Radiations

SPRING 2016

The official publication of Sigma Pi Sigma

page 7

page 12

page 19

Contents

7 Connecting Worlds

12 PhysCon Preview

The 2016 Quadrennial Physics Congress is quickly approaching. Here is a preview of what's in store. – *Rachel Kaufman*

19 Elegant Connections in Physics

26 Spotlight on Hidden Physicists

Departments

ON THE COVER
The ultra-bright X-ray laser pulses of the Linac Coherent Light Source at SLAC National Accelerator Laboratory can be used to strip electrons away from atoms, creating ions with strong charges. The ability to interact with atoms is critical for making the highest resolution images of molecules and movies of chemical processes. A tour of SLAC is on the agenda for PhysCon 2016. (Artwork by Gregory Stewart, SLAC.)

Radiations

Spring 2016
Volume 22, Issue 1

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

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

Impacting Lives

A farewell from the director

by Sean Bentley
Director (2014–2015), Sigma Pi Sigma and Society of Physics Students

As I finish my time at Sigma Pi Sigma and the Society of Physics Students (SPS) and prepare to return to academia, I am reflecting on why many of us find undergraduate physics education so important. It is at the heart of what Sigma Pi Sigma celebrates and what SPS works to improve and enhance. There is value in knowledge itself. There is value in having more people understand the fundamentals of physics, and how to reason through problems is certainly a plus for society. But for many of us, our work in education is more about impacting lives.

College is a transformational time in a person's life. For most, it is a transition from youth to adult, from dependent to independent, from student to professional. Many enter college not sure what they want to do with their lives, yet feeling pressure to choose a major and plan the next 50 years in a few months. As if this wasn't enough, students also struggle with financial, social, and personal issues. While these struggles are not limited to physics majors, those who choose to major in physics or a related field may more likely be people who excelled all through K–12. They suddenly face classes in which the average on an exam may be at a level considered failing in most majors. If anyone needs help, certainly an undergraduate in physics does.

Sean Bentley (in the wizard hat) with Adelphi University students (l to r) Bill Miller, Danielle Sofferman, Jess Scheff, Binayak Kandel, Monika Mohacsi, and Sajan Shrestha at PhysCon 2012.

Regardless of the details of the challenges we faced, all of us in Sigma Pi Sigma went through the life of an undergraduate in physics. That makes it even more real and more personal for us. We see ourselves in these students, and we feel their struggles as though they are our own. In my 13 years in academia, I have worked with many students whose problems exceeded any I ever went through. I am happy to say that many of them have gone on to successful lives and careers. As is a common theme in Sigma Pi Sigma, only a few ultimately earned a PhD in physics. Most went on to a variety of other fields, from medicine to Spanish literature. Helping students become professionals is the primary reason many of us want to make a difference in undergraduate physics education. Regardless of what career path you have chosen, I hope that as a Sigma Pi Sigma member or friend, you want to help the students of today.

So as I leave you, I want to remind you of three key ways you can impact the lives of undergraduates with an interest in physics through your involvement in Sigma Pi Sigma. You can give of your knowledge and time by connecting with students at your *alma mater* or a local chapter (and be watching for information on the new Sigma Pi Sigma mentoring network to be launched in the future). You can come meet the students and share your experiences with them firsthand at our Quadrennial Physics Congress in San Francisco this November (see page 12 for more information). Finally, you can help support them financially by giving to our scholarships, internships, Congress travel fund, and more at *donate.aip.org*.

It has been an honor to serve as director of our fine organization. Thank you for all that you do, and let's all keep working to positively impact young lives.

Scholar Off to Cambridge

Sigma Pi Sigma member plans a career in astrophysics

by Russell Nay, Correspondent at the University of South Florida's The Oracle

Sigma Pi Sigma member Michael Calzadilla is the first student from a Florida university to win the Gates Cambridge International Scholarship and one of 40 annually selected in the United States. The Gates Cambridge International Scholarship, sponsored by the Bill and Melinda Gates Foundation, funds graduate work and study abroad programs at the University of Cambridge in England.

Calzadilla, a senior double majoring in math and physics with a minor in astronomy at the University of South Florida, holds a 3.98 GPA and is a part of the USF Honors College. He began at Cambridge in October, where he plans to obtain his one-year master's degree before returning to the United States to earn a doctorate in astrophysics.

"Many great minds have walked along the steps of Cambridge, and I'm excited to walk where they have walked," he said.

The first in his family to attend college, Calzadilla was not always bound for a successful future in higher education—even attending college was an uncertainty.


Michael Calzadilla. Photo courtesy of Lauren Chambers/USF.

"Out of high school, there was a certain pressure to help out at home and get a job, so coming to college wasn't a popular idea," he said. "I had to find a lot of mentors, because this is uncharted territory being the first one in my family to go to college."

Calzadilla completed research in astrophysics and astronomy at MIT and Harvard, received funding from USF to build an astronomy telescope on campus, and revived student involvement in Sigma Pi Sigma, one of USF's major physics clubs.

"The purpose of the telescope is to cap off my astronomy education to show what I've learned," Calzadilla said. "Also, so other students in the future don't have to go off campus to do astronomy research."

Though he still enjoys a number of hobbies such as playing violin, boxing, running, and traveling, Calzadilla said his alternate dream job would be to become a concert violinist. His interest in math, physics, and astronomy began when he was young and in awe of space documentaries.

In the future, he said, he would like to become a professor in astrophysics and get involved with public outreach programs to promote scientific learning.

"I would like to be able to do what public figures like Carl Sagan and Neil deGrasse Tyson did for me when I was younger," he said. "Too many Einsteins lived a life doing things in which their best abilities weren't put to use."

The American Institute of Physics is an organization of scientific societies in the physical sciences, representing scientists, engineers, and educators. AIP offers authoritative information, services, and expertise in physics education and student programs, science communication, 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 the 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

Member Societies

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

Other Member Organizations

Sigma Pi Sigma, Society of Physics Students, Corporate Associates

Connect with Sigma Pi Sigma

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

Facebook
www.facebook.com/groups/sigmapisigma

Meet the Norfolk Chapter

Small but substantial chapter reminds students that physics is a “big deal”

by Doyle Temple
Professor of Physics and Optical Engineering and Center for Materials Research Director at Norfolk State University in Virginia

Norfolk State University (NSU) has a very small physics department, so small that the school tried to get rid of it a few years ago. As a physicist, I looked for data and did some research about the statistics of our department.

When we were on the chopping block, I started calling other state schools in Virginia. I learned that we had graduated fewer majors in physics than most of the other schools over the last 10 years. But we had more African American physics graduates than all the other schools combined.

After convincing the administration to keep the program, I started thinking about the students in the senior-level physics class I taught. They were really good students—too good not to be a part of Sigma Pi Sigma. I realized that I had to somehow get them into the honor society before they graduated, so I decided to form a new chapter at our school.

Sigma Pi Sigma is the first honor I put on my résumé, because it’s a big deal. Being part of any honor society is a big deal, but physics is special. I think students don’t really understand what it means to be a physicist in the eyes of the rest of society. They get stuck solving their mechanics problems for class and forget that we’re understanding how the universe works. They forget that people have a lot of respect for physicists. They forget that you can do pretty much anything with a physics degree.

Starting a new chapter, especially in a small department, wasn’t easy. It was a real race to get it done, and we made mistakes along the way. One student who didn’t understand the grade-point requirement was really upset when he discovered that his friends were getting in, but he wasn’t. I regret that; we should have explained things more clearly.

Thanks to help from the National Office, though, we were able to hold our first meeting last year. As we inducted new members, I could tell that they understood what it means to be a part of Sigma Pi Sigma. One student described his induction in his application essay for graduate school. (He got in!)

Faculty and students collaborate at the Center for Materials Research at NSU. Photo courtesy of NSU Center for Materials Research.

Together with the Society of Physics Students, our chapter is now setting up a nice outreach demo program for local schools. The students are really excited about it. They’re coming up with their own experiments. It’s going to be a lot of fun.

We’re hoping to use the outreach as a recruiting tool. If we can convince even one or two students at a local high school to study physics at NSU, that would double our average. It may even help our department to survive.

Chartered in 2016

Sigma Pi Sigma congratulates all of its newest chapters! We encourage you to share the story of how your chapter formed. Send your story to *Radiations* at *sigmapisigma@aip.org*.

- Bridgewater College
- Doane College
- Florida Atlantic University
- Indiana University–Purdue University Fort Wayne
- Mercyhurst University
- Missouri Southern State University
- Norfolk State University
- Saint Michael’s College
- Southern Polytechnic State University
- Xavier University of Louisiana

Doane College Sigma Pi Sigma Induction. Photo courtesy of Steve Feller.

www.sigmapisigma.org

Building a Better Guitar Pick

Thin film physicist coats steel picks to improve playability

by Gerald Mearini, Sigma Pi Sigma Ohio State Chapter, Class of 1985, President, GENVAC Aerospace in Highland Heights, OH

A few years ago I fabricated several stainless steel guitar picks in my company's machine shop. As a long-time guitarist, I loved the flex-free feel of the stainless pick, which limited response time during fast picking runs. But ultimately, the metal-on-metal contact of the hard pick wore down the strings and led to string breakage after only a few days of playing.

As a thin film physicist with decades of experience at NASA and in the private sector, I'm well aware of the benefits of very hard, very low friction coatings for wear applications. I was curious how such coatings could help my picks.

My company, GENVAC Aerospace, Inc., specializes in chemical vapor deposited diamondlike carbon (DLC) coatings. Over the last 20 years the company has developed high-frequency (millimeter wave and terahertz) amplifiers. We have made extremely robust DLC-coated infrared lenses for military aircraft for more than 15 years.

Our technical team, which had no previous experience working on metal coatings, began to modify the DLC deposition process to enable a robust coating on metal parts. We hoped to take advantage of numerous wear-resistant coating opportunities in the tool and metal fabrication industries.

I realized that optimizing a DLC coating for a stainless steel guitar pick would teach the GENVAC team how to deposit the coating on metals. The hardness and very low coefficient of friction attributes of diamondlike carbon could also potentially result in a revolutionary guitar pick by significantly reducing drag, enhancing playability, and eliminating the string breakage problem.

It took several months of iterating through deposition parameters in our 11,000-square-foot facility on the eastern edge of Cleveland, Ohio, but eventually our DLC no longer chipped off the edges of stainless steel guitar picks and other three-dimensional steel parts we tested. By early 2015 GENVAC had optimized DLC coatings for metals using two processes: plasma-enhanced chemical vapor deposition and direct ion-beam deposition. The coating properties were modified such that the coating no longer delaminated from the metal surface and conformed somewhat to flexing and ductile deformation. That was accomplished by reducing stress in the DLC coating and modifying the properties of the proprietary adhesion layer.

During this development period the company also developed metal finishing processes which provide an adequately smooth edge on hardened steel cutouts in mass quantities without hand working. This process chain, coupled with DLC optimized for wear resistance on metal substrates, led to a new product line at GENVAC: ROCK HARD Diamond-Like Carbon Coated Guitar Picks.

Although they're "just" guitar picks, they are significant because they actually enable faster picking with less effort (something my fellow guitar enthusiasts will certainly appreciate) due to the very smooth low-friction "no-drag" surface resulting from the hard DLC coating. Atomic force microscopy measurements made at Case Western Reserve University show that the thin DLC coating reduces the surface roughness of the electropolished stainless surface by a factor of 2. Also, the coefficient of friction is reduced more than a hundredfold, from about 0.78 for stainless steel on steel to less than 0.005 for DLC-coated stainless steel on steel.

Ultimately GENVAC intends to optimize DLC coatings for all metal wear points on the guitar, including the bridge, saddle, nut, tuners, and even possibly the frets. The elimination of wear and reduction in friction at these points will significantly reduce if not eliminate detuning and string breakage and likely result in a unique sound. Many other musical instruments can benefit from DLC as well.

The Tacoma Narrows Bridge Collapse

A new look at old video footage

by Donald W. Olson, Steven F. Wolf, and Joseph M. Hook

On November 7, 1940, the Tacoma Narrows Bridge in Washington State collapsed during a gale. The remarkable oscillations of its long and slender center span in the months leading up to the catastrophe earned the bridge the moniker "Galloping Gertie." The disaster is especially well known because of dramatic film footage taken the day of the collapse. Decades later the film was converted to video formats, but we have discovered that the conversion was not always faithful.

Disaster film

The original 16-mm motion picture record of the events was created by four people: bridge official Walter Miles; professional photographers Barney Elliott and T. Harbine Monroe from the Camera Shop in Tacoma; and Frederick Burt Farquharson, an engineering professor at the University of Washington and consultant regarding the bridge oscillations. Typically, the 16-mm cameras operated at 16 frames per second when recording silent films and at 24 fps when recording sound, though they sometimes ran at speeds slower or faster than those. In addition to his camera, Farquharson had a surveyor's transit, reference targets that he arranged to have set up along the bridge, and a stopwatch to determine the period of the oscillations.

On the morning of 7 November, the bridge oscillated vertically until a few minutes after 10 o'clock, at which time Farquharson observed a sudden change to the torsional, or twisting, motion captured on film. Elliott filmed Farquharson walking near the nodal line—the stationary line about which the twisting occurred—as the professor attempted unsuccessfully to save a dog stuck in an automobile stalled on the center span. The bridge withstood the torsional stresses for only about an hour. At 11:02 am a 600-foot section of roadway broke loose and fell into Puget Sound, and about six minutes later almost all the remaining center span dropped. Monroe managed to capture part of the collapse.

In the early 1960s, physicist Franklin Miller Jr. created a series of physics films, distributed in cartridges that played in Technicolor film-loop projectors. Miller converted 16-mm footage of the bridge collapse to 8-mm format for what became the best known of his films. Most physics teachers and students from the 1960s, 1970s, and even into the 1980s have a vivid recollection of the flickering images cast by the film-loop projector as the bridge twisted and collapsed. Counting frames proves that each 16-mm film frame was copied to a single 8-mm film frame.

Silent running

Video formats such as videodisc, VHS, and DVD generate video fields at rates near 30 fps. In 1982 physicists Robert Fuller, Dean Zollman, and Thomas Campbell produced a videodisc containing Miller's film, additional archival film footage, and interactive material. The American Association of Physics Teachers (AAPT) published some of the material from the videodisc as a VHS videotape in 1989 and in both VHS and DVD formats in 2000.

The technicians making the conversion from film to video assumed that all the 16-mm cameras were running at the sound speed of 24 fps, and they knew that video displays would operate at 30 fps. Therefore, they converted every four film frames to five video frames by a process known as telecine. As part of the process, video scans are interlaced—that is, created in two separate scans, one for odd lines and one for even lines—and some video frames are created as a hybrid mixture of two film frames. Those techniques are intended to make the action appear natural and at normal speed.

When the last torsional vibrations before collapse are stepped through frame by frame, the resulting count is 100 video frames per oscillation. At a running speed of 30 fps, that is equivalent to a period of $3\frac{1}{3}$ seconds and a frequency of 18 cycles per minute—values that can be confirmed by watching the video with a stopwatch in hand. But the period and the frequency observed in the video are definitely wrong.

In 1949 Farquharson published his stopwatch observations of the last oscillations of 7 November 1940; he measured a frequency of 12 cycles per minute and a period of five seconds. The frequency seen in the videos is too high by 50 percent. A "reverse telecine" reveals the reason. The original 16-mm and 8-mm films had 80 film frames per oscillation, four-fifths the video's 100 frames per oscillation. The frame rate for the original 16-mm camera can therefore be calculated as (80 film frames)/(5 s) = 16 fps, the rate commonly used for silent 16-mm films.

The surprising conclusion is that viewers playing any of the video formats have a mistaken impression of the bridge's motions. Because the telecine conversion was done by assuming that all the 16-mm cameras were running at the sound speed of 24 fps, the video formats show the torsional oscillations significantly sped up over the majestic 12-cycles-per-minute oscillations measured by eyewitnesses on November 7, 1940.

A different kind of analysis is required for the collapse sequence filmed by Monroe. Plan and elevation drawings of the bridge provide dimensions and distances that set a length scale for each film frame. The filmed accelerations of roadway sections dropping into Puget Sound match the acceleration of gravity only if Monroe's 16-mm camera was running at 24 fps, the speed assumed for the telecine conversion. Therefore, viewers of the video formats see the collapse sequence at the speed observed by eyewitnesses 75 years ago.

The rise and fall of resonance

Was the bridge collapse caused by resonance? That assertion perhaps first appeared in a newspaper article, "A great bridge falls," published in the *New York Times* on 9 November 1940: "Time successive taps correctly and soon the pendulum swings with its maximum amplitude. So with this bridge. What physicists call resonance was established." Miller's film loop included a title screen, "Nov. 7, 1940, 10:00 AM. Start of resonance vibration of bridge in torsional mode." The textbooks written by David Halliday and Robert Resnick in the early 1960s enlivened the section on resonance with photographs of the Tacoma Narrows Bridge and concluded that the "wind produced a fluctuating resultant force in resonance with a natural frequency of the structure."

But subsequent authors have rejected the resonance explanation, and their perspective is gradually spreading to the physics community. The user's guide for the current AAPT DVD states the bridge collapse "was not a case of resonance." Bernard Feldman likewise concluded in a 2003 article for *The Physics Teacher* that for the torsional oscillation mode, there was "no resonance behavior in the amplitude as a function of the wind velocity."

