he competed in the race with the same bike and placed well. I don't know if Castro ever saw the equations that describe the steering and stability of a motorcycle, but he clearly knew how to skillfully *apply* the physics of riding!

The wheels of a motorcycle or bicycle ("bike" for either) make the machine a kind of gyroscope. A gyroscopic effect is apparent when a bicycle is pushed without a rider—it rolls in a straight line for a while, until it slows down and begins to lean over. Then the front wheel turns in the direction of the lean and the bike falls over. The same phenomenon appears in a rolling coin. Could a leaning moving bike be a precessing gyroscope, where a horizontal displacement of the center of mass (CM) creates a torque that turns the bike? When riding a motorcycle or bicycle I find that when I lean to the left or right while trying to keep the front wheel pointed straight ahead, the machine indeed moves in the direction of the lean, but ever so slowly—more of a drift instead of a deliberate turn (not good strategy for armadillo avoidance). The hypothesis that a leaning bike is a precessing gyroscope evidently forms a minor part of the story.*

Look carefully at the bike's front wheel and the fork connecting it to the handlebars. Visualize a line

Figure 2: Showing the castor distance δ on a 1994 Kawasaki Vulcan (top) and a 1962 J.C. Higgins Flightliner (bottom). Their front wheels have been deliberately set straight ahead. Photos by Dwight E. Neuenschwander.

extending through the fork's steering axis to the ground. The steering axis meets the ground *in front* of the tire's point of contact with the ground. The distance between the steering axis–ground intersection and the front tire's ground contact point is called the "castor" or "trail," here denoted δ (Fig. 2).

When the handlebars are turned, the tire contact point revolves around the steering axis because of the castor. You can feel this torque with an upright bike at rest: turn the handlebars back and forth and the bike frame behind the steering axis turns in the same direction through a smaller angle. The castor provides the lever arm that, with friction between the ground and tire, produces a torque that turns the bike. We will see that when the bike leans from the vertical (even when resting on the kickstand) the front wheel readily turns in the direction of the lean (see Fig. 3). For moving bikes, a relationship exists between the angle α through which the front wheel turns from the straight-ahead direction and the angle θ that the bike leans from the vertical. In our sign convention, both angles are positive for turns and lean to the rider's left.

Consider a bike moving upright and straight ahead on a horizontal road. Both wheels spin in the same vertical plane. Each wheel contributes a spin angular momentum to give a total angular momentum vector **L** that points horizontally to the rider's left. When I ride my bicycle or motorcycle, I imagine this angular momentum as an arrow sticking out of the machine's front axle. This vector grows longer when I speed up and shortens when I slow down.

To entertain the possibility of precession as a consequence of leaning, consider the torque due to the bike and rider's weight. Refer to the tire patch axis defined by the two points where the tires touch the road. When moving in a straight line without lean, the weight of the bike, the rider's CM, and the normal forces on the tires pass through the tire patch axis, producing zero torque about that axis. As a torqueless gyroscope the moving bike appears to be stable until the speed becomes too slow. But what happens when the bike leans?

Suppose the rider leans to the left, shifting the CM to the left of the tire patch axis. This induces a nonzero torque, $\mathbf{r} \times (m\mathbf{g})$ that points horizontally toward the rear of the bike (Fig. 3).

According to Newton's second law, in its rotational form a torque $\boldsymbol{\tau}$ produces a changing angular momentum given by the rate equation $\boldsymbol{\tau} = d\mathbf{L}/dt$. The angular momentum vector acquires a component $d\mathbf{L}$ that points toward the back of the bike—in the same direction as the torque. If this were the end of the story, as long as the bike leans the angular momentum vector **L** would rotate about a *vertical* axis—and the bike would turn—or rather slowly drift—to the left.

Trying to turn the bike by merely shifting your body weight off to the side produces a slow response, woefully inadequate for avoiding the car that suddenly pulls out in front of you.

Incidentally, we see why motorcyclists and bicyclists lean into a strong crosswind. If a strong wind comes from my left, the wind pressure exerted on me and the machine produces a clockwise torque (as viewed by an observer following me). To restore zero net torque, I must lean to the left.

A more effective way to turn left is to apply a small horizontal force *forward* on the left handlebar grip. The bike abruptly moves—counterintuitively—to the left. This is called *countersteering*. Motorcyclists and bicyclists do this even when they do not realize it. Try

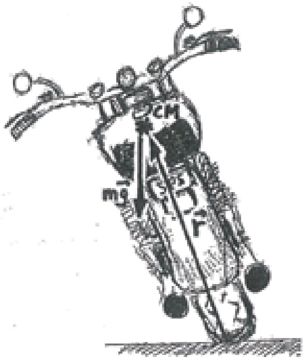


Figure 3: The torque produced by only the weight of the bike-rider center of mass (rider not shown) when leaning. The torque $\boldsymbol{r} \times (m\boldsymbol{g})$ points toward the back of the bike. All sketches by Dwight E. Neuenschwander.

it the next time you ride. When going straight, exert a gentle pressure forward on the left handlebar. The bike will respond quickly to the left. A preliminary way to think of it goes like this: when I gently apply a force forward on the left grip, I produce a torque about the steering axis that has a vertical downward component. To the horizontal angular momentum vector **L** is added an increment $d\mathbf{L}$ with a vertically downward component. Adding this $d\mathbf{L}$ to the original **L** tips the bike to the left, after which the center-of-mass offset contributes its torque.[1] Riding experience shows that with countersteering the bike turns deliberately and responsively, and the difference in response between countersteering and merely shifting one's weight arises from the interaction between the tires and the road. We must examine this in more detail. The physics of bike steering and stability is more complex to model than actually riding a bike—we learned to ride bicycles before we learned our multiplication tables!

The following analysis closely follows that of Lowell and McKell,[2] to which I hope to contribute a few value-added steps. Several other papers on this topic can also be recommended.[1,3-6] Figure 4 shows a schematic of the essential dimensions that concern us: a denotes the bike's wheelbase; Z is the point on the ground directly below the CM with the bike upright; b denotes the distance between Z and the rear tire's contact point with the ground; h is the height of the CM above the ground; and the castor distance δ is shown with an idealized vertical steering axis.

