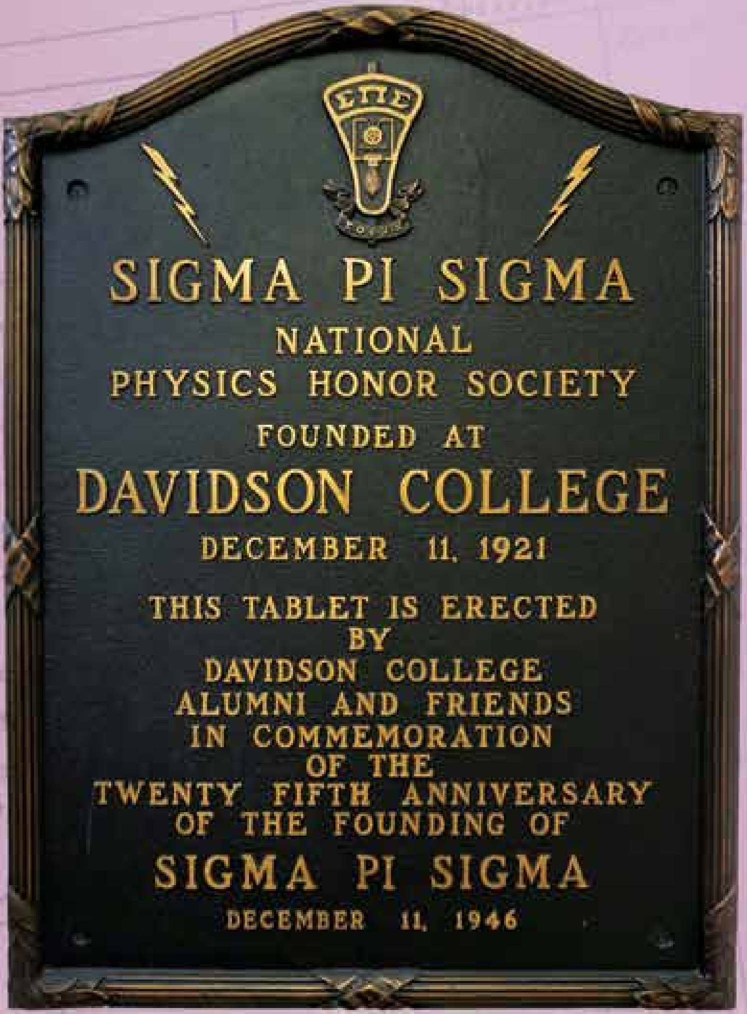
Radiations

SPRING
2022

The official publication of Sigma Pi Sigma

The Physics *and Astronomy* Honor Society



100
The Centennial Campaign
SIGMA PI SIGMA
1921–2021

A Physicist's Guide to Machine Learning

Cheers to 100 Years!

Letter from Outgoing ΣΠΣ President James D. Borgardt

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Recipients receive national recognition and certificate.

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ON THE COVER

A tablet donated by alumni and friends of the Sigma Pi Sigma chapter at Davidson College, in honor of the 25th anniversary of Sigma Pi Sigma. In the background is a page of the chapter's first record book, featuring some first-generation members of Sigma Pi Sigma.

Photo courtesy of Anthony Kuchera, Davidson College.

Radiations

Spring 2022
Volume 28, Issue 1

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Radiations (ISSN 2160-1119) is the official publication of Sigma Pi Sigma, the physics and astronomy 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 Sigma Pi Sigma President

Meeting the Challenges of the 21st Century and Beyond

by Professor James D. Borgardt, Sigma Pi Sigma President

Photo courtesy of James D. Borgardt.

Being a college student, especially in the fields of physics or astronomy, has been tough over the past couple of years. COVID has hampered many of the support systems that we all rely upon—innately or overtly—for our sense of purpose and community. It has been a challenge to maintain Society of Physics Students (SPS) on-campus activities and outreach events, have in-person Sigma Pi Sigma inductions, and otherwise engage with others in our discipline in the ways we were accustomed to.

Serving as your Sigma Pi Sigma president during the pandemic has limited my ability to interact with individual chapters and travel to help facilitate honor society inductions. Yet, this has been my favorite part of serving in this role—visiting chapters across the country and experiencing the unique and vibrant ecosystems that reside within them.

Fortunately, we've adapted and discovered new ways to maintain these relationships that have sustained us over this time (Zoom!). We've also been expertly supported by our amazing and dynamic National Office, which has steadfastly maintained contact, developed new initiatives, buoyed our regional zone councilors (ZCs) and associate zone councilors (AZCs), and helped us all weather this difficult time.

While we've experienced varying degrees of fatigue during the pandemic, we collectively owe a huge debt of gratitude to each and every member of the team at the National Office and the National Council (including AZCs and ZCs), for not only sustaining our community but also for growing it by developing novel initiatives to help students in key areas. These initiatives include the AIP-SPS Undergraduate Education Pandemic Assistance program and the Food for Hungry Physics and Astronomy Students program, efforts to promote diversity, and many others. Continuing our momentum and focusing on the future has helped individual students and chapters alike, and positioned us well for the future.

Speaking of...What are you doing October 6th–8th? I'm looking forward to gathering for the upcoming Physics Congress, or PhysCon, in our nation's capital to not only "Celebrate 100 Years of Momentum," the meeting's theme, but to also join as a community and carry this work forward into the next century of SPS. PhysCon is open to undergraduates with an interest in physics and astronomy, SPS advisors, SPS alumni, and Sigma Pi Sigma members, and is the largest undergraduate gathering of physics and astronomy students in the country. This will be one *phantastic* and *phun* event, with opportunities to hear and meet luminaries in our fields, visit campuses and labs in the DC area, and interact with students and chapters from across the country. So be sure to join us in celebrating Sigma Pi Sigma's centennial birthday and setting the course for our next century of supporting all of those who study physics and astronomy.

As I come to the end of my time as your Sigma Pi Sigma president, I'm also psyched that COVID restrictions are relaxing and campuses are again able to have functions and outside visitors. If you are interested in establishing an SPS or Sigma Pi Sigma chapter in advance of PhysCon, or resuming interrupted in-person Sigma Pi Sigma inductions for physics and astronomy students, the National Office and I stand ready to help. I'd love to complete my term by visiting some campuses to assist in this effort. Thanks for the opportunity to serve in this role, and I hope to see each of you at PhysCon in Washington, DC, come October! ●

100YEARS
OF MOMENTUM

physcon
2022 Physics Congress

Register today at
sigmapisigma.org/congress/2022

Early bird registration open until
September 6, 2022

OCTOBER 6-8, 2022 | WASHINGTON, D.C.

Plenary speakers


Julianne Pollard-Larkin
MD Anderson Cancer Center


K. Renee Horton
NASA


Rush Holt Jr.
former CEO of AAAS


Sarah Hörst
Johns Hopkins University

Events

- 5 Plenary Sessions
- Tours: Green Bank Observatory, National Labs, GWU, UMD, Smithsonian, and more
- 15+ workshops
- Poster Session & Physics Phine Art Exhibit and Competition
- Career Expo Chapter Showcase
- Grad School Fair
- High Energy Hot Chocolate and Game Night & Astronomy Night at GWU
- Dance Party & Physics Phestival

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

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American Association of Physicists in Medicine
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1


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Supporting Travel, Supporting Students in 2022

by AIP Foundation and Brad Conrad, Director of Sigma Pi Sigma

A hundred years ago, Sigma Pi Sigma was created at Davidson College, North Carolina, by students and faculty who donated their time and resources to help strengthen the undergraduate community of physics and astronomy students. Two of the founding pillars of the society are to support excellence in physics and astronomy and to encourage fellowship. These ideals are part of the charge that each Sigma Pi Sigma member agrees to upon joining, and they live on today through our support of the 2022 Physics Congress.

While travel remains something most students were not able to do much of recently, in-person conferences have begun again around the globe. Undergraduate research presentations remain one of the most important professional development activities we can support. The practice of effectively and succinctly communicating with peers and leaders in the field is excellent preparation for today's workforce. Engaging in conferences provides students with a wealth of skills and experiences that will serve them throughout their careers and that go beyond what can be taught in the classroom.

By presenting on their physics and astronomy research or 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. They practice their elevator speeches and make connections that can open up future career paths. They develop an awareness of what it means to be part of the scientific community beyond their immediate research groups and academic departments.

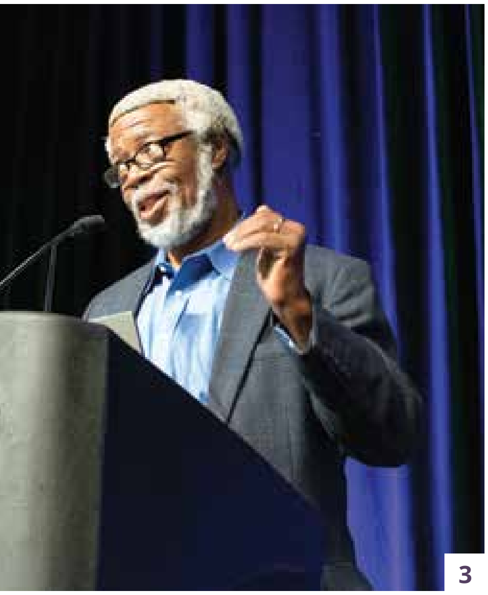
Often, students gain insights into how their research connects to other research groups—or entire fields of study of which they were not aware. Science that occurs in a vacuum runs the risk of failing to advance the field and our shared understanding of the universe. With your help, we can provide student leaders with opportunities to grow both professionally and socially. SPS and Sigma Pi Sigma are inviting students from all around the United States and beyond to join us October 6–8 in Washington, DC, for the 2022 Physics Congress. This event will bring together over 1,000 students for three days of professional development and networking.

Plenary speakers include

- Julianne Pollard-Larkin, Section Chief for Thoracic Radiation Physics at MD Anderson Cancer Center
- K. Renee Horton, Space Launch System (SLS) Quality Engineer at NASA
- Rush Holt Jr., Scientist, Politician, and former CEO of American Association for the Advancement of Science (AAAS)
- Sarah Hörst, Associate Professor of Planetary Sciences at Johns Hopkins University

This once-in-an-undergraduate-career opportunity only happens every few years, and we want as many students as possible to be part of the action.

> “I conduct research on the physics of smell. I presented this research at the PhysCon meeting last November and several other national meetings. I am excited to have been accepted to an REU in biophysics . . . Once again, thank you for your support. I know that many of the SPS programs, such as the scholarship program, would not be possible without the generosity and dedication of donors like you. I am especially grateful for the opportunities that your donation will provide me through this scholarship as I continue my education. Your generosity has truly made a difference in my life.”
>
> *- Carissa, an SPS member who received a donor-supported SPS travel award*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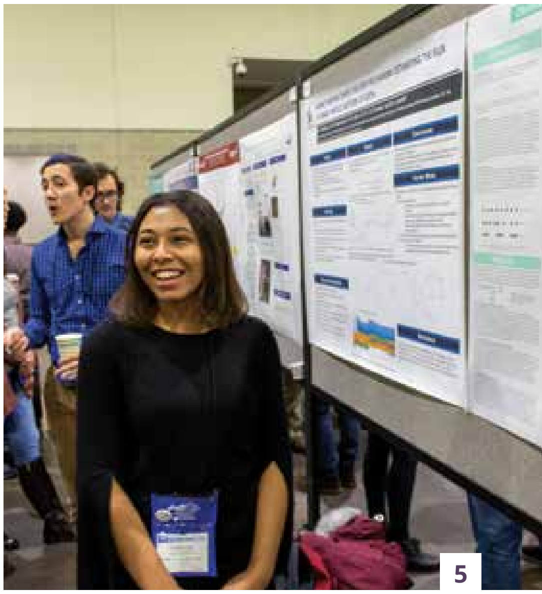
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With the direct support of donors such as yourself, SPS can offer students grants to help offset travel and registration costs for the 2022 Physics Congress. You can help students make connections that will last a lifetime by contributing to the Congress Centennial Endowment Fund at foundation.aip.org.

Considering that most juniors and seniors have limited opportunities to present before applying to their first jobs or graduate programs, PhysCon 2022 is an opportunity that could change their lives. This is where we, Sigma Pi Sigma, come in—many of these students simply cannot afford to attend PhysCon without a helping hand. Sigma Pi Sigma and SPS can support unique initiatives at over 800 different schools across the globe.

