PHYSICS TODAY

November 2017 • volume 70, number 11

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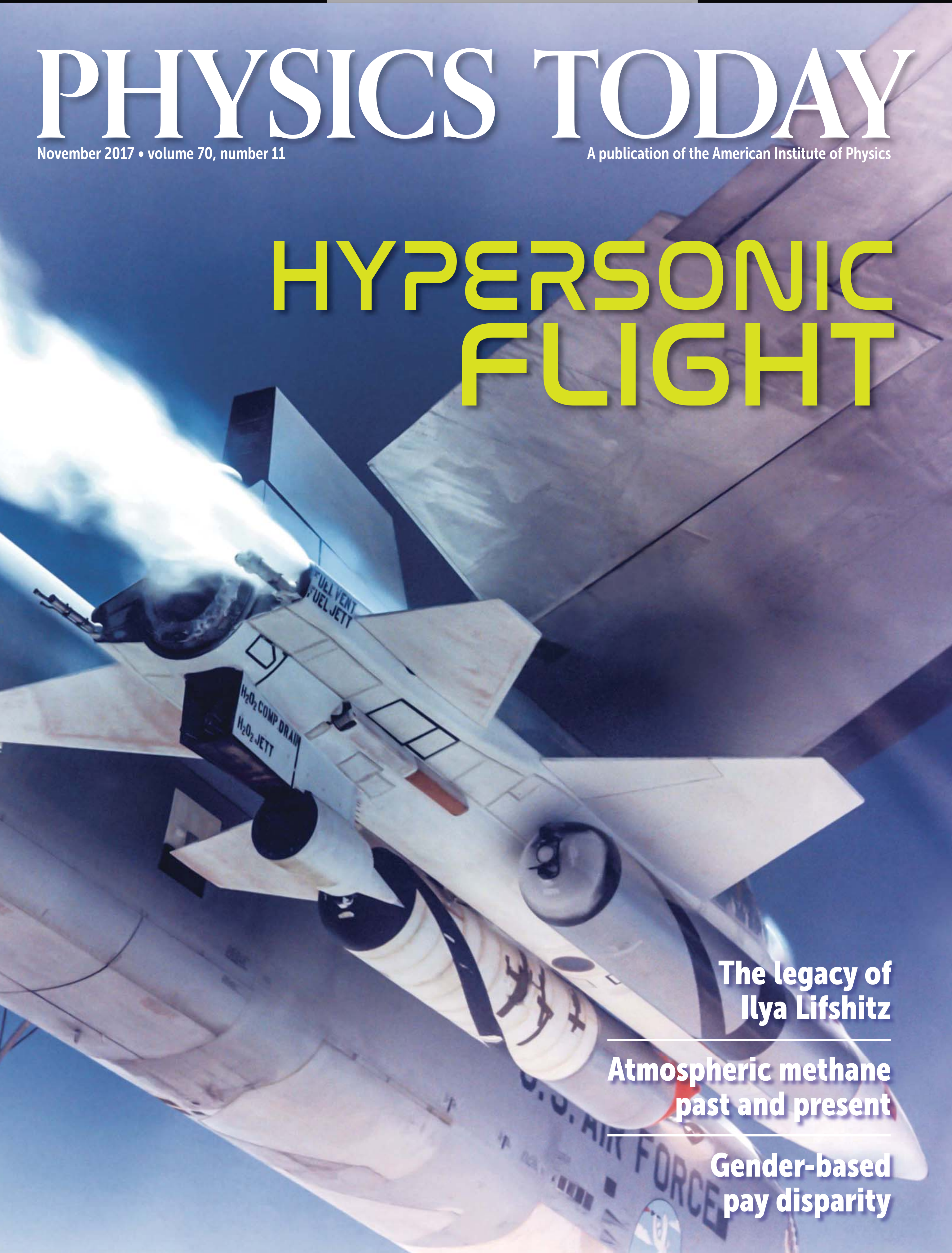
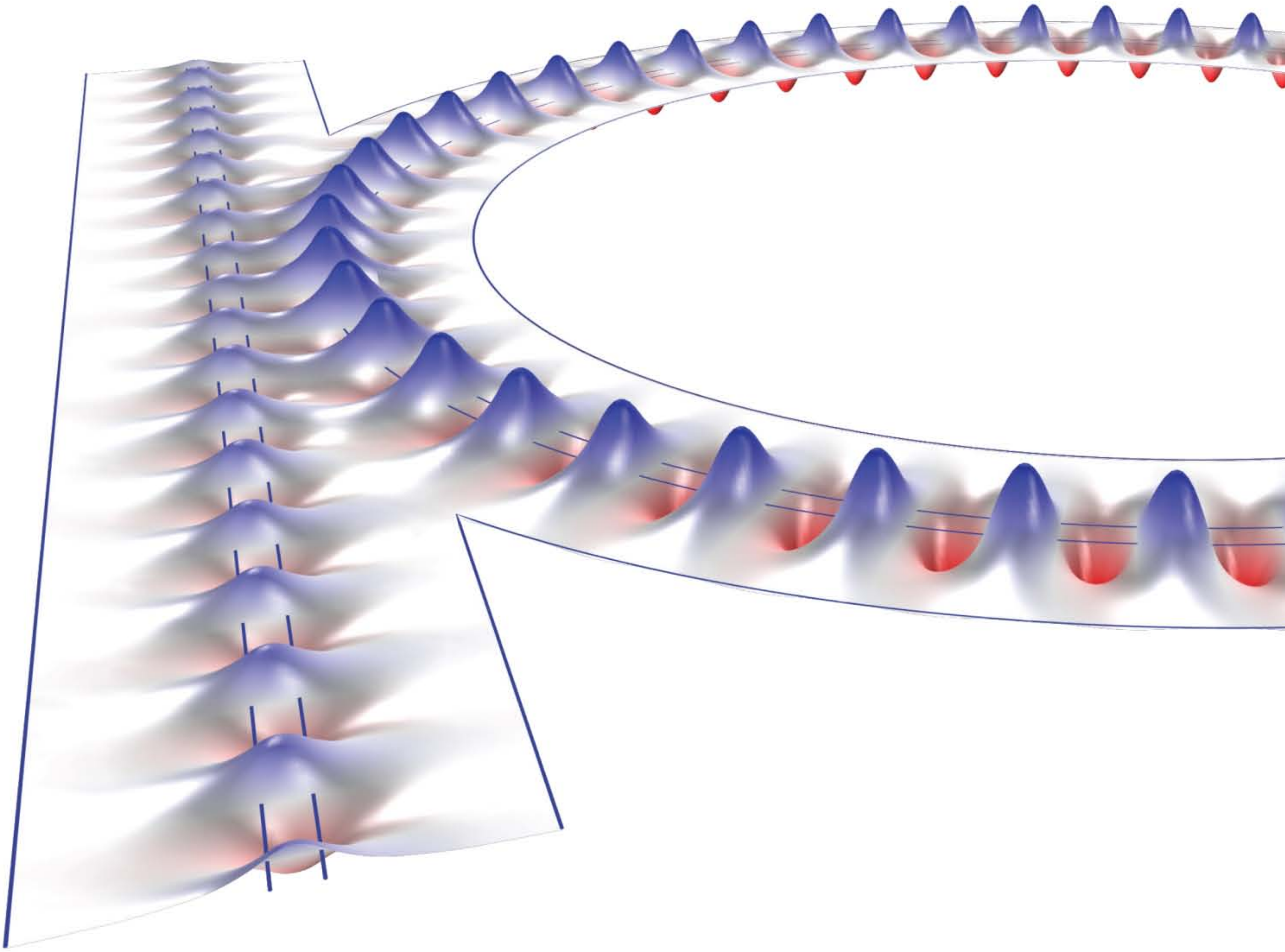


HYPERSONIC FLIGHT

The legacy of Ilya Lifshitz

Atmospheric methane past and present

Gender-based pay disparity



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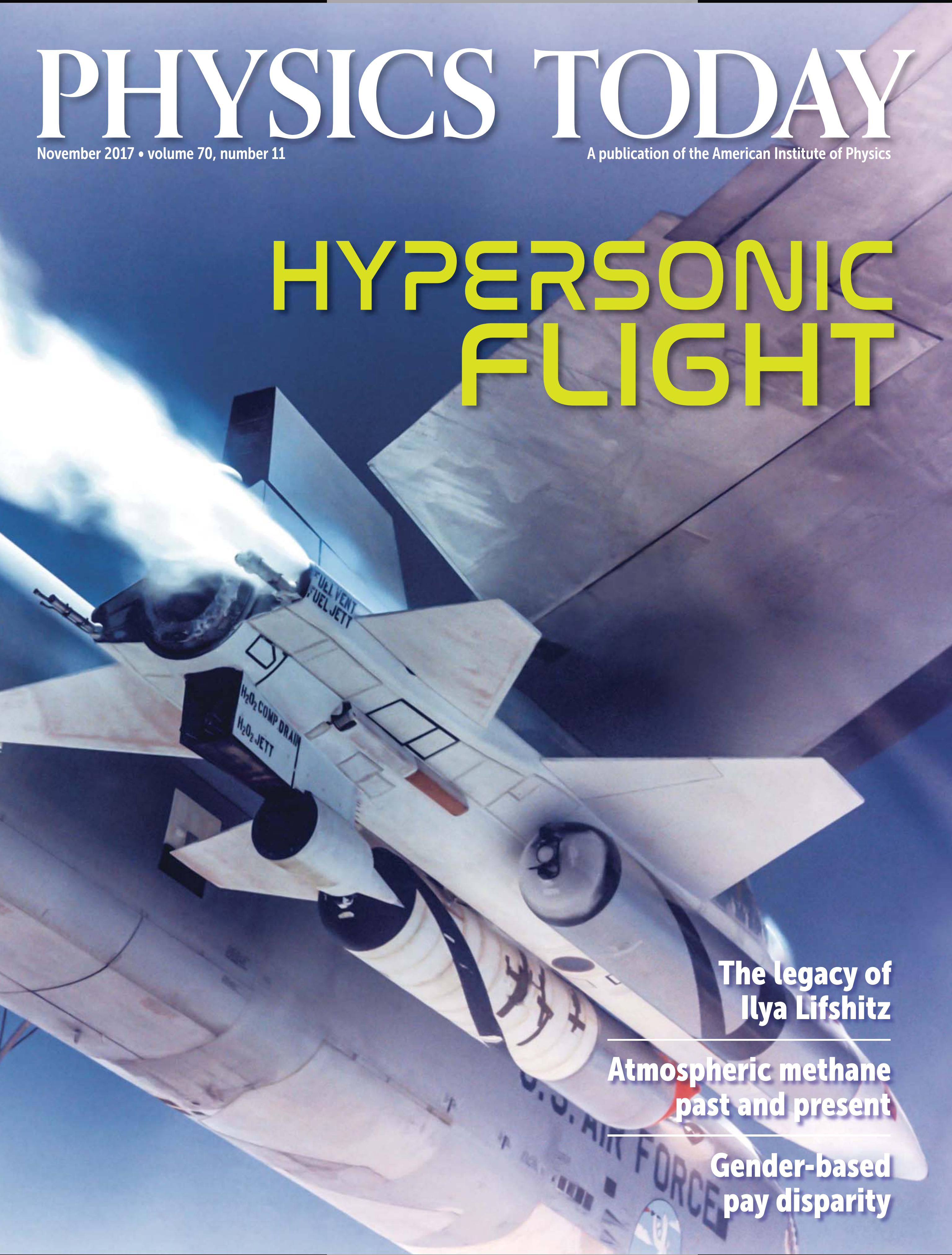

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FEATURES

ON THE COVER: NASA's experimental X-15 aircraft, shown here hitched to the wing of a B-52, could achieve speeds well above Mach 6—fast enough to fly from Los Angeles to Washington, DC, in half an hour. Although the X-15 was retired in 1968, the pursuit of hypersonic flight has continued apace. On **page 30**, Ivett Leyva describes scientists' ongoing efforts to understand and overcome the many challenges posed by high-speed flight. (Photo courtesy of the US Air Force.)

Recently on PHYSICS TODAY ONLINE

www.physicstoday.org

KIP THORNE

▶ Cécile snapshots

Cécile DeWitt-Morette, a leading mathematical physicist who founded the Les Houches School of Physics in France, died in May at age 94. PHYSICS TODAY editor Toni Feder shares anecdotes and photos that capture DeWitt-Morette's eventful life and substantial influence in the physical sciences.

VIRGO COLLABORATION

▶ GW frenzy

Within a month, gravitational-wave researchers announced both the first detection by the Virgo interferometer and the discovery of colliding neutron stars; in between, three LIGO architects were named recipients of the 2017 physics Nobel. PHYSICS TODAY has comprehensive coverage of all those developments.

AJ CANN, CC BY-SA

▶ Double-blind review

Despite the shift toward openness in publishing, some physicists want more anonymity in the review process. Dalmeet Singh Chawla reports on a yearlong trial by two journals to offer double-blind peer review, in which neither the authors nor the reviewers know each other's identities.

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FROM THE EDITOR

Is it time to change the undergraduate curriculum?

Charles Day

My two oldest nieces, Miriam and Sarah, are both 16. Later this year, they will start their respective searches for a place at college in earnest. Their experiences will be different, not just because Miriam is interested in science and Sarah is interested in teaching. Miriam lives in Conwy, an ancient town of 15 000 people in North Wales. Sarah lives in Olney, a Maryland suburb of 34 000 outside Washington, DC.

When it comes to undergraduates, the university systems of the UK and the US are significantly different. In the UK, students typically study just one subject for three years—physics, in my case. In the US, students spend less time studying a major; more on other subjects.

The UK system has advantages and disadvantages. In three years, a UK physics student will be taught more physics than a US physics major will in four. That's a plus. On the other hand, prospective students in the UK have to be sure of their chosen subject. And if their high schools don't teach, say, economics or sociology—two subjects that were not offered at my school—they could fail to embark on a fulfilling vocation.

The US system of majors, minors, and general education is more forgiving and flexible, yet I have little enthusiasm for it. That view might seem heretical, given the current crop of books on the virtues of a liberal education. But tuition rates at US universities have become so high that we should question whether students are getting value for the money borrowed and spent, even if we conclude that undergraduate curriculums don't need to change.

One purported benefit of a liberal education is that it exposes students to a rich range of learning. It prepares them to be knowledgeable participants in society and can give them the intellectual flexibility to adapt to a changing economy. The general education requirements that I looked at for this editorial do indeed proclaim those praiseworthy aims.

But I've found little love among my US-educated friends for the general education courses they were forced to take. For example, my wife majored in geography, a subject she loves. She wanted to take more geography courses, but couldn't. From a gen-ed course on the 18th-century British novel, she acquired the pleasureless skill of reading books as quickly as possible. The "eat-your-vegetables" approach to gen-ed also presents professors with the challenge of trying to engage students who would rather be studying something else. A friend of mine who's a professor at Boston University told me he felt he had to entertain his gen-ed students as much as teach them.

Then there's the complexity of the US system. Scheduling classes with a view to meeting all the requirements for graduation is evidently so challenging that at least one company, Hobson's, makes money selling software that navigates class timetables, prerequisites, previously earned credits, and so on. One friend of mine picked up his bachelor's diploma only to discover, decades later, that he had failed to take one required course. Neither he nor his adviser had noticed the deficit.

What is to be done? I see three promising ways to improve the US undergraduate curriculum. The first is to emulate the reforms enacted in Hong Kong in 2012. (See PHYSICS TODAY, December 2012, page 23.) At the turn of the 21st century, the territory's government concluded that the education system it inherited from the British was unsuited for preparing students for the modern economy. The system Hong Kong adopted is qualitatively similar to the US system, but with a crucial difference. Gen-ed requirements are less burdensome. There's also less choice, so the system is simpler.

The second promising route is to give students more freedom to pursue their interests. That's the approach adopted by project-based universities, such as Quest and Olin. (See PHYSICS TODAY, June 2017, page 28.) Students learn, say, writing and communication as part of carrying out projects, not because they have to take English 101.

Lastly, there's the approach recommended on page 38 of this issue. There you'll find a feature article by Laurie McNeil and Paula Heron that summarizes J-TUPP, the Joint Task Force on Undergraduate Physics Programs. Recognizing that only 5% of US physics majors land in academic jobs, J-TUPP recommends that they be taught the skills they'll need in nonacademic jobs, such as communication, facility with widely used software, and teamwork.

Adding courses to a physics curriculum risks taking time away from physics courses—but not if that time is taken from gen-ed. PT

READERS' FORUM

Readers weigh in on how to teach physics

As a longtime teacher of college-level physics, I read with interest Ricardo Heras's Commentary on traditional versus creative styles in solving physics problems (PHYSICS TODAY, March 2017, page 10). He has clearly been bitten by the excitement and satisfaction of studying physics, and he is already thinking deeply about how it can best be presented to students. My guess is that he will someday be a very highly regarded teacher.

I also think, though, that the traditional textbook problems Heras disparages have considerable value. Yes, we have all had (and probably were ourselves) students who can grind out an end-of-chapter or test problem without really internalizing the physics involved. But that is not the primary goal I have in mind when I have my students, particularly first-year students, do the problems.

Heras's model of a creative problem-solver is Richard Feynman, a rightly revered figure. But most of us, and most of our students, are not Feynman. I cannot expect my first-year students to develop deep physics insight. Before insight comes command of the foundational knowledge and techniques of the discipline, and my students are in desperate need of accruing practice in setting up and working through problems. The inevitable disappointment of seeing that their answer does not match the one in the back of the book and having to diagnose what went wrong is often the most educational aspect of the work. At higher levels, having students dig out an old-fashioned table of integrals and see how to compute an expectation value by hand—as Erwin Schrödinger might have done—gives them a sense of the nitty-gritty that underpins the insights of great creative minds.

Insight and expertise accrete over years of such grinding practice. Developing intuition in physics—or in any challenging discipline—is no different from learning to play a sport, speak a new language, or play a musical instrument proficiently: practice, practice, practice. Each boring problem is an incremental step along the climb, an investment that will eventually pay off in the form of a coherent foundation of knowledge and a grasp of techniques that will last a lifetime.

I have witnessed the evolution from blackboard- and overhead-based "static" lectures to powerful in-class computer and projector systems and laboratory sensor-interface units being used to illustrate concepts, calculations, and phenomena in ways I could only have dreamt of when I began teaching. But before a problem is thrown to the computer, it always goes up on the board first to have its physics, units, mathematical nuances, and orders of magnitude examined. To be sure, many traditions are inertia incarnate, impediments at best and destructive at worst. But not all are without virtue, and the best can be adapted to the times.

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Ricardo Heras writes that the basic courses in his first two years at University College London were disappointing. He says, "Most of my lecturers followed traditional teaching approaches based heavily on solving standard problems and learning by rote, with no hint of free inquiry or discussion."

My experience at the Colorado School of Mines in the early 1960s, where I worked for a degree in geophysics, was entirely different. I had all those basic courses, and frankly, I used them to learn. My interest in seismology started in middle school in Los Angeles because of the regular occurrence of earthquakes there. I devoured *Elementary Seismology* (1958) by Charles Richter. While in high school, I visited the seismological laboratory at Caltech several times. I was greeted cordially, and my questions were always answered.

In my first year at the School of Mines, I discovered an earthquake swarm in the Denver area.[1] Its origin was under contention, with the consensus view being that the earthquakes were spread over a 30-mile range and an alternative view being that they were the result of saltwater injection into a deep disposal well.

I took it as a research opportunity. The School of Mines was and is a small institution, with great freedom of inquiry and action. I located the pumping records for the well and then correlated that information with the energy released by the earthquakes. I found that with several weeks' delay, the energy released was proportional to the volume of liquid injected. Meanwhile, the US Geological Survey had installed seismometers close to the well, and the information from them seemed to confirm that the earthquakes were attributable to the pumping.

I caught up with a geology professor at a coffee shop and quizzed him about the Denver geology. At first he was reluctant, thinking I was a grad student trying to shortcut my research. After I explained my position and my interest, I spent 45 minutes trying to absorb the flood of information he provided.

My work led to the actual seismograms for the earthquakes. That, in turn, led to the discovery that a second earthquake event in these particular records had come almost immediately after the first. When the second event was removed, the earthquake locations all resolved around the well.

I used the materials taught in the early classes, including equations I learned in physics lab, the Fortran programming class I was taking, and other materials. So I found the basic classes not disappointing but rather a toolshed to dig out answers from conflicting data. With an open mind, an open campus, and a hunch, I was able to move from "I believe" to "from these data I conclude."

CONTACT PHYSICS TODAY

Letters and commentary are encouraged and should be sent by email to ptletters@aip.org (using your surname as the Subject line), or by standard mail to Letters, PHYSICS TODAY, American Center for Physics, One Physics Ellipse, College Park, MD 20740-3842. Please include your name, work affiliation, mailing address, email address, and daytime phone number on your letter and attachments. You can also contact us online at http://contact.physicstoday.org. We reserve the right to edit submissions.

I presented my data, and soon the institution came to agree.

Reference

1. J. H. Healy et al., *Science* **161**, 1301 (1968).

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Although one can sympathize with Ricardo Heras's plea for more creativity in physics teaching, the entire structure of physics education is currently founded on mastery of content, as reflected in tests taken at various stages. Those tests determine whether the student is qualified for promotion and even for admission to the PhD program.

To modify the didactic structure in favor of creative learning wouldn't accomplish the goals of physics departments as they are presently structured. For one thing, the time consumed for such learning would surely be much greater than for the current lecture–lab format. Of course, one could assign projects such as I have during my physics teaching career in the 1980s to early 1990s, but those would be *outside of class time*. Hence, they do not facilitate learning by supporting independent student creativity in class.

Heras mentions *The Feynman Lectures on Physics*; that three-volume work exemplifies its author's unconventional approach to physics teaching. But even today most physicists I know look at it as an interesting supplement to their undergrad courses and not as a standalone text.

The very reason Feynman's teaching and methods wouldn't work in physics departments as currently established is spelled out by Heras himself in his Commentary (page 11). He says, "Feynman's lectures successfully omitted proposed problems. His teaching style is also exemplified in the noncredit, no-homework, no-registration, tuition-free Physics X course he offered at Caltech."

What physics department today could even remotely entertain such a course? I am not saying it could never work, but it would require a radical rethinking of physics pedagogy and would come up against the existing system for promotion and qualification and for how we integrate students into the formal university course system.

Perhaps the optimal time for free inquiry might be when Heras pursues his PhD. Then he can find original expression for his curiosity, creativity, and inquiry. Of course, to reach that point, he will have to pass rounds of comprehensive examinations, and those will entail solving a lot of "traditional" problems.

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▶ **Heras replies:** Cameron Reed suggests that at the PhD level, a physics student will have worked lots of standard undergraduate problems and can finally acquire "a sense of the nitty-gritty that underpins the insights of great creative minds." I disagree. Richard Feynman, Julian Schwinger, and Lev Landau, for example, did not need a PhD to acquire that sense. Each published his first paper as an undergraduate.

Intuition in physics is, for Reed, a matter of "practice, practice, practice." Again, I disagree. Intuition is the key to, for example, imagining a new sport, inventing a new language, or composing a new symphony. To reach any of those goals, practice is necessary but not sufficient. I believe intuition triggers creativity, which is characterized by a crisis occurring when one imagines a plausible idea that seems inconsistent with previously established ideas (see my essay, "Individualism: The legacy of great physicists," PHYSICS TODAY online, 25 October 2013). One needs a passionate desire to solve such a crisis.

Philip Stahl clearly describes the current role traditional exams play in the formation of a physicist. Unfortunately, mastery of content is often taught at the expense of free inquiry and creative thinking. To paraphrase Albert Einstein, "The value of a college education is not the learning of many facts but the training of the mind to think."

Stahl claims that "to modify the didactic structure in favor of creative learning wouldn't accomplish the goals of physics departments." I think those goals should be critically reviewed. For undergraduate students, physics departments should be shelters for creativity and not solely examination factories. Regarding Feynman's Physics X course, Stahl asks, "What physics department today could even remotely entertain such a course? . . . It would require a radical rethinking of physics pedagogy." Precisely! After more than five decades of traditional physics teaching, I say it is time for physics departments to make a place for creative teaching.

I was invited by PHYSICS TODAY's editor to write "on how you are being taught physics and—more important—how you would prefer to be taught physics." I took the challenge as an exercise of academic integrity. I received positive comments from outstanding physicists such as Freeman Dyson, Frank Wilczek, and Eugene Parker. In particular, Dyson gave me the following advice: "I agree with you that the time spent in formal class-room lectures and course-work is mostly wasted. You don't need all that stuff to do science. . . . My advice to you is to skip the classes as much as the system allows, and get to work on a real problem. When you work on a real problem, you quickly find out what you really need to know."

Most of my professors were uncomfortable with my essay. Some said that I was an atypical student and that their traditional teaching had worked well so far. Unfortunately, I can say from experience that "atypical" students face many difficulties in traditional physics departments. Despite having published six papers (see www.ricardoheras.com), my institution has denied me financial support to finish my undergraduate studies. Tradition is indeed strong in my department! But as Mark Twain wrote in *The Adventures of Tom Sawyer*, "Often, the less there is to justify a traditional custom, the harder it is to get rid of it."

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Wastefulness not always a result of progress

Charles Day, in his column "Olive spoons and terrapin forks" (PHYSICS TODAY, February 2017, page 8), seems to lament the use of LED lighting as decoration because it uses energy that would otherwise never be consumed. Making the leap to the Internet of Things and the usual milk-carton example, he argues that wastefulness is a by-product of technological progress. However, if the LED display were the critically acclaimed work of an artist, it would still be as wasteful of energy, yet also pleasurable and beneficial.

Similarly, the Internet of Things may promise a notification that my milk is sour, but one can easily imagine having the carton call the milkman for a delivery rather than simply texting me.

That is the approach with POEM Technology's monitoring system, which optimizes oil deliveries by reading and uploading heating oil tank levels, in turn allowing suppliers and consumers to fine-tune scheduling. Rather than being wasteful, the monitors enhance efficiencies by eliminating excess deliveries and their greenhouse gas emissions. Perhaps the real promise of the Internet of Things comes when the market realizes the value of such a closed-loop system. I do not want to get a text from my milk carton, but I would like to see the milk truck show up automatically, like it did when I was a child.

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A reminder of the powers of π

In a two-sentence Letter to the Editor of *Physical Review*, Friedrich Lenz made the noteworthy observation[1] that the value of the ratio m_p/m_e could be expressed to all significant figures of the time by $6\pi^5$. That was in 1951, and remarkably, years later the observation holds true to good approximation. His note is perhaps also the shortest article ever published in *Physical Review* (27 words, 1 number, 1 equation, and 1 reference).

Its modern version could read as follows: The most exact value at present[2] for the ratio of proton to electron mass is $m_p/m_e = 1836.152\,673\,89(17)$. Despite years of experimental improvements, that number still coincides, to good approximation, with the simple, unambiguous representation $6\pi^5$.

With the 66th birthday of Lenz's intriguing observation, it seems fitting to make his result better known to the community. This reminder should not be construed as trumpery—a showy but worthless statement—but as a comfort that some facts remain true with the passing of time.

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They may not be out there

My colleagues Mario Livio and Joe Silk, in their article "Where are they?" (PHYSICS TODAY, March 2017, page 50), have underplayed the most straightforward answer by far to the question Enrico Fermi posed. That answer is that if they exist, they are too far away to have made it here. The universe is big and getting bigger, and the speed of light places a strict constraint on travel times. Possible signals from aliens, even if intelligence were abundant throughout the cosmos, would typically take thousands or even millions of years to reach us—and their spacecraft would take even longer. The main conclusion to be drawn is that we will probably be unable to know for a very long time whether they even exist.

Yes, some aliens might be nearby. Earth is located in a spiral arm of the Milky Way about 25 000 light-years from the center of the galaxy, whose disk spans 100 000 light-years. More precisely, the Sun lies in a cavity of interstellar gas called the Local Bubble, which extends over roughly 600 light-years.[1] It in turn is located in the Gould belt, a spur of stars, star clusters, and molecular clouds between two of the galaxy's spiral arms. The belt stretches to about 1200 light-years in its longest dimension. The approximate number of stars per cubic light-year in our immediate solar neighborhood is 0.004, to within a factor of two, so it holds about 30 million stars of all types.

Our earliest broadcasts have only made it out to about 100 light-years. What are the chances of chatting with alien neighbors if we wait and listen for the next 1200 years, long enough for the farthest signals in the neighborhood to reach us? The combined chances need to be better than about 1 in 30 million. If the stars are too big or too small, if the planets' orbit or obliquity are wrong, their sizes or chemical compositions unsuited, their surfaces ill equipped, their geologic and meteoritic history too inauspicious, then we are alone. Then add in the biological uncertainties, which are much less well understood: If the chemistry needed to generate life is too intricate or too slow, if evolution from proteins to intelligence is too often aborted or misdirected, or if civilizations die off quickly, then, too, we are alone.

I support the search for extraterrestrial intelligence. If we don't look, we won't find them. But it is a risky endeavor, and nonprofessionals should keep in mind the complex and contingent evolutionary history of intelligence on Earth and the enormous limitations imposed by the finite speed of light. Livio and Silk end their discussion by asking, "Are we alone? The answer may affect nothing less than our claim for being special in the cosmos. . . . We shall never know unless we search!" That search, however, could very likely last an astronomically long time.

I think my own community of scientists has hopped aboard an optimistic science fiction bandwagon while being insufficiently honest in highlighting the many cautions. Percival Lowell, famous for his search for Pluto and his studies of the canals of Mars, wrote in 1908, "From all we have learned of its constitution on the one hand, or of its distribution on the other, we know life to be as inevitable a phase of planetary evolution as is quartz or feldspar or nitrogenous soil. Each and all of them are only manifestations of chemical affinity."[2]

No one believes that today. Every schoolchild knows that Mars has no artificial canals and no Martians either. Lowell's confident assumption was wishful thinking, and we should beware of making similar assumptions.

A companion issue is not nearly as ambiguous: the ethical one. If the human race might be alone, with no one to talk with, then we face the possibility that neither we nor our planet are commonplace; we might even be rare. The implications are that Earth and its life have cosmic value, that we have concomitant responsibilities, and that we will have to solve our problems without advice from superintelligent beings from space. The prospect brings great urgency to the cause of protecting our rare planet and its precious inhabitants.

