the SPS Observer
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Spring 2013

The Scales of SPS

HOW INDIVIDUAL AND CHAPTER INVOLVEMENT AT THE REGIONAL, NATIONAL, AND INTERNATIONAL LEVELS EPITOMIZES THIS YEAR'S SPS THEME, "SCIENCE BEYOND BORDERS: PHYSICS FOR ALL."

the SPS Observer

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www.spsnational.org/about/social_media.htm

The Scales of SPS

by David Donnelly, SPS President


Photo by Sacha Purnell.

Greetings, fellow SPS Members! Welcome to the spring issue of *The SPS Observer,* where we'll be discussing the different scales at which SPS operates—from its individual members and chapters up to the national level. We'll even hear from SPS members abroad and learn about the growing number of international chapters and how they epitomize this year's SPS theme, "Science Beyond Borders: Physics for All."

I think SPS embodies the motto "think globally, act locally." The heart of SPS is its chapters, which function as its organizational units at universities, colleges, and two-year colleges. Chapters provide structure for students at those institutions and offer new ways to become professionally engaged.

At a smaller scale, each chapter is made of members. Those diverse individuals accomplish activities ranging from community outreach and field trips to career exploration and tutoring.

At a larger scale, chapters come together as geographic zones for regional meetings that feature student presentations and activities. Many zones held meetings this spring (read about them on the SPS website at www.spsnational.org/meetings/reports/). Elected student and faculty representatives from each of the 18 geographic zones make up the SPS National Council, which is largely responsible for setting the course for the society.

Providing support from above is the national organization, which creates an overarching structure that is consistent from chapter to chapter. It generates and provides resources for chapter activities such as the Science Outreach Catalyst Kits (SOCKs), financial support for zone meetings, and SPS reporter awards that support undergraduate members reporting on national physics meetings for SPS publications. The national organization also provides scholarships, research awards, and travel grants for student members presenting research at meetings of the American Institute of Physics' Member Societies.

I hope this issue helps readers to understand the structure and scale of SPS, and motivates all members to utilize the different resources the organization offers. Continue reading to find out how you as an individual SPS member can make your own unique contribution to this awesome organization. //

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Correction: In the Winter 2012-13 issue of *The SPS Observer*, Beth Cunningham was incorrectly identified as the president of the American Association of Physics Teachers. She is the organization's executive director. We apologize for the error.

Outstanding Researchers

RECIPIENTS OF THE 2013 SPS OUTSTANDING STUDENT AWARDS FOR UNDERGRADUATE RESEARCH

Congratulations to this year's recipients, who will represent the United States and SPS and present their research at the 2013 International Conference for Physics Students, August 15-21, 2013, in Edinburgh, Scotland. Expenses will be paid by SPS and its parent organization, the American Institute of Physics. In addition, this year's two recipients each receive a $500 honorarium and $500 for their chapters and will be invited to present at an SPS Research Session during a scientific meeting in 2013-2014.

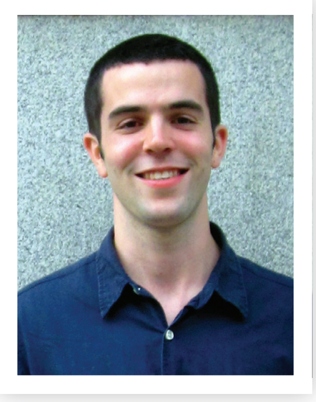

Photo courtesy of John Lurie.

John Lurie of Georgia State University in Atlanta studies solar systems around nearby red dwarf stars. He will present results from 14 years of astrometric observations by the Research Consortium on Nearby Stars (RECONS, recons.org) from a mountaintop observatory in the Chilean Andes.

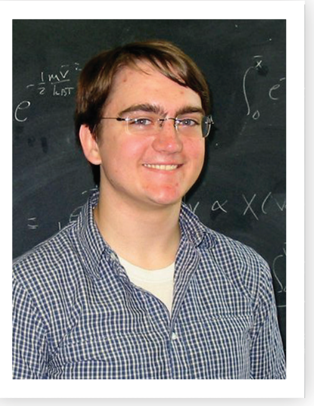

Photo courtesy of Patrick Donnan.

Patrick Donnan of Auburn University in Alabama works on a scheme for laser cooling applicable to an extremely dilute sample of magnetically trapped antihydrogen atoms (Hbar). Donnan finds that it should be possible to cool the Hbar's to ~20 mK. //

MORE INFORMATION

To learn more about the Outstanding Student Awards for Undergraduate Research and the application process, visit: www.spsnational.org/programs/awards/student.htm

To learn more about the 2013 International Conference for Physics Students (anyone is welcome to attend), visit: http://icps2013.hw.ac.uk

ON THE COVER

The Scales of SPS: How individual and chapter involvement at the regional, national, and international levels epitomize this year's SPS theme, "Science Beyond Borders: Physics for All."

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The American Institute of Physics is an organization of 10 physical science societies, representing more than 135,000 scientists, engineers, and educators. Through its Physics Resources Center, AIP delivers valuable services and expertise in education and student programs, science communications, government relations, career services for science and engineering professionals, statistical research in physics employment and education, industrial outreach, and the history of physics and allied fields. AIP publishes *Physics Today*, the most influential and closely followed magazine of the physics community, and is also home to Society of Physics Students and the Niels Bohr Library and Archives. AIP owns AIP Publishing LLC, a scholarly publisher in the physical and related sciences. www.aip.org

AIP Member Societies: American Association of Physicists in Medicine, American Association of Physics Teachers, American Astronomical Society, American Crystallographic Association, American Geophysical Union, The American Physical Society, Acoustical Society of America, AVS–The Science & Technology Society, OSA–The Optical Society, The Society of Rheology

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

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Physics Promoters

2013 MARSH W. WHITE AWARD RECIPIENTS

Marsh W. White Outreach Awards are made to SPS chapters to support projects designed to promote interest in physics among students and the general public. Congratulations to this year's 16 recipients, who each receive up to $300 in project funding. Here is a summary of their abstracts:

MORE INFORMATION

Have a great outreach project idea? Consider applying for a 2014 Marsh White Award. Proposals are due November 15, 2013. To learn more, visit www.spsnational.org/programs/awards/white.htm.

Abilene Christian University

LIGO Public Outreach Videos
The SPS chapter will write, film, and produce a new LIGO (Laser Interferometer Gravitational-Wave Observatory) video explaining general relativity to the public.

Central Washington University

Using Water Rockets to Launch Interest in Physics
Students in grades 6–12 will learn to design and construct rockets made from soda bottles, water, and other common items.

College of William & Mary

Demos in the Sun
During spring outreach events, outdoor physics demonstrations aimed at nonphysics students will highlight kinematics, propulsion, and rocketry.

Colorado School of Mines

Partnerships in Physics IV: An Exciting Catapult Outreach Project
Middle and high school students will learn about projectile motion and teach elementary students how to build small catapults.

Cleveland State University

Physics Club: Investigating Phases at Campus International School
A physics club program, begun two years ago, will expand after-school sessions at Cleveland Campus International School.

Drexel University

Physics Carnival
A carnival that includes a ring-toss game, a fun house, and ice cream frozen with liquid nitrogen will get middle and high school students excited about physics.

Eastern Michigan University

Annual Physics Building Competition
A new annual competition will challenge introductory physics students to build roller coasters.

Hartnell College

Physics Olympics
A Physics Olympics for SPS chapters and colleges in zone 18 will include events such as bridge building and egg drop competitions.

Indiana Wesleyan University

Physics Outreach Using Modern Medical Physics
Demos for students and citizens in a rural Indiana town will mix physics and medical technologies.

Rhodes College

Physics Extravaganza at Rites to Play
Bouncing magnets, air-zookas, and fire tornadoes will introduce students to physics at a college festival.

Sonoma State University

Elementary Electromagnetism in Action!
Magnetism demonstrations will inspire and educate fourth-grade classes.

University of Louisville

Updating a Display Case
An interactive display case maintained by the physics department will be upgraded to be more attractive and engaging.

Univ. of Southern Mississippi

Hubfest: Physics Outreach Day for Mississippi's Pine Belt Community
Laser demos will take place at a local community festival called Hubfest attended by 30,000 people.

University of Texas at Dallas

Rocket Competition: Physicists Versus Engineers
This SPS chapter will challenge engineering students and the public to a friendly rocket launch contest.

Univ. of Wisconsin–La Crosse

High in the Sky: An Elementary Physics Project
A high-altitude balloon project has lofty ambitions to inspire elementary students.

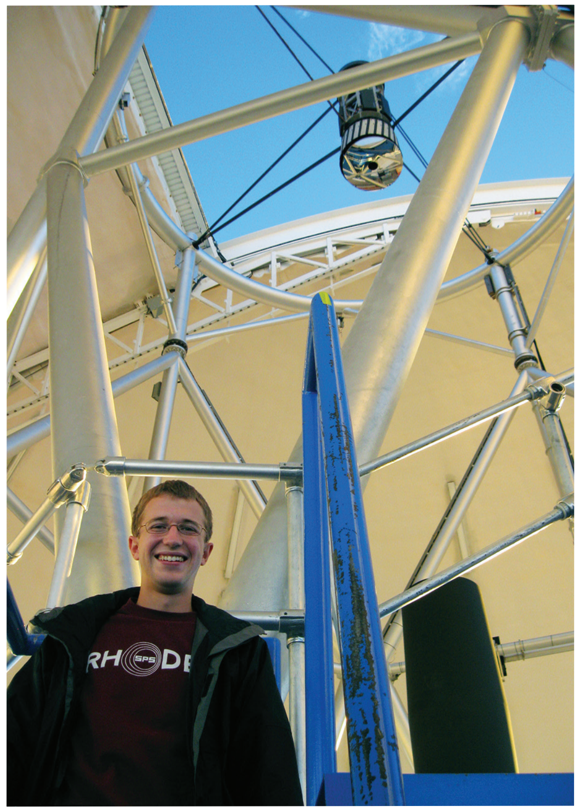
Univ. of Wisconsin–Platteville

Physics is Phantastic Phunstop 2013
Students from 25 elementary schools will be invited to a workshop that explores energy storage, conversion, and use.

Out of the Classroom, Into the Lab

TIPS FOR GETTING THE MOST OUT OF SUMMER RESEARCH

by Josh Fuchs at the University of North Carolina



THE AUTHOR stands in front of the Gemini North Telescope located on Hawaii's Mauna Kea, where he spent the summer of 2010. Photo courtesy of Josh Fuchs.

The school year is ending, and you have accepted a research position for the summer, either at your school or somewhere else. Pause for a moment. You don't want to wander blindly into it without thinking ahead about how to make the most of this opportunity.

I was fortunate to work on different research projects every summer I was an undergraduate student at Rhodes College. Those experiences taught me a great deal of physics, helped to clarify my interests, and led me to what I currently study in graduate school.