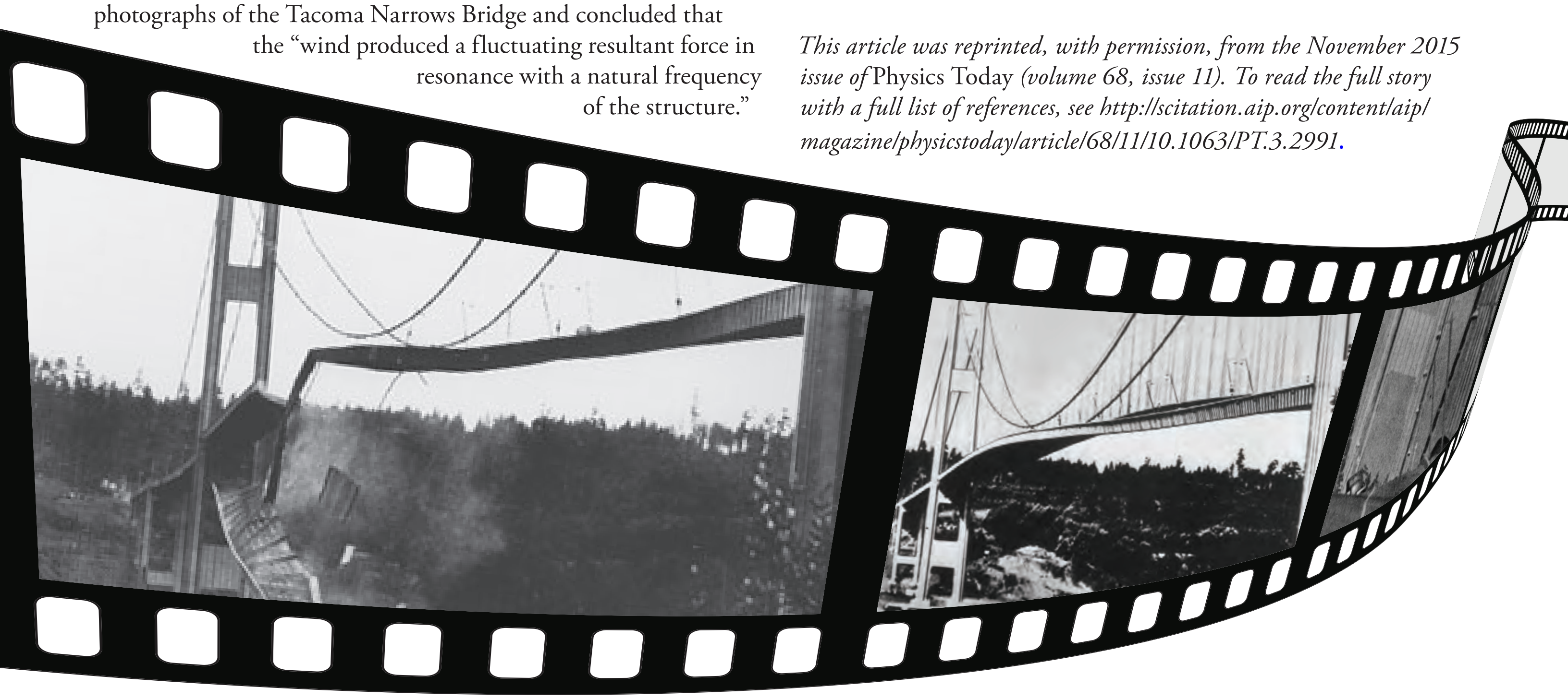
An important source for both the AAPT user's guide and for Feldman was a 1991 *American Journal of Physics* article by K. Yusuf Billah and Robert Scanlan. According to the two engineers, the failure of the bridge was related to a wind-driven amplification of the torsional oscillation that, unlike a resonance, increases monotonically with increasing wind speed. The fluid dynamics behind that amplification is complicated, but one key element, as described by physicists Daniel Green and William Unruh, is the creation of large-scale vortices above and below the roadway, or deck, of the bridge. Nowadays, bridges are constructed to be rigid and to have mechanisms that damp oscillations. Sometimes they include a slot in the middle of the deck to alleviate pressure differences above and below the road.

The Armistice Day storm

The strong winds in the Tacoma Narrows on 7 November 1940 were related to a remarkable low-pressure system that followed a track across the country and four days later produced the Armistice Day storm, one of the greatest storms ever to strike the Great Lakes region. For example, when the storm reached Illinois, the headline on the front page of the *Chicago Tribune* included the words "Heaviest winds in this century smash at city."

Additional details of the film and video analysis can be found in the November 2015 issue of *The Physics Teacher*, which also includes further description of the Armistice Day storm and the strong winds that earlier had caused the Tacoma Narrows Bridge to oscillate, twist, and collapse into the waters below.

This article was reprinted, with permission, from the November 2015 issue of Physics Today *(volume 68, issue 11). To read the full story with a full list of references, see http://scitation.aip.org/content/aip/magazine/physicstoday/article/68/11/10.1063/PT.3.2991.*



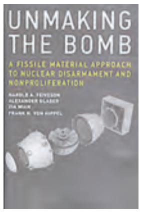
Five Fantastic Physics Books

Physics Today's selection of books that stood out in 2015

by Jermey N. A. Matthews
Associate Editor, American Institute of Physics in College Park, MD

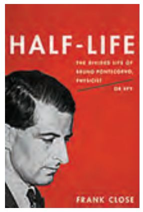
Now in its fifth year, the "end of the year holiday picks" feature highlights five of the most intriguing books that were reviewed in the pages of *Physics Today*. This year's emphasis was on books that are broadly accessible.

To Explain the World: The Discovery of Modern Science by Steven Weinberg (Harper/HarperCollins, 2015; $28.99; 432 pp.). Why did Aristotle not deduce Earth's sphericity when he saw ships appearing mast-first over the horizon? According to author and physics Nobel laureate Steven Weinberg, it is because the ancients "did not know how to interrogate nature in the systematic way necessary to wring reliable scientific knowledge from it," writes historian of science and book reviewer Joseph Martin. Instead, Weinberg credits the collective efforts of luminaries of the scientific revolution for launching "the sequence of scientific discovery that continues to this day.… Reconstructions of key discoveries made between Copernicus and Newton lead into his account of what distinguishes the modern scientific attitude from prescientific philosophizing." To historians, Weinberg's judgment of history by contemporary standards is "whiggish," a pejorative term that Weinberg embraces, writes Martin. The publisher's description on the front flap of *To Explain the World* goes even further, calling the physicist's historical account "irreverent."



Unmaking the Bomb: A Fissile Material Approach to Nuclear Disarmament and Nonproliferation by Harold A. Feiveson, Alexander Glaser, Zia Mian, and Frank N. von Hippel (MIT Press, 2014; $30.00; 296 pp.). This book presents a timely and scholarly perspective on the issue of controlling highly enriched uranium (HEU) and plutonium, "the essential ingredients of nuclear weapons," writes nuclear policy expert and book reviewer Matthew Bunn. The book makes clear that "few technical barriers exist to reducing stocks of HEU," writes Bunn, citing the US program that led, until 2013, to "1 in 10 light bulbs in the US ... being powered by [uranium] from dismantled Russian nuclear bombs."

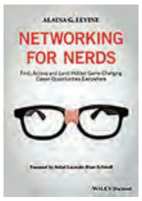
Plutonium, however, is a different beast: It's more costly to handle, to secure, and to reprocess into nuclear fuel. The authors recommend, among other options, storing the toxic material in geological repositories. Of relevance to the recent Iran nuclear agreement, the book briefly discusses "'nuclear archaeology' techniques that might be useful in determining whether countries' declarations of how much plutonium and HEU they have match up with the physical evidence from their production facilities." But by Bunn's account, it is surprisingly brief on the disarmament verification process; for more on verification, see this *Physics Today* news report (December 2015, page 26).



Half-Life: The Divided Life of Bruno Pontecorvo, Physicist or Spy by Frank Close (Basic Books, 2015; $29.99; 384 pp.). A handsome, charming, and ebullient Italian-born physicist, the scion of a wealthy, liberal Jewish family, joins the Communist Party and flees into Russia's arms during the Cold War. But did Bruno Pontecorvo end up spying for Russia, or did he simply carry out pure research on subnuclear particles? "Physicist Frank Close can conclude only that the spying is likely but not proven," writes historian of science and book reviewer Spencer Weart.

According to Weart, "Close does an excellent job of explaining the science and history of nuclear and particle physics" and argues that Pontecorvo, had he still been alive, might have received a share of the 2002 Nobel Prize in Physics for his theoretical work on neutrino oscillation. In bringing "several new source materials to bear," writes Weart, *Half-Life* is "the most complete and readable biography of a remarkable individual and his extraordinary response to extraordinary times."

Mondo Nano: Fun and Games in the World of Digital Matter by Colin Milburn (Duke University Press, 2015; $28.95 paper; 424 pp.). According to science writer and book reviewer William Atkinson, *Mondo Nano* employs several "conceptual filters" to explore nanotechnology, including history, military technology, speculative fiction, and video games. The interactive platform of massive, multiplayer online role-playing games allows experts and nonexperts to "rub shoulders" while they "explore the possibilities of new ideas such as combat exoskeletons and artery-cruising nanotherapeutics," writes Atkinson. Although the scholarly methods of Colin Milburn, a professor of English, cinematographic technology, and science and technology studies, are "not precisely those of the natural sciences," writes Atkinson, his book is "a thoroughly researched, thought-provoking read that offers many points to ponder."

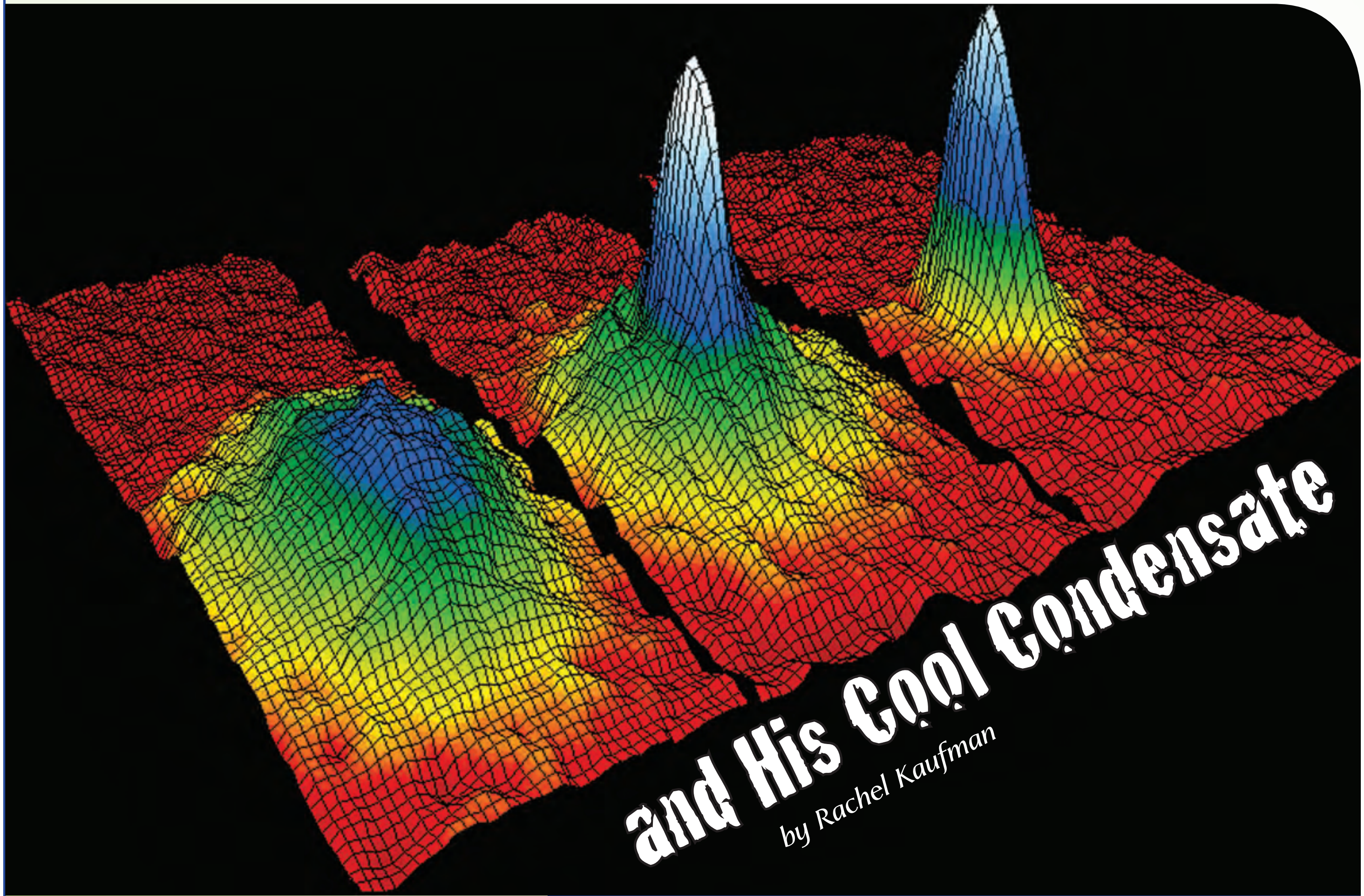


Networking for Nerds: Find, Access and Land Hidden Game-Changing Career Opportunities Everywhere by Alaina G. Levine (Wiley, 2015; $29.95 paper; 248 pp.). In case you're wondering what the author means by "nerds," her publisher describes the book as a resource for "established and early-career scientists and engineers." Expanding on that description, book reviewer Sean Bentley writes that "the aim of her book—to teach students and professionals in science and related fields the networking skills needed to become leaders—is something I have long promoted as an adviser, and director, of the Society of Physics Students and Sigma Pi Sigma." The book "covers a wide variety of topics, from dinner etiquette to critical tools for making the most of scientific conferences and social media," writes Bentley. Making her case, author Alaina Levine, founder and president of a leadership-training business and occasional guest blogger for Physics Today Online, notes that professional networking is critical for science because it leads to collaborations and the exchange of ideas. For students and other job-seeking physicists, it might also lead to gainful and rewarding employment.

To see the full story or purchase a book, visit http://scitation.aip.org/content/aip/magazine/physicstoday/news/10.1063/PT.5.3030.


The most complete directory of graduate programs in the physical sciences
Contact
301-209-3023
or email
info@gradschoolshopper.com
for more information.
GradSchoolShopper.com
A service of the American Institute of Physics

Eric Cornell and His Cool Condensate



by Rachel Kaufman

About the Author

Rachel Kaufman is a freelance writer and editor based in Washington, DC. Her work, on science, arts, business, food, health, and more, has been published in the *Washington Post*, *National Geographic News*, *Smithsonian Magazine*, *Scientific American*, and many other magazines, newspapers, and websites. She tweets infrequently at @rkaufman.

In preparation for Sigma Pi Sigma's 2016 Quadrennial Physics Congress (PhysCon), Kaufman sat down to talk with Nobel laureate Eric Cornell about his pioneering work in condensed-matter physics. She also delved into progress made on supersymmetry and string theory by S. James Gates, distinguished professor and Center for String & Particle Theory director at the University of Maryland. Cornell and Gates will be keynote speakers at PhysCon, which we cordially invite you to attend!

What happens when things get cold? Not just scarf-and-mittens chilly or even midnight-in-Antarctica cold—but really, *really* cold?

Answering that question earned Eric Allin Cornell a Nobel Prize.

He, along with Carl Wieman, synthesized in 1995 the first Bose–Einstein condensate using a process that cools matter to temperatures that seem impossibly low. Even the deep vacuum of space is far too warm for Bose–Einstein condensate (BEC). Only if you can get to about 170 nK—about 0.00000017 degrees above absolute zero—do some weird things start happening.

Born in Palo Alto in 1961, Cornell grew up in Cambridge, Massachusetts, where he was "an all-around curious kid," he told Sigma Pi Sigma, reading books surreptitiously during class and pondering physics brainteasers at night.

Eric Cornell. Photo by Brad Baxley, JILA.

As an undergrad at Stanford University, Cornell majored in physics, "but I wasn't necessarily gelled there," he told Sigma Pi Sigma. "I thought I would pursue something more on the humanities or social sciences side."

Ultimately, it was a job during the summers and after school that tipped the scales, as well as a year in Asia.

Cornell had taken a year off from college to study Chinese and teach English in Taiwan. He returned from that experience realizing that physics was something he enjoyed and was good at. He had been spending afternoons and summers working with the low-temperature physics groups to earn money. "The [physics] classes were OK," Cornell says. "It was really the after-school and summer thing that I found so thrilling. That was, I would say, really the thing that made me think I wanted to go and do physics."

After grad school at the Massachusetts Institute of Technology, he moved to a postdoc position at JILA, a joint institute of NIST and the University of Colorado Boulder. There his experience and interest in low-temperature physics led him to the discovery that won him his Nobel Prize.

"During those early years in Boulder, I spent a lot of time trying to imagine what a Bose–Einstein condensate would be like, if we could ever make one," he wrote. After his postdoc ended, he stayed at JILA to work on creating a condensate.

BEC is essentially a new form of matter, predicted by Satyendra Nath Bose and Albert Einstein in 1924 to occur when atoms are cooled to almost absolute zero. Physicists had been struggling to create BEC ever since to confirm Bose and Einstein's theory.

In 1992, when Cornell joined JILA as a professor, "the idea of BEC was in the air," Cornell once wrote. But the most advanced cooling techniques of the time were not powerful enough to reach the required temperatures.

"We were pretty optimistic in the face of a lot of skepticism," he told Sigma Pi Sigma. "We had some good arguments for why it would work."

Creating BEC at JILA required using laser and magnetic traps to bring a cluster of rubidium atoms close to absolute zero. Even 10 millionths of a degree above absolute zero is too warm to create BEC, so getting the substance cold enough took some doing.

Inspired by his advisor-then-supervisor Carl Wieman, Cornell tinkered with equipment using off-the-shelf parts ripped from fax machines and CD drives. "It was the fastest way," he said. "If you could put something together really fast like that, why bother to order some exotic thing that might or might not work?"

Speed was an important consideration. By the mid-1990s, skepticism in the scientific community had given way to excitement; Cornell says he was less worried about not succeeding and more worried "that people were going to beat us to the punch."

But in 1995, Cornell, Wieman, and the JILA team first created and observed BEC. Doing so not only confirmed a 71-year-old theory, but also opened up a new branch of physics.

"As things get colder, their quantum mechanical nature tends to get more pronounced," Cornell said. "They get wavier and wavier and less like particles. The waves of one atom overlap with another atom and form a giant superwave, like a giant, Reagan-esque pompadour."

Hair metaphors aside, BEC is a way for physicists to observe quantum phenomena on, as Wieman has said, "an almost human scale." The BEC behaves like one giant atom.

For this discovery, Cornell and Wieman shared the 2001 Nobel Prize, along with Wolfgang Ketterle, whose team at MIT created BEC a few months after the JILA team.