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Calling computers names in Swedish

I very much enjoyed reading Jim Fleming's article on Carl-Gustaf Rossby and the seminal contributions Rossby made to meteorology (PHYSICS TODAY, January 2017, page 50). However, the otherwise excellent article has two errors.

Something must have gotten lost in translation to cause Fleming to claim that "Rossby pursued numerical weather prediction in Sweden in an era in which there was no Swedish word for digital computer." With applied mathematician Germund Dahlquist, Rossby developed a weather model for the Binär Elektronisk Sekvens Kalkylator (BESK; Binary Electronic Sequence Calculator). Designed and built in Sweden, BESK was the world's fastest computer when it became operational in 1953. From September 1954, BESK weather simulations enabled routine 24-hour national forecasts.

The funding agency for the BESK project, Matematikmaskinnämnden (the Swedish Board for Computing Machinery), has a Swedish word for digital computer, *matematikmaskin* (literally, mathematics machine) in its name! Other contemporary Swedish terms for computer were *siffermaskin* (numbers machine), *datamaskin* (data machine), *kalkylator* (calculator), and the more fanciful *elektronhjärna* (electron brain), favored by the media. *Dator*, the now predominant term, was not introduced until 1968. Also, the correct abbreviation for Sveriges Meteorologiska och Hydrologiska Institut (Swedish Meteorological and Hydrological Institute) is SMHI.

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▶ **Fleming replies:** I thank Johan Carlsson for his comments. My statement about "an era in which there was no Swedish word for digital computer" was based on a 1946 report by Stig Ekelöf, a technician at Chalmers Institute of Technology.[1] I could have said there was no widely used term in *any* language for the new machines.

According to the digital archives of Sweden's two leading newspapers, *Dagens Nyheter* and *Svenska Dagbladet*, the term *elektronhjärna* appeared as early as 1946. *Matematikmaskin* became established in 1947. *Siffermaskin* was mentioned in 1907 and reappeared in 1948. *Datamaskin* was in frequent use by 1956.

By the early 1950s, BESK (Binary Electronic Sequence Calculator) was the best machine of its kind in the world. Sweden used it to issue the world's first real-time operational numerical forecast on 23–24 March 1953; it beat the actual weather events by some 90 minutes. In 1955 Joanne Malkus and Georg Witt used BESK to generate the first digital cloud models.

When Carl-Gustaf Rossby entered meteorological service in 1922, the Swedish Meteorological and Hydrological Institute was called Statens Meteorologisk-Hydrografiska Anstalt. The name change occurred in 1945. The confusion of the abbreviations SMHA and SMHI on page 53 of my article is an editorial glitch.

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Correction

September 2017, page 31—The amount of annual US hydrogen production is around 11 million tons, not 10 tons as stated. PT

SEARCH & DISCOVERY

Ancient clues help quantify modern methane

Natural geological emissions contributed little to the methane levels of the ancient atmosphere. The same could be true today.

FIGURE 1. MINING ANCIENT METHANE. At Taylor Glacier in Antarctica, Christo Buizert of Oregon State University helps to load ice cores into a melt-extraction chamber to measure their carbon-14 content. (Courtesy of Vasilii Petrenko.)

Methane is a potent greenhouse gas. Although present in the atmosphere at less than 1% of the level of carbon dioxide, it strongly absorbs IR radiation, so it's responsible for between 15% and 30% of greenhouse warming. Its atmospheric concentration has more than doubled since the Industrial Revolution, from 700 to 1800 ppb, and continues to rise at a rate close to that of many worst-case projections.

Tracking down exactly where all the CH_4 is coming from has proven stubbornly tricky. The gas has many possible sources, some natural and some anthropogenic. And sources in each of those categories can be either biologically active (wetland bacteria, livestock) or fossil (natural seepage from underground deposits, leaks from the production and use of fossil fuels). Much of the overall emission comes from remote parts of the world, so it's difficult to quantify.

The University of Rochester's Vasilii Petrenko and colleagues may now have found an important piece of the puzzle by taking a look back in time to CH_4 that was trapped in Antarctic ice between 11 000 and 12 000 years ago.[1] By measuring the amount of carbon-14 in the trapped gas, the researchers found that essentially all of the ancient CH_4 was biogenic and that natural fossil emissions at the time were minimal. The result may mean that today's anthropogenic CH_4 emissions, particularly the anthropogenic fossil emissions, are higher than previously thought. If that's the case, we humans have more power than we'd realized to reduce our influence on climate change.

Carbon controversy

Assessments of the current CH_4 budget fall into two broad categories. Top-down studies measure the concentration, distribution, and isotopic composition of the CH_4 already in the air and use models to figure out where it came from. Bottom-up studies measure emissions from known CH_4 sources, extrapolate them globally, and add them all up.

Both classes of studies are subject to large uncertainties, and even estimates of the same type can disagree substantially. Total global emissions are somewhere in the range of 500 to 700 teragrams per year, with bottom-up studies giving values some 20% higher than top-down ones.[2] The lion's share of that amount is biogenic, mostly from wetlands and agriculture. Only a minority—perhaps 100 to 150 Tg/yr—comes from fossil sources. But the CH_4 budget includes not only sources but also sinks, and CH_4 is generally removed from the atmosphere at more than 90% of the rate at which it's added. So even a small reduction in emissions could make a big difference.

The isotopic measurements in top-down studies often focus on carbon-13 and deuterium. Although those stable isotopes aren't created or destroyed on Earth in significant amounts, they're fractionated by various physical, chemical, and biological processes, so different sources of CH_4 have different isotopic makeup. But stable isotope signatures are imperfectly known, overlap for different sources, and can even change over time for a single source.

Radioactive ^{14}C is different. It's created by cosmic rays in the stratosphere and upper troposphere, and it decays with a half-life of 5700 years. The atmosphere therefore has a steady-state concentration of ^{14}C, as do living organisms, which are constantly taking in and expelling carbon. When an organism dies, the carbon exchange stops, and the ^{14}C content declines.

That ^{14}C decay is the well-known basis for carbon dating. It also offers a way to distinguish between CH_4 sources. Biologically sourced CH_4 has the same ^{14}C level as the organisms that created it; the atmospheric lifetime of CH_4, about 10 years, is too short for any appreciable decay to happen in the atmosphere. On the other hand, fossil CH_4, trapped underground for millions of years, has long lost all its ^{14}C. In principle, then, measuring the ^{14}C in a sample of CH_4 should reveal how much of it came from biological and how much from fossil sources.

In today's atmosphere, that measurement is hampered by the appreciable amount of $^{14}CH_4$ produced by nuclear power plants, and the biological–fossil breakdown of the modern CH_4 budget is still a matter of some controversy. The preindustrial atmosphere, as preserved in glacial ice, presents no such complication.

Cosmic correction

Petrenko and colleagues' first attempt to measure $^{14}CH_4$ in ancient ice was in 2009, when Petrenko was a graduate student with Jeffrey Severinghaus (also an author on the new paper) at the University of California, San Diego.[3] They had several reasons for focusing on the period from 11 000 to 12 000 years before the present. It's well before the rise of any anthropogenic emissions, but recent enough—just two half-lives ago—that enough ^{14}C remains to measure. And it was a period of rapid change, both globally and regionally. The world was just emerging from the Younger Dryas period, which saw much of the Northern Hemisphere covered in ice, and entering the more hospitable Preboreal period. During the transition, many parts of the globe experienced abrupt climate change—parts of Greenland, in particular, warmed by as much as 10 °C in just 20 years. And the global CH_4 level rose sharply—from 500 to 700 ppb—at an annual rate comparable to what we're experiencing today.

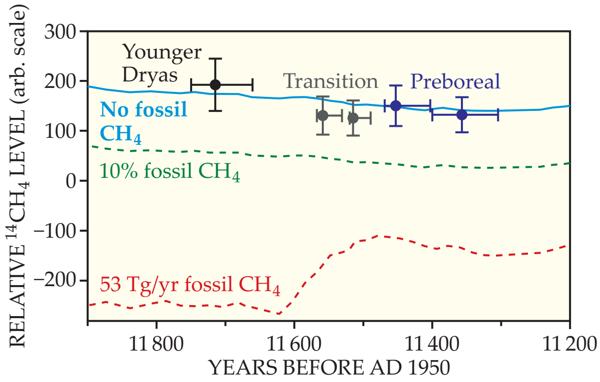

FIGURE 2. CARBON-14 IN METHANE from the Younger Dryas and Preboreal periods and the transition period between them. All measurements are most consistent with the conclusion that essentially all the atmospheric CH_4 came from biological, not fossil, sources. (Adapted from ref. 1.)

The researchers were interested in what sources drove that increase and how it was related to the regional warming.

Because CH_4 is a trace atmospheric gas and ^{14}C is a trace isotope, an accurate measurement requires about 1000 kg of ancient ice—a bit more than a cubic meter (see figure 1). That's too much to be feasibly obtained by the traditional method of drilling deep into a stratified ice sheet. Fortunately, certain locations in Greenland and Antarctica expose plenty of old ice at their surfaces. (Because the mixing time of the global atmosphere is about a year, an order of magnitude less than the CH_4 atmospheric lifetime, both Arctic and Antarctic ice record the same long-term trends.) The ice is dated through measurements of quantities, such as total CH_4 concentration and various stable-isotope levels, that changed in known ways over time.

In their 2009 study, Petrenko and colleagues analyzed several samples from across their period of interest. Surprisingly, all their ^{14}C values were far too high to be explained even by attributing all the ancient ^{14}C to biological sources. The discrepancy, they determined, was because ^{14}C creation by cosmic rays isn't limited to the upper atmosphere; the rays also penetrate near-surface ice to create ^{14}C *in situ*.

It took the researchers until 2016 to figure out how to correct for the cosmogenic ^{14}C. They travelled to Antarctica's Taylor Glacier, an extraordinary region where surface ice ranges from 8000 to more than 100 000 years old. They analyzed samples of 50 000-year-old ice—old enough that all its original ^{14}C was gone, and the only $^{14}CH_4$ remaining was cosmogenic.[4]

Then, for the present study, they moved 300 m along the glacier to collect samples from the Younger Dryas–Preboreal period of interest. They used the 50 000-year-old samples to correct for cosmogenic $^{14}CH_4$ and estimate the true amount of $^{14}CH_4$ present in the atmosphere 11 000–12 000 years ago.

Figure 2 shows their results, along with a few model calculations based on different assumptions. As indicated by the light blue curve, the data are most consistent with the scenario in which all the CH_4 throughout the period was biological, not fossil. Even the case of 10% fossil CH_4, shown by the green curve, is outside one standard deviation. Far outside the uncertainty limits is the red curve, which assumes a constant 53 Tg/yr of fossil CH_4, a common estimate of today's nonanthropogenic fossil CH_4 from bottom-up and ^{13}C studies.[5] In fact, Petrenko and colleagues found that at the 95% confidence limit, at most 15 Tg/yr of ancient CH_4—about 7% of the total—came from fossil sources.

It's not impossible that geological CH_4 seepage could have increased threefold over 11 000 years. But it would be a puzzling rate to explain. Geological processes don't usually change that much over mere millennia, and if anything, the emissions should have decreased over time. Sea levels have risen since then and covered up some potential CH_4 seeps (and it appears that CH_4 emitted deep underwater may be gobbled up by bacteria before it reaches the surface; see PHYSICS TODAY, August 2017, page 21). And as oil fields are drained of their natural gas, less remains to seep out naturally.

Petrenko and colleagues' work therefore suggests, but doesn't prove, that modern estimates of natural fossil CH_4 emissions may need to be revised downward—and thus that estimates of anthropogenic fossil CH_4 may need to be revised upward. The researchers plan to make similar measurements on ice from 200 to 250 years ago—much more recent but still largely preindustrial—to solidify their case.

Johanna Miller

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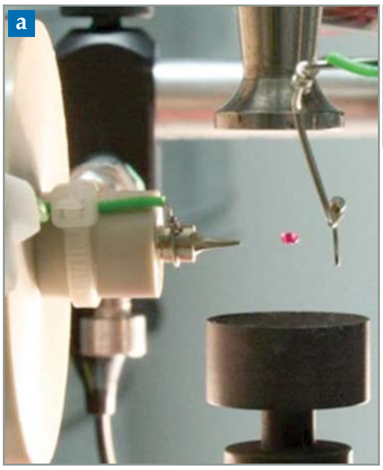
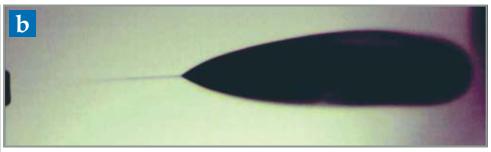
Acoustic levitation widens the study of droplet jetting

To investigate the fission of charged droplets, a pair of chemists holds one stationary in electrified midair.





ACOUSTIC LEVITATION. (a) A 5 μL droplet of methanol (red) sits in the antinode of an ultrasonic standing wave produced by a vibrating plate, or sonotrobe, above it and a reflector below it. A pointed electrode, or skimmer, to the left and a ring electrode, seen edge-on to the right, are held at a 9 kV potential. **(b)** As the droplet ruptures in the strong electric field, it emits a jet of charged daughter droplets into the skimmer, which doubles as the inlet to a mass spectrometer. (Adapted from ref. 1.)

Thunderclouds, combustion chambers, and inkjet nozzles are among the many settings where droplets break up in an electric field. More than half a century ago G. I. Taylor identified the mechanism behind the fission. Above some field strength known as the Taylor limit, the coulombic repulsion of charges on a droplet's surface overcomes the attractive intermolecular forces that hold it together. As a result, the droplet ruptures and spews a fine jet of tiny daughter droplets.

Despite the natural and technological relevance of the phenomenon, some details remain murky. Macroscopic properties such as solute concentration, pH, and charge density are not uniform along a parent droplet's radius, and its surface and bulk compositions can differ dramatically. No one precisely understands the fluid dynamics that determine what molecular and ionic solutes the daughter droplets inherit from their parent. The dynamics of the rupture are complex, and the mathematical singularity of the electric field at the sharp point that forms at the moment of breakup complicates numerical simulations.

Most research on droplet jetting is conducted with a 15-year-old technique known as field-induced droplet ionization, in which a series of parent droplets are dripped in air between the parallel plates of a charged capacitor. As they fall, the droplets become polarized in the capacitor's electric field, take on a lemon-like shape, and, depending on the droplets' net charge, squirt jets from one or both pointed ends toward the electrodes. But although the field strength and the net charge can be freely adjusted, experimenters can probe the droplets' dynamics only within the few milliseconds they remain in free fall.

Carsten Warschat and Jens Riedel from Germany's Federal Institute for Materials Research and Testing (BAM) have developed an acoustic technique that can probe those dynamics on the same droplet for as long as it lives—levitated in electrified midair.[1] As illustrated in the figure, their setup consists of a home-built levitator whose 40 kHz ultrasonic field produces a vertical standing pressure wave between two horizontal electrodes. A droplet placed at a pressure antinode can remain there for seconds to hours, limited only by its evaporation rate. What's more, the setup allows easy access to a nearby mass spectrometer that can capture the daughter droplets and analyze their composition.

Other researchers have studied jets from electrodynamically held droplets, but in that approach the electric field has to both rupture the droplet and hold it up, so neither role could be controlled independently. Optical levitation is another option, but the energy to hold the droplet aloft risks overheating it. Acoustic levitation doesn't suffer either problem. Moreover, whereas free-falling, electrodynamic, and optical methods are restricted to droplets with diameters on the scale of tens of microns, an acoustic wave can levitate droplets two orders of magnitude larger—up to 5 mm using a 40 kHz field. (See also PHYSICS TODAY, March 2015, page 17.)

That freedom may come in handy in efforts to chemically synthesize relatively large amounts of material using a single droplet as a microreactor or to produce daughter droplets at low electric-field strengths. The Taylor limit depends inversely on the square root of the droplet radius r. That dependence offers experimental flexibility in cases where the dielectric breakdown of air occurs at field strengths close to the Taylor limit. With their lower surface-to-volume ratio and slower evaporation, larger droplets also live longer.

In their demonstration, the BAM chemists used high-speed photography and mass spectrometry to image the rupture and chemically analyze the progeny of a methanol droplet roughly 2 mm in diameter. They found that the $r^{-1/2}$ dependence on the critical threshold field at which fission occurs is still valid at the millimeter scale, says Riedel. More importantly, the demonstration sets the stage for studies on the effects of a droplet's size, charge, and pH on the jet it emits. In preparation, Riedel and Warschat are currently building a controlled humidity chamber. Inside, a droplet's size will be an easily tunable knob and its lifetime effectively infinite.

Mark Wilson

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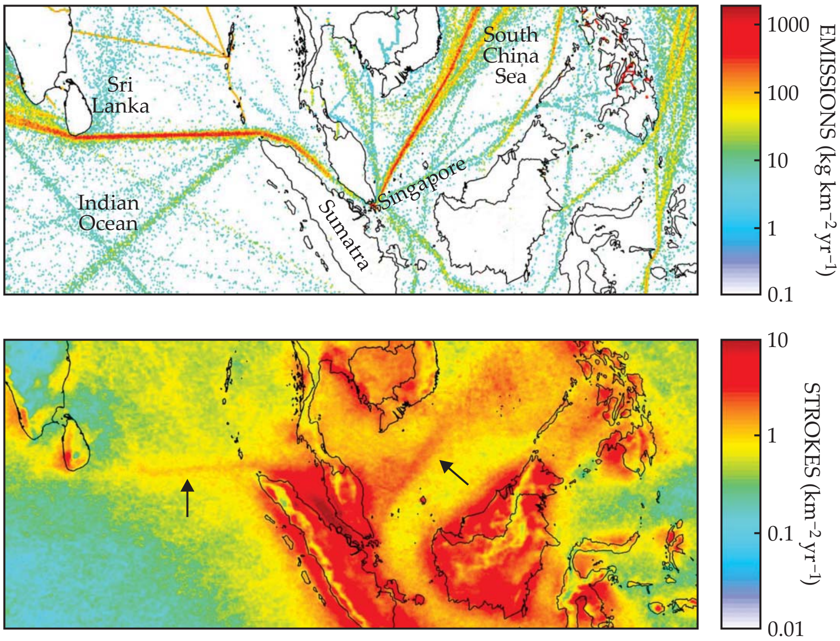
Ships cause their own stormy seas

Increased lightning frequency over maritime trade routes links pollution to the development of thunderclouds.

In centuries past, trading companies established shipping lanes—regularly trafficked routes for commercial vessels—based on prevailing winds and ocean currents. Commercial ships no longer use wind and sail for power, but many continue to travel those lanes. Two of the world's busiest lanes—one running due west from the northern edge of Sumatra to the southern end of Sri Lanka in the Indian Ocean and one running northeast from Singapore into the South China Sea—happen to cut through two of the world's rainiest regions.

If rain didn't make life aboard cargo ships tough enough, the lanes also turn out to be particularly prone to thunderstorms. From 12 years of global lightning data, Joel Thornton, Todd Mitchell, and Robert Holzworth of the University of Washington and Katrina Virts of NASA's Marshall Space Flight Center have found that lightning occurs above the two busy lanes twice as often as over adjacent regions.[1] But it's not that 16th-century ship captains had to put up with lightning for the sake of favorable winds. The researchers surmise that modern ships, through their aerosol emissions, are the cause of the increased lightning activity.



LIGHTNING OVER SHIPPING LANES. The lanes are evident in a map of estimated ship emissions of aerosol particles less than 2.5 μm in diameter (upper panel) for 2010. Average yearly lightning density during 2005–16 in the eastern Indian Ocean and the South China Sea (lower panel) shows two regions of enhanced lightning, indicated by arrows, directly above two heavily trafficked lanes. (Adapted from ref. 1.)

Polluted clouds

In addition to greenhouse gases, humans have pumped aerosol pollution into the atmosphere. Aerosol concentrations over land today may be an order of magnitude higher than in preindustrial times. Uncertainties about their overall effects remain one of the main uncertainties in modeling Earth's climate.

In principle, an aerosol-free sky would be a cloud-free sky. To form, cloud droplets must have aerosolized particles bigger than 50 nm in diameter that act as cloud condensation nuclei. But aerosols can play contradictory roles in cloud development.

When the concentration of particles in the air is low, clouds form large droplets that fall out quickly as rain. In general, the addition of condensation-inducing particles causes cloud droplets to be smaller and more numerous. Clouds with many small droplets might be expected to last longer, but small droplets evaporate away more easily. Highly polluted clouds may never develop into rain clouds. And because aerosols both absorb incoming sunlight and increase cloud reflectivity, they cool Earth's surface below and suppress water evaporation. Without enough water vapor, large clouds may not form in the first place (see PHYSICS TODAY, May 2004, page 24).

Small droplets should be more easily lofted via convection to heights of tens of kilometers. There, they can freeze, collide, electrify, and form thunderstorm-producing cumulonimbus clouds. That hypothesis has been dubbed the aerosol convective invigoration effect.[2] Evidence for the effect has come mostly from observations of soot-producing fires and other sporadic events.[3] But the presence of other meteorological factors such as winds and surface temperatures has muddled the results. If Thornton and his colleagues' conclusion that aerosols from ship exhaust increase lightning frequency proves true, their findings would be the clearest evidence to date that human-made aerosol pollution invigorates convection.

Lightning the way

How Thornton's team made their discovery starts with the World Wide Lightning Location Network (WWLLN), a global lightning detection network maintained by the University of Washington. As with other such networks, the WWLLN's radio receivers detect the very-low-frequency electromagnetic pulses that emanate from lightning. By examining the arrival times of those pulses at different receiving stations, the network can locate lightning anywhere on Earth to within 5 km.

Last spring, Thornton was chatting with Mitchell about wanting to use WWLLN data to look for signatures of aerosol effects. Mitchell told him that Virts had just found enhanced lightning over shipping lanes. While working on an unrelated project, Virts had decided to plot some WWLLN data at 10 km resolution. Although the WWLLN can locate individual strokes more precisely, previous global lightning distribution studies never looked at resolutions finer than 25 km. Virts, who had used WWLLN data for her PhD work, had noticed straight lines of lightning enhancement before in those coarser-resolution plots. But as can be seen in the figure, they were unmistakable in her high-resolution plots.

"I was floored to see something so clear," says Thornton. He realized immediately that ships' aerosol emissions might be the culprit. On land, researchers studying how aerosol pollution interacts with clouds have to contend with variations in terrain, heating of the lower atmosphere by the ground, and other confounding factors. Shipping lanes on the open ocean are largely free of such factors. And because archived WWLLN data go back to 2005, the group could investigate the lanes over a prolonged period of time.

The increased lightning activity, they found, was persistent. For example, even during summer, when the South Asian monsoon shifts storm activity northward in the Indian Ocean, lightning density showed a local maximum above the Indian Ocean lane. In addition, the enhancements above both lanes appeared to grow over time, perhaps suggesting the growth of ship emissions.

To rule out natural causes of lightning enhancement, the group consulted available satellite data and weather records. They found that sea-surface temperatures, rainfall rates, average convective available potential energy—a measure of thunderstorm updraft strength—and other meteorological measures exhibited no anomalous changes across the lanes.

Laboratory at sea

Thornton and his colleagues have yet to see comparably obvious signs of lightning enhancement over other shipping lanes. However, they note that the Indian Ocean and South China Sea lanes are particularly narrow, highly congested, and serendipitously located in warm regions with active convection. Data from other lanes may need more refinement to tease out the effect.

Importantly, the lanes can double as a kind of controlled experiment that's been going on for years. Aircraft-borne instruments flying over the lanes to measure droplet size distributions, aerosol concentrations, and other cloud properties will help cloud researchers refine their models of aerosol–cloud interactions. If they can get a good handle on the relationship between aerosol particle numbers and storm development in the relatively pristine ocean environment, they could apply their models to more complex situations over land.

Sung Chang

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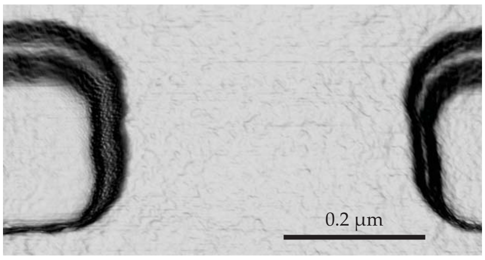
PHYSICS UPDATE

These items, with supplementary material, first appeared at www.physicstoday.org.

CONDUCTION ELECTRONS FLOW LIKE HONEY



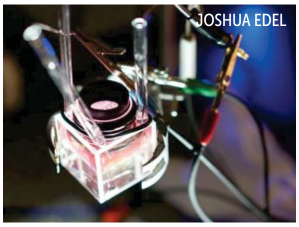
In most conductors, crystal defects and phonons scatter conduction electrons and impede the flow of current. But graphene exhibits anomalously weak electron–phonon scattering and can also be prepared in such a pure state that, at temperatures of a few degrees kelvin, an electron driven by a voltage difference moves ballistically. That is, the electron travels unimpeded through the bulk of the material until it hits a boundary, deposits some momentum there, and bounces back into the bulk to move freely until it again ricochets off a boundary. At higher temperatures, conduction electrons scatter off each other rather than off phonons. Due to those interactions, the electrons collectively flow as a viscous liquid, a phenomenon called electron hydrodynamics.

That collective flow has been observed in graphene samples with constant width, but Lancaster University PhD candidate Roshan Krishna Kumar, the University of Manchester's Andre Geim, and their international team have now added a new wrinkle by measuring the resistance of samples fabricated to have micrometer-scale constrictions such as those shown in the figure. At low temperature, the resistance was consistent with ballistic electron motion. But as the temperature was increased and collective effects became important, the investigators observed that the resistance fell. Though that so-called superballistic flow may be counterintuitive, the measured resistance drops were in accord with theoretical expectation, as was the observation that the drops were most pronounced for the thinner constrictions.

How does a fluid of electrons manage to flow through an aperture with less resistance than noninteracting, ballistically moving electrons? The key is that the flow is not uniform. Current density in the electron fluid is greatest near the centerline of the constriction and tapers off toward the sides. Because of that structure, the electron fluid is guided through the narrow channels in the graphene and avoids the boundary collisions that rob ballistic electrons of their momentum. (R. Krishna Kumar et al., *Nat. Phys.*, in press, doi:10.1038/nphys4240.) —SKB

NOW YOU SEE THIS NANOPLASMONIC MIRROR. NOW YOU DON'T.

Surface plasmons—collective, light-driven oscillations of electrons in metal—have given us stained glass, flat lenses, and home pregnancy tests. Now they bring us the mirror–window, a liquid mirror whose reflectivity can be tuned, or eliminated altogether, with an applied voltage.


JOSHUA EDEL

Developed by researchers led by Alexei Kornyshev, Anthony Kucernak, and Joshua Edel at Imperial College London, the device makes use of gold nanoparticles inside a cell filled with two immiscible electrolyte solutions—one aqueous, the other oily. Dispersed throughout one phase or the other, the nanoparticles interact negligibly with light, and the cell is transparent. But when the particles form a dense monolayer at the liquid–liquid interface, their plasmon resonances couple to each other and they become optically reflective.

To enable switching between those two states, Kornyshev and his coworkers charged their nanoparticles by tethering organic molecules to them. At equilibrium, the charged particles prefer the aqueous phase. But a few-hundred-millivolt potential applied across the two phases coaxes the particles to assemble at the interface. For the tactic to work, the particles must be just the right size: too small and the coupled plasmons won't resonate at visible wavelengths; too large and the particles will clump irreversibly. Particles around 16 nm in diameter gave the sought-after strong optical response—about 25% maximum reflectivity at visible wavelengths—and the organic tethers helped prevent agglomeration.

The video in the online version of this piece shows the mirror–window in action: As the initially transparent cell becomes reflective, the £10 symbol on a banknote positioned beneath the cell is displaced by the face of Queen Elizabeth II, which adorns a coin above. Currently, the transition from window to mirror takes a few hours, but the group's theoretical analysis suggests it should be possible to reduce the switching time to milliseconds. Once optimized, the technology could be used in a broad range of applications, including energy-efficient windows, switchable displays, and sensors. (Y. Montelongo et al., *Nat. Mater.*, in press, doi:10.1038/nmat4969.) —AGS

EVALUATING THE HABITABILITY OF EXOMOONS

Jupiter's moon Europa and Saturn's moon Enceladus are among the most promising places to look for extraterrestrial life in the solar system. Despite their distance from the Sun, the moons qualify as habitable because their proximity to their massive planetary hosts engenders tidal heating that is strong enough to melt water ice below their frozen surfaces. No one has yet detected a moon around an exoplanet. The objects are hard to find, even with the most powerful telescopes. Nevertheless, astronomers are theorizing about the habitability of exomoons.

For their study, Rhett Zollinger of Southern Utah University, John Armstrong of Weber State University, and René Heller of the Max Planck Institute for Solar System Research chose to focus on Mars-sized moons that orbit gas giants around M dwarf stars. Their choice was not arbitrary. Big moons are more likely to harbor life than small moons. Theory predicts that big moons are more likely found around gas giants than around terrestrial planets. And M dwarfs are the most abundant type of star in the Milky Way.

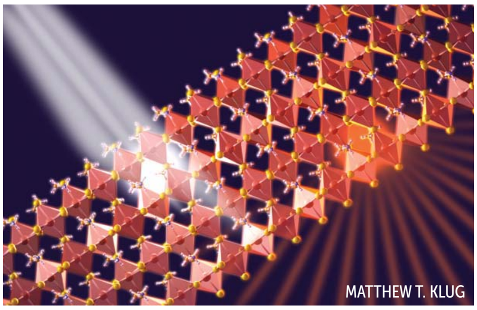
Because M dwarfs are dimmer than the Sun, their habitable zones—that is, the orbital locations where an Earth-like planet or moon with an Earth-like atmosphere can sustain surface water—lie closer to the star. From their modeling, Zollinger, Armstrong, and Heller discovered that for a wide range of M dwarf masses and other parameters, extreme tidal heating rendered the exomoons uninhabitable. So if there are moons around giant planets that orbit the most abundant type of star, in many cases, those moons could be uninhabitable, even when they occupy the star's habitable zone. (R. R. Zollinger, J. C. Armstrong, R. Heller, *Mon. Not. R. Astron. Soc.* **472**, 8, 2017.) —CD

HEALING DEFECTS IN PEROVSKITE FILMS

Since their debut in photovoltaic cells in 2009, organometallic halide perovskites have emerged as one of the most rapidly advancing photovoltaic technologies in history. Perovskite solar cells today exhibit a power-conversion efficiency of 22%, on par with that of commercial silicon-wafer cells. Perovskites can be printed as flexible polycrystalline thin films by solution processing, one of the least expensive methods available (see PHYSICS TODAY, May 2014, page 13). But the polycrystalline films contain a lot of atomic vacancies, interstitials, and other defects that trap photoinduced charge carriers and reduce the flow of current. To passivate those defects—that is, to tie up the dangling bonds that create trap states—a collaboration led by MIT and Cambridge University researcher Samuel Stranks has developed a treatment that could hardly be simpler: a half-hour exposure to white light in humid air.