Linked but distinct, the societies of Sigma Pi Sigma and SPS are volunteer driven and donor supported. With your help we can ensure that future generations have experiences that mirror the comments of the student leaders featured here. We each have a part to play in making the community more accessible and welcoming, and I invite you to join us in supporting the next generation and next 100 years of Sigma Pi Sigma. ●

1: Students from Grove City College, wearing T-shirts they designed, honor a poster tube that safely transported many of their scholarly works.

2: Students supported by Sigma Pi Sigma member donations at the 2019 Physics Congress.

3: Luminary and longtime friend of SPS, Jim Gates, addresses the 2019 Physics Congress.

4: Students attend a workshop at the 2019 Physics Congress.

5. Students present their research.

All photos courtesy of Ashauni Lennox, AAPT.

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We can help you make your IRA work for you

When you use the IRA Charitable rollover to support the mission of Sigma Pi Sigma, you can relax. It is like giving yourself a vacation.

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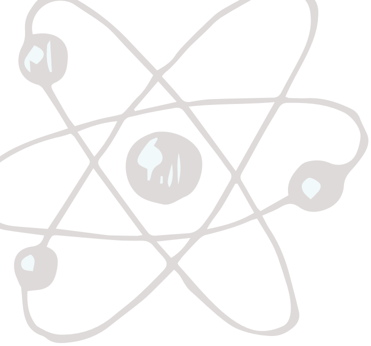
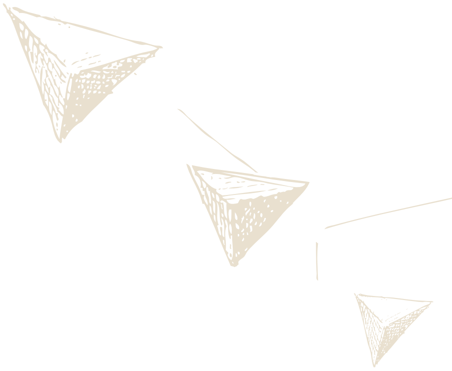
> One of our SPS donors writes,
>
> "I was able to help AIP and fulfill my desire to support SPS this year while reducing my tax burden."

To learn more or discuss your intentions, contact Brad Conrad or Mariann McCorkle in the AIP Foundation:

mmccorkle@aip.org
301-209-3098

> "The community of SPS, whether at my school or at PhysCon 2019, has blown me away, [especially] the number of people who are curious about the physical world. SPS has given me a platform to spread the passion for physics through our community outreach and campus ice cream socials. It's given me more information on what a life after my physics degree could look like. I am so grateful for what I have learned through this society, and the people I have met through this organization. For a long time, I was studying physics out of pure enjoyment, but this past year, being involved with SPS has opened the door for me to really think about what I am able to do after I graduate. Or after I graduate with a PhD, which is what I want to do after my bachelor's."
>
> *- Sophie, an SPS member who received a donor-supported SPS travel award*





Adopt-a-Physicist in Verse

by Matthew Anticole, Physics Teacher

Every year, Sigma Pi Sigma's Adopt-a-Physicist (A-a-P) program gives high schoolers from around the world the opportunity to "adopt" physicists for a few weeks and interact with them through an online forum. This year, students in Matthew Anticole's physics classes submitted poems about their experiences and what they learned from their adopted physicists.

Toward the end of the A-a-P session, students complete a short report that includes responses to questions about the physicist, their field of study, and notable points of conversation. Students are also asked to write a haiku that in some way connects with their physicist. I choose that format because, first, I just like haiku. But from an academic standpoint, the 5-7-5–syllable format forces students to be thoughtful both about which aspect of their conversations they pick and the words they choose to describe it. Not every student manages to pull off a perfect haiku, but it is neat to see them try.

For me, I think the most impactful haiku from this year is one written by one of my female students after a conversation with Dr. Sethanne Howard, who shared her experiences being the only female in her degree program. None of the male students would study with Dr. Howard outside of class, but being forced to always work on her own made her an expert on the material.

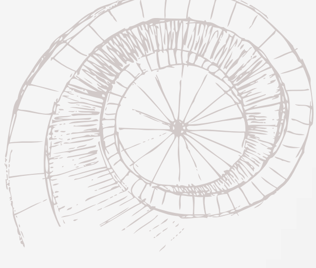
I look forward every year to this great opportunity for our students to get a window into a profession that most of them have no experience with. I always introduce things by retelling the story of a student from several years ago whose conversation with her adopted physicist catalyzed her decision to pursue an astronomy degree. Now she's a graduate student in astrophysics and a current participant in the A-a-P program herself! Thanks to everyone who volunteers for the program; you never know which kid you're going to connect with or whether your interaction will change their trajectory. It absolutely does happen!

#1:

All around you,
Situations come and go,
Learning to follow the flow

You will grow and change,
And learn tools to help you.
You will learn and apply

Let your tools help you
Become the best version
Of what you dreamed



#2:
You'd think Sports and
Science would be separate,
One in the classroom
and one on the field,
but how wrong you are.

Lacrosse, a sport of speed, intensity,
And science! With lacrosse and hockey
Sticks are involved creating an extension of
our bodies
which means torque and
Angular momentum is involved. The
placement
Of your hands causes your stick to undergo a
rotation. The lacrosse stick rotates at an
angular speed
Making your shot accelerate

Lacrosse isn't the only sport
To incorporate physics. Lacrosse,
hockey, and tennis are all examples
Of torque and angular momentum playing
A big role in the sport

#3:

What do you love most about physics
I love particle physics -whoosh-
Really, what are they like?

They are very strange like ghosts -booooo-
100 neutrinos passing through -oooooh-
How do you understand these if you're
confused?

Working with a partner always helped
me-eeeee.
Thank you for answering my question it
really helped

Now when I have a question
I won't yelp as much.
Oh yeah you're welcome a bunch.

#4:

Engineering is
More than just a simple task
Of tinkering things.

Teamwork makes everything tick,
The parts of the machine cannot
Work without everybody involved.

A childhood of trains
Has led me to believe that I
Belong in this field forever.

#5:

NASA was harder,
But they experienced more
Than the Navy.

The Navy had a way
With the rules.
But NASA was all
About breaking those rules.

NASA is breaking
All natural rules,
But these rules were meant
To be broken.

#6:

I have a question
Whether it's physics or not
I would like to know

How can you measure
Things you cannot see on Earth?
Seems impossible.

Well, I was informed,
Lasers can precisely make
Accurate answers.

#7:

Your favorite thing?
Telescope in the night sky,
Atop a mountain

#8:

Sethanne Howard is
The first woman in her class
Accomplished so much

Quotes from students:

> “One thing I learned from my physicist is that you really never stop learning. He summed it up metaphorically, [saying] that you are consistently adding tools to your toolbox. These 'tools' stay with you throughout your life and give you the ability to apply them to any situation that appears in your path. As your toolbox grows, the pride for your toolbox does as well.”

> “Physics is not just about physically discovering new worlds like in its applications to astronomy and cosmology, but it's also about conceptually discovering new worlds like the quantum world.”

> “[I learned] that having a career isn't always about the money you make; it's about having a sense of purpose and being a part of something.”

> “I learned that computer science is vital to the astrophysics field, and in order to be successful in this field it is important to learn different programming languages.”

> “It is important to consider your values when looking for a job so that you can find a workplace that you feel matches what you value.”

Sigma Pi Sigma — A Departmental Legacy of Fellowship

Part 5: The Contribution of Federal Science Policy to SPS and Sigma Pi Sigma

by Jack Hehn, Senior Fellow, American Association of Physics Teachers and Director of Education (Retired), American Institute of Physics, and Brad R. Conrad, Director of SPS and Sigma Pi Sigma

The development of federal science policy in the United States after World War II spurred not only the physics and astronomy curriculum as we know it today, but also the decades-long growth of both university research and the undergraduate ecosystem of SPS and Sigma Pi Sigma chapters. From 1945 to 1965 there was significant interest in and support for science in the United States, particularly for academic science. At the same time, the United States undertook a great deal of infrastructure improvement projects and supported more and broader education.

Part of the reason was that, coming out of World War II, the United States had the resources and pent-up demand to release a consumer economy that had been destroyed in so much of Europe. The United States was suddenly recognized as a "great world power." These factors influenced government support for science and technology and their wide recognition in national media, which led to the popularization of science and technology in general.

America started to become a world resource in scientific fields, creating the necessity of a much larger scientific workforce. This prompted a significant increase in federal investment in science and engineering education. And, in turn, to a rapid rise in Sigma Pi Sigma membership.

Much of this systematic and consistent government support was influenced by the Vannevar Bush report, "Science, the Endless Frontier." Bush was director of the US Office of Scientific Research and Development. In November of 1944, President Roosevelt sent a letter to Bush requesting recommendations on how to proceed with the nation's science efforts now that the war was over. In closing he wrote, "New frontiers of the mind are before us, and if they are pioneered with the same vision, boldness, and drive with which we have waged this war we can create a fuller and more fruitful employment and a fuller and more fruitful life."[1]

Bush responded in July of 1945 to Truman, who became president when Roosevelt died in April. Bush's document became the guiding narrative for the US scientific enterprise for decades to come. The report included appendices from distinguished committees: the Medical Advisory Committee, the Committee on Science and the Public Welfare, and the Committee on Discovery and Development of Scientific Talent.[2]

The mobilization of American industry in response to the war and the resulting new development of scientific knowledge and processes led to new advances against disease, in strategic defense, and in recognition of the public welfare and an improving quality of life for every citizen. The Bush report opines that these advances could only have been built on the knowledge provided by basic scientific research.

Most of the physics done during the war was applied science, largely carried out by academic faculty and students working as industrial or military personnel under federal contracts. Before the 1940s, most academic work in science, engineering, and medicine had been supported by endowments, foundation support, and private donations. The Bush report recognized a fundamental change in perception—the quality of life of the average citizen could and should be enhanced by government support of basic research. In short, basic science ought to be financially supported for long-term gains.

The federal government was ready to accept the responsibility for developing scientific knowledge and a scientifically talented labor pool among young Americans. One of the first policy recognitions was a dramatic need for all people to be educated in science, including physics and "space-oriented" subfields. A second policy recognition was the need to support basic research principally conducted on university and college campuses as an integral part of undergraduate and graduate programs. The Bush report advocated for the formation of a new federal agency, which became the National Science Foundation (NSF) in 1950. An important factor in these policies was that the decisions about federal support of basic science must be based on the advice of academic scientists more than that of federal bureaucrats.[2]

In the years following World War II, there was both a baby boom and a large number of men in uniform that were mustered out into the transitional economy. For many years the government had wisely supported academic institutions through the Morrill Act (1862) and the development of the Land Grant Colleges system. Building on this premise of federal support to universities, a federal program called the Servicemen's Readjustment Act of 1944, better known as the GI Bill, was created for World War II veterans. This bill funded the construction of additional VA hospitals, made mortgages more accessible, and established funds to cover tuition for veterans attending college. There developed in many universities larger and broader colleges of science and engineering to meet this student and labor demand. Physics departments were an important part of this growth. As far back as at least 1966, statistics on physics and astronomy departments were sent to chapters within Sigma Pi Sigma.

There followed a recognition at the NSF in 1956 that science education should be dramatically increased in the public schools so that an interest in science could be developed within families and the science talent pool could be developed at an earlier age. To review and implement improvements to introductory physics education, the Physical Science Study Committee (PSSC) was created at a 1956 conference at MIT. This led to the production of an entire series of instructional movies, textbooks, and laboratory materials widely used in high school classrooms around the world for the following decades.

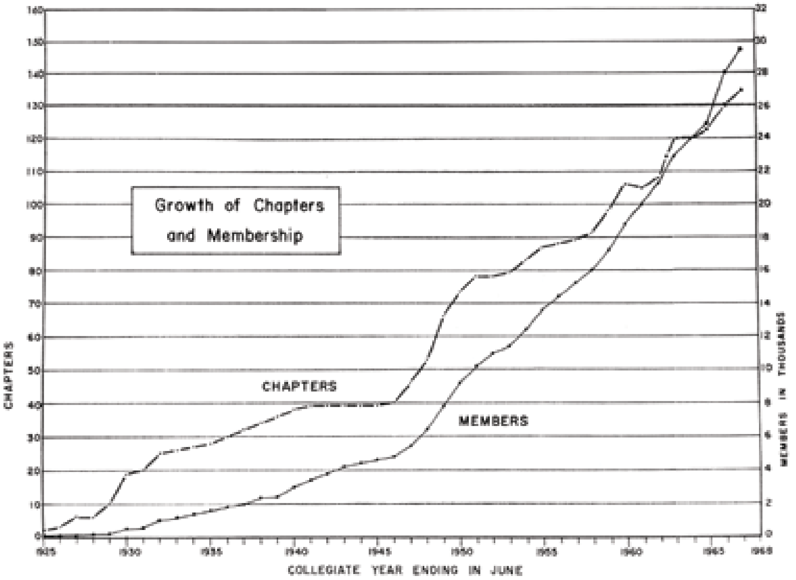
NSF continued supporting a number of science curriculum development programs (abbreviated as BSSC, Chem Studies, ECCP, ISIS) that emphasized summer institutes on college campuses, providing more in-depth science education for teachers. The teachers took information from these summer institutes directly back into their classes. The NSF also supported summer activities on college campuses for high school students to develop their interests and career aspirations in science and technology.