However, it was certainly not an easy path. Science never is. There are many things I learned during those summers and later on that, had I known them at the time, would have helped me make the most of my undergraduate summer research. Here are a few tips:

01 THINK ABOUT WHETHER THE PROJECT YOU'RE CONSIDERING HAS A WELL-DEFINED BEGINNING AND END. Depending on your situation, you will either be given a project to work on, or you will get to decide between a few different projects. Either way, it might be helpful to work with your advisor to write a few paragraphs about the project's motivations and goals. You want to understand the project before you get started. Try to plot the path you will follow.

02 IF YOU GET TO CHOOSE A PROJECT, DO NOT IMMEDIATELY CHOOSE THE ONE YOU KNOW THE MOST ABOUT! Remember, one of the primary benefits of undergraduate research is learning something new. If you choose a project you know very little about, it will push you in a new direction, and you might discover something new you enjoy.

03 READ UP ON THE SUBJECT YOU WILL BE EXPLORING BEFORE YOU GET STARTED. Reading abstracts of papers or sites such as Astrobites (http://astrobites.com) or Chembites (http://chembites.org/) can be helpful. But remember that you are not expected to know everything about what you will be researching. Otherwise, there would be no point to the research!

04 TAKE THE OPPORTUNITY TO TALK TO OTHER STUDENTS AROUND YOU AND LEARN ABOUT THEIR SUMMER PROJECTS. Many programs or schools organize weekly meetings; if yours doesn't, take the initiative and start meetings yourself. Something as simple as getting together once a week at lunch will help you learn a great deal and also strengthen your network and relationships with the others in the group.

05 IF YOU'RE DOING RESEARCH AT A NEW INSTITUTION, TAKE THE OPPORTUNITY TO LEARN FROM OTHER RESEARCHERS. Ask what they are doing and request lab tours. This is a great way to learn about all the variety of research projects happening at different places.

06 CULTIVATE A GOOD RELATIONSHIP WITH YOUR ADVISOR. Odds are, this person will write you a recommendation letter in the future. The best way to connect is to communicate clearly. Discuss expectations for the summer. As the summer progresses, ask for feedback so you can improve. Communication is the key to this whole process. Be open and honest.

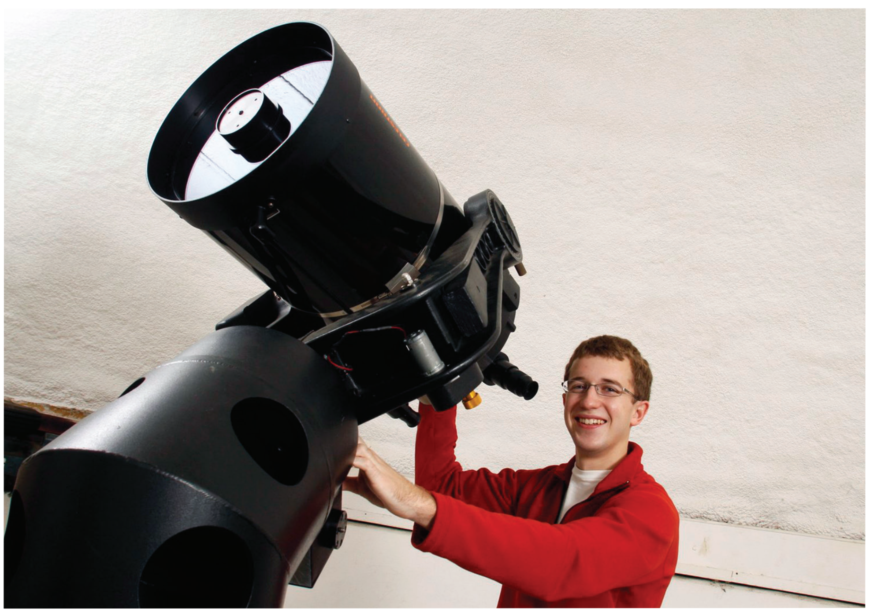
07 ASK QUESTIONS. You are there to learn, rather than to know everything at the onset. As the summer progresses, see if you can answer your own questions first. One of the most difficult things about learning to research is recognizing the progress you have made. You should ask a lot of questions early on as you learn different processes and methods. Eventually you will reach a point where you do not need to rely on your advisor for small things. It is a hard balance to strike, and one that I did not do a good job of at the beginning. But the growth you will achieve when you reach this step will be enormous.

08 EXPECT BAD DAYS. Research is hard and not always enjoyable. You will make mistakes. The best insight on research I ever heard came from the beginning of a National Science Foundation Research Experience for Undergraduates Summer Program. The director of the program told us all, "We make discoveries here everyday. Ninety-eight percent of them turn out to be mistakes." This is the nature of science.

09 SET GOALS ALONG THE WAY, SO YOU KNOW HOW THE PROJECT IS PROGRESSING. These checkpoints might change as the summer moves along, but they will help you to keep moving along.

10 PRESENT YOUR WORK AT THE END OF THE SUMMER OR AT A CONFERENCE. These are both great things to do. Communicating your science with different audiences is a skill that is imperative to learn.

11 MOST IMPORTANTLY, ENJOY YOURSELF. You are probably getting paid to do science. That is a beautiful thing. Learn as much as you can and work hard. But take some time to breathe too. Your research will suffer if you are worn out. Especially if you are in a new place, take the time for explorations outside of the laboratory and learn other things besides physics. //



JOSH FUCHS poses with the telescope at Rhodes College that he used in public outreach projects. Photo courtesy of Josh Fuchs.

BEYOND THE SUMMER

Want to publish the results of your summer research project? Consider submitting it to the *Journal of Undergraduate Research in Physics*, a peer-reviewed online journal of SPS and Sigma Pi Sigma. For more details, visit www.jurp.org.

A Revolution in Radio

SPS CHAPTER BROADCASTS SCIENCE IN EGYPT

by Gabriel Popkin, freelance science writer in Baltimore, MD

THE COSMOS RADIO TEAM produces a show. Photo courtesy of Taha Selim.

"We have many problems in Egyptian society related to the lack of scientific thinking," Taha Selim told an audience at the American University in Cairo (AUC) last summer. "Radio will be the solution." With this proclamation, the AUC physics major and SPS chapter president launched Cosmos Radio, Egypt's first on-air science programming.

Selim works with members of AUC's SPS chapter and others from the university community to record and edit programs at the university's campus in downtown Cairo's Tahrir Square. Like the crowds that gathered in the square two years ago, the

THE COSMOS RADIO TEAM hopes to launch a revolution

Cosmos Radio team hopes to launch a revolution. But this one will be about educating minds, not overthrowing regimes. "We are protesting also, but not protesting in the normal way," says Selim. "We are trying to present a real product for society that can enhance science."

The group's goal is to make people laugh while they learn. "We educate people in fun ways," says Selim, who takes inspiration from existing science radio shows such as *The Infinite Monkey Cage*, a BBC program co-hosted by a physicist and a comedian. Lacking a permanent studio right now, Cosmos Radio broadcasts mostly via the Internet. But the students behind the project have arranged for airtime on local radio stations in Cairo and hope to eventually have their own station.

The Cosmos team is putting the spirit of revolution to good use, says Mohamed Swillam, a physics professor at AUC and the university's SPS chapter advisor. "They started thinking about what they can do in order to make their country better."

Essam Heggy, an Egyptian-born space scientist who spoke about NASA's Curiosity rover on Mars for Cosmos' inaugural broadcast, agrees. He says the students are "amazingly active and motivated to bring a change to the society they live in."

But Heggy, who is also active in science outreach, cautions that reaching ordinary Egyptians may not be easy. "I think their big challenge is audience. People do not really like to hear about science. They like to hear about politicians and the solutions to their daily life." The students hope to change this situation and show how science can find solutions to societal problems.

Selim knows firsthand how difficult it can be to build an audience. Before launching Cosmos Radio, he wrote two physics books for the public; one of these won a prize in creative writing from a Cairo-based publishing house. He also organized physics seminars on relativity, the theory of everything, and the history of cosmology, and videotaped them so people could watch them online. Still, he wasn't reaching the broad audience he wanted. He found that many people don't have the time or interest to read an entire book or watch an entire lecture. Radio, Selim realized, could be different; people could tune in while doing other things, such as driving.

Fortunately, AUC's SPS chapter—the only one in the Middle East—was already a hub of physics outreach. Its events regularly drew hundreds of people, often by creatively combining science and drama in ways that proved readily adaptable to radio. In one drama written by Selim and his colleagues, entitled "The Doctor Manhattan Show," a physics professor hoping to discover the theory of everything becomes so immersed in his equations that his fiancé complains he has no time for her anymore. The physicist then calculates the solution to his dilemma: invite his sweetheart over for dinner and sing her a love song.

continued on page 8

The Teslathon

SPARKS FLY AT TESLA COIL LAB

by Jay Howson at the Rochester Institute of Technology

EXTREME CURRENTS pulsed into a small coil of wire shrank a quarter to the size of a dime. Photo by Niall O'Brien.

On October 11 the Rochester Institute of Technology SPS chapter rolled down a nondescript gravel road toward a large garage. We had arrived at the "lab" of Ed Wingate, who constructed his first Tesla coil when he was 12 and has been playing with high voltage for nearly 50 years. Every year for the past two decades, he has invited guests over for an event he calls the Teslathon.

WE WATCHED MAN-MADE LIGHTNING STRIKE **inches from our noses**

Made of steel sheets welded together and grounded, the building serves as a massive Faraday cage for the high-voltage goodies housed within. Walking inside, we saw tall coils of red magnet wire, stacks of Maxwell pulse capacitors, corona rings, and more than five large distribution transformers.

Starting off small, Wingate first demonstrated a tabletop device, a vacuum tube Tesla coil that filled the room with a low 60-hertz hum. Sparks—about 2 feet in length—sprouted from the top. Radiant fields lit fluorescent light bulbs and neon tubes several feet away.

The main event was the magnifier Tesla coil, built of three coils tuned to around 62 kHz. Wingate rolled one of the coils, 8 feet tall, to the center of the room. It burst to life with a sound so loud that ear protection was mandatory. The input power topped off at 13 kW, and the peak currents were in excess of 2 kA!

Relatively small sparks, 3 to 5 feet in length, were produced at first. Then 15- to 20-foot arcs were hitting the floor, ceiling, and garage door. Wingate kept the sparks in a localized area using a form of field control called a breakout point; think of a lightning rod, but in reverse.

Some of us stood inside the "Cage of Death," an enclosure of chicken wire. We watched man-made lightning strike inches from our noses. Up close we could see the individual paths produced by each pulse of the spark gap. Each pulse separated from the one before it as the heat of the plasma caused the ionized air to rise.

Then our host, the master tinkerer, asked rhetorically, "Is it time to shrink some

TAHA SELIM interviews an AUC student. Photo courtesy of Taha Selim.

Radio, *continued from page 7*

Meanwhile, the audience learns something about physics while being entertained. "By the end of the day people will understand the concept of superposition and the basic ideas of quantum mechanics in a very funny way," says Selim.

Cosmos Radio also draws material from the Middle East's rich scientific history. Last fall, one broadcast included a live talk by AUC science historian Karl Galle, who spoke about Abbas Ibn Firnas, a 9th-century Spanish Muslim inventor said to have made an early attempt to fly. The story goes that Firnas attached wings to his arms and jumped from a mountain; the landing was rough, but he survived. Galle's talk, heard by the 500 people attending the event and by countless more online, was part of an event centered around Felix Baumgartner's record-setting high-altitude balloon jump—a clever use of a current event to highlight a piece of science from the past.