When applied to thin films of the solution-processed methylammonium lead iodide, the treatment increased the films' internal photoluminescence quantum efficiency—a measure of how efficiently a material reemits light from every absorbed photon—from 1% to 89%. As more defect states become passivated, more photoinduced electrons and holes are free to recombine in transitions across the gap between the valence and conduction bands—emitting light as they do so. The lower the films' defect density is, the higher the luminescence and solar cell performance.

As charge carriers in the perovskite are generated by incident light, they react with air to create O_2^- ions. Those ions, in turn, react with the material's methylammonium cations and degrade the film into lead iodide and other debris products. But if the air exposure is temporary and the reactions halted, the researchers propose, the degradation doesn't run amok and the superoxide ions passivate iodine vacancies. The role of moisture is murkier, but the researchers hypothesize that humid air reduces the defect density to an even greater extent by forming a nanometer-thin amorphous shell of degradation products that further passivates the surface and hinders the degassing of the O_2^- species from the perovskite. When the films were irradiated in the presence of light and dry air, the observed rise in luminescence efficiency lasted for hours. When the air was humid, it persisted for weeks. A key question is how to make the improvement last for years. (R. Brenes et al., *Joule* **1**, 155, 2017.)


MATTHEW T. KLUG

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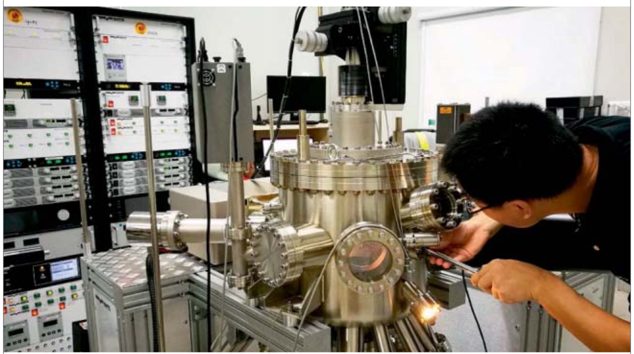


ISSUES & EVENTS

Salaries for female physics faculty trail those for male colleagues

Gender pay gap is tangled with many aspects of physics culture.

Nearly 25 years ago, Nancy Hopkins, then a tenured biology professor at MIT, went to the university provost to ask for 200 square feet of lab space. To make her case, she brought floor plans that showed she had less space than junior males in her department and arguments for why she needed the space for her research. At the time, the space was unused, but a senior male professor had stuffed it full of furniture and boxes to reserve it for himself.

The provost was "mystified" by her request, says Hopkins. "He was used to people asking for whole buildings; no one came to him asking for so little." She was asking for just one room.

Hopkins got the space. She shared her story with other tenured women science faculty at MIT and collectively they prompted the university to carry out a campus-wide comparison of conditions for men and women faculty. The university came out with a report in 1999, and then followed up with changes to make things fair. Among the measures to evaluate equity, MIT investigated lab space and other research resources, teaching assignments, administrative roles, named chairs, and time to promotion. In the years since, many universities have followed suit—Columbia University is currently working on a similar study.

Even so, things still are not equitable across academia in the US and elsewhere. In physics men earn, on average, 18% more than women, according to a survey by the Statistical Research Center (SRC) at the American Institute of Physics (which publishes this magazine). The survey looked at people who received their physics PhDs in the US in 1996, 1997, 2000, or 2001 and who were working in the country in 2011. After accounting for other factors, such as employment sector, postdoctoral experience, and age, a 5.7% disparity persists.

SHANE EPPING

WHY DOES ANGELA SPECK, a University of Missouri astrophysicist, take home 20% less pay than a male colleague of the same age, rank, and subfield?

That difference is attributable to sex, says the SRC's Susan White, who analyzed the data. "The model says that if we have two people who are identical in every way, the woman will make, on average, 6% less than the man." It's not the oft-cited 80 cents on the dollar that women make on average across all sectors in the US. But what is driving the gender pay gap in physics?

Small differences grow big

Unpacking the pay gap is complicated. At most institutions the numbers of women in physics and related fields are small, so identifying patterns is tricky. But a host of observations and studies boil down to two contributing factors in the pay disparity. The first is that women don't negotiate as aggressively as men. The second is that men favor each other, which affects recommendations to serve as an editor or chair a committee, the amount of a raise, teaching evaluations, and the phrasing of reference letters. There is implicit bias, says a senior researcher who has served in her university's administration. "Boys in the department give money to boys in the department."

MIT astronomer Claude Canizares cochaired a 2010 National Academy of Sciences (NAS) study, *Gender Differences at Critical Transitions in the Careers of Science, Engineering, and Mathematics Faculty*. The ambitious study sought to evaluate many variables at hundreds of institutions in the fields of biology, chemistry, civil engineering, electrical engineering, mathematics, and physics. As a rule, he says, universities do not purposely discriminate against women and minorities. Yet, he acknowledges, inequities persist.

Several stages in an academic career can dramatically affect salary: the initial hire; promotions to tenure and to full professor; receipt of a prestigious award or an endowed chair; advancement to leadership and administrative positions; outside offers; and retention offers. Maria Klawe, president of Harvey Mudd College in California, notes that in negotiating initial salaries, men are more likely than women to ask for more. "Women say 'Thank you very much,' " she says. "I've done that myself, several times—it's embarrassing." Even a small difference can grow over time to become significant.

Studies back up Klawe's observations on negotiation habits. They also indicate that men and women are perceived differently when they do negotiate. "The threshold for men to be seen as obnoxious and women to be seen as obnoxious is different," says Patricia Rankin, a physicist at the University of Colorado Boulder and current chair of the American Physical Society (APS) Committee on the Status of Women in Physics. An assertive man is seen as showing his self-worth, whereas a woman who says the same things is seen as bossy, she adds.

Kathy Prestridge, a physicist at Los Alamos National Laboratory, coaches women in negotiating as part of an APS seminar series on professional skills development. One tactic that works well for women, she says, is to couch a request in a nonthreatening way. For example, say, "This will benefit the project," instead of "I want more money." Says Prestridge, "Women have to achieve their goals in the culture we have now. By doing so, there will be cultural changes."

Raises at tenure and at promotion to full professor are not typically negotiated, and they vary by department and institution. Nonetheless, a pay gap creeps in and widens to reward senior men more than senior women. Across the fields examined in the NAS study, male full professors earned on average 8% more than their female counterparts.

MICHAEL CARDINALI, PHOTOGRAPHER/COURTESY OF MIT MUSEUM

TAKING MEASURE. In the early 1990s Nancy Hopkins measured all the labs and office spaces in her building to prove to the MIT provost that she had less space than male faculty members. She got more space, and the university went on to correct other gender disparities on campus. The tape measure she used is in the permanent collections of the MIT Museum.

One reason is that men are more likely to serve in leadership roles such as department chair or dean, which come with additional salary.

Another contributing factor may be that men are disproportionately paid as "rock stars," says Lori Taylor, a professor of public service and administration at Texas A&M University, where since 2010 she has been coordinating a longitudinal study that tracks cross-campus salary and other gender disparities. The rock-star status mostly arises when senior scientists are recruited, and those tend to be men. High outlier salaries are "a harder nut to crack from a managerial standpoint," says Taylor. An institution can find ways to raise salaries, but it's harder to fix if people are—comparatively—overpaid.

The retention dimension

Often the best opportunity for a faculty member to up his or her salary is to use an offer from another institution to negotiate a retention deal. A salary hike of 10–20% is typical, and it can be higher. Retention packages can also come with other perks, such as a reduced teaching load, additional lab space, renovations, or equipment. According to the NAS study, women were more likely than men to receive outside offers in electrical engineering and math, but less likely in physics and chemistry.

Multiple senior physicists told PHYSICS TODAY that women were less likely to seek a pay raise by courting outside jobs. That takes time and effort by people at both institutions. Sherry Yennello, a Texas A&M nuclear chemist who has been associate dean in the college of science, says she has seen universities make less effort to retain female faculty compared with what they do to keep male faculty members. "By the time women pursue outside offers, they are gone emotionally," she says. "They are frustrated not just because of money. They think the climate will be better elsewhere."

Moreover, although numbers are not available, several physicists observed that women are more likely to be in a relationship with another academic, which complicates a potential move (see the article by Laurie McNeil and Marc Sher, APS

NEGOTIATING PAY IS AMONG THE PROFESSIONAL SKILLS discussed in seminars sponsored by the American Physical Society. One venue is the annual Conferences for Undergraduate Women in Physics; shown above is the 2016 meeting at Wesleyan University. The conferences take place simultaneously at multiple sites.

PHYSICS TODAY, July 1999, page 32). Men more often have a partner who has a mobile profession or who does not work outside the home.

Angela Speck, an astrophysics professor at the University of Missouri, compared her salary with a male colleague's and came up 20% short, which she attributes to his retention deals. (Salary information is open at public institutions.) They both started their jobs at about the same time, are in the same subfield, are about the same age, and progressed in their careers more or less in parallel; she became full professor a year before him. He has more publications than she does. But she says she has brought in more grant money, advised more students, and won more prizes. Why does he earn so much more? He got bumps by using outside offers to negotiate, says Speck. "I have been offered jobs, but I am not willing to waste my time or others' time for a job I don't want."

"It's not that men are doing something underhanded. It's not that women are not working as hard," says Speck. "It's that the way things are valued and the way we are judged are leading to these disparities."

Implicit biases

This past June, Marika Taylor, a string theorist at the University of Southampton, gave a talk on gender disparities and academic climate at Strings 2017; it was the first time the issue was on the agenda of the annual conference. "A lot of universities are being forced to look carefully at their departments to see if people are being fairly paid, but very little [information] is in the public domain." For example, she says the average gender gap in pay for full professors in the UK is 10%. Last year the University of Essex raised the salaries of female full professors across the board to help close the gap. Another example is Canada's University of Waterloo, which in 2016 upped the salaries of all female faculty. Other universities, says Taylor, have discovered a pay gap but haven't corrected it because of the expense.

Because Taylor considers pay and other gender disparities in physics to be controversial, she ventures to discuss them publicly only now that she is head of applied mathematics in mathematical sciences at her university. Even so, she prefers not to talk about gender issues with other string theorists because she worries they won't take her research seriously.

In southern European countries, says Silvia Penati, a string theorist at the University of Milano–Bicocca, salaries are set nationally, so the problem is not in comparing salaries, but rather in comparing career progression. "For sure men have a faster career," she says. "And most men entering the profession reach the top, they become full professor. Women more often get stuck, typically at the associate professor level." The reasons, she says, are "subtle" and many of them are rooted in deep cultural patterns. (See the article by Barbara Whitten, Suzanne Foster, and Margaret Duncombe, PHYSICS TODAY, September 2003, page 46, and see August 2005, page 29.)

Robert Birgeneau was involved in the MIT report on the status of women faculty in science and the response to it, and he later served as chancellor of the University of California, Berkeley. In an example of just how ingrained cultural biases are, not long ago he was asked for advice by a physics chair at a state university on how to deal with male physics majors insulting their female counterparts in the undergraduate physics lounge—telling them that as "girls" they weren't smart enough to do physics.

"Use senior women wisely"

One way to improve the culture of academic physics is to ensure that senior female faculty members serve on committees in proportion to their numbers in the field, says Hopkins, now an MIT professor emerita. Hiring and promotion panels, editorial boards, and powerful positions in the university administration would be a good place to start. "You need to use senior women wisely," she says. "Sometimes there are so few that you can overuse them and this becomes very time-consuming for the women." Fixing salaries and other inequities, says Rankin, requires a balance of actions by the rank and file and by people in positions of power.

Actions aimed at improving the physics climate for women would help everyone, says Canizares. He notes that university careers have become less attractive as postdoc stints and the time to tenure have become increasingly protracted. People are often over 40 before they can settle down. That lifestyle is unattractive generally, but "it's even more unattractive to women than to men," he says. "It's a profession where you live with uncertainty for a long time."

Men need to be more proactive about equity for women and underrepresented minorities, says Canizares. "It's hard to break a glass ceiling by banging your head on it from below. It's easier to break it from above with a sledge hammer."

Toni Feder

Refracturing may not be all it's cracked up to be

Restimulating oil and gas wells that have been fracked will be worthwhile in some cases, but not all.

Hydrofracturing, or fracking, has been extremely effective in unlocking natural gas and oil from shale and other low-permeability rock formations in the US. So it might seem intuitive that refracturing the tens of thousands of existing fracked wells could unleash a second boom at comparatively low cost and without the environmental effects of drilling new wells. Experts say it's not so simple.

A recent analysis by Richard Middleton and colleagues at Los Alamos National Laboratory (LANL) of 20 000 shale gas wells in Texas concluded that refracturing previously fracked horizontal wells "has profound implications in the potential revitalization of the hundreds of thousands of shale gas wells across the United States." Refracturing the wells could turn them into higher-producing assets, said the study, published in the online journal *Applied Energy* in May.

The combination of horizontally drilled wells and fracking with large volumes of fluid has resulted in a dramatic increase in US gas and oil production since the turn of the century (see the articles by Donald Turcotte, Eldridge Moores, and John Rundle, PHYSICS TODAY, August 2014, page 34, and by Michael Marder, Tadeusz Patzek, and Scott Tinker, PHYSICS TODAY, July 2016, page 46). Separately, many conventional vertical oil and gas wells are fracked at lower pressures and with smaller volumes of water to stimulate continued production. Most horizontal wells run 1 km or more through the shale reservoir. Vertical wells, by comparison, penetrate the reservoir for a far shorter distance.

According to the LANL analysis, on average just 13% of the gas from any given US shale is recovered. The potential for restimulating existing wells is therefore huge. What's more, notes Hari Viswanathan, a coauthor of the LANL paper, drillers have learned a lot in recent years about controlling the fracking process and how to create well-connected fracture networks.

A SHALE GAS hydraulic fracturing rig in Texas's Barnett Shale formation.

Other experts are less enthusiastic. Of the tens of thousands of horizontal wells, only a small number—600, by one estimate—have been refractured to date. Refracturing is economically justifiable only for a subset of wells, says Frank Male, a postdoc at the University of Texas at Austin's Bureau of Economic Geology. "Since around 2012, [drillers] have reached the point of having a relatively stable fracture formula, and you won't get any improvement" from refracturing, says Male, who estimates a total of 129 000 horizontal wells have been drilled in the US since 2001.

Over the years, fracking technology has improved, mainly through practice, so that the distance between individual fracking operations along the horizontal leg of wells has narrowed to around 6 m, down from 30 m in 2004, says Male. That has vastly improved recovery of hydrocarbons; production rates doubled in 2007–11 alone.

The Los Alamos study examined wells drilled over 23 years in the Barnett Shale, a major US oil- and gas-bearing shale formation in the Fort Worth Basin of Texas. The analysis began with what the researchers said were the first "technically successful" wells in 1998. Poorly performing wells that were first fracked before 1998 and refractured in 2000–04 performed better than those first fracked in 1998–2006, according to the LANL analysis.

But Male notes that LANL's data source, the Texas Railroad Commission, which regulates oil and gas drilling in the state, doesn't differentiate in publicly released data between refractures of existing horizontal wells and the conversion of vertical wells to horizontal ones, followed by the fracking of their horizontal sections. Male says that conversion—essentially the creation of new wells, not refracking—was actually occurring most frequently throughout the period in the Barnett Shale.

Viswanathan agrees that wells fracked in the past five years aren't good candidates for refracturing with water. But he says that fracking with nonaqueous fluids such as supercritical carbon dioxide or other inert gases could make even recently drilled wells good candidates for refracturing.

A WELL IN THE BAKKEN SHALE formation in North Dakota undergoing hydraulic fracturing.

JOSHUA DOUBEK VIA WIKIMEDIA (CC BY-SA 3.0)

Refrack or not?

It's far more common to refracture vertical wells than horizontal wells; Tim Leshchyshyn, president of FracKnowledge in Calgary, Alberta, Canada, estimates that the process has been performed 100 000 times, and says some vertical wells are refractured every 3 to 4 years during their 20-year lifetime. For horizontal wells, though, only about half of refractures produce enough additional gas or oil to recover the cost of the job, he says. "Refracturing is a great way to recycle [horizontal] wells and squeeze another 25% to 400% more production out of them. But you can't just do it anywhere," he says. "You have to know you are doing it to solve some problem, and that fracturing it again will solve that problem." One good reason to refracture could be a deposit buildup in the fracture network caused by the precipitation of heavy crude-oil components, says Leshchyshyn.

A 2015 study by the research firm IHS found that just 600 horizontal wells in the US had been refractured. It predicted that as many as 11% of US horizontal wells may be refractured by 2020, but it found that the refracking that has been done had mixed results. On average, the initial production rate of refractured wells was equivalent to 98% of the wells' initial production rate after the original fracking. Refractured wells had slightly better 12-month production decline rates compared with the 12-month declines that followed the original fracking.

The IHS report said the average increase in performance was heavily skewed by some of the earliest horizontal fracked wells, mainly in the Bakken Shale of North Dakota and Montana, which had been particularly poor performers. Most of the refractures that occurred in other formations, such as the Marcellus Shale formation in the Appalachians, were less productive.

Looking for a quick payback, drillers tend to focus on production from the initial 12 months after fracking, the LANL report stated. Left alone, however, a fracked well will typically produce 75% of its 10-year output in years 2–10.

The IHS report said that due to technical challenges, uncertainties, and costs, companies with a portfolio of new well prospects will likely drill them first and wait for further technological advances before refracturing their older producing wells.

Industry consultant George King says that recovery rates in gas shales such as the Marcellus are very different from those in oil-rich shale basins such as the

Bakken. He notes that some oil-shale wells could be stimulated with enhanced oil-recovery technology, including a technique known as "huff and puff," in which CO_2 or steam is injected into a formation and allowed to sit prior to the well's being put back into production.

Explosive growth

Although hydraulic fracturing has been in use for more than 60 years, it has only been a significant source of US oil production since the turn of the century. As of 2015, the Energy Information Administration (EIA) estimated that hydrofractured wells, both horizontal and vertical, accounted for half of US crude-oil production. Growth has been explosive: In 2000 approximately 23 000 fracked oil wells produced a combined total of 102 000 barrels per day—less than 2% of the US total. By 2015 the number of fracked oil wells in service grew to around 300 000, which produced 4.9 million barrels per day, according to the EIA. So-called tight oil production from shale and sandstone is expected to increase through around 2030, when two of the major formations begin to decline.

As for natural gas, the 37 billion cubic feet per day produced by some 300 000 fracked horizontal and vertical gas wells accounted for two-thirds of total US production in 2015, according to the EIA. That is up an order of magnitude from the 3.6 billion cubic feet per day, or 7% of US output, from 26 000 fracked wells in 2000.

In a 2016 report, the EIA said just three other countries—Argentina, Canada, and China—had commercial shale gas and tight oil production. But technological improvements are expected to encourage the development of shale resources in other countries, primarily Mexico and Algeria. Forty-two other countries have technically recoverable but so far uneconomic oil and gas shales, the EIA said.

Alternative frack fluids

Due to their low permeability, shales and sandstones must be fractured to provide paths for the gas and oil to flow from the rock to the well bore. Water, with chemical additives, is almost always the fracturing fluid, coupled with sand or ceramic material that is forced into the fractures to hold them open. A typical fracked well uses 7.5 million to 15 million liters; anywhere between 15% and 80% of the liquid flows back to the surface in the early stages of gas production, depending on geology and other factors. But Male cites one study of shale wells in the Permian Basin of Texas showing that some wells yielded more water than was injected.

One advantage of using a nonaqueous fracking fluid such as supercritical CO_2 would be to reduce the need to dispose of the contaminated water, which can contain acids, gelling agents, bactericides, corrosion inhibitors, and friction reducers, in addition to radionuclides and metals from the shale. Another plus is that unlike water, CO_2 is miscible with oil and gas, and it won't block hydrocarbons from flowing to the well. Third, Viswanathan says that CO_2 creates more-productive branched fractures in the rock, while water typically produces simple planar fractures.

Disadvantages include the need to separate the CO_2 from the natural gas, and capturing and pressurizing the CO_2 for reuse. Nearly all of the CO_2 that is used for industrial applications and for enhanced oil recovery in the US today is supplied from naturally occurring underground formations located mainly in the Four Corners region, where Arizona, Colorado, New Mexico, and Utah meet. Liquefied natural gas and mixtures of CO_2 and nitrogen are other candidate alternative fluids, says Andres Clarens, associate professor of civil engineering at the University of Virginia.

Leshchyshyn participated in fracks using supercritical CO_2 some 20 years ago. "It's a great technology," he says. Limited availability of CO_2 and the expense of getting it to the well site may make it economically unattractive now, but Leshchyshyn foresees that possible government bans on the use of clean water for fracking could change the equation.

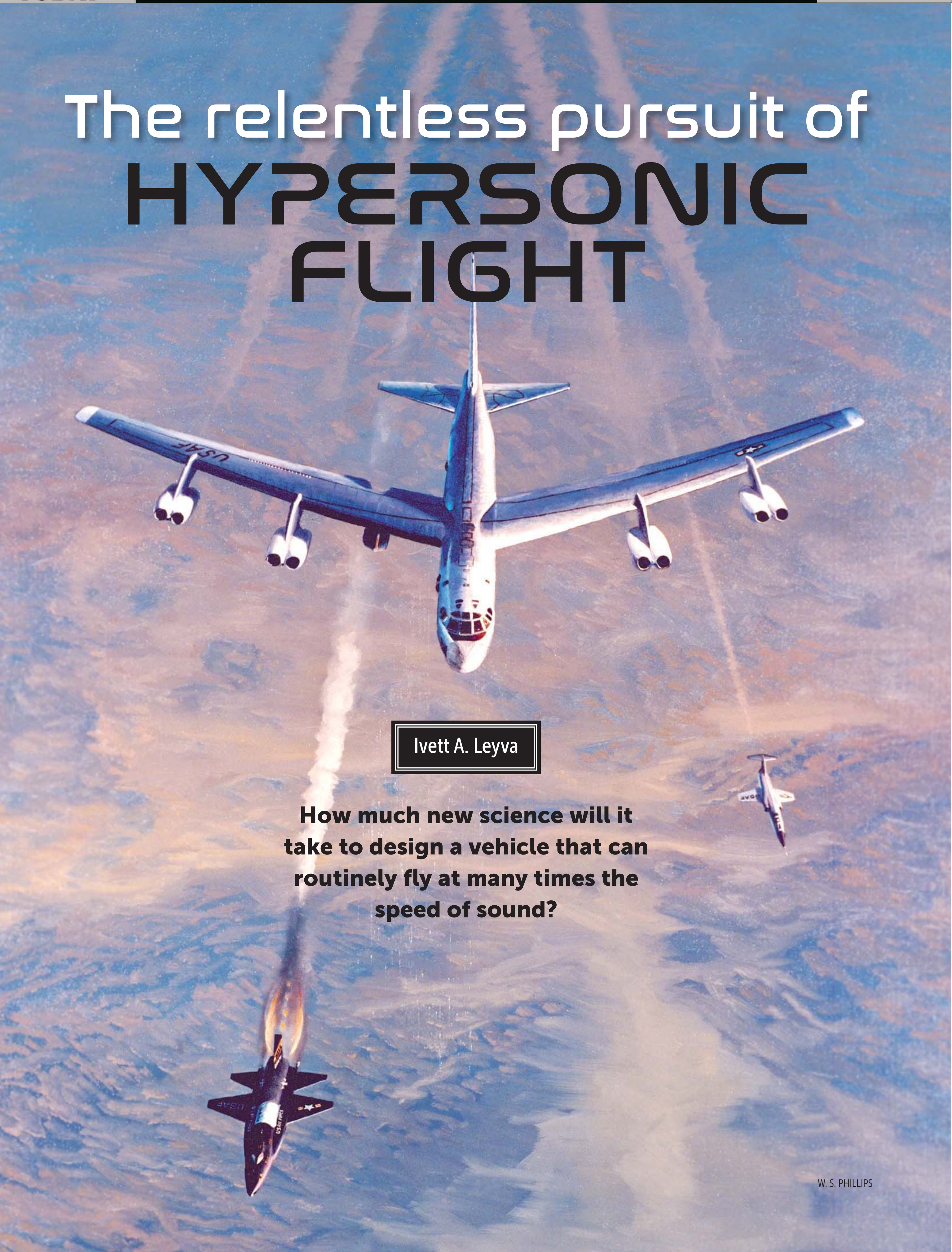
A potential future environmental benefit from using supercritical CO_2 would be the permanent sequestration of the greenhouse gas underground. Compared to water, the superior fracturing obtained with CO_2 will increase the holding capacity of the well, says Viswanathan. Moreover, CO_2 injection can occur at the same time the oil or gas is being extracted. Depleted shale formations would be able to hold as much as five times the amount of CO_2 compared with the methane they once held, says Clarens, who has examined the storage capacities of fractured wells.

David Kramer PT

The relentless pursuit of HYPERSONIC FLIGHT

Ivett A. Leyva

How much new science will it take to design a vehicle that can routinely fly at many times the speed of sound?



W. S. PHILLIPS

Ivett Leyva is the program officer for high-speed aerodynamics at the Air Force Office of Scientific Research in Arlington, Virginia.

In the early afternoon of Tuesday, 3 October 1967, a ramjet engine fell out of the southern California sky. Moments earlier, it had been attached to the underbelly of an experimental, rocket-propelled flight vehicle known as the X-15; NASA engineers grafted the dummy engine onto the X-15 to see how the added weight would affect the vehicle's high-speed handling.

By then, X-15s had flown more than 100 test flights and had, on several occasions, reached speeds exceeding Mach 5, a commonly accepted threshold for hypersonic flight. That Tuesday, the plane's pilot, William "Pete" Knight, pushed the aircraft to new extremes. After its release from a B-52 carrier above Mud Lake, Nevada, the vehicle climbed to the stratosphere and accelerated to more than 7000 km/h, or Mach 6.7—an X-15 speed record. In all, Knight's trip from Mud Lake to Edwards Air Force Base, 500 km to the south, took less than ten minutes.[1]

But by the time the vehicle approached Edwards, intense heating associated with shock waves around the vehicle had partially melted the pylon that attached the ramjet engine to the fuselage.[1] The engine tore loose and crashed into a bombing range below. Knight lived to fly another day, but the lesson was clear: The fluid mechanics of hypersonic flight are exceedingly complex, and the practical risks they pose are immense.

Half a century later, after extensive efforts that have cut across disciplines and involved organizations both public and private, researchers have made a lot of progress but still don't completely understand the physics of hypersonic flight. Yet the dream retains its allure. Hypersonic aircraft could revolutionize the defense industry and, in time, would likely spur commercial applications similar to those emerging in the space-tourism industry. A hypersonic vehicle flying at six times the speed of sound could cruise the US from Los Angeles to Washington, DC, in about 30 minutes.

A discussion of all the technological impediments to hypersonic flight could fill volumes. To make such travel practical and routine, scientists and engineers will need to devise new approaches to propulsion, material design, and flight control and develop deeper understandings of fluid mechanics and other topics. This article focuses primarily on the fundamental fluid mechanics challenges. I describe the key scientific questions that need to be answered and the progress that's been made so far.

Shock waves and chemistry

Any vehicle flying at greater than the speed of sound generates a leading shock wave at which air pressure, temperature, and density jump sharply. (See figure 1.) But at hypersonic speeds, the magnitudes of the jumps are often so extreme as to have profound thermodynamic consequences.

A useful quantity for characterizing the impact of a shock wave on a flow is the stagnation enthalpy, which represents the total thermal energy onrushing air molecules and atoms would attain if they slowed to a halt by way of a steady, adiabatic process. Stagnation enthalpy generally increases with the Mach number of a vehicle and—assuming a steady, adiabatic flow—is conserved across a shock. It reflects the fact that the airflow's momentum upstream of a shock wave contributes to its thermal energy in the shock layer, the envelope of compressed air between the shock wave and the vehicle surface.

When the stagnation enthalpy exceeds about 5 MJ/kg, which for a vehicle flying at 30 km altitude corresponds roughly to Mach 10, the amount of energy deposited in the shock layer is so great that the air molecules' internal energy modes—electronic, rovibrational, and so forth—equilibrate with the newly energetic environment at different time scales, which are comparable to the time scales of the flow. As a result, the air molecules can no longer be characterized by a single temperature.

Figure 2 shows results from a simulation of a one-dimensional, normal shock wave at Mach 16 speed and 40 km altitude. The fluid upstream of the shock is molecular nitrogen and flows left to right in the figure. At low stagnation enthalpies, the translational, rotational, and vibrational temperatures would be identical everywhere downstream of the shock wave. But in the simulation, the translational temperature quickly peaks at about 15 000 K (more than twice the average temperature of the surface of the Sun), whereas the rotational and vibrational temperatures lag behind. Only after a small number of intermolecular collisions do the rotational modes thermally equilibrate with the kinetic energy of the molecules, and only after many more collisions do the vibrational modes follow suit. Real atmospheric flows, composed mostly of diatomic nitrogen and oxygen, are expected to behave similarly.