Further reading:

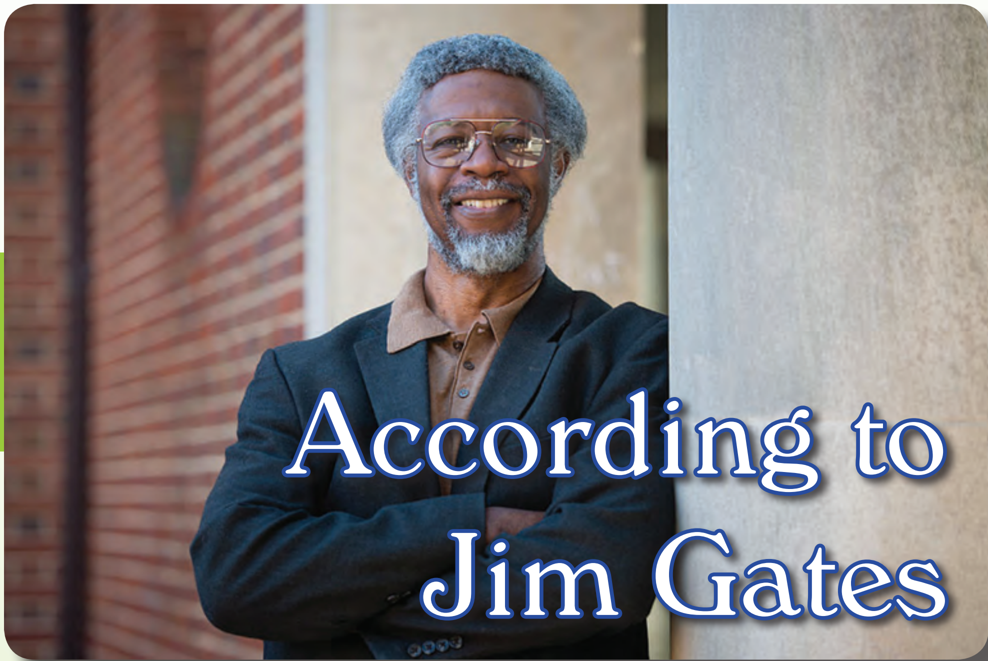
Check out Cornell's biography at the Nobel Prize site: http://www.nobelprize.org/nobel_prizes/physics/laureates/2001/cornell-bio.html

Read the lecture he gave upon receiving his Nobel Prize: http://www.nobelprize.org/nobel_prizes/physics/laureates/2001/cornellwieman-lecture.pdf

Unifying Fields
Science Driving Innovation

physcon
2016 Quadrennial Physics Congress
PREVIEW

The Universe According to Jim Gates



COLLEGE PARK, MD – JANUARY 29, 2016: S. James Gates is pictured outside the physics building at the University of Maryland, College Park. Photo by Sarah L. Voisin/*The Washington Post* via Getty Images.

by Rachel Kaufman

***Supersymmetry expert S. James Gates,** distinguished professor and Center for String & Particle Theory director at the University of Maryland, will be featured as one of the keynote speakers at PhysCon.*

If we are living in the Matrix, Jim Gates will probably be the first one to figure it out.

The theoretical physicist, who will give one of the plenary talks at PhysCon this year, has spent his entire career looking for supersymmetry. It's a concept tough for many to wrap their heads around, but it proposes that all particles have partners (that we haven't discovered yet).

Along the way, Dr. Gates has gotten attention for discovering what he says is computer code in the math of supersymmetry. Specifically, he said he has found an error-correcting mechanism; others have analogized this code to the checksums that make the Internet work by ensuring that transmitted information is accurate. This find has led him to speculate—in a mostly joking way—that we might be living in a giant computer simulation.

What this would mean for our universe is not yet clear. But Gates is content to keep looking until he finds out.

Sylvester James Gates, born December 15, 1950, in Tampa, Florida, was fascinated by science at an early age. He cites books on space travel that his father bought him at age eight as sparking his interest. “A world exploded in my head,” he said in 2013, “because I could see from these books that these tiny points of light in the sky at night were places you could go. And somehow in my young mind I knew that mathematics and science had something to do with going to those places.”[1]

A bit character in an episode of the sitcom *Make Room for Daddy* inspired him to set his sights on MIT. Gates told *NOVA* that seeing a smart kid who attended MIT on that show was “how I found out that there's a place you can go to college where they only make you study the good stuff,” the good stuff being math, science, and engineering.[2]

But as he grew older, Gates, who is African American, faced racial biases on the road to college. “I had to learn to be black,” he said in a 2013 speech.

A few years prior to Gates discovering MIT, his father left the US Army and moved to Orlando, Florida. At that time, the army had integrated schools, but Orlando did not.

"Segregation is an interesting phenomenon to experience," he said. "The people that are the minority come to believe the things that are said about them…One day on the playground…another African American said, 'You're pretty good at school.' And I said, 'Thank you.' And he said, 'But you can't be as smart as a white guy.'"

When it came time to apply to college a few years later, "I understood lots of things about the rules of how our society worked in those days, and I thought there's no way in the world that I would have the opportunity to go to such a place." He would have stopped himself from applying, but his father "literally forced me to fill out the application form." [3]

Gates was accepted. At MIT he earned two degrees, one bachelor's in math and another in physics, and went on to earn his PhD there four years later. His dissertation was the first written about supersymmetry at MIT, and no professors there could help him. Undaunted, he taught himself, earned his degree, and moved on to Harvard.

After a number of prestigious research and teaching positions, Gates landed at the University of Maryland in 1984.

Since then, Gates has been plugging away at supersymmetry and string theory. His research has been recognized with the National Medal of Science and the Mendel Medal, as well as an appointment to the President's Council of Advisors on Science and Technology.

We do not yet know whether string theory or supersymmetry is true. The first round of experiments at CERN's Large Hadron Collider found no evidence of supersymmetry. But that's just a push to keep going, Gates says.

"String theory is often criticized as having had no experimental input or output, so the analogy to a religion has been noted by a number of people," Gates told *NOVA*. "In a sense that's right; it is kind of a church to which I belong. We have our own popes and House of Cardinals. But ultimately, science is also an act of faith—faith that we will be capable of understanding the way the universe is put together."[4]

And if string theory is correct, so what? Well, Gates admits he doesn't know. But think of scientists like James Maxwell who unified electricity and magnetism. "One can imagine saying, 'Professor Maxwell, what do your equations mean?' He would struggle for answers. He would say, 'Well, you know, the electric and magnetic phenomena are not separate, they're part of a unity.' But beyond that I think he would be rather hard-pressed to tell you what it means. One hundred and fifty years later we can answer this question very easily. A large fraction of our technological basis rests on his work."[5]

"So if string theory is correct, what does it mean? Well, one can imagine 150 or 200 years from now some marvelous piece of technology that's beyond my imagining. Maybe it's a transporter from *Star Trek*, perhaps it's warp drive, maybe our species finally is released from … being contained in a single solar system."[6]

Until then, Gates will keep looking.

1 World Science Festival. "The Moth: Go Tell It on the Mountain - Jim Gates". *YouTube* video, 21:17. December 5, 2013, https://youtu.be/gDCbBWfhJ1o.

2 Gates, Jim. Interview with Joe McMaster. *NOVA*, Public Broadcasting Service, July 2003.

3 World Science Festival, 2013.

4 McMaster, *NOVA*, 2003.

5 Ibid.

6 Ibid.

2016 PhysCon Art Contest

Attendees are invited to submit 2-D and 3-D works of art for judging or display in Sigma Pi Sigma's third Quadrennial Physics Congress (PhysCon) art contest.

Art Categories

- Congress Theme: *Unifying Fields—Science Driving Innovation*
- Congress Site Visits: *Inspired by SLAC National Accelerator Laboratory, NASA Ames Research Center, and Google X*
- General Science

Abstract deadlines and contest details can be found on the PhysCon website at: ***www.sigmapisigma.org/congress/2016***.

Here we feature some of the winning pieces from the 2012 PhysCon Art Contest. To see larger images of all of the artwork, visit the 2012 website at ***www.spscongress.org/physconprogram/artwork-contest.***

Best in Show:
Pirouette, by Glenn Marsch, Grove City College

First Prize: Connecting Worlds
Nothing Going on Here, or So It Seems, by Jordan Guzman, University of Central Florida

Artists' Choice & People's Choice:
Particle Detection in the Search for New Matter, A collaboration by Christopher Frye and Emily Daniels, University of Central Florida

Images courtesy of AIP.

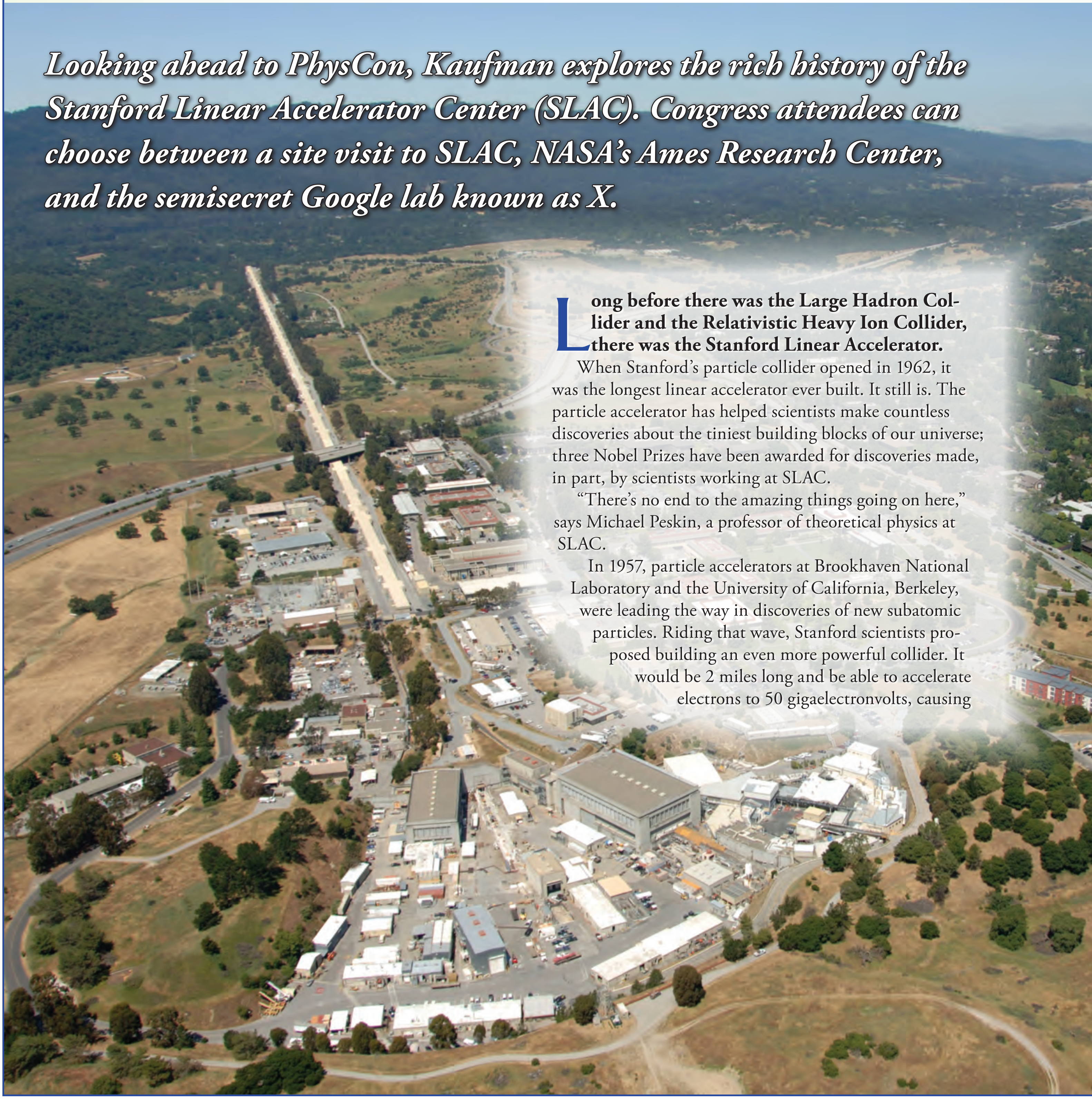
Unifying Fields
Science Driving Innovation

physcon
2016 Quadrennial Physics Congress
PREVIEW

SLAC Probes Building Bl

by Rachel Kaufman

Looking ahead to PhysCon, Kaufman explores the rich history of the Stanford Linear Accelerator Center (SLAC). Congress attendees can choose between a site visit to SLAC, NASA's Ames Research Center, and the semisecret Google lab known as X.



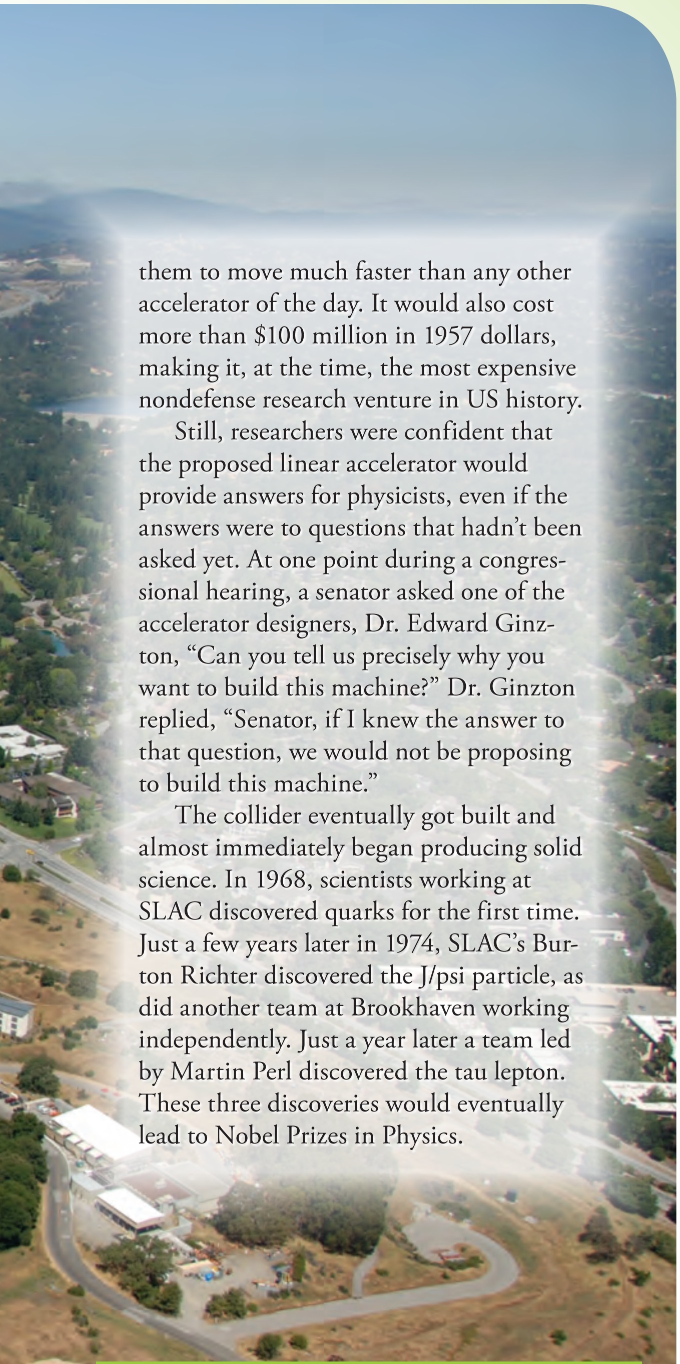
Long before there was the Large Hadron Collider and the Relativistic Heavy Ion Collider, there was the Stanford Linear Accelerator.

When Stanford's particle collider opened in 1962, it was the longest linear accelerator ever built. It still is. The particle accelerator has helped scientists make countless discoveries about the tiniest building blocks of our universe; three Nobel Prizes have been awarded for discoveries made, in part, by scientists working at SLAC.

"There's no end to the amazing things going on here," says Michael Peskin, a professor of theoretical physics at SLAC.

In 1957, particle accelerators at Brookhaven National Laboratory and the University of California, Berkeley, were leading the way in discoveries of new subatomic particles. Riding that wave, Stanford scientists proposed building an even more powerful collider. It would be 2 miles long and be able to accelerate electrons to 50 gigaelectronvolts, causing

locks of Matter



them to move much faster than any other accelerator of the day. It would also cost more than $100 million in 1957 dollars, making it, at the time, the most expensive nondefense research venture in US history.

Still, researchers were confident that the proposed linear accelerator would provide answers for physicists, even if the answers were to questions that hadn't been asked yet. At one point during a congressional hearing, a senator asked one of the accelerator designers, Dr. Edward Ginzton, "Can you tell us precisely why you want to build this machine?" Dr. Ginzton replied, "Senator, if I knew the answer to that question, we would not be proposing to build this machine."

The collider eventually got built and almost immediately began producing solid science. In 1968, scientists working at SLAC discovered quarks for the first time. Just a few years later in 1974, SLAC's Burton Richter discovered the J/psi particle, as did another team at Brookhaven working independently. Just a year later a team led by Martin Perl discovered the tau lepton. These three discoveries would eventually lead to Nobel Prizes in Physics.

SLAC National Accelerator Laboratory is home to a two-mile linear accelerator—the longest in the world. Originally a particle physics research center, SLAC is now a multipurpose laboratory for astrophysics, photon science, accelerator, and particle physics research. Photo courtesy of SLAC National Accelerator Laboratory.

Around the same time, says Peskin, "Professor William Spicer noticed that the synchrotrons here emit X-rays at a rate which is… potentially a billion times more intense than one got from the standard equipment at the time. And so this enabled all kinds of new X-ray experiments, which were done here for the first time." The Linac Coherent Light Source, or LCLS, reuses a third of SLAC's old accelerator. (The other two-thirds is dedicated to the FACET project, which is an R&D project for experimental beam physics.)

Now, SLAC's X-ray free-electron laser "has pretty much taken over the whole laboratory," Peskin says. The LCLS, when it opened, was a billion times brighter than any other X-ray source in existence, says Alan Fry, division director of laser science and technology for the LCLS. "It's the difference between a high-powered laser and moonlight." The LCLS also produces extremely short pulses that last just a few femtoseconds. "This is the time scale on which stuff actually happens at the molecular and atomic scale," Fry says. That means researchers can use the LCLS to create essentially stop-motion movies of molecules breaking apart or electrons redistributing themselves. Mike Minitti, a SLAC scientist whose "molecular movie" of 1,3-cyclohexadiene unfurling was on the cover of *Physical Review Letters* last summer, told the journal at the time, "This fulfills a promise of LCLS. Before your eyes, a chemical reaction is occurring that has never been seen before in this way."

Because scientists are clamoring for time on the LCLS (SLAC runs around the clock almost every day), and because there's even more to be done with X-ray lasers, SLAC is building the LCLS-II, which will increase the number of X-ray pulses from 120 per second to a million per second. LCLS-II is under development now but won't open for another 5 or 6 years. When it does, researchers will be able to perform new kinds of experiments in emerging fields like quantum chemistry, structural biology, and surface physics, potentially leading to new understandings of basic matter, as well as new technologies and materials.

SLAC's equipment is used for more than just probing the properties of tiny particles. Scientists have studied the bone chemistry of Archaeopteryx with SLAC's synchrotron radiation lightsource and revealed hidden text written by Archimedes on a manuscript that had later been overwritten with 10th-century Greek Orthodox prayers. Other SLAC researchers are helping to develop an experiment that detects dark matter, or hunting for ways to improve rechargeable batteries, develop better antibiotics, and even improve computer hard drives.

"It's always been an exciting place, with people coming up with crazy ideas," Peskin says.

Fry agrees. "This is really only the beginning of the story of these machines and what they're going to be able to do and the science they're going to be able to produce."