In 1958, the National Aeronautics and Space Administration (NASA) was established when President Eisenhower signed the National Aeronautics and Space Act. This new civilian agency was tasked with institutionalizing America's efforts in space exploration.

NASA was created to respond to the launch of the Soviet Union's Sputnik I on October 4, 1957, the first artificial satellite successfully placed into orbit. This launch caught everyday Americans by surprise and signaled the beginning of the US–Soviet "Space Race," as the White House saw a clear need to demonstrate technological superiority. While embarrassing for officials, this also began an era of rapid technological development and continued investment in science and engineering.

Public information and public understanding have been a fundamental undertaking for NASA, particularly through the Apollo project in the 1960s. NASA estimates that a total of 400,000 people across the United States were involved in the Apollo program. These developments and an influx of both funding and interest in physics can be seen in publications at the time. The November 1963 issue of *Radiations* states, "The National Aeronautics and Space Agency plans to increase sixfold the number of graduate students subsidized to study 'space-oriented' subjects. The goal is to double the number of PhD graduates by 1970, as compared with present productions. These expanded enrollments will materially increase the number of potential members for the chapters of the Society."[3]

Sigma Pi Sigma started in 1921 and grew steadily before WWII. It would be remiss to not mention that well before World War II, historians and sociologists documented Americans as a "nation of joiners," particularly before 1940.[4] After WWII (1946–1967) there was huge growth in the number of Sigma Pi Sigma chapters, so much so that the number of zones the chapters are divided into jumped from 10 to 19.[3] Some of this growth may have been driven by federal science policy and national support for science. After the glow of the space race faded, NASA continued to make a significant impact on many college campuses, primarily through the National Space Grant College and Fellowship Project, also known as the Space Grant,



The number of Sigma Pi Sigma chapters and members from 1925 to 1965. Image courtesy of the SPS National Office, reproduced from the 11th Sigma Pi Sigma Physics Information Handbook (1967).

Astronaut Walter Cunningham in field training in preparation for a mission on a trip to the moon. Walter became a member of the UCLA chapter of Sigma Pi Sigma in 1959 while he was an undergraduate physics major. He received his MS in physics from UCLA in 1960 and visited the chapter in October 1965 through the support of Sigma Pi Sigma. Image courtesy of the SPS National Office, reproduced from *Radiations of Sigma Pi Sigma* XXVII, no. 1, May 1965.

created in 1989. Space Grant is a national network of colleges and universities. In addition to doing research, many Space Grant colleges administer pre-college and public service education projects in their states.

Many of us who grew up in the 1950s and 1960s remember an era and an environment when science offered many exciting new and rapidly expanding opportunities. We saw science nightly in the national TV news, in popular magazines and newspaper headlines, and even newspaper sections, heard our teachers' excitement about new opportunities to teach science, and experienced summer opportunities to attend NSF workshops for students and teachers. It is no surprise that so many people in that cohort have lived careers in science and education. It has been a great adventure for us, and federal support has been essential. ●

The authors wish to thank Rachel Ivie, AIP Senior research Fellow, for valuable contributions and discussions.

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3. *Radiations of Sigma Pi Sigma*, XXV, no.1, November 1963.
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READ MORE

This article is Part 5 in "Sigma Pi Sigma – A Departmental Legacy of Fellowship," a series highlighting the history of Sigma Pi Sigma and SPS in celebration of our centennial. 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

Part 4: SPS — A Society for All
www.sigmapisigma.org/sigmapisigma/radiations/spring/2021

Alumni Engagement Program

Help to strengthen our national physics community!

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SPS facilitates virtual and in-person speaking opportunities, job-shadowing, mentoring, and more through this unique program.

On the Value of Sharing Your Imperfections

by Maggie Fritts, 2021 Sigma Pi Sigma Inductee, Furman College

When I started here at Furman University in fall 2018 as a physics major, the community I met was small and close-knit; all of the majors were friends and would hang out together doing homework in our physics student lounge, affectionately dubbed “the Fishbowl.” However, in March of my sophomore year we were all sent home because of COVID-19, unable to return to campus or our community until September.

The impact of COVID on the Furman community cannot be overstated. During the 2020–21 school year, campus activities were heavily limited due to the pandemic, which meant that as the seniors we knew graduated, one year and then the next, we were not able to build that community with the incoming classes.

Returning for the 2021–22 academic year as one of only three senior physics majors in a department without grad students, it fell largely on me to recreate the physics community that had welcomed me when I arrived. One of the most important things we did for the first- and second-year students was invite them to everything. The SPS chapter hosts multiple events each month, most of which allow us to escape the “Furman bubble” and spend time together outside of the classroom, out from under the pressure college puts on us. We’ve also held impromptu “group therapy”—as we three seniors apply for graduate school, we’ve been sharing our successes and failures with the other physics majors, often confiding in them when we’re not feeling confident.

Physics is a field of big names, important research, and incredible advances, and it can be hard to feel like you matter in a community as beautiful and terrifying as physics. As a first-year student, you may look at the seniors in your department as these incredible students, with summers of research and publications under their belt, and feel like you’ll never measure up. The reality is, none of us know what we’re doing either. We’re the same as you—we’ve just had a little more time. Imposter syndrome has been a huge topic in our discussions lately. I think physics majors appreciate hearing from us seniors how stupid we feel sometimes. Sharing our experiences with them, the struggles, the wins, the tears, and the fears, has helped to show them that there are a million ways to be successful.

This is so important to the future of the physics community—if all you see around you is success, everything that’s less than perfect is going to make you feel like you don’t belong. But if you know your role models and that they’ve struggled in the same way, you might be more likely to meet the challenges with confidence. If you get a chance, spend some time with those who are going through what you’ve gone through already. If they’re anything like me, they could use a friend in physics.

My role in the physics community at Furman has been one of, if not *the* most fulfilling part of my time as an undergrad. I’m so happy to have been part of Sigma Pi Sigma and the Society of Physics Students, and making the physics community a little less intimidating for someone else. ●

A PHYSICIST'S GUIDE TO MACHINE LEARNING AND ITS OPPORTUNITIES

by Kendra Redmond, Editor

As we browse, drive, watch, and order, data pours into the ether. Our behaviors and preferences are collected and analyzed, and in response, the world changes. The combination of advances in semiconductor computation devices and this new and extremely large influx of data has powered rapid growth in machine learning.

"The world is becoming more digitized, whether or not we want it," says Evgeni Gousev, a PhD physicist and senior director at Qualcomm Technologies Inc., a company working toward an internet-of-things reality where billions of devices are intelligently connected. "We are all living in a data-driven world now," he says.

Companies like Facebook (now Meta) are paying unfathomable sums of money to acquire technology startups, often for access to their data. And it's not just tech companies buying tech startups. The pharmaceutical company Pfizer gave Israel COVID-19 vaccine priority in 2021, in part because Israel agreed to share health data on its citizens. "Data is an integral component of the digital economy," says Sandeep Giri, a staff project manager at Google and honorary member of Sigma Pi Sigma.

With data—and the ability to interpret it—comes power. That may include economic power and the power to influence public opinion, but it can also include the power to improve access to education and healthcare, the diagnosis and treatment of diseases, car crash survival rates, severe weather predictions, our understanding of the universe, and many other aspects of the human experience.

Finding meaning in massive amounts of messy, real-world data is a challenge, but it's one that physicists are uniquely poised to tackle. We're in the midst of "a once-in-a-century opportunity for physicists to play a bigger role in society," says Gousev.

Machine learning

That opportunity lies in the rapidly growing field of machine learning. A subset of artificial intelligence (AI), machine learning is perhaps the most powerful tool we have for making sense of data that isn't neatly organized or for which we don't know all the governing rules. Machine learning describes a system in which an algorithm, or set of algorithms, learns from data and adapts. It's a salient correlation to the process of applying physics to the real world.

↑ After an upgrade that will begin in 2027, the Large Hadron Collider (LHC) will yield ten times more data per year than it does now. To predict how this will affect the ATLAS detector, scientists developed a machine learning–based algorithm that is less costly and time intensive to run than traditional simulations. Shown here: The ATLAS collaboration upgrades parts of its detectors in preparation for the LHC upgrade. Image by Maximilien Brice, copyright CERN.

“There is a disconnect between physics departments and the AI-based economy that is inevitably coming our way.”

Evgeni Gousev is senior director at Qualcomm Technologies Inc. and chairman of the board of directors of the tinyML Foundation, www.tinyML.org. He has a PhD in solid state physics. Photo courtesy of Gousev.

“Machine learning is essentially a system in which rather than building an algorithm or a model from an explicit description of desired behavior, we provide a set of examples that define the desired behavior of the system,” says Chris Rowen, vice president for engineering for Collaboration AI at Cisco.

Rowen gives this example: Say you want a program that classifies something as a dog or a cat. You probably don’t want to try to describe what makes a cat a cat or what makes a dog a dog, in algorithmic terms. Instead, machine learning allows you to train a generalized system with a bunch of pictures of cats and dogs. From these inputs, the system extracts the relevant features of dogs and cats and infers an algorithm that distinguishes between these two classes of inputs across a wide variety of kinds of pictures.[1]

“Machine learning is really great for cases where you don’t have an algorithm with explicit rules on how to accomplish a certain task,” says Michelle Kuchera, a computational physicist and assistant physics professor at Davidson College. She says that it’s also great for discovery—looking for patterns, outliers, or unexpected behavior in data—and for making fast theoretical predictions. In cases when a prediction would typically take an extremely long time to calculate, you can use machine learning to build a surrogate model that can make much faster calculations.

From toolbox to sandbox

Machine learning has direct applications in physics and astronomy research. As co-PI of the Algorithms for Learning in Physics Applications group at Davidson, Kuchera collaborates with theoretical and experimental physicists to address computational challenges. Machine learning is ideal for overcoming some of these challenges, such as identifying interesting particle interactions among the huge data sets produced at particle accelerators and speeding up time-consuming theoretical predictions.

“If you look at the Large Hadron Collider (LHC), or any of the scientific instruments where there’s a lot of fine-tuning that’s all happening in real time with the magnets and so forth, and if you want to control them, it’s great to be able to do that using machine learning. . .You’re going to infer very complex patterns much more easily,” says Vijay Janapa Reddi, associate professor of engineering and applied science at Harvard University.

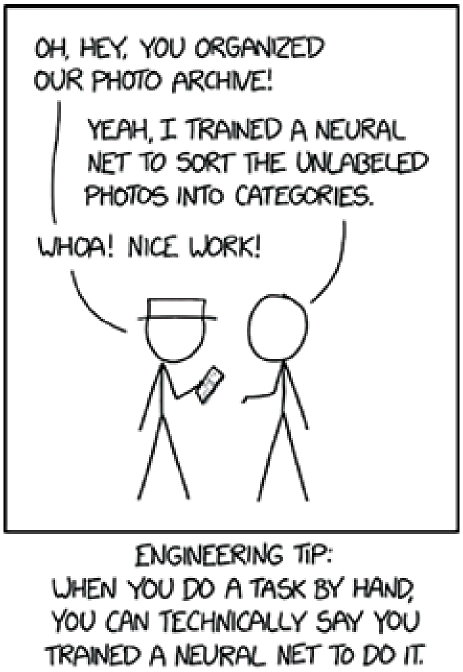
It’s not just the big particle physics collaborations that use machine learning. Scientists are using it to design new materials, find turbulent motion on the sun, uncover anomalies in the US power grid, give robots humanlike sensitivity to touch, and much more.

Machine learning isn’t a magic bullet for all situations. “If you have a really solid understanding of the physics and the explicit mathematical rules to accomplish a task that you’re interested in, then that’s the preferred method, unless there’s some challenge with implementing it or it’s taking too long to be reasonable,” Kuchera says. But it’s one more powerful tool in the data analysis toolbox.

Applying machine learning to areas outside of physics and astronomy also constitutes a gratifying and fulfilling career for many physicists and astronomers.