The comparable time scales for thermal and fluid mechanical equilibration complicate the task of computing hypersonic flow fields. The gas in the shock layer is in a constantly evolving, nonequilibrium state. Some collisions, particularly those involving molecules in a high rovibrational state, may even result in dissociation. That can have important design consequences. Because atomic oxygen is much more reactive than molecular oxygen, dissociation can hasten the deterioration of thermal protection coatings—particularly those made of carbon–carbon composites.

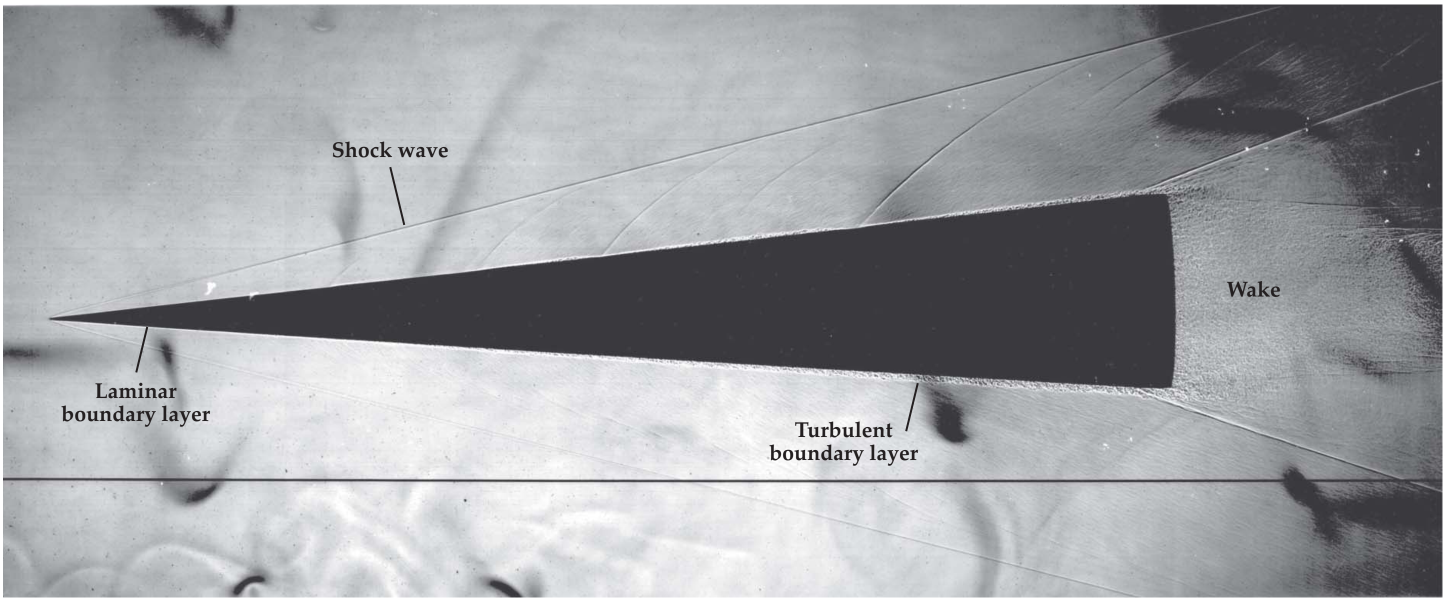


FIGURE 1. A SHOCK WAVE emanating from the nose of a cone travelling at Mach 4 in a ballistic range shows up as a thin dark line in this Schlieren image; the sharp jump in density across the shock produces a steep refractive-index gradient, which in turn deflects transmitted light, thereby producing the contrast that we observe in the figure. Also visible are laminar and turbulent boundary layers and the wake. (Figure adapted from S. P. Schneider, *Prog. Aerosp. Sci.* **40**, 1, 2004.)

One of the big unknowns in hypersonic aerodynamics is how the molecular processes of vibration, rotation, translation, and dissociation interact with each other. Until a few years ago, models of nonequilibrium interactions were based on empirical observation and intuition.[2,3] Recently, theoretical chemists have found success with potential energy surfaces (PESs), which describe the energy of a molecule or system of molecules as a function of the molecule's geometry, including bond lengths and angles.[4] PESs are traditionally the purview of computational chemists, but fluid dynamicists are increasingly using them to rigorously account for vibration and rotation in calculations of dissociation rates. Recently, N_2 dissociation rates computed with PES data were found to differ by up to an order of magnitude from those computed based on common empirical models.[5] The result served as a wake-up call—a stark example of the limitations of using empirical dissociation rates to describe flows with high stagnation enthalpy.

Turbulence rising

Although the entire shock layer around a hypersonic vehicle is marked by high temperatures and pressures, a large portion of the viscous drag and heating the vehicle experiences can be traced back to a thin region near the surface known as the boundary layer. (See the article by John D. Anderson Jr, PHYSICS TODAY, December 2005, page 42.) Across that layer, which can be just a few millimeters thick, the velocity of the air relative to the vehicle can plunge from thousands of meters per second to zero, at the surface.

Near the nose of the vehicle, the flow in the boundary layer is typically laminar—that is, it's organized into streamlines nearly parallel to the vehicle's surface. But by the time the flow reaches the vehicle's rear, the boundary layer often will have transitioned to a chaotic, turbulent state. Understanding how and where that transition occurs is one of the long-standing problems in hypersonic aerodynamics.

We know that flow disturbances—minuscule fluctuations in pressure, density, or velocity—play a role. Regardless of whether they occur naturally in the atmosphere or are caused by designed or accidental surface roughness, disturbances can trigger instabilities that grow into turbulence. Curiously, the boundary layer acts like a selective filter to those disturbances: Only certain frequencies and wavelengths are sufficiently amplified to induce a laminar-to-turbulent transition.

The state of the boundary layer has a profound effect on drag and heating rates. Wind-tunnel experiments with cone-shaped models suggest that as the boundary layer transitions from laminar to turbulent, the heating rate can jump by as much as a factor of eight. (Cones have been used as a canonical shape in hypersonic wind tunnels for decades.) For most practical applications, the thermal protection required to safeguard the length of a vehicle against turbulent heating rates over the duration of a flight would render the vehicle too heavy to fly. So part of a designer's task is to predict when and where on the vehicle a boundary layer will become turbulent. A 1988 report by the US Defense Science Board Task Force neatly summarizes the issue:

> The largest uncertainty [in a hypersonic plane design] is the location of the point of transition from laminar to turbulent flow. Estimates range from 20% to 80% along the body span. That degree of uncertainty significantly affects the flow conditions at the engine inlet, aerodynamic heat transfer to the structure and skin friction. These in turn affect estimates of engine performance, structural heating and drag. The assumption made for the point of transition can affect the design vehicle gross take off weight by a factor of two or more.[6]

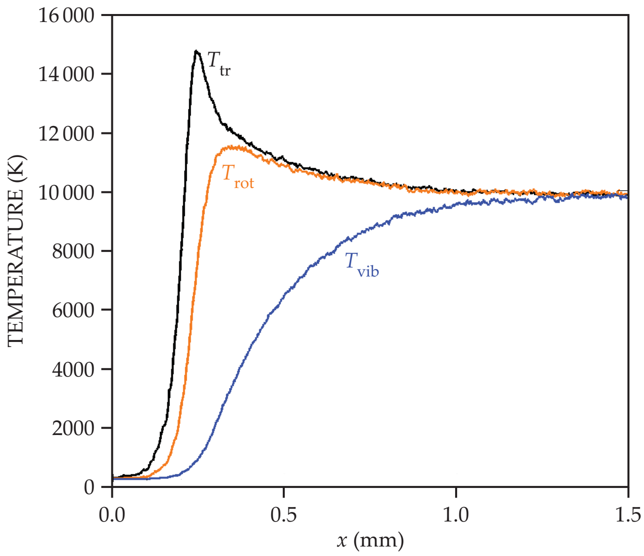


FIGURE 2. A SIMULATION OF A MACH 16 FLOW at 40 km altitude predicts a shock wave so energetic that the translational (T_{tr}), rotational (T_{rot}), and vibrational (T_{vib}) temperatures of the nitrogen downstream of the shock are no longer defined by the same value. The various modes equilibrate over length scales comparable to the characteristic length scales of the flow; under hypersonic conditions, the shock layer, the region between the shock wave and the vehicle surface, may be just millimeters or centimeters thick. Here, the shock wavefront is located at $x = 0$, and the flow is from left to right. (Figure courtesy of Maninder Grover and Tom Schwartzentruber, University of Minnesota.)

To reduce that uncertainty, one must unravel the different mechanisms that contribute to boundary-layer transition and be able to predict the onset of transition for complex flow geometries. Figure 3 illustrates one particular transition mechanism in the boundary layer of a circular cone at Mach 10 conditions: the trapping of acoustic waves inside the boundary layer.[7,8] In the experimental image, known as a Schlieren image, the alternating light and dark regions correspond to well-defined acoustic waves, which lose their periodic nature as the flow within the boundary layer becomes turbulent.

Under realistic flight conditions, boundary-layer transition becomes far more complicated. Different transition mechanisms come into play depending on the Mach number, the vehicle shape, the angle of attack, and other factors. And the nature of the boundary layer changes during the course of a flight as the Mach number and angle of attack change, the thermal protective coating ablates, and panels deform under thermal and mechanical loads. Hypersonic boundary-layer transition continues to be an active area of basic research.

One might wonder whether a fully turbulent boundary layer would be simpler to model than a transitional one. The answer is a qualified no. The relevant governing equations for turbulent flow are myriad: conservation of mass, momentum, and energy; an equation of state relating pressure, temperature, and density; and equations for transport properties, including mass diffusivity, viscosity, and thermal conductivity. The most advanced computations can solve those equations at resolutions down to the smallest turbulent length scales. That's a big feat; under conditions typical of hypersonic flight, the relevant length scales span many orders of magnitude. One such computation stressed available research computing resources by using more than 30 billion grid points and 102 000 cores to simulate a Mach 2.5 flow over the simplest of surfaces—a flat wall.[9]

So, yes, researchers can accurately model fully turbulent flow. But until we vastly improve the speed and availability of supercomputers, optimize codes for massively parallel computations, find clever new ways to interrogate and postprocess terabytes of computational data, and develop more efficient algorithms to solve the governing equations, those computations will be impractical for all but the simplest geometries. Meanwhile, applied math techniques such as resolvent analysis[10] and analytical methods that find exact coherent solutions of simplified computational domains[11] have produced new insights into incompressible turbulence and promise to shed light on turbulence at hypersonic conditions.

Interacting shocks and boundary layers

So far we've focused on simple cone models to illustrate the key fluid mechanical phenomena at play in hypersonic flight. But real aircraft are geometrically complicated, with wings that jut and control surfaces that move. Such shape discontinuities introduce what are among the most complex phenomena in hypersonic flight: interactions between shocks and boundary layers.

Consider the example, shown in figure 4, of a double cone—more slender near the nose than at the base—in a Mach 6.6 wind-tunnel flow of N_2. The stagnation enthalpy, 8.4 MJ/kg, is high enough for nonequilibrium effects to be important. The high-speed flow generates an oblique shock at the nose and a bow shock where the flow encounters the wide base. Just upstream of the junction of the slender and wide parts of the cone, the two shocks intersect. A high-pressure region results that disturbs the boundary layer upstream of the junction, giving rise to what's known as separated flow: The boundary layer detaches from the cone's surface, creating a pocket of fluid known as a separation zone, where pressure and heating loads can fluctuate at kilohertz frequencies. Downstream of the shocks' intersection, a shear layer forms as the air processed by the bow

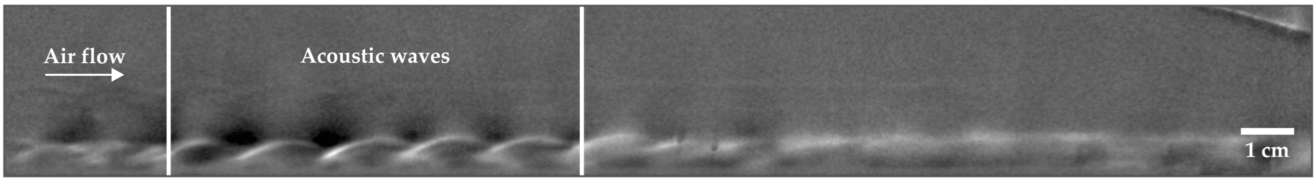


FIGURE 3. ACOUSTIC WAVES in the boundary layer of a Mach 10 flow along the surface of a 1.55-m-long circular cone are evidenced in this Schlieren image. Here, the flow is from left to right, and the image is taken roughly 1.3 m from the tip of the cone. (Image courtesy of Eric Marineau, Air Force Research Laboratory, and Stuart Laurence and Richard Kennedy, University of Maryland.)

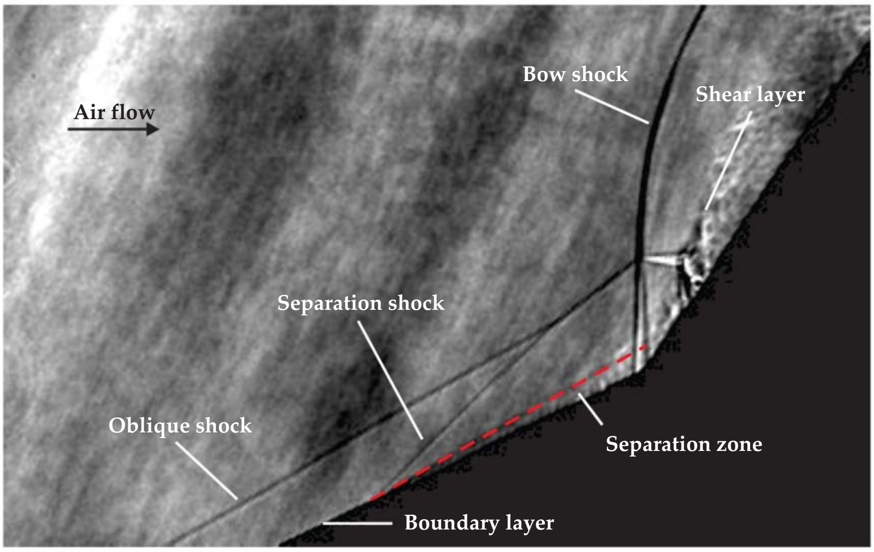


FIGURE 4. A SCHLIEREN IMAGE of a Mach 6.6 flow past a double cone reveals a complicated system of interacting shock waves and boundary layers. The oblique shock generated by the slender nose intersects the bow shock generated by the wider base and causes the boundary layer to separate from the cone surface. The mixing of the fluid processed by the two shocks gives rise to a shear layer. Maximum heating rates occur where the shear layer impinges on the surface. (Figure adapted from ref. 17, courtesy of Andrew Knisely and Joanna Austin, Caltech.)

and oblique shocks mixes. The region where that shear layer impinges on the surface is where heating rates are highest.

The double-cone example illustrates why it's so difficult to predict the mean values and fluctuations of heating rates and pressure in flows with shock wave–boundary layer interactions. Imagine now that instead of a double cone we have a surface with control flaps that can be raised and lowered to adjust the vehicle's pitch. A designer would have to carefully consider the complex thermal and mechanical loads imposed by hypersonic flow to ensure a robust control system.

The vicious cycle

In designing a hypersonic vehicle, one must account for the feedback between the airflow and the structures that make up the vehicle. As Ravi Chona, an expert in the field, once shared in a personal communication, "The structure that takes off is not the same structure that lands." The airflow at hypersonic speeds is often strong enough to deform a vehicle's surface panels, and those deformations—even if they are on the order of millimeters or less—can affect the development of the boundary layer.

The double-cone flow in figure 4 could easily develop such a two-way feedback if, say, the frequencies of the pressure fluctuations in the separation zone are close to the frequencies of a deformation mode of the corresponding surface. At best, that unstable situation would shorten the life of the structure; at worst, it could cause the structure to fail midflight.

Absent such frequency matching, the thermal and pressure loads imposed on a structure can still diminish a vehicle's life expectancy and affect its aerodynamic properties, so they must be accurately predicted, especially for the design of reusable aircraft. Even in a fully turbulent boundary layer, pressure and temperature fluctuations can deform the panels and give rise to shock waves and flow-field expansions that exacerbate temperature and pressure gradients. All those phenomena work to reduce the life of the vehicle.[12]

The designer who seeks to mitigate flow–structure feedbacks faces a tradeoff. Feedbacks tend to be strongest in lighter vehicles with lighter panels, much the way flutter in conventional, subsonic planes is strongest in planes with lighter wings. But a bulky, heavy vehicle would likely run up against performance constraints and engineering limitations that would prevent it from engaging in routine hypersonic flight.

The study of flow–structure feedback is gaining momentum as a multidisciplinary field in hypersonics. Sophisticated high-fidelity flow–structure simulations are being developed in parallel with computationally cheaper, reduced-order modeling techniques. Both approaches are being paired with creative validation experiments that push the limits of our abilities to detect and measure panel deflections and forces imposed by high-speed wind-tunnel flows.[13]

Diagnostics and ground testing

Because hypersonic test flights are exceedingly expensive, most of our empirical knowledge and intuition comes from ground tests at wind-tunnel facilities. No single facility is equipped to simulate all the key physical variables for hypersonic flight, so instead the research community relies on various facilities that individually probe different aspects of high-speed flight.

Only a handful of wind tunnels in the world—and even fewer in academia—can reproduce the high stagnation enthalpies typical of hypersonic flight. (One of them, Caltech's T5 Hypervelocity Shock Tunnel, was used to capture the image in figure 4.) The test times in those facilities are typically on the order of a millisecond. That's because the flows are generated by expanding dense gas from a reservoir through a nozzle, and to achieve a realistic air temperature downstream of the nozzle, the temperature in the reservoir must be extremely high—hot enough to start melting most metals in milliseconds. Also, the power necessary to produce high-enthalpy flows with cross-sectional areas large enough to accommodate reasonably sized models can typically be sustained for only a few milliseconds at a time.

Luckily, most hypersonic flows take less than a millisecond to settle around a typical test model and form a more or less steady shock-wave system. Megahertz-frequency cameras, temperature transducers, and pressure transducers and other high-speed instrumentation can capture useful data in that time. And nitric oxide emissions can be measured to study the chemical changes in the shock layer.

Conventional wind tunnels can sustain high Mach numbers for much longer times but with lower stagnation enthalpies.

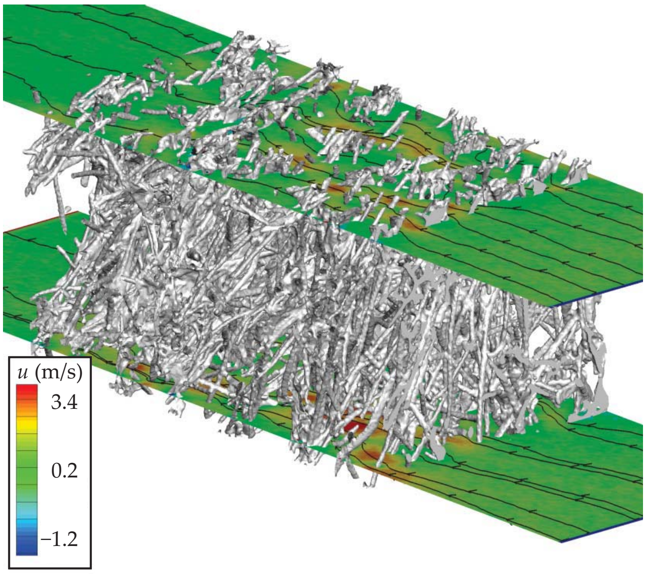


FIGURE 5. A DETAILED IMAGE OF THE CARBON FIBERS in a sample of a thermal protective material, reconstructed using x-ray tomography. The sample shows significant ablation due to exposure to high-temperature flows. The green planes show the simulated velocity *u* (see color key) and streamlines (black) of an oxygen flow through the ablated sample, computed using direct simulation Monte Carlo methods. (Figure courtesy of Eric Stern and Tom Schwartzentruber, University of Minnesota.)

Some of those tunnels can be run in continuous mode, though an enormous infrastructure is required to achieve the feat. Conventional wind tunnels are invaluable for characterizing complex phenomena such as turbulent flows, whose characteristic length and time scales can only be determined from statistics accumulated over relatively long observation times. The tunnels are also critical for gathering classical aerodynamic data such as forces and moments. In some experiments, test models are coated with temperature- and pressure-sensitive paint to obtain spatially continuous measurements.

Even if one could combine the realistic thermal conditions of a high-enthalpy wind tunnel with the long observation times of a conventional wind tunnel, there remains the challenge of replicating natural atmospheric disturbance patterns. So-called quiet tunnels, specialized to produce low-disturbance flow streams, approximate those relatively calm conditions. Quiet tunnels are singly equipped to probe the intricacies of the boundary-layer transition mechanisms. Test times in those facilities are typically on the order of a few seconds.[14] Comparisons between data gathered in quiet tunnels and those gathered under similar conditions at other facilities help to distill the influence of facilities' unique disturbance patterns on transition mechanisms.

Re-creating the atmosphere

Although various wind tunnels allow us to study models under a wide range of free-stream disturbance conditions, we don't precisely know how those disturbances compare with true atmospheric conditions. Accurate data on the type, amplitude, frequency, and probabilities of atmospheric disturbances would set the stage for a giant leap forward in computational fluid dynamics. The computational framework for high-accuracy simulations of disturbance growth and propagation already exists—the simulations just need the right initial inputs.

The task, however, is easier said than done. The wavelengths and amplitudes of disturbances relevant to hypersonic flow can be incredibly small. For example, ground tests[14] suggest that in a hypersonic flow past a circular cone oriented at zero angle of attack, the frequencies of interest for boundary-layer transition range from 10^2–10^3 kHz. For a vehicle flying at Mach 6 speed and at altitudes where the temperature is between 220 K and 250 K, those frequencies correspond to wavelengths in the millimeter to centimeter range—much smaller than the kilometer length scales studied in weather research.

Little research has been done to measure small-scale atmospheric disturbances, and new instruments are being developed to measure subcentimeter fluctuations in pressure, density, and temperature.[15] Measuring the amplitudes of those fluctuations is also challenging. Recent measurements at Purdue University's quiet hypersonic tunnel[14] suggest that the amplitudes of the relevant atmospheric pressure fluctuations relative to the mean are probably around 0.05% or smaller. Detecting such tiny fluctuations will call for inventive new measurement techniques.

After scientists obtain local measurements of atmospheric fluctuations, they will need to interface those results with regional and global atmospheric models to construct models that are applicable beyond just the location where the data were gathered. Multidisciplinary teams consisting of atmospheric scientists, high-speed fluid dynamicists, statisticians, and instrumentation experts will need to be assembled to accomplish that feat.

The ablation problem

Another multidisciplinary problem in hypersonic flight is understanding ablation—the gradual wearing off or disintegration of the materials exposed to the vehicle's hottest surfaces. I'm often asked why we should bother to study ablation, when for decades NASA successfully returned Apollo capsules and space shuttles to Earth at hypersonic speeds. Don't we know all we need to know?

If you consider that those spacecraft crossed the atmosphere in minutes but that a hypersonic aircraft might travel through the atmosphere for many times that long, you can start to appreciate why the thermal protection requirements for hypersonic vehicles are so much more demanding. The materials that work beautifully for NASA's missions don't seem to meet the needs of extended hypersonic flight.

To predict ablation, materials scientists need to know the temperature, pressure, density, and dissociation rates of the gas in the shock layer; what species the protective coating, or ablator, decomposes into when it contacts gas from the shock layer; and how those species evolve as they continue to mix and react with the surrounding gas. In the past five years, scientific understanding of the ablation of carbon materials—including carbon–carbon composites being considered for thermal protection systems—has progressed in leaps and bounds.

Figure 5 provides a case in point. It shows the actual microstructure of an ablated carbon sample, reconstructed using x-ray tomography. The flow around the microstructure was computed via direct simulation Monte Carlo methods, which can be used to model rarified and near-rarified flows. The technique was needed in this case because the flow's mean free path was on the order of the fiber dimensions.[16] Just 10 years ago, no one could have imagined being able to produce such an image. The capability opens new paths to understanding how flow interacts with ablated and ablating materials.

In hot pursuit

It's been almost 50 years since NASA ended its pioneering X-15 program, one year after Pete Knight's record-setting Mach 6.7 flight. Since then, the pursuit of hypersonic flight has continued around the globe. Due in large part to computations and experiments, researchers now understand high-speed flight far better than they did in the 1960s when scientists and engineers started bringing reentry capsules back to Earth. There has been steady progress in creating new classes of numerical solvers and experiments—often in concert with improvements in ground test facilities, diagnostics, and supercomputing capabilities—that allow us to more accurately probe and compute the flow around objects traveling at hypersonic speeds.

The effort has been, and will continue to be, an interdisciplinary one. Collaborations with atmospheric scientists, materials engineers, computational chemists, applied mathematicians, and structural engineers will be critical to formulating the right questions and finding their answers. Scientists and engineers will likely need to invent yet new types of experiments, facilities, diagnostics, and instruments to solve the scientific challenges listed here—and new challenges we are bound to discover. But the obstacles are surmountable. There is every reason to believe that the arrival of the era of routine hypersonic flight is only a matter of time.

The author thanks all the people who provided figures. The opinions herein are those of the author and do not represent the opinions of the US Air Force.

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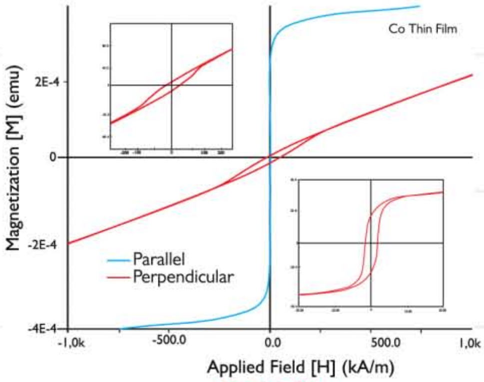

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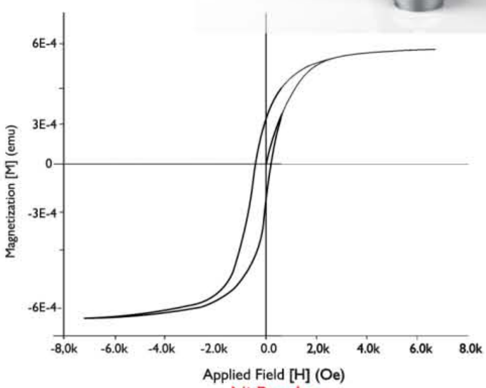

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Preparing physics students for 21st-CENTURY CAREERS

Laurie McNeil and Paula Heron

Whether they end up in industrial, governmental, business, or academic settings, college graduates need plenty of skills beyond an ability to solve problem sets.

If you are a physics professor, you probably followed the traditional path to get where you are: undergraduate and graduate degrees in physics, one or more postdoctoral positions, and then a faculty position. Perhaps you think most of the physics majors you now teach will follow in your footsteps and that you best serve them by preparing them to become physics professors. If so, you are mistaken.

According to data from the Statistical Research Center of the American Institute of Physics (AIP; publisher of PHYSICS TODAY), only about 5% of US physics bachelor's degree graduates end up employed as physics professors—though others may pursue academic careers in related fields, such as engineering or computer science. The vast majority of physics bachelor's degree recipients are employed outside academia for at least part, and often all, of their careers and are engaged in various jobs, about half of which are in the private sector. (Figure 1 illustrates the data on recent graduates' initial employment.)

Few physics programs are explicitly designed to prepare students for that likely career outcome. Both physics graduates and their employers report that graduates should be better prepared for positions requiring scientific training. That observation is equally applicable for physics PhD holders (see PHYSICS TODAY, June 1995, page 13). Almost half of them hold positions outside academia one year after receiving their degrees, and more of them move to private-sector or government positions after completing a postdoc. When surveyed, physics graduates working in the private sector report that they regularly need to use skills beyond their knowledge of physics; figure 2 presents the data. Working in teams, technical writing, programming, applying physics to interdisciplinary problems, designing and developing products, and managing complex projects are all acquired skills. But for most physicists, developing them was only a small part of their educational experience.

In 2014 the American Physical Society (APS) and the American Association of Physics Teachers (AAPT) convened a joint

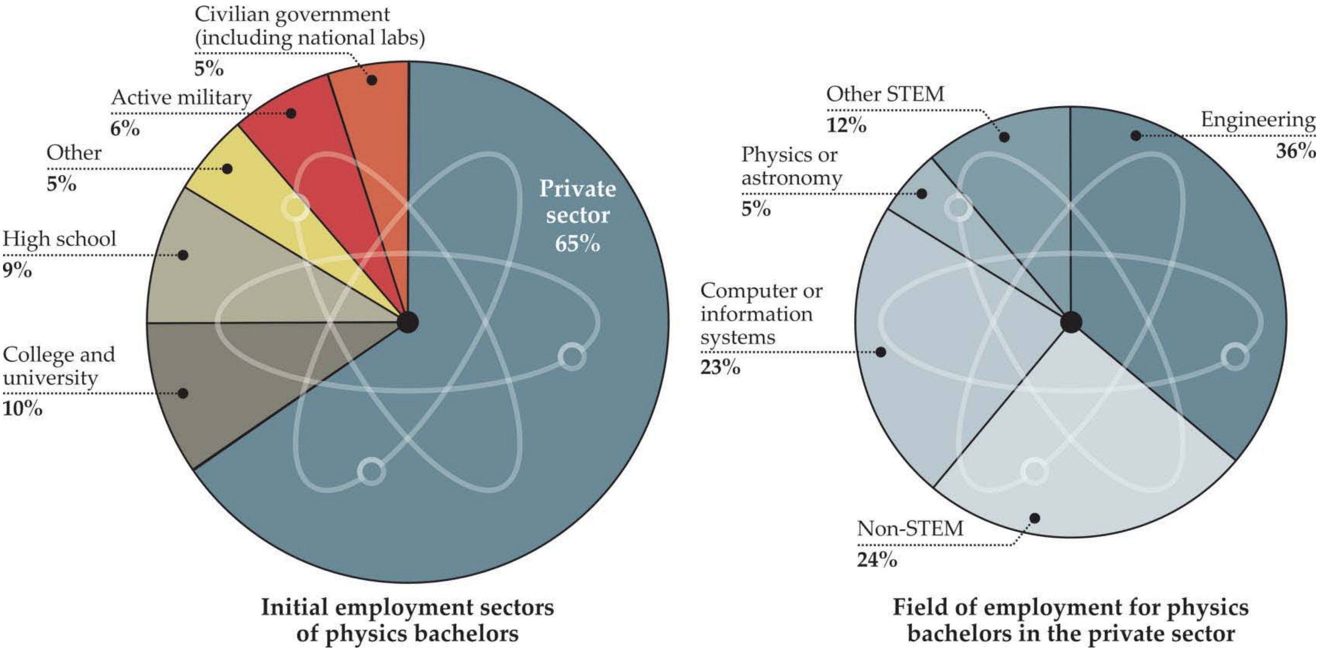

FIGURE 1. THE PRIVATE SECTOR employs 65% of physics bachelors who entered the workforce after receiving their degrees, according to a survey of graduates from 2013 and 2014. (This chart does not include the 54% of all degree recipients who entered graduate school immediately.) College and university employment refers primarily to staff, not faculty, positions. "Other" employment includes elementary and middle schools, hospitals and other medical facilities, and nonprofit organizations. In the private sector, the graduates are primarily employed in STEM (science, technology, engineering, and mathematics) jobs, though a significant fraction are employed in non-STEM fields, such as finance and the service industry. (Adapted from ref. 4.)

task force on undergraduate physics programs (J-TUPP) to address that shortcoming. We and our colleagues on J-TUPP, whose members were drawn from the academic and industrial-physics communities, were asked two broad questions: What skills and knowledge should the next generation of undergraduate physics degree holders possess to be well prepared for a diverse set of careers? And how might physics departments revise their undergraduate programs to help students? Our report is now available.[1]

We consulted several resources to answer those questions. To develop a clear picture of what, ideally, a physics graduate should know to be successful in a wide range of careers, we studied the findings of other academic societies, education associations, and business and government groups; conducted interviews with, among others, physicists in nonacademic careers and developers of innovative university programs; and commissioned a study of physics graduates and their employers. We also drew heavily from previous work, such as the Career Pathways Project report prepared by AIP's Statistical Research Center and the Society of Physics Students,[2] and commissioned a set of case studies of departments that have modified their programs to enhance graduates' career readiness in order to find examples of strategies that other departments could adopt.