Though less than a year old, Cosmos Radio has already taken on a life of its own. Students and professors from outside of the SPS chapter and the physics department have gotten involved, covering other scientific disciplines. New members of the team create programming in languages other than English and Arabic. The university is in the process of building the group its own studio; until now the students have been using mobile equip-

MEMBERS OF THE RIT SPS CHAPTER pose in front of one of Ed Wingate's devices. Wingate is pictured at far right. Photo by Rachel Fracek.

quarters?" He rolled out a cart with two massive series capacitors charged to 8 kJ. When the capacitors discharged, a current topping out at about 10 kA pulsed into a small coil (less than 10 turns of number 10 magnet wire) around a quarter inside small steel vault bolted shut. After this release of energy, there was no coil left—just a million tiny coil pieces. The quarter shrank—crushed by a powerful magnetic field—and was smaller than a dime!

For his last trick Wingate connected a length of hair-thin tungsten wire across the capacitors. He gave the device some extra juice, just for us. We saw a flash and heard a sound like a gunshot. There were no wires or wire bits left this time. It was an incredible experience. //

FURTHER READING

Learn more about RIT's SPS chapter:
www.rit.edu/sg/physics

ment and borrowing space where they can find it. As part of the expansion, the radio station recently became a separate entity from the SPS chapter, but the two organizations remain closely connected.

As a result of all this activity, Selim is in constant motion—updating the group's Facebook and Twitter pages, recruiting volunteers, developing new programs, and fielding interview requests. Between the radio station and his studies of advanced quantum mechanics, he sleeps an average of four hours a night and no longer takes vacations. But that's the life of a revolutionary, one who will do whatever he can to make science a part of his fellow Egyptians' daily lives.

"A lot of people think that science is only in the lab or only in the university," he says. "But actually everything around us is science." //

FURTHER READING

Cosmos Radio website:
http://pacs.aucegypt.edu/ecosmos

YouTube channel:
www.youtube.com/user/ECosmosRadio

Twitter:
https://twitter.com/ECosmosRadio

Facebook:
www.facebook.com/ECosmosRadio

Lightning Master

From an interview with Ed Wingate by Kayla Emerson at the Rochester Institute of Technology

I *hated* school! The teachers used to let me have the run of the back room where all the physics apparatus were. I kind of had special privileges, I was one of the few students they let back there. Other than that, I really didn't like school that much.

I have been building Tesla coils since I was in eighth grade, which was around 1960. I have always been interested in science and mechanics and what makes things work.

Then I got out of school, went into other things. Got a job in my hometown, then finally moved to Rochester, got a job at Kodak. Quite a few years went by when I did nothing with coils. Then the bug bit me again around 1985 to 1990, when my wife and I moved to the house out here [in Brockport, NY] where I had room to do the Tesla coil stuff.

I started in the basement here in the house. The insurance company probably would not have appreciated what was happening in the basement. Then I decided, when the sparks got to seven feet and were hitting everything in the basement, it was time to build a lab out back. //

A TESLA COIL in action generates a streak of man-made lightning. Photo by Andrew Carly.

LIVING THE SPS LIFE

SPS LEADER FOUND FREE PIZZA, AND MORE

by Chris Faesi at Harvard University

In my first week as a first-year physics student at Indiana University (IU), I noticed fliers posted around campus advertising something called "Physics Club." The fliers also mentioned free pizza. I didn't know what the club was all about, but I knew I liked physics, and I knew I liked pizza (especially *free* pizza).

SPS represents the physics world
AS IT CAN AND SHOULD BE

That was enough to get me in the door. What kept me coming back every week after that, and what made me get more and more involved in what I later learned was the Society of Physics Students (SPS), was the remarkable camaraderie. The support of my fellow students helped me get through difficult classes, and the fun we had together made me remember not to take life too seriously. Interacting with faculty gave us a safe introduction to the professional world of physics. The outreach we conducted taught us that science is for everyone and not just for scientists. Without SPS, I don't know if I would have continued on to pursue a PhD program in astrophysics.

In November of 2008, our chapter president asked if anyone was interested in going to a "Sigma Pi Sigma Congress" in Chicago. I didn't know what that meant, aside from a road trip and a chance to meet other people who liked physics. But like walking into that first club meeting, I decided to give it a chance.

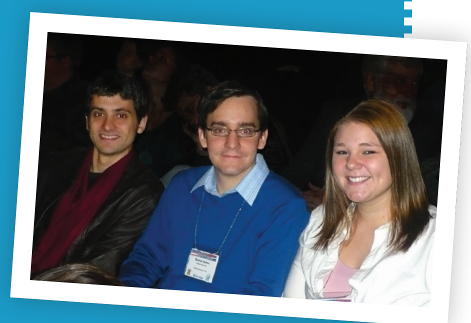
If joining the IU Physics Club opened the door to the world of physics beyond the classroom for me, Congress 2008 knocked the entire wall down. I was not prepared for the flood of energy and excitement that accompanied what amounted to a three-day takeover of FermiLab by 600 excited physics students from across the country. Between the thought-provoking lectures, the organized discussion sessions, tours of the lab, and the late nights talking with new friends, I think I totaled only 4 hours of sleep the entire weekend!

At Congress 2008 I learned that IU's physics club did not exist in a vacuum. We are just one of hundreds of chapters across the country, all part of a national organization called the Society of Physics Students. Discovering that network was like suddenly realizing that not only is our solar system just one of many in the galaxy, but that the galaxy possesses ordered motion and organized structure that promotes the formation and evolution of those solar systems.

The theme of that congress was "Scientific Citizenship." Though I've always felt that everyone has a responsibility to bring their professional expertise to bear on global issues, I had no idea what scientific citizenship *really* was. It turned out that I was in good company, as the goal of the congress was to help define what it meant and explore how we as physics students could participate as good scientific citizens and spread what we had learned to the wider world.

Many ideas came out of the discussions. Central to all of them was the idea that scientists have not just the ability, but also the responsibility to engage with the public. This responsibility includes explaining our science in comprehensible terms, as well as utilizing our analytical skills to contribute to debates on nonscience issues. I never would have guessed when I enrolled at IU as a physics major that I would soon be sitting at one of 50 or so tables full of physics students discussing not quantum mechanics or thermodynamics, but broadly relevant and critical issues such as the

The 2010 Indiana University (IU) SPS chapter poses for photos.



Chris Faesi (left) and two other IU chapter members attend the 2008 Sigma Pi Sigma Quadrennial Physics Congress, held at Fermilab.

During a trip to Washington, DC, SPS's 2009-2010 associate zone councilors ride the subway.

Photos courtesy of Chris Faesi.

energy crisis, diversity, and science policy.

After coming back from FermiLab, I wanted to revitalize IU's chapter and took on the role of chapter president with reckless abandon. By the following semester, we had tripled meeting attendance and increased the number of national SPS members by a factor of two. Our newly invigorated chapter built demonstrations, went to elementary school science fairs, posted videos on YouTube, and hosted lectures on science and career issues (such as what to do with a physics degree after graduating). With departmental support, we even upgraded to gourmet pizza.

Motivated by our success, I wanted to spread this momentum to other chapters. I learned at Congress 2008 that the SPS National Council, the governing body of SPS, is composed of 18 faculty advisors ("zone councilors") and 18 student representatives ("associate zone councilors," or "AZCs"), each from a different geographic region, or "zone." Joining the National Council seemed like the perfect way to become more involved, so I put my name on the ballot for AZC in zone 8, the zone that includes IU.

I honestly didn't expect to be elected. I knew no one outside my chapter, but my candidate statement must have conveyed my enthusiasm effectively; the chapters of zone 8 voted me into office. Working at the national level allowed me to connect with students across the country and shape the global direction of the society through council actions. For example, we drafted and approved key statements on undergraduate research and diversity, which were then promoted nationally both within and outside the organization. Statements like these, developed by the SPS National Council, serve to drive programs and initiatives for the society. In my fellow councilors, I found a new level of camaraderie: the other AZCs were among the most motivated, thoughtful, and well-rounded individuals I've ever had the pleasure of interacting with. And I've never seen a group of faculty care more about students than the professors who served on the council. During my second term, my fellow AZCs elected me to be the student representative to the Executive Committee, the highest position of student leadership in the SPS organization.

At every step, I was motivated to keep seeking leadership roles. For the first time in my life, I truly believed in the mission of an organization. SPS helped me realize that in science and in life, it's okay sometimes to not have all the answers. Issues such as scientific citizenship are tough, and the solutions aren't trivial—just like in nonlinear magnetohydrodynamics—and in both cases, pursuing the question is more important than solving the problem.

SPS has also taught me the importance of mentorship. I've been lucky to have some great mentors, such as former SPS Director Gary White. Among many things, White demonstrated to me that leadership is not about telling people what to do, but about sharing your enthusiasm and enabling others to pursue their interests and develop their talents. I now hope to mentor the next generation of undergraduates, passing on what I have learned.

SPS has also taught me that in science, communication is central. If you can't explain your scientific breakthrough clearly, no one will understand its importance.

Communication has become a central part of my graduate school career. I visit SPS chapters and give talks about astronomy and science communication. I am an author for Astrobites, a popular astronomy research blog for undergraduates. I'm helping to organize a workshop for graduate students this summer specifically focused on communicating science. And because of my own experience at Congress 2008, I leapt at the chance to help organize Congress 2012 (a.k.a. PhysCon) this past fall and maybe inspire another first-year student or two to get involved in physics beyond the classroom.

Perhaps someday I'll be a chapter advisor myself, pushing my students to apply for leadership positions and continuing the cycle into the future. SPS represents the physics world as it can and should be: open, collegial, energetic, and optimistic.

My involvement with SPS has changed my life. But some things haven't changed since my first semester as an undergraduate. I still never turn down an opportunity for free food. //

Chapter Reborn

SPS CHAPTER RISES FROM THE GRAVE

an interview with Jorge Palos-Chavez of the University of Texas at San Antonio

Why did you decide to found an SPS chapter at the University of Texas at San Antonio?

Originally it was just me and couple of friends. We were all physics majors who liked to get together and talk about physics. We didn't know where to find other people who were interested in the deeper stuff. Physics didn't seem to have a strong presence at our university. We want to create more of a community feeling in the department, so we decided to found a club where people could come and talk. A young postdoc who would talk to undergraduates a lot and was always there for the students was willing to be our patron. She has been serving as our faculty advisor for the last three years now.

When we decided to form the club, we had to register the organization on campus. That was when we discovered that the school used to have a Society of Physics Students chapter. We didn't know about it because it had gone into disarray years ago. The school still had the old constitution. We basically reworked that constitution and reinvigorated the SPS chapter into its current state.

What challenges did your chapter face in the early days?

The hardest thing was just getting started in the first place. For about a year and a half, the chapter didn't seem to grow. Trying to get physics students in one place was like herding cats. No one seemed to be interested.

