the SPS Observer

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Spring 2015

On Doing Research

TIPS FOR CARRYING OUT AND COMMUNICATING RESEARCH

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Physics Needs Research and Balance

by Sean Bentley
Director, Society of Physics Students and Sigma Pi Sigma

Photo courtesy of AIP.

Curiosity may have killed the cat, but it has also inspired many physicists. (In Schrödinger's case, perhaps it did both.) Our natural curiosity leads us to start asking questions from the time we are young, questions like, "Why is the sky blue?" "What causes the seasons?" and "How do planes fly?"

These are questions that could be quickly answered by a parent, a teacher, a book, or, if all else fails, a quick search on your phone. But if you keep asking deeper questions, you will eventually come upon one for which we do not yet know the answer.

Many would call it a day, at that point, and go happily on their way. Those of us who don't, who must get to the answer, do research. Welcome to science!

I will make two major claims (that I hold to be self-evident): First, there cannot be physics without research. Second, physicists need to strive for balance.

Many groups, including SPS, have official statements declaring that all students of physics should have a meaningful research experience, and for good reason.[1] Learning what came before is of great importance, but until you have a moment of discovery in which you are creating new knowledge, you haven't fully experienced the

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ERRATA
"Through Thick and Thin," an article in the Winter 2014 issue of *The SPS Observer*, mistakenly referred to the author's advisor as "he." Zoey Warecki's advisor at Towson University was Rajeswari Kolagani, a female professor who studies metal oxide thin films. We apologize for this mistake and celebrate Kolagani, as well as all faculty who support undergraduate research.

joy of physics. Some love research, and others decide it is not for them. Either way, it is something you should explore firsthand.

A problem is that much like watching your favorite show on Netflix, research can be addictive. Many professional physicists eat, sleep, and breathe research. While this drive can lead to great breakthroughs, I find that there's an inherent danger in the lack of balance. All physicists should also engage in teaching, outreach, and advocacy. Unfortunately, many researchers find other endeavors to be a distraction. (Perhaps you've known some of these researchers, and possibly even had them for a class.)

Without dedication to teaching, though, we are not properly preparing the next generation. Without outreach, the public will not understand and appreciate the value

ALL PHYSICISTS SHOULD ALSO ENGAGE IN
teaching, outreach, and advocacy.

of physics. Without advocacy, the government will not have the information it needs to deal with critical issues facing the world.

I hope you will have wonderful undergraduate research experiences. You may be starting a career in research or just having a taste before starting a career in a field such as engineering, law, medicine, finance, or teaching. Wherever your dreams may take you, I hope that you will strive for balance in all that you do. //

REFERENCES

1. www.spsnational.org/governance/statements/2008undergraduate_research.htm

ON THE COVER
SPS member Nicole Johnson takes a selfie with a quadrupole magnet at the CERN museum near Geneva, Switzerland. Learn more about her research on glass and how you can get involved in research in this issue's feature section, "On Doing Research."
Photo by Nicole Johnson.

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Other Member Organizations: Sigma Pi Sigma physics honor society, Society of Physics Students, Corporate Associates

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Fall 2014 Award Recipients

SPS CONGRATULATES SPS CHAPTERS AT SCHOOLS ACROSS THE COUNTRY

Note: The Fall 2014 Future Faces of Physics Award winners were announced in the Winter 2014–15 issue of The SPS Observer.

Marsh W. White Awards

Several awards of up to $300 are made each year to chapters for physics outreach activities to grades K–12 and the general public.

ADELPHI UNIVERSITY
Lab for Kids
Project Leader: Michael Fernez
SPS Advisor: Matthew Wright

CLEVELAND STATE UNIVERSITY
Reinventing a Bicycle: Discovering Physics via a Common Object Well Known to Every Kid
Project Leader: Janna Mino
SPS Advisor: Kiril Streletzky

INDIANA WESLEYAN UNIVERSITY
Making Waves: The Physics of Sound and Light
Project Leader: Alexander Waters
SPS Advisor: Roberto Ramos

Spotlight on:
RHODES COLLEGE
A Visit to St. Jude Children's Research Hospital's Target House

The Rhodes College Society of Physics Students chapter will begin working with St. Jude Children's Research Hospital. They will bring demonstrations to Target House, the hospital's housing for patients undergoing long-term treatment, to perform outreach for patients there.

Project Leader: Catherine Miller
SPS Advisor: Brent Hoffmeister

SONOMA STATE UNIVERSITY
A Night of Astronomy at Sugarloaf Ridge
Project Leader: Wesley Watson
SPS Advisor: Hongtao Shi

TEXAS LUTHERAN UNIVERSITY
Outreach & Inreach–Building the TLU SPS Phenomenal Physics Outreach Program
Project Leader: Stephen Bratz
SPS Advisor: Toni Sauncy

THE GEORGE WASHINGTON UNIVERSITY
The "Phun"-damentals of Physics
Project Leader: Srividya Murthy
SPS Advisor: Gary White

THE UNIVERSITY OF SOUTHERN MISSISSIPPI
Physics Outreach for the Entire Community: Reaching the Region at Hubfest
Project Leader: Robert McGrath
SPS Advisor: Michael Vera

UNIVERSITY OF MINNESOTA TWIN CITIES
Physics Outreach Program
Project Leader: Luke DeMars
SPS Advisor: Dan Cronin-Hennes

SPS Chapter Research Awards

Several awards of up to $2,000 are made each year to chapters for research activities that are deemed imaginative and likely to contribute to the strengthening of the chapter.

AMERICAN RIVER COLLEGE
Cosmic Ray Detector for Ground and Stratospheric Observations
Project Leader: Carlos Moya
SPS Advisor: Paulo Afonso

DREXEL UNIVERSITY
Cosmic Ray Induced Bit-Flipping Experiment (CRIBFLEX)
Project Leader: Matthew Parsons
SPS Advisor: Luis Cruz Cruz

GEORGIA INSTITUTE OF TECHNOLOGY
Inertial-Electrostatic Confinement Fusion Reactor
Project Leader: Conner Herndon
SPS Advisor: Edwin Greco

Spotlight on:
KETTERING UNIVERSITY
Enhancing Cellular Uptake of Magnetic Nanoparticles for Cancer Therapy via Nanoparticle Engineering and Sonoporation

Iron oxide nanoparticles heat up when placed in an alternating magnetic field, and because of this may have use as a noninvasive cancer treatment without the side efforts of chemotherapy and ionizing radiation. Kettering University SPS students will explore guiding iron oxide nanoparticles to targeted cells with the use of magnetic fields, where they will then be forced into the cells by ultrasound via sonoporation. By investigating different properties of nanoparticles and ultrasound conditions, the team hopes to optimize the uptake of the particles by cancer cells.

Project Leader: Alexis Siegel
SPS Advisor: Ronald Kumon

PURDUE UNIVERSITY
Roswell III, Space Balloon: Journey into the Stratosphere
Project Leader: Carlos Blanco
SPS Advisor: Rafael Lang

TUSKEGEE UNIVERSITY
Identification of Paint Samples using Laser Induced Breakdown Spectroscopy
Project Leader: Kumasi Salimu
SPS Advisor: Prakash Sharma

SPRING 2015 AWARD DEADLINES

April 15
Blake Lilly Prize
Outstanding Chapter Advisor Award

June 15
SPS Outstanding Chapter Award

FALL 2015 AWARD DEADLINES

October 15
Future Faces of Physics Award

November 16
Marsh W. White Award
SPS Chapter Research Award

For details on all SPS awards, visit www.spsnational.org/programs/awards/.

Welcome New Chapters!

Congratulations and welcome to the newest SPS and Sigma Pi Sigma chapters, finalized in 2014:

SPS

- American River College
- Austin Community College
- Saint Michael's College
- University of Alaska Anchorage

SIGMA PI SIGMA

- Doane College
- Indiana University–Purdue University Fort Wayne
- Southern Polytechnic State University
- Saint Michael's College

SPS Chapter Update: iPad Giveaway

In 2014 SPS transitioned to a new membership system, accessible at membership.spsnational.org. As part of the transition, SPS advisors were challenged to update their chapter information last fall and participating advisors were entered into a drawing for an iPad.

Congratulations to **Kerstin Nordstrom, SPS advisor at Mount Holyoke College**, for winning the drawing, and a big THANK YOU to all of the advisors that updated their information! If you are not sure whether your chapter information is up-to-date, visit membership.spsnational.org to find out.

SPS Membership Drive Results

The following SPS chapters dramatically increased their membership numbers during the fall 2014 SPS membership drive and received fantastic gifts for doing so!

5–10 NEW MEMBERS

Gift: Light demonstration kit celebrating the International Year of Light (IYL).

- Dartmouth College
- DePaul University
- Kalamazoo College
- Randolph College
- Seattle Pacific University

10–15 NEW MEMBERS

Gifts: IYL demo kit and a physics book for their lounge.

- Sun Yat-sen University
- Washington University

15–20 NEW MEMBERS

Gifts: IYL demo kit, physics book, and $50 pizza gift card.

- Juniata College

20–50 NEW MEMBERS

Gifts: IYL demo kit, physics book, $50 pizza gift card, and signed copy of either *What If?* by Randall Munroe or signed copy of *The Physics of Superheroes* by James Kakalios.

- Carthage College
- Rhodes College
- University of Maryland

50 OR MORE NEW MEMBERS

Gifts: IYL demo kit, physics book, $50 pizza gift card, signed copy of either *What If?* or *The Physics of Superheroes*, and a superexciting physics outreach kit.

- Coe College
- University of Minnesota
- Virginia Tech

Join SPS!

SPS is open to any student interested in physics, and membership costs only $24/year. Undergraduate members receive many benefits, including *The SPS Observer* (quarterly) and *Physics Today* (monthly); membership in two professional physics societies from among the ten that make up the American Institute of Physics; free membership in the National Society of Black Physicists and the National Society of Hispanic Physicists (if desired); a bimonthly e-newsletter, eligibility for SPS awards, internships, and scholarships; and much more.

To join, visit membership.spsnational.org.

Outstanding SPS Advisor

RANDY BOOKER OF THE UNIVERSITY OF NORTH CAROLINA AT ASHEVILLE WINS AWARD FOR EXCEPTIONAL GUIDANCE

In what has become an annual tradition, the Society of Physics Students presented its highest honor, the Outstanding Chapter Advisor Award, during an awards session at the American Association of Physics Teachers 2015 Winter Meeting. Randy Booker of the University of North Carolina at Asheville was the distinguished 2014 recipient. The award celebrates an individual who has made exceptional contributions toward promoting student leadership, developing a broad spectrum of activities, and inspiring enthusiastic student participation.

Booker has been a tireless champion for SPS, both in his local chapter and at the national level. The UNC Asheville SPS chapter has won the society's Outstanding Chapter Award for 12 consecutive years. The chapter's service activities include helping K-12 students by teaching Super Saturday classes and volunteering at the annual Science Olympiad hosted on campus. The chapter also has arranged behind-the-scenes tours for physics students of NASA's Kennedy Space Center. And just for fun, the chapter socializes with liquid nitrogen ice cream parties and by carving jack-o'-lanterns with famous physics equations. Booker has also served for several years on the SPS National Council. By seamlessly picking up where the classroom efforts leave off to ensure the success of students, he has impacted countless lives. For these reasons and more, Randy Booker is truly an outstanding SPS chapter advisor. //

RANDY BOOKER (center) is pictured with SPS President DJ Wagner (right) and SPS Director Sean Bentley (left). Photo by Lydia Quijada.

This story originally appeared in AIP Matters.

Spotting and Measuring Oil Spills

NEW TECHNOLOGIES UNDER DEVELOPMENT AT SAINT PETER'S UNIVERSITY

by Prajwal Niraula, Class of 2015, and Sabin Pradhan, SPS Chapter President, Class of 2016, Saint Peter's University, Jersey City, NJ

On April 20, 2010, a violent explosion occurred at the oil-drilling rig Deepwater Horizon in the Gulf of Mexico. A sludge of mud, oil, and water poured out of the well, shooting high into the sky. A fire broke out and claimed the lives of 11 people. The oil poured out for months in what would go down as the largest marine oil spill in the history of petroleum drilling.[1]

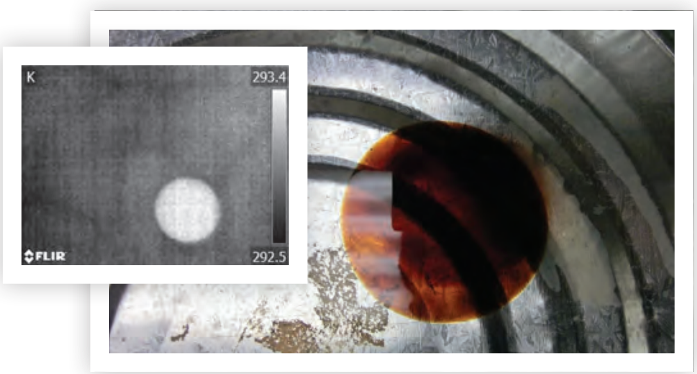
Photo courtesy of NASA.

At Saint Peter's University, the Society of Physics Students chapter is using an SPS Chapter Research Award to explore technologies that could help to prevent or minimize the impact of accidents like the one at Deepwater Horizon. We are exploring the potential of infrared cameras for early oil spill detection and remote measurement of an oil spill's volume. Such technologies are important because they could detect early failures in equipment and operations, and inform response teams about the best course of action. Even though alternative energy sources have been developed, it is very likely that the world will continue using fossil fuels for decades to come to meet high energy demands.

INFRARED TECHNOLOGY

Every object, whether hot or cold, emits radiation. The nature of this radiation is governed by Planck's radiation law, which says that the spectrum of radiation emitted by an object depends only on its temperature. For bodies at room temperature, the dominant form of emission occurs in the infrared region at wavelengths ranging from about 700 nm to 1 mm. This radiation is invisible to us because our eyes respond only to light in the visible spectrum, the narrow window of about 400–700 nm. Infrared technology allows us to detect radiation in the infrared region and thus determine the temperatures of objects.