What do physics graduates need?

We concluded that physics graduates are generally already prepared to pursue many careers and are sought for their flexibility, problem-solving skills, and exposure to a range of technologies. But most would benefit from a wider and deeper knowledge of computational-analysis tools, particularly industry-standard packages; a broader set of experiences, such as internships and applied research projects, that engage them with industrial work; and a closer connection among physics content, applications, and innovation. Graduates would also be more successful in the workplace if their undergraduate physics program included basic business concepts and professional skills such as teamwork and effective communication.

Faculty members have traditionally focused on ensuring that students master the fundamental physics concepts of the core curriculum—mechanics, electricity and magnetism, thermodynamics and statistical mechanics, quantum mechanics—and their application in areas such as optics, nuclear physics, and condensed-matter physics. Students also gain skills in numerical, analytical, and experimental methods while studying those subjects. It is less common, however, for them to pick up skills associated with applying fundamental physics in interdisciplinary contexts and in the wide variety of nonacademic career settings they are likely to encounter.

Faculty members can serve their students well by providing opportunities to acquire scientific and technical skills not necessarily specific to physics—for example, problem solving beyond the typical problem sets needed to master basic concepts; generic experimental skills in optics, vacuum technology, and electronics; coding and software use; data processing, acquisition, and analysis; and troubleshooting, calibrating, and repairing equipment. Some aspects of those skills are components of traditional coursework and advanced laboratories. However, without an explicit goal of inculcating such skills and developing specific activities to achieve it, some students may fall through the cracks. Perhaps equally problematic, they may fail to recognize the marketable skills they actually have acquired and which employment opportunities suit them best. Interestingly, in the list of common job titles given in figure 3, only one—high school physics teacher—includes the word physics.

When a physics graduate enters the workplace (or, for that matter, undertakes a dissertation project), she is likely to face the challenge of solving complex, ambiguous problems in real-world contexts. She will need to define and formulate specific questions, perform literature searches, and understand what she discovers well enough to develop a strategy for answering her questions—whether by conducting experiments, performing a simulation, making an analytical model, or taking countless other approaches. To implement the strategy, she will need to identify resource needs and make decisions or recommendations for beginning or continuing a project, determine the appropriate next steps, and place the results in a broad perspective. It is likely she will have had little experience doing such tasks unless her undergraduate program offered the opportunity to develop the needed skills.

Competency in instrumentation, software, computation, and data analysis is vital to success in key parts of the workplace or dissertation challenge. A recent report by the AAPT Undergraduate Curriculum Task Force contains useful recommendations for incorporating computational physics into undergraduate programs.[3] Computational software packages are widely used in the private sector, and many are available in an educational version at little or no cost. Although the student versions may lack some functions found in full-price ones, they suffice as an introduction. The graduates we interviewed were virtually unanimous in their desire for more programming skills. Competency in analyzing data, distinguishing between models, and presenting results is important in many careers pursued by physics graduates. The omission of that type of preparation from their college programs puts graduates at a disadvantage compared with their engineering-major peers, who are more likely to have had such experience.

Members of the broader physics community are well aware of graduates' need for good communication skills. But too often a physics program focuses primarily on the preparation of refereed publications. A physicist in an industrial or government setting is likely to need the ability to make her ideas and results accessible to people untrained in science, including managers, sponsors, members of Congress, marketing personnel, technicians, and members of the public. The graduate will also need to articulate her understanding and be persuasive in communicating the worth of her and others' ideas using words, equations, tables, diagrams, pictures, animations, and other visualization tools. Or she may need to teach a complex idea or method to others, evaluate how well it was absorbed, and develop a strategy to more effectively communicate the idea. But most physics programs include no specific opportunities to develop such skills, even for students who coauthor scientific publications and present their research at professional conferences.

Most physics programs also shortchange their students in another way: They rarely help them learn about career opportunities in physics, how to find a job, or how to assess the relevance of their skill set to that job. That many physics faculty members are only vaguely aware of careers outside academia makes their students' transition to the workforce doubly challenging.

What can physics programs do?

The long list of skills and knowledge that physics graduates need may seem daunting to both students and faculty members. How can a program provide a student with all that career preparation and yet still make sure she can solve Schrödinger's equation? Fortunately, most of the skills can be pursued through more than one channel. Depending on such factors as an institution's human and financial resources, the size and aspirations of its student body, and the existence of local industries, physics departments can choose different strategies. They may redesign their programs entirely, infuse skill development into already existing courses, or build the skills primarily with cocurricular activities. In the J-TUPP report, we provide many examples of approaches that have been adopted by physics departments.[1] (For an earlier account of approaches and innovations made by departments to prepare their students for various job opportunities, see the article by Barrett Ripin, PHYSICS TODAY, April 2001, page 43.)

Most faculty members will think that their standard courses already provide a firm foundation of physics knowledge, and rightly so. But why stop there? The content of virtually any

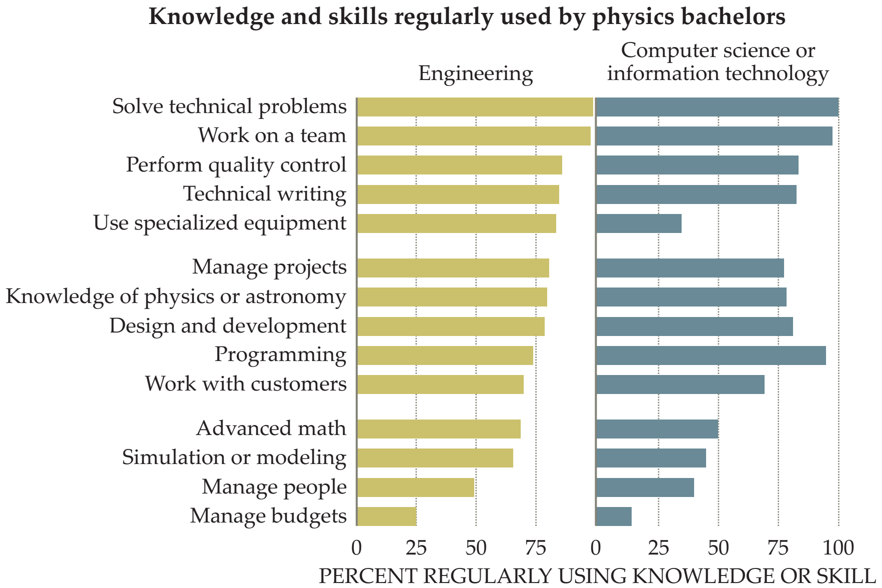

FIGURE 2. WHEN POLLED ABOUT WHAT KINDS OF KNOWLEDGE AND SKILLS they rely on daily, weekly, or monthly, physics graduates from 2013 and 2014 now working at private-sector jobs in engineering or computer science cited the broad range listed here. Graduates in both fields ranked several technical and professional skills as more useful—or more precisely, used more regularly—than a knowledge of physics. (Adapted from ref. 4.)

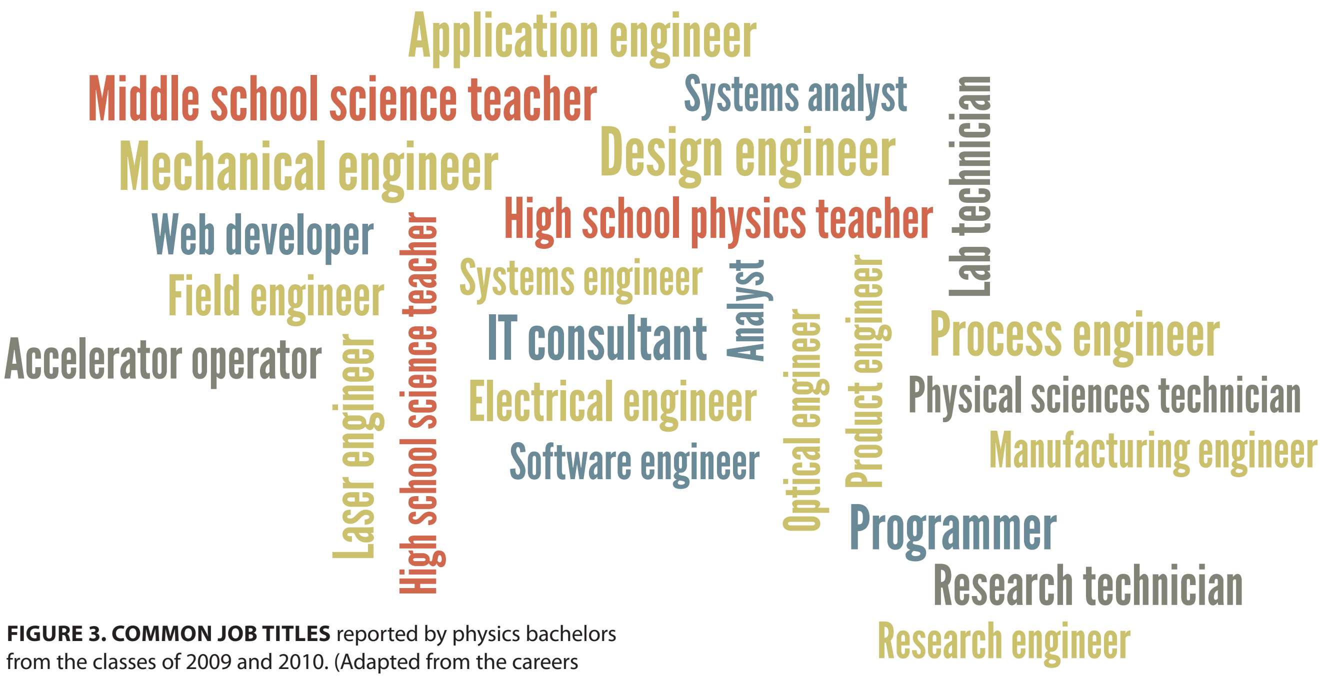

FIGURE 3. COMMON JOB TITLES reported by physics bachelors from the classes of 2009 and 2010. (Adapted from the careers toolbox for undergraduate physics students, AIP Career Pathways Project, www.spsnational.org/careerstoolbox.)

physics course can be related to career-relevant applications while maintaining a focus on fundamentals. Even general relativity finds a practical use—in GPS technology. Physical principles can be applied to industrial processes or commercial devices, say, without sacrificing an appreciation of the core fundamentals. As mentioned earlier, commercial products can also be incorporated into laboratory courses to familiarize students with industry-standard software packages.

Students' communication skills can be addressed at many points in a curriculum. For example, students may produce oral reports on topics relevant to a course or as part of a seminar. Or they may give presentations on their research to the public—perhaps as part of outreach efforts. And not all skill development needs to take place in the physics department. Writing and editing skills can be cultivated in English or communications departments. Basic business concepts can be learned through courses taught in engineering departments or in business schools. Career-placement offices on campus can partner with physics departments to help students conduct a successful job search by honing their resumé-writing and interview skills.

Cocurricular activities are often overlooked as opportunities to develop professional skills. Departments can host talks and other events that feature physics graduates in diverse careers. They can support student organizations in industrial site visits and educational outreach activities. And they can encourage students to take advantage of development activities offered at conferences sponsored by national professional organizations such as the AIP member societies. Formal opportunities to teach or tutor others are yet another way to help students without expanding the physics major.

Collaborations and a flexible curriculum

A department that is prepared to make significant changes can collaborate with other departments and offices on campus, such as career services or industrial relations, and with employers off campus to create immersive internships or intensive interdisciplinary programs on themes such as innovation and entrepreneurship. (See the article by Douglas Arion, PHYSICS TODAY, August 2013, page 42.) Such collaborations are brilliant ways for students to pursue multiple learning goals in a single coherent program. Used in engineering schools for decades, internships allow students to spend time in an off-campus workplace. In addition to giving direct exposure to product development and manufacturing, internships can help students focus on nontechnical aspects of science, such as documentation and business development. Students placed at scientific service companies are exposed to proposal preparation, project cost tracking, corporate structures, and project execution. Technology-transfer offices at national laboratories can allow students to learn about patents, licensing, and commercialization.

Internships often lead to job opportunities, and students interested in a particular industry would do well to intern with a leading firm in that industry. In designing such programs, departments should work closely with other campus groups that may have relevant connections and expertise, such as career-services offices, engineering departments, and business schools. For students with an interest in big data, some institutions offer boot camps that provide students with hands-on experience and assistance landing jobs in that specialty (see PHYSICS TODAY, August 2016, page 20).

A physics department that chooses not to implement significant changes in its program may nevertheless benefit students by making its curriculum flexible enough to be tailored to specific career paths. Some students, for example, could replace a few traditional core courses with electives of industrial relevance, such as condensed-matter physics and optics. Others might opt for electives from engineering, biology, statistics, computer science, speech, business, technical and creative writing, or even philosophy. The substitutions can be made on a student-by-student basis or organized into predetermined tracks of recommended electives. Alternatively, new courses can be designed around specific applications that involve important physics concepts. A course focused on solar cells, for instance, could encompass quantum mechanics, thermal physics, solid-state physics, and more. And a course designed around the challenges and solutions associated with clean energy, clean water, and the environment could offer a broad perspective on the use of physics to solve societal problems.

Another program modification that can enhance students' career preparation is a capstone activity: a thesis, senior seminar, or some other relevant experience. Often students will intern in a research laboratory, conduct research on a historical scientific breakthrough, or carry out an experiment of their own under faculty guidance—and write up the work in each case. The activities can be tailored to address one or more of the learning goals we have mentioned in this article or in some cases can even incorporate industry-standard skills—commercial simulation or graphics packages, say, or computer-aided design—as part of the project.

What's in it for the department?

Even the most minor changes that are made to enhance graduates' career preparedness require sustained effort by faculty members. What would be the reward for you and your department? First, if you investigate the employment outcomes of your program's recent graduates and the career aspirations and prospects of your current and future students, you will better know your students and be able to help them achieve their full potential after graduation. Second, adopting career-preparedness strategies will enhance your department's reputation and attract a talented and diverse group of students who might otherwise have chosen different disciplines or other institutions. Third, enhancing your students' engagement with applied research is likely to lead to new, interesting research questions. Finally, those relatively few students who go to graduate school will have developed skills that are as useful in a research group as they are in the workforce.

Ultimately, we believe that you and your department should follow our recommendations because you desire two things. One is to prepare 21st-century graduates as effectively as possible for the diverse careers they can be expected to have. The other is that your department obtain the many benefits that will follow from fulfilling the first desire—in other words, to pursue enlightened self-interest. If enough of you choose to follow the suggestions, we are confident that the discipline of physics will continue in robust health through this century and beyond.

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In celebration of ILYA LIFSHITZ

This year marks the centenary of the birth of Ilya Mikhailovich Lifshitz, who helped found the field of fermiology and made important contributions to condensed-matter physics and biophysics.

Alexander Y. Grosberg, Bertrand Halperin, and John Singleton

Virtually every physicist has encountered the famous Landau and Lifshitz textbooks, but many may not know that there were two Lifshitz brothers, both physicists. The textbook Lifshitz is the older, Evgeny Lifshitz (1915–85); this article concerns the younger, Ilya Lifshitz (1917–82), shown in figure 1 as a young man. Their parents were Mikhail Lifshitz, a physician, and Berta. Mikhail was from a poor Jewish family that lived in the Pale of Settlement in tsarist Russia. He received his medical education in Heidelberg, Germany, where he won a gold medal for student research and, according to family legend, was presented to Queen Victoria as one of the best European medical students. As was traditional in such families, Evgeny and Ilya received a sound early education at home. Evgeny excelled in languages; Ilya was proficient in music.

The family lived in Kharkov, Ukraine, a cultural and industrial center that was also becoming a notable science hub. The Ukrainian Institute of Physics and Technology (UPTI), founded there in 1930, attracted visits from the likes of Niels Bohr and Paul Ehrenfest. In 1932, fresh from his 18-month stay in Europe, Lev Landau arrived in Kharkov to lead the theoretical division at UPTI and, simultaneously, to take up a chair in theoretical physics at Kharkov's Mechanical Engineering Institute.

The following year, Ilya became a physics student at the Mechanical Engineering Institute. In parallel, he studied pure mathematics at Kharkov University, whose faculty included several first-rate mathematicians. Ilya also studied music at the Kharkov Conservatory. Though he never completed the program, he took great pleasure in playing piano at home for his family and friends. Much later he took up stamp collecting as a hobby and achieved an international reputation.

Always independent, Ilya carried out his PhD work without an adviser; he would later emphasize tactfully that although Landau was a hugely beneficial influence, he had never been Landau's student. In light of that, Landau's Moscow disciples jokingly called Ilya an appanage prince, referring to the younger members of a royal family who are given a small portion of the kingdom to provide income until they inherit a more important position. Nevertheless, on Landau's death in 1968, it was Ilya who became his successor as head of Moscow's prestigious theoretical division in the P. L. Kapitza Institute for Physical Problems. Thus, for the last 14 years of his life, Ilya worked next door to his older brother.

A man of deep decency

Ilya and Evgeny shared a devotion to science, but in many ways they were very different. Meticulously dressed, efficient, lean, and unsmiling, Evgeny hardly ever supervised graduate students. By contrast, Ilya was stouter and radiated friendliness; students, colleagues, and collaborators seemed unable to

FOR DOLORES (*Flores para los muertos*), by Tony Smith, was inspired by the Fermi surface of lead. (Raymond and Patsy Nasher Collection, Nasher Sculpture Center, Dallas. Photographer: David Heald. © 2017 Estate of Tony Smith/Artists Rights Society (ARS), New York.)

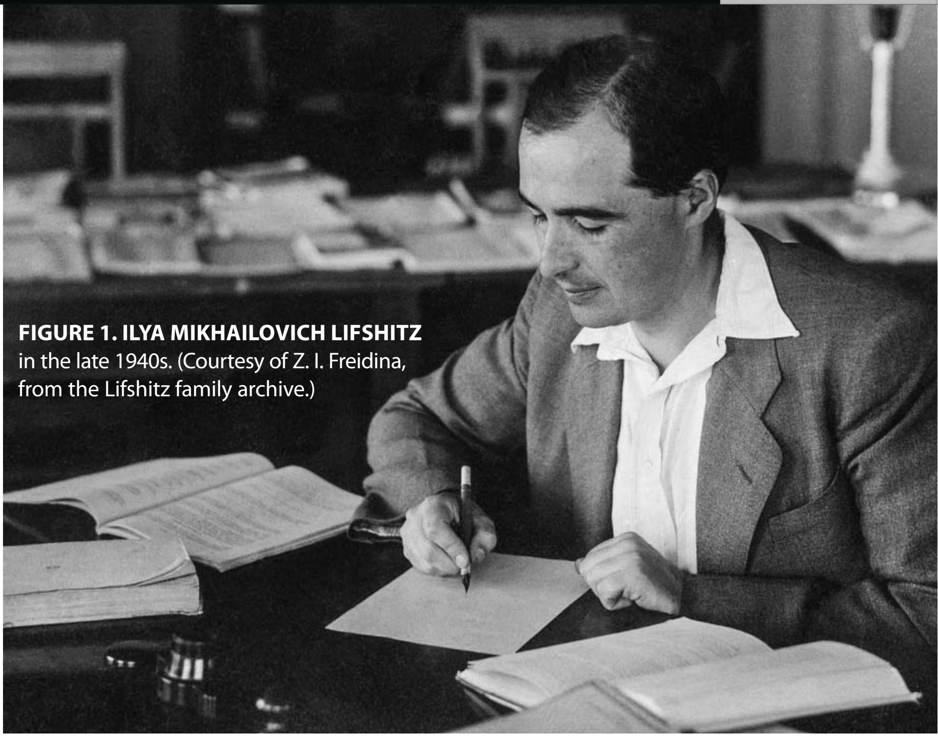


FIGURE 1. ILYA MIKHAILOVICH LIFSHITZ in the late 1940s. (Courtesy of Z. I. Freidina, from the Lifshitz family archive.)

resist his charm. When he taught or delivered a seminar, his enthusiasm was infectious. Excited, he could easily forget his somewhat old-fashioned manners: Once, when trying to explain knots in DNA to a large audience, he theatrically removed the belt from his trousers.[1] Even in later life, after he had received many honors, Ilya was almost childishly excited about any discovery—his or someone else's—that showed intellectual beauty. In his office, one met mathematicians, polymer chemists, and biophysicists besides the usual theoretical and experimental physicists.

Ilya had harmonious relationships with his students. He worked individually with each and was sensitive to the moment when one was mature enough to become independent. Often, he would take a few students and start a new research direction; his colleagues would shrug their shoulders and ask, "Why metals?" When, after some years, those students had become renowned authorities in their still-fertile field, Ilya would suddenly abandon it, take a few new students, and jump into something entirely different. Yet again there would be muttering: "Why polymers?"

In the USSR of those days, it was impossible to hide from difficult interactions with the authorities. Neither Lifshitz was an open dissident, but each refused to tarnish himself with a morally questionable act. For instance, during a press campaign accusing Andrei Sakharov of anti-Sovietism, senior scientists came under enormous pressure to sign condemnatory letters. Many did, but not the Lifshitzes. When Mark Azbel, one of Ilya's outstanding disciples, became a refusenik—that is, the authorities refused to permit his emigration—many colleagues were afraid even to talk to him. But not Ilya. One of us (Grosberg) witnessed how Mark stood alone in the lobby of a Moscow seminar room, with no one approaching him, until Ilya entered and, with his friendly smile, started a conversation. He was not a hero; he was just a man of a deep decency—and that's not insignificant in a totalitarian state.

Ilya did not aim to climb high on the administrative ladder, but he did receive the highest scientific distinctions in the USSR. He was particularly proud to be elected a member of the Soviet Academy of Sciences in 1970; he explained privately that voting for academy membership was the only secret ballot in the country. Neither his academic title nor the tremendous reputation he enjoyed among his colleagues protected him from disappointing treatment by administrators; the many bitter setbacks he endured ranged from issues of student recruitment and employment to the leadership of his departments at Moscow State University.

Having described the man, we now turn to three of his scientific achievements.

Fermiology

Rudolf Peierls told one of us (Singleton) that Ilya Lifshitz was the person who defined a metal as "a solid with a Fermi surface," even though others set those words down in print first.[2] Be that as it may, Lifshitz and collaborators certainly expressed themselves memorably on the subject. For example, in a paper with Moisei Kaganov he wrote, "Each metal acquired its own 'face'. . . . its Fermi surface, a 'visiting card' describing the constant-energy surface which at zero temperature separates the occupied from the empty states in quasi-momentum space."[3] The reference to the constant-energy surface is the definition of the Fermi surface that we nowadays teach to students. The earlier part of the quote refers to one of Lifshitz's major achievements—a model that, for the first time, allowed three-dimensional Fermi-surface shapes to be deduced from experimental observations.[4]

Why is the Fermi surface important? To quote Lifshitz and Kaganov again, it is "the stage on which the 'drama of the life of the electron' is played out."[2] The Fermi surface is the only place in k space where filled and empty states are adjacent (k is the quasi-momentum mentioned above, the conserved quantity that replaces momentum for a particle in a spatially periodic potential). As such, it determines all of a metal's properties. A knowledge of the Fermi surface—the goal of fermiology—enables one to check band-structure models and to understand most of the mechanical, electrical, and magnetic properties of a metal.[2,4,5]

Lifshitz's interest in fermiology came via Landau. In 1930, soon after Arnold Sommerfeld successfully applied quantum statistics to the theory of metals, Landau famously predicted diamagnetism due to the orbital motion of band electrons. His paper contains a laconic statement about magnetization oscillations that are periodic in 1/(magnetic field), a phenomenon now known as the de Haas–van Alphen (dHvA) effect. Landau, however, dismissed the effect as unobservable under the experimental field strength and homogeneity then available. He was certainly correct for most metals, but ironically, just a few weeks after his paper appeared, Wander de Haas and Pieter van Alphen reported their first experimental observations of magnetization oscillations in the semimetal bismuth.[4]

The Hamiltonian of an electron in a magnetic field can be solved analytically only for a Fermi surface that is a sphere or an ellipsoid of rotation; that was the approach followed by Peierls, Landau, and others during the 1930s to analyze increasingly sophisticated dHvA experiments on bismuth. However, bismuth is a special case, a semimetal with a simple Fermi surface consisting of four tiny, ellipsoidal pockets. The small

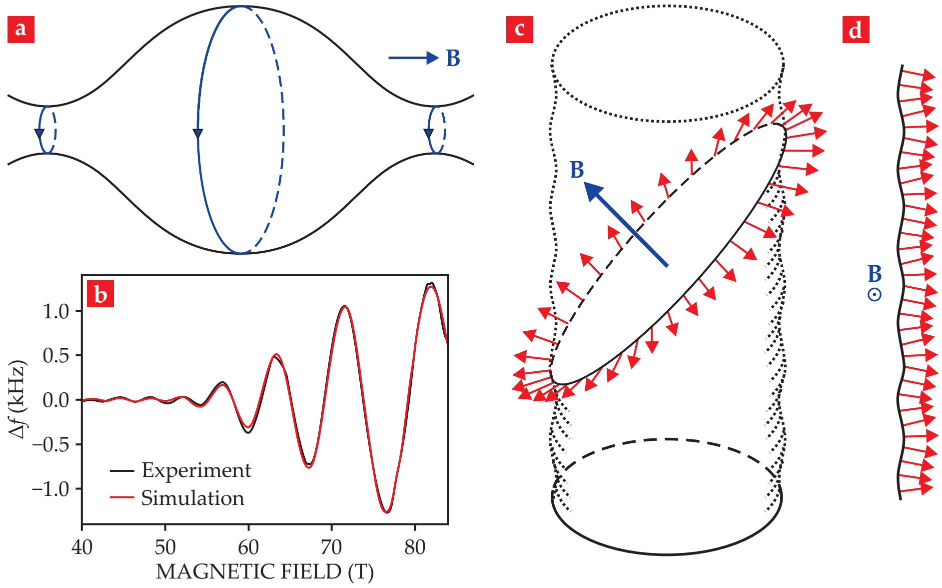


FIGURE 2. FERMIOLOGY. (a) The Fermi surface of a metal lives in so-called *k* space, with the quasi-momentum *k* being the conserved quantity that replaces momentum for a particle in a spatially periodic potential. In the presence of a magnetic field **B**, the closed orbits of electrons define planes perpendicular to **B**. The orbit frequency, which gives the spacing between energy levels, is proportional to **B**; increasing the magnitude of **B** forces those levels to leave the Fermi surface one by one, so the metal's properties oscillate. Extremal orbits such as the ones shown in color dominate the response. **(b)** Resistivity oscillates in response to an increasing magnetic field. The experimental measurements (black) used an RF technique in which frequency change (Δf) is proportional to the change in resistivity. The simulated results (red) were obtained using a variant of a formula derived by Ilya Lifshitz and Arnold Kosevich. The beating shows that more than one extremal orbit contributes to the resistivity change. (Adapted from ref. 15.) Orbits on the Fermi surface can be closed **(c)** or open **(d)**. In both cases, the electron velocity is perpendicular to the surface, as illustrated by the arrows. The corresponding real-space trajectories result in different behaviors of the resistivity.

pocket size causes widely spaced dHvA oscillations, so field inhomogeneities are not worrisome. The ellipsoidal shape gives rise to an easily understood dependence of the oscillations on the orientation of the field with respect to the crystal axes.

After World War II and its interruption of further investigations, it came as something of a surprise when a succession of true metals exhibited a plethora of dHvA oscillations with much more complex field-orientation dependences. The ellipsoidal-surface model was inadequate to explain those data, which demanded a theory for the quantum mechanics of electrons on an arbitrarily shaped Fermi surface exposed to a magnetic field.

Fantasies of a modern artist

Lifshitz's insight was to apply Bohr's correspondence principle to closed electron orbits on the Fermi surface in a magnetic field—that is, to assume that the difference in energy of adjacent levels is $\hbar$ times the angular frequency of the corresponding classical motion. The frequency at which electrons orbit, known as the cyclotron frequency, is proportional to the field; it determines the separation of the electrons' energy levels, now called Landau levels (LLs). Each closed orbit about the Fermi surface (see figure 2a) will have its own set of LLs, but it turns out that the LLs associated with extremal orbits dominate the response of the metal.