Consider the bike moving through a turn, its path the arc of a circle of radius R. From Fig. 5a, an overhead view of the bike, let α be the angle relative to

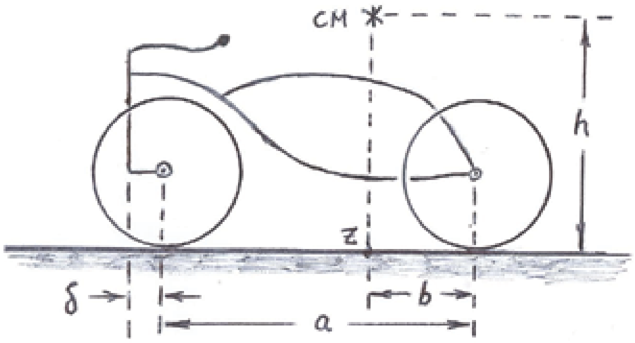


Figure 4: View of bike from the side, showing the distances a, b, h and δ.

the bike frame through which the front wheel is turned; let η be the angle relative to an arbitrary fixed direction through which the frame has turned as the bike moves along the arc; and let $\hat{\boldsymbol{n}}$ denote a unit vector normal to the bike's frame and pointing toward the center of curvature of the circular arc. From Fig. 5b, a view of the bike from behind it, let θ be the lean angle of the bike from the vertical. For dynamic variables let m denote the mass of the bike and rider and g the magnitude of the gravitational field.

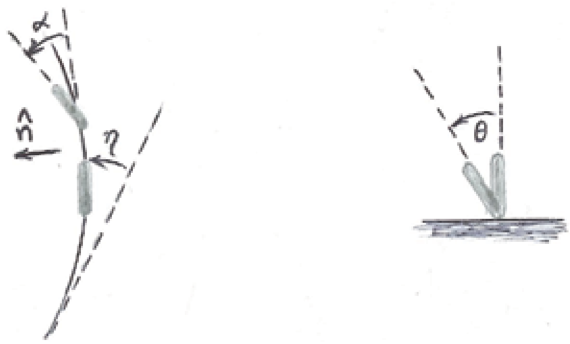


Figure 5. (a, left) View of bike from above, showing angles α and η and the unit vector $\hat{\boldsymbol{n}}$. (b, right) View of bike from behind it, showing the angle θ.

As the bike moves through the circular arc, its acceleration in the direction of $\hat{\boldsymbol{n}}$ comes from three displacements. If the bike were a point mass, it would undergo the centripetal acceleration

$$a_R = \frac{v^2}{R}, \tag{1}$$

where v denotes the bike's speed—which we assume to be constant throughout the turn. But as the bike leans the CM at height h gets displaced towards the arc's center of curvature, which contributes to the acceleration the amount

$$a_\theta = h\ddot{\theta}. \tag{2}$$

In addition, as the bike sweeps through the curve and its frame rotates through angle η, the CM acceleration also picks up the contribution

$$a_\eta = b\ddot{\eta} \quad (3)$$

in the same direction. Gathering all these contributions, the acceleration in the direction of $\hat{\boldsymbol{n}}$ is

$$a_n = \frac{v^2}{R} + h\ddot{\theta} + b\ddot{\eta}. \quad (4)$$

From the geometry of the bike and the definition of the radian, it follows that

$$v = R\dot{\eta} \quad (5)$$

and

$$\alpha = \frac{a}{R}. \quad (6)$$

Combining Eqs. (5) and (6) yields

$$v = \frac{a}{\alpha}\dot{\eta}. \quad (7)$$

From Eq. (7) we may write

$$\ddot{\eta} = \frac{v\dot{\alpha}}{a}, \quad (8)$$

and with this and Eq. (6), Eq. (4) becomes

$$a_n = \frac{v^2\alpha}{a} + h\ddot{\theta} + \frac{bv}{a}\dot{\alpha}. \quad (9)$$

The component of the gravitational force in the $\hat{\boldsymbol{n}}$ direction is $mg\sin\theta \approx mg\theta$, where we assume θ to be small. Neglecting friction (you *can* turn a bike on ice, but it's tricky—friction keeps the lean from going all the way to $\theta = \pi/2$ after the turn begins), the $\hat{\boldsymbol{n}}$ component of Newton's second law says

$$mg\theta = m\left(\frac{v^2}{a}\alpha + h\ddot{\theta} + \frac{bv}{a}\dot{\alpha}\right),$$

or, upon rearranging,

$$\ddot{\theta} + \frac{bv}{ha}\dot{\alpha} + \frac{v^2}{ha}\alpha - \frac{g}{h}\theta = 0. \quad (10)$$

Since leaning and turning the front wheel are related, if the angles are small, we might be justified in assuming a linear relation of the form

$$\alpha = k\theta, \quad (11)$$

where $k = const$. If this is valid, then Eq. (10) becomes

$$\ddot{\theta} + \left(\frac{kbv}{ha}\right)\dot{\theta} + \frac{1}{h}\left(\frac{v^2k}{a} - g\right)\theta = 0. \quad (12)$$

If $k > {}^{ga}/_{v^2}$, this is the equation of a damped simple harmonic oscillator, raising the possibility of front-wheel oscillations. We consider these oscillations below.

With two spinning wheels giving a net angular momentum vector, one might think that gyroscopic effects would keep the bike stable, increasingly so with increasing speed. But in a series of experiments David Jones cleverly demonstrated that the gyroscopic effects are minor and not as essential to stability as one might assume.[6] Jones attached a third axle and wheel to the frame of a bicycle. The third wheel, parallel to the original two, did not touch the ground and could be made to spin in either sense. Its angular momentum added to that of the original wheels, changing the bike's gyroscope parameters to test the efficacy of gyroscopic action for stability. Jones found that the third wheel had negligible effects on stability. He then emphasized the importance of castor.