THE SAINT PETER'S UNIVERSITY SPS RESEARCH TEAM. Photo courtesy of Saint Peter's University.



AN OPTICAL IMAGE of oil on water is compared side-by-side with an infrared image (inset) taken by the authors. Photo courtesy of Prajwal Niraula.

LEFT: A NASA satellite image reveals the oil slick off the coast of Louisiana.

RIGHT: Ships spray the burning oil rig with seawater to fight the flames.


Photo courtesy of US Coast Guard.

The apparent temperature of a substance depends on its emissivity, and oil and water have slightly different emissivities. Therefore, even when oil and water are in thermal equilibrium, an infrared camera is able to detect two distinct liquids.

We showed that this contrast can be used to easily find the total area of a puddle of oil floating on water. This means that oil should be detectable by an infrared camera, even when visibility conditions for the human eye are poor.

We also wanted to explore techniques for finding the thickness of a puddle of oil so that we could determine the total quantity spilled. We attempted to find a relationship between thickness and emissivity but found no measurable relationship within the range our camera can detect, forcing us to turn to other means.

OIL FLUORESCENCE

Dr. Clyde Bethea and Dr. Debing Zeng, who were advising our team at the time, encouraged us to look into the fluorescence property of our oil samples. Fluorescence occurs when an object absorbs a fraction of the incident light striking it and emits the energy as light with a longer wavelength after a brief interval of time.[2]

We recorded the fluorescence of three different oil samples, using an incident laser with a wavelength of 405 nm. The oil samples, distinguishable to the eye by their color, also had unique fluorescence spectra. We attributed these signature spectra to the nature of the chemical bonds in each sample.

Since fluorescence spectra are unique for different oils, they can be used to detect the type of oil spilled. They also greatly minimize the chance of a false alarm about a spill by providing a more rigorous test for oil detection than infrared cameras, which show only the contrast between two materials and cannot be used to identify the constituents themselves.

Fluorescence can also be used to measure the thickness of a layer of oil. Water is fairly transparent to laser light, while oil is not. The thicker the layer of oil floating on the surface of water, the more laser energy it should absorb and emit. We exploited this relationship to qualitatively measure oil heights.

We used laser pointers operating on batteries for this measurement. However, the batteries drained quickly and the power gradually decreased. To quantify layers of oil thicker than a few microns, we needed a constant-power laser. Fortunately we were recently able to purchase one and are looking forward to exploring this further during the spring semester. //

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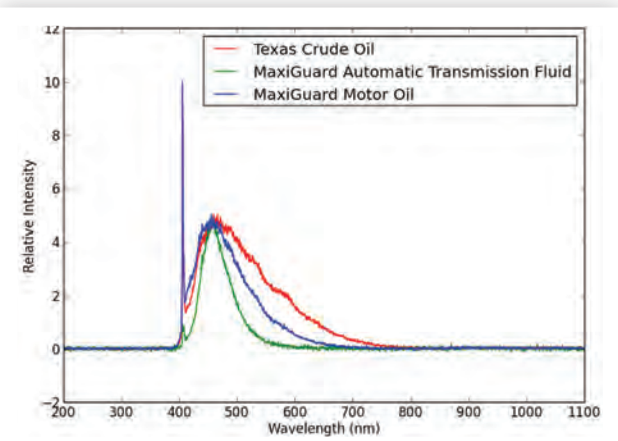
1. *The Gulf Oil Disaster and the Future of Offshore Drilling.* National Commission on the BP Deepwater Horizon Oil Spill and Offshore Drilling. January 2011.

2. S. R. Swift and L. Trinkle-Mulcahy. *Basic Principles of FRAP, FLIM, and FRET.* Source: http://www.trinkle-lab.com/pubpdf/04/rms04.pdf.



THE FLUORESCENCE SPECTRA of three different types of oil all peaked at 405 nm but were distinguishable from each other. Graph courtesy of Prajwal Niraula.

GET MONEY FOR CHAPTER RESEARCH

SPS chapters are eligible for up to $2,000 in funding for research projects through the SPS Chapter Research Award (formerly the Sigma Pi Sigma Undergraduate Research Award). Applications are due November 15 each year. For details see http://spsnational.org/programs/awards/research.htm.

Zoning In

Across the country, SPSers have been traveling to other schools, other cities, even other states. The occasion? Zone meetings! Hosted by individual chapters, these events feature talks by renowned scientists, research and outreach presentations by undergraduates, and other activities that bring us together and build our community. They're also a lot of fun.

Zone 8 @ the University of Illinois at Urbana-Champaign

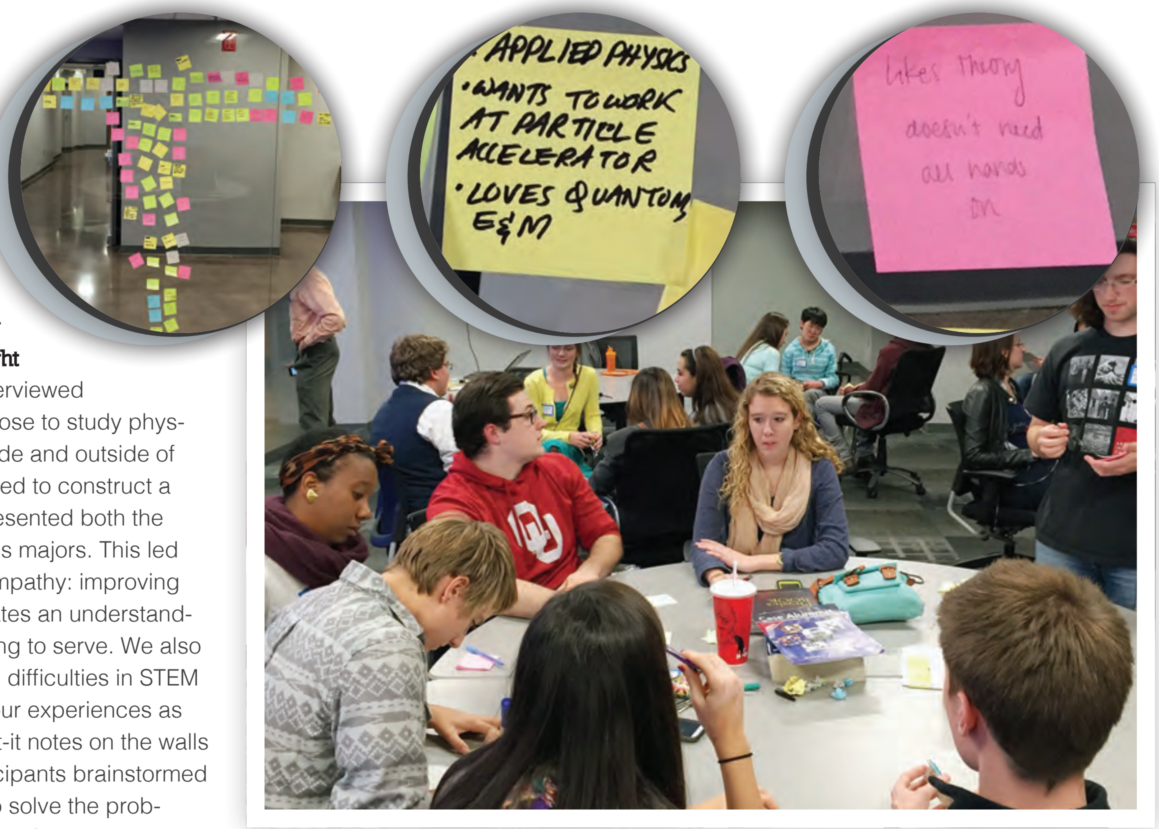
Costumes at the Halloween-themed meeting included vampires, Schrödinger cats, and the Voyager 2 spacecraft. SPS advisor and experimentalist Mark Neubauer even dressed up as the theoretical character Green Lantern. We staged a Fermi Problem Challenge that asked groups to answer order-of-magnitude questions made popular by Enrico Fermi, such as "How many humans worth of blood would be needed to feed all the inhabitants of Transylvania for the entire day of Halloween?" (answer:106), and "How many seconds could you survive buried alive in an average-sized coffin?" (answer:104).

Speakers included Nobel laureate Anthony Leggett, who talked about how during World War II he convinced a British draft board that he would make a better physicist than soldier; he went on to formulate a theory explaining that atoms in a superfluid form pairs, like the pairs electrons form in superconductive materials. Alfred Hübler, a professor who investigates nonlinear dynamics in physics, demonstrated the unusual behavior of ball bearings in corn syrup exposed to an electrical potential. Professor Aida El-Khadra talked about quantum chromodynamics, the theory that explains the strong force, and her work that quantizes space-time onto a lattice which can then be simulated by a computer in a more straightforward manner. //

TOP LEFT: Nobel Laureate Anthony Leggett talks about his experiences. **TOP RIGHT:** Attendees pause for a snapshot. **BOTTOM LEFT:** Professor Aida El-Khadra explains how her work has led to better simulations. **BOTTOM RIGHT:** Students show off their Halloween costumes. Photos courtesy of the University of Illinois at Urbana-Champaign SPS chapter.

Zone 12 @ William Jewell College

In addition to research presentations by students, talks by faculty, and a visit from SPS Director Sean Bentley, the zone 12 meeting featured a workshop that introduced the methods of design thinking and applied them to reinventing the way that physics is taught in higher education. We interviewed each other about why we chose to study physics and our experiences inside and outside of physics. The results were used to construct a T-shaped diagram that represented both the breadth and depth of physics majors. This led to a key conclusion about empathy: improving physics education necessitates an understanding of the people we are trying to serve. We also talked about challenges and difficulties in STEM education generally and in our experiences as physics students, using Post-it notes on the walls to document thoughts. Participants brainstormed freely about creative ways to solve the problems identified by their peers, after which we unpacked the solutions and thought about their potential impacts, as well as the assumptions that were made about each problem or solution. //



TOP: Post-it notes document why attendees chose to study physics and their interests. **BOTTOM:** Attendees interview each other about their experiences. Photos courtesy of William Jewell College SPS chapter.

Zone 9 @ Marquette University

The annual zone 9 meeting was held in conjunction with the Wisconsin Association of Physics Teachers (WAPT) meeting. Students, faculty, teachers, and WAPT attendees all gave talks. One of the highlights was a talk by Destin from the *Smarter Every Day* YouTube channel. He works as an aerospace engineer for the US Army's missile division. His popular YouTube channel looks at the science behind everyday things such as a falling cat, a helicopter, or the sport curling. He performed a demonstration of Prince Rupert's drops, created by dripping molten glass into cold water, and showed clips of his online videos.

Another highlight was when Father George Coyne, former head of the Vatican Observatory, gave a talk entitled "The Dance of the Fertile Universe: Change and Destiny Embrace." He discussed his time at the observatory, the quest for understanding the origins of the universe, and the relationship between theology and the physical sciences. //

TOP LEFT: Father Coyne gives his talk. **BOTTOM LEFT:** Students show off a project to detect neurinos at the IceCube Neutrino Observatory. **ABOVE:** A still shot from a YouTube video shows Destin demonstrating the physics of curling. Photos courtesy of Marquette University SPS chapter.

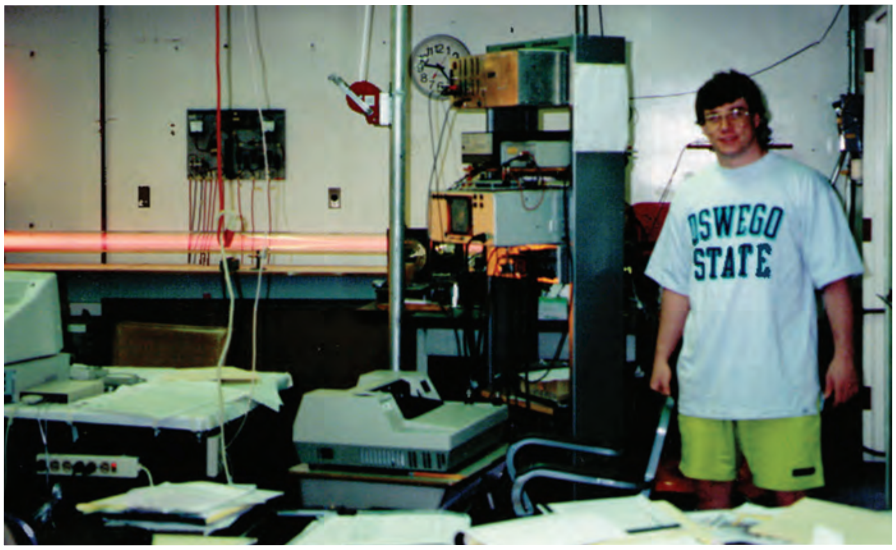
UPCOMING ZONE MEETINGS

Interested in attending a zone meeting? Check out the SPS calendar for information about upcoming zone meetings, www.spsnational.org/meetings/calendar/.

My First Research Experience

THE MOST TRANSFORMATIVE ELEMENT OF MY UNDERGRADUATE EDUCATION

by Michael Jackson
Professor of Physics, Central Washington University, Ellensburg
Physics and Astronomy Division Chair, Council on Undergraduate Research



SUMMER OF '92. A young Mike Jackson poses for a photo in the laser spectroscopy lab at SUNY Oswego. Photo by Robert Jackson, Jr.

Without a doubt, the summer of 1990 was the most transformative, influential, and memorable period of my undergraduate education. It was the summer after my second year in college; the summer I got my start in research.

During my sophomore year I had been having doubts about my academic trajectory. I was performing reasonably well in my physics classes at the State University of New York at Oswego, nestled on the shores of Lake Ontario. But I had come away from my courses feeling that I could not apply what I had learned to anything.

A SUMMER WITH SUDHA

As a result, I wanted to test my abilities in physics outside the classroom environment, in a lab. The question was how? I went to those I trusted most; I knocked on the doors of the physics faculty, one by one. No one I knew had any research opportunities for me, but they all recommended a faculty member whose office was at the end of the hall that I passed daily, Dr. G. R. Sudhakaran (Sudha).