Because the LL spacing is proportional to the magnetic field, an increase in the field causes LLs to successively approach, pass through, and exit the Fermi surface as their energies rise above the surface's energy—the Fermi energy. The field increase thus modulates the density of states at the Fermi energy and causes the metal's properties, including magnetization, to oscillate. Each extremal orbit contributes a series of such oscillations (see figure 2b).

The correspondence principle is only valid for large quantum numbers. But Lifshitz realized that it always applied to conventional metals in the experimental fields of the time, which even in pulsed magnets rarely exceeded 10 T. Proceeding from that premise, he found that the inverse of the periodicity of each series of dHvA oscillations is proportional to the corresponding extremal cross-sectional area of the Fermi surface in the plane perpendicular to the magnetic field. (Figure 2a shows the geometry.) Consequently, dHvA data in which the field is applied at various angles to a crystal could be used to map the 3D Fermi-surface shape. Lifshitz described the idea in a seminar in 1950; Lars Onsager independently published similar conclusions in 1952. With Arnold Kosevich, Lifshitz further developed the theory to take into account temperature and impurity scattering. Their Lifshitz–Kosevich formula enables the extraction of such electronic parameters as effective masses, *g* factors, and scattering rates.

Lifshitz and coworkers then studied how a metal's resistivity in a magnetic field depends on the kinetics of electrons at the Fermi surface. They analyzed the Shubnikov–de Haas (SdH) effect—resistivity oscillations analogous to dHvA oscillations in magnetization. They also showed that the field-orientation dependence of various components of a metal's resistivity tensor could be used to map out details of the Fermi surface, an observation that follows from the fact that trajectories on the surface can be closed or open, as illustrated in figures 2c and 2d.

Even today, dHvA and SdH oscillations are experimental tools of choice for studying many aspects of metals. They are applied to substances as diverse as heavy-fermion compounds, whose novel properties derive from partially filled *f* orbitals of rare-earth or actinide ions, cuprate semiconductors, and crystalline organic conductors. All those and more are now regarded as metals because they possess Fermi surfaces.

This introduction to fermiology concludes with a hot topic in condensed-matter physics: changes in the topology of a Fermi surface, or Lifshitz transitions. If a metal is subject to pressure, to give one example, a Fermi-surface section such as that shown in figure 2a may constrict so much that the narrow necks disappear. At that instant, the Fermi-surface topology changes from an extended object to a series of isolated pockets. Lifshitz transitions are thought to be important in many areas of physics, including high-temperature superconductivity, topological insulators and other topological materials, and even black holes.[6]

Lifshitz was modest about his pivotal contributions to fermiology. He likened the increasingly exotic Fermi surfaces extracted from his insights to the fantasies of a modern artist. It was a prophetic description. The Fermi surface of lead inspired the sculpture shown on page 45: *For Dolores (Flores para los muertos)*, by Tony Smith.[2]

Disordered systems

Lifshitz published his first paper on disordered systems when he was only 20 years old. It was an analysis of the diffuse scattering of x rays due to defects in a crystalline lattice. Soon afterward, he turned to the impact of defects on absorption and refraction of IR radiation.[7] Since an IR wavelength is very large compared with the atomic spacing in a crystal, Lifshitz analyzed the problem in terms of the coupling of vibrational modes to a uniform electric field that oscillates at the IR frequency.

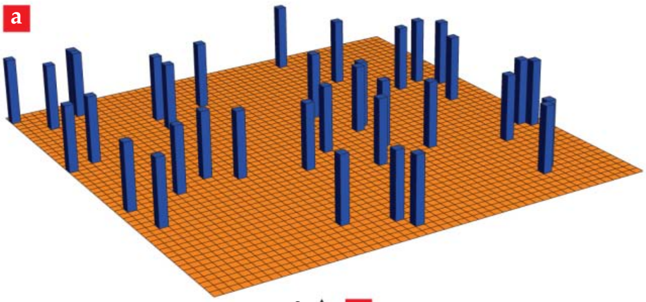
For a lattice without disorder, IR radiation can be absorbed only if the incident photons are matched to the frequency of a vibrational mode with quasi-momentum $k = 0$. Below each absorption frequency is a finite frequency band for which incident radiation will be totally reflected at the crystal surface. For frequencies outside the bands of total reflection, a fraction of the incident power will be transmitted into the crystal and propagate without absorption.

The situation is qualitatively different for a crystal with disorder. Because the disorder allows momentum to be freely transferred to the lattice, the energy of an incident photon can be transferred to any phonon with a matching frequency, regardless of the phonon's k. Consequently, radiation of any frequency within the range covered by the entire set of the crystal's phonons will have a finite absorption length. In addition, defects can lead to localized vibrational modes outside the frequency range of the perfect crystal; IR radiation with frequencies matched to those extra modes will also be absorbed.

Lifshitz tails

Many of the effects of disorder on vibrational modes have parallels in the theory of electronic states in a disordered system. Hence, Lifshitz was naturally interested. His most famous contribution was his 1964 description of what are commonly referred to as Lifshitz tails, regions of energy in which the electron density of states might be expected to be zero but is actually nonzero because of rare fluctuations in the local density of impurities.[8]

As a simple example, consider a model in which space is divided into cubic cells with sides of length a. Within any cell, the potential V is constant and takes on one of two values: Either $V = U$, with probability p, or $V = 0$, with probability $1 - p$ (see figure 3a). If p is small, one can think of the cells with $V = 0$ as the host crystal and the remaining cells as impurities. The issue to be addressed is the density of states at low energies for a quantum particle of mass m moving in the potential V. Suppose that $|U|$ is very small compared with $\hbar^2/ma^2$, an expression that estimates the kinetic energy E_K paid to confine the mass to a single cell. In that case, a low-energy particle would not be



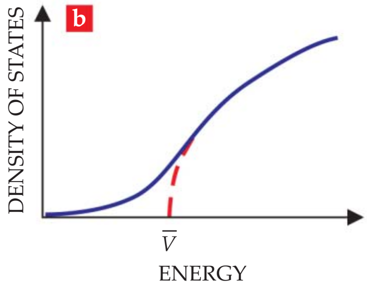


FIGURE 3. A LIFSHITZ TAIL. (a) In a simple model of a disordered crystal, impurities are randomly distributed regions of space in which the potential is U (blue bars) rather than 0. The average potential $\overline{V}$ is equal to U times the probability that a crystal site houses an impurity. **(b)** In a uniform potential of $\overline{V}$, the density of states as a function of energy would go to zero at $\overline{V}$, as indicated by the red portion of the curve. Because of the random nature of the impurities, however, the density of states has a Lifshitz tail, an exponential tail extending down to zero energy.

sensitive to the potential in any one lattice cell but would instead respond to the potential averaged over a region containing many cells.

To a first approximation, the particle would behave as though it were moving in a uniform potential equal to the average potential in the crystal, $\overline{V} = pU$. The density of states would thus be zero for energies E less than $\overline{V}$ and otherwise would be that of a free particle, proportional to $(E - \overline{V})^{1/2}$.

In reality, however, there will always be states with energies less than $\overline{V}$. For example, if U is positive (and thus so is $\overline{V}$), the lower bound to the energy spectrum will actually be at $E = 0$. After all, statistical fluctuations guarantee that an infinite sample will have impurity-free regions of arbitrarily large size, and a particle confined to a sufficiently large empty region can have an energy arbitrarily close to zero. For a spherical region of radius R without impurities, there must exist at least one electronic state that is localized in the region and that has an energy E equal to or less than a value on the order of $E_K a^2/R^2$. The probability P that a region of radius R actually is devoid of impurities is given by $P = (1 - p)^N$, where N is the volume of the sphere in units of a^3. Noting that $N \propto R^3 \propto E^{-3/2}$, one obtains in the limit of small E a rough estimate for the number of energy states per unit volume with energy less than E: $\exp[-p(E_0/E)^{3/2}]$, where E_0 is on the order of E_K. The analysis for the case $U < 0$ proceeds similarly, but the bottom of the energy band is at U rather than 0.

Figure 3b shows the low-energy density of states according to the argument just sketched. A more careful analysis reveals that the most probable spherical region for confining a state of low energy is not completely devoid of impurities but instead contains a small residual density that depends on E and U/E_K. Further refinements take into account fluctuations about the optimal distribution of impurities. Those improvements lead to a more accurate value of the parameter E_0 and to better estimates of the preexponential factor in the density of states, but do not affect the overall conclusion that the density of states has an exponentially falling tail at energies below $\overline{V}$. In his 1964

To read authors' personal memories, visit http://doi.org/10.1063/PT.3.3764

FIGURE 4. AT A MEETING WITH PHYSICS STUDENTS. During the 1979 gathering at which this photo was taken, Ilya Lifshitz was asked what kind of person should become a theorist. He replied, "If you feel clumsy and break equipment in the lab, this itself is not a sufficient reason to become a theorist. There should be some positive motivation." (Courtesy of Z. I. Freidina, from the Lifshitz family archive.)

paper,[8] Lifshitz used extensions of the above reasoning to estimate the density of states in the entire region between the bottom of the energy band and the mean potential $\overline{V}$ for both positive and negative U.

The concept of Lifshitz tails has influenced thinking in several fields. Lifshitz tails have been invoked, for example, in discussions of electron mobility in disordered systems and of optical absorption at frequencies below the threshold that would exist for a perfect crystal. Related concepts have been used to describe peculiar phases of disordered magnetic and ferroelectric systems.[9]

Polymers and biophysics

In the mid 1960s, Lifshitz shifted his interest to polymers, which were also attracting the attention of Samuel Edwards and Pierre-Gilles de Gennes. The three revolutionized the way physicists think about polymers and in the process spawned the field of soft condensed-matter physics. However, their paths to polymers were very different. Interested in chemical engineering applications, Edwards was attracted by gelation and rubber elasticity, whereas de Gennes famously recognized a mathematical mapping between polymers and a particular limit of critical phenomena. By contrast, Lifshitz (shown later in his career in figure 4) came to polymers from biophysics—not a trivial point given that in the USSR of the 1960s, any involvement in modern biology had a clear flavor of political disobedience. Excited by the initial discoveries of molecular biology, Lifshitz was the first to recognize the connection between biopolymers and disordered systems.

Based on that connection, Lifshitz's main contribution to polymer physics is the theory of the coil–globule phase transition, also called polymer collapse (see figure 5). That a concept such as a phase transition can be applied to a single molecule is not obvious; even the longest polymer chains have nowhere near the number of particles found in conventional macroscopic systems. Nevertheless, polymer collapse is a phase transition in the sense that the width of the ambiguous zone separating the fluffy fluctuating coil from the dense liquid-like globule systematically decreases as the chain length increases. The coil–globule transition is, in most cases, very smooth—an almost pure second-order transition. However, the presence of surface energy makes the transition weakly first order, one that produces a small latent heat proportional to the surface area of the globule rather than to the number of particles in the chain.

To approach the equilibrium statistical mechanics of polymer globules, Lifshitz assumed that a chain link at spatial point x feels an external potential $U(x)$. He then considered the partition sum over all spatial conformations of a chain and noticed that the sum was mathematically similar to the Feynman path integral for a quantum particle moving in a potential proportional to $U(x)/k_BT$, with k_B being Boltzmann's constant and T the temperature; Edwards had independently reached the same conclusion.

Unlike Edwards, however, Lifshitz paid attention to the corresponding Schrödinger equation. In that context, when $U(x)$ is a potential well, the effective potential $U(x)/k_BT$ becomes deeper as the temperature decreases. Lifshitz elegantly interpreted the simplest coil–globule transition as occurring at the temperature at which the discrete ground-state energy level splits from the lower border of the continuous spectrum. Indeed, the discrete-level wavefunction corresponds to the globule form of the polymer chain, confined within the potential well. Lifshitz's theory is quite a contrast to the critical-phenomena concepts developed simultaneously, mostly by the de Gennes group, and it was initially received with skepticism. The controversy was fruitful, as its resolution brought forth an understanding of where the critical-phenomena and mean-field approaches were applicable.

Another interesting controversy arose in the early to mid 1970s, when the Lifshitz theory, with its predicted almost-second-order transition, was compared with experiments on protein

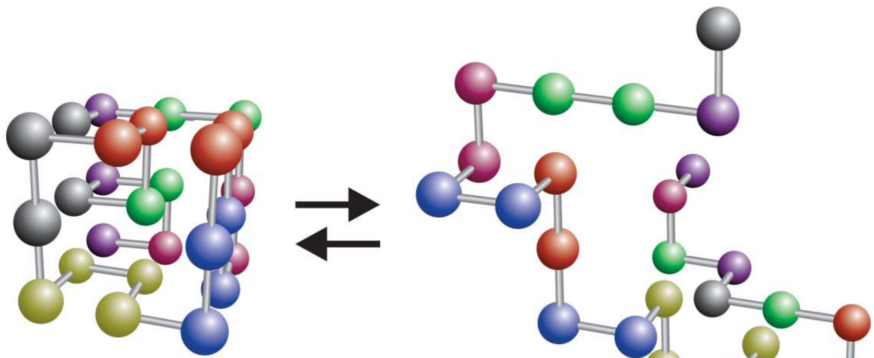


FIGURE 5. THE COIL–GLOBULE TRANSITION. A polymer, here represented in a ball-and-stick model, can transition between a space-filling globule (left) and a fluffy coil (right).

globules. At the time, Lifshitz and others thought of the denaturation and renaturation as the globules' unfolding and refolding and viewed those processes as coil–globule transitions par excellence. But the experiments showed that the transitions produced a large latent heat, comparable per particle to that observed in the melting of regular molecular crystals. The first explanation was rather dismissive: The Lifshitz theory was for homopolymers consisting of a single monomer species, whereas proteins are obviously heteropolymers. Such a discouraging conclusion could be justified from Lifshitz's papers, which addressed homopolymers only. But in seminars that , unfortunately, were not presented anywhere outside the USSR, more generally applicable arguments were discussed and honed.

Years later Lifshitz's ideas bore fruit in biophysics, once it was understood that the first-order nature of coil–globule transitions in proteins is a property of particular amino-acid sequences. Theoretically, such sequences could be identified and created by computer or in real experiments via a process called sequence design. The new understanding permitted biophysicists to estimate the number of sequences exhibiting first-order folding transitions and led to the idea that such sequences have been selected by evolution for their stability against mutations and environmental perturbations.[10,11]

Lifshitz's insights into polymer globules have also informed the now hot topic of genome folding. The puzzle is to understand how 2 m of DNA are housed and accessible in the 10 μm nucleus of every cell of the human body.[12–14]

Ahead of fashion

In a career spanning from the end of the 1930s to the start of the 1980s, Ilya Mikhailovich Lifshitz had a remarkable influence on the study of fermiology, disordered systems, and biophysics. He also made other contributions, no less impressive, some of which are among his most cited. Those include work with Vitaly Slezov on the kinetics of first-order phase transitions (including the famous $t^{1/3}$ law describing the growth of the nucleus of a new phase), a study with Alexander Andreev on quantum diffusion of vacancies, and an investigation of quantum-tunneling kinetics of nucleation with Yuri Kagan. Many times, when Lifshitz entered a field, he was not following fashion. But fashion often followed him, even if it sometimes took 20 years to catch up.

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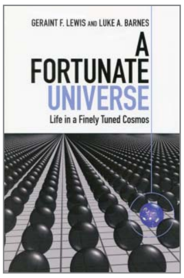
BOOKS

A Fortunate Universe

Life in a Finely Tuned Cosmos



Geraint F. Lewis and Luke A. Barnes

Cambridge U. Press, 2016. $27.99 (388 pp.). ISBN 978-1-107-15661-6

Geraint Lewis and Luke Barnes's lucid, fast-paced, and funny new book might best be summed up in their own words: "Our conclusion is that the fundamental properties of the Universe appear to be fine-tuned for life." As the authors carefully explain in *A Fortunate Universe: Life in a Finely Tuned Cosmos*, it doesn't matter whether other kinds of life are out there. It's enough that there is life here on Earth to raise the question of why the universe is the way it is, seemingly fine-tuned to allow for life. After all, in the vast parameter space of hypothetical universes, life is a tight fit. Change the fundamental constants, or the basic laws of physics, or the low-entropy, free-energy-rich initial state of the universe, and the story on Earth would have been radically different. Life has very little wiggle room.

The fine-tuning problem tends to elicit strong responses. Some physicists are casually dismissive, claiming it's a non-problem: What else could the fundamental constants be? They are what we measure them to be, period. Others extrapolate beyond current experimentally validated theories. Multiple universes may exist in addition to ours, and in them the values of the fundamental constants might differ. If many other universes exist, it's not so surprising that in one or a few, the values will conspire to be what they are here. After all, sooner or later someone wins the lottery. We could be a rare statistical fluke in a vast landscape of potential universes. (But how can we know how rare?)

Lewis and Barnes lay it bare for anyone who wants to understand what's at stake. They find inspiration in this quote from Albert Einstein:

> I would like to state a theorem which at present cannot be based upon anything more than faith in the simplicity, i.e., intelligibility, of nature: there are no *arbitrary* constants . . . that is to say, nature is so constituted that it is possible logically to lay down such strongly determined laws that within these laws only rationally determined constants occur.

That is Einstein's dream, the ultimate triumph of theoretical physics: a metatheory that explains why the fundamental constants appear to be fine-tuned to have the values we measure them to have. No coincidences or unknowables allowed, only certainty.

Consider, though, that even if scientists were one day to be in possession of such a metatheory, one could ask why nature operates by *that* metatheory and not another that predicts different outcomes. We end up mirroring the original fine-tuning problem one step removed.

Lewis and Barnes are entirely open about the potential pitfalls of speculative theories. They argue, quite correctly, that we only find if we look, and that's what we should be doing. Their tone is optimistic and validating. Let's push current theories as far as possible and see where they lead us, they say. Fill those dustbins with fake universes.

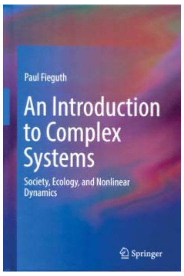
The authors end the book with a theological discussion on the nature of God and on naturalism versus theism. That path may be a turnoff for those with little patience for religious arguments, but it is entirely justifiable given the ontological nature of the fine-tuning problem. When it comes to fundamental questions of existence—in this case, the existence of our universe and its properties—we humans are like a fish in a bowl trying to figure out the nature of the ocean. It's wiser to accept our ignorance with humility and embrace uncertainty than to claim certainty with blind arrogance and risk future embarrassment.

To make predictions with physical theories, scientists must be able to measure initial conditions of the system under examination: positions and velocities of particles, temperatures and pressures, density profiles and energy levels. But deriving the reasons why the fundamental laws of nature are what we observe them to be seems beyond the scope of what current science can do. Theories depend more on subjective experiences than most of us are willing to admit. As Werner Heisenberg once wrote, "What we observe is not Nature itself but Nature exposed to our methods of questioning." Try as we may, we can't jump out of the fishbowl.

Marcelo Gleiser
Dartmouth College
Hanover, New Hampshire

An Introduction to Complex Systems

Society, Ecology, and Nonlinear Dynamics



Paul Fieguth

Springer, 2017. $59.99 (346 pp.). ISBN 978-3-319-44605-9

Traditional coursework makes ample use of the assumptions that systems are small, linear, and governed by Gaussian statistics, and for good reason: They make for tractable math. One could therefore forgive a STEM undergraduate for the belief that one can approximate most real systems with the simple harmonic oscillator, perhaps with a bit of white noise thrown in for good measure. Unfortunately, real systems typically violate all three assumptions, with dramatic consequences. Power blackouts, financial panics, and ecosystem collapses are just a few examples of problems that can be understood only in light of the large, the nonlinear, and the non-Gaussian. The ubiquity and outsize impact of such phenomena beg for broader awareness of the mathematics and consequences of complex systems. But how is that to be achieved without stripping away the attributes that make systems complex in the first place?

In *An Introduction to Complex Systems: Society, Ecology, and Nonlinear Dynamics*, Paul Fieguth takes on that challenging task. An engineer by training, he combines a practitioner's sensibility with a hobbyist's knowledge of a grab bag of fields ranging from climate change to soil science. His book represents a new take on the pedagogy of complex systems, emphasizing concepts and consequences over calculations.

The book reads like a play in three acts. The first portion, motivated by the timely problem of global warming, introduces the reader to systems theory. With the stage thus set, Fieguth tackles the question of how to define a system in the first place. What are the system's boundaries? Is it open or closed? If open, what are its inputs and outputs, and what does thermodynamics imply about its operation? The book then deals with the representation of a system's dynamics and associated dynamical state. Are the governing equations stationary in time? In space? What do we need to measure to make meaningful statements about the system's behavior? The intent in posing those questions is not to provide one-size-fits-all answers, but to accustom the reader to thinking about the nuances of systems modeling.

The middle third of the text can be described as an atlas of complex systems, using the relatively bland linear systems as a counterpoint. Along the way, the author delves into new phenomena unlocked by each new layer of complexity; for instance, chapter 6 introduces nonlinearities in one-dimensional systems and with them the possibility of multi-stability, bifurcations, and hysteresis. Later chapters discuss higher-dimensional nonlinear systems and what the author terms "spatial systems"—those properly modeled by partial differential equations or agent-based models. Fieguth covers critical modeling issues like discretization, resolution, stability of numerical methods, and boundary-value constraints. That nod toward the fact that the science of complex systems is unavoidably computational gives the book a practical flavor that I like.

The final act covers behavior and problems common to most large complex systems. Chapter 9 shatters the illusion that bell curves dominate the statistics of real-world systems and uses examples as varied as drought lengths, city sizes, and movements of the Dow Jones Industrial Average to show that "extreme" and "improbable" are not synonymous. Next, readers are exposed to the key concept of emergent behavior, and chapter 11 provides a good introduction to the challenges of observation and inference in large complex systems. In a fitting coda, chapter 12 ties the themes together with an in-depth case study of water, from ocean acidification to groundwater availability.

Of course, one cannot treat many of the above topics without some appeal to the underlying mathematics. Fieguth strikes a good balance. He strips derivations to the bare essentials and sequesters the dry machinery of, say, eigendecomposition to an appendix. That frees him to focus on the interpretation of the problem at hand.

Occasionally, by emphasizing broad themes over nuances, Fieguth does a disservice to his readers. Take, for instance, the focus on power-law distributions, which Fieguth claims are the ubiquitous face of non-Gaussian statistics across nature and society. In fact, many reported power laws lack statistical support or a plausible generative mechanism; the author would have done better to emphasize the contrast between thin-tailed and heavy-tailed distributions in general. Conversely, at times the text pursues tangents at the expense of the main message. A cursory, few-page excursion into control theory, for example, ends up being more jarring than illuminating. But such misfires are the exception.

I can envision at least two ways Fieguth's book could be used in a classroom setting. On its own, it would be a fine primary text for an interdisciplinary course at the intermediate undergraduate level. For a more specialized course tailored to advanced physics majors, the book would naturally complement a more mathematical text in dynamical systems, chaos, or network science. For those texts I can recommend Steven Strogatz's *Nonlinear Dynamics and Chaos: With Applications to Physics, Biology, Chemistry, and Engineering* (2014), *Chaotic Dynamics: An Introduction Based on Classical Mechanics* by Tamás Tél and Márton Gruiz (2006), and Albert-László Barabási's *Network Science* (2016). But regardless of how Fieguth's text is used, students of all stripes will find at the end of each chapter a wealth of appropriately challenging exercises ranging from the conceptual to the analytical and computational.

An Introduction to Complex Systems largely accomplishes what it sets out to do. Its application-forward approach is likely to appeal to readers in fields like environmental science and economics, in which complex systems are typically underemphasized but no less important. And if even a specialist like me can read about climate change, lake eutrophication, or any of the panoply of other case studies in this book and exclaim "I never thought about it that way!" then the book should be regarded as a success.

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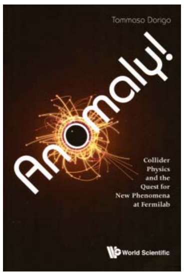
Anomaly!
Collider Physics and the Quest for New Phenomena at Fermilab

Tommaso Dorigo

World Scientific, 2016. $110.00 (304 pp.). ISBN 978-1-78634-110-5



The desire to discover something new is a powerful driver of the research process. In particle physics, the potential for discovery is especially great at the laboratories with the highest-energy particle accelerators, where particle collisions have the best chance of producing novel states and processes. The Tevatron collider at Fermilab constituted that "high-energy frontier" from 1989 until 2010; two collaborations, the Collider Detector at Fermilab (CDF) and DZero, each collected data from the collisions at the Tevatron during this period. They stopped roughly 18 months after data collection began at CERN's more powerful Large Hadron Collider.

In *Anomaly! Collider Physics and the Quest for New Phenomena at Fermilab*, Tommaso Dorigo provides an engaging and insightful perspective on the pursuit of physics discoveries at CDF. The book, written for a nonspecialist but scientifically literate audience, begins with informal explanations of the physics of the standard model and colliding-beam experiments. Dorigo takes a breezy approach with that introductory material and deftly employs analogies so that he can get to the real business at hand: Fermilab's work in the 1990s and 2000s. Much of the narrative centers on the process of discovery, including that of the top quark, long predicted in the standard model. CDF claimed to have found evidence of the top quark in 1994 but ultimately shared credit with DZero for discovering it in 1995.

Dorigo arrived at CDF as an undergraduate student in 1992 as the collaboration began its first serious data run, which culminated in the discovery of the top quark. He draws on conversations with many of his CDF colleagues to detail the fascinating and sometimes contentious episodes that led to the discovery. Observing and confirming evidence for the top quark required the scientists to make hard choices about both detector technology and approaches to data analysis. Dorigo succeeds in maintaining the lively character of their sometimes arcane disagreements. He explains the scientific aspects of the disputes succinctly and clearly while also bringing their human dimensions to life.

Anomaly! reveals the ways in which individual scientists' personalities, loyalties, and enthusiasms shape their contributions to the labors of the collaboration. One of the most poignant passages concerns Japanese physicist Kunitaka Kondo's attempts to gain approval of a novel likelihood-based approach to identifying the top-quark signal. Kondo's approach was not adopted at the time, although physicists use it frequently now. Dorigo acknowledges that the obstacles to implementing Kondo's ideas lay not so much in the method itself as in the way Kondo presented it; part of the difficulty was cultural differences that created "a barrier between him and his collaborators."

Dorigo's point is not to undermine the results that were published but to make clear the human aspects of the process by which physicists decide how to present their results. He proclaims, "The enormous wealth of the collaboration was the competence, the knowledge, and the experience of its members; and the best way to use such assets was through a free communication." But as the Kondo anecdote teaches, the best approach is not always an easy one.

The most dramatic part of the book, and the part in which Dorigo seems to have the most personal involvement, comes last, as he discusses disputes over anomalies in CDF's data that seemed—for a time, at least—to point to physics beyond the standard model. In the aftermath of their 1995 discovery of the top quark, some CDF members noticed an apparent excess of events involving a W boson and two energetic jets. The quest to understand that anomaly led to what is sometimes called the "superjets affair," a contentious internal dispute over the existence, size, and interpretation of the effect in question, which, some argued, indicated a supersymmetric partner to the bottom quark.

Dorigo skillfully conveys the drama of the debate within CDF. Physicist Paolo Giromini was determined to publish the anomaly but was furiously opposed on the grounds that it could be the result of an unspecified detector effect, among other things. In a contentious collaboration meeting, Melissa Franklin argued that even if the result were an error, the interest of the broader physics community would be better served by publishing a result that might point to important new physics. Passages such as those exemplify the difficulty of balancing the scientific interest in avoiding error with the desire to facilitate discovery. Eventually, CDF did publish the 13 anomalous events, but without any discussion of them in terms of new physics. A subsequent run with a much larger data set did not yield a similar effect.

Scholars will be shocked to learn that Dorigo's book does not include a single citation of any published work or source. He acknowledges a long list of colleagues and other interlocutors who helped him piece together his narrative, but he provides no means for determining the basis for any particular claim. Dorigo's defense of that peculiarity is that he aims "to teach some physics in an entertaining way" rather than "to contribute to the history of science." However, to my knowledge, the only comparable monograph on CDF's history and the top quark's discovery is my own book, *The Evidence for the Top Quark: Objectivity and Bias in Collaborative Experimentation* (2004), which pursues a different agenda and emphasizes different aspects. Dorigo's book is thus almost certainly going to be an important source for anyone interested in the history of CDF, whether or not that was his intent.

Scholars who manage to set aside their usual reading habits, and readers who do not care about scholarly documentation, will be rewarded. *Anomaly!* is a personal yet highly informative story of discovery and almost-discovery from the perspective of someone who saw the events firsthand.

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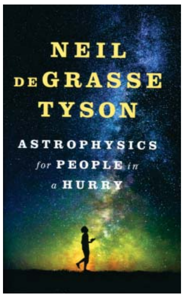
Astrophysics for People in a Hurry

Neil deGrasse Tyson
W. W. Norton, 2017. $18.95 (224 pp.).
ISBN 978-0-393-60939-4

If anyone has the knowledge to popularize science, it's Neil deGrasse Tyson. The Harvard- and Columbia-educated astrophysicist has published more than 10 books, hosted the TV series *Cosmos: A Spacetime Odyssey* in 2014, and continues to host *StarTalk*. The latest addition to his outreach career is his new book, *Astrophysics for People in a Hurry*.



As its title suggests, this small hardcover book offers curious laypeople a quick, easy-to-read overview of the world of astrophysics. Tyson keeps the reader engaged by combining scientific facts with historical anecdotes, etymological discussions, and stories of his own experiences in science, such as when he learned of an asteroid being named in his honor. He also offers some of his own opinions as an astrophysicist and demonstrates his wit with a suggestion that aliens from Jupiter's moon Europa might be called Europeans.

Astrophysics for People in a Hurry covers a broad selection of topics: from the largest scales of the universe and its main components, such as dark matter, to the smaller scales of the solar system and Earth. He discusses subjects that are currently puzzling scientists like me, such as dark energy, and those that are well understood by the physics community, such as the round shape of planets and the electromagnetic spectrum. The book's material was drawn from the essays Tyson wrote for his Universe column in *Natural History* magazine between 1995 and 2005. As a result, *Astrophysics for People in a Hurry* sometimes feels like a collection of short stories. That may well be appropriate for people in a hurry, but it also leads to a feeling that the book's chapters are disconnected and lack a flowing train of thought.