Unifying Fields
Science Driving Innovation

Unifying Fields

Science Driving Innovation

PLENARY SPEAKERS

- **Jocelyn Bell Burnell**, Visiting Professor at the University of Oxford
- **Eric Cornell**, Senior Scientist at JILA, NIST, and the Department of Physics, University of Colorado at Boulder, and 2001 Physics Nobel Laureate
- **Persis Drell**, Dean of Stanford University School of Engineering and Director Emerita of the SLAC National Accelerator Laboratory
- **S. James Gates**, Distinguished Professor and Director, Center for String & Particle Theory at the University of Maryland
- **Neil Turok,** 2016 Tate Medalist for International Leadership, South African physicist and the Director of Perimeter Institute for Theoretical Physics

WORKSHOP TOPICS

- Unifying Fields: Science Driving Innovation
- Careers for Physicists
- Public Relations for Physicists
- Taking your SPS Chapter to the Next Level
- Building up the Community
- Life as a Graduate Student

SCIENCE & TECHNOLOGY SITE VISITS

- SLAC National Accelerator Laboratory
- NASA's Ames Research Center
- Google X

REFLECTIONS FROM 2012

"What advice would you give to students thinking about attending an upcoming Physics Congress? GO!"

– Gus Hart, Professor at Brigham Young University, 2012 attendee

"Attending the 2012 Congress was one of the most influential weekends of my undergraduate career."

– Danielle Weiland, 2012 attendee

"I had always felt a bit like a 'pretend' physicist, or perhaps I didn't fit right. While I'm not working in physics after graduation, PhysCon cemented my belonging in the science world."

– Audrey Burkart, 2012 attendee

physcon

2016 Quadrennial Physics Congress

POSTER SESSIONS • ART CONTEST • EXHIBIT • DANCE PARTY

BREAKFAST WITH THE SCIENTISTS • MORE DETAILS TO COME!

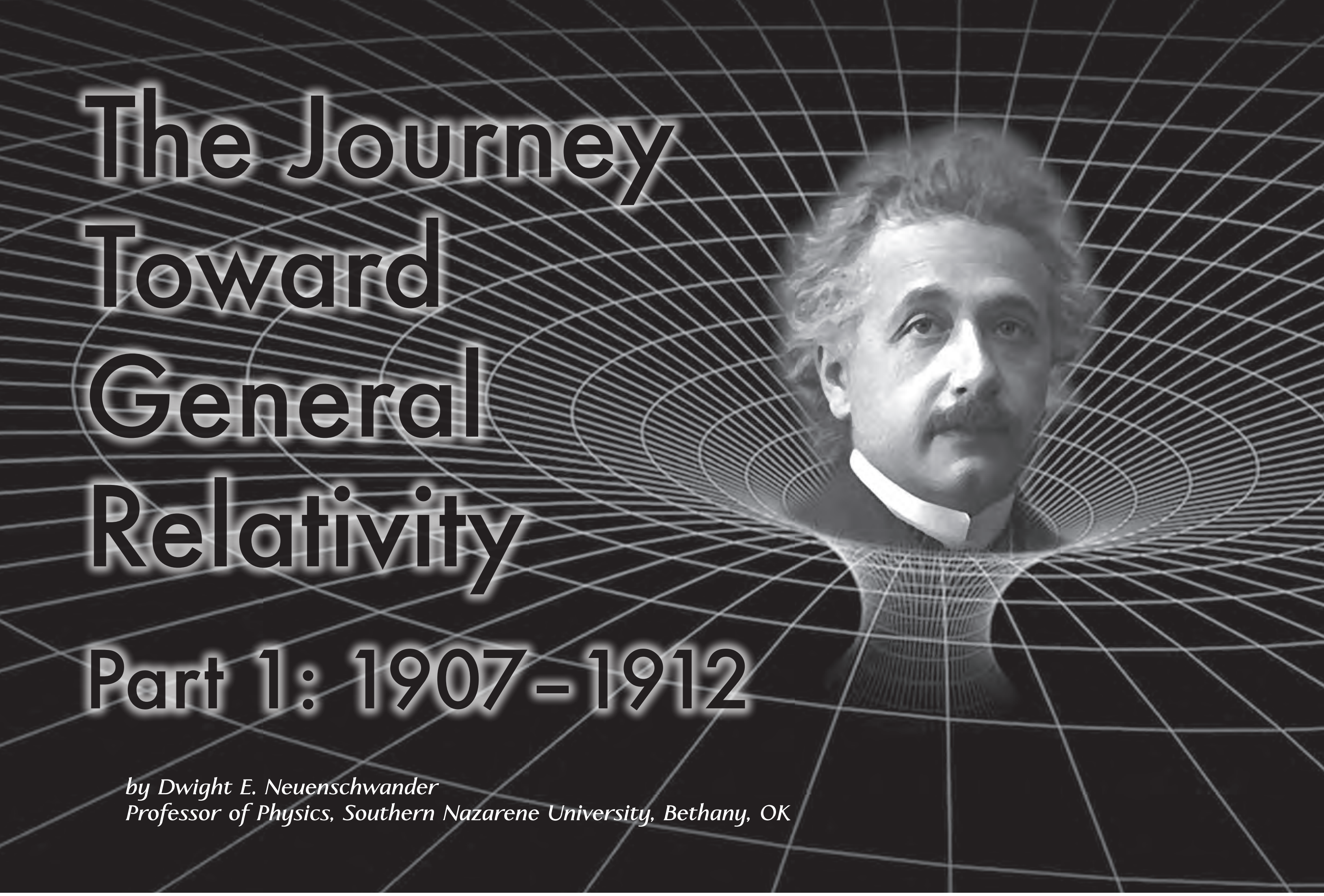
Dr. Jocelyn Bell Burnell is the Honorary Chair of the 2016 Physics Congress. Best known for her pioneering work on the discovery of radio pulsars, Bell Burnell is a Dame Commander of the Order of the British Empire, Fellow of the Royal Society, and a Fellow of the Royal Astronomical Society. She was a plenary speaker at both the 2012 and 2004 Physics Congresses.

November 3–5, 2016 • Silicon Valley

www.sigmapisigma.org/congress/2016

AIP American Institute of Physics

Hosted by Sigma Pi Sigma, the physics honor society



The Journey Toward General Relativity

Part 1: 1907–1912

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

Image by Matt Payne

Just over one century ago, on November 25, 1915, Albert Einstein presented to the Prussian Academy of Sciences the completed version of his general theory of relativity. His journey toward that theory had begun in 1907, was interrupted until 1911, and then continued with nonstop intensity until the end of 1915.[1]

Despite the great triumphs of the 1905 papers that introduced special relativity through electrodynamics,[2,3] they could not be the last word, because they excluded accelerated reference frames and gravitation. Those gaps weighed heavily on Einstein's mind after 1905. In 1907 Einstein was asked to write a review of special relativity for the prestigious journal *Jahrbuch der Radioaktivität und Elektronik*.[4] He took this opportunity to begin extending relativity to gravitation. This effort appeared in the last part of the article, Sec. V, which the editor received on December 4, 1907. Einstein's close friend and biographer Abraham Pais notes, "It is here that he begins the long road from the special theory to the general theory of relativity."[5]

The "happiest thought"

In 1920, Einstein recalled that his attempts between 1905 and December 1907 to extend relativity to gravitation "did not satisfy me because they were based on physically unfounded hypotheses….Then there occurred to me the happiest thought of my life…"[6] That thought was reminiscent of the electrodynamics puzzle with which Einstein introduced one of the 1905 relativity papers:[2] when a magnet passes through a coil of conducting wire, the changing magnetic flux as observed in the coil's reference frame induces an *electric* force on charges in the coil. But an observer aboard the magnet sees the coil's charges carried with nonzero velocity past the magnet, experiencing a *magnetic* force. The electric field can be transformed away by a change of reference frame. Einstein's "happiest thought" was his realization that a gravitational field could also be transformed away, at least locally, by a change of reference frame. In the 1920 manuscript he wrote, "The gravitational field has only a relative existence in a way similar to the electric field generated by magnetoelectric induction. *Because for an observer falling freely from the roof of a house there exists—at least in his immediate surroundings—no gravitational field*"(Einstein's emphasis).[6] In a lecture given at Kyoto University in Japan in December 1922 he again recalled,[7] "The breakthrough came suddenly one day. I was sitting on a chair in my patent office in Bern. Suddenly a thought struck me: If a man falls freely, he would not feel his weight. I was taken aback. This simple thought experiment made a deep impression on me. This led me to the theory of gravity."

Since gravity could be transformed away locally by going into a free-fall frame, Einstein saw that the principle of relativity—the postulate that laws of physics must not depend on the frame of reference—when extended to include *accelerated* frames, could be a theory of gravitation. The 1907 *Jahrbuch* paper was his first public attempt to include gravity within the principle of relativity.

Uniform acceleration and the relativity of time

Let us follow Einstein's 1907 treatment of the relativity of time and length for a reference frame moving with constant acceleration relative to inertial ones. Einstein had at his service the tools of the equivalence principle, the principle of relativity, and the results of his 1905 papers. He began with kinematics, and with clever insight applied his tools to *three* reference frames. Two of them were inertial, and the third one was accelerated. He called them S, S', and Σ, respectively; here I call them the lab frame L with coordinates (t,x), the coasting rocket frame CR with coordinates $(t'x')$, and the accelerated rocket frame AR with coordinates (t'',x'').[8] The layout is the usual one found in introductory special relativity discussions. The CR frame moves with constant velocity v relative to L; the x and x' axes are parallel and CR moves in the direction of $+x$; and when their origins coincide, the arrays of synchronized clocks in both frames read $t = 0$ and $t' = 0$.[9] Thus transformations from (t,x) to (t',x') coordinates are described by the familiar form of the Lorentz transformation:

$$t' = \gamma(t - vx/c^2), \qquad (1)$$
$$x' = \gamma(x - vt), \qquad (2)$$

where $\gamma \equiv (1 - v^2/c^2)^{-1/2}$, and c denotes the speed of light in vacuum. With Einstein, we further suppose the AR frame moves with acceleration a relative to L, with its x'' axis parallel to those of x and x', and $t'' = 0$ when the three origins coincide, at which event the AR begins accelerating from rest relative to L. Hence, relative to the lab frame, the location of CR and AR origins are, respectively, $x_{CR} = vt$ and $x_{AR} = \frac{1}{2}at^2$, and the velocity of each rocket relative to L is $v_{CR} = v$ and $v_{AR} = at$. To first order in v/c (an approximation used throughout Sec. V), AR accelerates at the same rate a relative to both L and CR.[10]

Designate as E(v) the event were AR has the same velocity as the CR moving at speed v relative to L. At event E(v), CR and AR are instantaneously at rest relative to one another. Einstein asks about the kinematics of AR, relative to L and CR, for a short time interval after E(v). If the acceleration a and the time interval following E(v) are sufficiently small, then the relation between AR and CR is given *approximately* by the Lorentz transformation. Further approximations result by dropping terms quadratic in v/c and a. In 1907 Einstein was willing to sacrifice rigor to get a feel for the problem—always a good starting strategy.

With Einstein, we seek the effect of acceleration on coordinate transformations between inertial and the AR frames. At event E(v), by Eq. (1), for which $x = vt$, clocks aboard the CR frame read time t', where [11]

$$t' = \gamma t\,(1 - v^2/c^2) \approx t. \qquad (3)$$

Similarly, for any two spatial points 1 and 2 that are the coordinates of events simultaneous in the lab frame, we find by Eq. (2), to first order in v/c, that $x_2' - x_1' \approx x_2 - x_1$. Notice that the time dilation and length contraction effects of special relativity are effectively being ignored; Einstein seeks the effects of gravitation as acceleration on kinematics. But the Lorentz transformation provides the necessary tool, because the second term on the right-hand side of Eq. (1) will turn out to be crucial, where v in Eq. (1) will be replaced with at, as we shall see.

Consider next the time interval between t and $t + \delta$, where t is the lab time coordinate of E(v), and δ is small. With Einstein, we ask about the relativity between L and AR for this interval. At some time t' within this interval [resetting $t' = 0$ in the CR at E(v)], relative to CR the accelerated rocket's origin is located at $x' = \frac{1}{2}at'\,2$ and moves with velocity $v' = at'$. Now transform the CR time coordinate to the AR coordinates, assuming the acceleration to be modest enough that the transformation is approximately Lorentzian within a brief interval after E(v). By Eq. (1), we obtain

$$t'' = \gamma'[t' - (at')(\tfrac{1}{2}at'^2)/c^2] \qquad (4)$$

so that, to order v/c, $t'' \approx t' - O(a^2) \approx t - O(a^2)$, where $O(a^2)$ means terms of order a^2.[12] Also, as it was between L and CR, to first order in v/c, the length contraction reduces to $x_2'' - x_1'' \approx x_2' - x_1'$.

Now comes the main point. Consider two events, E1 and E2. They are simultaneous in the CR frame if and only if $t_1' = t_2'$ exactly. By Eq. (1), in terms of lab coordinates this means

$$t_2 - t_1 = v(x_2 - x_1)/c^2. \qquad (5)$$

Let E1 be E(v), and let E2 be an arbitrary event that occurs shortly after E(v), within the lab time interval t to $t + \delta$. Thus $v = at_1$, and by our previous results we may set $t_2 \approx t_2'' + O(a^2)$ and $x_2 - x_1 \approx x_2'' - x_1''$. Equation (5) can now be expressed in terms of L-to-AR coordinates as

$$t_2'' = t_1\,[1 + at_1\,(x_2'' - x_1'')/c^2] + O(a^2). \qquad (6)$$

Noting that E(v) occurs at the origin of the AR frame, we set $x_1'' = 0$ and drop the subscripts. To first order in a we obtain [13]

$$t'' = t\,(1 + ax''/c^2). \qquad (7)$$

Now comes the punch line: We invoke Einstein's postulate of the local equivalence of acceleration and a gravitational field, and set $a = -g$. In other words, when the AR moves with acceleration a in the $+x$ direction relative to the lab, a passenger aboard the accelerated rocket cannot locally distinguish this acceleration from a gravitational field g in the $-x''$ direction, where $|g| = |a|$. The gravitational field g and its potential Φ are related by

$$\Phi(x'') = -\int g\,dx'' + const., \qquad (8)$$

which yields, for uniform $g = -a$, $\Phi(x'') = ax''$ with the integration constant set to zero. This turns Eq. (7) into

$$t'' = t\,(1 + \Phi/c^2). \tag{9}$$

In his 1905 relativity papers, Einstein introduced *global* Lorentz invariance, where a unique velocity v describes the relative motion between two inertial frames; the same Lorentz transformation held *everywhere* between those frames. But now, the *local* equivalence between accelerated frames meant that if he held on to the principle of relativity, then *global* Lorentz transformations would have to go; in general, the Lorentz transformation only holds *locally*. Abraham Pais observed that, in 1907, "Others might have shied away from the equivalence principle in order to retain the global invariance. Not so Einstein. With a total lack of fear he starts on the new road. For the next eight years he has no choice. He has to go on."[14] Pais put the 1907 Sec. V into perspective. It "does not have the perfection of the 1905 paper on special relativity. The approximations are clumsy and mask the generality of the conclusions. Einstein was the first to say so, in 1911… Despite all that, I admire this article at least as much as the perfect relativity paper of 1905, not so much for its details as for its courage…."[15]

Despite its shortcomings, Eq. (9) implies predictable consequences. Einstein mentioned them in the *Jahrbuch* paper, and revisited them in more detail when he returned to this subject in 1911. These include gravitational redshift; position dependence of the speed of light in a gravitational field, and thus the deflection of light rays by massive bodies; and the demonstration that $E = mc^2$ applies to both inertial and gravitational mass. Because my space is limited, here I will merge his 1907 and 1911 discussions of these applications.

After the 1907 paper, Einstein said no more in public about gravitation until 1911. In the interim he was focused on quantum theory and radiation. His life was busy in personal ways, too. In July 1909 he could finally resign his post at the patent office to accept his first faculty position that October, as an associate professor of theoretical physics at the University of Zürich. In July 1910 a second son, Eduard, was born to Albert and Mileva Einstein. The family moved in March 1911 when Albert accepted his first full professorship at Karl-Ferdinand University in Prague.

In Prague, Einstein turned his focus back to gravitation with the 1911 publication "On the Influence of Gravitation on the Propagation of Light."[16] He began with a backward glance. "In a memoir published four years ago, I tried to answer the question whether the propagation of light is influenced by gravitation. I return to this theme, because my previous presentation of the subject does not satisfy me, and for a stronger reason, because I now see that one of the most important consequences of my former treatment is capable of being tested experimentally." In 1907 Einstein was thinking of terrestrial experiments to measure the gravitational deflection of a light ray, and he realized this deflection would be too small to detect with such experiments. By 1911 he realized that astronomers looking beyond Earth might be able to test it. He continues, "For it follows from the theory here to be brought forward, that rays of light, passing close to the sun, are deflected by its gravitational field, so that the angular distance between the sun and a fixed star appearing near to it is apparently increased by nearly one second of arc."[17] He also revisited the 1907 inferences on gravitational redshift and whether $E = mc^2$ applies to both gravitational and inertial mass.

Gravitational redshift

In the 1907 paper Einstein made a qualitative observation in a subsection called "Influence of the Gravitational Field Upon Clocks." He wrote, "If at a point P of the gravitational field Φ there is situated a clock which indicates the local time, then according to Eq. (9) its indications are $1 + (\Phi/c^2)$ greater than the time [t], i.e., it runs $1 + (\Phi/c^2)$ faster than in an identically constructed clock situated at the origin of coordinates."[18] In 1911 he turned this qualitative comment into a quantitative prediction and derived the same result in a much simpler way than the path that led to Eq. (9), this time by starting with the relativistic Doppler shift for light. The Doppler shift says that when a source light at rest relative to the CR gets carried with velocity v along the x-axis relative to L, the light's frequency as observed in the lab frame is [19] $f_{\text{moving}} = f_{\text{rest}}\,\gamma\,(1 + v/c)^{-1}$. Einstein applied this to radiation emitted and detected within a uniformly accelerated frame. Let the light be emitted from point P1, to arrive at a detector at point P2 some distance h away in the same system. If the radiation has the frequency f_1 relative to the clock at P1, then upon the radiation's arrival at P2, that detector moves with velocity $v = at = ah/c = \Phi/c$ (neglecting length contraction effects). Therefore, by the Doppler formula just mentioned, to first order in v/c the radiation would have a greater frequency f_2 at P2,

$$f_2 = f_1(1 + ah/c^2) = f_1\,(1 + \Phi/c^2). \tag{10}$$

To see consistency with the 1907 result, consider a clock of period T_1 at location 1, where the gravitational potential is Φ_1. At location 2 where the potential is Φ_2, an identical clock has period T_2. According to Eq. (9) their periods are related by

$$1 = [T_2\,(1 + \Phi_2/c^2)]\,[T_1\,(1 + \Phi_1/c^2)]^{-1}$$

$$\approx (T_2/T_1)\,[1 + (\Phi_2 - \Phi_1)/c^2], \tag{11}$$

where the binomial expansion has been used assuming $\Phi/c^2 \ll 1$. Equations (10) or (11) give the frequency shift,

$$(f_2 - f_1)/f_1 = (\Phi_2 - \Phi_1)/c^2, \tag{12}$$

the same as Eq. (10).