I had not interacted with Sudha prior to that time, and I knew nothing about him. So it was with apprehension that I approached his office, provided him with some background information about myself, and asked if he had any research opportunities open to students during the summer. He told me to stop by the following week. I was in!

That summer my research experience focused on using a hydrogen cyanide laser and analyzing Stark spectra for methanol and its isotopologues. Sudha was a fabulous mentor. I was exposed to his research methodology, the challenges he faced, and his ways of dealing with unexpected problems. He told me stories of his time in graduate school and what life was like where he grew up in India—stories that I sometimes tell my students today. He even invited me to his home to share the joy of Indian cuisine.

THE LASTING IMPACT OF RESEARCH

Fortunately, I was able to continue working with Sudha for the remainder of my undergraduate education. He would become my PhD advisor and, eventually, my department chair when I held a faculty position at the University of Wisconsin–La Crosse. We have published nine papers together over the years, two of which came from my time as an undergraduate in his research lab.

During my undergraduate research experience, I learned how to abide by the principles of working in a lab, ask the right kind of questions, and deal with seemingly insurmountable problems that had no obvious solutions. The experience gave me the confidence later on to propose and develop my PhD dissertation topic. I was able to convey why my research needed to be funded and establish collaborations with world-renowned scientists at the University of Oxford and the National Institute of Standards and Technology. I am uncertain what else in my education could have allowed me to develop the skills to accomplish these and many other activities.

TAKING THE PLUNGE

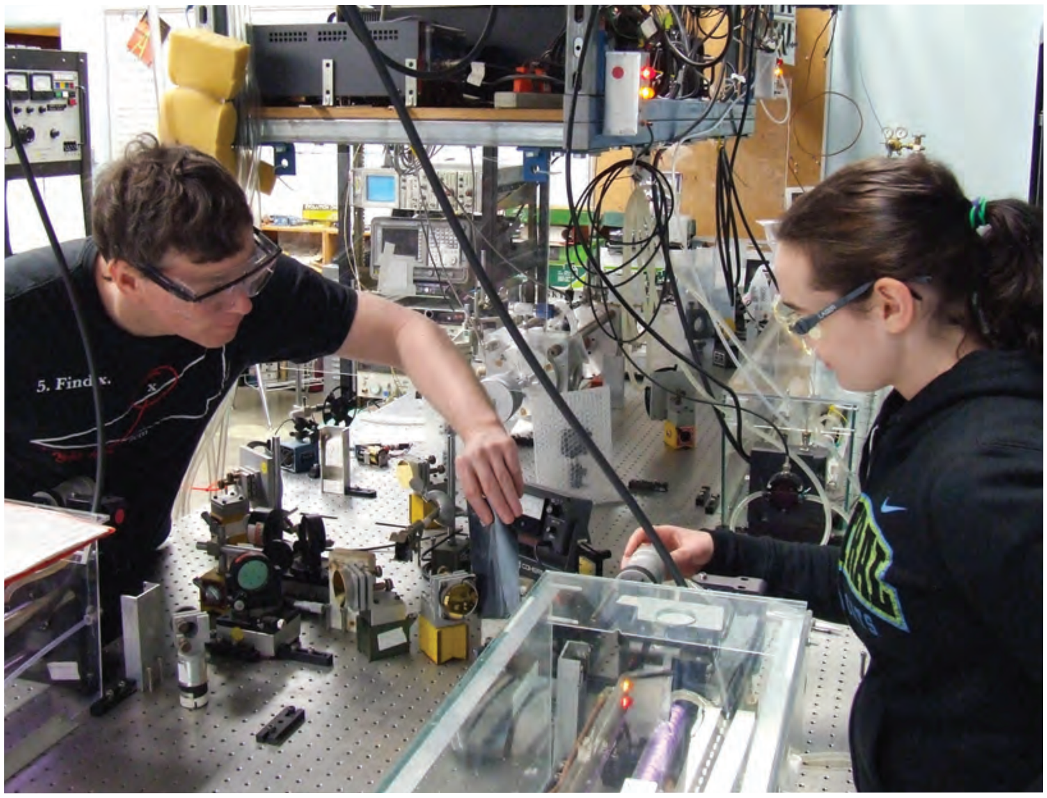
Valuable research experience can come in many forms and take place during the summer or the academic year. You might find a research position or internship, doing a project that you formulate or one that is assigned to you. The end result of your labors may be a final report, a presentation, or, if you are extremely lucky, a manuscript submitted for publication. At this point in your education, the key is to focus on exploring what interests you and as well as learning what you do not enjoy doing (which can sometimes be even more important).

Be sure to consider both on-campus and off-campus research opportunities in physics. The Research Experiences for Undergraduates program, funded by the National Science Foundation, provides summer research opportunities. National laboratories, private sector companies, and nonprofit organizations such as the Society of Physics Students offer research experiences as well. A great place to search from among many different kinds of summer research opportunities is the SPS Jobs site at http://jobs.spsnational.org.

You may also be interested in research opportunities at your school in disciplines related to physics that pique your interest, such as biology, chemistry, geology, mathematics, engineering, and beyond. Society's problems are seldom confined to one field. As a physicist you can bring a unique skill set to research groups in other fields, from which you will undoubtedly gain both content knowledge and skills that can help you function in an interdisciplinary setting.

How many positions should you apply for? Identifying at least six is a good start. Because many programs are competitive, applying for several enhances your chances of getting an offer. Had I not kept knocking on faculty doors, I may never have had the opportunity to work with Sudha.

If you get an opportunity, take full advantage of it. Be prepared to work through concepts on your own as well as with mentor guidance. Talk to your mentor about developing a presentation that you could give at a conference on your home campus, a regional professional meeting (like an SPS zone meeting), or a national conference such as the National Conference on Undergraduate Research (NCUR). Presentations are not only great resume builders but also great opportunities to convey science to your peers.



MIKE JACKSON and his undergraduate researcher Clarissa Gerke work in the far-infrared laser lab at Central Washington University. Photo courtesy of the author.

In collaboration with your mentor, you might also consider developing a written summary of your work, an internal report, or a publication. Scientific writing is rarely taught and yet it is one of the most important skills we expect from the community. See page 22 for tips on writing about your research.

Don't be disappointed if your opportunity consists of working under the supervision of a postdoc or a graduate student instead of a faculty member or full-time researcher. Take advantage of this option, which can provide you with a better understanding of what one actually does in graduate school and what it takes to succeed.

Finally, don't take rejection personally. There are a lot of factors that go into selecting students for research opportunities, many of which go beyond your formal academic training. Since it is hard to predict if you will be selected, I recommend taking an optimistic approach and applying for every opportunity that really interests you. You will never be selected if you do not apply.

The bottom line: Find a way to get involved! In most cases, no one will come to you with opportunities. You will need to take the first steps. Take the plunge! //

FIND YOUR RESEARCH EXPERIENCE

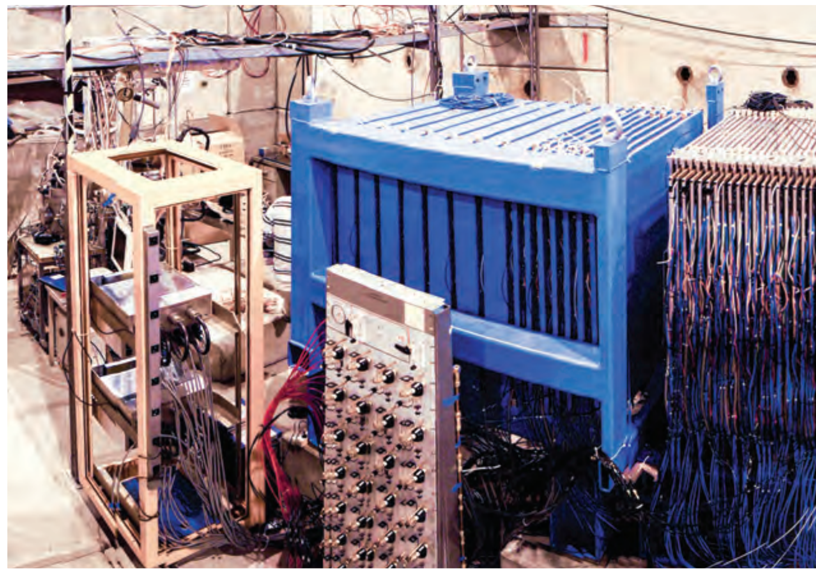
- **Check out SPS internship opportunities at www.spsnational.org/programs/internships.**
- **Search for opportunities at SPS Jobs at http://jobs.spsnational.org.**
- **Find an REU at www.nsf.gov/crssprgm/reu/reu_search.jsp.**
- **Land a NIST internship at www.nist.gov/surf.**
- **Apply to NASA at https://intern.nasa.gov.**
- **Check out DOE positions at http://energy.gov/student-programs-and-internships.**

THE AUTHOR takes a selfie with a quadrupole magnet at the CERN museum near Geneva, Switzerland. Photo courtesy of Nicole Johnson.

FROM COLLEGE STUDENT TO SCIENTIST

One thing can lead to another when you start down the path of research

by Nicole Johnson
Class of 2015, Coe College, Cedar Rapids, IA



THE CALICE TUNGSTEN CALORIMETER PROTOTYPE at CERN uses a resistant plate chamber with conductive glass. Photo courtesy of CERN.

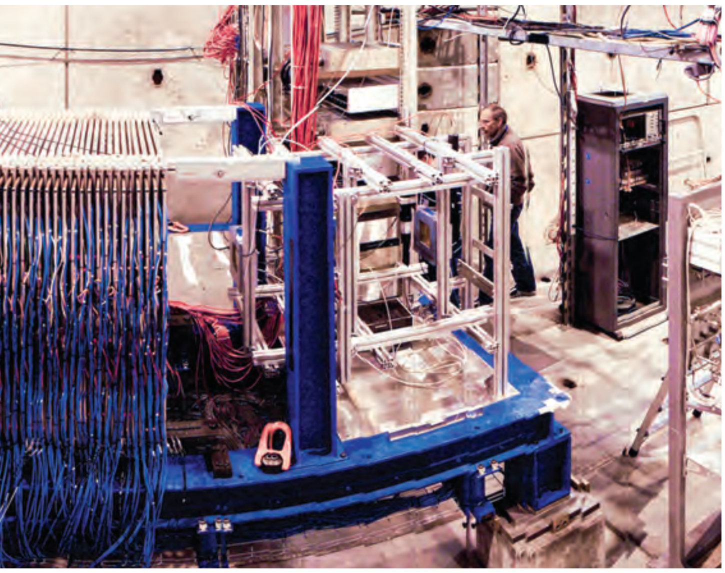
A few weeks into my freshman year at college, two of my professors talked to me about working on a project for Argonne National Laboratory near Chicago, Illinois. The project might take many years, they told me. Its goal was to develop a conductive glass for particle detectors.

I, of course, said yes. Thus began a new path in research, a path that I have followed ever since. It has led me to internships and conferences and academic journals and other things I never would have imagined a few years ago.

Coe College is known for its research on glass, so this project was a perfect fit. I started right away, working over the summer to develop a glass to use in a prototype. I even had the wonderful experience of seeing the prototypes tested. My prototypes weren't just tested in any ol' lab; they were tested at CERN near Geneva, Switzerland.

Thanks to my research, I got to travel to Europe and spend two weeks at CERN. I had the chance to control the particle beam and monitor the health of the prototypes throughout testing. The most important part of the experience was working with my collaborators face-to-face and seeing their points of view as high-energy physicists, which were much different than my perspective as someone with a materials physics background. Being at CERN inspired me to continue my education and pursue a career in research.

After my trip to CERN, I continued my project during the school year and a second summer. My advisor and I developed another glass using what we learned from the first prototype. The second



NICOLE JOHNSON proudly displays her CERN ID. Photo courtesy of Nicole Johnson.

prototype was successfully tested at the Fermi National Accelerator Laboratory in Batavia, Illinois, just in time for me to present my work at a professional conference.

It was my first conference. I wouldn't call myself a nervous person, but for a few minutes before I gave my first oral presentation I had butterflies. For the first time I was speaking to a room full of professors and professionals who all studied glass. The conference was a joint meeting in Aachen, Germany, between the Glass and Optical Materials Division of the American Ceramics Society and the equivalent society in Germany. Once I started speaking, it was exciting! It went off without a hitch, and I went on to meet experts from around the globe who were attending the meeting.

On the strength of my glass research at Coe, I applied for and was awarded a summer internship at Corning, Inc. Right after the conference, I flew straight to New York to start the internship. Corning is one of the world's premier glass companies and has developed products such as Gorilla Glass and optical fiber. (See Ethan Lawrence's story on page 20 for more details about what it's like to work at Corning.) While I was there, I had an inspiring supervisor who challenged me to ask questions and not be afraid to seek out experienced staff to find the answers I needed. Along the way, I had some wonderful mentors who helped me with everything from finding the bathroom to preparing for graduate school. My experience that summer solidified my desire to become an industrial research scientist.

"Seek the answers to the questions that inspire you."

When I came back for my final year of college, I learned that I had received the Alfred R. Cooper Scholars Award for outstanding undergraduate work in the field of glass science. Then there was more traveling! I went to Pittsburgh, Pennsylvania, to present my work at a professional conference that was even larger than my first one. Once I returned home, I started writing up my work for publication. My first paper will appear in the *International Journal of Applied Glass Science* in a few months.

Perhaps, after reading this, you are thinking to yourself, "This could never happen to me." Let me assure you that I never thought this could happen to me. I didn't even become interested in physics until my last year in high school. I didn't apply to Coe College because of physics. It just happened to be the case that Coe had a thriving physics program. I didn't even know that program existed; I applied only because I had taken a calculus class there, and the application was free.

I got my start in physics only after I told one of the professors there how interested I would be in summer research. He asked if I wanted to shadow a student researcher for a few weeks during the summer before my freshman year.