Surprisingly, Tyson includes only a single paragraph on gravitational waves, whose discovery was announced in 2016 and widely reported in the mass media. A chapter on gravitational waves would have added cutting-edge material to the book, and it would have allowed readers to familiarize themselves with one of the biggest scientific breakthroughs of this decade.

The first chapter describes the evolution of the universe from the first instants after its birth to billions of years later. It may seem ideal to start an accessible book on astrophysics with a summary of the cosmic history of the universe. In my opinion, though, the chapter would be a bit overwhelming for someone with no knowledge in physics.

The rest of the book, however, is very easy and pleasant to read. I particularly enjoyed chapters 11 and 12. Chapter 11, "Exoplanet Earth," describes our planet from the perspective of interstellar observers. Tyson's playful twist manages to teach readers about terrestrial features such as chemical elements, electromagnetic radiation, and life while simultaneously discussing the rationale and scientific methodology behind the search for life on other planets.

Chapter 12, "Reflections on the Cosmic Perspective," provides an unexpected yet welcome meditation on how knowledge and awareness of our incredibly vast universe can lead to a more tolerant and empathic society. Readers may or may not be willing to embrace Tyson's cosmic perspective. But in a time when scientific evidence is disregarded by some of the world's most influential people, the ideas presented in that concluding chapter invite relevant and necessary discussion on topics such as inequality and climate change.

Overall, *Astrophysics for People in a Hurry* goes beyond familiarizing busy readers with different topics of astrophysics. It offers entertaining insights into broader challenges in science, some of the unknown frontiers that scientists face at present, and the implications of understanding our surroundings and the almost unfathomable vastness of the universe.

Macarena Lagos
University of Chicago
Chicago, Illinois

NEW BOOKS

Plasmas and fusion

Magnetic Confinement Fusion Driven Thermonuclear Energy. B. Zohuri. Springer, 2017. $99.00 (185 pp.). ISBN 978-3-319-51176-4

Plasma Remediation Technology for Environmental Protection. C. Du, J. Yan. Zhejiang U. Press and Springer, 2017. $99.00 (79 pp.). ISBN 978-981-10-3655-2

Popularizations

Anomaly! Collider Physics and the Quest for New Phenomena at Fermilab. T. Dorigo. World Scientific, 2017. $48.00 *paper* (285 pp.). ISBN 978-1-78634-111-2

Astrophysics for People in a Hurry. N. D. Tyson. W. W. Norton, 2017. $18.95 (222 pp.). ISBN 978-0-393-60939-4

Bad Choices: How Algorithms Can Help You Think Smarter and Live Happier. A. Almossawi. Viking, 2017. $20.00 (145 pp.). ISBN 978-0-7352-2212-0

Beyond Infinity: An Expedition to the Outer Limits of Mathematics. E. Cheng. Basic Books, 2017. $27.00 (284 pp.). ISBN 978-0-465-09481-3

The Digital Mind: How Science Is Redefining Humanity. A. Oliveira. MIT Press, 2017. $29.95 (317 pp.). ISBN 978-0-262-03603-0

The Mathematics Lover's Companion: Masterpieces for Everyone. E. Scheinerman. Yale U. Press, 2017. $28.00 (274 pp.). ISBN 978-0-300-22300-2

Rigor Mortis: How Sloppy Science Creates Worthless Cures, Crushes Hopes, and Wastes Billions. R. Harris. Basic Books, 2017. $28.00 (278 pp.). ISBN 978-0-465-09790-6

Scienceblind: Why Our Intuitive Theories about the World Are So Often Wrong. A. Shtulman. Basic Books, 2017. $30.00 (311 pp.). ISBN 978-0-465-05394-0

Where the River Flows: Scientific Reflections on Earth's Waterways. S. W. Fleming. Princeton U. Press, 2017. $26.95 (204 pp.). ISBN 978-0-691-16878-4 PT

NEW PRODUCTS

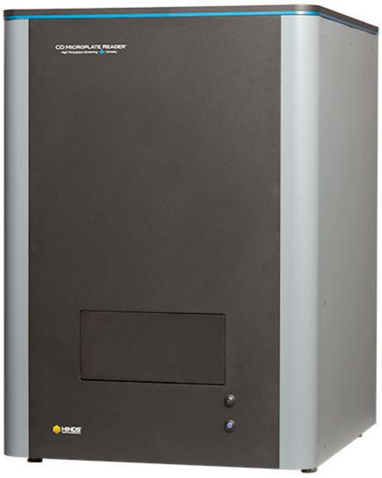
Focus on lasers, imaging, and photonics

The descriptions of the new products listed in this section are based on information supplied to us by the manufacturers. PHYSICS TODAY can assume no responsibility for their accuracy. For more information about a particular product, visit the website at the end of the product description. For all new products submissions, please send to Rnanna@aip.org.

Andreas Mandelis

Superresolution camera for fluorescence microscopy

Andor Technology, an Oxford Instruments company, has made a superresolution microscopy technology available on its single-photon-sensitive iXon electron-multiplying (EM) CCD cameras. Superresolution radial fluctuations (SRRF)-Stream uses conventional fluorophores at low-illumination intensities to make possible real-time superresolution fluorescence microscopy on most modern microscopes. Andor claims it has enhanced the technology to run optimally on its iXon EMCCD cameras and provide powerful superresolution at low cost. Advanced graphics-processing-unit optimization techniques execute the SRRF algorithm up to 30 times as fast as the existing SRRF implementation, and the camera produces real-time, high-resolution, large field-of-view live-cell images. ***Andor USA****, 425 Sullivan Ave, Ste 3, South Windsor, CT 06074, www.andor.com*



Circular dichroism microplate reader

Hinds Instruments has announced a circular dichroism (CD) microplate reader and named BioLogic Science Instruments its worldwide distributor. According to Hinds, it is the first commercially available system that can read CD directly from standard laboratory microwell plates. It facilitates investigating the properties of enantiomers—organic molecules that exist in at least two forms that are mirror images of each other. Increasingly, the Food and Drug Administration and other agencies require drug companies to fully separate, characterize, and control enantiomers. The novel CD spectroscopy instrument can measure the enantiomeric excess of 96 reaction products in less than 2 min and provide high-throughput screening for chiral pharmaceuticals. ***Hinds Instruments Inc****, 7245 NE Evergreen Pkwy, Hillsboro, OR 97124, www.hindsinstruments.com*

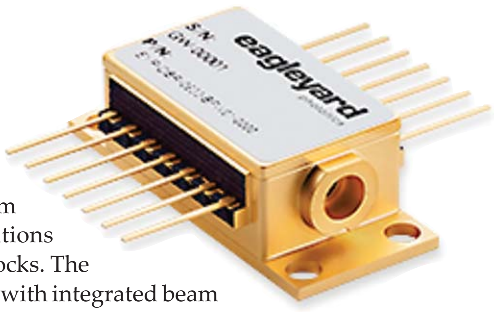
Instrument combines Raman and FE-SEM

WITec's correlative Raman imaging and scanning electron (RISE) microscopy is now available with the Zeiss Sigma 300 field-emission scanning electron microscope (FE-SEM). The Raman technique can identify and image the molecular composition of a sample. It is a suitable complement to an FE-SEM, which enables structural characterization of particles, surfaces, and nanostructures. The system features a standard vacuum chamber, a SEM column, and a confocal Raman microscope and spectrometer. The software facilitates switching between modes and transforming Raman spectroscopic data so they can be overlaid onto the SEM image to produce a RISE image. The approach can benefit researchers in nanotechnology, life sciences, geosciences, pharmaceutics, materials research, and other fields. ***Carl Zeiss Microscopy LLC****, 1 Corporation Way, Peabody, MA 01960, www.zeiss.com*

Deep-UV spectrum measurements

McPherson's VUVAS UV spectrophotometer systems can now be equipped with integrated digital mass flow controls (MFCs) that can improve measurement accuracy and the lifetime of short-wavelength UV lamps. The high energy of UV light can cause organic contaminants to photo-polymerize on optical surfaces and degrade performance. To reduce or eliminate photochemical deposition of organic films in UV instruments, measurements can be made under an inert gas atmosphere—typically nitrogen—rather than in vacuum. McPherson claims that digital control of the purge environment in UV optical systems such as its VUVAS spectrophotometers delivers more stable and reproducible results than can be achieved without the MFCs, which offer precise thermal sensing and accurate flow rate control. ***McPherson***, *7-A Stuart Rd, Chelmsford, MA 01824-4107, http://mcphersoninc.com*

Laser diode for rubidium spectroscopy



Eagleyard has added a 795 nm distributed feedback laser to its product portfolio and has thus expanded the choices for rubidium spectroscopy and related applications such as optically pumped atomic clocks. The 14-pin windowed butterfly package with integrated beam collimation has ready-to-use single-frequency-emission features. It includes a thermoelectric cooler and thermistor to enable precise wavelength tuning. The package provides electrical input and optical output in the same layer and allows convenient use of standard peripheral equipment such as mounts and drivers. The laser features a linewidth of less than 1 MHz, a mode-hop-free tuning range greater than 10 GHz, and output power of 80 mW. An optional integrated microisolator is available. ***Eagleyard Photonics GmbH***, *Rudower Chaussee 29, 12489 Berlin, Germany, www.eagleyard.com*

Laser-beam control platforms

With millisecond response and settling time and high dynamic linearity, S-335 miniaturized fast steering mirror platforms from Physik Instrumente are suitable for use in microscopy, optics, photonics, and semiconductor manufacturing. Specific applications include laser-beam steering, image processing and stabilization, and materials processing. The piezo-based stages provide precise angular tip and tilt motion of the top platform around two orthogonal axes. The company claims the flexure-guided, electroceramic-driven systems can provide higher accelerations than other actuators. They thus enable step response times in the submillisecond range. The systems deliver frictionless backlash-free motion and their single pivot-point design prevents the drawback of polarization rotation. ***Physik Instrumente LP***, *16 Albert St, Auburn, MA 01501, www.pi-usa.us*

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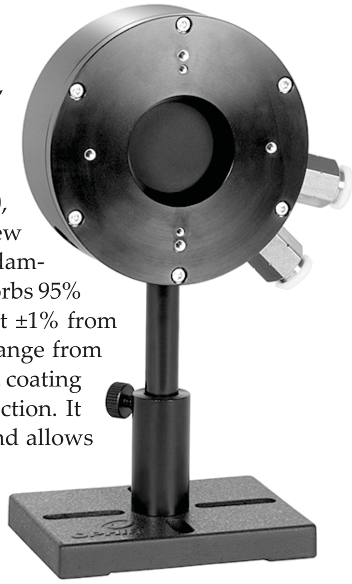
Randolph A. Nanna, Publisher

NEW PRODUCTS

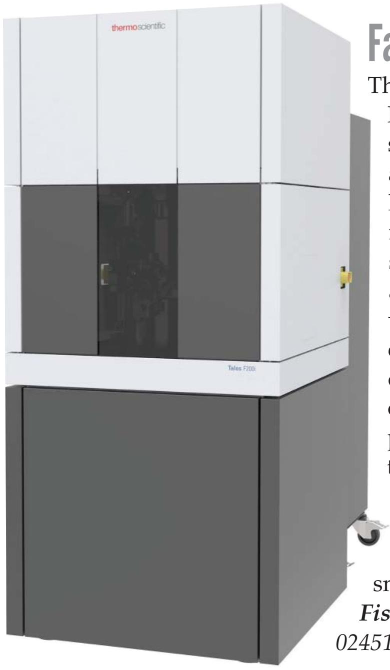
Air-cooled fiber-optic cables

Coherent has introduced its RQB fiber-optic cables for use with fiber lasers operating at CW power levels up to 1.5 kW and pulsed lasers to 1 MW. The air-cooled, beam-delivery cables have a standard QBH interface, which lowers cost and can enhance system simplicity in air-cooled fiber-laser applications. Quartz block technology enables the use of antireflection coatings to reduce overall losses to under 3%. A mode stripper prevents unwanted back reflections and pump light from propagating in the cladding. An integrated thermoswitch in the connector protects against overheating, and a safety interlock continuously monitors the status of the fiber. RQB fiber-optic cables are available with a 0.20 numerical aperture, core diameters from 50 µm to 1000 µm, and lengths of 5 m to 200 m. ***Coherent Inc****, 5100 Patrick Henry Dr, Santa Clara, CA 95054, www.coherent.com*

High-power laser sensors



MKS Instruments, which includes Ophir-Spiricon, offers a line of high-damage-threshold laser power and energy sensors for CW lasers with high power densities and for pulsed lasers. The Ophir models 1000W-LP2-34, L1500W-LP2-50, 5000W-LP2-50, and FL600A-LP2-65 feature a new reflection-reducing LP2 coating that provides a damage threshold of 10 kW/cm^2 at 1 kW power. It absorbs 95% at most wavelengths and is totally spectrally flat ±1% from 0.2 µm to 1.1 µm. The sensors cover a spectral range from 0.35 µm to 2.2 µm. The high absorption of the LP2 coating reduces dangerous and often harmful back reflection. It provides very low dependence on beam angle and allows the sensors to measure divergent high-power lasers, such as diode laser bars, and collimated beams. ***Ophir-Spiricon LLC****, 3050 N 300 W, North Logan, UT 84341, www.ophiropt.com*



Fast STEM for materials studies

Thermo Fisher Scientific developed its Talos F200i scanning transmission electron microscope for advanced material characterization applications. Extensive automation facilitates high productivity and fast switching among multiple users. Easy mode switching and constant power lenses allow for fast changes among imaging and analytical modes, so users do not need to wait for the system to equilibrate. With automated daily tuning of operational parameters, users can maintain optimal imaging conditions and thereby improve the repeatability of measurements and their reproducibility. The system's small footprint and accessible enclosure expedite service and reduce infrastructure and support requirements. Options include fast cameras, smart software, and sample holders. ***Thermo Fisher Scientific Inc****, 168 Third Ave, Waltham, MA 02451, www.thermofisher.com* PT

PHYSICS TODAY SNAPSHOT ADS

OBITUARIES

To notify the community about a colleague's death, send us a note at http://contact.physicstoday.org. Recently posted notices will be listed here, in print. Select online obituaries will later appear in print.

Karl-Heinz Rieder

Physicist and surface scientist Karl-Heinz Rieder, referred to by colleagues as the "quiet pioneer," died in Zürich, Switzerland, on 7 March 2017 following a prolonged illness.

Born on 1 September 1942 in Eisenstadt, Austria, Karl-Heinz studied physics and mathematics at the University of Vienna. During his studies, in 1965 he was able to attend the Lindau Nobel Laureate Meeting, an annual gathering in Germany that brings together about 30 Nobelists and hundreds of young scientists. He met such luminaries as Otto Hahn, Paul Dirac, and Werner Heisenberg, who greatly influenced his career.

In 1968 Karl-Heinz obtained his doctorate at the Seibersdorf Laboratories in Austria. His thesis was on inelastic neutron scattering of microscopic crystallites, a subject he continued working on after he took a position at the Max Planck Institute for Solid State Research in Stuttgart, Germany. In 1975 he moved to the IBM Research Laboratory in Rüschlikon, Switzerland. There he and Thomas Engel developed helium scattering as a method to study surfaces. Ten years later he went to the Free University of Berlin, where he initially continued to work on elastic and inelastic helium scattering and on high-resolution electron energy-loss spectroscopy.

Subsequently, Karl-Heinz became active in low-temperature scanning tunneling microscopy; his research group was the second, after the IBM Almaden group, to manipulate individual atoms, molecules, and surfaces. He retired in 2005 yet continued to work at the Swiss Federal Laboratories for Materials Science and Technology in Dübendorf and at the Fritz Haber Institute in Berlin.

Karl-Heinz's accomplishments cover a broad range of surface science. As a result of his work, helium scattering and helium-atom microscopy have become established methods for studying surfaces down to atomic resolution. Early in his tenure at IBM, he realized the impact of the scanning tunneling microscopy technique that his colleagues Gerd Binnig and Heinrich Rohrer were developing in the late 1970s. He loaned them his single-crystal samples for the initial measurements, and he sometimes received them back as molten lumps of metal.


Karl-Heinz Rieder

Karl-Heinz might be most renowned for his later work developing methods for targeted manipulation of individual atoms and molecules at surfaces. His measurements offered insight into the fundamental physics of place-exchange processes, the associated forces, and excitation by transient attachment of electrons. In a particularly noteworthy achievement, he and his group used a scanning tunneling microscope as a nanoscale manipulator to conduct the chemical synthesis of an organic species one molecule at a time by forming a covalent bond between two surface-attached phenyl radicals. In the 1990s they studied graphene nanoribbons.

In addition, Karl-Heinz is remembered for his appreciation of the arts. For instance, a humorous poem he wrote about the surface-science community was included in the special issue of *Journal of Physics* published in his honor for his 70th birthday. A clarinet and saxophone player, he was part of several ensembles. For a while, he also focused on painting.

Karl-Heinz had a unique combination of scientific curiosity, brilliance in predicting experimental results, openheartedness, and supportiveness—always seasoned with kind humor. Those attributes enabled his research group to prosper and its members to feel appreciated and ready to tackle grand challenges. Despite his success, Karl-Heinz remained humble. His coworkers treasure the time they spent in his research group; some 20 of them are now faculty members at various research universities in Germany, the US, Austria, Switzerland, and elsewhere. The guidance Karl-Heinz gave and the example he was to them has made them better group leaders. He has achieved a lasting impact on the surface-science community in particular. He is missed most for his kindness and generosity.

Ludwig Bartels
University of California, Riverside
Saw-Wai Hla
Argonne National Laboratory
Lemont, Illinois
Ohio University
Athens
Joseph Manson
Clemson University
Clemson, South Carolina
Alexis Baratoff
University of Basel
Basel, Switzerland
Leonhard Grill
University of Graz
Graz, Austria
Karl-Heinz Ernst
University of Zürich
Zürich, Switzerland

Sheldon Schultz

Sheldon "Shelly" Schultz, a professor in the physics department at the University of California, San Diego (UCSD), who received worldwide recognition for his contributions to the discovery of metamaterials, passed away at home on 31 January 2017 from complications due to Parkinson's disease.

Born in New York City on 21 January 1933, Shelly received his undergraduate degree in mechanical engineering in 1954 from Stevens Institute of Technology. He earned his PhD in physics in 1960 from Columbia University, where he worked under the supervision of Nobel laureate Polykarp Kusch. That

OBITUARIES

year he joined UCSD as a founding member of the physics department. He was part of the UCSD faculty until 2016, and he served as the director of the university's Center for Magnetic Recording Research (CMRR) from 1990 to 2000. In addition, Shelly cofounded and was president of Seashell Technology LLC, which has made several important contributions to nanotechnology, nanomaterials, and functional coatings.

Shelly received many academic honors and awards, including an Alfred P. Sloan Research Fellowship in 1964. In 2003 CMRR endowed a graduate student annual prize named in Shelly's honor. His codiscovery of metamaterials was hailed by *Science* as one of the top 10 breakthroughs of 2003. In 2009 Thomson Reuters added Shelly to its list of potential future recipients of the Nobel Prize in Physics for the revolutionary discovery.

With his team at UCSD, Shelly in 2000 first reported the discovery of a "left-handed" or negative-refractive-index material, with which the researchers created a new class of artificially structured materials known as metamaterials. That breakthrough and the lab's first experimental demonstration of negative refraction led to an explosion of interest in the physics and application of metamaterials. The two papers detailing those foundational experiments are pillars of the metamaterials field. They initially generated considerable skepticism and controversy in the physics community, which prompted Shelly to become one of the staunchest and most eloquent defenders of the field. His dedicated efforts greatly publicized the discovery and contributed to the eventual widespread acceptance of negative refraction and metamaterials. The first publication was selected as one of only four *PRL* Milestones in 2000 by *Physical Review Letters*, and both papers have been cited thousands of times.

Shelly's research interests were broad. His most salient contributions include designing, fabricating, and range-testing highly efficient subwavelength antennas operating at 1–2 GHz; using plasmon resonant particles (PRPs) as optical transducers for biochemical and clinical medical applications; and developing PRP-based Kerr scanning near-field optical microscopy. Additionally, he used magnetic field–modulated microwave spectroscopy for sensitive detection of high-temperature superconductivity; applied conduction electron spin resonance (CESR) to probe the nature of dilute local moments, spin glasses, and superconductors; and measured Landau Fermi-liquid parameters by transmission electron spin resonance, a variant of CESR of which Shelly was particularly fond.

SPECIAL COLLECTIONS & ARCHIVES, UC SAN DIEGO

Sheldon Schultz

Shelly was an animated and inspirational lecturer, no doubt due to his lifelong penchant for showmanship (of the best kind) and his flair for the dramatic. He especially enjoyed the excitement and drama of science; he infused his lectures and talks with puzzles and demonstrations that would quickly grab the attention of his audience. Hundreds of UCSD undergraduates had the remarkable fortune of taking Shelly's freshman physics course, which showed off his delight in experimental demonstrations and his not-so-well-hidden joy in revealing the beauty of physics to young minds.

Especially noteworthy was the way Shelly celebrated the PhD defenses of his students. He and his wife, Carol, would hold PhD party "roasts" at their home, complete with a mock ceremony and a "final exam" in which the PhD student had to solve several of Shelly's physics-related brain teasers in order to "pass." A few students even managed to turn the tables on Shelly and effectively roast him in return.

During his long academic career, Shelly supervised and mentored numerous doctoral students and postdoctoral scholars. He cared deeply about the members of his research group, and his enthusiasm, leadership, and high standards brought out the best in them. He taught his doctoral students how to think physically and estimate on the spot. Within reason, they were expected to learn how to conceive, design, build, and repair experimental apparatus. Many of his PhD students have gone on to exceptional careers in research and teaching.

Shelly Schultz was an extraordinary individual, a superb scientist, and a loyal and reliable friend. He had a warm personality, a keen sense of humor, and seemingly boundless energy. He will be greatly missed.

M. Brian Maple
David C. Vier
University of California, San Diego
David R. Smith
Duke University
Durham, North Carolina
Donald M. Eigler
Wetnose Institute for
Advanced Pelagic Studies PT

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Joseph Andrew Johnson III
26 May 1940 – 25 June 2017

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26 January 1935 – 20 June 2017

Van E. Wood
25 May 1933 – 19 May 2017

Arthur H. Muir Jr
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Ernest Henley
10 June 1924 – 27 March 2017

Peter H. Rose
30 November 1924 – 23 March 2017

Haim Goldberg
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academic positions

Assistant Professor of Experimental Quantum Optics or AMO Physics (Tenure-Track)
Louisiana State University

The Department of Physics and Astronomy at Louisiana State University invites applications for a tenure-track Assistant Professor position in experimental quantum optics or atomic, molecular and optical (AMO) physics starting Fall 2018. The faculty in LSU's Quantum Science and Technology (QST) group include Thomas Corbitt, Jonathan Dowling, Hwang Lee, Ravi Rau, Georgios Veronis and Mark M. Wilde. The group carries out an active research program in quantum optics theory, as well as the quantum optics experimental activity of Corbitt. The QST group forms half of the Hearne Institute for Theoretical Physics, with the other half comprising the experimental and theoretical general relativity group, whose faculty members consist of Ivan Agullo, Thomas Corbitt, Peter Diener, Joseph Giaime, Gabriela Gonzalez, Warren Johnson, Robert O'Connell, Jorge Pullin, and Parampreet Singh. The experimental component is largely part of the LIGO Scientific Collaboration, with an extensive presence at the LIGO Livingston Observatory situated 24 miles from campus. LSU also hosts a theoretical attosecond theory group including Mette Gaarde and Ken Schafer. For the complete job announcement, full statement of qualifications and directions on how to apply, visit https://lsu.wd1.myworkdayjobs.com/LSU/job/LSU---Baton-Rouge/Assistant-Professor-of-Experimental-Quantum-Optics-or-Atomic--Molecular---Optical-Physics--Tenure-Track-_R00017436-1. *LSU is committed to diversity and is an equal opportunity/equal access employer.*

USC University of Southern California

The Department of Aerospace and Mechanical Engineering at USC is seeking applications for tenure-track or tenured faculty candidates. We seek outstanding candidates for a position at any rank. The Viterbi School of Engineering at USC is committed to increasing the diversity of its faculty and welcomes applications from women, underrepresented groups, veterans, and individuals with disabilities.

We invite applications from candidates knowledgeable in all fields of aerospace and mechanical engineering, with particular interest in advanced manufacturing and robotics, aerospace structures, energy engineering/propulsion, and physics-based computational engineering. Applications are also encouraged from more senior applicants whose accomplishments may be considered transformative. Outstanding senior applicants who have demonstrated academic excellence and leadership, and whose past activities document a commitment to issues involving the advancement of women in science and engineering may also be considered for the Lloyd Armstrong, Jr. Endowed Chair, which is supported by the Women in Science and Engineering (WiSE) Program endowment.

Applicants must have earned a Ph.D. or the equivalent in a relevant field by the beginning of the appointment and have a strong research and publication record. Applications must include a letter clearly indicating area(s) of specialization, a detailed curriculum vitae, a concise statement of current and future research directions, a teaching statement, and contact information for at least four professional references. Applicants are encouraged to include a succinct statement on fostering an environment of diversity and inclusion. This material should be submitted electronically at http://ame.usc.edu/facultypositions/. Applications should be submitted by **December 15, 2017**; any received after this date may not be considered.

USC is an equal opportunity, affirmative action employer. All qualified applicants will receive consideration for employment without regard to race, color, religion, sex, sexual orientation, gender identity, national origin, protected veteran status, disability, or any other characteristic protected by law or USC policy. USC will consider for employment all qualified applicants with criminal histories in a manner consistent with the requirements of the Los Angeles Fair Chance Initiative for Hiring ordinance.

USC Viterbi School of Engineering

Santa Clara University
Tenure-Track Assistant Professor in Experimental Physics

The Department of Physics at Santa Clara University invites applications for a new tenure-track Assistant Professor position in experimental physics beginning September 1, 2018. Our department offers distinct B.S. degrees in physics and engineering physics, and graduates about 10-15 majors each year. We seek an energetic physicist in a research area other than astronomy, astrophysics or physics education. Applicants must have a Ph.D. in experimental physics or a closely related field, as well as post-doctoral research or teaching experience. The successful candidate must have the ability to teach courses across the undergraduate physics curriculum and must demonstrate a strong commitment to establishing and sustaining an externally-fundable research program that can actively involve undergraduates. The application deadline is **November 17, 2017**. Applications should be submitted electronically as specified at: http://www.scu.edu/hr/careers/faculty.cfm. Inquiries about the position are welcome and should be directed to physics@scu.edu. *Santa Clara University, a Jesuit Catholic institution in the heart of Silicon Valley, is an Equal Opportunity / Affirmative Action employer. Women, people of color and other members of underrepresented groups in physics are particularly encouraged to apply.*

Assistant or Associate Professor in Experimental Condensed Matter Physics
Georgia State University

The Department of Physics and Astronomy at Georgia State University (GSU) is recruiting an experimental condensed matter physicist for fall 2018 in research areas that complement current departmental strengths. The position is at the assistant professor level, although a hire at the associate professor level can be considered for a candidate with an outstanding track record of scientific research and funding. With a commitment to excellence in teaching, the new departmental hire will develop an independent externally funded research program, work closely with existing faculty members on collaborative research, and help develop research proposals in departmental focus areas that include nanoplasmonics, nanophotonics, nanobiophysics, spintronics, ultrafast optics, 2D materials, materials growth, and device/detector development. More information on the department and its research can be found at http://phy-astr.gsu.edu. Information on GSU's Center for Nano-Optics (CeNO) can be found at http://nanooptics.gsu.edu. Applicants should have a Ph.D. in physics or a closely related field and postdoctoral research experience. Applications should include 1) a curriculum vitae with a publication list, 2) a statement of research interests describing how the proposed research will complement existing research efforts, 3) a statement of teaching philosophy and experience, and 4) contact information for at least three references. All materials should be sent via email to PhySearch@phy-astr.gsu.edu. Questions regarding the position can be addressed to **Dr. Unil Perera, Chair of the Search Committee**, at uperera@gsu.edu. Applications received by **December 1, 2017**, will receive full consideration. *An offer of employment will be conditional on background verification. Georgia State University is an Equal Opportunity Employer and does not discriminate against applicants due to race, ethnicity, gender, veteran status, or on the basis of disability or any other federal, state or local protected class.*

Postdoctoral Fellowship Positions in Artificial Intelligence in Medicine

Multiple postdoctoral positions are immediately available in the Medical Artificial Intelligence and Automation (MAIA) Lab at the **University of Texas Southwestern Medical Center** (**UTSW**). We are looking for highly motivated Ph.D. graduates in the fields of physics or other engineering and physical sciences with experience in deep learning who are interested in pursuing a career in developing and applying AI techniques in solving important medical problems. Demonstrated research experience and publication record are necessary. Successful candidates should have programming skills in Python, Java or C++. A strong interest in collaborative and interdisciplinary research is required. Initial appointment is full time for one year with renewable appointments subsequent years. Interested individuals should send a CV, statement of interests, and three references to **Gabrielle Hawthorne, UT Southwestern Medical Center, 5323 Harry Hines Blvd., Dallas, TX 75390-9303**, Gabrielle.Hawthorne@UTSouthwestern.edu.