For his PhD thesis, Sean Grullon studied neutrino fluxes at the IceCube particle detector at the South Pole. He dabbled with machine learning at times, as one of many data analysis techniques. When he graduated and decided to leave academia, machine learning was starting to take off. Grullon jumped in and has been applying machine learning to healthcare-related challenges ever since. He’s now the lead AI scientist at Proscia, a startup that builds tools to help pathologists find better ways to fight cancer. They’re using deep learning, a subset of machine learning that utilizes neural networks, to analyze pathology images for melanoma. Deep learning is particularly powerful for natural language processing and computer vision applications, which are notoriously difficult to do with conventional approaches.

“A physics background is really appropriate for the field of deep learning,” Grullon says, in part because of the math background physics requires—most machine learning algorithms reflect different applications of linear algebra—and in part because physicists understand data. Compared to what you might find in a computer science class, data from the real world is messy. But physicists are comfortable with error bars, uncertainties, and probabilities. Grullon



Credit: XKCD, https://xkcd.com/2173/.

Sandeep Giri is a staff project manager at Google, cloud.google.com/tpu, and on the AIP Foundation's board of trustees. He has a BS in physics and an MS in materials science and engineering. Photo courtesy of Giri.

has found his career path to be gratifying. "I've found it rewarding, very interesting, and also very impactful," he says.

Machine learning is "a wonderful, wide-open area," says Helen Jackson, a PhD nuclear physicist and machine learning researcher. Jackson's PhD thesis focused on the effects of radiation on high-electron-mobility transistors. Upon graduation she had lots of data analysis and software experience, and while looking for a job, she taught herself machine learning. That opened the door to a position applying deep learning to airport security—using computer vision to detect threats in the cluttered airport environment. Since then she's worked as a contractor on machine learning applications ranging from position-sensitive detection in computer vision to complex document understanding.

In Jackson's opinion, physicists are primed to work in machine learning. She has found that some companies "actually prefer to hire someone like a physicist or chemist rather than a straight computer science major, because a computer science major knows the mechanics of the code, but we know the underlying application and what this machine learning [system] is supposed to do." She says the work is a lot of fun, and the applications are "just fascinating."

At Cisco, Rowen leads the team charged with improving the audio and video environment of the WebEx collaborative platform with machine learning and AI. With a bachelor's degree in physics and a PhD in electrical engineering, he finds the mixture of important societal questions, computer architecture, and fundamental physics in machine learning fascinating.

Machine learning deals with computationally hard problems, like what makes up speech, but uses physical systems that you can trace all the way down to electrons, Rowen says. "This continuity of understanding from physics on up through the computer architecture questions, the computationally hard algorithm questions, and the application questions surrounding machine learning and neural networks has been so exciting and interesting," he says.

Opportunities for physicists

Gousev earned his PhD in solid state physics and has spent most of his career at IBM and Qualcomm developing new technologies, many involving machine learning. As the AI-based economy comes racing toward us, he sees not just an opportunity but a need for physicists to get involved. "We look at the whole world around us through a different type of lens, through a different type of mindset. We look at connecting dots in the environment, because we've been trained to look at the laws of physics and understand how things are connected in the world," he says.

That holistic picture of machine learning ranges from electrical components to program architecture and even ethics. What is the problem? What are possible solutions? Should we even be solving this problem? Who else might utilize this solution? What biases and inequities might emerge if this method is used with other data sets, like data on humans?

Sorting through these questions requires a well-equipped, critically thinking, and creative workforce. "We have to prepare students for this new economy, and I strongly believe physics departments have a big opportunity," Giri says. But taking advantage of that opportunity will require some changes. "There is a disconnect between physics departments and the AI-based economy that is inevitably coming our way," he says.

After earning bachelor's degrees in physics and mathematics, Giri was on his way to a PhD in materials science and engineering when he decided to change course and take a job in industry. He's worked at Qualcomm and then for Google on projects ranging from head-mounted displays to supercomputers. He's also been an advisor for undergraduate physics education efforts through the American Institute of Physics (the parent organization of Sigma Pi Sigma) and the American Physical Society, and is a board member of the AIP Foundation.

Giri says that the tools exist to prepare physics and astronomy students for this new paradigm, but physics departments need to embrace them. Physics departments often leave students feeling intimidated by and unprepared for careers in industry, whether by lack of knowledge or in favor of promoting a more traditional academic degree path. Many young students think the only physics career path is academia, and some choose not to major in physics for this reason.

"I believe that a majority of physics majors today don't only want to learn Newton's laws or the Schrödinger equation. They want to know 'What type of skills do I need to solve the problems that bring meaning to me? How can I build a product or service that leaves an impact on the world?'" Giri says.

"Physics students would benefit from an awareness of all the technical and nontechnical career paths that exist in the machine learning and AI space," says Giri. That ranges from software engineering to hardware design, systems engineering, supply chain, operations, product and project management, sales and business development, and beyond. These are all careers that people with a physics background can and do grow into.

Machine learning is at the intersection of skills, opportunity, and change-the-world capacity, and that's a huge opportunity for physics and astronomy departments to attract and retain new students—including students from groups that are traditionally underrepresented in physics. For example, in 2020 the TEAM-UP report noted the following key findings during its study of systemic issues that contribute to the underrepresentation of African Americans in physics and astronomy:[2]

- The connection of physics to activities that improve society or benefit one's community is especially important to African American students.
- Having multiple pathways into and through the major helps to recruit and retain students who may not have initially considered physics or astronomy as an option.

There is a vast set of existing resources that departments, physics students, and professional physicists can utilize to take advantage of machine learning and its opportunities. Many are free or low cost and don't require anything but curiosity, a willingness to learn and explore, some logical thinking, and a bit of math—all things every physicist and astronomer has in good measure. ●

Notes

1. To read more about classification algorithms in machine learning, see Sidath Asiri, "Machine Learning Classifiers," Towards Data Science (blog), June 11, 2018, towardsdatascience.com/machine-learning-classifiers-a5cc4e1b0623.
2. The TEAM-UP report was written by the AIP National Task Force to Elevate African American Representation in Undergraduate Physics & Astronomy (TEAM-UP) in 2020. It's the result of a two-year investigation into the long-term systemic issues within physics and astronomy that have contributed to the underrepresentation of African Americans in these fields and includes actionable recommendations for reversing the trend. See TEAM-UP Task Force, The Time Is Now: Systemic Changes to Increase African Americans with Bachelor's Degrees in Physics and Astronomy (American Institute of Physics, 2020), www.aip.org/diversity-initiatives/team-up-task-force.

Spotlight on TinyML

In its early days, machine learning was done at large-scale data centers, but now the technology has moved into our phones and homes—think Alexa and Siri. There's so much data that it's not cost-effective, energy efficient, or at times even practical to move all of this data into the cloud for processing. In the cutting-edge research area of TinyML (tiny machine learning), scientists are running machine learning models on ultra-low-power microcontrollers. They aim to keep the data processing as close as possible to the data, thereby enabling always-on sensors or other devices, more secure networks, and the ability to add features like voice recognition to small devices that can't be recharged frequently. Learn more at www.tinyML.org.

Get Up to Speed on Machine Learning

There are many widely available, internet-based resources on machine learning. This list is compiled from recommendations given by the physicists interviewed for A Physicists Guide to Machine Learning and Its Opportunities. In most cases URLs are not listed, but if you're interested in machine learning you won't have any trouble finding them.

Learning Python

- Machine learning is commonly done using Python. Google's Python Class and Microsoft's Introduction to Python are good, free online classes.

Blogs and background

- To get a sense of machine learning, its vocabulary, and what's happening in the field, check out blogs like *Google AI, Facebook AI, Berkeley AI Research,* and *Stanford AI Lab*. If what they're writing about excites you, that's a good indication you should investigate it further.
- *Towards Data Science* is another great blog if you're just getting started. They have a lot of introductory articles that explain machine learning and deep learning algorithms and how to get started.

Setting up your system

- Scikit has a package for Python for machine learning with a good overview of machine learning algorithms and how to incorporate them in Python.
- Environments like TensorFlow (Google) and PyTorch (Facebook) allow you to quickly build models for whatever kind of data you have.

Online courses

- Platforms like edX, Coursera, Udemy, and Udacity have free or low-cost Python classes and machine learning classes with projects that you can complete and show a prospective employer. Andrew Ng's machine learning course out of Stanford is very popular, and it's free on Coursera.
- HarvardX's Tiny Machine Learning (TinyML) and Google are collaborating on a series of courses focused on TinyML. The courses cover topics from the fundamentals of machine learning to collecting data, designing and optimizing machine learning models, and assessing their outputs. The first three courses are available now on edX, https://tinyml.seas.harvard.edu/courses/.
- The Google Cloud AI Platform has tools, videos, and documentation for data science and machine learning, https://developers.google.com/learn/topics/datascience. The following resources may be especially helpful:
  - ☐ Google's codelab "TensorFlow, Keras and deep learning, without a PhD"
  - ☐ Online learning channel, www.youtube.com/user/googlecloudplatform
  - ☐ Product documentation, https://cloud.google.com/docs
- fast.ai has courses, tools, and articles for people interested in getting into machine learning.

Getting data

- Don't have data? There are public domain data repositories with data on almost anything you could want, and most machine learning courses will direct you to them. Kaggle has lots of public datasets.

Resources for teaching

- In support of departments that want to teach their students about machine learning, Harvard has made much of its TinyML content and classroom materials, open source licensed and available at https://tinyml.seas.harvard.edu/#courses.

SIGMA PI SIGMA, THE PHYSICS *AND ASTRONOMY* HONOR SOCIETY

by the SPS Governance Committee: Julia Bauer, Shannon Clardy, Brad Conrad, Van Haslett, Larry Isenhower, Taylor Knapp, and Emma Rasmussen

Sigma Pi Sigma has strived for 100 years to support those who study physics *and* astronomy.[1] But as we approached its centennial celebration, society leaders recognized that for all of those students to know that they belong in SPS and Sigma Pi Sigma, we must be explicit and intentional about including astronomy in our communications and governing documents.

Astronomy has been explicitly mentioned—hand-in-hand with physics—in many communications dating back to our founding, such as in the 1931 recommendations on physics and astronomy texts.[2] We state loudly and clearly that Sigma Pi Sigma was founded to support **physicists and astronomers.** To best achieve this goal, both societies need to be explicit and intentional in their support of everyone under the umbrella of SPS and Sigma Pi Sigma.

SPS goes by a variety of names on its diverse campuses, such as Physics and Astronomy or PandA, Women in Physics or WiP, Physics Club, Departmental Undergraduate Group or DUG, and, of course, SPS, and they all support those with an interest in physics and astronomy. Yet it has come to the attention of the SPS leadership that astronomy students may feel less welcome in our community.

Changes to governing documents

To remedy this, during the September 2021 meeting of the SPS National Council, SPS leaders proposed changes to the SPS bylaws and constitution to make completely clear that the societies are for students who have an interest in physics *and astronomy* and to support them in their education and as SPS members. This means that we also support astronomy and astrophysics clubs as part of SPS. The SPS National Council's governance committee wrote the following rationale:

> *While Sigma Pi Sigma has strived for almost 100 years to support those who study physics and astronomy, the society should be explicit in its support of the students within Physics and Astronomy so that everyone knows they belong within SPS and Sigma Pi Sigma. It has come to the attention of the Society of Physics Students that those with an interest or focus in Astronomy may not feel included within our society. Going back to our founding[1-3] documents, the intention has always been to support students who study within physics and astronomy departments.*

The National Council unanimously approved the proposed changes in the fall of 2021. Early in 2022, all SPS chapters were asked to vote on these constitutional changes. Chapters overwhelmingly supported and welcomed astronomy students with votes of approval.

The parent organization of SPS and Sigma Pi Sigma, the American Institute of Physics (AIP), also fully supports these changes. "Coming from the astronomy community, this acknowledgement by SPS and Sigma Pi Sigma is personally important to me," says Michael Moloney, the CEO of AIP. "This affirmation of inclusivity can only serve to strengthen budding astronomers' and astrophysicists' affinities with SPS and their member communities. The move further underscores SPS's overarching culture of inclusion—all those who pursue the physical sciences are welcome, and AIP is committed to their journey."

The physics–astronomy connection

The fields of physics and astronomy are a closely coupled set within the physical sciences. Observations of the universe have led people to seek an understanding of the world around them and often bring people into the world of physics. Those who study physics frequently come to a deep appreciation for the vastness of space and the incredible processes that occur around us. Neither field would be where it is today without the other. New generations of instruments and detectors, enabled by modern technology, are gathering so much raw data that we need an increasing number of scientists to study and learn from this new information. With their long history of data collection and analysis, astronomy departments are rising to the challenge.