Then we had an idea: Let's do demonstrations around campus, do cool things that people would really stop and think about while we taught them a little physics. We were only a small group, about 15 members, and we only had so many resources to work with, a little money the physics department handed us for certain activities or for food for the meetings.

One of the smartest things we did to get our image out on campus was to do fund-raisers. We started by making ice cream using liquid nitrogen. People got really excited about that, so we could get people interested in physics while making a little money. Soon we were known as the club that makes liquid nitrogen ice cream.

How did the growth of the club lead to new opportunities?

One we got enough people, we started helping out with small events. We worked with a nanotechnology group on campus, leading high school students around and showing them demonstrations. Some of us volunteered to be judges at middle school science fairs. We were trying to get the community excited about science.

Last year we went to a public library and built a makeshift space shuttle. Kids could come in and sit down. There was an iPad with real footage of a rocket blasting off. We explained the physics going on and talked about stars and solar system stuff.

It wasn't until the point that we got 30 or more members that we could do things like that.

Liquid nitrogen ice cream and dry ice drinks make for a great chapter fund-raiser at the University of Texas at San Antonio (UTSA). Photo courtesy of UTSA.

How did your chapter become connected to the national society?

We thought it would be cool to form an honor society. Then we found out that SPS already had one, called Sigma Pi Sigma. That was when we started learning more about the national society. We discovered that it provided access to journals and the opportunity to learn more about what else is going on in the nation: what conferences and what special events are happening, and what scholarships are offered for students.

One of our original core ideas was to try to provide students with funding to attend conferences. We have at least one member who has taken advantage of the SPS scholarships. Applying for more of the awards is definitely something we plan to do in the future.

What does the chapter look like today?

Now we have a pretty stable chapter. We're shifting our structure as a bunch of the seniors in leadership positions graduate, passing the club on to soon-to-be juniors who are very passionate about the chapter.

We've been trying to encourage undergraduate students to get involved in research on campus. Graduate students visit our meetings and talk about research. Close to one-third of our SPS chapter is now actively involved in undergraduate research.

Thanks to our chapter, the physics community at the university is better off now than it was a few years ago. Whenever the professors want to get a message out to the students, they come to one of our meetings. Between one-third and one-half of the 100 physics undergraduates at the university also come to each meeting. That's pretty remarkable. We have become the connection between the students and department. //

FURTHER READING

UTSA submitted a chapter report last year and won a 2012 Outstanding SPS Chapter award! To learn more about how to submit a chapter report visit www.spsnational.org/governance/chapters

SPS Nation

THE HISTORY AND ROLE OF THE SPS NATIONAL COUNCIL

by Earl Blodgett, SPS Historian, and David Donnelly, SPS President

So you've joined your local SPS chapter and you're loving it. Maybe you enjoy the talks at pizza parties, the outreach events that connect physics to the larger world, or the zone meetings in your region. That's great! But how much do you know about what goes on in SPS at the national level?

SPS and Sigma Pi Sigma are led by a team of faculty and students who serve on the SPS National Council. The council has two presidents, one for SPS and one for Sigma Pi Sigma. An executive committee composed of six individuals specified in the SPS constitution forms a smaller leadership team within the National Council.

The council has, in recent years, taken steps to increase SPS's visibility. Members can now get a free one-year student membership in one of the 10 member societies that belong to the American Institute of Physics (AIP). SPS is also regarded as a serious organization for science policy, thanks in large part to policy statements carefully crafted by the members of the council. Those statements have spanned issues such as evolution in science classrooms, undergraduate research, and ethics in professional conduct.(1)

Another long-standing concern of the National Council for the past decade has been to increase the diversity of the physics community. This has led to the development of the Future Faces of Physics kits(2) and, most recently, the Future Faces of Physics Award.(3)

To understand the history and structure of the council, you have to look back a few decades. Prior to 1968, Sigma Pi Sigma was led by another National Council comprised of faculty who represented its 12 districts. SPS traces its origins to 1950, when AIP's student organization plan provided for the establishment of student sections of AIP and established their structure. Much of this structure persists today in the chapter structure of SPS. To quote from the "Institute Doings" section of the January 1958 issue of *Physics Today*,

The broad purpose of our student section organization will be much the same as that in other fields of science and technology—where the value of the activity has been proven by experience. We aim to serve and stimulate the student, to enhance his professional pride and responsibility at the start of his career, and to recruit him as a worthy member of our professional societies, i.e., the member societies of the Institute.

Congratulations to all of the 2012 SPS Outstanding Chapters! See the full recipients list at www.spsnational.org/governance/chapters/. Photo courtesy of SPS.

A recent photo of the SPS National Council, taken at the American Center for Physics in College Park, MD. Photo by Tracy Schwab.

In 1968 the student sections of AIP merged with Sigma Pi Sigma to form a new organization, the Society of Physics Students, with Sigma Pi Sigma being an honor society within SPS. That merged entity had one National Council with two presidents, to retain the distinctive elements of the linked organizations. The very first SPS National Council met in April 1969. Following precedent, there were 12 geographic zones. But to better reflect the student-focused nature of SPS, the new National Council was composed of both faculty representatives (zone councilors) and student representatives (associate zone councilors). In 1976 the Executive Committee was redesigned to include an associate zone councilor representative to further ensure that a significant student perspective be maintained. SPS and Sigma Pi Sigma grew rapidly in the first two decades after merger, and the number of zones increased to 18.

The National Council has taken the lead in continuing to expand the reach of SPS and Sigma Pi Sigma. After a hiatus of 25 years, a Sigma Pi Sigma congress was held in Dayton, OH, in 1992, and has been followed by increasingly successful congresses every four years, including last year's conference in Orlando.(4) The National Council, and especially its student members, have been instrumental in the successful implementation of these congresses.

Over the past 15 years, the National Council has also pushed hard to provide resources and encouragement for zone meetings, which offer even more opportunities for chapters to connect with each other. There have been more zone meetings per year in the past two years than at any time on record!(5)

And let's not forget the SPS internship program, enthusiastically supported by the National Council. During the summer of 2001, the very first SPS intern, Mark Lentz, helped develop the first Science Outreach Catalyst Kit (SOCK). (6) Over the years, a remarkable number of SPS interns have been inspired to run for associate zone councilor, and vice versa.(7)

How do you get involved in SPS's national activities? First and foremost, start with being active in your local chapter. Attend meetings and share your ideas about how your chapter can make an impact in your department and community. You can pursue a leadership role by becoming a chapter officer. Officers help to guide the activities of their chapters and, along with faculty advisors, act as liaisons between chapters and university departments. Each officer also serves as his or her chapter's representative to the zone councilor and associate zone councilor.

Become a national member by paying SPS dues. If you would like to assume an even larger leadership role, run for associate zone councilor for your zone (if you're a student) or zone councilor (if you're a chapter advisor). If elected, you will have the opportunity to serve on the National Council. Most who have served on the council have found it to be a very rewarding experience that provides opportunities for personal and professional growth. //

FURTHER READING

1) A full listing of the statements and endorsements issued by the National Council can be accessed at www.spsnational.org/governance/statements/index.htm.
2) For details about the Future Faces of Physics kits, see www.spsnational.org/programs/futurefaces/future_faces_kit.htm.
3) Plan your chapter project now! Details at www.spsnational.org/programs/awards/futurefaces.htm.
4) A short history of all the modern Sigma Pi Sigma congresses is available at www.sigmapisigma.org/congress/index.htm.
5) If your chapter has never attended a zone meeting, you are missing out on a great opportunity! www.spsnational.org/meetings/zones/index.htm has a calendar of zone meetings and a host of resources, useful if you want to host a zone meeting yourselves.
6) The many SOCK designs over the years offer a wealth of ideas for science outreach. Though you can't get the old SOCKs, you can download the resources that were compiled for each SOCK from www.spsnational.org/programs/socks/index.htm.
7) For details of the SPS internship program and a listing of all the SPS interns, go to www.spsnational.org/programs/internships/.

DANGER ZONE

TORNADO NO MATCH FOR SPS ZONE 12 MEETING

by Karen Williams of East Central University, zone councilor of zone 12

A zone meeting can give your chapter a boost of energy like you have never seen. Especially when you have to outrun a tornado to get there, as you may have to in Zone 12.

At last year's spring meeting in Oklahoma, my chapter was heading west, coming up I-35 from Chickasha when I saw a wall cloud. I turned on the radio, which confirmed it. We stopped at a Love's Country Store in McCloud and were told to leave. They were locking up and leaving. So we decided to run back east. Guided by an iPhone weather map, we got far enough away to head north on a flooded road. The tornado hit at the spot where we turned north, behind us. Pittsburg State was coming down I-44 and hit the same tornado and had to miss the Friday afternoon events due to the delay.

In the middle of the storm, we had a great indoor picnic at the University of Central Oklahoma, which was hosting the meeting. Once the weather had passed, we borrowed some rental bikes and took a ride around the lake.

I think what makes a zone meeting successful is students talking with students from other universities and realizing we are all the same and face the same challenges. Some classes are just hard. Every student that has attended a zone meeting has come back enthused and energized about physics. //

Want a free kit for your next zone meeting? Go to www.spsnational.org/zones/, where you'll find tips for hosting a successful zone meeting, along with the zone meeting closest to you.

Photo by Tracy Schwab.

SPS in CHINA

NEW SPS CHAPTERS SUPPORT CHINESE STUDENTS

by Elizabeth Hook, SPS Communications Specialist

SPS MEMBERS AT SOUTHEAST UNIVERSITY in Guangzhou, China, outside an observatory with an ancient Chinese astronomy instrument in the back. Photo courtesy of Zhi-Yong Zhou.

No two SPS chapters look exactly alike. But physics students tend to share similar interests and needs, whether participating in outreach events or just getting together for pizza.

That's true here in the United States. It's also proven true in other countries where SPS has taken on new international chapters in recent years. Some of the latest chapters come from two schools, Southeast University in Nanjing and Sun Yat-sen University in Guangzhou, that have laid the groundwork for SPS in China.

Despite being on the other side of the planet, the SPS chapters in China are very similar to those here in the States. Since its inception on December 20, 2010, the Southeast University chapter has been very active, earning an Outstanding Chapter Award in 2012. Last year the chapter also received an SPS Undergraduate Research Award for a project entitled "Controlled Growth of Graphene by Chemical Vapor Deposition."

Members in the Southeast chapter participate in physics competitions and outreach events; their favorite is making ice cream using liquid nitrogen. In addition to holding regular meetings, SPS also helps to organize lectures and social outings such as hikes and card games for the students, many of whom now study together.

Says chapter member Zhicheng Liu:

Before our establishment, there was no special place for us to study together. But now we have our own activity room in the department, and most of our members choose to study or do their homework here because they can have somebody to discuss [physics] with. We can even stay overnight if we cannot stop the discussion and are worried about disturbing our dorm mates.

The chapter is excited about its new members, many of whom are actually engineers! "We have 39 members in our chapter now, and nearly half of our members come from engineering schools," says Liu. "This means we have a chance to communicate with students in different majors. We provide a platform to bridge physics and engineering students."