The effect of castor is easily demonstrated with a parked bike. With the kickstand down the bike leans over (most bikes to the left), and unless you deliberately set it otherwise the front wheel turns in the direction of the lean. When riding normally (no power slides), a nonzero lean angle θ turns the front wheel through a nonzero angle α with the same sign as θ. Conversely, turning the front wheel of a moving bike produces a lean, a point of physics exploited in countersteering: to move the machine to the left one pushes slightly *forward* on the left handlebar[7]—and to go the other way, a slight pull backwards on the left handlebar moves the machine to the right. Why? Pushing forward with a slight pressure on the *left* handlebar turns the front wheel to the *right* through a tiny angle $d\alpha < 0$, but because of the castor, the line of action of the force of friction acting sideways on the tire produces another torque, a restoring torque, that swings the front wheel to the left through a larger angle $\alpha > 0$ (Fig. 6b), and the bike leans into the direction of the turn—by Eq. (10), α and θ have the same sign after these angles stop changing. Restoring torques can produce oscillations, but consider what happens if the tire contact point sits behind the steering axis–ground intersection point (negative castor): then the torque is not a restoring torque, but a "repulsive" one (Fig. 6c).

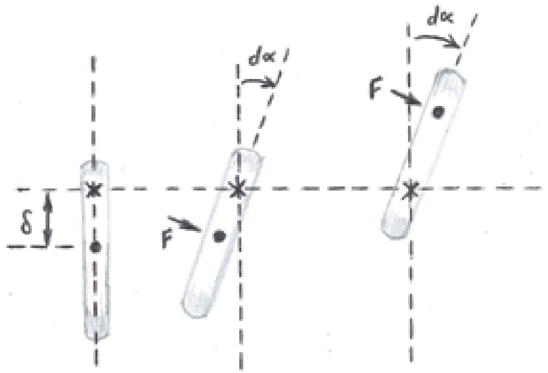


Figure 6: X denotes the point of intersection between the ground and the steering axis. The filled circle represents the tire contact point with the ground. δ is the castor. (a, left) $\alpha = 0$; (b, center) $d\alpha < 0$. F is the component of the frictional force perpendicular to the plane of the tire. $F\delta$ produces a restoring torque about X, which swings the tire to the left. (c, right) If X were behind the contact patch, then $F\delta$ would be a repulsive torque, not a restoring one. If δ were zero there would be very little lever arm for the tire's ground contact patch to turn the bike.

If I try to turn a moving bike left by cranking the handlebars toward the left initially, $d\alpha$ would change sign and the frictional torque in response would turn the bike to the right. If δ were zero, then friction would have very little lever arm to turn the bike at all, and if the steering axis intersects the ground behind the tire patch contact point, then a forward nudge on the left handlebar would cause a repulsive torque with positive feedback, steering the bike farther to the right (Jones reports such a bike to be the "nearest to being 'unrideable'"[6]).

The lean lowers the CM to produce a gravitational torque. That is crucial, so let's take a closer look. When the front wheel turns through the angle α, as seen in Fig. 7, the bike frame behind the steering axis turns through an angle φ,

$$\alpha\delta = a\varphi. \qquad (13)$$

This moves the CM in the direction of $\hat{\boldsymbol{n}}$ by the amount $b\varphi$ (Fig. 8a) so that by Eq. (13),

$$b\varphi = b\left(\frac{\alpha\delta}{a}\right). \qquad (14)$$

When the bike leans at angle θ, the CM drops the distance Δy (Fig. 8b), where

$$\Delta y = (b\varphi)\sin\theta$$
$$\approx \left(\frac{b\delta}{a}\right)\alpha\theta. \qquad (15)$$

Figure 7: Turning the front wheel through angle α turns the bike frame behind the steering axis through the smaller angle φ in the same sense.

This drop corresponds to a decrease in the bike and rider's gravitational potential energy in the amount $mg\,\Delta y = (mgb\delta/a)\alpha\theta$. But a change in potential energy equals work, which in terms of torque τ about the steering axis is $\tau\alpha$ for the front wheel turning through angle α.Therefore $\tau\alpha = (mgb\delta/a)\alpha\theta$, and the torque associated with the lean of the bike is

$$\tau_{lean} = \left(\frac{mgb\delta}{a}\right)\theta. \qquad (16)$$

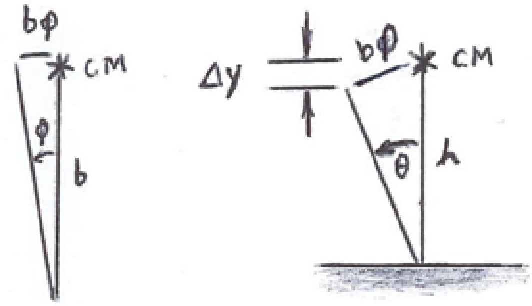


Figure 8: (a, left) Overhead view of the bike frame turning through angle φ. (b, right) View from behind the bike, showing the drop on the CM as the bike leans through angle θ.

Now let's add friction for a bike already in a turn, when θ and α are constants. With the front wheel turned from the straight-ahead direction, friction exerts a "sideways" force on the tires. Let F_f and F_b be the sideways component of the force of friction on the front and back tire, respectively, when the bike moves through a turn of radius R (Fig. 9). The $\hat{\boldsymbol{n}}$ direction component of $\mathbf{F} = m\mathbf{a}$ applied to the entire bike now gives

$$F_f + F_b = \frac{mv^2}{R}. \qquad (17)$$

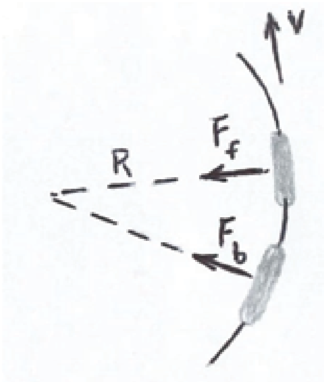


Figure 9: The sideways frictional forces acting on the bike tires as the bike moves through a turn of radius R.