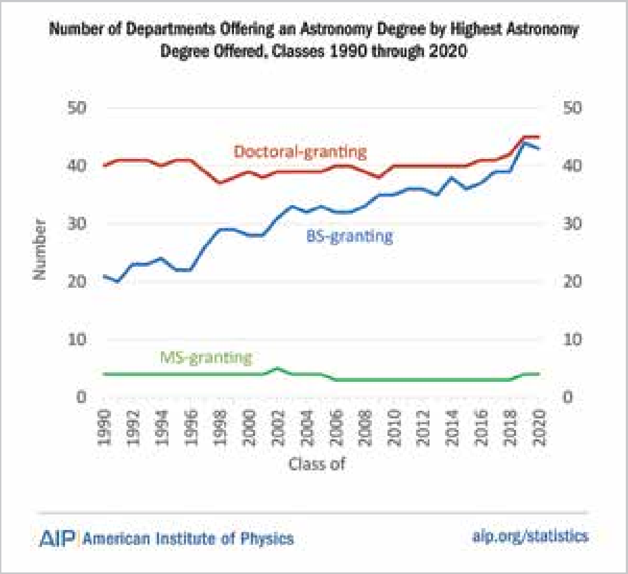


Image courtesy of the Roster of Astronomy Departments with Enrollment and Degree Data, 2020: Results from the 2020 Survey of Enrollments and Degrees by Starr Nicholson and Patrick J. Mulvey.

To SPS and Sigma Pi Sigma director Brad Conrad, there is a very clear connection between physics and astronomy. "Astronomy is a cornerstone of physics. The search for what was beyond the world we can easily touch has led to scientific wonders and our modern world. Astronomy is physics and physics is astronomy."

The number of undergraduates earning bachelor's degrees in physics is at an all-time high, reaching 9,296 in 2020. So, too, is the number of students earning bachelor's degrees in astronomy, reaching 820 in 2020. As of 2020 there were 52 combined physics and astronomy departments and 43 stand-alone astronomy departments.[4] The mission of SPS is to help all of these students, as well as those from stand-alone physics departments, transform themselves into contributing members of the professional community.

What do these changes mean?

The Society of Physics Students and Sigma Pi Sigma won't change their names, but Sigma Pi Sigma has officially become the "physics and astronomy honor society." The language on the SPS and Sigma Pi Sigma websites and in print publications will shift to reflect the inclusion of astronomers and astronomy students.

Additionally, the Society of Physics Students is more explicitly supporting astronomy students. Collegiate astronomy clubs will have the option to associate or more formally merge with the SPS chapter at their institution, or form a new SPS chapter if their university does not already have one.

Becoming an SPS member gives astronomy students access to all of the resources and funding opportunities provided through the SPS and Sigma Pi Sigma National Office. The SPS Executive Committee, in consultation with the SPS National Council and SPS National staff, is exploring how to best serve astronomy-focused students and faculty with new or updated SPS resources and opportunities.

SPS will make intentional efforts to recognize and honor the important contributions of astronomers to our understanding of the universe, including with induction into Sigma Pi Sigma. We also hope that chapters will honor many more astronomy students through induction into their local Sigma Pi Sigma chapter, or through a new chapter if one doesn't already exist at their institution.

As part of this large and ongoing effort, SPS will collaborate with the American Astronomical Society (AAS) and its members to ensure that we have a welcoming and inclusive environment for astronomy-focused students. Kevin Marvel, the CEO of AAS and a long-time friend of SPS, says, "It is truly an honor to have astronomy now intentionally included in SPS and Sigma Pi Sigma . . . having astronomy specifically called out in their foundational documents will welcome those identifying more closely with astronomy and let them know they can join and support SPS and Sigma Pi Sigma." Marvel is also looking forward to collaborating with SPS and Sigma Pi Sigma "to bring the excitement of astronomy to more people than ever before." Going forward, SPS will expand its events for astronomy students and faculty attending AAS meetings.

Plans are currently underway for a broad announcement of this change to reach all US physics and astronomy departments. This will be done in coordination with SPS, AIP, and AAS.

SPS wants every undergraduate student with an interest in physics and astronomy to excel. We seek to assist every undergraduate department in helping its students succeed. It is our hope that in the next 100 years, Sigma Pi Sigma and SPS can support astronomy programs and their students at the same level that it has supported physics programs and their students over the last 100 years.

What comes next? It turns out a whole lot! While this change is an affirmation of the original intent of the founding organization and documents, the implications are far reaching and will take time to implement.

It will take years, lots of hard work on the part of the National Council, and many discussions to build the inclusive community we set out to 100 years ago, but the Society of Physics Students and Sigma Pi Sigma, the physics and astronomy honor society, is up for the challenges ahead! ●

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2. D. W. Cornelius and Ralph Weatherford, "Recent Textbooks for Advanced Undergraduates and Graduate Students," *Radiations of Sigma Pi Sigma*, vol. II, no. 1, December 1931, 58.
3. Sanford Gladden, "The Largest Telescope in the World," *Radiations of Sigma Pi Sigma*, vol. III, no. 1, September 1932, 30.
4. Starr Nicholson and Patrick J. Mulvey, *Roster of Astronomy Departments with Enrollment and Degree Data, 2020: Results from the 2020 Survey of Enrollments and Degrees* (College Park, MD: American Institute of Physics, Statistical Research Center, 2020).

Physics and astronomy students celebrating together at the 2019 Physics Congress. Photo courtesy of Ron Kumon.

CHEERS TO 100 YEARS!

by Anthony Kuchera, Assistant Professor,
Davidson College

ΣΠΣ

SIGMA PI SIGMA
NATIONAL
PHYSICS HONOR SOCIETY
FOUNDED AT
DAVIDSON COLLEGE
DECEMBER 11, 1921
THIS TABLET IS ERECTED
BY
DAVIDSON COLLEGE
ALUMNI AND FRIENDS
IN COMMEMORATION
OF THE
TWENTY FIFTH ANNIVERSARY
OF THE FOUNDING OF
SIGMA PI SIGMA
DECEMBER 11, 1946

This tablet hangs in the physics department at Davidson College as a gift from alumni and friends for the 25th anniversary of Sigma Pi Sigma. Photo courtesy of Anthony Kuchera.

On December 11, 2021, Sigma Pi Sigma celebrated its 100th birthday. In these ten decades, much has changed, from the organization itself to the physics being studied. However, taking a look back at what college physics was like for the original members, there are some striking similarities to what you might see in today's physics courses.

Sigma Pi Sigma originated at Davidson College, a small liberal arts college about 20 miles north of Charlotte, in Davidson, North Carolina. At the time of its formation, the college only awarded degrees to men. Eight members created the alpha chapter—three faculty members and five students.

While our history says Sigma Pi Sigma was founded on the evening of December 11, 1921, it appears that plans for this society started slightly earlier. In the October 27, 1921, issue of the *Davidsonian*, the student newspaper, an article titled "Students and Professors Form Physics Fraternity" states that "A Physics fraternity has been organized for the purpose of promoting scholarship and friendship among the students and faculty members of Davidson College who are interested in the science of Physics. This club is to be called Sigma Phi Sigma, and is to be the Alpha chapter."[1]

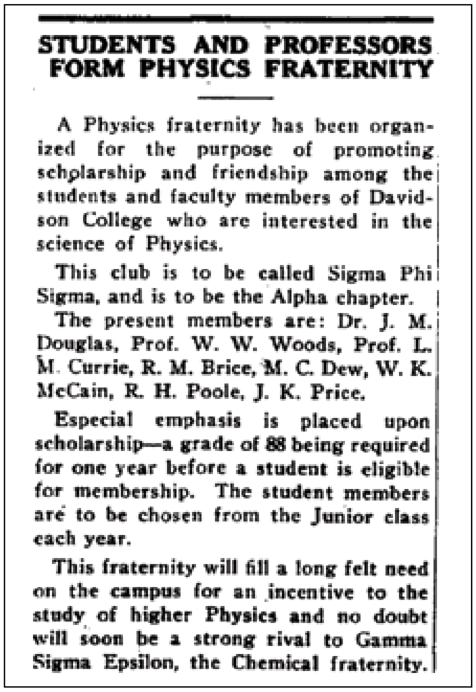
Either the "Phi" was a typo or there was a quick name change between October and December. The latter is probable, as "Phi" might be used to describe "physics," and a national fraternity named Sigma Phi Sigma had already been established in 1908 (and ceased existing during WWII). Sigma Pi Sigma is a member of the Association of College Honors Societies. While the initial announcement was made in October, the December date marks the society's official formation. Sigma Pi Sigma grew quickly after becoming a national society in 1925. Duke University and Penn State University became the second and third chapters. Today, over 100 years later, we have nearly 600 Sigma Pi Sigma chapters!

When students and faculty at Davidson formed Sigma Pi Sigma, the college had only one physics professor, Dr. James M. MacDowell. One hundred years later the department has grown, with seven tenured or tenure-track faculty members and two visiting professors.

At Sigma Pi Sigma's start, the physics course of study was a three-year program, according to the 1920–21 Davidson College Bulletin.[2] In year one, students studied General Physics. During the fall semester "the class studies matter and its general properties. Elementary dynamical principles and their application to machines, dynamics of liquids and gasses, and elementary mechanics are considered." In the spring term there was a focus on "the study of heat, sound, electricity, and light."

In the second year, students studied Advanced Physics, where "the fall term of this course is a continuation of the work done during the previous year in mechanics, molecular physics, magnetism, and electricity." Interestingly, the spring term was "devoted to the study of direct currents and their practical applications." In year three, students studied Electricity, which was clearly an important subject. This included a focus on "the useful application of these principles to the dynamo, motor, transformer, induction coil, lighting, etc."

It is no surprise that the original Sigma Pi Sigma insignia bears the image of a dynamo, voltmeter, light bulb, and lightning bolt. Similar to today, the bulletin states that students were expected to work three to four hours per week in the lab. Courses in mathematics were prerequisites to take Physics 2 and 3. To take Advanced Physics and Electricity, it was required that students had taken Analytical Geometry and Calculus. In addition to physics and mathematics, an astronomy course was offered by Professor William Wood and covered "a general knowledge of the fundamental principles underlying the motions and physical state of the heavenly bodies, so far as known, as well as a description of these bodies and an outline of the methods by which this knowledge has been attained." There were even occasional classes at



STUDENTS AND PROFESSORS FORM PHYSICS FRATERNITY

A Physics fraternity has been organized for the purpose of promoting scholarship and friendship among the students and faculty members of Davidson College who are interested in the science of Physics.

This club is to be called Sigma Phi Sigma, and is to be the Alpha chapter.

The present members are: Dr. J. M. Douglas, Prof. W. W. Woods, Prof. L. M. Currie, R. M. Brice, M. C. Dew, W. K. McCain, R. H. Poole, J. K. Price.

Especial emphasis is placed upon scholarship—a grade of 88 being required for one year before a student is eligible for membership. The student members are to be chosen from the Junior class each year.

This fraternity will fill a long felt need on the campus for an incentive to the study of higher Physics and no doubt will soon be a strong rival to Gamma Sigma Epsilon, the Chemical fraternity.

An article from the October 27, 1921, issue of the *Davidsonian* (student newspaper) describing the formation of a physics fraternity Sigma "Phi" Sigma, which later settled on the name Sigma Pi Sigma. Courtesy of Archives, Special Collections and Community, Davidson College.

night to " insure familiarity with the principal constellations." Today you can still find many similar topics covered at Davidson College and at other institutions around the world, with the addition of the physics that was being developed during the time of Sigma Pi Sigma's creation, such as quantum mechanics, atomic physics, and nuclear physics.

The formation of Sigma Pi Sigma wasn't without challenges. On November 28, 1921, the college suffered a major catastrophe. The Chambers Building, which housed lecture halls and laboratories, was destroyed by a fire. The newly formed Sigma Pi Sigma members and other students were so passionate about their field of study that they risked their very lives for the cause. It was written in the December 2, 1921, issue of the *Davidsonian* that "Due to the quick work of a group of students and Dr. Douglas, much valuable equipment was rescued from the physics laboratory."[3] A temporary building was built and opened just a few months later, in March of 1922. Later that fall the laboratories were outfitted with exciting new laboratory equipment, as described in another issue of the *Davidsonian*. The equipment included new motors, generators, galvanometers, ammeters, voltmeters, and even inclined planes! The article later mentions that the department would also soon have "a modern X-Ray outfit." Today you will still find some of those same types of equipment, but many more computers, lasers, and other modern electronic instrumentation.