While this ratio is a little higher than that of a typical SPS chapter in the United States, it is in line with the organization's goal to bring together all students interested in physics, even those studying other fields such as engineering, biology, or chemistry.

The SPS chapter also helps send students to professional physics conferences abroad. Six attended the 2011 AAPT summer meeting in Omaha, NE. Last November, a delegation from the chapter traveled more than 11,000 miles to the 2012 Quadrennial Physics Congress, hosted by Sigma Pi Sigma, in Orlando, FL. Recognized as the participants who had traveled the farthest to attend, the students toured NASA's Kennedy Space Center, went to workshops and plenaries, and presented research posters.

"Attending the 2012 PhysCon was definitely an unforgettable trip," says Yulu Liu, who snagged an honorable mention in the APS Forum on Physics and Society, Outstanding Student Poster Award category. "The workshops and poster sessions were our favorites. Even though there was a little problem with our communication with our American peers, we enjoyed the kind of free atmosphere for discussion. It was really amazing!"

Southeast is the first but not the only chapter in China. In 2012 SPS added a Sun Yat-sen University chapter. Thanks in part to advice from Southeast University on how to apply and get started, the new chapter is now in full swing.

"We may be hosting the annual FuLan's Science Fair this year, and we will have our own academic tournament for students, and other kinds of local activities," says chapter member Gustav Ho. //

Southeast University's 2012 SPS "Hot Pot" party, with food similar to fondu. Photo courtesy of Zhi-Yong Zhou.

APS: A Few Days in Physics Land

ATTENDING THE AMERICAN PHYSICAL SOCIETY (APS) MARCH MEETING 2013, MARCH 18–22, IN BALTIMORE, MD

by Vasilii Bushunow at Duquesne University

VASILII BUSHUNOW visits the SPS booth. Photo courtesy of Vasilii Bushunow.

In January I found out that my research on Mössbauer spectroscopy of a lithium-oxide hematite solid solution had been accepted for a poster session at the American Physical Society (APS) March Meeting 2013. Called "the biggest physics meeting in the world," the conference draws thousands of attendees. The excitement I felt was only slightly tinged with anxiety when my advisor told me that she would be unable to attend. I would have to go by myself.

Because of other classes, I was only able to attend the second half of the meeting and arrived after many of the SPS sessions and activities specifically designed for undergraduate students had already ended. On Wednesday I attended the APS sing-along, a rousing event organized by Walter Smith of Haverford College. Without a doubt, this was the social highlight of the meeting. Hundreds of physicists sang along to songs such as "Complex Z" (based on the Beatles' "Let it Be") and "I Got Funding" (Gershwin's "I Got Rhythm").

On Thursday it was difficult to choose from the many sessions listed in the phone book–sized directory. The first I attended discussed an optomechanical transducer, a small oscillating plate connected to a piezoelectric chip, used to convert electrical signals into optical quanta. After visiting a special session on the physics of cancer, I then went to a presentation on the thermoelectric characteristics of tetrahedrites [minerals with the chemical formula $(Cu,Fe)_{12}Sb_4S_{13}$] and the potential to enrich naturally obtained minerals. The research was very interesting to me because it had a direct industrial application: enrichment significantly lowers costs compared to synthesizing materials from scratch in the laboratory.

During the poster session, I spoke with fellow undergraduate presenter Philip Dee, a senior physics major from Cleveland State University. Dee presented research on the characterization of ferric oxyhydroxide (FeOOH) nanorice particles. By measuring the scattering of either polarized or nonpolarized incident beams, Dee's team determined the size and motion of the nanoparticles in solution. This new way to calibrate measurements could potentially improve medical imaging.

By 6 pm, I was drained. I had attended over a dozen presentations, and I felt like I had learned more physics that single day than in the three years prior at college.

One presentation I saw on Friday morning was by Kamal Kadel, a PhD candidate from Florida International University who studies indium-doped lead telluride nanoparticles. His advice for undergraduate students interested in physics was simple: "You just have to find something you're interested in and be willing to work hard at it." Indeed, everyone at the conference was united not only by their interest in physics, but by the diligence and the hard work they had put into their research.

This meeting was more than just an opportunity to present data. It was a chance to catch up with old colleagues, to network, and to enjoy the company of like-minded people. I met a Duquesne alumnus who had worked in the lab in which I did my research, saw an old friend from my hometown now at the Johns Hopkins Applied Physics Lab, and bumped into a professor who had come to Duquesne for a guest lecture.

I would strongly encourage any undergraduate student to go to the APS March Meeting. For an undergraduate doing research, the meeting provides an opportunity to develop your presentation skills and exhibit your work alongside that of the brightest minds in your field. Even those not doing original research can benefit from the breadth of material presented and learn more about the many avenues explored by physicists, as well as the industrial, medical, and academic applications of their work. //

I FELT LIKE I HAD LEARNED MORE PHYSICS
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THAN IN THE THREE YEARS PRIOR AT COLLEGE

NEXT UP

The next APS March Meeting will take place in Denver, CO, March 3–7, 2014. Details will be posted at www.aps.org/meetings/meeting.cfm?name=MAR14. APS and SPS plan many events specifically for undergraduates at this meeting that take place early on in the conference, so be sure to check them out in 2014!

AAS: An Opportunity to Network

LEARNING TO NETWORK AT THE AMERICAN ASTRONOMICAL SOCIETY (AAS) 221ST MEETING, JANUARY 6–10, 2013, IN LONG BEACH, CA

by Jill Pestana at California State University, Long Beach

SPEAKING INSIDE THE SOFIA AIRCRAFT, Eric Becklin talks to a tour group. Photo courtesy of NASA.

My experience at the AAS 221st meeting was that of an outsider. Having graduated from college the previous month, I was no longer a student and not yet a professional. Nor was I an astronomer; I am in the process of applying to PhD programs in materials science.

I attended the meeting as an SPS reporter and an exhibitor for the NASA Stratospheric Observatory for Infrared Astronomy (SOFIA) program. Although I did not fit the profile of a typical attendee, I found the meeting to be a valuable opportunity for networking with students, professionals, educators, and other SPS members. I tried to follow the best networking advice I have ever received: "Keep asking lots of questions . . . It shows what a good critical thinker you are!" One of my mentors wrote the statement on my poster about SOFIA, a departing gift from my summer internship in 2010.

My official tasks at the AAS meeting included being an SPS reporter, presenting information to people who stopped by the SOFIA booth in the exhibit hall, and filming a tour of the SOFIA Boeing 747SP aircraft. During the tour, my coworker Stephanie Sodergren and I followed SOFIA's chief science advisor, Eric Becklin, and his tour group. The 15 people he led fit comfortably in the aircraft's main cavity, facing the bulkhead that connects a science instrument to a 2.5-meter diameter telescope. Becklin spoke about the telescope's capability to observe visible or infrared spectra. The aircraft, a uniquely flexible observatory, can fly to a particular location to watch a specific event, as demonstrated during a Pluto occultation mission.

The tour group seemed amazed and impressed by the work that has gone into establishing SOFIA. Becklin spoke with passion about the program and astronomy in general, which reminded me of the rewards that hard work brings. During the almost 20 years he has invested in SOFIA, Becklin has contributed significantly to investigations of the center of our galaxy.

The rest of the AAS meeting was a time to greet old friends and make new acquaintances. I deliberately wore a name tag that highlighted my accomplishments. Instead of a plain "nonmember undergraduate" label, thanks to SPS my tag read "PRESS" below my name. (Hint: If you want a "PRESS" label, become an SPS reporter!) I also attached pins from NASA, SOFIA, and SPS. To my surprise, people noticed my ensemble and conversed with me about my affiliations. I met SPS members, people familiar with the SOFIA program, and others interested in learning about my involvement and career path in materials science. For my part, I pursued conversations with others bearing "MENTOR" or "CAREER ADVISOR" ribbons on their name tags.

> I made it a point
> TO CARRY BUSINESS CARDS AND ATTEND SOCIAL EVENTS

I also carried a notebook and a pen. I jotted down awesome astronomical facts from press conferences, noted unfamiliar jargon from research presentations, and recorded words of wisdom from interviews. During a career networking reception, I started writing down information given to me by an employee at RAND. She took our conversation more seriously, and we exchanged business cards at the end.

Finally, I made it a point to carry business cards and attend social events. At the opening reception at Long Beach's Aquarium of the Pacific, we filed past sharks and stingrays to tables of food and drinks. The graduate reception also had good food, friendly students, and wise mentors offering practical advice. At the infamous AAS party, hundreds of astronomers crashed a salsa night at a nightclub, and I invited a group of students to my local residence for a night of card playing. Each of these events provided time to network on a more informal level than the daytime activities. Handing out business cards never failed to impress, and the bulk of the people I will remain in contact with from this meeting are those with whom I conversed during the social events.

"Outsiders" can have valuable experiences at any professional event, as long as they actively seek opportunities and make an effort to network. There was only one awkward moment, when a professional at the graduate reception asked me what I was doing there since I was not yet a graduate student. I broke the tension of the moment with a quick response: "the free food!" He smiled and nodded in understanding. //

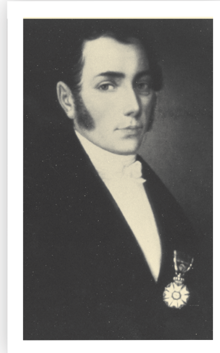
NEXT UP

The AAS 223rd Meeting will take place January 5-9, 2014 in Washington, DC. To learn more, visit http://aas.org/meetings/223rd-aas-meeting-washington-dc.

Diffraction, Part 2

MULTIPLE POINT SOURCES, APERTURES, AND DIFFRACTION LIMITS

by Dwight E. Neuenschwander, Southern Nazarene University



JOSEPH VON FRAUNHOFER (also Frauenhofer, 1787-1826). The namesake of diffraction by plane waves, Fraunhofer invented the diffraction grating, which transformed spectroscopy. With his spectrometer Fraunhofer discovered the dark lines in the solar spectrum, which now bear his name. Photo credit: Bavarian Academy of Sciences, courtesy AIP Emilio Segre Visual Archives.

If you have ever looked at a streetlight through an umbrella's fabric and seen a neat array of tiny bright spots; noticed thin streaks of light emanating from images of small, bright lights in photographs; or wondered how the metallic mesh in a microwave oven door allows visible light but not microwaves to pass, then you have encountered diffraction. Many physics experiments, from spectroscopy to measurements of the wavelength of laser light, employ diffraction. Diffraction is the signature phenomena of wave motion.[1]

In Part 1 of this series on diffraction,[2] we met Huygens' principle and applied it to the interference produced by two slits, modeled as point sources that coherently radiate equal-amplitude and equal-wavelength harmonic waves. The corresponding experiment, first done by Thomas Young in 1801, demonstrated that light is a wave, or, as we would say today, that light *behaves* as a wave in this situation. In our analysis of the Young experiment we observe waves sufficiently far from their source to make the wave-front curvature negligible across an aperture. Diffraction with such plane waves is called "Fraunhofer diffraction."