Don't ever think that research is too big, too difficult, or too demanding for you. Seek the answers to the questions that inspire you. If you accept this challenge, you will find a way to rise to the occasion. //

THE AUTHOR adjusts an oscilloscope in her laboratory at Coe College. Photo by Steven Feller.

HOW TO MAKE THE MOST OF YOUR RESEARCH EXPERIENCE

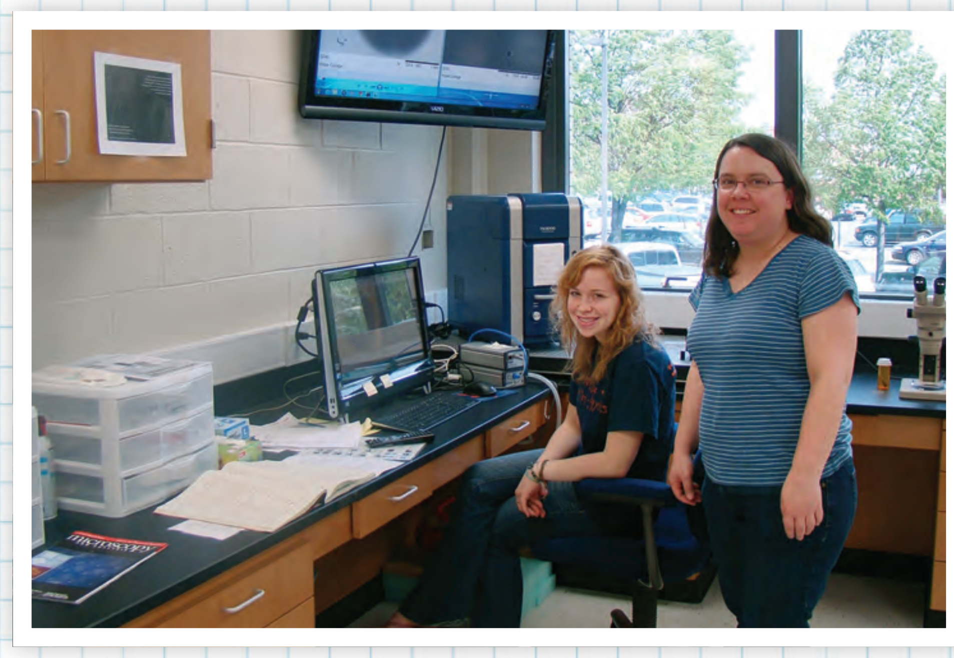
Top five habits of highly effective undergraduate researchers

by Steven Feller, SPS Advisor, Professor of Physics, Coe College, Cedar Rapids, IA
Jennifer Hampton, Associate Professor of Physics, Hope College, Holland, MI
Catherine Mader, Professor of Physics, Hope College, Holland, MI

01 **CLARIFY EXPECTATIONS.** Research is not necessarily a punch-the-clock type of job. Exactly when and how the work gets done can depend significantly on the type of project you are working on. Your advisor might expect you to be in the lab at specific times or for specific shifts, or might be more flexible about exactly when you work as long as deadlines are met. It's important to understand your advisor's expectations about your schedule and the amount of work you will be doing.

02 **DOCUMENT EVERYTHING.** Make careful, detailed records of everything in a dedicated research notebook. This includes the conditions of your experiment, analysis, or simulation, as well as the names of files and the locations where they are saved. Print things out and tape them in your notebook, if that is useful. While doing so, think about the researchers who will come after you and whether they will be able to understand what you've done. Use the lab notebook as a journal to record what you've done, as well as your thoughts about the results. It's important to record observations and conclusions (even if they are only tentative), not just raw measurement data or analysis parameters. Ideally, writing your notes and making your records should happen at the same time that the work itself is being done. It's inevitable that you will get behind from time to time, but don't let yourself get too far behind! And don't forget to add units to your numbers!

03 **REFLECT AND PLAN REGULARLY.** Regularly review what you have done and what you plan to do next. The time you spend doing this might be scheduled by your advisor (group meetings or individual/small group conversations), but even if someone hasn't developed a schedule for you, do it for yourself. It will help you to keep on track and make steady progress.



KYLA KOBOSKI (HOPE COLLEGE '14) AND JENNIFER HAMPTON work with a scanning electron microscope used by a variety of research groups at Hope College. Photo by Catherine Mader.

04 **ASK QUESTIONS.** If you don't understand something your mentor says or asks you to read, ask questions. It's important that you understand what you are doing and why you are doing it. Similarly, your mentor may ask questions of you. Don't take this as a sign of lack of trust or an indication that he or she doesn't think you are capable. Your advisor needs to understand what you are doing and why you are doing it. Your advisor also needs to be certain that you understand what you are doing and why you are doing it.

05 **TAKE INITIATIVE AND BECOME INDEPENDENT.** Learn as much about your project as possible and make as much progress as you can. Ask lots of questions. Think about the details of your project. How does what you're doing contribute to the big picture? If you're not sure of the answer, ask! Have conversations with the other people in your research group, whether they are other undergraduates, graduate students, or postdocs. Talk about all the projects in the group and how they fit together (or not!) into the bigger picture. Make suggestions on how to proceed or what steps to take next in the investigation. Be willing to make decisions on how to proceed when mentors aren't around, within the scope of your understanding of the project. //

On Doing Research:

A NOTE FROM ADVISOR TO STUDENT

Why do faculty do research with undergraduate students? It is a part of our commitment to teaching. Faculty research mentors want not only to generate new knowledge in their fields, but also help their students become researchers and continue generating new knowledge. Remember the motivation of your mentor as your research experience progresses, and treat a research opportunity as a learning experience in which you develop skills, not just as a job in which you do what you are told to do.

When you first start a research project, you will be given papers to read. You will be encouraged to help others in the group with their experiments and join group meetings. You will learn to make samples and use instruments or software. You will be given your own research notebook for recording background information, experimental details, errors, and comments on how things went with earlier work. At this stage, the student–faculty relationship is designed to be less formal than it is during class. It will involve much discussion and encouragement.

As you progress, you will become more independent. You will no longer just help others but will take on more significant roles in specific investigations. You may present findings to outside audiences, rather than contributing information to be presented by others. You may even have the opportunity to publish articles on your findings, with input from the team. You can step out of your "home base" and explore research opportunities in new groups and new institutions, or even in industry.

Once you've become a proficient undergraduate researcher, you will start to mentor younger students. When you do, reflect back on your own experience and find ways to help your mentees develop good habits like those listed on page 14. //

TALES FROM THE LAB

"I remember an undergraduate from a large university who wasn't doing well and wasn't certain he should even continue to major in physics. One of his faculty mentors convinced him he should give research a try so he could see what doing physics was all about. He then participated in the Hope College Physics Research Experiences for Undergraduates program. Not only did he do an awesome job on his projects, but he found out he really enjoyed doing physics research. He has since completed his bachelor's degree and is continuing to do exciting research while pursuing his PhD." //

—Catherine Mader

"My research depends on equipment shared by a number of groups on campus. This means that the group must be flexible with the timing of when the work is done. Communication is vital, not only between me and my students, but also among the students themselves. One time last summer, that communication began to break down, which led to a backlog in planned tasks and some frustration among the group. After talking through the issues, the students took matters into their own hands. They put together a weekly schedule on the whiteboard in the lab where everyone could record equipment-use plans for the coming days. This helped the whole group be more aware of what was coming, and helped me know what the group was doing as well." //

—Jennifer Hampton

"Several years ago a student in my lab took the initiative late one evening to make a borosilicate glass. It was a high-silica-content sample, and he kept pushing the temperature of the furnace higher and higher. Finally at around 3 a.m. he called to say he couldn't find the platinum crucible in the furnace! It took me a few seconds to comprehend what had happened, but then I told the student to turn the furnace off and check it in the morning. Josh had melted the crucible, and a small plug of platinum remained at the bottom of the furnace! I didn't mind really; the student had made much progress before that point and stumbled upon the fact that the furnace doesn't have uniform temperature. This work led to a comprehensive study of alkali borosilicate glasses." //

—Steve Feller

ISABELLA SORENSON enjoys research in summer 2014 just after her first year at Coe College. Photo by Steven Feller.

FROM THEORY TO EXPERIMENT

A view of the types of physics research

by Jess McIver, Graduate Student, University of Massachusetts Amherst

Physics research can usually be classified as theory, experiment, computation, or somewhere in between. Each type of research has its own challenges and rewards.

THEORY

Theorists use mathematics and models to explain current phenomena, predict new ones, and describe the laws of the universe. Often these researchers tackle specific problems limited in scope, such as modeling nuanced particle interactions or predicting the amplitude of gravitational waves propogating from shortly after the big bang.

EXPERIMENT

Experimentalists test theoretical predictions as well as investigate observable interactions and physical behavior. This generally involves constructing and operating instrumentation used for measurement or observation, on a scale from the rather small (equipment that fits easily inside a small room) to the very large (e.g., the Large Hadron Collider, which has a 27-km circumference). Experimental physics often leads theory, as when a new unpredicted particle is discovered. Likewise, theory often leads experimental activities.

COMPUTATION

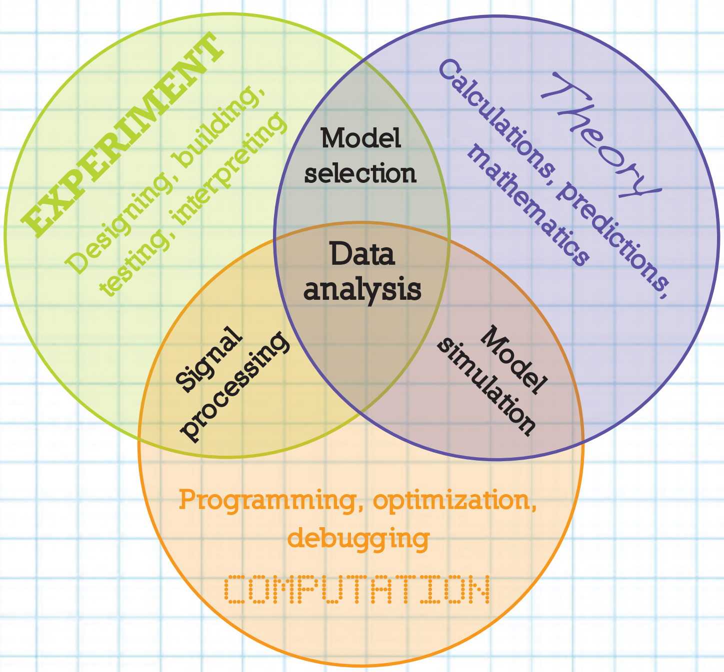
Computational physics is increasingly becoming a field unto itself. These researchers apply numerical analysis and other computational techniques to physics problems, including large-scale weather simulations, investigations of the properties of semiconductors, or models of protein folding. Computation has deep connections to both theory and experiment.

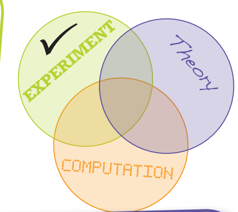
INTRODUCING LIGO

The Laser Interferometer Gravitational-Wave Observatory (LIGO) is a great example of a project that draws on different types of physics. LIGO consists of two state-of-the-art interferometers, one in Hanford, Washington, and the other in Livingston, Louisiana. They are designed to measure gravitational waves, tiny perturbations in the fabric of space-time emitted by astrophysical events great distances away.

Using strain measured by LIGO's giant Michelson interferometers, we should be able to reconstruct the signal of a passing gravitational wave created by, for example, a neutron star merger, a galactic supernova, or a pulsar. If detected, gravitational waves would be especially interesting for probing astrophysical objects and events that are difficult to observe via telescopes.

(continued on page 18)





LIGO

UNDERGRADUATE EXPERIMENTALIST

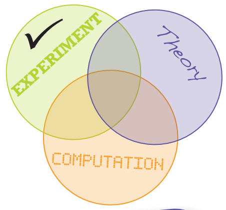
Nutsinee Kijbunchoo
Class of 2015, Louisiana State University

I worked at the LIGO Livingston site in 2014, characterizing the instruments in preparation for the first observational run of Advanced LIGO, an upgrade to LIGO scheduled to start collecting data in 2015. Being in the control room meant I was never working solely on my project, which was sometimes frustrating but also meant I got the chance to help with different projects. This way I really learned more about the interferometer and what's going on with LIGO as a whole.

Key skills. I acquired quite a few useful skills while working at LIGO. The two most important skills were Python coding and data analysis. Coding is king at LIGO, and data analysis skills are crucial for theorists and experimentalists.

Future plans. I have recently accepted a position at LIGO Hanford and will be joining the team as an operations specialist. The LIGO interferometers are very complicated instruments, and my goal is to learn as much as I can while being an operator there. After that, I plan to go to grad school to pursue LIGO-related research.

LIGO All-Stars



LIGO

EXPERIMENTALIST

Josh Smith

Assistant Professor of Physics
California State University, Fullerton

In our lab in California, undergraduates and master's students characterize the laser-light scattering properties of optics for gravitational-wave detectors.

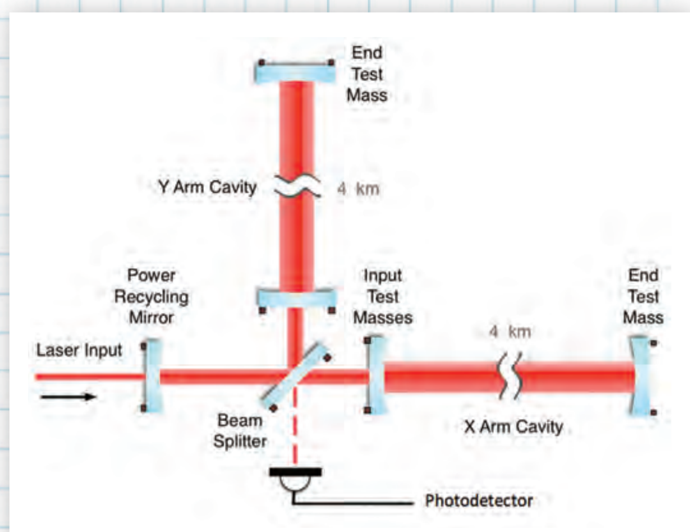
Key skills. For the experimental design and analysis, we use skills learned in the undergraduate-level optics textbook *Optics* by Eugene Hecht for many experiments. In addition, we use scattering theory from books like *Optical Scattering* by John Stover. For analysis of the data, we use MATLAB programming.