The 10th anniversary of Sigma Pi Sigma was celebrated at Davidson College in part by taking the lead of the college chapel services, according to the December 16, 1931, issue of the *Davidsonian*. At this time, there were 21 Sigma Pi Sigma chapters. Henry Fulcher, professor of physics, praised the organization and gave a eulogy for one of the founding members, Dr. Douglas. Also, as part of this celebration of ten years, it was said that alumni of the alpha chapter were sending money to create a tablet recognizing the accomplishment, to be presented to the college. Currently, a large tablet hangs inside the Dana Building, which houses the physics department at Davidson College, from its 25th anniversary. This celebration was held on December 16, 1946. It featured an address from Lehigh University president and former director of the Atomic Energy Commission Laboratory at Oak Ridge, Dr. Martin Whitaker. The plaque was presented and unveiled. A response was given by Davidson College president John R. Cunningham. This was followed by a symposiums from Dr. Marsh W. White titled "Physicists in Industry" and another titled "Atomic Energy" from Dr. Whitaker.

At the time of the 50th anniversary, there were around 30,000 members and 250 active chapters. The 50th anniversary was celebrated at the 1972 Southeastern Section of the American Physical Society meeting at the University of South Carolina in Columbia. This included addresses by Marsh W. White, SPS director Dion W. J. Shea, and H. William Koch, the director of the American Institute of Physics. That same year, women were finally able to pursue a degree at Davidson College.

The 100-year celebration has been slightly altered due to the COVID-19 pandemic. The Physics Congress (PhysCon) in Washington DC was rescheduled from 2021 to 2022, but will still take place in the 100th year. The Davidson College chapter had a small outdoor gathering to celebrate and plans to send a record number of students to PhysCon in October 2022 to complete the celebration with all other chapters in attendance. It is impressive to look back and think that the first Physics Congress took place in 1928 on the campus of Davidson College with just six chapters. The physics department, SPS, and Sigma Pi Sigma have certainly grown over the last century. I can't wait to see what happens in the next 100 years! ●

References

1. *The Davidsonian*, October 27, 1921.
2. Davidson College Catalog, 1920–1921 (Davidson, NC, Davidson Office of Communications, 1920).
3. *The Davidsonian*, December 2, 1921.

In 2019 Davidson had 20 students and three faculty members attend PhysCon in Providence, Rhode Island. Photo courtesy of Anthony Kuchera.

Physics students and faculty at Davidson College help promote Sigma Pi Sigma's Centennial Run during a visit from Sigma Pi Sigma director Brad Conrad and past president Willie Rockward. Photo courtesy of Brad Conrad.

Chapters Celebrate Sigma Pi Sigma's Centennial Anniversary!

Proud members of Sigma Pi Sigma and the Society of Physics Students at Embry-Riddle Aeronautical University in Prescott during their celebration.

The Boston College SPS chapter grabs some treats to celebrate the centennial.

Moravian University's SPS chapter celebrates the centennial with a bridge-building competition along with their party.

During the fall semester, Indiana University South Bend's SPS chapter began to rebuild after being disrupted by the pandemic. The 100th birthday of Sigma Pi Sigma was an excellent opportunity for our chapter to fully gather in person and celebrate!

University of Tennessee-Chattanooga SPS students and their advisor together during their centennial celebration.

The University of Wisconsin - River Falls chapter celebrated Sigma Pi Sigma's 100th birthday with cake and community!

A cake for the 100th birthday of Sigma Pi Sigma, baked and decorated with the SPS spherical cow by Worcester Polytechnic Institute SPS treasurer Brigitte Lefebvre.

The University of San Diego celebrated the Sigma Pi Sigma centennial with past Sigma Pi Sigma president Dr. Rockward's message on the four pillars of Sigma Pi Sigma—and cake!

University of Colorado-Denver SPS students pose with their "secret" physics handshake as part of the centennial celebration!

The Randolph College SPS chapter enjoyed pizza, wings, and the Party of the Century livestream in their physics lab, and relaxed with Jackbox games afterward!

The South Dakota School of Mines & Technology physics community celebrated with a delicious SPS-themed cake accompanied by homemade liquid nitrogen ice cream.

The Marshall University SPS chapter celebrated the 100th birthday of Sigma Pi Sigma with cake and ice cream, a presentation on the national and local history of SPS and Sigma Pi Sigma, and a look at upcoming chapter outreach opportunities.

Missouri Southern State University SPS chapter members share pizza and a 100th birthday cake at their Sigma Pi Sigma centennial celebration.

The Lycoming College SPS chapter celebrates the centennial with homemade cakes, Sigma Pi Sigma pi(e) cutters, and a Sigma Pi Sigma themed party!

Raising the Excitement Level

by Jillian Guthrie, Sammi Rosenfeld, and Jason Torchinsky, SPS Students, and Nelia Mann, SPS Advisor, Union College

The heart of the Union College physics and astronomy department lies on the ground floor of the new Integrated Science and Engineering Center, in the physics student lounge. Here, students gather to study together, relax, and attend regular SPS meetings. Although the building is new, the physics and astronomy department has a rich history at Union. Today, Union graduates between 5 and 15 physics majors a year, and they go on to work in fields as diverse as education, medicine, engineering, and finance, in addition to pursuing graduate studies in physics and astronomy.

Our chapter's primary goal is always to get students—and the local community—excited about physics. One of our most successful events in recent years was the Ooblek Run, for which members filled kiddie pools with 750 pounds of cornstarch and added water to create a non-Newtonian fluid. We then invited members of the college community to experiment by running across it or applying different amounts of force, among other tests. For this demonstration, the chapter won a campus-wide award for the most unique event. Another successful event brought a group together to attend a public lecture by Neil deGrasse Tyson and to meet with the well-known astrophysicist.

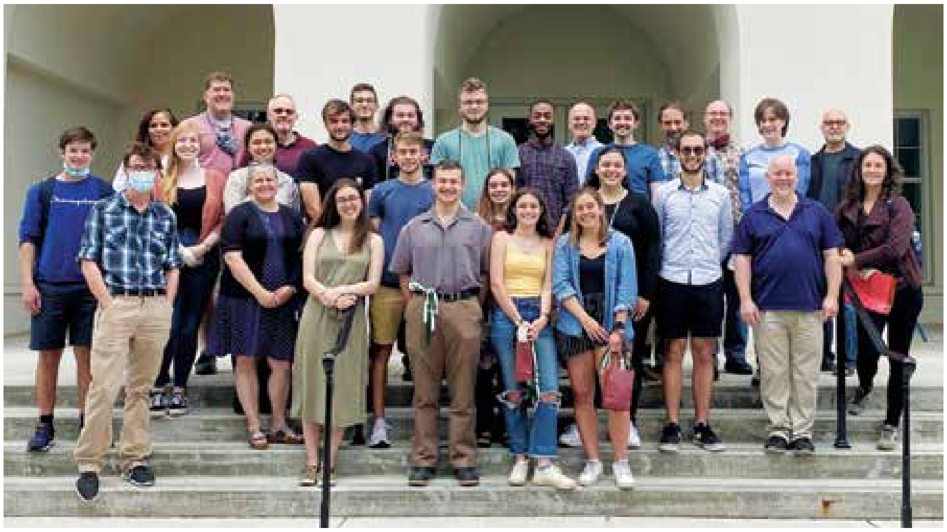
We're particularly enthusiastic about being able to conduct events in person, which has been more difficult lately because of COVID-19. In the coming year we hope to have movie nights, as well as another Ooblek Run. We're also exploring the idea of partnering with the Classics Club to run a stargazing/mythology night, and we want to have some form of invited speaker series or possibly host dinner-and-discussion events. Ideally, we'd also like to build stronger connections with nearby chapters.

Union SPS has a tradition of running workshops each year that teach students how to use LaTeX, Mathematica, and Excel. These attract a lot of different student groups on campus and have even, on occasion, been attended by faculty. We also have outreach ties with our local public library, the Jewish Community Center, and the local science museum.

Our members regularly attend a variety of local conferences and meetings, including the Lunar and Planetary Science Conference and meetings of the New York State Section of the American Physical Society (NYSS/APS), the NY6 (a group of six small colleges in New York), the Astronomical Society of New York, and the American Geophysical Union.

Our Sigma Pi Sigma induction ceremony includes signing a ledger that we've had since our chapter was founded in 1975. There are even current faculty members at Union who signed the ledger when they were students. In the spring of 2020 the ceremony was virtual, so we weren't able to continue the tradition at the time. But one year later we held a special joint induction ceremony and honored new members from both the current and the previous year. The event was held outdoors and was attended by all inductees. We're looking forward now to a future filled with more SPS and Sigma Pi Sigma events. ●

SPS president Sammi Rosenfeld and member Christos Kakogiannis work with oobleck in a still from a video entered into a science outreach contest. Image courtesy of the Union College SPS chapter.



The spring 2021 Sigma Pi Sigma induction ceremony included both the current and previous classes, pictured here along with faculty members. Photo courtesy of Nelia Mann.

The Data Privacy Scientist

Claire McKay Bowen

Principal Research Associate at the Center on Labor, Human Services, and Population and leader of the Statistical Methods Group at the Urban Institute

Claire Bowen. Photo courtesy of Bowen.

I'm a principal investigator for many different projects that tie into our tagline at the Urban Institute, "Elevating the debate on social and economic policy." The Urban Institute is a nonprofit public policy research institute that provides data and evidence for data-informed decision-making. We work in all kinds of policy—health policy, justice policy, tax policy. We have a dozen or so different centers focused on domestic public policy issues.

Often an entity such as the Internal Revenue Service or the U.S. Census Bureau has a data set that is used for public policy discussions but contains confidential information. These entities must carefully consider what information to release without violating a records' privacy. Some people think there is a way to do this that perfectly preserves privacy and maintains accuracy. But that's impossible, because privacy and information naturally oppose one another. The more you know about somebody, the less privacy they have. So how do you make these kinds of trade-offs in a way that respects individual privacy but enables evidence-based public policy? That's my area of specialty.

Recently, I've been investigating how to implement a privacy definition called differential privacy. Differential privacy is a complex and nonintuitive concept, but here's a kind of high-level overview.

Everybody has their own definitions of privacy and risk. For a long time, decisions about what information should be considered private were made ad hoc by those releasing data or data stewards. They had to assume how someone might attack the data (are they looking for a specific person or group of people?) and with what possible information and computing power. Differential privacy basically throws that way of thinking out the window, or at least starts with a clean slate, because trying to predict how somebody might attack data is extremely difficult.

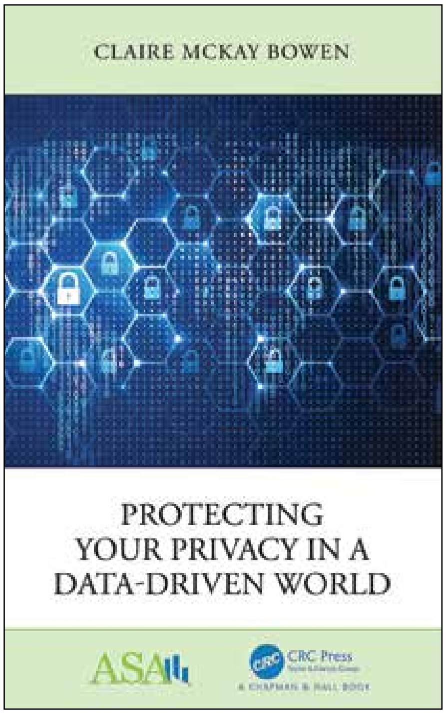
Differential privacy basically says that you have to think of the worst-case scenario. You have to consider that somebody may have any possible version of the data you're trying to release and any future versions—you have to think of the universe of all possible versions of this data set. And then you have to protect privacy in that context.

Most of my day-to-day work is assessing and communicating about methods that satisfy differential privacy. Although I'm always working in privacy, I get to work on different data sets for different areas of public policy all the time. I never get bored! The statistician John W. Tukey once said, "The best thing about being a statistician is that you get to play in everyone's backyard."

I have bachelor's degrees in physics and math and a PhD in statistics. I went into physics because I wanted to know how the world worked. After working in several different labs, my then boyfriend (now spouse) pointed out that I seemed to like the statistics side of research. I realized he was right. When I entered graduate school in statistics, my advisor told me that she didn't care what application I worked on as long as my research involved Bayesian statistics. That left the door wide open, so I looked at research funding opportunities to see what was there and what interested me. This led me to the field of data privacy and confidentiality, and specifically, differential privacy applications. I realized that it was a big area with a big impact and that the work was really interesting. I kept winning funding to work on applying differential privacy to data to expand access, and here I am.