Testable predictions follow immediately. In a uniform gravitational field $\Phi = gy$, where $y_1 = 0$ is the level of the floor and $y_2 = h$ is the top of a building, the frequency shift is gh/c^2, the basis of the 1960 Pound-Rebka experiment [20] that offered the first precise terrestrial affirmation of gravitational redshift. The atom in the stronger potential emits light of lower frequency (longer wavelength). For the gravitational potential about a star of mass M, $\Phi = -GM/r$. If point 2 denotes the solar surface where $\Phi_2 = -GM/R$ (M is the Sun's mass = 2×10^{30} kg,

R is the solar radius ≈ 7×10^8 m, and G = 6.67×10^{11} Nm^2/kg^2 denotes Newton's gravitational constant), and $\Phi_1 \approx 0$ denotes the gravitational potential at Earth's orbit, Eq. (12) gives $f_2/f_1 = f_1(1 - GM/Rc^2) < f_1$, or $\Delta f / f_1 = 2\times10^{-6}$.[21] Even though he derived Eq. (9) for a *uniform* gravitational field, in the solar potential example Einstein boldly assumed the result also holds for an *inhomogeneous* gravitational field.

Does $E = mc^2$ hold for gravitational mass?

In September 1905 Einstein had showed that an object of mass m corresponds to an energy mc^2.[3] He derived this by considering a body that emits light and therefore suffers a change in mass. That paper was concerned with *inertial* mass, as signaled by its title, "Does the Inertia of a Body Depend on Its Energy Content?" Using a result for the relativity of energy derived in the June 1905 paper,[2] he imagined a source in the lab frame emitting light of energy E above the x-axis at angle φ. As seen by the CR frame, the emitted energy is

$$E' = \gamma E\,[1 - (v/c)\cos\varphi]. \qquad (13)$$

Let the AR frame start from rest and accelerate with acceleration a relative to a lab frame that has no gravity. At $t = 0$ when the AR frame begins accelerating, it simultaneously emits a light pulse of energy E_2 from a point at the distance h beyond the AR origin. A detector resides at the origin that will receive this pulse of radiation. As seen from the L frame, because length contraction is assumed negligible, it takes time h/c between the light being emitted and absorbed, and upon absorption the AR frame moves at speed ah/c relative to L. Applying Eq. (13) and noting that $\varphi = 180^{\circ}$, Einstein finds, to first order in v/c, that the energy absorbed is $E_1 \approx E_2(1 + ah/c)$. According to the principle of equivalence, $a = g$ in magnitude, and in a uniform field the potential is $\Phi = gh$. Therefore,

$$E_1 = E_2 + E_2\Phi/c^2. \qquad (14)$$

By virtue of $E = mc^2$, upon reception of the signal the mass equivalent has gone from $m_2 = E_2/c^2$ to $m_1 = m_2 + m_2\Phi$. Therefore, $E = mc^2$ holds for both inertial *and* gravitational mass.[22]

On the speed of light in a gravitational field

In the June 1905 paper that introduced special relativity,[2] Einstein predicted from his postulates the Lorentz transformations [23] of the electric field **E** and the magnetic field **B**, for inertial frames in relative motion with constant velocity **v**.[2] In terms of an unprimed "rest" frame and a primed "moving" frame, to first order in v/c the transformations read [24]

$$\mathbf{E}' \approx \mathbf{E} + \mathbf{v}\times\mathbf{B}/c \qquad \mathbf{B}' \approx \mathbf{B} - \mathbf{v}\times\mathbf{E}/c. \quad (15)$$

In the 1907 paper Einstein applied them to the Faraday-Lenz and Ampère-Maxwell laws to study the relativity of the speed of light in accelerated frames. In the same spirit, but following a different (we hope shorter) route, here we apply them to the electromagnetic wave equation and draw the same conclusion as Einstein. In source-free regions, consider an electromagnetic wave traveling in the x''-direction of the AR frame, with an electric field polarized in the y''-direction and the magnetic field in the z''-direction. An observer in the AR frame writes the homogeneous wave equation [25]

$$\partial^2E''_y/\partial x''^2 - (1/c''^2)\,\partial^2E''_y/\partial t''^2 = 0. \qquad (16)$$

Let us transform this to the CR frame shortly after event $E(v)$, when the speed v' of the AR relative to the CR is small, and apply Eqs. (15) in the form

$$\mathbf{E}'' \approx \mathbf{E}' + \mathbf{v}'\times\mathbf{B}'/c, \qquad \mathbf{B}'' \approx \mathbf{B}' - \mathbf{v}'\times\mathbf{E}'/c. \qquad (17)$$

Thus for events nearby in space and time to $E(v)$, the fields in the AR will be given by Eq. (15). With v' in the x''-direction, we find that $E_y'' \approx E'_y - v'B'_z/c$. Recalling that $dx'' \approx dx'$ to first order in v'/c, and leaving dt'' alone for the moment, we find

$$\partial^2E'_y/\partial x'^2 - (1/c^2)\,\partial^2E'_y/\partial t''^2 - (v'/c)[\partial^2B'_z/\partial x'^2 - (1/c''^2)\,\partial^2B'_z/\partial t''^2] \approx 0. \qquad (18)$$

The wave operators for the electric and magnetic field components vanish separately, and in each case, the denominator that is essentially $c^2(\Delta t'')^2$ becomes $c^2(1 + \Phi/c^2)^2(\Delta t')^2$. This says that, in the presence of acceleration, and thus in the presence of gravitation characterized by the potential field $\Phi(\mathbf{r})$, the speed of light in vacuum is the position-dependent quantity,[26]

$$c(\mathbf{r}) = c_o[1 + \Phi(\mathbf{r})/c^2], \qquad (19)$$

where c_o denotes the speed of light in vacuum without gravity.

Analogous to the speed of light being c/n in a medium of refractive index n, the gravitational potential produces, in effect, a variable index of refraction, $n = (1 + \Phi/c^2)^{-1}$. In the *Jahrbuch* paper Einstein qualitatively observed, "It follows from this that the light rays that are not propagated in the [x''] direction are bent by the gravitational field."[27] In the 1911 paper he offered a quantitative estimate of the deflection, beginning with Huygens' principle (Fig. 1a). Consider a plane wave front AA. Suppose the speed of light, due to the gravitational potential of a nearby body, differs at points 1 and 2, which are the distance ℓ apart, with the potential larger at point 1. By Huygens' principle, the wave front after the elapse of time dt is inclined at the angle φ relative to AA, where $d\varphi = (c_2 - c_1)dt/\ell$ or by Eq. (19), in terms of arc length, $ds = \ell d\varphi = -\Delta\Phi dt/c_o = -(\nabla\Phi\cdot d\mathbf{r})dt/c_o$.[28] Thus the deflection per unit path of light ray is $d\alpha \equiv ds/(c_o dt) = -(\nabla\Phi\cdot d\mathbf{r})/c_o^2$. Let a light ray come from infinity and pass the Sun (mass M and radius R, $\Phi = -GM/r$) at grazing incidence. As shown in Fig. 1b, the angle of deflection follows from

$$\alpha = \frac{2}{c_0^2}\int_\infty^R \frac{GM}{r^2}\,dr = \frac{2GM}{c_0^2 R}; \qquad (20)$$

the 2 coming from symmetry about the point of closest approach. Einstein obtained the numerical value of 0.83 seconds of arc (half of what general relativity would predict four years later), and concluded, "It would be a most desirable thing if astronomers would take up the question here raised. For apart from any theory there is the question whether it is possible with the equipment at present available to detect an influence of gravitational fields on the propagation of light."[29]

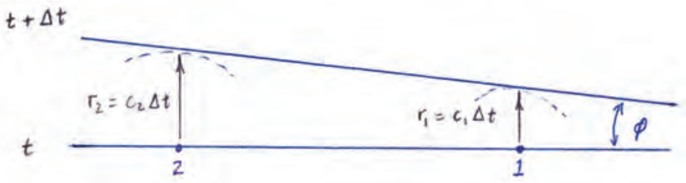


Fig. 1 (a)

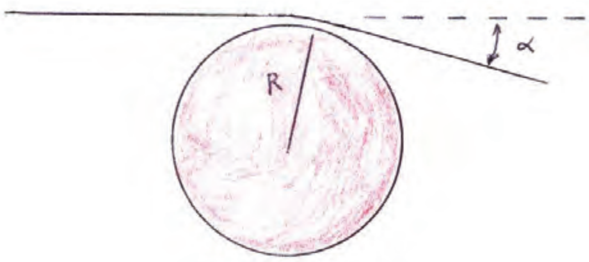


Fig. 1 (b)

Fig. 1. (a) The Huygens wave fronts used to estimate light wave deflection. (b) Deflection of a light ray passing the Sun.

An expedition was planned for 1914, but it was cancelled by the outbreak of World War I.[30] While the war was a disaster for humanity, for Einstein's measurement the cancellation turned out to be fortuitous, for although he did not realize it at the time, his 1911 result gave the same deflection as Newtonian gravitational theory. Newton thought of light as a swarm of particles. In *Opticks* (1704) he asked, "Do not bodies act upon light at a distance, and by their action bend its rays…?" Because m cancels out of $\mathbf{F} = m\mathbf{a}$ when $\mathbf{F}$ is the force of gravity, in a uniform field the deflection of a particle of light becomes just another projectile problem, and becomes a scattering problem with the $1/r$ potential.[31] In a little-known paper of 1804, Johann Georg von Soldner calculated the Newtonian deflection and obtained $\alpha = 0.84''$.[32]

Einstein published two more papers on gravitation-as-relativity in February and March 1912.[33] They mark Einstein's first attempt to go beyond gravity as kinematics, into a dynamical field theory by trying out the field $c(\mathbf{r}) \sim \Phi(\mathbf{r})$ of Eq. (14). The 1912 scalar theory did not survive into the final results of 1915, but the issues it raised helped prepare the way. Let us say a few words about the February and March 1912 papers.[34] The departure from Newtonian theory entered with the crucial result, carried over from the 1907 and 1911 papers, that the speed of light is a *scalar field*, where

$$c(\mathbf{r}) = c_o + \Phi(\mathbf{r})/c_o. \qquad (21)$$

In Newtonian gravitation theory—a *static* field theory—the potential follows from a mass distribution according to Poisson's equation, $\nabla^2\Phi = 4\pi G\rho$, with ρ the mass density. Introducing $\sigma_m = \rho c_o^{\,2}$ as the energy density of matter, Einstein's *ansatz* turns Poisson's equation into

$$\nabla^2 c = 4\pi G\, c_o^{-3}\sigma_m, \qquad (22)$$

still a static field theory. However, a particle of mass m moving *through* the static field would, in Einstein's 1912 theory, have the equation of motion similar to that of special relativity, even when the speed of light is a function of position. In special relativity, a free particle moves such that the integral of proper time is stationary, $\delta\int d\tau = 0$, where $c^2d\tau^2 = c^2dt^2 - d\mathbf{r}\cdot d\mathbf{r}$. Allowing c to be a function of spatial coordinates, this gives [35]

$$d/dt(\gamma\mathbf{v}/c) = -\gamma\nabla c, \qquad (23)$$

where $\mathbf{v} = d\mathbf{r}/dt$ (AR frame coordinates, primes dropped) and $\gamma = (1 - v^2/c^2)^{-1/2}$. Pais writes, "Einstein was stirred by the fact that [the equations of motion] still apply if c is a static field!...It is hard to doubt that this insight guided Einstein to the ultimate form of the mechanical equations of general relativity, in which eq. [$\delta\int d\tau = 0$] survives, while [the expression for $d\tau^2$] is generalized further."[36]

Pais wonders how Einstein could consider a *static* gravitational field coupled to a *dynamic* electromagnetic field. Pais never had the opportunity to ask Einstein about this, because he never saw these 1912 papers until after Einstein had passed away. So Pais imagined that Einstein pushed as far as he could with the simplest assumptions possible, until the inevitable contradictions would suggest to him the next step.[37] Such an instance came up at once. Since electrodynamics and gravity are coupled through Eq. (22), Einstein knew that the mass density of Poisson's equation for Φ would have to be generalized beyond the Newtonian paradigm to include the energy density of the electromagnetic field. Letting σ_{me} denote the sum of σ_m and the electromagnetic energy density $\sigma_e = \frac{1}{2}\varepsilon_o E^2 + B^2/2\mu_o$, the resulting Poisson equation, $\nabla^2 c = 4\pi G\, c_o^{-3}\sigma_{me}$, unfortunately did not satisfy local energy and momentum conservation.[38] The static Newtonian gravitational field $\mathbf{g}$ carries the energy density $\sigma_g = -g^2/8\pi G = -(\nabla\Phi)^2/8\pi G = -c_o(\nabla c)^2/8\pi G$ and thus Einstein postulated that

$$\nabla^2 c = 4\pi G\, c_o^{-3}(\sigma_{me} + \sigma_g), \qquad (24)$$

or in terms of Φ,

$$\nabla^2\Phi + \tfrac{1}{2}\, c_o^{-2}(\nabla\Phi)^2 = 4\pi G\, \sigma_{me}, \qquad (25)$$

a manifestly nonlinear theory. Pais quotes Einstein: "It has been a grave decision to make this last modification of the c-field equation, Einstein wrote, 'since [as a result] I depart from the foundation of the unconditional equivalence principle.'" In the absence of ponderable matter or electromagnetic radiation, so that $\sigma_{me} = 0$, Eq. (22) becomes $\nabla^2 c = 0$ in the AR frame, which by the unconditional equivalence principle would have to produce $\nabla^2 c = 0$ in the lab frame too. But if $\sigma_{me} = 0$ in Eq. (25), then $\nabla^2 c \neq 0$, *unless* the region where the equation is applied is so small that the gradient of the potential is negligible. Einstein continued, "It seems that [the equivalence principle] holds only for infinitely small fields…" Pais comments, "This is the dawn of the correct formulation of equivalence as a principle that holds only locally."[39]

With the February and March 1912 papers that Einstein wrote while living in Prague, he saw far enough into gravitation with relativity to see that if the principle of relativity was universal, then the principle of equivalence and Lorentz invariance could hold only locally, equations of motion could nevertheless follow from a variational principle, and gravity would couple to itself and thus its field equations be nonlinear. But he still lacked the language to pull it all together.

In August 1912, Einstein and his family moved back to Zürich. In the meantime he decided that the scalar theory would not do the job and space, as well as time, had to be non-Newtonian. For instance, in the early 1912 papers he mused on the possibility that the ratio of a circle's circumference to its diameter might not be π, because of a length contraction when the circle spins about its axis. In his Kyoto speech 10 years later he recalled, "If all accelerated systems are equivalent, then Euclidean geometry cannot hold in all of them…This problem remained insoluble to me until 1912, when I suddenly realized that Gauss's theory of surfaces holds the key for unlocking this mystery. I realized that Gauss's [non-Euclidean] surface coordinates had a profound significance. However, I did not know at that time that Riemann had studied the foundations of geometry in an even more profound way. I suddenly remembered that Gauss's theory was contained in the geometry course given by Geiser when I was a student…I realized that the foundations of geometry have physical significance. My dear friend the mathematician Grossman was there when I returned from Prague to Zürich. From him I learned for the first time about Ricci and later about Riemann…"[7, 40]

Marcel Grossman and Albert Einstein were students together at the Zürich Polytechnic. Grossman was a mathematician who knew tensor calculus. When Einstein returned to Zürich to teach at his alma mater (renamed the ETH in 1911), the former classmates got together in a collaboration that was to prove fruitful indeed, as we shall see in the next installment.

References

[1] Much of the history related here is adapted from *Subtle is the Lord: The Science and the Life of Albert Einstein* by Abraham Pais (Oxford University Press, 1982). Like other biographers, Pais had access to primary documents. Unlike most Einstein biographers, Pais knew Einstein personally and the physics thoroughly.

[2] Albert Einstein, "On the Electrodynamics of Moving Bodies," *Ann. der Phys.* **17** (1905) 891–921; see John Stachel (ed. and trans.) and Roger Penrose, *Einstein's Miraculous Year: Five Papers that Changed the Face of Physics* (Princeton University Press, 1998); or H.A. Lorentz, A. Einstein, H. Weyl, and H. Minkowski, *The Principle of Relativity*,W. Perrett and G.B. Jeffery, tr. (Methuen, 1923; reprinted by Dover, 1952). In addition, Einstein's 1905 relativity papers are annotated and expressed in modern notation in the "Elegant Connections in Physics" column: "On the Electrodynamics of Moving Bodies (Part A: Kinematics) by Albert Einstein," *SPS Observer* (Fall 2005), 10–15 and "On the Electrodynamics of Moving Bodies (Part B: Electrodynamics) and Its Corollary, $E = mc^2$, by Albert Einstein," *SPS Observer* (Winter 2005), 10–20.

[3] Albert Einstein, "Does the Inertia of a Body Depend on Its Energy Content?", *Ann. der Phys.* **18** (1905) 639–641; in ref. 2 see Stachel & Penrose, or *The Meaning of Relativity*, or Part B of "Elegant Connections."

[4] Albert Einstein, "On the Principle of Relativity and the Conclusions Drawn Therefrom," *Jahrbuch für Radioaktivität und Elektronik* **4** (1907) 411. For an annotated translation, see the three-part series by H.M. Schwartz: "Einstein's Comprehensive 1907 Essay on Relativity, Part I," *Am. J. Phys.* **45** (6), June 1977, 512–517; "Einstein's Comprehensive Essay on Relativity, Part II," *Am. J. Phys.* **45** (9), September 1977, 811–817; "Einstein's Comprehensive 1907 essay on Relativity, Part III," *Am. J. Phys.* **45** (10), October 1977, 899–902. The section of Einstein's 1907 paper that extends relativity to a frame moving with constant acceleration relative to inertial ones occurs in his Sec. V, whose translation appears in part III of Schwartz's paper. See also Pais, ref. 1,178–183.

[5] Pais, ref. 1, 178.

[6] The 1920 manuscript, never published, resides in the Pierpont Morgan Library, New York, NY; see Pais, ref. 1, 177–178.

[7] Albert Einstein, "How I Created the Theory of Relativity," translated by Yoshimasa A. Ono, *Physics Today*, Aug. 1982, 45–47.