In addition, the sum of torques about a vertical axis through the CM vanishes, so that

$$F_f\ (a-b) = F_b\ b. \qquad (18)$$

Solving Eqs. (17) and (18) for the frictional forces gives

$$F_b = \left(\frac{mv^2}{R}\right)\frac{a-b}{a} \qquad (19)$$

and

$$F_f = \left(\frac{mv^2}{R}\right)\frac{b}{a}. \qquad (20)$$

With the front wheel turned and the bike in the turn, the force F_f produces a frictional torque $\tau_{fric} = F_f\ \delta$ about the steering axis, in the opposite sense of τ_{lean}, so that

$$\tau_{fric} = -\left(\frac{mv^2}{R}\right)\frac{b\delta}{a},$$

which by Eq. (6), used to rewrite R in terms of the bike's wheelbase a, becomes

$$\tau_{fric} = -\frac{mv^2 b\alpha\delta}{a^2}. \qquad (21)$$

Newton's second law in rotational form says that net torque about the steering axis on the handlebars-fork-front wheel system—torques due to lean and friction—produces a change in the vertical component of angular momentum according to

$$\frac{mb\delta}{a}\left(g\theta - \frac{v^2\alpha}{a}\right) = \frac{d}{dt}\left(I_f\dot{\alpha} - I_o\omega\sin\theta\right) \quad (22)$$

where I_f denotes the moment of inertia of the handlebar-fork-front wheel assembly and I_o denotes the front wheel's moment of inertia about its axle with ω the wheel's angular velocity. Since Jones's experiments suggest that a gyroscopic effect does not dominate, if we ignore it and set $I_o = 0$, then Eq. (22) reduces to

$$\frac{mb\delta}{a}\left(g\theta - \frac{v^2\alpha}{a}\right) = I_f\ddot{\alpha}. \qquad (23)$$

Notice that $\ddot{\alpha} = 0$ if

$$\theta = \left(\frac{v^2}{ag}\right)\alpha, \qquad (24)$$

in which case the bike moves uniformly—in a straight line and upright if $\alpha = 0$, or in the arc of a circular path while leaning if $\alpha \neq 0$.

In the next installment we will consider bike stability and the effects of gyroscopic action.

Acknowledgment

I thank David and Kathy Hoenig of Flat Trak Fotos for graciously granting permission to use the photo in Fig. 1.

~~~~~~

* This article offers a drastic revision of the Summer 2003 article, which was ridiculously over-simplified.

References

1. A. J. Cox, "Angular Momentum and Motorcycle Counter-Steering: A Discussion and Demonstration," *Am. J. Phys.* 66, no. 11 (1998): 1018–1020.
2. J. Lowell and H. D. McKell, "The Stability of Bicycles," *Am. J. Phys.* 50 (1982): 1106–1112.
3. J. Fajans, "Steering in Bicycles and Motorcycles," *Am. J. Phys.* 68, no. 7 (July 2000): 654–659.
4. J. Higbie, "The Motorcycle as a Gyroscope," *Am. J. Phys.* 42 (1974): 701–702.
5. Thomas B. Greenslade Jr., "More Bicycle Physics," *Phys. Teach.* (Sept. 1983): 360–363.
6. David E. H. Jones, "The Stability of the Bicycle," *Phys. Today* (Sept. 2006): 51–56.
7. In countersteering for a left turn, one can push the left handlebar forward, or pull the right handlebar backward, or both. Either way produces a clockwise initial torque, which is overcome by the counterclockwise torque due to sideways friction on the tire. For a right turn, push the right handlebar forward and/or pull the left handlebar backward. These are very subtle gentle pushes, not yanks, but the response is immediate.
~~~~~~

Find your future at
spsnational.org/jobs

SPS JOBS

ACHIEVE YOUR CAREER GOALS!

Access free science-specific career development tools – including document templates, recorded webinars, and career advice – from a STEM careers consultant.

Click on the **Resources** tab at **spsnational.org/jobs** to fortify your job search

Now!

Thank you

for your generous donations

Your contributions go directly to fostering the talents and careers of America's next generation of physicists, scientists, researchers, and professionals in physics, astronomy, and related fields. Sigma Pi Sigma and the Society of Physics Students connect students to a world outside of their classrooms and colleges, broadening their perspectives on what they can achieve. By supporting our programs you are investing in the future of our society. Thank you for your support in 2020! You can make a donation at **donate.aip.org**.

(*) indicates a donation of over $500.

Abilene Christian University
Horacio Gasquet
Rodney Smith

Adelphia University
Michael Delahunty
Peter Esser
David Martin
Neal Redmond

AIP Board of Directors
Susan Avery
Susan Burkett
Bruce Curran
Judy Dubno
Eric Furst
Jack Hehn*
David Helfand*
John Kent
Allison Macfarlane
Michael Moloney*
Michael Morgan
Elizabeth Nolan
Tyrone Porter
Nathan Sanders*
James Taylor
Charles Woodward
Tyrone Porter

AIP Board of Trustees
Sandeep Giri*
Nancy Greenspan*
Ray Johnson
Ruel Mercure*
Robert Meyers*
Julia Phillips*

Akron, University of
Patricia Pitts
John Redfield

Alabama, University of
Samuel Denham
George Hamner
Marcus Pearson

Alabama–Huntsville, University of
James Huckle

Alma College
Paul Splitstone

American Assoc of Physics Teachers
Beth Cunningham*

American Institute of Physics
Liz Dart Caron
Brad Conrad
Tanya Easton*
Steve Mackwell*
Steve McAlister
Sherry Render
Catherine Swartz

American University
Radoslav Antonov

Angelo State University
Brock John

Appalachian State University
Thomas Rokoske

Arizona State University
Robert Marzke

Arizona, University of
Edwin Jones
Peter Lyons
Dale Shellhorn

Arkansas–Fayetteville, University of
Dean Berry
Gary Culp
Karen Williams
Richard Anderson

Arkansas–Little Rock, University of
Karl Straub

At Large
Harold Bautista
Louis Beyer
Mel Blake*
Richard Dalby
Kenneth Ford*
Peter Hakel
Donna Hammer
Lyle Haugen
Richard Haymaker
Stephen Martin
Jami Miller
Joseph Othmer
Rebecca Rank
Brian Sabo
Brian Schwartz
William Shields
Ben Stein
John Tranchina
Bela Vastag
Kevin Yarnell*
Tamara Young

Auburn University
Leanne Catrett-Tamblyn
Cherh-Lin Chen
Timothy Fitzsimmons
Michael Haworth
Harold Jackson
Lawrence Karch
William Roquemore

Augsburg College
Brian Anderson

Augustana College
Mark Taylor
Scott Slaith

Austin College
Terrance Lingren

Baylor University
Roy Brown
Joseph Cipriano
Bertram Geeslin

Benedictine College
Joseph Anthony
Joseph Hickert
Thomas Lahey

Birmingham–Southern College
John Darby
William Stalcup

Bloomsburg University
Chad Moore

Boston College
Michael Gigliotti
Rayford Hosker
Robert Pagliarulo
William Plansky
Paul Sullivan