My physics background has served me well. In physics you learn to be a critical thinker, to use what you do know to solve what you don't know. Physics is also a very broad field—as an undergrad you're trying to encompass a very large field and thinking of all the different ways you might tackle different problems. It also works to my advantage that I came from a very different background than most of my colleagues. Even though the field of expanding access to valuable data through data privacy and confidentiality methods affects everybody, computer science dominates the discussion. It's been helpful to have a different perspective.

If I were to give just one piece of career advice to students, I'd tell them that if you don't have issues of finance or family obligations or other constraints, you should optimize happiness. Easier said than done, I know, but this is the life that you live. You might as well enjoy it as much as possible. ●



Claire Bowen's new book, *Protecting Your Privacy in a Data-Driven World*, was released by Routledge in 2022.

A Solid Foundation:
Jumping from Physics to GIS

Kevin Cheriyan. Photo courtesy of Cheriyan.

"Astronomy was my gateway to physics," says Kevin Cheriyan, a software developer who primarily focuses on creating GIS (geographic information systems) and geospatial applications. "Finding out about how the universe plays by natural and predictable laws and how the same laws (mostly) apply to bodies of all sizes—from entire galaxies and black holes to subatomic particles—made me hungry for more," he said.

Born in Kerala, India, Cheriyan moved to Brooklyn, New York, at age 12. He attended high school in Brooklyn and afterward did undergraduate studies at the University of Maryland, College Park (UMD). While at UMD, Cheriyan decided to major in physics and astronomy, and joined the Society of Physics Students in his sophomore year. "The community and support I found was encouraging and essential to staying sane in a tough program!" he says. "Taking part in outreach events with other students and engaging the public with liquid nitrogen demonstrations were important in conveying the relevance of science in everyday life."

Cheriyan took on leadership roles with the UMD chapter and became an associate zone councilor at SPS National. "I had several important chances to influence how other students view the larger physics community," he says. "I was part of a trip to Capitol Hill to meet with congressional staff and advocate for solutions to issues in science and science funding. Talking with congressional staffers and hearing their responses helped me gain some perspective about the need for physics to coexist with a million other fields and studies that also need federal funding and attention."

Being inducted into Sigma Pi Sigma, Cheriyan says, was "a great honor, as it meant being part of a community that encouraged interest in physics and promoted service to others." It also offered a lifetime of being part of a group with many shared interests.

While still an undergraduate, Cheriyan served as an assistant at the University of Maryland's Cosmic Ray Energetics and Mass (CREAM) laboratory, supporting the building and testing of cosmic ray detectors used in high-altitude balloon flights from Antarctica and eventually for the International Space Station (ISS-CREAM). In addition to engineering and assembly support, Cheriyan tested various UNIX kernels and provided repair support to computers and other hardware used by researchers.

Then Cheriyan changed course. He had decided, somewhere along his undergraduate journey, that as fulfilling as the fields of physics and astronomy were, he wanted to focus on practical knowledge that could apply directly to industry after graduation.

"I was drawn to geography, and particularly its quantitative and technical side, because the University of Maryland's Department of Geography was well known for its remote sensing research and faculty," Cheriyan says. Remote sensing is the process of observing the physical characteristics of an area on Earth's surface using reflected and emitted radiation from a distance. "The moment I realized that remote sensing of Earth's surface is similar in principle to observational astronomy, which is just remote sensing on a larger, *extraterrestrial* scale, I was hooked." In 2020 he received a master's degree in geospatial information sciences from UMD.

Today, Cheriyan works at GeoMarvel, a GIS-focused software development company based out of Alexandria, Virginia. There, he uses development and IT tools to make various forms of location data available to clients, enabling them to access and analyze the data to make informed decisions. When not creating spatially aware applications, he also uses statistical techniques that are optimized for geospatial needs to identify patterns and relationships between variables and to visualize them on digital map products.

"I greatly enjoy the process of devising solutions to challenging problems, whether the challenges are created by data standardization issues, conversion errors between different coordinate systems, or finding user interface– or user experience–based solutions to interesting and unusual client requests," he says.

Cheriyan says the skills he learned from physics and SPS were so important and fundamental that he applies them every day. "Whenever I encounter a difficult programming task, I reduce the problem to first principles, which can help [me] understand how the different parts are related," he says. "I also find myself utilizing the communication skills I learned from doing physics outreach when needing to explain a technical concept to a client or project manager. If you can explain the conservation of angular momentum to middle schoolers, you can explain how asynchronous operations work in JavaScript to a client."

To those looking to start their careers, Cheriyan advises not overlooking the importance of good communication and writing skills. "One can easily pick up most technical skills and concepts in a matter of weeks to basic proficiency levels," he says, "but interpersonal skills are more challenging and can take a lifetime to perfect."

And for those considering a major in physics, his advice is to avoid dismissing the importance of other sciences and the humanities. "There is a prevalent notion among physics majors and physicists that science is all physics or stamp collecting," he says. "As a field that has considerable difficulty attracting and retaining underrepresented minorities, statements that amount to discounting the importance or difficulty of other sciences can turn potential students off from what could be a great time learning about physics and the natural world."

Cheriyan offers one final piece of advice: "Take proper safety precautions when performing physics demonstrations, or you will end up with a disproportionately dry dominant hand that your doctor won't believe is caused by you trying to demonstrate the Leidenfrost Effect by repeatedly sticking your hand in containers of liquid nitrogen." ●

Coupled Oscillations in Diverse Phenomena

Part 1: A simple mathematical model

by Dwight E. Neuenschwander, Southern Nazarene University

If you are a musician or a music appreciator, you have encountered "sympathetic vibrations," where striking one string of a piano or guitar makes nearby unstruck strings vibrate. As the vibrations of the struck string vibrate the surrounding air, the jiggling air makes neighboring strings vibrate too. Sympathetic vibrations are examples of *coupled oscillations.* A simple mathematical model of a coupled oscillator also beautifully describes diverse phenomena from ammonia masers to neutrino oscillations. The parameters are different, but they are described by essentially the same equations.

Coupled oscillations are manifestly visible in a classroom demonstration with two pendulums whose upper ends are attached to a common rod. When pendulum 1 swings it communicates its motion to the coupling rod, which eventually sets pendulum 2 in motion. Due to conservation of energy, as one pendulum swings more, the other swings less. As long as damping is negligible, the two pendulums take turns swinging with the larger amplitude.

To make a simple mathematical model that gets at the essence of the coupling, begin with two springs. Let the left and right spring have spring constant k, each attached to identical masses m. The springs are coupled by connecting them with a third spring with a spring constant k' (Fig. 1).

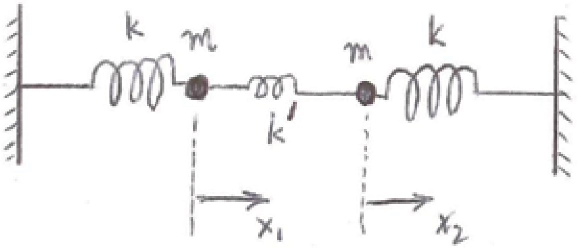


Figure 1. A coupled oscillator represented with springs with spring constants k, k', and k.

Apply Newton's second law to each of the two masses, using Hooke's law to model the forces exerted on them by the springs. With the coordinates of Fig. 1, for the left spring (spring 1) we have

$$-kx_1 - k'(x_1 - x_2) = m\ddot{x}_1 \qquad \text{(1a)}$$

and for the right spring (spring 2) Newton's second law gives

$$-kx_2 - k'(x_2 - x_1) = m\ddot{x}_2 \qquad \text{(1b)}$$

where overdots denote time derivatives. Regroup Eqs. (1) to collect coefficients of each coordinate:

$$-(k + k')x_1 + k'x_2 = m\ddot{x}_1 \qquad \text{(2a)}$$

$$k'x_1 - (k + k')x_2 = m\ddot{x}_2. \qquad \text{(2b)}$$

Equations (2) present us with two equations and two unknowns for $x_1(t)$ and $x_2(t)$. We can try two strategies: (a) solve for $x_1(t)$ and $x_2(t)$ separately, or (b) think of the two masses and the three springs as a single system and find the modes of its oscillation where each mode has a unique frequency—the so-called "normal modes," a.k.a. the "eigenstates" of the system, with their corresponding frequency "eigenvalues" (German *eigen* = English *own*). Let's look first at strategy (a). Then we'll turn to strategy (b).

(a) Solving for $x_1(t)$ and $x_2(t)$

To solve for $x_1(t)$ and $x_2(t)$ separately, since Eqs. (2) are linear in both variables they can be easily combined by superposition into two other equations, one for $x_1(t) + x_2(t) \equiv \sigma(t)$ and another one for $x_1(t) - x_2(t) \equiv \delta(t)$. Adding Eqs. (2a) and (2b) gives

$$\ddot{\sigma} + \omega_\ell^2 \sigma = 0 \quad (3a)$$

whereas subtracting Eq. (2b) from (2a) produces

$$\ddot{\delta} + \omega_h^2 \delta = 0 \quad (3b)$$

where

$$\omega_\ell \equiv \sqrt{\frac{k}{m}} \qquad (4a)$$

is a lower frequency and

$$\omega_h \equiv \sqrt{\frac{k+2k'}{m}} \qquad (4b)$$

is a higher frequency. Equations (3) give the solutions

$$\sigma(t) = a\sin(\omega_\ell t) + b\cos(\omega_\ell t) \quad (5a)$$

$$\delta(t) = p\sin(\omega_h t) + q\cos(\omega_h t) \quad (5b)$$

where a, b, p, and q are constants. Suppose the initial conditions include $\dot{x}_1(0) = \dot{x}_2(0) = 0$, with both masses initially at rest. This means $\dot{\sigma}(0) = 0 = \dot{\delta}(0)$, which gives $a = p = 0$. But to produce oscillations, one of them has been displaced from equilibrium, then released at $t = 0$. Therefore, let $x_1(0) = b$ and $x_2(0) = 0$, which implies $q = b$. Now Eqs. (5) are

$$\sigma(t) = b\cos(\omega_\ell t) = x_1(t) + x_2(t) \qquad (6a)$$

and

$$\delta(t) = b\cos(\omega_h t) = x_1(t) - x_2(t). \qquad (6b)$$

Equations (6) can be inverted to give

$$x_1(t) = \frac{b}{2}[\cos(\omega_\ell t) + \cos(\omega_h t)] \qquad (7a)$$

and

$$x_2(t) = \frac{b}{2}[\cos(\omega_\ell t) - \cos(\omega_h t)]. \qquad (7b)$$

The trig identities

$$\cos(\alpha) + \cos(\beta) = 2\cos\left(\frac{\alpha+\beta}{2}\right)\cos\left(\frac{\alpha-\beta}{2}\right) \quad (8a)$$

$$\cos(\alpha) - \cos(\beta) = -2\sin\left(\frac{\alpha+\beta}{2}\right)\sin\left(\frac{\alpha-\beta}{2}\right) \quad (8b)$$

allow Eqs. (7) to be written in a way that exhibits beats. The two frequencies result in a rapid oscillation of frequency $(\omega_h + \omega_\ell)/2$, which is modulated by a slowly oscillating envelope of frequency $(\omega_h - \omega_\ell)/2$.[1]

$$x_1(t) = 2b\cos\left(\frac{(\omega_\ell+\omega_h)t}{2}\right)\cos\left(\frac{(\omega_h-\omega_\ell)t}{2}\right) \quad (9a)$$

$$x_2(t) = 2b\sin\left(\frac{(\omega_\ell+\omega_h)t}{2}\right)\sin\left(\frac{(\omega_h-\omega_\ell)t}{2}\right) \quad (9b)$$

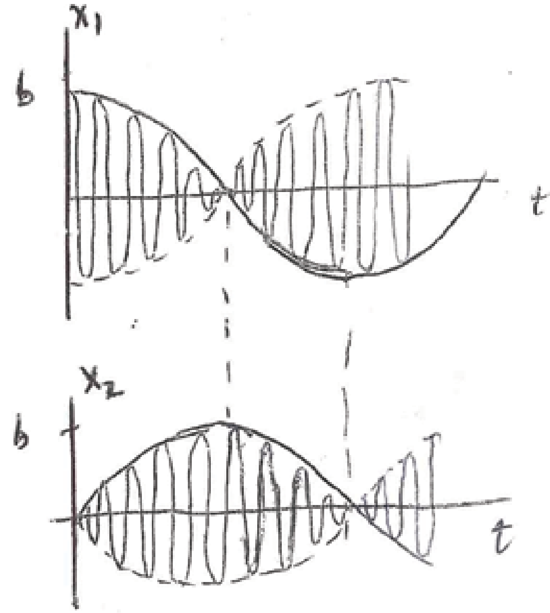


Figure 2. An illustration of the motions $x_1(t)$ & $x_2(t)$.