[8] I use the "rocket frame" motif along the lines of *Spacetime Physics* by John A. Wheeler and Edwin Taylor (Freeman, 1966).

[9] The *y* and *z* dimensions are suppressed because we consider here no relative motion in those directions. Einstein considered them, which meant considering the *shape* of an accelerated body. He concluded "we do not have therefore to assume any influence of the acceleration on the shape of the body" (see Schwartz, ref. 4).

[10] Consider a particle moving with velocity v relative to the L frame and v' relative to the CR frame, where v_o denotes the constant relative velocity between the two inertial frames, so that, by the Lorentz transformation, $v' = (v - v_o)/(1 - vv_o/c^2)$. The particle's acceleration relative to L is $a = dv/dt$, and $a' = dv'/dt'$ relative to CR. It follows that $a' = (dv'/dt)(dt/dt') = a\gamma_o^{-3}(1 - vv_o/c^2)^{-3}$ where $\gamma_o = (1 - v_o^2/c^2)^{-1/2}$. Thus, $a' \approx a$ to order v/c.

[11] Quantities that will be approximated as unity (such as γ) or zero (such as terms of order v^2/c^2) are initially retained so the logic of the steps will be easier to follow.

[12] If the $O(a^2)$ terms were neglected from the outset, these results could have been written at once simply by setting $\gamma \approx 1$ for the time dilation and length contraction formulas. But determining the effect of acceleration on the kinematics was the point of the calculation. Albert Einstein was not one to take short cuts.

[13] Einstein speaks of σ as "local time" and τ as "time at the origin"; our Eq. (9) is his *Jahrbuch* Eq. (30a), which reads $\sigma = \tau[1 + (\Phi/c2)]$. He comments, "We have defined two kinds of time for [AR]. Which of the two definitions do we have to utilize in the different cases?...For the definition of physical quantities at a given place of the gravitational field, we quite naturally utilize the time σ….But if one deals with a phenomenon that necessitates the simultaneous consideration of objects situated at places of different gravitational potential, then we must employ the time σ." One can interpret our t'' (or Einstein's σ) as proper time for the situation under consideration, and our Eq. (9) [his Eq. (30a)] as the low-speed, gravitational field contribution to time dilation. Proper time is the time as recorded on the wristwatch of a passenger in AR, viz., a passenger in a gravitational field, and t is the time "at the origin" (Einstein's words) as recorded by a clock back at the origin of the lab frame (see E. Taylor and J.A. Wheeler's discussion of local time vs. "far-away time" in the Schwarzschild metric, *Exploring Black Holes: An Introduction to General Relativity* (Addison, Wesley, Longman, 2000), chs. 1, 2. In addition, from the Schwarzschild solution of general relativity, the relation between proper time dt_p and the time as recorded by an observer at some far-away station that receives data from local clocks around a star of mass M, for which $\Phi = -GM/r$, the relation between proper and far-away time is $dt_p = (1 - 2MG/rc^2)1/2dt \approx (1 + \Phi/c2)dt$, which agrees with our interpretation of Einstein's 1907 result.

[14] Pais, ref. 1, p. 183.

[15] *ibid*., 182–183.

[16] Albert Einstein, "On the Influence of Gravitation on the

Propagation of Light," *Ann. der Phys.* **35** (1911) 898, or *The Principle of Relativity* (ref. 2), 97–108.
[17] *The Principle of Relativity*, ref. 16, 99.
[18] See Schwartz, ref. 4, paper III, 900–901.
[19] E.g., B.W. Carroll and D.A. Ostlie, *An Introduction to Modern Astrophysics* (Addison-Wesley, 1996), 108.
[20] R.V. Pound and G.A. Rebka, "Apparent Weight of Photons," *Phys. Rev. Lett.* **4** (7), (1960), 337–401. These authors cited Einstein's 1911 paper, ref. 16. See also Taylor and Wheeler, ref. 8, 154–155.
[21] Einstein, ref. 16 (Perret & Jeffrey, tr.), 108.
[22] Einstein, ref. 4 (or Schwartz III, 902) and Einstein, ref. 16 (or Perret & Jeffrey, tr., 101–102).
[23] Introduced by H.A. Lorentz in "Electromagnetic Phenomena in a System Moving With Any Velocity Less Than That of Light," *The Principle of Relativity*, ref. 2, 9–34 ([original, Proceedings of the Academy of Sciences of Amsterdam, **6** (1904)].
[24] E.g., J.D. Jackson, *Classical Electrodynamics*, 2nd ed. (Wiley, 1975), 552. With no approximation the transformations read $\mathbf{E}' = \gamma(\mathbf{E} + \boldsymbol{\beta}\times\mathbf{B}) - \gamma^2(\gamma+1)^{-1}\boldsymbol{\beta}(\boldsymbol{\beta}\cdot\mathbf{E})$ and $\mathbf{B}' = \gamma(\mathbf{B} - \boldsymbol{\beta}\times\mathbf{E}) - \gamma^2(\gamma+1)^{-1}\boldsymbol{\beta}(\boldsymbol{\beta}\cdot\mathbf{B})$, where $\boldsymbol{\beta} = \mathbf{v}/c$.
[25] Here I follow the same *strategy* as Einstein used on Faraday-Lenz and Ampère-Maxwell laws.
[26] Referring back to note [13], in the 1907 paper Einstein uses $\partial/\partial\tau = (1 + \Phi/c^2)\,\partial/\partial\sigma$, equivalent to our method here.
[27] Einstein, ref. 4 (Schwartz III, 902), Einstein, ref. 16 (Perret & Jeffrey) 107. In the term Φ/c^2, one may use either $c(\mathbf{r})$ or c_o, since they are the same to first order in Φ/c^2. Einstein used c, I use c_o for definiteness.
[28] The minus sign appears because Φ gets smaller in magnitude as c gets larger, and the gradient points in the direction of increasing Φ.
[29] Einstein, ref. 16, *The Principle of Relativity* (ref. 16), 108.
[30] W. Isaacson, *Einstein: His Life and Universe* (Simon & Schuster, 2007), 202–205.
[31] "Elegant Connections in Physics: Starlight Deflection in Newtonian Mechanics," *SPS Observer*, www.spsnational.org/the-sps-observer/physics-connections.
[32] J.G. von Soldner, *Berliner Ast. Jahrbuch* (1804), 161; see also Pais, ref. 1, 194.
[33] A. Einstein, "Lichtgeschwindigkeit und Statik des Gravitationsfeldes," *Annalen der Physik* **38** (1912) 355–369; "Zur Theorie des Statischen Gravitationsfeldes," *Ann. der Phys.* **38** (1912) 443–458.
[34] See Pais, ref. 1, 201–206.
[35] $\delta\int d\tau = 0$ is a problem in the calculus of variations. Let us illustrate with one spatial dimension. Write $d\tau = [c^2 - (dx/dt)^2]^{1/2}dt$, giving the Lagrangian $L = [c^2 - v^2]^{1/2}$ so that the Euler-Lagrange equation, $\partial L/\partial x = d/dt(\partial L/\partial v)$, gives $-(dc/dx) = d/dt(\gamma v/c)$. Generalizing to three spatial dimensions yields Eq. (23).
[36] Pais, ref. 1, 203.
[37] *Ibid.*, 204.
[38] The electromagnetic field carries energy density σ_e and momentum density S/c^2 where $\mathbf{S} = (\mathbf{E}\times\mathbf{B})/\mu_o$ is Poynting's vector [e.g., see David Griffiths, *Introduction to Electrodynamics*, 2nd ed. (Prentice-Hall, 1999), ch. 8]. If the charged particles are also coupled to gravity, energy and momentum conservation are not accounted for only by the electromagnetic field and its coupling to matter; gravitational energy density and its current must be included.
[39] Pais, ref. 1, 205.
[40] Pais, ref. 1, 211–212, offers minor differences in translation as ref. 7; I have used the Pais translation here.

The Imagineer

Joel Peavy
Principal R&D Imagineer, Walt Disney Imagineering, Research & Development, Inc.
Sigma Pi Sigma University of Redlands Chapter, Class of 1995

Photo courtesy of Joel Peavy.

"I want to be an electrical-mechanical-chemical scientist!" That was the answer I gave to my fifth-grade teacher when she asked me what I wanted to be when I grew up. Come junior high school, I quickly learned that physics, the foundational science upon which nearly all other of the hard sciences are built, was the passion I had been trying to articulate in my answer to that elementary-school question.

Electrical engineering was another obvious passion; I taught myself electronics starting in sixth grade. But in high school I was never 100 percent content just knowing "how" something worked. I wanted to know "why"! The physicist inside me wouldn't give up.

In high school I won a grant from the National Science Foundation to build a pulsed-nitrogen laser and perform experiments with it at the University of Redlands in California. I measured the energy transfer between the fluorescent molecules coronene and rhodamine 6G. After that, it was an easy decision to pursue my undergraduate degree in physics and math at the University of Redlands.

"I wanted to know 'why!' The physicist inside me wouldn't give up."

I was a part of research projects every summer through college, mainly projects in nuclear physics involving reaction cross-section studies. I traveled to the cyclotrons at the University of California, Davis, and Uppsala University in Sweden to gather data. I then completed my MS in electrical engineering at the University of Southern California in Los Angeles.

After working for five years at General Atomics' DIII-D Nuclear Physics Research Facility in San Diego and nine years at Delta Design designing robots for the semiconductor industry, I wanted to find a way to marry my passions for both science and art.

That's when, out of the blue, Disney Imagineering Research and Development found my resume. The company ultimately offered me a job as a Principal R&D Imagineer at the Walt Disney Imagineering headquarters in Glendale, California.

There are few, if any, places better in the world for marrying science and art together. Since I was a child it had always been a dream of mine to be a part of this exclusive group and make wonderful things that bring people joy.

Although most of what I design now is secret and must be kept confidential until the projects hit the public eye, I can say that designing things that haven't been done before, or even thought of before, all begins with physics.

In this work environment it's not uncommon to hear "You're up against physics on this one," or "We've run out of physics!" That's when using physics in creative ways comes heavily into play. It's amazing to see an effect come to life based on putting a few key principles of physics together to create a bigger whole.

Now, many years into my career, I'm blessed to work with some of the best scientists, engineers, and artists the world has to offer. And it all started with my love of physics.

The Patent Trial Lawyer and Professor

Bruce Wexler
Partner, Litigation Department, Paul Hastings, LLP in New York, NY
Sigma Pi Sigma Rensselaer Polytechnic Institute Chapter, Class of 1989

Photo courtesy of Bruce Wexler.

Throughout my childhood and continuing into high school, I loved and excelled at science and math. When it came time for college, I thought about engineering, but my true passion was pure science. So I went early decision to Rensselaer Polytechnic Institute (RPI), where I majored in physics.

I was not completely sure of my future in physics, but I figured I would see where things took me. The study of physics was intellectually challenging and completely fulfilling, and I made sure to take a broad variety of coursework outside my major, such as electives in chemistry and biology. I also minored in psychology, for really no other reason than I found the subject matter intriguing.

In my third year of college, a brother in my fraternity (Sigma Phi Epsilon) told me about patent law. I knew nothing of the law at the time, but it sounded fascinating. I decided to let fate decide: I would take the LSAT entrance exam, and if I got into a good law school I would go. I wound up attending New York University School of Law.

The most shocking thing about law was that there was no "correct" answer. The law was about analyzing human behavior through a lens of history, logic, precedent, and reason, and creating arguments for the right answer. Physics had been an excellent training ground, since it is fundamentally about thinking creatively to solve complex puzzles.

I graduated magna cum laude from NYU and was offered a job as a law clerk to the chief judge of the Court of Appeals for the Federal Circuit in Washington, DC, the court that hears all appeals in United States patent cases. As a judicial law clerk, I worked on decisions that have shaped patent law, including the case that articulated the process for interpreting patent language—Markman v Westview Instruments, Inc.—in which the court held that judges, not juries, would evaluate and decide the meaning of the words used in patent claims.

After my clerkship, I joined an intellectual property boutique law firm where I eventually became a partner. In 2006, one of my partners and I left in order to start a life sciences patent litigation practice within a large general practice firm, Paul Hastings, LLP. We built the practice from the ground up and now have over 40 lawyers in our group focused on life sciences patent law. Our cases are multimillion- or multibillion-dollar matters involving chemistry, biology, and physics. Every day I use the tools I honed in my study of physics and continue to learn new science for each of my cases.

Most recently, I have returned to NYU, now as an adjunct professor of law, teaching life sciences patent litigation. My students are, for the most part, former scientists. The class combines discussions of science, law, and social policy.

Physics was not an easy major. I remember trying to teach myself vector calculus so I could solve problems in an advanced mechanics class, all the while thinking about what life might have been like if I'd taken an easier path. But for those of us who love challenges, taking the easiest path is, to be blunt, boring. The study of physics trains you to think in a way that lets you take on and conquer intellectual challenges. So whatever path you ultimately follow, you will have the power not just to succeed, but to do so with a deep understanding of the physical world, which keeps everyday life interesting.

The Startup Founder

Francisco LePort
Founder and Head of Research, Data Physics, and Hardware at Tachyus
Sigma Pi Sigma University of California, Irvine Chapter, Class of 2002

Photo courtesy of Tachyus.

I've always had two interests: building things and understanding how things work at a fundamental level. Growing up I wanted to be an inventor (whatever that meant to a 5-year-old!), but when I discovered physics I fell in love. After earning my bachelor's degree at the University of California, Irvine, I went for a PhD in experimental particle physics at Stanford University.

Building a very complex experimental apparatus to study the fundamental physics of neutrinos was extremely exciting. I learned a great deal and enjoyed my time at Stanford immensely, but toward the end of my PhD I began to feel that there was an aspect of my interests not being satisfied. Being at the center of Silicon Valley had gotten me interested in business.

Then Tesla Motors went public with its first initial public offering the summer before I graduated. My advisor was acquainted with the CFO. I applied to the company and got a job in battery R&D, though they admitted they were taking as much of a gamble as I was. I didn't know anything but academia, and they didn't know exactly what to expect from a physics PhD.

The gamble paid off. I contributed to core technology, and I learned a tremendous amount about running a successful Silicon Valley startup. I even hung out with Elon Musk. After 2.5 years I was ready to move closer to starting my own company and joined a very early-stage stealth startup as employee number eight. Unfortunately, that startup didn't work out, but it left me in a great place to found my own company.

Throughout my graduate studies and time in industry, a common theme of my work has been looking at large data sets obtained from a physical system—whether a neutrino detector or a car battery—through the lens of physics. I developed a unique set of methods that

"I contributed to core technology, and I learned a tremendous amount about running a successful Silicon Valley startup."

allowed me to extract useful information quickly from such data sets. Interestingly, I haven't needed specific experience in any of the disparate areas in which I've worked to make progress quickly. This is because of what I learned while running the experiment I worked on at Stanford, which required me to be flexible in dealing with different kinds of data.

Now I have brought my methodology to Tachyus, where I am a cofounder and leading research. At Tachyus we have developed a novel approach to optimize oil and gas energy production. We call it "Data Physics," and it has been very successful. The company is young. We have an enormous amount of research to do and an enormous amount of software to build. I credit our success so far in large part to the skills I learned as a physics PhD, which continue to help me develop unique solutions to unsolved problems.

Thank You

Support Level Key

Donor names appearing beside the following symbols have given $100 or more to Sigma Pi Sigma. The four highest levels of giving are:

★ Leader
⌘ Patron
♦ Mentor
○ Sponsor

for your continued dedication to AIP's student programs. Your contributions go directly to fostering the talents and careers of America's next generation of physicists, scientists, researchers, and professionals in the physical sciences. Sigma Pi Sigma and the Society of Physics Students connect students to a world outside of their classrooms and colleges, broadening their perspectives on what they can achieve. By supporting our programs you are investing in the future of our society. Thank you for your support in 2015! Donate now at donate.aip.org.

Abilene Christian University
○ Smith, Rodney C.' 63

Adelphi University
○ Bentley, Sean J. '10
○ De Feo, Cesare '62
Martin, David S. '62
Rallo, Jack '62
○ Redmond, Neal J. '80
○ Roldan, Susan Yvonne '10
Sukhanova, Maria '06

Albion College
○ Zook, John William '69

Alma College
○ Splitstone, Paul '81

Appalachian State University
Marzke, Robert & Mary '83

Arizona State University
○ Zook, John William '69

Auburn University
Catrett-Tamblyn, Leanne '86
Cauthen, Kendall Darren '93
Echternacht, Kenneth Lee '85
Fitzsimmons, Timothy E. '79
Jackson, Harold Wofford '58
Karch, Lawrence George '65
Rearn, Richard Lee '59
Roquemore, William M. '63

Augsburg College
○ Anderson, Brian Jay '80
○ Williams, Donald C. '86

Augustana College
Slaith, Scott A. '83
Taylor, Mark Stevern '75

Austin College
Lingren, Terrence Dale '75

Austin Peay State University
○ Slosberg, Carson Ronald '94

Ball State University
Taylor, Ronald M. '79

Baylor University
○ Brown, Roy B. '67
Geeslin, Bertram B. '69
Legate, Gail Lamar '69

Benedictine College
Anthony, Joseph Benedict '71

Berea College
Karamichalis, Menelaos N. '89

Birmingham-Southern College
Darby, John Littrel '70
Hoehn, Duncan Marion '69

Boston College
Hosker, Rayford P. '64
Pagliarulo, Robert P. '54
Plansky, William M. '55
♦ Vary, James P. '64

Boston University
Gata, D. George '81

Bowling Green State University
Davis, Kevin Patrick '92
⌘ Hirche, Hans Joachim '71
Synk, Joseph William '72

Bradley University
○ Keith, Scott Alan '79

Brigham Young University
Olsen, Randy Dick '79
○ Polgar, Peter '61
○ Staffanson, Forrest Leland '50
Wilcox, Joseph F. '69
Wood, Lew '57

Bucknell University
Fawcett, Matthew J. '00
Lowrie, Richard William '48

Butler University
○ Dixon, H. Marshall '08

Cal Poly-San Luis Obispo
Kallas, Endel '69
Leff, Harvey S. '94

California State University-Dominguez Hill
Moreno, Amaro '10

California State University-LA
Lymberis, Costas '70
♦ Miranda, Gilbert A. '64
Swank, Jean Hebb '67

California State University-Long Beach
○ Franco, Albert J. '74
Hu, Chi Yu '00
Perk, Neil K. '73

California State University-Northridge
○ Anticevich, Steven Edward '74
Goffman, Hirsch T. '72
Stevenson, Lance Charles '72

California State University-Sacramento
○ Brandt, Victoria L. '06
⌘ Hunt, Charles Harriso '73