Daily challenges. We want to measure the intrinsic scatter of samples. If the optics are not pristinely clean, we measure the scatter of dust or residue instead. So we spend a lot of time in a clean room wearing clean room apparel and cleaning the optics using ultrapure methanol and dust-free optic wipes.

Advice to students. Speak with other students involved in research you want to do, and see if they like it.

LIGO *All-Stars*

LIGO USES MICHELSON INTERFEROMETRY TO MAKE VERY PRECISE MEASUREMENTS. As shown in this simple schematic, a laser beam is split and any difference in length between the two arms is observed as a change in phase of the light. This signal is translated to gravitational-wave strain. Image courtesy of LIGO.

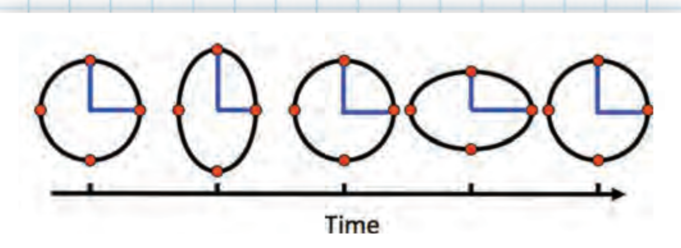


FABIAN MAGAÑA-SANDOVAL, a former student at California State University, Fullerton, measures scattered laser power. Photo courtesy of Matt Gush (CSU Fullerton).

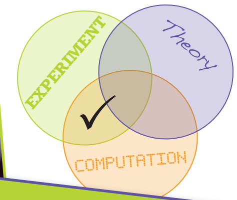
(continued from page 16)

Experimental physicists from around the world design, test, and install the cutting-edge technology that makes the interferometers work, from optic cavities and coatings to systems that isolate the optics from the constantly moving ground. Reading out the data that LIGO produces, calibrating it correctly, transmitting it for immediate analysis, and storing it all for future use requires an enormous amount of computing power. To search for small signals in that noisy data, data analysts blend theory, experiment, and computation techniques to build algorithms that search for different types of gravitational-wave signals. An especially powerful method compares the data with gravitational-wave templates generated with known astrophysical models, supplied by theorists and computational theorists called numerical relativists. It's an enormously complicated project with many different specialties.

The scientists of the LIGO Scientific Collaboration are a diverse group at different stages of their careers, based at institutions big and small, focusing on many types of physics research that are all integral to the goal of observing new astrophysics from gravitational waves. //



A GRAVITATIONAL WAVE INCIDENT on the plane of this paper would stretch and squeeze spacetime as shown for polarized waves (not to scale!). Image courtesy of LIGO.



LIGO

DATA ANALYST

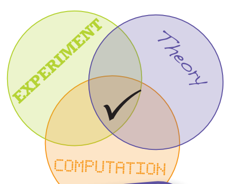
Nelson Christensen
Professor of Physics
Carleton College

I am searching for stochastic gravitational waves produced in the big bang. I also spend a lot of time investigating noise in LIGO.

Key skills. My PhD advisor said you need to know everything about everything. It's true. With LIGO and gravitational-wave detection, I use programming, statistics, data analysis, optics, general relativity, cosmology, seismology, geophysics, electronics . . . the list of skills never seems to end.

Advice to students. Just do it! See what your professors are doing and find the topic you are most interested in. Then bang on their doors and ask for a research project. Don't take "No" for an answer. Get started on a project, no matter how small, and build on that. Undergraduate research experience is important. So are internships. Put the books down and get your hands dirty in a field that interests you.

LIGO All-Stars



LIGO

THEORETICAL COMPUTATIONALIST

Sarah Gossan
Graduate Student
California Institute of Technology

I work on trying to infer the core-collapse supernova explosion mechanism using state-of-the-art simulations of core-collapse supernovae. All electromagnetic signals from core-collapse supernovae originate from the outer layers of the progenitor star, and so to look at what is going on in the central engine, one must observe emissions in gravitational waves and neutrino messengers.

Key skills. Bayesian statistics! I develop statistical techniques and software to infer information about the physical parameters describing the supernova progenitor star, so great programming skills and thorough knowledge of supernova physics are essential for me.

Daily challenges. Without a doubt, signal processing. To extract information from gravitational waveforms, lots of processing must be carried out, and so extensive knowledge of signal processing methods is invaluable to me on a day-to-day basis.

LIGO All-Stars

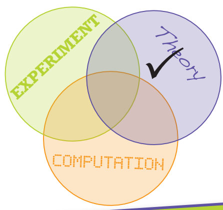
LIGO LIVINGSTON. Photo courtesy of LIGO.

MORE INFORMATION

- Learn more about LIGO at www.ligo.org/.
- Apply for the LIGO Summer Undergraduate Research Fellowship at www.ligo.caltech.edu/LIGO_web/students/SURF/.

EXPERIMENT + COMPUTATION → **Extraction of new astrophysical information from gravitational wave signals.** ← COMPUTATION + *Theory*

- Small-scale experiments, advancing instrumentation technology.
- Design and installation of Advanced LIGO.
- Observation and data collection.
- Design of data analysis pipelines using modeled signals, or known properties of gravitational waves.
- Generation of gravitational wave signal models, or other predictions.



LIGO

THEORIST

Lorenzo Sorbo
Associate Professor of Physics
University of Massachusetts Amherst

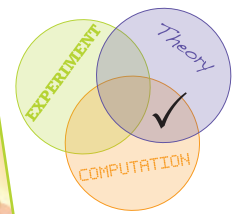
I am particularly interested in primordial inflation, a period of very fast expansion during a tiny fraction of a second after the big bang, when, among other things, a large amount of gravitational waves might have been produced.

Daily challenges. Carrying out long paper-and-pencil calculations in the context of general relativity and quantum mechanics can be tricky. We stop from time to time to make sure that the solutions we get agree with what physical intuition would tell. When this does not happen, the fun part begins: Is the calculation wrong, or was our intuition wrong?

Motivation. At the undergraduate level, an interest in theory often starts with a fascination for "the most beautiful theory in physics." Sometimes you get to theory through cosmology. At a later stage of education, interest in the purely mathematical aspects of theory can also come up.

Advice to students. Accept the fact that progress in research is slow and that most of the time the work you will do is not very glamorous. Make sure that you enjoy the process more than its outcome.

LIGO *All-Stars*



LIGO

NUMERICAL RELATIVIST

Deirdre Shoemaker
Associate Professor of Physics
Georgia Institute of Technology

I collide black holes for a living! Basically, I do the theoretical (computational) predictions of what gravitational waves will be emitted when two black holes collide.

Key skills. Programming, statistics, writing, speaking, time management, knowledge about gravitational waves, relativity, partial differential equations, and general relativity.

Daily challenges. The really important research goals do not have a fixed deadline, while the less important tasks often do. The problem then becomes getting the important research done without dropping the ball on the little tasks.

Advice to students. Be persistent! I have about five to ten students a year request to work with me. I cannot accommodate that many in my group; however, the students who stop by frequently to chat about research are the ones most likely to get into my group. Seek out faculty, find out what they do and what interests you, and then engage them.

LIGO *All-Stars*

IN MEMORY

The editorial staff of *The SPS Observer* would like to express our deepest sympathies to the students and colleagues of Cristina Torres, who passed away on March 9, 2015. Dr. Torres, a 37-year-old native of Harlingen, Texas, was a research assistant professor of physics at the Center for Gravitational Wave Astronomy (CGWA) at the University of Texas at Brownsville (UTB) and a member of the LIGO Scientific Collaboration. She received her BA in physics from UTB in 1999 and her MS in physics from the University of Texas at El Paso in 2001. After earning a PhD in physics from the University of Texas at Dallas in 2007, she was a senior postdoctoral researcher at the California Institute of Technology in the LIGO Laboratory. At the time of her untimely departure she was UTB's SPS chapter advisor. Her love for science inspired those around her. Our thoughts are with her colleagues, students, and loved ones. //

COMPANY MAN

An industrial internship shapes student's career

by Ethan Lawrence
Graduate Student, Arizona State University, Tempe

At the end of my junior year in college, I accepted an internship at the glass company Corning, Inc., in Corning, New York. I had already done two summers of glass research in academic settings, at Coe College, where I was an undergraduate, and at the University of Manitoba. However, I did not know what to expect from a Fortune 500 company.

THE AUTHOR TESTS A GLASS SAMPLE IN THE LAB.
Photo courtesy of Ethan Lawrence.

Now that I am a graduate student, I realize what a luxury it was to be able to do research in both an academic and an industrial setting. The industrial research experiences at Corning—and, later, at the avionics and information technologies company Rockwell Collins—helped me to decide what direction I want my life to take after I receive my PhD.

When I started at Corning, one thing I noticed right away was that this large company had a lot of resources at its disposal. There were many tools and microscopes I could use to characterize samples at Corning that we didn't have at Coe. For example, I was able to use a scanning electron microscope and learn a lot about electron microscopy. In academia, research funding comes primarily from grants, and professors always seem to be searching for research money. At Corning, funding for glass research seemed abundant. I enjoyed having the flexibility to request resources to add extra tests and materials to my experiments.

> "Someone with a fresh perspective can often spot a simple solution to a problem."

The biggest challenge of being in industry was learning to adjust to the atmosphere. As a student in academic research your colleagues are also your classmates. They are often your age and experience level. As an intern in a company setting your colleagues are typically older and more experienced than you. When I joined a group at Rockwell Collins I was the youngest member by 10 years. Everyone else had years of experience in the company, and it was intimidating to be working with them. I was afraid to speak my mind at first, because I felt that I didn't know anything compared to them. As I started to find my way around and became more comfortable, I realized that I was actually able to contribute.

My colleagues and supervisor taught me that anyone has the potential to contribute to a project; every person has his or her own unique perspective on things. Someone with a fresh perspective can often spot a simple solution to a problem that has evaded someone who has been working on it for a very long time. Once I felt comfortable and gained confidence, I was able to cut costs by designing new test equipment that moved the project forward.

Management styles and deadlines are very different in an industrial setting, as well. Professors know that students have classes and other matters to worry about, so academic research tends to be more relaxed. Even when doing summer research at my college, I felt like it was still a very relaxed atmosphere in which to work. However, at the company I was seen as an employee. I was held responsible and expected to perform at a high level to contribute to the overall good of the company. My managers instilled a sense of urgency to finish tasks. Deadlines were enforced. Fortunately, I am a goal-oriented person, and these deadlines appealed to my work style.

I believe the biggest advantage of working in an industrial setting is networking. While at Corning I was able to meet top executives and influential scientists during luncheons and other events that were put on by the company. One instance that stands out is the time I met the inventors of Gorilla Glass. I talked to them about how the glass that is now a part of so many smartphones became a reality. It was somewhat surprising to hear about the number of failed attempts that were made in search of the correct technique to create the ultrastrong glass. Being able to meet influential people provided opportunities for me to gain inspiration and learn from the trials and errors of others.

Working in industry is a very different experience from doing research at a university. It may or may not be for you. My own experiences convinced me that I would enjoy a future in industrial research. I plan to find a job in the fuel cell industry once I graduate with my materials science PhD. //

Photo courtesy of Corning.

GORILLA GLASS samples. Photo courtesy of Corning.

FIND RESEARCH OPPORTUNITIES ON SPS JOBS

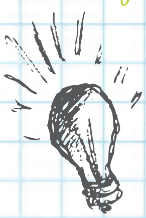
SPS Jobs is the ideal place for undergraduates to find exciting job opportunities in science and engineering fields. Hundreds of current bachelor-level physics and engineering jobs are published in a searchable database each month in the industrial, academic, national laboratory, and nonprofit sectors. Exciting summer internships and Research Experiences for Undergraduates (REUs) are listed and available for students still pursuing their degree who want to gain useful real-world experience. Job seekers registered with SPS Jobs can easily create job alerts notifying them of new listings that fit any number of specific criteria, and may also post their resume or CV to the site to simplify online applications. SPS Jobs also features an ever-expanding Career Resources section, offering job seekers helpful tips to assist them in the sometimes daunting job-hunting process. Information from SPS members detailing their own research experiences is available to provide students with an idea of the varied career paths that may be taken with a physics degree. In addition, the SPS Jobs resource library will soon include online expert career advice, document templates, and webinars geared specifically toward helping the scientific job seeker demonstrate his or her potential to hiring employers. In 2015, webinars will include such topics as how to interview, what to do as graduation approaches, and how to make the most of attending a scientific conference. Stay tuned! //

MORE INFORMATION

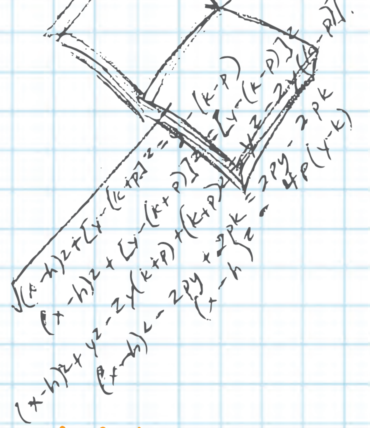
Visit SPS Jobs, search for opportunities, and make a profile at http://jobs.spsnational.org.

Explore career resources at http://jobs.spsnational.org/resources.cfm.

Read about the experiences of other SPSers at www.spsnational.org/jobs/career-information-current-students.



RESEARCH COMMUNICATION 101



Six tips for communicating your research project outside of the lab

by Justin Peatross, Professor of Physics, Brigham Young University, Provo, UT
Michael Ware, Associate Professor of Physics, Brigham Young University, Provo, UT

As a physics student, you rightfully spend most of your time assimilating centuries of general physics knowledge, which your professors try to cram into your brain in four years. Acquiring this foundation is your top academic priority. But in the midst of absorbing all of these "old" ideas, you also need to foster the skill of originating new ideas.