(b) The Normal Modes

Return to Eqs. (2) and arrange them into a matrix equation,

$$\begin{pmatrix} -(k+k') & k' \\ k' & -(k+k') \end{pmatrix}\begin{pmatrix} x_1 \\ x_2 \end{pmatrix} = m\begin{pmatrix} \ddot{x}_1 \\ \ddot{x}_2 \end{pmatrix}. \quad (10)$$

Introducing column vectors and deploying the Dirac bracket notation,[2] let

$$|x\rangle \equiv \begin{pmatrix} x_1 \\ x_2 \end{pmatrix}. \qquad (11)$$

Define a matrix K of spring constants:

$$K \equiv \begin{pmatrix} (k+k') & -k' \\ -k' & (k+k') \end{pmatrix}. \qquad (12)$$

With Eqs. (11) and (12), Eq. (10) takes the abbreviated form

$$-K|x\rangle = m\frac{d^2|x\rangle}{dt^2}. \qquad (13)$$

In strategy (a) the two-mass system, as mapped by $x_1(t)$ and $x_2(t)$, had two oscillations with different frequencies going on at the same time. We now set for ourselves the task of finding single-frequency modes of oscillation of the entire two-mass, three-spring system. This means we seek a set of two new position variables where each oscillates with some as-yet-unknown constant angular frequency. Let's call these two modes $\eta_1 \equiv A_1\cos(\omega t)$ and $\eta_2 \equiv A_2\cos(\omega t)$, where ω is a constant angular frequency (or set of constant frequencies) to be determined. Let $|\eta(t)\rangle$ denote these coordinates arranged as a special case of generic states $|x\rangle$,

$$|\eta(t)\rangle = \begin{pmatrix} \eta_1(t) \\ \eta_2(t) \end{pmatrix} = \begin{pmatrix} A_1 \\ A_2 \end{pmatrix}\cos(\omega t) \equiv |A\rangle\cos(\omega t) \qquad (14)$$

where $|A\rangle$ is time-independent. Insert these coordinates—this eigenvector—into Eq. (13), which becomes (after cancelling $\cos(\omega t)$)

$$K|A\rangle = m\omega^2|A\rangle. \qquad (15a)$$

Transpose this into the form

$$\begin{pmatrix} -m\omega^2 + (k+k') & -k' \\ -k' & -m\omega^2 + (k+k') \end{pmatrix}|A\rangle = |0\rangle \quad (15b)$$

where $|0\rangle$ means the zero vector. Now we appeal to the theorem of alternatives, a.k.a. the invertible matrix theorem.[3] Recall what it says about a homogeneous matrix equation of the form

$$M|x\rangle = |0\rangle \qquad (16)$$

with square matrix M and column matrix $|x\rangle$; Eq. (15b) is an example of such a matrix equation. There are two alternatives for $|M|$, the determinant of M: it is either zero or it is nonzero. If $|M| \neq 0$ the theorem shows that Eq. (16) has the unique but trivial solution $|x\rangle = |0\rangle$. But if $|M| = 0$ the theorem guarantees a nontrivial but not unique solution. Since we want a nontrivial solution, we set to zero the determinant of the square matrix in Eq. (15b) and solve for ω. We get

$$\omega = \sqrt{\frac{k+k'\pm k'}{m}} \qquad (17a)$$

choosing the positive sign when taking the square root since frequencies are non-negative. There are two distinct roots. The minus sign under the radical gives

$$\omega_\ell = \sqrt{\frac{k}{m}} \qquad (17b)$$

and from the plus sign,

$$\omega_h = \sqrt{\frac{k+2k'}{m}} \qquad (17c)$$

[compare to Eqs. 4]. These results—two angular frequency eigenvalues—means there are two modes of vibration, each with its distinctive frequency. Let's see what kinds of vibrations these eigenvalues imply. To do this we take one eigenvalue at a time, insert it into Eq. (15a), and see what ratio A_2/A_1 results. without further assumptions we can't do better than the *relative* values of these amplitudes because the theorem of alternatives promised a nontrivial solution but not a unique one.

Begin with ω_ℓ of Eq. (17b). When inserted in Eq. (15a) this gives the pair of equations

$$k'A_1 - k'A_2 = 0 \qquad (18a)$$

$$-k'A_1 + k'A_2 = 0. \qquad (18b)$$

Both yield $A_1 = A_2 \equiv a$. Label as $|\eta_\ell\rangle$ the state $|\eta\rangle$ that has ω_ℓ for its eigenvalue. Omitting the time dependence in the eigenstates for now by setting $t = 0$ in Eq. (14), so far we have

$$|\eta_\ell(0)\rangle = a\begin{pmatrix}1\\1\end{pmatrix}. \qquad (19a)$$

When we repeat this procedure but insert ω_h into Eq. (15a), we find that $A_2 = -A_1$ so that at $t = 0$ we find this eigenstate $|\eta_h\rangle$ to be

$$|\eta_h(0)\rangle = a\begin{pmatrix}1\\-1\end{pmatrix}. \qquad (19b)$$

Restoring the time dependence via Eq. (14), within the scaling factor a we now have the eigenstates with their respective eigenvalues:

$$|\eta_\ell(0)\rangle = a\begin{pmatrix}1\\1\end{pmatrix}\cos(\omega_\ell t) \qquad (20a)$$

$$|\eta_h(0)\rangle = a\begin{pmatrix}1\\-1\end{pmatrix}\cos(\omega_h t). \qquad (20b)$$

What kinds of motions do these states describe? Let us appropriate Eq. (11) for each of the eigenvectors. For $|\eta_\ell(t)\rangle$ we can write

$$|\eta_\ell(0)\rangle = a\begin{pmatrix}1\\1\end{pmatrix}\cos(\omega_\ell t) = \begin{pmatrix}x_1\\x_2\end{pmatrix} \qquad (21a)$$

which says that $x_1 = x_2$. If spring 1 moves its mass to the right by 1 cm, then spring 2 simultaneously moves its mass to the right by 1 cm too. This behavior is illustrated in Fig. 3a. For the eigenvector $|\eta_h(t)\rangle$ we have

$$|\eta_h(0)\rangle = a\begin{pmatrix}1\\-1\end{pmatrix}\cos(\omega_h t) = \begin{pmatrix}x_1\\x_2\end{pmatrix} \qquad (21b)$$

which says that $x_1 = -x_2$. If spring 1 moves its mass to the right by 1 cm, then spring 2 simultaneously moves its mass to the left by 1 cm. This behavior for the coupled oscillators is illustrated in Fig. 3b. When vibrating in one of the eigenstate modes, the two masses move together in a single-frequency choreography.

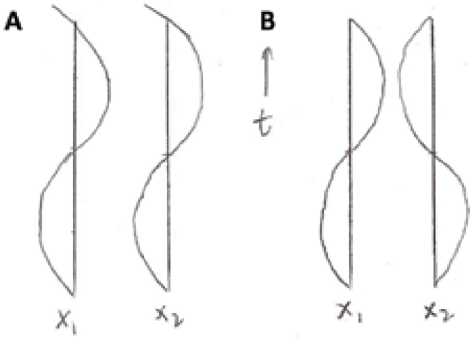


Figure 3. The two eigenstate modes for the coupled oscillator: (a) the mode of Eq. (21a) with angular frequency ω_ℓ, and (b) the mode of Eq. (21b) of angular frequency ω_h.

Eigenvectors as a Basis

The original set of state vectors of Eq. (11) expresses the instantaneous state of the coupled oscillators. Analogous to how a vector $\mathbf{r}$ in the Euclidean plane can be written as $\mathbf{r} = x_1\hat{\mathbf{\imath}} + x_2\hat{\mathbf{\jmath}}$, the abstract state vector $|x\rangle$ can be split into a superposition of "basis vectors" as follows:

$$|x\rangle = \begin{pmatrix}x_1\\x_2\end{pmatrix} = x_1\begin{pmatrix}1\\0\end{pmatrix} + x_2\begin{pmatrix}0\\1\end{pmatrix}$$
$$\equiv x_1|1\rangle + x_2|2\rangle \qquad (22)$$

where

$$|1\rangle \equiv \begin{pmatrix}1\\0\end{pmatrix} \qquad (23a)$$

and

$$|2\rangle \equiv \begin{pmatrix}0\\1\end{pmatrix}. \qquad (23b)$$

These are the basis vectors of the "1-2 basis." Let $\langle x|$ be the row vector made by transposing the column vector $|x\rangle$ (when we get to quantum mechanics, which uses complex numbers, $\langle x|$ will be the transpose and complex conjugate of $|x\rangle$). Then by the rules of matrix multiplication, the scalar product (a.k.a. the "dot product") between two vectors can be written $\langle x|y\rangle$. Like $\hat{\imath}$ and $\hat{\jmath}$, we see that $|1\rangle$ and $|2\rangle$ are also "orthonormal", a hybrid word which means they are orthogonal: $\langle 1|2\rangle = 0$; and they are unit vectors, i.e., "normalized" to have magnitude unity: $\langle 1|1\rangle = \langle 2|2\rangle = 1$. An orthonormality condition can be summarized by saying $\langle i|j\rangle = \delta_{ij}$, where δ_{ij} denotes the "Kronecker delta," equal to 1 if $i = j$ and 0 if $i \neq j$. Any state vector in two-dimensional space can be written as a superposition of $|1\rangle$ and $|2\rangle$, as Eq. (22) illustrates. As basis vectors, $|1\rangle$ and $|2\rangle$ are said to "span the space." Equivalent to the statement that $|1\rangle$ and $|2\rangle$ form an orthonormal basis is the statement that they satisfy the "completeness relation,"[2]

$$|1\rangle\langle 1| + |2\rangle\langle 2| = \tilde{1} \tag{24}$$

where $\tilde{1}$ denotes the unit matrix, which in the case before us is 2×2. *The eigenstates form another orthonormal basis in the same space.*

We have seen how the theorem of alternatives guarantees nontrivial but nonunique solutions. In our example this shows up in the arbitrary scale factor a that, in this system, is common to $|\eta_\ell(t)\rangle$ and $|\eta_h(t)\rangle$. To determine a we push farther. We have the freedom to make these eigenvectors be unit vectors. In so doing they form a set of orthonormal basis vectors.[4] Eigenvectors do not have to be *unit* vectors in order to be a basis, but why would you give $\hat{\imath}$ or $\hat{\jmath}$ a magnitude of 2 or 17—those factors would have to be divided out of your calculations. So let's normalize the eigenvectors $|\eta_\ell(t)\rangle$ and $|\eta_h(t)\rangle$. This determines the scale factor a. Requiring $\langle \eta_\ell|\eta_\ell\rangle = 1$ and $\langle \eta_h|\eta_h\rangle = 1$ gives $a = 1/\sqrt{2}$ in both cases, and therefore from Eqs. (19),

$$|\eta_\ell(0)\rangle . = \frac{1}{\sqrt{2}}\begin{pmatrix}1\\1\end{pmatrix} \tag{25a}$$

and

$$|\eta_h(0)\rangle . = \frac{1}{\sqrt{2}}\begin{pmatrix}1\\-1\end{pmatrix}. \tag{25b}$$

You can verify their orthogonality, $\langle \eta_\ell|\eta_h\rangle = 0$, and, now normalized, that they satisfy the completeness relation at $t = 0$,

$$|\eta_\ell(0)\rangle\langle \eta_\ell(0)| + |\eta_h(0)\rangle\langle \eta_h(0)| = \tilde{1}. \tag{26b}$$

The next installment will investigate the connection to two-state systems and neutrino oscillations.

References

[1] If you are used to "the beat frequency" being $|\omega_h - \omega_\ell|$ as encountered in musical acoustics, note that the frequency of the *intensity* (what we hear) is proportional to the square of the wave function, and thereby the intensity has twice the frequency of the wave function.

[2] D.N., "Synthesis & Analysis, Part 1: The Completeness Relation and Dirac Brackets," *SPS Newsletter*, Oct. 1996, 10-12.

[3] David Lay, *Linear Algebra and its Applications* 3rd. ed. (Boston, MA: Pearson Addison-Wesley, 2006), 128-130.

[4] Any vector can be normalized to have unit length simply by dividing the vector by its magnitude. But if the eigenvectors are not already orthogonal, which happens when two eigenfunctions share the same eigenvalue, one can make linear combinations of them to form an orthogonal set. The systematic way of doing so is called the "Schmidt orthogonalization procedure." See Eugen Merzbacher, *Quantum Mechanics*, 2nd Ed. (New York: Wiley, 1970), 149, 317-318.

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