Boulder, University of Colorado
John Bellotti

Bowling Green State University
Pamela Darwin
Michael Grone
Joachim Hirche*
Joseph Synk

Bradley University
Scott Keith

Bridgeport, University of
Douglas Basarab
Marc Read

Brigham Young University
Layne Jensen
Randy Olsen
Peter Polgar
Larry Smith
Joseph Wilcox

Bucknell University
Richard Bitzer
Frances Faylor
Donald Miller
Daniel Taylor
Mark Torrence

Butler University
H. Marshall Dixon

Cal Poly Pomona
William DeGraffenreid

Cal Poly San Luis Obispo
Endel Kallas

Cal State Dominguez Hills
Amaro Moreno

Cal State LA
Jean Swank

Cal State Long Beach
Albert Franco
Chi Hu
Neil Perl

Cal State Northridge
Hirsch Goffman
Robert Johnson
Donald Sparks
Lance Stevenson

Cal State Sacramento
Gwendolyn Buchholz*
Charles Hunt*
Tim Miller
Michael Shea

Cal State San Bernardino
Karen Lowande

Cameron University
John Nolan

Catholic University of America
Hall & Carol Crannell

Central Missouri State University
Merlin Ring

Charleston, College of
William Bridgman

Cincinnati, University of
John Cummings

Clark University
Robert Groman

Clarkson University
Kendra Eagan
Stephen Ford
Eileen Romano

Clemson University
Michael Kalinosky
John Meriwether
Barbara Rice

Coe College
Mario Affatigato
Steve Feller
Andrew Gunsch

College of William & Mary
Richard Babcock
Lee Harrell
John Hoppe
William Slauson
Robert Stevens
William Tropf
DJ Wagner

Colorado–Boulder, University of
Michael Francis
Dewitt Harrison
Edward Kraft*
Charles Luke
Kenneth Moran
Kenneth Parker
Robert Wallis

Colorado Mesa University
Michael Peterson

Community Supporters
Susan Allen
Leonard Beavis
Louis Beverino
Peter Bingham
Sue Broadston
Marc Brodsky*
James Burch*

Brenda Cabell
Gay Canough
Morrel Cohen
Donella Darby
Fred Dylla*
Hedy Eckert
Theodore Einstein
Fred Erskine
Samuel Gasster
Mary Gehrke
George Glass
Alfred Goldhaber
Jorgen Hansen
Ethel Hills
Nelson Hoffman
Judy Holoviak*
James Hook
Rosamond Hooper-Hamersley
Albert Huen
Kern Kenyon
John Klauder
Anthony Leggett
Myron Mann
Michael Maturo
Steven Moszkowski
Charles Myers*
Paul Nordin
Jens Oberheide
George & Joan Paulikas*
Jennifer Pursley
Xiaohui Qin
Ryan Rairigh
Chester Reft
Barbara Roldan*
Keith Runge*
Myriam Sarachik
David Schaich
Brian Schuft
Siavash Sohrab
Cherrill Spencer
David Strozzi
Jay Tittman
Samuel Valle
Berthold Weinstein*
Khurt Williams
Carl Zeisse

Connecticut, University of
Gary Austin
Richard Barrett
Robert Bossoli
Robert Delboca*
Roger Desnoyers
Robert Erickson
Gerald Holst
Quentin Kessel
Gerry Morgan
John Owens
Peter Poulos
Thomas Welsh

Cooper Union
Kenneth Krane

Corporate
Ball Corporation
Benevity Community Impact Fund*
Charities Aid Foundation of America
Craig Walters Associates
Dominion Energy
Fidelity Charitable Gift Fund*
LinkedIn Matching Gift Program
Lockheed Martin Employee's PAC Charity Match Program
MechSigma Consulting, Inc.
Schwab Charitable Fund*
T. Rowe Price*
Texas Instruments Foundation
The Judice Family Foundation, Inc.
United Way of Central New Mexico

Creighton University
Edward Huston

Davidson College
John Hill
Michael Owen

Dayton, University of
Thomas Graham
Allen Jackson
Howard Schumacher
Virgil Stegner

Delaware, University of
David Barsky
Roland Hultsch*
Floyd Lovorn
Tom Lovorn
Willard White

Denver, University of
Stephen Behnen
C. Klepper

DePauw University
James Adney
Chris Gottbrath
Keith Kenter

Detroit, University of
Thomas White

Dickinson College
Greg Ajamian
Todd Baker
Michael Hickey
Karen Hirsch
John Luetzelschwab
Michael Murphy

Drew University
Leonard Feldman
Robert Fenstermacher

Drexel University
Franklin Robinson
Elizabeth & Robert Stanton

Duke University
Lewis Branscomb*
Ronald Burns
Leroy Gross
Gary Lunsford

Duquesne University
Bruce Martin
James Messmer

East Carolina University
Thomas Sayetta

East Stroudsburg University
James Nesbitt
Scott Richardson
Stephen Semanek
George Svok

Eastern Illinois University
Merri Horn

Eastern Michigan University
Neil Eriksen
Mark Moverman
Tumer Sayman

Eastern Oregon State College
Kevin Bier

Elmhurst College
Roy O'Kelly
Alice Ramsay

Emory University
Matthew Abrams
George Dyer
John Funke
Jack Rowe
David Sliney

Emporia State University
Gary Shepek

Evansville, University of
Stephen Berry
Darrell Megli
Stephen Thomas
Frederick Van Haaften

Florida Institute of Technology
Susan Chambers
Rudy Frahm

Florida State University
Jean Lane
Charles Schmidt
Louis Sica

Florida, University of
Evelyn Boettcher*
John Danese
Charles Jackman
Ronald Keyser

Fordham University
Edward Grissing

Fort Hays State University
Monte Kopke

Francis Marion College
Samuel Meggs

Franklin & Marshall College
James Balent
John Dommel
Yancy Edwards
Michael Mumma
William Parker
Thomas von Wiegand

Frostburg State University
Gary Hendrickson
Francis Tam

Furman University
Jerry Wilson

Gannon University
David Jordan
Walter LaPrice

George Mason University
Christine Bjorklund
Mark Nagurney

Georgia State University
Alan Hull
Eongwei Lai
Donald Taylor

Georgia Tech
Laurence Epstein
Robert Fortenberry
Clinton Gilliland
Werner Metz
William Ogle
Eugene Patronis
Michael Thackston