Working within the Fraunhofer paradigm, here we extend Young's experiment to multiple point sources. We will go to the limit of an infinite number of contiguous infinitesimal point sources to derive the diffraction patterns produced by a single slit as well as its complement, an opaque ribbon. That will put us in the position to consider double slits of finite width as a better model of Young's apparatus. The result illustrates the array theorem, which says that the image produced by an array of N identical apertures equals the

Working within the Fraunhofer paradigm,

HERE WE EXTEND YOUNG'S EXPERIMENT TO MULTIPLE POINT SOURCES

diffraction pattern of one aperture times the interference pattern of N point sources. We will also consider diffraction from all four edges of a rectangular aperture and from a circular aperture.

Before leaving plane waves we will discuss what it means to say that the image on the screen is the Fourier transform of the aperture. For Fraunhofer diffraction, Fourier transforms provide the link between waves, aperture, and image.

INTERFERENCE FROM *N* POINT SOURCES

Consider three point sources equally spaced and separated by the distance a. Place a screen some distance z away (Fig. 1). Let locations on the screen be mapped by the coordinate y (or alternatively, the angle θ), where $y = 0$ ($\theta = 0$) describes the point opposite the source array's midpoint. Assume the three sources emit coherently, and their waves leave in phase.

A portion of the signal from each source arrives at location y on the screen at time t. The part of the total signal coming from source 1 travels along the ray of length r_1. The signal from source

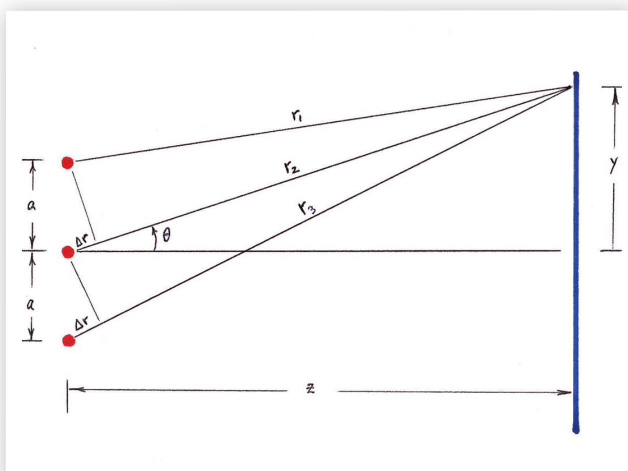


FIG. 1: The geometry of the three-point-source interference experiment. In practice, $z >> a$ and y, so that $\sin\theta << 1$. Note that the lines of length r_1, r_2 and r_3 are then approximately parallel near the slit.

2 travels the distance $r_2 = r_1 + \Delta r$, and the ray from source 3 has length $r_3 = r_1 + 2\Delta r$. Due to the different path lengths, the three signals acquire phase differences, causing interference when the signals are added together at y. Assuming equal amplitudes ψ_o upon arrival,[3] the total wave function $\psi(y,t)$ at y is

$$\psi(y,t) = \psi_o\,[\cos(\alpha) + \cos(\alpha + \delta) + \cos(\alpha + 2\delta)], \qquad (1)$$

where $\alpha = kr_1 - \omega t$ and $\delta = k\Delta r$. Typically, Δr is too small to measure directly with a meterstick, but z is large, so θ is small, and $\Delta r = a \sin\theta \approx a \tan\theta = ay/z$.

Our task is to sum the three cosines in an interpretable way. Phasor diagrams fall readily to hand. Pretend that Eq. (1) is the horizontal component of a vector sum, add the vectors graphically, and then evaluate the horizontal component of the resultant to obtain $\psi(y,t)$, as in Fig. 2.

The condition for the resultant to achieve maximum magnitude requires the three vectors to be collinear, corresponding to places on the screen where $\delta = 2n\pi$, with $n = 0,1,2,3\ldots$. In these places, $\psi = 3\psi_o\cos(\alpha)$, a primary maximum. Since one source by itself produces an intensity I_o proportional to $|\psi_o|^2$, the intensity of a primary maximum will be $9I_o$. Zero intensity occurs when the three phasors close back on themselves to make a triangle. This requires δ to be one-third of a rotation or a whole number of rotations beyond that, in other words, $\delta = 2\pi(n + ⅓)$, where, again, $n = 0,1,2,3,\ldots$. When two of the three phasors cancel out, so that $\delta = (2n+1)\pi$, then $I = I_o$, a secondary maximum.

Imagine a phasor diagram in which the value of δ can be controlled by turning a knob while the intensity is monitored. Steadily increasing δ corresponds to sliding the observation point along the y-axis. When the three phasors are initially lined up with $\delta = 0$, the intensity is $9I_o$. As δ (and y) increases, the intensity first declines, reaching zero at $\delta = 2\pi/3$. The intensity then increases to I_o at $\delta = \pi$, decreases again to zero when $\delta = 4\pi/3$, and increases back to $9I_o$ when $\delta = 2\pi$. This pattern repeats periodically thereafter and is symmetric at about $y = 0$. The intensity distribution, as a function of position y on the screen, is shown schematically in Fig. 3a.

With four equally spaced point sources emitting coherently, the four vectors in the phasor diagram predict principal intensity maxima of $16I_o$ when all four vectors are collinear, or $\delta = 2\pi n$. Zero intensity occurs when all phasors cancel at $\delta = (n+1)\pi/2$. Secondary maxima, when three of the four waves cancel leaving $I = I_o$, occur where $\delta = 2\pi(n + ⅓)$. (Fig. 3b)

One may continue such analyses with $N = 5, 6, 7,\ldots$ coherent, equally spaced point sources. The primary maxima occur for $\delta = 2\pi n$, the same as occurs with two point sources. On the screen, in between adjacent primary maxima of intensity $N^2 I_o$, one finds $N-2$ secondary maxima of intensity I_o and $N-1$ minima of zero intensity.

When the number of sources per centimeter reaches into the hundreds or thousands, the array is called a diffraction grating. Made with fine parallel lines on a transparent sheet (etched into glass, or created by photolithography on plastic), each line scatters the incoming light and serves as a point source. The energy emerging on the far side of the grating becomes concentrated in the well-separated primary maxima intensity peaks, leaving negligible the secondary maxima and making such gratings useful for spectroscopy by sending principal maxima of different wavelengths to widely separated angles.

Suppose that along a line of fixed width w the number of point sources N is allowed to become arbitrarily large. The spacing between adjacent sources must, of course, grow smaller. In the limit as $N \to \infty$, the array becomes a slit of finite width. The geometry is similar to that in Fig. 1. Let the slit be mapped with a y'-axis, with edges at $y' = \pm w/2$. Let the slit and screen be separated by the distance z and locations on the screen be mapped with a y-axis. By Huygens' principle, a segment of width dy' of the harmonic plane wave passing through the slit becomes the source of a new wave $d\psi$. In terms of complex numbers, which like phasors have an amplitude and a phase,[4] when this little wave arrives on the screen at time t it has the form

$$d\psi = dA\, e^{i(kr - \omega t)}, \qquad (2)$$

where k is the wavenumber and ω the angular frequency of the harmonic wave, with

$$r = \sqrt{z^2 + (y - y')^2}. \qquad (3)$$

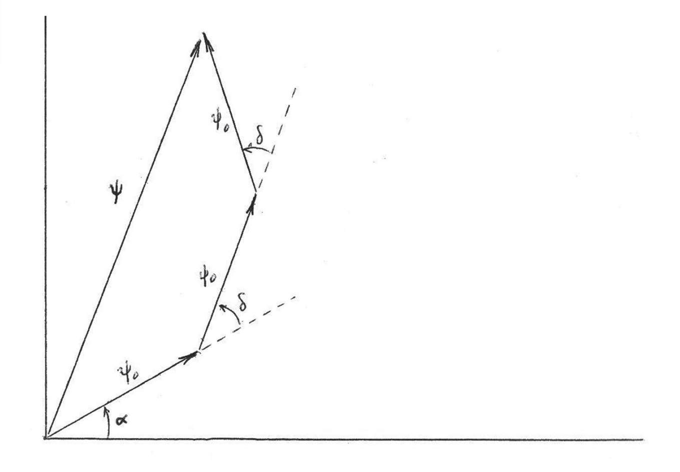


FIG. 2: Phasor diagram construction for three coherent point sources, where Eq. (1) is considered a component of the vector sum $\psi = \psi_1 + \psi_2 + \psi_3$.

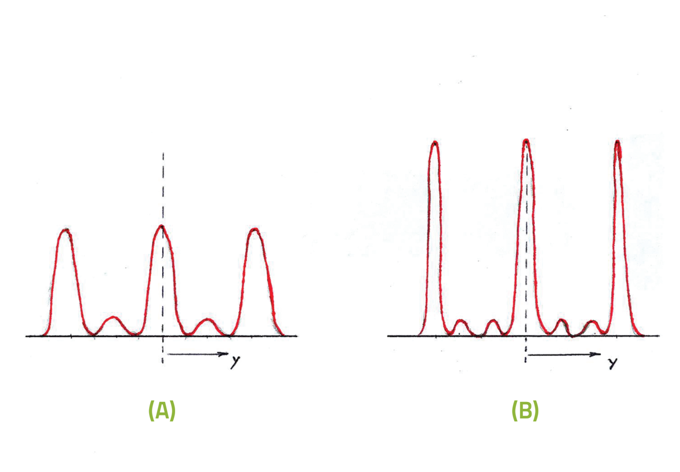


FIG. 3: The intensity pattern of (a) three and (b) four equally spaced coherent point sources.

The amplitude of $d\psi$ can be written as a fraction dy'/w of the amplitude A_o that would have been emitted if the entire signal passing through the slit were instead sent from a point, so that $dA = A_o(dy'/w)$. At a location y on the screen and at a time t, the total wave function $\psi(y,t)$ is the superposition of all the infinitesimal Huygens waves,

$$\psi(y,t) = \frac{A_o}{w}\int_{-w/2}^{w/2} e^{i(kr-\omega t)}dy'. \quad (4)$$

Assuming $z >> y$ and w, to the first order in small parameters, Eq. (3) yields

$$r \approx z - yy'/z. \quad (5)$$

Denoting $kz - \omega t = \gamma$, Eq. (4) becomes

$$\psi(y,t) \approx \frac{A_o}{w}e^{i\gamma}\int_{-w/2}^{w/2} e^{-ikyy'/z}dy' = A_o e^{i\gamma}\frac{\sin(\beta/2)}{\beta/2} \quad (6)$$

where $\sin(x) = (e^{ix} - e^{-ix})/2i$ has been used and $\beta \equiv kwy/z = 2\pi wy/\lambda z$, with λ the wavelength. The intensity distribution on the screen is

$$I(y) = I_o\left(\frac{\sin\frac{\beta}{2}}{\beta/2}\right)^2 \quad (7)$$

as illustrated in Fig. 4a. Incidentally, the combination $(\sin x)/x$ occurs so frequently in diffraction problems that it has been dignified with the name "sinc x."

The first minimum occurs when $\beta = 2\pi$, where $y = \lambda z/w$, giving $2\lambda z/w$ for the width of the central diffraction peak. The width of the intensity pattern is inversely proportional to the width of the aperture—a hallmark of diffraction.