At the next level (graduate school or a job), one's creative skills differentiate excellence from mediocrity. Nobody solves textbook problems or takes exams for a living. Soon, others will judge you on your research initiative, your imagination, and your ability to communicate in writing and in presentations.

01 TAKE FULL ADVANTAGE OF EVERY OPPORTUNITY TO IMPROVE YOUR COMMUNICATION SKILLS. When professors require you to write reports or a senior thesis, they add a significant burden to themselves by agreeing to mentor you and edit your reports. They know that writing is essential, and good writing comes only with experience. When participating in a research group, seek to publish with your advisor in an academic journal or to present a talk or poster at a professional meeting. Some professional meetings even sponsor travel for undergraduates. It never hurts to inquire.

02 START THE WRITING PROCESS AS SOON AS YOU IDENTIFY YOUR PROJECT, EVEN BEFORE YOU HAVE RESULTS. If you can't write about your project, you probably haven't done enough homework in defining it. Writing can expose weaknesses in your plan and force you to get some real ideas. Writing will clarify the scope and direction of your project.

03 WRITE AS MUCH AS POSSIBLE AS YOU DO YOUR RESEARCH. Begin by outlining section titles of your document and by sketching in information as you gather it. Describe the motivation for your research. Place it in the context of prior work. Make a list of references as you read academic papers and give appropriate credit as you summarize the works of others. Not doing so is a form of plagiarism.

04 OBTAIN FEEDBACK AT EVERY STEP. Go over your outline with your research mentor and rearrange, add, and delete sections. This is much less painful in outline form before you write full paragraphs. Make brief notes indicating what will go into each section (e.g., a summary of research by Group X, a schematic of an experiment, a blowup view of a critical component, etc.). Generate professional-looking figures, schematics, and tables while they are fresh in your mind. These will help refine the structure of your writing. Schematics and graphs should be simple, well organized, and labeled.

05 REMEMBER THAT THE SEQUENCE OF INFORMATION PRESENTED IN EACH SECTION AND PARAGRAPH SHOULD FOLLOW A LOGICAL FLOW. Continually ask yourself which paragraphs and sections should appear before others. Use a key sentence in each paragraph, usually near the beginning, to define the ideas that the paragraph conveys. Don't hesitate to split long paragraphs at logical places.

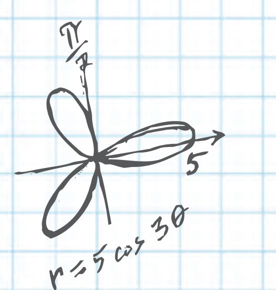
06 EDIT YOUR WORK. Learn to fix mechanical and grammatical errors yourself. If you think you don't have a problem, ask yourself whether you understand the difference between "effect" and "affect." Should the period in the previous sentence be placed before or after the quotation mark? Have your work reviewed by someone in your campus writing center or a writing tutor. You don't want people to miss your message because they don't understand what you mean! Before asking others to review your document, have the common courtesy to reread it yourself first, preferably after setting it aside for some time. Expect to go through multiple drafts.

Good talks have much in common with good writing. If possible, write a report before you give a talk. It will crystalize your ideas. When introducing your talk, never underestimate the pleasure that it gives your audience to hear something they already know; if they get lost in the beginning, they will be lost for the entire presentation. Put a title or a concise descriptive sentence at the top of each slide, which helps wandering minds rejoin you. Use large fonts and high contrast (e.g., dark text on white background). Label your graphs and keep your slides free of extraneous information. Remember, the talk is not about you; don't dwell on early attempts or failures. Get to the good stuff. Speak clearly. Speak loud enough. No "uhms." Smile.

Good writing and excellent presentations require clarity of thought. Communicating your work should never be an afterthought. Everyone has experienced the frustration of being on the receiving end of poor communication. Don't be that person! No matter how well you understand physics and no matter how imaginative your research, if you cannot communicate your ideas clearly, they benefit no one. //

ADDITIONAL RESOURCES

- **AIP Publishing Author Resources Center**
- **http://publishing.aip.org/authors**



ON GROWING RESEARCH ROOTS

An undergraduate research advisor's influence lasts beyond college

by Rachael Roettenbacher
Graduate Student, University of Michigan, Ann Arbor

I was sitting in a room of about 20 graduate students recently when a visiting astronomer asked whose research projects were related to their undergraduate research. He wanted to know what had gotten us interested in our current projects. More than half of the students, myself included, proudly raised our hands.

Many of the students spoke about how their undergraduate advisors had inspired them. That was also the case for me. I love starspots, which are analagous to sunspots but on other stars. They were the subject of my first research project as an undergraduate, for which I received an SPS Outstanding Student Award for Undergraduate Research.

My affinity to starspots surely had something to do with the challenges of understanding magnetic fields and imaging techniques, but it also owed much to the encouragement of Robert Harmon, my undergraduate advisor at Ohio Wesleyan University in Delaware, Ohio. He cultivated my attachment to these dark regions of distant cool stars.

I met my research mentor as a student in his observational astronomy class. After I learned about summer research opportunities on campus, I took a chance and applied to work with him. Soon after, we began working together on my first research project.

I spent many nights observing spotted stars and my days analyzing and modeling the data I had collected. This opportunity was incredible; I was working to find answers to questions that no one knew how to definitively answer. I had little practical knowledge when I began but was encouraged to ask as many questions as I needed to. Research was different from coursework, in which the professor knew what answers I was supposed to reach. Instead, research was a collaborative effort to find the answers. I realized that I was working with Dr. Harmon rather than for him.

My never-ending list of questions about the research led to long discussions with my advisor that evolved over the semesters, from questions about how to sort through literature to conversations about what I might consider doing beyond college. In the course of these discussions, my relationship with my advisor morphed from one based solely on research to one in which I realized he was invested in my future.

The support and encouragement I received from my advisor molded my path, which led me to pursue a graduate degree in astronomy at the University of Michigan. Dr. Hamon became became an ally and role model, and I still collaborate with him. Stumbling upon someone who fed my curiosity and believed in me not only during my first research project, but at every step along my path, has been essential to the progress I have so far enjoyed.

Fostering a relationship with your advisor is an important part of an undergraduate research experience. In order to get as much as possible out of a research experience, you need to be comfortable asking questions. You should be confident in what you know and be willing to fill gaps in your knowledge. The best research advisors encourage this curiosity in students by providing opportunities to question and facilitating methods for working toward answers. Research advisors should also lead by example, by being conscientious and ethical researchers themselves. //

THE AUTHOR poses for a photo with the MDM Observatory (left) and Kitt Peak National Observatory (right). Photo courtesy of Rachael Roettenbacher.

"The support and encouragement I received from my advisor molded my path, which led me to pursue a graduate degree in astronomy at the University of Michigan."

Photo courtesy of Matthew Parsons.

In the Big Leagues

THE 35TH ANNUAL MEETING AND SYMPOSIUM OF THE FUSION POWER ASSOCIATES, DEC. 16–17, 2014, WASHINGTON, DC

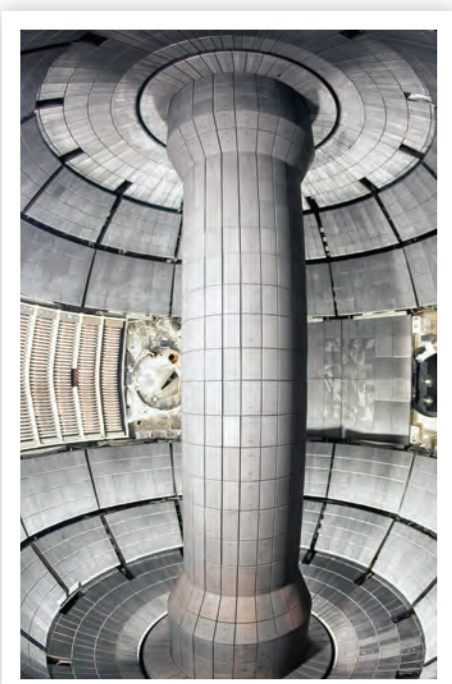
by Matthew Parsons
Class of 2015, Drexel University, Philadelphia, PA

Surrounded by fusion program managers from across the United States and around the world, I was one of perhaps five people under the age of 50 in the room of about 100 attendees. The 35th Annual Meeting and Symposium of the Fusion Power Associates was quite different from other physics conferences I have been to. It brought together research program managers from around the world who work on projects supported by huge collaborations—projects that are sometimes considered the "big leagues" of science research.

Soon after the meeting began, physicist and then-congressman Rush Holt made a brief appearance to accept an award. He is a staunch advocate for science, education, and fusion energy in particular, so his enthusiastic comments about fusion were not surprising. “We need fusion energy for our world’s future,” said Holt.

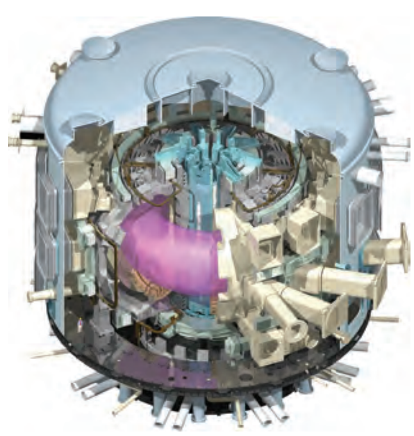
A number of presenters gave updates on the magnetic fusion energy programs of various countries throughout the world. First we heard about the European roadmap to put fusion energy on the grid by 2050, which was similar to the plans of Korea, China, and Japan that we heard about later. The first step in everyone’s plan is ITER, a multinational collaboration currently building the world’s largest fusion device. Recent highlights from ITER have included the completion of the concrete basemat for the reactor building, the arrival of the first major shipment to the site (paid for by the United States!), and the obtainment of nuclear licensing from the French Nuclear Safety Authority.

During a short break between morning sessions, I was excited to introduce myself to the US ITER project manager, Ned Sauthoff, and the head of communication at ITER, Michel Claessens. I had previously been in touch with both of them while developing a project for a Fulbright scholarship application, and it was great to be able to meet them in person.



LEFT: A photo shows the interior of the National Spherical Torus Experiment Upgrade at US Department of Energy’s Princeton Plasma Physics Laboratory (PPPL). Photo courtesy of PPPL.

BELOW: An illustration depicts the inside of the ITER experiment currently under construction in France. Photo courtesy of ITER.



NEXT UP

- **The next FPA meeting will be in December. Keep tabs on the date and on other nuclear-themed meetings at http://fpa.ucsd.edu/calendar.shtml.**

LEARN MORE

- **Check out the meeting program and presentations at** http://fire.pppl.gov/fpa_annual_meet.html.
- **Find out more about ITER at** www.iter.org.
- **Check out the US fusion program participants at** http://science.energy.gov/fes/research/fusion-institutions/.

The rest of the meeting addressed everything from inertial fusion energy to private companies pursuing the technology. Exploration of these topics is left as an exercise for the reader.

Attending this meeting reiterated for me that fusion research requires long-term planning, and that collaboration is absolutely necessary for success. For me, the idea of contributing to the success of such a significant endeavor is magnetic (pun intended), and it was reassuring to hear that fusion program managers are actively seeking collaboration.

Lastly, it was apparent that fusion is as much a political endeavor as a scientific one. As much as I love doing research, I am equally interested in the practical challenges that these large projects face. //

Matthew Parsons received an SPS Reporter Award to attend and report on this meeting. Read his full meeting article on the SPS website at http://spsnational.org/meetings/reports/.

An Exchange of Knowledge

TAKING ON THE 2014 AMERICAN GEOPHYSICAL UNION (AGU) FALL MEETING IN SAN FRANCISCO, CA, DEC. 15–19, 2014

by Jordan Eagle
Class of 2016, Radford University, VA

PRESENTATIONS IN ONE OF THE MEETING'S TWO ENORMOUS POSTER HALLS. Photo by Jordan Eagle.

The AGU Fall Meeting is one of the largest scientific conferences in the nation, with more than 20,000 attendees. Its poster hall is gigantic, with hundreds upon hundreds of presenters. But there was one poster presenter in particular who stands out in my memory.

My research team had been set up in the cryosphere section. We were presenting research findings from an ongoing study looking for a correlation between the surface temperature of Arctic Sea ice and its thickness; finding a relationship could allow us to study larger areas of ice in shorter amounts of time and with more cost-effective methods.

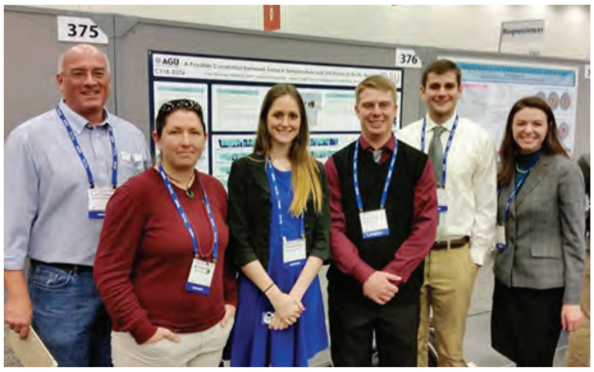
As it happened, a graduate student presenting a poster near us was studying the same location we studied, the shore of the Chukchi Sea in Barrow, Alaska. She shared with me her research about the influence of water movement on ice and her work surveying bodies of water using aerial methods. It was thought provoking to hear how this aerial data could improve our own future work.

Being able to compare results and share data with other student researchers was something new to me. Exchanging knowledge can be crucial as a scientist; new information from collaborations with other scientists allows you to make changes to your ongoing research. AGU, I learned, can be a great place for this exchange.

Walking around the thousands of posters, I had the opportunity to speak with others who had conducted research in many different fields. From radioactive elements to heliophysics to pollution in the Chesapeake Bay, the research topics included really anything under the sun.