Georgia, University of
Marvin Maddox
James Moss

Georgian Court University
Amy Applegate

Gettysburg College
Bruce Horne
Ruth Kumler

Grambling State University
Willie Rockward

Guilford College
Andrew Degges
Christopher Field
Bruce James
Lois Wright

Hanover College
Joseph S. Wakefield

Heidelberg College
Robert Parker

Hofstra University
Theodor Andresen
Mary Hickey
Robert Klatt
William Terrone

Holy Cross, College of the
Salvatore Lamesa
Frank Tangherlini

Houston, University of
Charles Dejohn

Hunter College of the CUNY
Padmanabhan Santhanam

Idaho State University
Larry Morford

Idaho, University of
Clifford Schoff

Illinois Benedictine College
William Cavallo
John Homer
Dominick Stella

Illinois Institute of Technology
Roland Juhala

Indiana State University
Susan Grow

Indiana University, Bloomington
William Goodwin

Iowa State University
John Hill
James Vary*

Ithaca College
Colin Howard

James Madison University
Howard Dawson
Raymond Serway

John Carroll University
Douglas Blakeley
Branden Melich
Catherine Newell
Ernest Petti*
Joseph Szente
Joseph Ursic

Juniata College
Jim Borgardt
Wilfred Norris

Kansas State
Mark Plano Clark

Kansas, University of
David Brice
Larry Dike
Charles Francis
Dean & Cynthia Halderson
Richard Leamon
Richard Moore
Sara Rubida

Kent State University
Gregory Latta
Jack Stanford
James Visintainer

Kentucky, University of
Alan Arvin

Kettering University
Ronald Kumon

Lake Forest College
Mary Ann Hayes

Lamar University
Emanuel Dimiceli
George Durling
Darla Smith

Lewis University
Chi Hu

Linfield College
Ira Cohen

Louisiana State University
Richard Rauch*

Louisiana Tech University
Ken Evans
Jonathan Gaston
Thomas O'Kuma

Louisiana University at Lafayette
Danelle Tanner

Louisville, University of
David Blanchard
David Brown
Nareshchandra Shah

Loyola University
James Gross

Luther College
Roger Scholten

Maine, University of
Allan Ames
Ernest Brigham
David Dunlap
Arthur Harris
Richard Knight
Victor Mortenson
Robert Saltzman
Craig Smith

Manchester College
Morris Firebaugh
Gary Heisler
Gary Stauffer

Manhattan College
John Gulbin
Michael Shea

Marquette University
Edward Mattson
Paul Miller

Maryland–College Park, University of
Richard Graham
Jean Krisch*
William Lupton

Massachusetts–Boston, University of
James O'Brien

Massachusetts–Lowell, University of
Bruce Gordon
Edward Hanfling
Tim Largy
Michael O'Hara

Memphis, University of
Daniel Ladner
Broadus Weatherall

Miami University
Edward Caner
Scott Leonard
James McCord

Miami, University of
Michael Jacobs

Michigan State University
Mary Anderson
Henry Darlington

Michigan, University of
John Dodds
Susan Fischer*
Thomas Heller
Peter Zuercher

Michigan–Flint, University of
David Zick

Millersville University
Zenaida Uy

Minnesota, University of
Vanessa Bailey
Thomas Christensen
Jeanne Hladky
Gregory Roelofs*

Mississippi College
James Taylor

Missouri–Kansas City, University of
Teresa Froncek

Missouri–Rolla, University of
Howard Brown
Albert Cawns
David Fahey
Harry Hardebeck
John McDaniels

MIT
John Driscoll
Lajos Molnar & Austin Hudler*

Monmouth University
Eric Englestein

Moravian College
Richard Harney

Morehouse College
James Milton
Orhan Oz

Morningside College
Brett Beckfield
Jerry Yoder

Mount Holyoke College
Elinor Gates

Mount Union College
Brian Friedmann

Muhlenberg College
David Detwiler

Murray State University
Robert Johnson
Charles Robertson

Nebraska Wesleyan University
Marvin Bures
Leemer Cernohlavek
Barry Hammond

Nebraska–Lincoln,
University of
David Sellmyer

Nevada–Reno, University of
Robert Gehrke
Edwin Moore
Robert Rosenbaum

New Mexico State University
Bernard Cataldo
Paul Daggett
Patti Gillespie
Foo Lam
Elwin Nunn

New Mexico Tech
Timothy Hamlin*

New Orleans, University of
Thomas Lawrence
Louis Vedros
Carl Ventrice
Richard Waguespack

New York Institute of Technology
Kenneth Frankel

New York University
Judah Levine
Louis Markatos
Allen Wolfert

North Carolina State
Christopher Gould
Jeffery Hurley
Douglas Knight
Jack Penny
Charles Philbrick
Scott Wilburn

North Dakota State University
James Glass
Jeffrey Schmidt

North Texas, University of
Robert Gardner

Northern Arizona University
Jeremy Smith

Northern Illinois University
Steven Overmyer
Larry Sill

Northern Iowa, University of
Paul Heller

Occidental College
Nariman Dastur*
Brian Newnam*

Ohio Northern University
Michael Garee

Ohio State University
David Carpenter
Vincent Donlan
Lewis Hecht
Ints Kaleps
William Robinette
Raymond Roop
Sylvia Whitt

Ohio University
Folden Stumpf

Oklahoma City University
David Davison

Oklahoma State University
John Freeman
James Hurt

Oklahoma, University of
Bruce Evatt
Dale Willhite

Old Dominion University
John Lescher
Russell Lutton
Charles Welch

Oregon State University
Sam Ghaleb
Bruce Gibbs
Todd Goldsmith
Stephen Henning
Dennis Henry
Eric Jones
William McLain
Robert O'Brien
Frank Stekel

Penn State
James Brunner
Sandor Caplan
Elizabeth Cox
Barbara Faust
John Herritt*
Edward Mebus
Donald & Barbara Owens
Janda Panitz
Richard Pryor
Julian Reinheimer
Fredrick Shaffer
Ernest Stonebraker

Pittsburgh, University of
Robert Devaty

Polytechnic University (NY)
Colin Fredericks
John Lafemina
Anthony Ratkowski
Victor Sank
Edward Yarr