In terms of the small angle θ (Fig. 1), the first condition for a minimum requires $w \sin\theta = \lambda$, which answers two questions. First, how is the diffraction of visible light, as revealed in such experiments, consistent with the observation that we do not readily notice optical diffraction in everyday life? Second, why do some radio telescopes use metallic meshes for their parabolic reflectors, and how can the doors of microwave ovens include a mesh that allows one to see inside without the microwaves escaping?

In response to the first question, Young's experiment shows that the wavelengths of visible light lie in the range 400–750 nm, thousands of times smaller than apertures encountered in everyday life—indeed, a thousand times smaller than the diameter of a human hair (~0.1 mm)! Thus when $\lambda << w$, then $\sin\theta << 1$, and all the minima from diffraction at a slit's edge crowd together in the forward direction. That makes the separated minima of diffraction hard to see, so the result approaches a sharp shadow.

In reply to the second question, the wavelength of microwaves is larger than the holes in the mesh: $\lambda > w$, so $w \sin\theta = \lambda$ becomes the absurd relation $\sin\theta > 1$. The waves cannot pass through the opening, making it a reflector.

That $w \sin\theta = \lambda$ describes the first minimum in single-slit diffraction may seem counterintuitive at first. This relation for the single slit often follows soon after a discussion of $a \sin\theta = ½\lambda$, the condition for the first minimum in two-point-source interference. Why the factor of ½ that distinguishes these cases when both describe minima? When we muse over it, $w \sin\theta = \lambda$ for a minimum holds because of $a \sin\theta = ½\lambda$. To see this, subdivide a plane wave passing through the slit into, say, 600 Huygens sources. When the signals from sources 1 and 300 cancel out, then so do those from sources 2 and 301, 3 and 302, and so on, all the way through sources 299 and 600. Pairwise cancellation occurs, and, for each pair of sources, $(w/2)\sin\theta = \lambda/2$.

Point sources are an idealization; real sources have finite size. Consider, then, the diffraction produced by two identical slits, each of width w, whose centers are separated by the distance a. The signal arriving at a point $y = z \sin\theta$ on the screen can be predicted by adjusting the integration limits in Eq. (6):

$$\psi(y,t) = \frac{A_o}{w}e^{i\gamma}\left[\int_{(a-w)/2}^{(a+w)/2} e^{iky'\sin\theta}dy' + \int_{(-a-w)/2}^{(-a+w)/2} e^{iky'\sin\theta}dy'\right]. \quad (8)$$

Upon evaluating the integrals and squaring the result to obtain the intensity on the screen, we find (Fig. 4b),

$$I(y) = I_o\cos^2\left(\frac{\delta}{2}\right)\left(\frac{\sin\frac{\chi}{2}}{\frac{\chi}{2}}\right)^2 \quad (9)$$

where $\delta = ka \sin\theta$ and $\chi = kw \sin\theta$. We recognize $\cos^2(\delta/2)$ as the two-

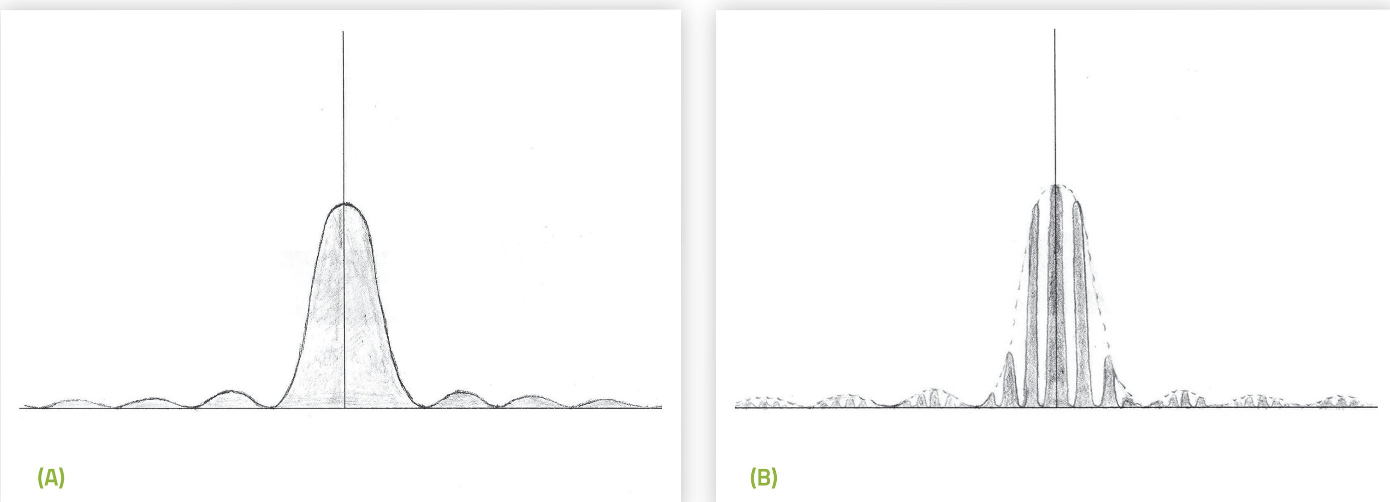


FIG. 4: The Fraunhofer diffraction pattern of an (a) single and (b) double slit.

point-source interference distribution and $\text{sinc}^2(\chi/2)$ as the single-slit diffraction distribution. This result for two identical slits illustrates a larger result, the array theorem: the Fraunhofer intensity pattern produced by *N* identical apertures equals the diffraction pattern of one aperture multiplied by the interference pattern of *N* point sources.[5]

What happens when we take away the slit and replace it with an opaque ribbon of the same width? We can conceptualize the situation as follows. Begin with an opaque sheet and cut out an aperture. By itself, the aperture (e.g., a slit) produces on the screen the wave function ψ_{ap}; by itself the cut-out piece (e.g., a ribbon) produces on the screen a wave function ψ_{co}. When the cutout fills the aperture, the total wave function on the screen vanishes, $\psi_{tot} = 0$. By the superposition principle, $\psi_{tot} = \psi_{ap} + \psi_{co}$. Therefore $\psi_{ap} = -\psi_{co}$. But the intensity goes as the wave function squared; hence $I_{ap} = I_{co}$, a marvelous result known as Babinet's principle.[6] An experiment you can easily do, as my students have done many times, is to measure the diameter of a hair from your own head using a laser beam. One industrial application of this principle is the manufacture of fine wire in which the diameter is continuously checked by passing the wire through a laser beam while monitoring the diffraction pattern.

Most readers will have performed in a general physics lab the kinds of diffraction experiments we have been describing. The apparatus used in such experiments typically consists of a small laser with a beam diameter sufficient to illuminate the edges of a slit but not its ends. Now let's shorten the slit or pull the laser back (its beam, too, spreads by diffraction) to illuminate all the edges.

FRAUNHOFER DIFFRACTION PRODUCED BY AN APERTURE

Consider an aperture of area Γ, uniformly illuminated by monochromatic plane waves. Let the plane of the aperture be mapped with an $x'y'$ coordinate system, and let the screen be mapped with xy coordinates (the $x'y'$ and xy planes are held parallel, separated by distance z). According to Huygens' principle, each infinitesimal patch of area $dx'dy'$ on the wave front in the aperture radiates a wave $d\psi$. Upon the arrival of this wave increment at the screen, it has amplitude dA and an acquired phase, so that

$$d\psi(x,y,t) = dA\, e^{i(kr - \omega t)}, \tag{10}$$

where

$$r = \sqrt{(x-x')^2 + (y-y')^2 + z^2}. \tag{11}$$

At location (x,y) on the screen at time t, the total wave function $\psi(x,y,t)$ is the superposition of the infinitesimal waves:

$$\psi(x,y,t) = A_o \int e^{i(kr-\omega t)} \frac{dx'dy'}{\Gamma}, \tag{12}$$

where the limits, still to be put on the integral, will describe the aperture. When r is large compared to other length scales, then to first order in small quantities,

$$r \approx r_o - (xx' + yy')/r_o, \tag{13}$$

where $r_o = [x^2 + y^2 + z^2]^{1/2}$. Denoting $kr_o - \omega t = \gamma$, Eq. (12) becomes

$$\psi(y,t) \approx A_o e^{i\gamma} \int e^{-ik(xx'+yy')/r_o} \frac{dx'dy'}{\Gamma} = A_o e^{i\gamma}\, \xi(x,y) \quad , \tag{14}$$

in which we have introduced the modulation factor

$$\xi(x,y) \equiv \int e^{-ik(xx'+yy')/r_o} \frac{dx'dy'}{\Gamma} \tag{15}$$

with integration limits over Γ understood. If all the signals coming through the aperture were instead concentrated at the $x'y'$ origin, then $A_o e^{i\gamma}$ would be the signal arriving on the screen, where it would produce the uniform intensity $I_o \sim A_o^2$. The factor $\xi(x,y)$ describes the effect of the aperture's finite size and shape in redistributing the signal across the screen. For a rectangular aperture, the integration limits on x' go from $-a/2$ to $+a/2$, y' goes from $-b/2$ to $+b/2$, and Eq. (15) becomes

$$\xi(x,y) \equiv \int_{-a/2}^{a/2} \int_{-b/2}^{b/2} e^{-ik(xx'+yy')/r_o} \frac{dx'dy'}{ab} \tag{16}$$

and therefore

$$I(x,y) = I_o \left(\frac{\sin\frac{\alpha}{2}}{\alpha/2}\right)^2 \left(\frac{\sin\frac{\beta}{2}}{\beta/2}\right)^2, \tag{17}$$

where $\alpha = kax/r_o$ and $\beta = kby/r_o$ (Fig. 5a).