Exhibitors were also present in the poster hall to showcase new technologies, give talks on topics such as global climate models, and discuss graduate school and career paths. At the NASA booth I was introduced to new software that was absolutely breathtaking. Developed by NASA, Eyes on the Solar System is an accurate computer model of the solar system that feels like a video game. Users can observe the motions of celestial bodies in real time and view events from 1950 to 2050, touring the past, present, and future. You can even view Voyager 1 in real time!

I look forward to further indulging my desire to learn new knowledge about the world around me at future conferences, and I encourage every student to nourish his or her knowledge and enjoy the company of colleagues and fellow scientists at conferences. //



(FROM LEFT TO RIGHT) Dr. Rhett Herman, Melissa Brett, Jordan Eagle, Corey Roadcap, Cameron Baumgardner, and Sarah Montgomery pose for a photo in front of their poster presentation. Photo courtesy of Jordan Eagle.

Jordan Eagle received an SPS Reporter Award to attend and report on this AGU meeting. Read her full meeting article on the SPS website at http://spsnational.org/meetings/reports/.

NEXT UP

The 2015 AGU Fall Meeting will take place Dec. 14–18, 2015, in San Francisco. Learn more at http://fallmeeting.agu.org/2015/. Check out other AGU meetings at http://meetings.agu.org/.

CUWiP: The APS Conferences for Undergraduate Women in Physics

HIGHLIGHTS FROM A FEW OF THE CUWIPS, JANUARY 15–17, 2015

PARTICIPANTS AT THE 2015 APS CONFERENCE FOR UNDERGRADUATE WOMEN IN PHYSICS AT THE UNIVERSITY OF TEXAS BROWNSVILLE. Photo courtesy of Ashley DaSilva.

In January, undergraduate women majoring in physics came together at eight sites across the country. The goal of these regional conferences was to help undergraduate women thrive in physics by providing them with an opportunity to experience a professional conference, to gather information about graduate schools and professions in physics, and to interact with women in physics of all ages with whom they could share experiences, advice, and ideas.

CUWiP @ the University of California, Santa Cruz

by Kayla Mendel, University of Southern California, Los Angeles

As the only woman attending the CUWiP in Santa Cruz from my university, I was excited to have the opportunity to meet other women with similar interests who are coping with the challenges associated with pursuing a career in the male-dominated field of physics. I plan to attend graduate school in medical physics this coming fall, so I was especially interested in meeting other women going to graduate school in physics disciplines.

One of the highlights for me was a poster session for students where I presented a poster about the research I did last summer at Massachusetts General Hospital in Boston. The work was made possible by the American Association of Physicists in Medicine (AAPM) Summer Undergraduate Fellowship Program. My project focused on proton therapy treatment for ocular melanoma, specifically, dose fidelity. I really enjoyed sharing my work with other people and hearing their questions and ideas. Presenting to a group of my peers helped build my confidence and made me feel more inclined to present my research at the next opportunity.

The keynote speaker of the conference, Dr. Gabriela González, gave a talk entitled "LIGO, Gravitational Waves and Me: A Wonderful Life in Physics with More to Come!" She shared her incredible journey and spoke about moving from Argentina to the United States to work at LIGO. This talk was video-cast from another CUWiP site to all of the sites across the country. Over the course of the weekend, we heard from many other inspiring female physicists. Hearing each of these women was incredibly empowering, and at the end I felt encouraged by the support of the community of women in physics.

Prior to the conference, I had felt that I was on my own navigating this male-dominated field. However, I feel better knowing that there is such a strong community of women in physics who care so much about supporting others.

CUWiP @ Duke University

by Jenny Su, Duke University, Durham, NC

At the Research Triangle CUWiP, it was incredibly interesting to get a sense of the vast number of opportunities that are available for physics students. One panel brought together female physicists with careers in areas ranging from patent law and public health to defense think tanks and Silicon Valley startups. Even though some of the work was in fields that seem far from the physics roots of the panelists, it was evident that their love of science (the reason they became physics majors) is still present in the work that they do today. Many of the panelists are still involved in the physics community, helping out at science fairs or working at planetariums. As one of the panelists said, "You don't have to be an educator to be educating." Physics is definitely not something that is relevant only to academics or researchers at national labs. The conference also focused on helping students develop workforce skills.

Another highlight was a talk by Christina Hammock, a NASA astronaut candidate, who

(continued on page 31)

NEXT UP

The 2016 CUWiPs will take place January 15–17 at the following institutions. For details, visit the American Physical Society's website at www.aps.org/programs/women/workshops/cuwip.cfm.

Black Hills State University, Spearfish, SD • Georgia Institute of Technology, Atlanta • Ohio State University, Columbus • Oregon State University, Corvallis • Old Dominion University, Norfolk, VA, & Thomas Jefferson National Accelerator Facility, Newport News, VA • Syracuse University, New York • University of California, San Diego • University of Texas at San Antonio • Wesleyan University, Middletown, CT

> "Having the opportunity to talk with the physicists invited to give talks was amazing, but simply talking to physics students from around the country helped to open our eyes to the larger physics community."
>
> *—2012 Congress attendees from Idaho State University*

Unifying Fields

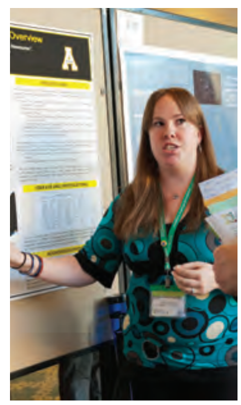
SCIENCE DRIVING INNOVATION

SAVE THE DATE: NOVEMBER 3–5, 2016

2016 Quadrennial Physics Congress

November 3–5, 2016 • Silicon Valley

Hosted by Sigma Pi Sigma, the physics honor society



Once every four years hundreds of physics students, faculty, and Sigma Pi Sigma alumni from all walks of life gather for the Quadrennial Physics Congress. They spend a packed weekend making new connections, interacting with scientists and distinguished speakers, debating common concerns for the discipline and society, and touring iconic scientific venues. Make plans now to attend the 2016 Congress in California's Silicon Valley!

Confirmed Speakers

Jocelyn Bell Burnell
Eric Cornell
Persis Drell
S. James Gates

Confirmed Tour Sites

SLAC National Accelerator Laboratory
NASA's Ames Research Center

Interactive Workshops... Poster Sessions... Art Contest... More details to come!

Complex Numbers Have Real Uses

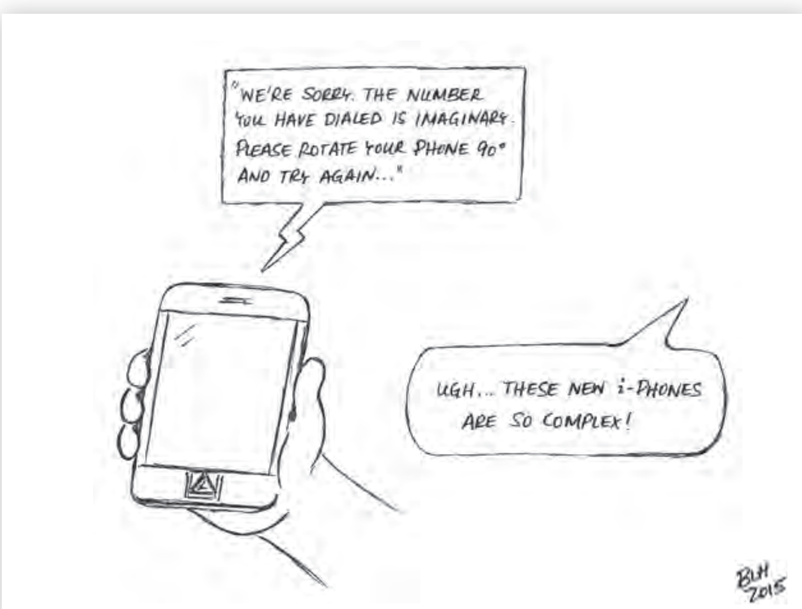
by Dwight E. Neuenschwander
Professor of Physics, Southern Nazarene University, Bethany, OK

Complex numbers are not widely used in introductory physics. When we start taking upper-division courses in mechanics, optics, electrodynamics, or quantum physics, we may find unsettling the ubiquitous use of complex numbers. How can the imaginary number *i*, the square root of −1, have anything to do with the *real* world? Let us consider a scenario from introductory optics.

Consider two point sources of waves that emit monochromatic radiation of wavenumber k and angular frequency ω. Let the two sources emit coherently and in phase. At time t an observer receives at her location the superposition of the two signals. Suppose the wave from source 1 travels the distance r to the observer at point P. Let the wave from source 2 travel the distance $r + \Delta r$ to P. Assume both waves arrive at P with the same amplitude.[1] The observer at P receives the signal

$$\psi(P,t) = A[\cos\theta + \cos(\theta+\delta)] \qquad (1)$$

COMPLEX NUMBERS INTRODUCE NO MYSTERIES INTO PHYSICS.
They are merely a language.



Bobby Logan Hancock.

where $\theta \equiv kr - \omega t$, and $\delta = k\Delta r$ denotes the phase difference between the two waves upon their arrival at P. The standard way to write Eq. (1) in a readily interpretable form employs the trick of adding zero to the first cosine's phase, $\cos\theta = \cos(\theta + \tfrac{1}{2}\delta - \tfrac{1}{2}\delta) \equiv \cos(\varphi - \tfrac{1}{2}\delta)$ where $\varphi \equiv \theta + \tfrac{1}{2}\delta$, and writing the second cosine as $\cos(\theta + \delta) = \cos(\varphi + \tfrac{1}{2}\delta)$. With the assistance of the trig identity $\cos(\alpha \pm \beta) = \cos\alpha\cos\beta - \sin\alpha\sin(\pm\beta)$, one derives

$$\psi(P,t) = \left(2A\cos\frac{\delta}{2}\right)\cos\left(\theta+\frac{\delta}{2}\right). \qquad (2)$$

Another method for deriving Eq. (2) from Eq. (1) uses phasor diagrams, introduced in general physics textbooks. When adding two (or more) cosines as in Eq. (1), one pretends the equation to be the x-component of a vector equation, constructs the corresponding vector sum, draws the resultant, and takes the x-component of that resultant. Phasor diagrams are complex numbers in disguise. Using complex numbers we can derive Eq. (2) from Eq. (1) in two lines.

A QUICK REVIEW OF COMPLEX NUMBERS

Let us refresh our memory of the complex number. Its central character is i, whose square *by definition* equals -1, $i^2 \equiv -1$.[2] Most of us met i when solving quadratic equations,

$$z^2 + pz + q = 0 \qquad (3)$$

with real numbers p and q. By completing the square we derived the generic solution

$$z = \frac{1}{2}\left[-p \pm \sqrt{p^2 - 4q}\,\right]. \qquad (4)$$

If $p^2 - 4q < 0$, by writing $x = -p/2$ and $y = \pm\tfrac{1}{2}\sqrt{(4q - p^2)}$ and noting that x and y are real numbers, we are led to the invention of complex numbers that have a real part x and an imaginary part y:

$$z = x + iy. \quad (5)$$

I suppose the difficulty in accepting complex numbers for use in physics problems comes from the word "imaginary" attached to i. But when we reflect on this word, we realize that *all* numbers are products of the imagination. For instance, the number zero, with its symbol and rules for its use in mathematical systems, was invented twice—once in India, once again by the Maya. It's a rather abstract concept, the notion that *nothing* can be represented by a *number*. Before any numbers can be applied they must first be invented as concepts.

The complex number $z = x + iy$ can be plotted on the xy plane. Call the x-axis the real axis and the y-axis the imaginary axis. Two complex numbers are equal, $a + ib = p + iq$ (where a, b, p, and q are real), if and only if $a = p$ and $b = q$. Anything that can be mapped on an (x,y) coordinate grid can be expressed as complex numbers, since the ordered pair (x,y) and the vector $\mathbf{r} = x\mathbf{i} + y\mathbf{j}$ exists in a one-to-one correspondence with the complex number $z = x + iy$.

The distance from the origin (0,0) to (x,y) is $\sqrt{(x^2 + y^2)}$. In the language of complex numbers, this length is not the square root of z^2, because $z^2 = (x+iy)^2 = (x^2 - y^2) + 2ixy$, which is another complex number, not a single non-negative real number as any length must be. To define the distance from the origin to the complex number z, it is convenient to introduce the complex conjugate of z, denoted z^*, defined by $z^* = x - iy$. The distance from the origin to z is $|z| = \sqrt{(z^*z)} = \sqrt{(x^2 + y^2)}$, the "modulus" of z.

The point (x,y) in the plane can also be mapped in polar coordinates. Let r be the distance from the origin to (x,y), and let the line from (0,0) to (x,y) make the angle θ with respect to the positive x-axis. From the definition of cosine and sine we have $x = r \cos\theta$ and $y = r \sin\theta$. Now the complex number $z = x + iy$ can be written

$$z = r(\cos\theta + i \sin\theta). \quad (6)$$

The feature of complex numbers that makes them wonderful is Euler's formula:[3]

$$e^{\pm i\theta} = \cos\theta \pm i \sin\theta. \quad (7)$$

It follows that the trig functions can be written in terms of complex exponentials:

$$\cos\theta = (e^{i\theta} + e^{-i\theta})/2 \quad (8)$$

and

$$\sin\theta = (e^{i\theta} - e^{-i\theta})/2i. \quad (9)$$

With Euler's formula we may also write a complex number of modulus r and phase θ in the polar form

$$z = r\,e^{i\theta}. \quad (10)$$

Trigonometry identities tricky to prove by standard methods often become easy when the sines and cosines are written as complex exponentials. For example, consider

$$\sin\theta \cos\theta = \frac{(e^{i\theta} - e^{-i\theta})}{2i}\frac{(e^{i\theta} + e^{-i\theta})}{2}. \quad (11)$$

After multiplying out the exponentials it follows at once that $\sin\theta \cos\theta = \frac{1}{2}\sin(2\theta)$.