Cameron University
Little, David Richard '74
Douglas, S. '71

Carson-Newman College
Shafer, Douglas S. '71

Central Michigan University
Spalsing, Roger Dean '78

Central Missouri State University
♦ Rambow, Frederick H. K. '71
Ring, Merlin Dale '70
Taylor, James H. '86

Central Washington University
○ Bennett, Robert '87

Clark University
Smith, Webster F. '80

Clarkson University
○ Eagan, Kendra A. '92
⌘ Feller, Steven Allen '72
Ford, Stephen John '80

Clemson University
○ Hughes, Carroll '57
○ Kalinosky, Michael Anthony '88
Lunsford, Ralph D. '55
○ Rice, Laurence B. '58

Cleveland State University
Horvath, Joseph Anthony '72

College of Charleston
○ Bridgman, William Thomas '87

College of the Holy Cross
LaMesa, Salvatore Francis '73
Tangherlini, Frank Robert '70

College of William & Mary
○ Babcock, Richard R. & Judy '65
Harrell, Lee E. '91
Muench, Jean A. '67
Slauson, William E. '64
♦ Stevens, Robert Bruce '72
Tropf, William Jacob '66

Cooper Union
○ Krane, Kenneth S. '70
Kraus, Marilyn '69
McMahon, James Michael '79

Davidson College
○ Benton, Frederick Davis '53
Griffin, Henry Claude '55
○ Neal, Donald C. '50
Thompson, James R. '63

DePaul University
Burlingame, C. Mark '79
Stinchcomb, Thomas G. '72

DePauw University
Adney, James R. '66
Kenter, Keith '84

Dickinson College
Ajamian, Greg Mark '74

Drew University
Feldman, Leonard C. '94
○ Fenstermacher, Robert L. '88

Drexel University
○ Barchet, William R. '65
Degnan, John James '67
Reetz, Ferdinand '75
Robinson, Franklin L. '66
Stanton, Robert J. '67

Duke University
Daniel, Jerome Madsen '72
Friauf, Robert J. '45

East Carolina University
○ Hinnant, Davis F. '81

East Stroudsburg University
○ Nesbitt, James B. '73
Semanek, Stephen George '90
Svok, George '71

Eastern Illinois University
Horn, Merri Lynn '80
♦ Mednick, Kenneth '85

Eastern Michigan University
○ Hanawalt-Jacobs, Diane A. '85
Marvin, Timothy H. '90
Moverman, Mark Ira '90
○ Mutart, Douglas '92

Elizabethtown College
○ Dotter, Ray Edward '92

Elmhurst College
Betinis, Emanuel James '89
O'Kelly, Roy J. '89
Ramsay, Alice J. '97

Emory University
Abrams, Matthew S. '96
○ Dyer, George Richard '61
Funke, John '78
○ Rowe, John E. '63
Sheffield, Burnette T. '68

Fairfield University
Tall, Edward G. '92

Florida Institute of Technology
Chambers, Susan Ann '75
Frahm, Rudy A. '77
○ Pearlman, Melvin '69

Florida Southern College
Klein, Walter George '84

Florida State University
○ Kromhout-Schiro, Sharon Eileen '78
Lane, Jean Willits '58
Sica, Louis '57
⌘ Wyatt, Philip J. '58

Fordham University
Krupp, Joseph '70

Fort Hays State University
○ Kopke, Monte F. '95
Schmeidler, Neal F. '69

Franklin & Marshall College
○ Balent, James Stephen '90
Dommel, John Gerald '62
Edwards, Yancy Donald '82
○ Kozak, Mark '79
♦ Weiss, Adam Jacob '84

Frostburg State University
Hendrickson, Gary Lee '73

Gannon University
○ Selvaggi, Jerry Anthony '72

George Mason University
Bjorklund, Christine L. '73

George Washington University
⌘ Hughes, Mark V. '69
Kelsall, Thomas '56
⌘ Schmid, Paul Emil '54
Wiest, Quentin W. '39

Georgia Institute of Technology
○ Albritton, Daniel L. '61
○ Fortenberry, Robert Scott '80
♦ Gilliland, Clinton R. '58
Metz, Werner Adam '81
○ Patronis, Eugene T. '52
Stansbury, Paul S. '69
○ Thackston, Michael G. '74
Vogel, David Arthur '80

Georgia State University
Blackburn, Thomas Eudene '71
Hull, Alan '72
○ Lai, Eongwei '75

Gettysburg College
Horne, Bruce K. '59
Keiser, Richard Leon '49

Guilford College
○ Field, Christopher Treadwell '10
Remmes, Nicholas Brendan '97

Heidelberg College
Adams, Paul Eugene '82
⌘ Falvey, Suzanne Eleanore '78

Hillsdale College
Tulloch, John T. '98

Hofstra University
Hickey, Mary J. '52
Klaiber, Robert J. '60
Murnick, Daniel E. '60
Pirone, Alfred D. '51
○ Stahl, Frieda A. '55
○ Terrone, William M. '68
Walther, Adriaan '78

Hunter College of the CUNY
Ng, Carolyn Yee-Han '80
○ Santhanam, Padmanabhan '78

Idaho State University
○ Morford, Larry J. '76
○ Morford, Linda Marie '76

Illinois Benedictine College
○ Kotek, Thomas J. '64
Laho, Ralph R. '63
○ Stella, Dominick John '91

Illinois Institute of Technology
○ Harling, Otto Karl '52
Zwicker, Earl '56

Indiana University of Pennsylvania
Couch, Russell Harriso '89
Stobie, James Allen '72

Indiana University-Bloomington
Small, Timothy M. '62
Volkman, Sylvia M. '63

Iowa State University
Keever, Mark Robert '76
Swenson, Clayton A. '76

Ithaca College
○ Rogers, Michael '04

James Madison University
○ Dawson, Howard F. '89
Zimmerman, Bryan Allen '88

John Carroll University
Blakeley, Douglas M. '75
⌘ Melich, Branden Thomas '92
Newell, Catherine '10
♦ Petti, Ernest John '96
Szente, Joseph John '84
Ursic, Joseph John '76

Juniata College
Norris, Wilfred Glen '75

Kent State University
Latta, Gregory P. '82
Stanford, Jack Dale '76
Visintainer, James '72

Lamar University
○ Dimiceli, Emanuel V. '68
Durling, George Ervin '79

Lewis & Clark College
Clarkson, Kathleen Marie '99

Louisiana State University-Baton Rouge
Giammerse, Jr., Jack '75
○ Moore, John T. '59
○ Paine, Richard Allen '80
Rauch, Richard T. '76
Stoessell, Alfred L. '61

Louisiana Tech University
Evans, Ken '74

Louisiana University at Lafayette
○ Meriwether, John R. '71
Miller, James Edward '60

Loyola University New Orleans
Barrera, Carlos M. '78
Faust, Donald C. '08
○ Gross, James M. '65

Luther College
Scholten, Roger C. '84

Lycoming College
Howes, Michael Lynn '73
○ Stover, David R. '73

Manchester College
Brill, Wilfred G. '51
○ Ebbinghouse, Joe C. '48
○ Firebaugh, Morris W. '57
Heisler, Gary Lee '71
Stauffer, Gary William '73

Manhattan College
Basener, Richard F. '65
○ Drigert, Mark W. '78
Marczyk, Richard F. '57
Shea, Michael Joseph '71

Marquette University
Budlong, Albert Henry '49
○ Maruszewski, David Paul '91
Mattson, Edward J. '63
○ Miller, Paul George '62

Massachusetts Institute of Technology
Donahue, Megan Elizabeth '84

Miami University
○ Imhoff, Eugene A. '75
Johnson, Ramsey D. & Bonnie '58
Leonard, Scott Randall '79
♦ Stewart, William M. '58

Michigan State University
○ Anderson, Mary K. '08
Brazee, Ross D. '53
Hopkins, Richard Bruce '55
Musser, Susan E. '03
○ Wagner, Richard N. '59
Zimmerman, Walter Bruce '56

Michigan Technological University
○ French, Todd '88

Monmouth University
Bleier, Steven Arnold '74

Montana State University
○ Kirkpatrick, Larry D. '78

Morehouse College
○ Oz, Orhan Kemal '82
⌘ Rockward, Willie S. '85

Morningside College
Yoder, Jerry L. '58

Mount Holyoke College
○ Gates, Elinor Louise '92

Murray State University
Rose, Gerald T. '63
○ Taylor, Patricia Lynn '79

Nebraska Wesleyan University
Bures, Marvin George '52
Hammond, Barry L. '61

New Mexico State University
♦ Daggett, Paul H. '75
Gillespie, James Bryce '40
Gillespie, Patti Linn '73
Nunn, Elwin Charles '63
⌘ Preslar, Tony M. '73
Voss, Robert A. '61

New York Institute of Technology
Frankel, Kenneth Lee '10
○ Nothdurft, Robert H. '71

New York University
○ Hodara, Morris '48
○ Kainer, Selig '58
Markatos, Louis G. '64
○ Richman, Monroe Franklin '49
Spruch, Grace Marmor '51

North Carolina State University
Duncan, Donald P. '67
○ Herman, Martin '64
○ Hurley, Jeffery D. '91
Knight, Douglas '94
Page, Earl M. '55
Penny, Jack M. '73
○ Philbrick, Charles R. '65
Stamm, Alfred J. '62
○ Wilburn, Wesley Scott '86

Northern Arizona University
○ Sande, Linda Rae '80

Northern Illinois University
○ Gibson, Robert '73
○ Overmyer, Steven A. '78
Sill, Larry R. '73

Occidental College
⌘ Dastur, Nariman M. '86
○ Newnam, Brian Emerson '62
Worcester, John L. '51

Ohio Northern University
○ Garee, Michael J. '07

Ohio State University
Clark, Brian O. '69
♦ Donlan, Vincent L. '68
○ Hagenlocker, Edward E. '61
Hecht, Lewis C. '64
○ Hill, John H. '60
Keane, Joseph A. '66
○ Ki Leech, Frank Judson '61
○ Kidder, Ray E. '46
○ Lubich, Jeffrey N. '04
○ Marshall, James Leon '76
McCaa, David J. '62
Needels, Theodore S. '42
Niple, Edward R. '73
Robinette, William H. '67
Roop, Raymond M. '64
○ Simonson, Simon Christian '66
Walters, Craig T. '62
○ Whitt, Sylvia J. '03

Ohio State University - Research Foundation
Bingley, John D. '62

Oklahoma State University
Davison, David '64
○ Freeman, John A. '65
○ Hurt, James E. '56
○ Northrup, Clyde J. M. '61
○ Rhoads, John E. '71

Old Dominion University
○ Glaser, Ronald Charles '71
○ Lutton, Russell T. '72
Wehrle, John Patrick '78
Welch, Charles R. '72

Oregon State University
Finster, Kirstie Lee '90
Ghaleb, Sam H. '77
Gibbs, Bruce '79
○ Goldsmith, Todd Andrew '85
Henning, Stephen M. '62
Henry, Dennis C. '67
○ Jones, Eric D. '56
O'Brien, Robert M. '56
Wood, Clyde R. '69

Pennsylvania State University
○ Bergey, George C. '60
Brunner, James S. '58
Davies, Emlyn B. '49
○ Faust, Barbara C. '64
✶ Herritt, John A. '67
○ Kost, Lawrence M. '65
○ Mebus, Edward Arthur '63
♦ Owens, Barbara R. '10
Reinheimer, Julian '48
Schiff, Conrad '86
Weldon, Rodney G. '52

Polytechnic University
Dalsass, Louis J. '59
De Canio, Thomas C. '65
○ Guidone, Raffael J. '67
LaFemina, John A. '69
Sank, Victor J. '65
Yarr, Edward G. '65

Portland State University
Martwick, Andrew '04

Providence College
○ Coussa, Michael R. '57

Purdue University-West Lafayette
Alexander, David H. '67
Boesch, Harold E. '63
♦ Born, Richard Gustav '72
○ Bower, William W. '69
○ Brown, Ronald A. '60
⌘ Cable, Daniel H. '66
Carter, Robert E. '43
Connell, Edward Charles '73
♦ Cunningham, Gary Randall '72
○ Goodwin, Robert M. '62
○ Gotwals, John K. '63
Harke, Douglas J. '68
Lambert, Ralph E. '68
○ Lawnicki, Victor F. '76
Litscher, Helen F. '49
Mennel, John J. '66

Purdue University-West Lafayette (continued)
○ Miller, Robert J. '64
Montgomery, Stephen Tedford '70
⌘ Nelson, Donald L. '65
O'Loughlin, Carol B. '61
○ Richards, Gerald T. '63
Rinker, Jack Noll '50
Rittmann, Paul Douglas '72
○ Seiler, John P. '68
♦ Skelley, Elder D. '55
⌘ Stendahl, Steven J. '76
Stretchberry, D. Michael '61
○ Thieme, Gary Alan '71
Tozer, William F. '67

Rensselaer Polytechnic Institute
Berman, Paul R. '63
Flanders, Bradley Arnold '73
○ Gunning, William John '72
Kalnin, Andrew '77
Leonardi, John C. '67
○ Rapids, Richard F. '66
○ Reynders V, John '86
Simon, John Francis '78
Tishkoff, Julian M. '65
○ Tollin, Mark Joseph '71
Van Vranken, Randy Charles '73
Vitko, John '66
○ Wexler, Bruce Matthew '88

Rhodes College
Atkinson, John Timothy '68
Kendrick, Stephen Ellis '69
○ Smith, Jenna K. '08
○ Smith, L. Montgomery '77

Rice University
Bragg, Ann Elizabeth '95

Ripon College
Polanski, Xavier Michael '73

Roanoke College
Johnson, Robert Stephen '73

Rochester Institute of Technology
○ Andersen, John D. '89
Federation, Dolores A. '70
○ Manginell, Ronald Paul '89
Schwaneflugel, Franklyn K. '69

Rose-Hulman Institute of Technology
Sorrell, Lee Ronald '85

Rutgers University-Camden
Coates, Joann Marie '83
Sorrell, Lee Ronald '85

Saint Joseph's University
Dibiase, James A. '59
Morris, Robert A. '60
Sunderland, Robert Joseph '72
○ Young, Kenneth C. '71

Sam Houston State University
Decker, John '52

San Diego State University
♦ Cahill, Gerald D. '64
Lindman, Nils Gosta '69
Mannix, Richard Charles '71
Maurer, Edward H. '58
Morris, Richard H. '58
Muhl, William O. '58
Zarnowitz, Richard M. '47

San Jose State University
Strandburg, Donald '50

Santa Clara University
♦ Brown, David Shaw '81
Claiborne, Ken M. '69

Seton Hall University
♦ Kreidler-Moss, Jennifer Lynn '94
○ Stamer, Peter E. '69

Shippensburg University
○ Imler, James Harold Eugene '73

Siena College
♦ Knight, Charles T. '83
♦ Smith, Paul Joseph '80

South Dakota School of Mines & Technology
Dorland, Louis Jack '78

South Dakota State University
Cherney, Joseph F. '49

Southern Arkansas University
○ Rutledge, Carl T. '65

Southern Illinois-Carbondale
Berman, Leonard M. '86

Southwest Missouri State University
Armstrong, Charles H. '78

Southwestern Oklahoma State University
Duerksen, Kenneth D. '97
○ Geswender, Chris Eugene '71

Spelman College
Hill, Adrienne W. '05

St. Bonaventure University
Kovar, Frederick R. '60

St. Lawrence University
Clark, Doris Louise '41
Kirby, June C. '46
Wells, Lois S. '53

St. Mary's College of Minnesota
○ Morin, George J. '89

St. Olaf College
Arenson, John Dean '69
Bongard, Michael W. '01
○ Gimmestad, Gary Gene '66
Halsted, Lizabeth L. '78
Kullberg, Craig '69
○ Logghe, Sean Brian '75
○ Rockstad, Howard K. '55
Schlichting, William H. '64

St. Peter's College
Lopez, Jose L. '07

Stetson University
○ Williams, David Charles '10

Suffolk University
Sharma, Prashant '10

SUNY at Albany
Bono, Paul Charles '77
Coppola, Richard A. '66
○ Sanders, Stephen J. '71
○ Sullivan, Joseph M. '67

SUNY at Binghamton
○ Rossabi, Joseph '84
Zendle, Howard Mark '74

SUNY at Fredonia
♦ Bicknell, Paul Arthur '75
Zendle, Howard Mark '74

SUNY at Plattsburgh
○ Kauder, Lonny R. '03

Syracuse University
○ Lehmann, William L. '47

Temple University
Roffman, Martin M. '68
Rudin, Bernard '54

Texas A&M University-College Station
Gruben, James H. '72

Texas A&M University-Kingsville
Wheeler, Bob Lee '77

Texas Christian University
○ Gist, Thomas Elmar '71
Hilley, Larry L. '63
✶ Kent, Graham G. '65

Texas Tech University
Hilley, Larry L. '63
○ Borst, Walter L. '85
♦ Buckner, Spencer L. '79
○ Butler, Dwain Kent '67
Dannecker, Max F. '59
○ Glenn, Stephen W. & Mariglyn '65
○ Kelly, William F. '59
Pleil, Matthias Werner '88
Thacker, George H. '63

The Citadel
○ Calvert, William M. '50
Purcell, Trent K. '79

Thiel College
Chesonis, Dawn Corleen '76

Thomas More College
○ Barker, Thomas Edward '98
Eismann, Michael Theodore '84
Schmidt, Michael Joseph '85
○ Wells, Jack C. '84

Towson University
♦ Mather, John C. '10

Trinity College
○ Ewart, Hugh W. '59
Knutson, Donald S. '53
○ Twardy, Stanley A. '46
○ Washington, Allyn J. '50

Trinity University
Moore, Charles Darnell '74

Truman State University
Lindevald, Ian Morgan '91

Tufts University
Altshuler, Edward E. '54
Bruns, Charles Alan '50
○ Halladay, Maurice E. '51
Lynch, David D. '55
Striker, William W. '50

Tulane University
Daubert, Henry Conrad '50
Schorr, David Edward '66
Yeager, William M. '67

Union College
○ Johnston, John B. '82
○ Maliner, Lloyd Ian '85

United States Naval Academy
Jourdan, David Walter '74
Matzelevich, William Walter '74
McCumber, Leonard D. '68
Schreiber, James Edward '73
Studt, Kurt Friedrich '90
Waddell, James Bryant '69

University of Akron
Harris, Gary M. '70
Pitts, Patricia S. '71
Redfield, John Stearns '81
Rosich, Michael Alan '88

University of Alabama
Denham, Samuel '77
Moore, Robert A. '52

University of Alabama-Huntsville
Huckle, James Roger '71

University of Arizona
Herman, Benjamin M. '60
○ Hochdorf, Marrin '50
Ingraham, Stephen E. '66
♦ Jones, Edwin Rutledge '58
Lipsky, Sanford '64
Mitchell, Todd '79
⌘ Schutt, Paul Frederick '58