When the aperture is a circle of radius a, in the evaluation of ξ it becomes convenient to switch to polar coordinates ($x' = \rho'\cos\varphi'$, $y' = \rho'\sin\varphi'$) and similarly for the screen coordinates:

$$\xi(\rho,\varphi) = \frac{1}{\pi a^2} \int_0^a \rho' d\rho' \int_0^{2\pi} e^{-ik\rho\rho'\cos(\varphi'-\varphi)/r_o}\, d\varphi'. \tag{18}$$

Noting that the system has rotational symmetry about the aperture axis, we may evaluate ξ at $\varphi = 0$. The definite integral over φ' offers an instance from the family of Bessel functions, which are damped, oscillatory, nonperiodic functions that often appear as solutions to differential equations in cylindrical coordinates. The acoustics of brass, percussion, and woodwind musical instruments, as well as the electrostatics of cylindrical charge distributions, are among the many examples in which Bessel functions appear. Most of us probably first encounter Bessel functions of order μ, denoted $J_\mu(\rho)$, as the solutions of the differential equation,[7,8]

$$\frac{d^2F(\rho)}{d\rho^2} + \frac{1}{\rho}\frac{dF(\rho)}{d\rho} + \left(1 - \frac{\mu^2}{\rho^2}\right)F(\rho) = 0, \tag{19}$$

which does not arise explicitly in our discussion here but offers a backdrop to it. Equation (19) emerges as the radial part of the linear homogeneous wave equation in cylindrical coordinates,[9]

$$\nabla^2\psi - \frac{1}{v^2}\frac{\partial^2\psi}{\partial t^2} = 0, \tag{20}$$

which describes locally any wave traveling with speed v and without dispersion, for which $\psi(x,y,z,t) = \psi(r \pm vt)$. An elegant integral representation of the Bessel function of order μ exists:[10]

$$J_\mu(x) = \frac{i^{-\mu}}{2\pi} \int_0^{2\pi} e^{ix\cos\theta} \cos(\mu\theta)\, d\theta. \tag{21}$$

In terms of a Bessel function, Eq. (18) becomes

$$\xi(\rho) = \frac{2\pi}{\pi a^2} \int_0^a \rho' J_o\left(\frac{k\rho\rho'}{r_o}\right) d\rho'. \tag{22}$$

Now make a change of variable and borrow a result from tabulated integrals of Bessel functions:[11]

$$\int_0^{\eta} x J_o(x)dx = \eta J_1(\eta) \tag{23}$$

to obtain $\xi(\rho) = 2J_1(\kappa)/\kappa$, where $\kappa = k\rho a/r_o$, to find

$$I = 4I_o\left(\frac{J_1(\kappa)}{\kappa}\right)^2. \tag{24}$$

This pattern features a central peak of intensity maximum (called an Airy disk for the central bright spot that appears on the screen), surrounded by a dark circular line at the intensity minimum and circular ripples of intensity maxima and minima outside the first minimum (Fig. 5b). The first minimum occurs when κ is the first root of $J_1(\kappa) = 0$, or $\kappa = 3.823$.[7,8,10] In terms of the angle θ, $ka \sin\theta = 3.823$, which is typically expressed by relating the aperture diameter to wavelength:

$$(2a)\sin\theta = 1.22\lambda. \tag{25}$$

When the circular aperture is replaced by a circular disk of the same diameter, Babinet's principle predicts a bright spot directly behind the disk, in the region that would, but for diffraction, be in shadow! This "unexpected" bright spot is called Poisson's spot, named after Siméon D. Poisson, thanks to an incident of intellectual dispute that occurred between him and Augustin Fresnel in 1818—therein lies an amusing story.[12]

If two sources close together are viewed from a large distance away, diffraction sets a limit on how well they can be resolved, that is to say, distinguished from a single source. A simple criterion put forward by Lord Rayleigh says that the two circular apertures can be resolved if the center of the Airy spot from one aperture lands on top of the first minimum from the other aperture.[13] The critical angle at which this occurs satisfies Eq. (25). If $\theta > \sin^{-1}(1.22\lambda/2a)$, then the two apertures can be resolved. Familiar applications include distinguishing two stars (e.g., the double star Mizar in the handle of the Big Dipper), and the two taillights of a distant car, when the pupil of your eye is the aperture. Diffraction places a limit on what we can expect from an optical system consisting of radiation, an aperture, and an image.

FRAUNHOFER DIFFRACTION AS A FOURIER TRANSFORM

We can formally generalize the aperture-image, diffraction-limited relationship in the Fraunhofer far-field zone. The crucial insight comes from an appreciation of Fourier transforms that gives one the choice between describing a signal in terms of its spatial-temporal variation, or in terms of its mixture of harmonic frequencies.

Any signal that is periodic with period T in time, or period λ in space, can be written as a harmonic series of sines and cosines, with each contributing frequency an integral multiple of the fundamental temporal frequency $\omega = 2\pi/T$ or of the fundamental spatial frequency $k = 2\pi/\lambda$. For instance, imagine freezing a wave in space at the instant $t = 0$. One side of Fourier's theorem says that, given the amplitudes A_n and B_n, one synthesizes ψ(x) according to

$$\psi(x) = \frac{A_o}{2} + \sum_{n=1}^{\infty}\left[A_n cos(nkx) + B_n sin(nkx)\right]. \tag{26}$$

For this to be meaningful the inverse problem must be solved, and the theorem goes on to show that, given $\psi(x)$, the amplitudes of the harmonics are

$$A_n = \frac{2}{\lambda}\int_0^{\lambda} \psi(x) cos(nkx)dx, \tag{27}$$

and similarly for B_n, with the sine replacing the cosine. A nonperiodic signal, or wave pulse, can be modeled by first giving it a finite period and then taking the limit as the period goes to infinity. Using complex forms of the trig functions through $e^{i\theta} = \cos\theta + i\sin\theta$, and assuming the superposition principle holds, a nonperiodic wave can be written as a superposition of harmonics.[14] However, because such a wave is unbounded, it no longer has a fundamental frequency. The sum over frequencies becomes continuous. For instance, looking again at the signal frozen in space, in this limit and in the language of complex numbers Eq. (26) becomes

$$\psi(x) = \int_{-\infty}^{+\infty} \zeta(k) e^{ikx} \frac{dk}{\sqrt{2\pi}}, \tag{28}$$

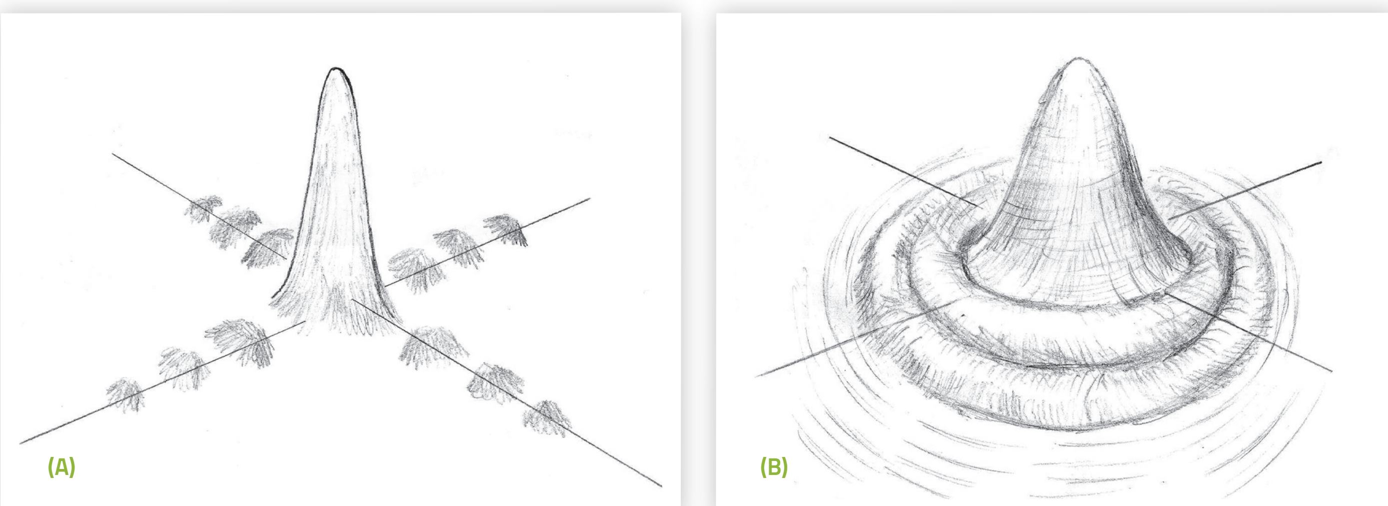


FIG. 5: The diffraction of (a) a square aperture and (b) a circular aperture.

where ζ(k) is the amplitude of the harmonic of wavenumber k (see below). Conversely, given ψ(x) one can find the spectrum of amplitudes ζ(k). For the inverse problem, define $\zeta_n = ½(A_n - iB_n)$, then take the limit as λ → ∞. Equation (27) and its counterpart for B_n give together

$$\zeta(k) = \int_{-\infty}^{+\infty} \psi(x) e^{-ikx} \frac{dx}{\sqrt{2\pi}}. \quad (29)$$

Go back now to the integral of Eq. (6) and set $t = 0$, so that before being evaluated the integral says

$$\psi(y) = \frac{A_o}{w} e^{ikz} \int_{-w/2}^{w/2} e^{ikyy'/z} dy'. \quad (30)$$

Let $\kappa = k/zy'$, allow A_o to become a function ζ of y', and hence a function of κ (so it gets pulled back behind the integral sign), absorb remaining constants into the amplitude ζ(κ), and integrate over the entire κ-axis by allowing $w \to \infty$. Now Eq. (30) becomes

$$\psi(y) = \int_{-\infty}^{+\infty} \zeta(\kappa) e^{iy\kappa} d\kappa, \quad (31)$$

the synthesis side of a Fourier transform. Given the distribution of amplitudes ζ(κ) along the κ (and thus y') axis, one can do the integral and find the wave function on the screen. For instance, if $\zeta(\kappa) = A_o$ for $w/2 \le y' \le w/2$ and ζ(κ) = 0 for $|y'| > w/2$, then the result following Eq. (6) is recovered. The smaller the value of w, the wider the spread of the pattern on the screen, and vice versa. That is the diffraction limit.

BEYOND THE DIFFRACTION LIMIT

Diffraction ultimately limits the resolution of a telescope, microscope, camera, or eye. In less-familiar settings, the ability of a computer chip manufacturer to further reduce the size of circuits that are made by mask-and-etch techniques [15] is also diffraction limited. This limit must be appreciated if we are to have a realistic understanding of what is possible, in principle, for imaging.

However, the diffraction limit is not absolute, being susceptible to loopholes offered by quantum mechanics. One example of a quantum loophole is the tunneling effect, in which a particle's probability to pass through a classically forbidden potential barrier is not zero but is exponentially damped. Another example is the Hawking mechanism of black hole evaporation, where, due to the Heisenberg uncertainty principle, vacuum fluctuations just outside a black hole's event horizon can occasionally produce a particle–antiparticle pair and one member of the pair escapes.

One can move the source and image close together into the near-field region, eschewing the Fraunhofer far-field region. In this setting, if the apertures are about the same size as the object being imaged, the latter can be imaged at a resolution below the diffraction limit. For example, if light is sent one photon at a time through a thin extruded optical fiber with a diameter on the nanometer scale, and if those photons hit a molecule and make it fluoresce, then an array of fluorescing molecules offers an image in which the diffraction resolution limit has been bypassed.[16]

Another method for beating the diffraction limit uses stimulated emission, whereby an originally excited molecule is induced to de-excite by the passage of an appropriately tuned incoming photon. One begins this process by passing a laser pulse through a lens to make the light mimic a point source as closely as possible, then shining the light on a sample. This excitation pulse excites target molecules into fluorescence. The pulse is followed by another one whose frequency is tuned to cause stimulated emission, de-exciting those molecules. To circumvent the diffraction limit, the de-excitation pulse is split into two beams with a relative offset Δκ [the κ of Eq. (24)]. The beams' two Airy disks land outside the Airy disk of the original excitation pulse. The central peak survives the de-excitation, leaving a pattern smaller than it would have been if limited by diffraction.[17]

In the next installment we will consider Fresnel diffraction, wave physics in the near zone that takes into account the curvature of wave fronts. //

ACKNOWLEDGMENT

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