Providence College
Michael Coussa

Puget Sound, University of
Bert Brown*

Purdue University–West
Lafayette
Harold Boesch
Richard Born
Edward Connell
Gary Cunningham*
Robert Daniell
Robert Goodwin
John Gotwals
John Kay
Marvin Kemple
Ralph Lambert
Victor Lawnicki
William McFerran
John Mennel
David Michel
Stephen Montgomery
Melvin Moriwaki
Donald Nelson*
Clarence Oyer
Frederick Reed
Steven Stendahl
William Tozer

Ramapo College of New Jersey
Jelena Pjesivac-Grbovic

Rensselaer Polytechnic Institute
Jennifer Bartlett
Paul Berman
Robert Dorsch
Andrew Kalnin
John Leonardi
Richard Rapids
John Reynders
Julian Tishkoff
Mark Tollin
Randy Van Vranken
John Vitko
Rosemary Walikis
Bruce Wexler

Rhode Island, University of
Thomas Jenckes
Thomas Turano*

Rhodes College
Steve Kendrick
Charles Robertson*
Jenna Smith*
L. Montgomery Smith

Rice University
David Monyak*
Mark Zimmermann

Richmond, University of
Michael Kusheba
Carlton Ragland
William Ryan

Ripon College
Lita Katz
Xavier Polanski
Michelle Witt

Roanoke College
James Hagan

Rochester Institute of Technology
Ronald Manginell
George Privon

Rochester, University of
Michael Heinecke

Sam Houston State University
Kelly & Debra Jacobsen
Robert Steele*

San Diego State University
Gerald Cahill
Nils Lindman
Richard Mannix

San Jose State University
Donald & Patricia Strandburg

Santa Clara University
Kenneth Claiborne

Scranton, University of
Christopher Corey

Seton Hall University
Jennifer Kreidler-Moss
Stephen Natale
Renata Weber

Sewanee: The University of the South
Paul Drake

Shippensburg University
James Imler

Siena College
Kimberly Baker
Charles Knight

South Carolina, University of
John Palms
Carl Rosenfeld

South Dakota Mines
Louis Dorland
Fred Kopp
James Stoebner

South Dakota State University
Joan & Harold Leinbach
Steven Ness

South Dakota, University of
Martin Predoehl

South Florida, University of
Don Booth
Joan McCall

Southern California, University of
Thomas Shigemitsu

Southern Colorado, University of
Richard Dickson
Timothy Van Loon

Southern Mississippi, University of
Mary Agner
Alina Gearba-Sell*
Grayson Rayborn
Harold Stevens

Southwest Missouri State University
Charles Armstrong
Luis Rivera

Southwestern Oklahoma State University
James Bates
Chris Geswender

Spelman College
Adrienne Hill

St. Joseph's University
James Dibiase
Kenneth Young

St. Lawrence University
Sylvia Watkins
Ann Yates

St. Mary's College of Minnesota
George Morin
Richard Smith

St. Olaf College
Gary Gimmestad
Craig Kullberg
Paul Larson
Bernhard Molldrem
Howard Rockstad
Royal Thern

Stetson University
David Williams

SUNY Albany
Paul Bono
Richard Coppola
Stephen Sanders

SUNY Binghamton
Mildred Calistri-Yeh
Joseph Rossabi
Howard Zendle

SUNY Brockport
Robert Baden

SUNY Fredonia
Paul Bicknell

SUNY Geneseo
Douglas Harke
Paul King*

SUNY Oswego
Ronald Brown

SUNY Plattsburgh
Lonny Kauder

SUNY Stony Brook
Michael Shlesinger

Temple University
Bernard Rudin
William Weston

Tennessee Tech University
Raymond Kozub
Carl Ventrice

Tennessee–Chattanooga, University of
Arvel Fincher
Jon Visser*

Tennessee–Knoxville, University of
J. Breeding
E. Crume
Rose Dishman
Edward Fleming
Jackie Hill
Sandra Hinsdale
James Jarratt
Rex Lewis
Leo Riedinger

Texas A&M
Douglas Abraham

Texas A&M Kingsville
Bob Wheeler

Texas Christian University
Glenn Carroll

Texas State University
Rahul Toley
Douglas Wolff

Texas Tech University
Walter Borst
Max Dannecker
Stephen Glenn
William Kelly
David Smith
Kevin Walter

Texas–Arlington, University of
Don Guthrie
Robert Skinner
Hugh Southall

Texas–Austin, University of
Arthur Chester
Christopher Hackert
Edward Monahan
Dennis Wylie

Texas–El Paso, University of
Aurora Bustos
Randal Gibson
Wade Mayo

The Optical Society of America
Elizabeth Rogan

Thiel College
Dawn Chesonis

Thomas More College
Michael Eismann

Toledo, University of
James Schweikert

Towson University
Jacob Huang

Transylvania University
John Kuchenbrod

Trinity College
Stanley Twardy

Trinity University
Larry Luckett
Charles Moore
Erwin Myrick
Gustav Van Steenberg

Tufts University
Maurice Halladay

Tulane University
David Schorr
William Yeager

Tulsa, University of
Michael Wetzel

UC Berkeley
Julian Cummings

UC Davis
James Landry*

UC Irvine
Darrel Smith
Dane Stone*
Stanley Tyler
Richard & Nancy Vodhanel

UC Los Angeles
Robert Acquarelli
David Aires
Sonia Balcer
Christopher Crane
David Garfinkle
Steven Gelb
Stuart Goldenberg
Reynold Kagiwada
Michael Kriss*
Joel Kvitky
John Markley
Gilbert Miranda
Edward Rhodes, Jr.
Erno Ross
Douglas Scharre
Larry Simmons
Richard Stanton
John Wood

UC Santa Barbara
Clifford Wylie

Union College
John Johnston
Lloyd Maliner

Upsala College
Albert Helfrick

US Military Academy
Julian Holder

US Naval Academy
John Giessner*

David Jourdan
Carl Klee
William Matzelevich
Tobin McNatt
James Spaman
Kurt Studt
Wesley Summers
James Waddell

Utah State University
Robert Luke
Richard Meservey

Utah, University of
Alan Blackburn
Richard Fletcher
Jessica Gledhill
Richard Hills
Calvin Wood