University of Arkansas-Fayetteville
○ Anderson, Richard '68
Culp, Gary '61
○ Manka, Charles K. '61
○ Sourlis, George '65
○ Williams, Karen A. '86

University of Arkansas-Little Rock
Quilty, Eddie George '81

University of Bridgeport
Basarab, Douglas John '86
Read, Marc Edward '71

University of California-Berkeley
○ Cummings, Julian Clark '88
Schweitzer, Laurence Britt '85

University of California-Irvine
♦ Stone, Dane Eric '75
Tyler, Stanley C. '75
Vaccarella, Brigitte J. '55
Vodhanel, Richard & Nancy '73

University of California-Los Angeles
✶ Aires, David L. '75
Ando, Ken J. '60
○ Balcer, Sonia C. '84
○ Cady, Robert L. '64
○ Castrup, Howard T. '72
Clemens, Reginald W. '61
Crane, Christopher M. '87
Eggum, Gordon '63
○ Garfinkle, David Raymond '61
Goldenberg, Stuart '64
Hai, Francis '60
○ Kagiwada, Reynold '60
Kvitky, Joel S. '65
Lane, Gerald R. '57
Rhodes, Edward J. '67
Ross, Erno H. '53
○ Scharre, Douglas William '77
♦ Sherman, Max Howard '73
Simmons, Larry L. '67
○ Stanton, Richard H. '64
Stearns, Ronald C. '70
Wood, John J. '66

University of California San Bernardino
Lowande, Karen '08

University of Central Florida
○ Johnson, Michael D. '07

University of Central Oklahoma
Alexander, Buster Owens '10

University of Colorado-Boulder
Beavers, Glenn A. '61
Conklin, Richard L. '57
○ Guiteras, Joseph J. '50
○ Harrison, Dewitt Edward '85
♦ Kraft, Edward Stephen '71
Ostwald, L. T. '51
Parker, Kenneth L. '60
Rosing, Michael George '75
Talbert, Willard L. '52

University of Connecticut
Austin, Gary Raymond '76
Barrett, Richard L. '72
Carricato, Richard H. '59
Desnoyers, Roger W. '57
Helbig, Herb F. '10
Holst, Gerald C. '65
Meli, Jerome A. '64
Morgan, Gerry H. '57
Poulos, Peter T. '08
Powers, Donald E. '58

University of Connecticut (continued)
Szymanski, Richard C. '62
⭘ Welsh, Thomas Joseph '74

University of Dallas-Irving
⭘ Laba, Jeffrey '88

University of Dayton
⌘ Anthony, Philip John '73
Crume, Stephen V. '68
Schumacher, Howard Herman '68
Stegner, Virgil Franklin '72
Tiernan, Thomas O. '68

University of Delaware
Barsky, David Joseph '82
White, Willard W. '64

University of Denver
⭘ Behnen, Stephen W. '69
⭘ Risley, Allan Sanford '54

University of Detroit
⭘ Sarna, Donald S. '64

University of Evansville
Batteiger, Byron B. '61
Megli, Darrell '63
Morgan, Lester Wayne '68
⭘ Schultheis, Frederic J. '86
Van Haaften, Frederick W. '63

University of Florida
Danese, John B. '66
Keyser, Ronald M. '66
⭘ Richardson, David M. '61

University of Georgia
Ivey, Henry F. '41
⭘ Maddox, Marvin Robert '62

University of Idaho
Bennett, Gary L. '61

University of Illinois-Chicago
Ares, Julian Y. '89

University of Kansas
♦ Agin, Gary P. '62
⭘ Dike, Larry L. '59
⭘ Halderson, Dean W. & Cynthia '67
⭘ Leamon, Richard G. '65
Lemon, Dennis R. '62
Lowe, Forrest G. '62
Moore, Richard A. '50
Nahman, Norris Stanley '59
Pippert, Raymond E. '58
⌘ Smith, Robert G. '54
Spahn, Robert G. '66
Woelk, Darrell W. '69

University of Louisville
Erhart, Herbert George '61

University of Maine
Ashton, Stephen E. '61
Atkinson, Leland Guy '77
Connor, Edward John '51
Henderson, Wallace D. '56
⭘ Hennings, John H. '57
Knight, Richard A. '50
⭘ Larson, Reginald E. '53
McGuire, Paul F. '66
⭘ Moore, Duncan T. '67
Mortenson, Victor A. '68
Otto, Fred B. '54
Saltzman, Robert S. '49
Williams, John Richard '49

University of Maryland-College Park
⭘ Bingham, Susan & Peter '64
Graham, Richard S. '69
⌘ Krisch, Jean P. '59
⭘ Lupton, William H. '56
⭘ Messina, Carla Gretchen '58
Mulvey, Patrick
Reuss, Max L. '52
Spachner, Sheldon A. '50
Young, Frank C. '59

University of Massachusetts-Boston
O'Brien, James John '70

University of Massachusetts-Lowell
DeMartinis, Guy Bernard '93
Hanfling, Edward Benjamin '78
Largy, Timothy Paul '94

University of Memphis
Ladner, Daniel Ray '68

University of Miami
Jacobs, Michael M. '71

University of Michigan-Ann Arbor
⭘ Dodds, John A. '94
⭘ Rose, Hugh '00

University of Minnesota
Christensen, Thomas M. '79
Hladky, Jeanne '79
⭘ Pepin, Robert O. '80
⭘ Wollack, Edward J. '86

University of Missouri-Kansas City
⭘ Froncek, Teresa M. '82

University of Missouri-Rolla
Cawns, Albert E. '58
Kvale, Thomas '80
McDaniels, John L. '59
McKee, William Dean '52
Schwenker, Robert O. '61

University of Nebraska-Lincoln
Gustafson, Lyal V. '64
Sellmyer, David J. '86

University of Nevada-Reno
Burge, Dennis K. '61
⭘ Pitchford, Ann M. '75
Rosenbaum, Robert Phillip '62

University of New Orleans
♦ Lawrence, Thomas N. '67
Morris, Dane Joseph '79
⭘ Vedros, Louis Albert '69

University of North Carolina-Chapel Hill
Long, Virginia Carolyn '86

University of North Carolina-Asheville,
Booker, Randy '88

University of North Carolina-Greensboro
⭘ Garner, Larry Wayne '77

University of North Texas
⭘ Gardner, Robert Arthur '82

University of Northern Iowa
Heller, Paul Richard '84

University of Oklahoma
⭘ Evatt, Bruce Lee '59
Rhyne, James J. '57

University of Pittsburgh
Devaty, Robert Philip '88
Serenka, Russell George '52

University of Rhode Island
Ashton, Robert Alan '70
Caleshu, Jefrey Dean '94
✶ Turano, Thomas Arthur '70

University of Richmond
Foy, M. L. Grayson '62
Kusheba, Michael C. '63
Rothschild, Barbara G. '46
⭘ Ryan, William S. '62
⭘ Stromswold, David C. '66

University of Scranton
Strelchum, Thomas Francis '82

University of South Carolina
Laster, Donald R. '59
⭘ Rosenfeld, Carl '86
Sayetta, Thomas Charles '58

University of South Dakota
Predoehl, Martin Carl '54

University of South Florida
Curry, James A. '92
Rose, David A. '67

University of Southern California
⭘ Shigemitsu, Thomas Mamoru'72

University of Southern Colorado
Dickson, Richard L. '74
Neuenschwander, Dwight E. '75
♦ Van Loon, Timothy Grant '74

University of Southern Mississippi
Rayborn, Grayson H. '71
Stevens, Harold Wallace '71

University of Tennessee-Chattanooga
⭘ Fincher, Arvel L. '55
⌘ Visser, Jon Raymond '63
Wingo, Kenneth W. '68

University of Tennessee-Knoxville
Breeding, J. Ernest '61
Cooper, David A. '68
Crume, Charles '68
⭘ Dishman, Rose Marie '10
⭘ Fleming, Edward R. '67
⭘ Hubisz, John L. '64
⭘ Jarratt, James Stroud '67
⭘ King, Philip Woodson '68
⭘ Lewis, Rex D. '61
Reeves, Charles Allison '68
Shimony, Joshua Shai '84

University of Texas at Arlington
⌘ Guthrie, Don Wayne '68
⭘ Skinner, Robert D. '66
Southall, Hugh L. '68
Stein, Cathy Alys '80

University of Texas at Austin
⭘ Chester, Arthur N. '61
⭘ Evans, Steven Wendell '73
⭘ Herbst, Walter Egon '51
⭘ Kodosky, Jeff Leo '72
⭘ Monahan, Edward C. '60
⭘ Otto, William M. '55
Wylie, Dennis Cates '00

University of Texas at El Paso
Gibson, Randal Eric '73
⭘ Mayo, Wade H. '66

University of Texas-Pan American
⭘ Cantu, Juan Manuel '73

University of Toledo
⭘ Bagley, Brian G. '92
Federman, Steven Robert '90
Pommeranz, Matthias R. '03

University of Tulsa
⭘ Davis, Linda Rae '77
♦ Wetzel, Michael G. '67

University of Utah
Andersen, Terrell Neils '60
Blackburn, Alan David '71
⭘ Bowman, Carlos M. '56
Fletcher, Richard William '63
⭘ Gledhill, Jessica T. '61
Hills, Richard G. '59
Jones, Allen S. '61
Kingsbury, Paul I. '62
Tatro, L. Dick '52
Woodbury, John Walter '48

University of Virginia
Ashe, Gregory A. '87
Modlin, Raymond E. '68

University of West Florida
Barlow, Paul Michael '75
Holloway, John H. '82

University of Wisconsin-Eau Claire
⭘ Schneider, Robert Steven '80

University of Wisconsin-Madison
⭘ Schwartz, Brian P. '00

University of Wisconsin-Platteville
Bonde, Chris '00

University of Wisconsin-River Falls
⭘ Blodgett, Earl '53
⭘ Deml, Ann M. '06
⭘ McCann, Lowell I. 89

University of Wisconsin-Superior
⭘ Diesslin, Blaine Robert '71
Eschels, Curtis Peter '72
Lane, Richard H. '71
⭘ Sjostrom, Keith Jerome '84
⭘ Wooden, William Hugh '72

University of Wisconsin-Whitewater
De Voe, Michael James '77
Zagorski, William George '71

University of Wyoming
⭘ Meyer, Edmond Gerald '64

Upsala College
Hirvonen, Alice P. '63

Utica College of Syracuse University
Capparelli, Michael J. '62

Valdosta State University
Rumstay, Kenneth S. '86

Vanderbilt University
⭘ Perez, Gina M.

Villanova University
⭘ Lochner, James Charles '80
♦ Martino, Anthony Joseph '79

Virginia Military Institute
Benda, Peter Hans '80
⭘ Serenbetz, Stuart Weygand '76
⭘ Tucker, John Hackworth '78

Virginia Tech
Allison, Dennis O. '64
Huang, Jacob Wen-Kuang '62
Nimick, Daniel Spencer '78

Wabash College
Livengood, C. David '62
Monroe, Bruce M. '60

Wake Forest University
Love, Lane Alan '77

Washburn University of Topeka
⭘ Miles, Vincent A. '86

Wayne State University
Gubbins, Harry L. '49
⭘ Katz, Fern Sally '49
Morin, Dornis C. '48

West Virginia University
♦ Allen, Anna M. '92

West Virginia University (continued)
Carpenter, Thomas J. '50
Exton, Reginald J. '60
Ford, George D. '59
○ Hoge, Frank E. '60
Huffman, Gerald P. '60

Western Illinois University
Forbes, Jerry W. '61
Legner, Ronald F. '84
Meservey, Richard H. '61
Tomlinson, Francis K. '63

Western Kentucky University
Bennett, Maury Thomas '80
Glasgow, Glenn P. '64
Harris, Donald T. '63

Western Washington University
Cline, John Robert '76

Westminster College
Harris, Donald T. '63
Mansell, Edward R. '89
Metzler, Roger Allen & Helen '69
Smith, Harry W. '65

Wheaton College
Abraham, Douglas Scott '86
Richert, Norman John '71
○ Riedesel, Charles Paul '72

Wichita State University
♦ East, Larry V. & Judith '58
♦ Ladd, Nelson S. '62
○ Pistotnik, Frank S. '72
♦ Scrivner, Timothy T. & Jeanne '75
Wood, Gordon L. '61

Widener University
Garneski, Charles J. '70

William Jewell College
Dixon, John William '58
○ Hilton, John W. '66
McElwee, Carl D. '63
Philpot, John L. '55

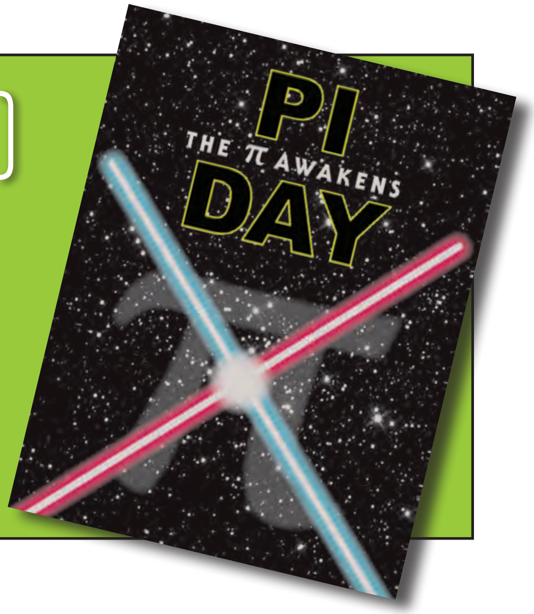
Worcester Polytechnic Institute
Bernacki, Stephen Edward '70
Lawry, Stephen Richard '79

Wright State University
Beard, James B. '69

Xavier University
Grothaus, Jeffery T. '77
○ Zeitz, William M. '68

Youngstown State University
Adams, Louis W. '72

At Large Members and Friends of Sigma Pi Sigma
⌘ Abkas, Ziya & Marie
Andresen, Ted
⌘ August, Terence
✶ Avenir Foundation, Inc.
Baker, Blane
Bardi, Jason S.
○ Beaini, Sara
Bebee, Jeffrey G.
○ Bermudez, Matthew
Beyer, Louis M.
Bourne Marth, Mary
⌘ Brodsky, Marc H.
○ Brown, Robert
Bustos, Aurora V.
○ Byers, Sherry
Cabell, Brenda & Ryan
Call, Demitra
○ Canright, Jared
Cardwood, Alexandria
Carlos, Jose
○ Carr, Rachel
Cohen, Morrel H.
Coleman, Trina
Corwin, Vera-Anne V.
✶ Culigun, Cameron Evan
✶ Cunningham, Beth A.
♦ Curran, Bruce H.
✶ Dabney, John
○ Daigneault, Michael & Alessandra
○ Dart Caron, Elizabeth
○ Davis, Carolina
○ DeCanio, Thomas
DePorzio, Nicholas
Dunlap, David
○ Early, Stephen
Feldmann, Peter
⌘ Ford, Kenneth W.
French, Mary
Fulling, Stephen A.
Glass, George
○ Golden, Bruce
Goodwin, Thomas J.
○ Gordon, Leonard
○ Gottbrath, Christopher
○ Greenland, Arnold
Gu, Liyi
○ Guenzel, Jeffrey
Haag, Brooke
Hall, John Randu
○ Hammer, Philip W.
Hauze, Brittney
Haworth, Mike
○ Head, Timothy L.
⌘ Hehn, Jack G.
✶ Helfrick, Albert D.
Hennig, Lee Ann
Hoppmann, Eric
○ Hudiburgh, Gary
Ivie, Rachel
Kaufman, Brian M.
♦ Keller, William E.
Kidd, Tim
○ Kirby, Kate Page
Konno, Rikio
Konoplich, Rostilav
Kozlowski, Ryan
Krivanek, Jennifer
○ Kubiak, Greg
Kuhlman, William
○ Kumon, Ronald
Kushner, David M.
Lazar, Madeline
○ LeGrand, Alan
♦ Lee, Marvin & Annette
♦ Lee, Deishin
○ Levin, Jon
Lewis, Tanya
○ Long, Jerome R.
○ Lucas Jr., Henry C.
Ludvigsen, Angela M.
Martin, James
Matthews, Yolanda
McDowell, H. Clay
McDonald, Lisa
McLennan, Ray
○ Meadors, John Gilmore
Mehta, Deval Kishor
✶ Meyers, Robert & Patricia
Micklavzina, Stanley
Miller, Catherine
♦ Ming, Liu
Mittu, Anjali
○ Mordecai, Donald
○ Moyers, Martha
Mysore, Ajay
♦ Newell, John
♦ Nielsen, Aaron
○ Nilson, Lennart H.
Nobile, Emma
♦ Novak, Jennifer
♦ Novak, Steven
○ O'Riordan, Catherine
♦ Paulikas, George
Payne, Matthew
○ Peterson, Michael Eric
○ Price, Robert D.
Prins, Nathan
Pryor, Richard J.
Pyle, Bobby E.
Qin, Xiaohui
♦ Raghavan, Subramanian
Rastogi, Rohit
○ Rawls, Meredith
Reidinger, Franz
Rickerson, Ella
Riedinger, Leo L.
○ Rimer, Anne
○ Rogan, Elizabeth
✶ Runge, Keith
○ Salloum, Tony
Schaich, David
Schwartz, Brian B.
♦ Scott, Suzanne
Searan, Georgette
Sheldon, Peter
○ Sheriff, Jack W.
○ Shields, William W.
♦ Shin, Hyo Duk
Shteyman, Alan G.
Shurkin, Joel
○ Slaton, William
○ Smith, David & Diane
○ Stein, Ben P.
Stillwell, John Wayne
Stone, Charles
Strandburg, Patricia
Strelchun, Thomas F.
Streltzky, Kiril
Strozzi, David
Swartz, Gigi
Taylor, James H.
♦ Unal, Haluk
Unger, Christina
♦ Urbanowicz, Tom
○ Varriano, Louis
♦ Wagner, DJ
Waizoba, Umaru
Wallace, Rosa
Ward, Bryant
♦ Warner, Gregory S.
White, Susan
Williams, Khurt
○ Woodson, Robert L.
○ Xu, Yi
♦ Yarnell, Kevin Arthur
York, Joe
Zollinger, Rhett




SPS JOBS

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

LET'S GET TO PHYSCON!

The national office of the Society of Physics Students and Sigma Pi Sigma has fundraising kits for your local chapter that can help finance your attendance at PhysCon 2016, held November 3-5 in Silicon Valley, CA.

physcon
2016 Quadrennial Physics Congress

Order your free kit today by going to this web page:
sigmapisigma.org/congress/2016/physcon-fundraising-kits