COMPLEX NUMBERS, AN INCISIVE TOOL OF PHYSICS

Let us return to our two waves and derive Eq. (2) from Eq. (1) using complex numbers. Equation (1) is the real part of

$$\psi(P,t) = A\,(e^{i\theta} + e^{i(\theta+\delta)}) \quad (12)$$

(the imaginary part is redundant, also true with phasor diagrams). Factoring out $e^{i\theta}\, e^{i\delta/2}$ turns Eq. (12) into

$$\begin{aligned}\psi(P,t) &= Ae^{i\theta}\, e^{i\delta/2}\,(e^{-i\delta/2} + e^{i\delta/2}) \\ &= 2Ae^{i\theta}\, e^{i\delta/2} \cos\left(\tfrac{\delta}{2}\right), \quad (13)\end{aligned}$$

and its real part is Eq. (2), QED.

Because the complex plane and the xy plane express the same information, any mechanics problem that can be solved in the plane can be solved with complex numbers. Projectile problems spring to mind as an illustration. Write Newton's second law in complex variables language as

$$F = m\frac{d^2z}{dt^2} \quad (14)$$

where $z = x + iy$. In a projectile problem without air resistance the force F is represented by the complex number $0 - img$. Separate Eq. (14) into its real and imaginary components and integrate twice to get the familiar $x(t)$ and $y(t)$. Notice that the complex numbers are not "doing anything" to the principles of physics or to the space in which the motion occurs; complex numbers merely offer another way to encode information. As another illustration, the position vector $\mathbf{r}$ of a particle moving in a plane may be expressed as the complex number $z = re^{i\theta}$. Using overdots to denote time derivatives, you can easily show the particle's velocity to be [4]

$$\dot{z} = (\dot{r} + ir\dot{\theta})e^{i\theta} \quad (15)$$

and its acceleration to be

$$\ddot{z} = [(\ddot{r} - r\dot{\theta}^2) + i(2\dot{r}\dot{\theta} + r\ddot{\theta})]e^{i\theta}. \quad (16)$$

Besides motion in a plane, any other system that has an amplitude and a phase can be analyzed with complex numbers. A driven damped oscillator moving in one dimension can be modeled in the simplest case with a linear restoring force and a damping force linear in the velocity. For motion along the x-axis, $F = ma$ becomes

$$-kx - b\dot{x} + F_d(t) = m\ddot{x} \quad (17)$$

where $F_d(t)$ denotes a time-dependent driving force, k is the spring constant, and b is a damping coefficient. For a harmonic driving force operating at frequency ω, Eq. (17) may be rearranged to read

$$\ddot{x} + 2\beta\dot{x} + \omega_o^2 x = F_o \cos\omega t \quad (18)$$

where $2\beta = b/m$, and $\omega_o = \sqrt{(k/m)}$ denotes the "natural" frequency. When the driving force is first turned on, transient effects occur, which can be handled by an exact solution to the differential equation.[5] After the transient effects damp out, the mass oscillates with the same frequency as the driving frequency, and its oscillations are phase shifted compared to the driving force. This steady-state solution can be parameterized as $x(t) = A \cos(\omega t + \delta)$. To solve the problem means to find the amplitude A and the phase shift δ in terms of the system parameters β, ω_o, ω, and F_o. In introductory treatments this is done with phasor diagrams. Because phasors are complex numbers in disguise, you may find it easier to work directly with the complex numbers. Try writing the driving force as $F_o e^{i\omega t}$ and the steady-state response as $x(t) =$

$Ae^{i(\omega t + \delta)}$. We see at once that Eq. (18) becomes

$$A[\omega_o^2 - \omega^2 + 2i\beta\omega]e^{i\delta} = F_o \qquad (19)$$

Evaluate the modulus of Eq. (19) to obtain

$$|A| = \frac{F_o}{\sqrt{(\omega_o^2 - \omega^2)^2 + 4\beta^2\omega^2}}. \qquad (20)$$

Consider the real and imaginary parts of Eq. (19) to obtain $\tan\delta = (2\beta\omega)/(\omega_o^2 - \omega^2)$. These results are identical to those obtained with a phasor diagram. This approach also applies to the analysis of AC circuits, such as the series RLC circuit.[6]

Suppose a wave suffers absorption as it travels through the refractive medium. The amplitude gets exponentially damped so that, after the wave penetrates a distance r into the medium, $A(r) = A(0)e^{-\mu r}$, with μ an empirically measured constant. Complex numbers offer an efficient vocabulary for handling such situations. Consider a monochromatic light wave moving through a refractive medium of refractive index n, so that $v = c/n$ is the speed of the wave compared to its speed c in vacuum. The phase of the wave function, $kr - \omega t$, may be written $\omega(nr/c - t)$. In terms of a trig function, the expression for the wave takes the form $\psi(r,t) = A\cos[\omega(nr/c - t)]$, or in complex notation, the real part of $A\,e^{i\omega(nr/c - t)}$. The damping can be taken into account by leaving A alone and introducing into the index of refraction an imaginary part! Replace n with $n_o + in_1$, where n_o and n_1 are real. Now the wave function becomes

$$\psi(r,t) = A\exp[i\omega(n_o + in_1)r/c - i\omega t]. \qquad (21)$$

The in_1 hits the $i\omega$, giving a damped amplitude $A\exp[-\omega n_1 r/c]$, so that the absorption coefficient is $\mu = \omega n_1/c$, and the speed of the wave is c/n_o. In the language of waves described with complex numbers, saying "this glass has a complex index of refraction" is a fancy way to say "this glass absorbs light."

Complex numbers introduce no mysteries into physics. They are merely a language. Any quantity that carries two pieces of information about magnitude and direction, or amplitude and phase, can be expressed in the language of complex numbers. In physics, complex numbers are tools that fall readily to hand.

POINTS BEYOND

In mechanics and optics, the decision to use real or complex functions is a matter of taste and convenience. The real part of the complex number describes the physical motion or signal; the imaginary part is redundant because the original fundamental equations have only real coefficients. For instance, Eq. (18) contains no imaginary coefficients from $F = ma$ itself; complex numbers only came into it when we decided to write the driving force and $x(t)$ as complex numbers.

The story is different for the de Broglie waves of quantum mechanics. The real and imaginary parts are coupled, not redundant. What is a de Broglie wave?[7] In 1924 Louis de Broglie suggested that where one may say a free particle carries momentum p, one may also say there exists a harmonic wave of wave number k, such that $p = \hbar k$, and $\hbar$ denotes Planck's constant divided by 2π. From this notion—and the earlier inverse hypothesis from Max Planck (1900) and Albert Einstein (1905) that a harmonic wave of angular frequency ω corresponds to a free particle of energy $E = \hbar\omega$—quantum mechanics was developed. The interpretation of the waves provided by Max Born asserts that a modulus squared of the wave function, $\psi^*\psi$, equals the probability density for locating the particle.

The real and imaginary parts of de Broglie waves are coupled, not redundant, because the fundamental equation of quantum mechanics, the Schrödinger equation, has an imaginary coefficient already built in. The equation has the structure $H\psi = \hbar i\partial\psi/\partial t$, where H expresses kinetic plus potential energy in terms of derivatives with respect to spatial coordinates, and in most instances we assume H to be real.[8] You can easily show that if we write $\psi = u + iv$ and assume $H^* = H$, the real and imaginary part of the Schrödinger equation respectively become $Hu = -\hbar\partial v/\partial t$ and $Hv = \hbar\partial u/\partial t$. Thus u and v are not independent or redundant, but coupled.

A deeper question asks why i appears in the Schrödinger equation in the first place. We make an argument with three points. First, a harmonic wave may be written $\psi \sim \exp[i(kx - \omega t)]$, and, in terms of the Planck-Einstein and de Broglie postulates, it becomes $\psi \sim \exp[i(px - Et)/\hbar]$. Second, notice that $p\psi = (\hbar/i)\partial\psi/\partial x$ and $E\psi = -(\hbar/i)\partial\psi/\partial t$. Third, in nonrelativistic mechanics a free particle's energy is entirely kinetic, $p^2/2m = E$. Multiply this by the free-particle wave function $\psi \sim \exp[i(px - Et)/\hbar]$:

$$\frac{p^2\psi}{2m} = E\psi. \qquad (22)$$

Now write $p = (\hbar/i)\partial/\partial x$ and $E = -(\hbar/i)\partial/\partial t$ to get the Schrödinger equation for a free particle:

$$-\frac{\hbar^2}{2m}\frac{\partial^2\psi}{\partial x^2} = \hbar i\frac{\partial\psi}{\partial t}. \qquad (23)$$

When interactions are included by the addition of a potential energy term $U\psi$, the left-hand side is customarily denoted $H\psi$ (H is called the "Hamiltonian") and U is usually real. Whether or not U is real (the presence of an imaginary part offers a way to represent the loss of probability, as in particle decays), the Schrödinger equation is *intrinsically* complex because of the original Planck-Einstein-de Broglie hypotheses, and because E is proportional to p^2.

In special relativity, in contrast, the relation between E and p for a free particle is more symmetrical: $E^2 = (pc)^2 + (mc^2)^2$, where c denotes the speed of light in vacuum. The same treatment applied to the relativistic energy–momentum relation leads to the Klein-Gordon equation of relativistic quantum mechanics (for integer-spin particles). If we went there, we would arrive at a fine vantage point to see an interesting landscape ahead. Just as complex numbers were invented to factor expressions such as $x^2 + 1$ into $(x + i)(x - i)$, in a similar manner *hypercomplex numbers* can be invented to factor a sum of squares into the square of a sum (here I speak loosely and informally). This strategy factors the Klein-Gordon equation into a pair of Dirac equations, one for particles and another for antiparticles—another version of relativistic quantum mechanics which describes spin-½ particles.

But now I am baiting you; all of this goes beyond the scope of this article, and we must leave it for another day. Going at it step by step would carry us there in the same jaunty spirit that brought us here. //

ACKNOWLEDGMENT

Thanks to Sean Bentley for reading the first draft of this article and making many useful suggestions

REFERENCES

[1] Here we neglect the $1/r$ dependence of the amplitude that normally occurs with point sources.

[2] Because electrical engineers already use i to denote electric current, they use j to denote the unit imaginary number. We won't hold that against them.

[3] Euler's formula can be proved at least two ways. Because the cosine is an even function and the sine an odd function, it is sufficient to prove the formula with the + sign. (a) Define $z \equiv \cos\theta + i \sin\theta$. Take its derivative $dz/d\theta$, factor out i, then separate variables and integrate using the initial condition $z = 1$ at $\theta = 0$. (b) Alternatively, expand $e^{i\theta}$ in a Taylor series, and compare it term by term to the Taylor series expansion of $\cos\theta + i \sin\theta$.

[4] It is instructive to compare these results to those derived conventionally using time derivatives of $\hat{\mathbf{r}}$ and $\hat{\boldsymbol{\theta}}$. See, e.g., Jerry B. Marion and Stephen T. Thornton, *Classical Dynamics of Particles and Systems,* 4th ed. (Saunders College Publishing, Fort Worth, TX, 1995), 31–34, where velocity and acceleration are worked out in terms of unit vectors for spherical and cylindrical coordinates.

[5] Transients may be handled by standard differential equation techniques, such as the method of undetermined coefficients or variation of parameters. See, e.g., Earl D. Rainville and Phillip E. Bedient, *Elementary Differential Equations,* 5th ed. (Macmillan, New York, NY, 1974), 116–126 for undetermined coefficients, 127–139 for variation of parameters. Transients may also be handled by the use of Green's functions. See, e.g., "Discrete Sources and the Continuum, and the Functions of Dirac and Green," *SPS Newsletter* (October 1996), 10–12.

[6] See, e.g., Paul Tipler, *Physics* (Worth Publishers, New York, NY, 1976), 933–934.

[7] For an interesting discussion of the de Broglie wave function being complex, see David S. Saxon, *Elementary Quantum Mechanics* (Holden-Day, San Francisco, CA, 1968), 70–71.

[8] A nonconservation of probability, as in a decay problem, can be handled by giving the potential energy, and thus H, the Hamiltonian, an imaginary part, analogous to handling optical absorption by giving the index of refraction an imaginary part.

Bobby Logan Hancock.

CUWiP *(continued from pg. 26)*

spoke to us about her exciting life. What stood out to me about Christina and her journey was her dedication to challenging herself. She inspired the audience of physics students not to shy away from things that seem intimidating, but rather to seek out opportunities where we will be "literally in over [our] heads." Her adventures exploring worldly frontiers and knowledge frontiers demonstrated what we can do if we don't let fear get in the way of our dreams.

CUWiP @ Purdue University

by Lisa McDonald, Coe College, Cedar Rapids, IA

Talks, panels, tours, and a wonderful banquet speaker carried us through a fast-paced 48 hours at the Purdue University CUWiP. While the talks were very enjoyable, covering topics from research at CERN to geodynamic modeling, the panels gave attendees a more personal chance to speak to graduate students currently working toward their masters and PhDs. During lunch on Sunday I had the opportunity to talk with one such grad student, Cassie Reuter, and find out about the research she's been conducting for her degree. She came to Purdue with the intention of doing work related to the Large Hadron Collider, but after meeting Professor Rafael Lang, she turned her attention toward the study of dark matter, specifically, investigating claims of discovered dark matter by analyzing systematic errors in dark matter detectors. Not only was hearing her talk about her work fascinating, but discovering that she had taken a year off before grad school to recuperate from her undergraduate experience highlighted the importance of giving yourself the time you need before launching into graduate studies.

The conference event that struck me the most was not a talk given by a physics professional, but one by Professor Tracey Jean Boisseau, director of women's studies at Purdue. In "Confidential Matters: The Science and the Art of Becoming Confident," she discussed the challenges women face from external forces and their internal struggles with preconceived notions of gender inequalities. She told an inspiring story about how her mother, after losing her waitressing job at age 40, enrolled in a college programming class. Today her mother works at IBM. The story beautifully illustrated the idea that we are usually our own worst enemy. If we believe in our potential as successful, intelligent physicists, nothing can stop us from achieving our goals. //

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