Vanderbilt University
Michael Turner

Villanova University
James Lochner

Virginia Military Institute
Peter Benda
Stuart Serenbetz
Terry Stoneman
John Tucker

Virginia State University
James Stith

Virginia Tech
Dennis Allison
Anne Costolanski
F. Joseph McCrosson
James McDonald
C. Robins

Virginia, University of
Gregory Ashe
Steven Carter
Timothy Jarrett
Edward Lynch
Raymond Modlin
George O'Brien

Wabash College
C. Livengood

Washburn University of Topeka
Vincent Miles

Wayne State University
Fern Katz

West Florida, University of
Paul Barlow

West Virginia University
Anna Allen
Thomas Carpenter
Frank Hoge
John Lannon
Robert Pierson
Wesley Shanholtzer
Fred Smith

Western Illinois University
Shirley Chan
Jerry Forbes
Charles Horton*

Western Kentucky University
Mark Rogers

Westminster College
Edward Mansell
Thomas Mansell
Roger & Helen Metzler

Wheaton College
Norman Richert
David Wright

Whittier College
Seamus Lagan

Wichita State University
John Baldwin
Larry East
James Madl
Frank Pistotnik
Timothy Scrivner

Widener University
Kenneth Miller
John Trumbull

William Jewell College
David Baker
Carl McElwee

Wisconsin–Eau Claire, University of
Keith Daniels
Robert & Barbara Schneider

Wisconsin–Oshkosh, University of
William Weber

Wisconsin–Platteville, University of
Erin Draeger

Wisconsin–River Falls, University of
Earl Blodgett
James Hendrickson*
Gary Holm
Lowell McCann
Neal Schumacher*

Wisconsin–Superior, University of
Blaine Diesslin
William Wooden

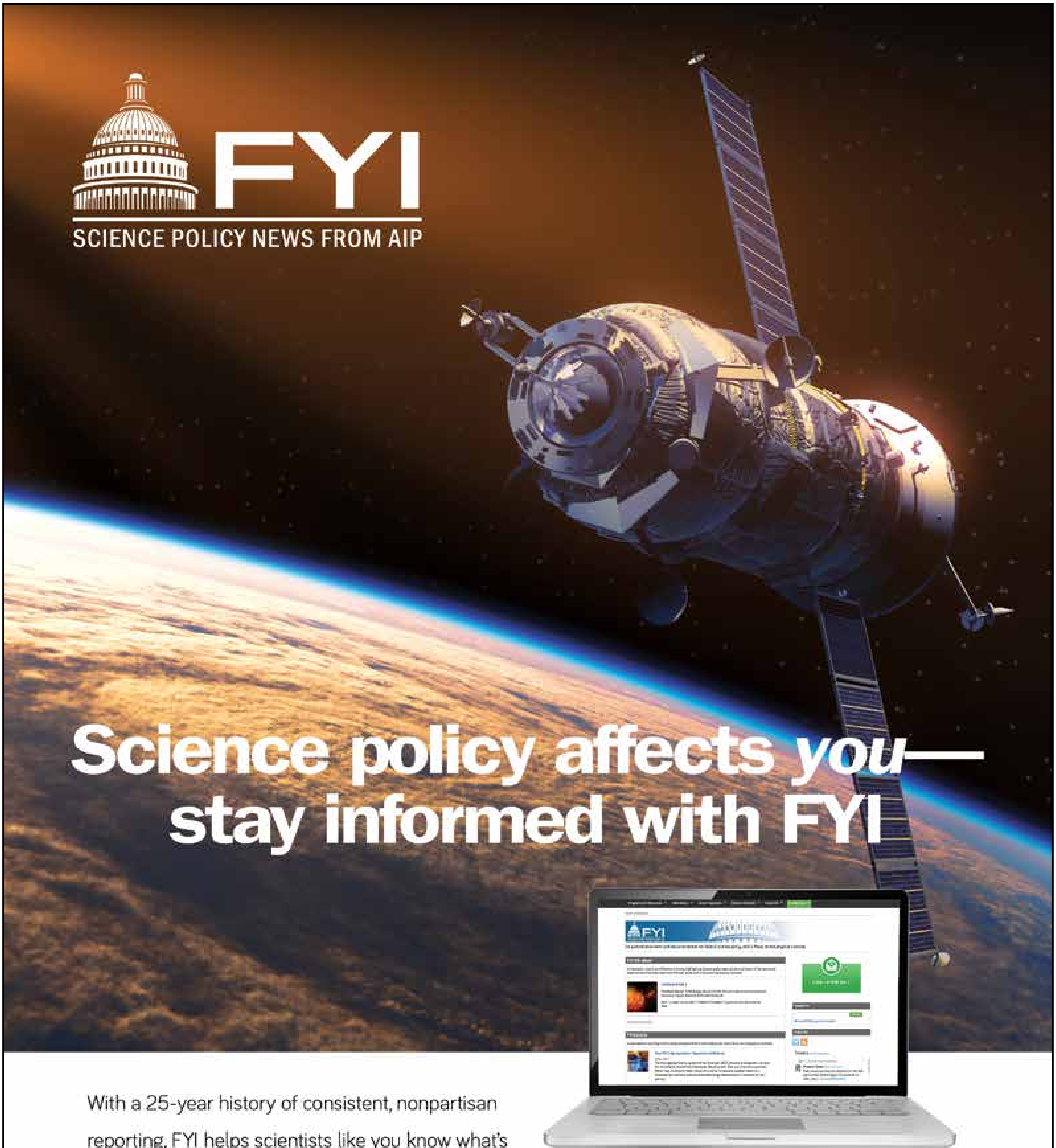
Wisconsin–Whitewater, University of
Michael Devoe
Marvin Johnson
William Zagorski

Worcester Polytechnical Institute
Stephen Bernacki
Stephen Lawry
Cliff Weiner

Wright State University
Matthew Dierking
Doug Glass
John Hehmeyer
Kimberly Wiefling

Wyoming, University of
Charles Bruch
Edmond Meyer

Xavier University
Austin Church
Jeffery Grothaus
William Kuhlman
Anthony Martino
John Swyers
William Zeitz


FYI
SCIENCE POLICY NEWS FROM AIP
Science policy affects *you*—
stay informed with FYI

Radiations
American Institute of Physics
1 Physics Ellipse
College Park, MD 20740