Samuel P. Langley PITT PACC Fellow University of Pittsburgh

The Pittsburgh Particle physics, Astrophysics and Cosmology Center (PITT PACC, www.physicsandastronomy.pitt.edu/pittpacc) at the University of Pittsburgh invites applications for a named senior postdoctoral research fellow in theoretical and experimental particle physics starting in the fall of 2018. The appointment is initially for two years with the possibility of extension for a third year. The successful candidate must have a PhD degree and strong research credentials. Interested candidates should apply online at **AcademicJobOnline** (preferred), or email a cover letter, CV, and three reference letters to **Cindy Cercone** (cmc138@pitt.edu) by **December 15, 2017**. *The University of Pittsburgh is an Affirmative Action/Equal Opportunity Employer and values equality of opportunity, human dignity and diversity. EEO/AA/M/F/Vets/Disabled.*

Tenure Track Faculty Position in Astrophysics

The Department of Astronomy at **Boston University** invites applications for a tenure track Assistant Professor position to begin on July 1, 2018. The successful candidate will be an early-career astrophysicist who will lead a robust research program and participate fully in the department's teaching mission. Minimum qualifications include a PhD, with postdoctoral experience expected in Astronomy, Physics, or related field. Applications from all areas of astrophysics will be considered. Applications from astrophysicists with strong research programs in the following areas are particularly encouraged: star-planet interactions in exoplanet systems; early galaxies; the interstellar medium; and "big data" applications to astrophysics. In addition to this position, the Department of Astronomy expects to search for several additional faculty members over the next five years. Information about the department and its affiliated research centers can be found at http://www.bu.edu/astronomy/. Applications should be submitted at https://academicjobsonline.org/ajo/jobs/10120 . Complete applications should include a cover letter, curriculum vitae, and brief statements of teaching interests (no more than 1 page) and research interests (no more than 2 pages). Candidates should also arrange for three confidential letters of reference to be submitted through the same website. Review of applications will begin on **December 15, 2017** and will continue until the position is filled. Inquiries may be directed to **Ms Anne Smartvlasak** (asmart@bu.edu), Department of Astronomy. *Boston University is an equal opportunity employer and all qualified applicants will receive consideration for employment without regard to race, color, religion, sex, national origin, disability status, protected veteran status, or any other characteristic protected by law. Boston University is committed to building a culturally, racially, and ethnically diverse scholarly community. Applications from women and underrepresented minorities are strongly encouraged. Boston University is a VEVRAA Federal Contractor.*

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You have an MSc in Physics, you are highly motivated and looking for the perfect **PhD position**? Join the high-qualified European Training Network **Quantum Electronics Science & Technology** (QuESTech)! The main topics include **molecular electronics, single electronics, quantum thermodynamics, spintronics** and **transport in low-dimensional structures**. You will get an all-round training in one of the participating universities (Grenoble, Leeds, Göteborg, Konstanz, Zürich, San Sebastian, Helsinki) & companies (Raith Dortmund, Graphenea San Sebastian). You will enroll into a regular PhD program, participate in one ESONN session and undertake a secondment in a complementary sector. You will receive training in scientific presentation, writing, communication, and entrepreneurial skills to be fully prepared for a successful scientific career. The contract is for 36 months, the salary attractive. The recruitment is gender-balanced. European mobility rules apply. Deadline first recruitment campaign **December 15, 2017**. Interested? Visit our website www.questech.org.

The Hadronic Nuclear Physics Group at Florida State University invites applications for a **postdoctoral researcher** to work on the GlueX experiment at Jefferson Lab. More information on the research group can be found at http://hadron.physics.fsu. The GlueX experiment (http://gluex.org) has begun a multi-year data-taking program, and we seek a candidate to be based at Jefferson Lab with a strong interest in the GlueX physics program to lead physics analyses of this data. Applications including a cover letter, a curriculum vitae, a brief statement of research experience and interests, and three letters of recommendation, or any questions should be sent to **Prof. Sean Dobbs** (sdobbs@fsu.edu). Review of applications will begin **October 31, 2017** and will continue until the position is filled.

Assistant Professor in Theoretical and/or Computational Physics
Grand Valley State University

The Department of Physics at Grand Valley State University invites applications for a tenure-track Assistant Professor position beginning August 6, 2018 in Theoretical and/or Computational Physics. Any area that will strengthen existing and/or broaden research activities in the department will be considered. Candidates must have their Ph.D. in physics or closely related field in August 2018. The department is seeking to fill this faculty position with a strong preference for those in the fields of Theoretical and Computational Physics, but exceptional candidates in other areas will be considered. They will have a demonstrated commitment to excellent undergraduate education, a clear plan for an active research program involving undergraduate physics majors, and should expect to participate in the service needs of the department. Applicants should apply online at jobs.gvsu.org. They should submit the following online: cover letter, curriculum vitae, 1-2 page statement of teaching philosophy and experience, 1-2 page statement of research/scholarly plans involving undergraduates, and three letters of recommendation. Review of applications will begin **November 10, 2017** and will continue until the position is filled. *Grand Valley State University is an EOE which includes protected veterans and individuals with disabilities (consult* http://www.gvsu.edu/affirmative *for more information).*

EPFL ÉCOLE POLYTECHNIQUE FÉDÉRALE DE LAUSANNE

Faculty Position in Experimental High-Energy Physics

at the Ecole polytechnique fédérale de Lausanne (EPFL)

The School of Basic Sciences of the Ecole Polytechnique Fédérale de Lausanne (EPFL) seeks to appoint a tenure-track assistant professor of experimental high-energy physics in the Institute of Physics.

The Laboratory for High-Energy Physics is strongly involved in the LHCb experiment at CERN's Large Hadron Collider from the time of its conception, and is currently making a major contribution to the detector upgrade, with a view to enhance data-taking capability to extend the science reach from 2021 onwards. The position offers the opportunity to capitalize on this investment while also developing ideas for the longer-term future, in an environment providing strong technical support in detector development.

A PhD degree in particle physics as well as a strong and growing track record in research and scientific leadership are required. The appointed professor is expected to initiate a creative experimental program, and engage in physics teaching at undergraduate and graduate levels.

Significant start-up resources, research budget and state-of-the-art research infrastructure are available. Salaries and benefits are internationally competitive.

Applications should include a motivation letter, a curriculum vitae with a list of research outputs, a statement of research (max. 3 pages) and teaching interests (max. 1 page), as well as the names and addresses (including e-mail) of at least three references.

Application files should be submitted in PDF format and uploaded by **December 15th, 2017** to

https://facultyrecruiting.epfl.ch/position/6848513

Enquiries may be addressed to:

Prof. Harald Brune
Chairman of the Search Committee
E-mail: iphysdirector@epfl.ch

For additional information, please consult www.epfl.ch, sb.epfl.ch, iphys.epfl.ch

EPFL is committed to increasing the diversity of its faculty, and strongly encourages women to apply.

Faculty Position in Biophysics
Physics Department
College of Sciences and Mathematics
Auburn University

Biophysics is a new research emphasis within the College of Sciences and Mathematics and is the basis of a developing partnership between Biological Sciences and Physics. As part of this partnership, the Department of Biological Sciences hired two tenure-track biophysicists in 2017. This is an announcement for a tenure-track biophysics faculty position in the Physics Department. The Physics Department at Auburn University is seeking a highly qualified individual for a tenure-track faculty position in the area of biophysics; candidates at all faculty ranks (i.e., Assistant, Associate and Full Professor) will be considered. Applications from both experimental and theoretical/computational physicists are encouraged. Research subspecialties within biophysics that are of interest include (but are not restricted to) soft matter and biological materials, statistical physics of living systems, complexity in biological systems, modeling of cellular processes from molecular to intracellular processes, and the interface between biological and physical systems. Post-doctoral research experience is highly desirable. The successful candidate will be expected to: (1) demonstrate strong leadership potential in the area of biophysics, (2) establish a new research group in the area of biophysics at Auburn University, (3) provide direction to undergraduate, graduate students and post-doctoral researchers in biophysics, and (4) conduct excellent instruction at the undergraduate and graduate level in the Physics curriculum. Applicants must possess a Ph.D. or equivalent degree in Physics or a closely related field. Excellent written and interpersonal communication skills are required. Candidates must apply online at: http://aufacultypositions.peopleadmin.com/postings/2437. Applications need to include a cover letter, curriculum vitae, statement of teaching philosophy, statement of research and the names and contact information for three professional references. More information about the department can be found at: http://www.physics.auburn.edu. The review of applications will begin on **December 1, 2017** and will continue until the position is filled. The desired starting date is August 16, 2018. *The candidate selected for this position must be able to meet eligibility requirements to work in the United States at the time the appointment is scheduled to begin and continue working legally for the proposed term of employment. Auburn University is an EEO/Vet/Disability Employer.*

Assistant Professor in Experimental Soft Matter or Biological Physics

The Department of Physics at **Brandeis University** invites applications for the position of tenure-track Assistant Professor beginning in the fall of 2018 in the interdisciplinary areas of biophysics, soft condensed matter physics and biologically inspired material science. We seek candidates interested in broad collaborations with a vision towards integrated sciences in which physics overlaps with other disciplines. Candidates are expected to contribute to undergraduate and graduate teaching programs while engaging in forefront research. Brandeis University offers a unique opportunity to participate in diverse interdisciplinary programs such as the NSF funded Materials Research Science and Engineering Center (MRSEC) focused on biologically inspired materials and a NIH supported training program in Quantitative Biology. Review of applications will begin on **December 15, 2017**, and will continue until the position is filled. Applicants should submit a detailed curriculum vitae, a statement of teaching interests, a research plan, and arrange to have three letters of reference submitted to **AcademicJobsOnline** at https://academicjobsonline.org/ajo/jobs/9873. A research-intensive liberal arts university, Brandeis fosters highly collaborative science both within and between departments and is currently conducting multiple searches that will strengthen cross-disciplinary studies across the sciences. The suburban campus in Waltham, MA is close to the academic and biotechnology centers of Boston and Cambridge. *Brandeis University is an equal opportunity employer, committed to building a culturally diverse intellectual community, and strongly encourages applications from women and minorities. Diversity in its student body, staff and faculty is important to Brandeis' primary mission of providing a quality education. The search committee is therefore particularly interested in candidates who, through their creative endeavors, teaching and/or service experiences, will increase Brandeis' reputation for academic excellence and better prepare its students for a pluralistic society.*

The Hong Kong University of Science and Technology
Department of Physics
Tenure-track Faculty Positions

The Department of Physics invites applications for tenure-track faculty positions at the Assistant Professor level in both theoretical and experimental physics, with specialty in any area of particle physics, cosmology, or string theory. Appointments at the rank of Associate Professor or above will be considered for candidates with an exceptional record of research excellence and academic leadership. The current faculty at The Hong Kong University of Science and Technology in particle physics and cosmology include Professor Andy Cohen, Professor George Smoot, Professor Henry Tye, Dr Tao Liu, and Dr Yi Wang. The department is growing its effort in particle physics and cosmology by hiring five new faculty in theory and experiment. Further information about the Department can be found at http://physics.ust.hk. Applicants must possess a PhD degree in physics or a related field. The successful candidate should have a strong track record of research in high energy physics and/or cosmology. In addition to pursuing a vibrant research program the candidates are is expected to engage in effective teaching at the undergraduate and graduate levels. Starting salary will be highly competitive and commensurate with qualifications and experience. Fringe benefits including medical and dental benefits, annual leave and housing benefits will be provided where applicable. Benefits including annual leave and medical/dental benefits will be provided. Housing benefits will also be provided where applicable. A contract-end gratuity will be payable upon successful completion of contract. **Application Procedure:** Applicants should submit their curriculum vitae, together with a cover letter, a list of publications, a brief statement of current interests, a plan for future research program, and three reference letters, via **AcademicJobsOnline.Org** at https://academicjobsonline.org/ajo/jobs/5236. **Please quote reference number "PHYS1017" in your application materials.** Screening of applications will begin as soon as possible, and will continue until the positions are filled.

TENURE TRACK ASSISTANT PROFESSOR IN EXPERIMENTAL BIOPHYSICS and RELATED AREAS

The Physics and Astronomy Department at **California State Polytechnic University, Pomona** invites applications for a tenure-track Assistant Professor in experimental biophysics, broadly construed including biophotonics, biomaterials, and closely-related areas of material science and condensed matter physics, to begin in August 2018. The successful candidate will be expected to teach both introductory and advanced undergraduate courses in physics, as well as engage in publishable research involving undergraduate students. Applicants must obtain a Ph.D. in Physics, Biophysics, or a closely-related field by August 2018. Previous college teaching experience (at least at the teaching assistant level) and the ability to establish an independent research program are required. The successful candidates will be expected to contribute to the diversity and excellence of the academic community through research, teaching and/or service, and be committed to teaching and working in a multicultural environment. The application deadline is **November 27, 2017**. For a full position description, as well as the application procedure, please visit the Department web site at http://www.cpp.edu/~sci/physics-astronomy/ and https://www.cpp.edu/~sci/physics-astronomy/news-events/tenure-track-biophysics.shtml. *EOE/Minorities/Females/Vet/Disability.*

The University of Virginia's Department of Physics in the College and Graduate School of Arts & Sciences invites applications for a **tenure-track Assistant Professor position in Experimental Atomic, Molecular, and Optical Physics**, broadly defined. The anticipated appointment start date is July 25, 2018. Applicants must have earned a Ph.D. in physics or a related field by the start date of the appointment. The successful candidate must have a record of research excellence, and is expected to: establish and maintain a high-quality, externally funded, experimental research program; be effective in classroom teaching and research mentoring at the undergraduate and graduate levels; and provide service to the Department, University and professional organizations. Review of applications will begin **December 1, 2017**. To apply, candidates must submit a Candidate Profile through **Jobs@UVa** (https://jobs.virginia.edu , search on posting number **0621444**) and electronically attach the following: a curriculum vitae, contact information for at least three references, and a cover letter which includes a proposed research plan and teaching statement. Candidates should have their references email letters directly to Phys-AMO-Exp-pos@Virginia.EDU. Questions regarding the application process in **Jobs@UVa** should be directed to: **Tammie Shifflett, 434-924-6565,** tms4t@Virginia.EDU. The University will perform background checks on all new faculty hires prior to making a final offer of employment. The University of Virginia assists UVA faculty spouses and partners seeking employment in the Charlottesville area. To learn more about these services, please see http://provost.virginia.edu/dual-career. *The University of Virginia is an equal opportunity and affirmative action employer. Women, minorities, veterans, and persons with disabilities are encouraged to apply.*

Assistant, Associate or Full Professor in Quantum Information Physics
University of Oregon

The University of Oregon's Physics Department invites applications for a tenure-track faculty position to begin in fall 2018. We seek candidates who are AMO (atomic, molecular and optical) physics experimentalists in quantum information science/quantum physics, with preference for those working with atomic systems, ions or neutrals. Competitive applicants will be capable of outstanding research and teaching at the graduate and undergraduate levels. While the expectation is to fill the position at the rank of Assistant or Associate Professor, we will also consider exceptional applications from more senior applicants. Minimum Requirements: Ph.D. in Physics or related field in hand by time of appointment. Salary is competitive. Candidates are asked to apply online by completing the online application on the UO Careers website at **http://careers.uoregon.edu, job #520982**, including submitting a letter of application, a curriculum vitae, a statement of research interests and future research plans, and provide the names and contact information for three professional references by **November 15, 2017**, or until the position has been filled. Applicants should also arrange to have a minimum of three letters of reference sent to the Search Committee at amosearch@uoregon.edu no later than **November 15, 2017**. If you are unable to use this online application, please contact amosearch@uoregon.edu to arrange alternate means of submitting application materials. *The University of Oregon is dedicated to the goal of building a culturally diverse and pluralistic faculty committed to teaching and working in a multicultural environment and strongly encourages applications from minorities, women, and people with disabilities. Applicants are encouraged to include in their cover letter information about how they will further this goal.*

The Hong Kong University of Science and Technology
Department of Physics
Tenure-track Faculty Position

The Department of Physics invites applications for a tenure-track faculty position at the Assistant Professor level. Appointment at the rank of Rank at Associate Professor or above will also be considered for candidates with exceptional record of research excellence and academic leadership. Applicants must possess a PhD degree in physics or related fields and have evidence of strong research productivity. We seek **experimentalists in the area of condensed matter physics. Preference will be given to candidates specialized in the field of low dimensional materials, materials with strong electronic correlations, as well as novel wavefunctional materials for manipulating light and sound. Experience in sample/material growth or fabrication is a plus.** The appointee is are expected to assume teaching responsibilities for undergraduate and graduate courses, and to conduct vigorousresearch programs. Further information about the Department is available at http://physics.ust.hk. Starting salary will be commensurate with qualifications and experience. Fringe benefits including medical and dental benefits, annual leave and housing will be provided where applicable. Initial appointment will normally be on a three-year contract. A gratuity will be payable upon successful completion of contract. **Application Procedure:** Applicants should submit their curriculum vitae, together with a cover letter, a list of publications, a brief statement of current interests, a plan for future research program, and three reference letters, via **AcademicJobsOnline.Org** at https://academicjobsonline.org/ajo/jobs/6695. **Please quote reference number "PHYS2509" in your application materials.** Screening of applications will begin as soon as possible, and will continue until the position is filled.

MATERIALS SCIENCE AND ENGINEERING - Faculty Positions - Open Rank

University of Illinois at Urbana-Champaign

The Department of Materials Science and Engineering (MSE) at the University of Illinois at Urbana-Champaign (UIUC) is seeking to fill multiple tenured or tenure track faculty positions in all ranks. Candidates with research interest in the broad areas of materials science and engineering, materials physics, materials chemistry or biomaterials are welcome to apply. Successful applicants are expected to initiate and sustain a vigorous research program and have strong commitment to undergraduate and graduate teaching. Please visit the website http://www.matse.illinois.edu/about/openings.html to view the complete position announcement and application instructions.

Applications received prior to December 1, 2017 will receive full consideration.

The University of Illinois conducts criminal background checks on all job candidates upon acceptance of a contingent offer.

Illinois is an EEO Employer/Vet/Disabled – www.inclusiveillinois.illinois.edu and committed to a family-friendly environment (http://provost.illinois.edu/worklife/index.html).

ILLINOIS
UNIVERSITY OF ILLINOIS AT URBANA-CHAMPAIGN

Superintendent, Chemistry Division

www.nrl.navy.mil

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*Actual salary may vary depending on the scope and complexity of the position and the qualifications and current compensation of the selectee.

Become a member of an elite research and development community involved in basic and applied scientific research and advanced technological development for tomorrow's Navy and for the Nation

The Chemistry Division located at the Naval Research Laboratory (NRL) in Washington, DC. The Division's mission is to conduct a program of basic research, applied research, development, and evaluation, leading to the creation, adoption, and application of new concepts, principles, methods, and techniques in the various areas of chemistry, including chemical physics, chemical engineering, surface science, nanoscience and nanotechnology. The Division is comprised of five branches; the Chemical Dynamics and Diagnostics Branch, the Materials Chemistry Branch, the Center for Corrosion Science and Engineering, the Surface Chemistry Branch, and the Navy Technology Center for Safety and Survivability. The Division has 113 civilian employees and operates an annual budget of $100M and substantially influences an additional $600M. The Superintendent manages, directs, and administers a recognized scientific work force conducting a broad spectrum research program in the various areas of chemistry including chemical physics, chemical engineering, surface chemistry, nanoscience and nanotechnology. The Superintendent executive direction and technical visionary leadership in development of programs, policies, and objectives necessary in conducting a program of research, development, and evaluation leading to creation, adoption and application of improved and new concepts, principles, methods, and techniques applicable to understanding and observing in a chemical environment. The Superintendent is the principal consultant to the Navy, other agencies and nations on the science and developing applications for the R&D programs under his/her cognizance.

Applicants should be recognized as national/international authorities and should have planned and executed difficult programs of national significance or specialized programs that show outstanding attainment in their field of research.

For qualification requirements and specific instructions on how to apply, go to **www.usajobs.gov**, from **30 October 2017** through **28 November 2017** and enter the following announcement number: **DE-10058935-18-JS**. Please carefully read the announcement and follow instructions when applying. The announcement closes **28 November 2017**. Please contact Lesley Renfro at **lesley.renfro@nrl.navy.mil** for more information. E-mailed resumes cannot be accepted.

NRL is an Equal Opportunity Employer.

NRL, 4555 Overlook Ave SW, Washington DC 20375.

Faculty and Postdoctoral Positions

INTERNATIONAL CENTER FOR QUANTUM MATERIALS
PEKING UNIVERSITY, CHINA

北京大学

The International Center for Quantum Materials (ICQM, http://icqm.pku.edu.cn/), Peking University, China, invites applications for tenured/tenure-track faculty positions and postdoctoral positions in the fields of experimental and theoretical condensed matter physics; atomic, molecular, and optical (AMO) physics; solid-state based quantum information science (QIS); material physics and related areas. Established in 2010, ICQM has attracted both internationally-renowned scientists and excellent young researchers from diverse areas of condensed matter, material physics, AMO, and QIS, and enabled them to work together productively. In 2015 the center has successfully completed its first 5-year international peer review. During the next phase of enhancement, the center has 12 faculty lines (tenured and tenure-track faculty members) and an unlimited number of postdoctoral positions open for applications.

Positions and Qualifications

We are seeking exceptional candidates for all levels of faculty positions, including distinguished chair professors, tenured full/associate professors, as well as tenure-track assistant professors. Candidates should have a Ph. D in a relevant discipline, an outstanding record of research accomplishments, and the capability to lead an independent research group. The position offered will be commensurate with individual's work experience and research track-record. In particular, candidates applying for position of distinguished chair are expected to be internationally influential in a relevant discipline.

We are also seeking qualified candidates for postdoctoral positions. Candidates should have a Ph. D in a relevant discipline or expect a Ph. D within a year, with a substantive record of research accomplishments, and the ability to work collaboratively with faculty members in the center. The research directions and information of prospective advisors can be found in our website http://icqm.pku.edu.cn/index.html.

Salary and Benefits

All newly hired faculty members will be offered competitive startup resources and office/lab spaces. Annual salaries for faculty positions are competitive with US research universities, for distinguished chair professors are to be separately negotiated in each case. Peking University provides employee benefits package.

Postdoctoral fellows will be provided an annual stipend up to 250K RMB (equivalent to US $37,000), based on individual's experience and research performance. Housing subsidies will also be provided.

To Apply:

Applicants for a faculty position should send full curriculum vitae; copies of 3-5 key publications; three letters of recommendation; and a statement of research to **Professor Rui-Rui Du** at ICQM@pku.edu.cn. Application for a postdoctoral position should be directly addressed to an individual prospective advisor.

BROWN UNIVERSITY
FACULTY POSITION
IN
THEORETICAL CONDENSED MATTER PHYSICS

The Department of Physics at Brown University invites applications for a tenure-track Assistant Professor position in Quantum Condensed Matter Theory, starting in the summer of 2018. This position is part of an initiative for further growth in interdisciplinary condensed matter research at Brown University, including a concurrent search in condensed matter experiment. We seek candidates who have the potential to create a vigorous and sustainable research program at Brown. A strong commitment to teaching at the undergraduate and graduate levels is also required. Current research in quantum condensed matter physics at Brown is very active across many topics, including topological matter, strongly correlated electronic systems, spintronics, quantum liquids and solids, superconductivity, nanoscale physics, semiconductor physics and devices, and magnetism. Application materials including a curriculum vitae, a statement of research and teaching plans, and three letters of recommendation should be submitted electronically to http://apply.interfolio.com/45161. Inquiries about this position should be directed to Search_CMT@brown.edu or to **Prof. Dima Feldman, Chair of Condensed Matter Theory Search Committee, Department of Physics, 182 Hope Street, Box 1843, Brown University, Providence, Rhode Island 02912.** Applications received by **December 1, 2017** will receive full consideration. *Brown University is committed to fostering a diverse and inclusive academic global community; as an EEO/AA employer, Brown considers applicants for employment without regard to, and does not discriminate on the basis of, gender, race, protected veteran status, disability, or any other legally protected status.*

BROWN UNIVERSITY
FACULTY POSITION
IN
EXPERIMENTAL CONDENSED MATTER PHYSICS

The Department of Physics at Brown University invites applications for a tenure-track Assistant Professor position in Experimental Condensed Matter Physics, starting in the summer of 2018. This position is part of an ongoing initiative for further growth in interdisciplinary quantum condensed matter research at Brown University, including the upgraded clean-room microfabrication and electron microscopy facilities in the new School of Engineering building adjacent to the Physics Department and a concurrent search in condensed matter theory. We seek candidates who have the potential to create a vigorous research program at Brown. A strong commitment to teaching at the undergraduate and graduate levels is also required. Current research in condensed matter physics at Brown is very active across many topics, including topological matter, strongly correlated electronic systems, spintronics, quantum liquids and solids, superconductivity, nanoscale physics, ultrafast and quantum optics, semiconductor physics and devices, and magnetism. Candidates planning to pursue other condensed matter sub-fields are also strongly encouraged to apply. Application materials including curriculum vitae, a statement of research and teaching plans, and three letters of recommendation should be submitted electronically to http://apply.interfolio.com/45163. Inquiries about this position should be directed to Search_CME@brown.edu or to **Prof. Vesna Mitrovic, Chair of Condensed Matter Physics Search Committee, Department of Physics, 182 Hope Street, Box 1843, Brown University, Providence, Rhode Island 02912.** Applications received by **December 1,2017** will receive full consideration. *Brown University is committed to fostering a diverse and inclusive academic global community; as an EEO/AA employer, Brown considers applicants for employment without regard to, and does not discriminate on the basis of, gender, race, protected veteran status, disability, or any other legally protected status.*

Leon N Cooper Postdoctoral Fellowship at Brown University

The Department of Physics at Brown University is inviting applications for the Leon N Cooper Postdoctoral Fellowship. This prestigious fellowship will be given to an outstanding physicist with an opportunity to work at Brown for two years with the possibility of an extension (http://www.brown.edu/academics/physics/research). Applicants from all physics research fields, both experimental and theoretical, conducted at Brown are encouraged. This includes Astrophysics & Cosmology, Biological Physics, Condensed Matter, Elementary Particle Experiment, High Energy Theory, and Brain/Neural Systems. A competitive annual stipend will be offered along with research and travel funds. Application materials including a CV, statement of research plans, and three letters of recommendation should be submitted electronically to http://apply.interfolio.com/45510. Inquiries about this position should be directed to LNC-search@brown.edu or to **Prof. Richard Gaitskell, Chair of the Leon N Cooper Fellowship Committee, Department of Physics, Box 1843, Brown University, Providence, Rhode Island 02912.** Applications received by **November 30, 2017** will receive full consideration. *Women and minorities are strongly encouraged to apply. Brown University is committed to fostering a diverse and inclusive academic global community as an EEO/AA employer. Brown considers applicants for employment without regard to, and does not discriminate on the basis of gender, race, protected veteran status, disability, or any other legally protected status.*

Faculty Positions
Center for Condensed Matter Sciences
National Taiwan University

Center for Condensed Matter Sciences, as a premiere research center at National Taiwan University, has immediate openings for tenure-track faculty positions. Rank of faculty positions will match the candidate qualifications. Applicants with excellent credentials in cutting edge condensed matter research fields, such as emerging materials or advanced spectroscopic and microscopic techniques, in both fundamental and applied aspects, will be considered. Applicants should send resume, publication list, research plans and three letters of recommendation to: **Director, Prof. Li-Chyong Chen, Center for Condensed Matter Sciences, National Taiwan University, Taipei 106, Taiwan, Center Assistant: Wei-Lin Chou, Email: cwli1828@ntu.edu.tw, Phone: (02) 3366-5201, Fax: (02) 2365-5404.** Closing date for applications is **Nov. 30, 2017.**

Assistant Professor in Theoretical Astro-Particle Physics/Cosmology
Rice University

The Department of Physics and Astronomy at Rice University in Houston, Texas, invites applications for a tenure-track faculty position (Assistant Professor level) in Theoretical Astro-Particle physics and/or Cosmology. The department seeks an outstanding individual whose research will complement and connect existing activities in Nuclear/Particle physics and Astrophysics groups at Rice University (see http://physics.rice.edu). This is the second position in a Cosmic Frontier effort that may eventually grow to three members. The successful applicant will be expected to develop an independent and vigorous research program, and teach graduate and undergraduate courses. A PhD in Physics, Astrophysics or related field is required. Applicants should send the following: (i) cover letter; (ii) curriculum vitae (including electronic links to 2 relevant publications); (iii) research statement (4 pages or less); (iv) teaching statement (2 pages or less); and (v) the names, professional affiliations, and email addresses of three references. To apply, please visit: https://jobs.rice.edu/postings/11772 Complete applications will be accepted until the position is filled, but only those received by **Dec 15, 2017** will be assured full consideration. The appointment is expected to start in July 2018. Further inquiries should be directed to the chair of the search committee, **Prof. Paul Padley** (padley@rice.edu). *Rice University is an Equal Opportunity Employer with commitment to diversity at all levels, and considers for employment qualified applicants without regard to race, color, religion, age, sex, sexual orientation, gender identity, national or ethnic origin, genetic information, disability or protected veteran status.*

Assistant Professor in Experimental Condensed Matter Physics
Rice University

The Department of Physics and Astronomy at Rice University in Houston, TX invites applications for a tenure-track faculty position in experimental condensed matter physics. The department expects to make an appointment at the assistant professor level. This search seeks an outstanding individual whose research interest is in hard condensed matter systems, who will complement and extend existing experimental and theoretical activities in condensed matter physics on semiconductor and nanoscale structures, strongly correlated systems, topological matter, and related quantum materials (see http://physics.rice.edu/). A PhD in physics or related field is required. Applicants to this search should submit the following: (1) cover letter; (2) curriculum vitae; (3) research statement; (4) teaching statement; and (5) the names, professional affiliations, and email addresses of three references. For full details and to apply, please visit: http://jobs.rice.edu/postings/11782. Applications will be accepted until the position is filled. The review of applications will begin **October 15 2017**, but all those received by **December 1, 2017** will be assured full consideration. The appointment is expected to start in July 2018. Further inquiries should be directed to the chair of the search committee, **Prof. Emilia Morosan** (emorosan@rice.edu). *Rice University is an Equal Opportunity Employer with commitment to diversity at all levels, and considers for employment qualified applicants without regard to race, color, religion, age, sex, sexual orientation, gender identity, national or ethnic origin, genetic information, disability or protected veteran status.*

Department of Civil and Environmental Engineering
Open Rank Faculty Positions
College of Engineering
University of Illinois at Urbana-Champaign

The Department of Civil and Environmental Engineering (CEE) at the University of Illinois at Urbana-Champaign invites applications for multiple full-time tenured or tenure-track faculty positions; all ranks will be considered. The Department seeks to expand its expertise in emerging interdisciplinary areas that are critical in addressing global challenges through innovative education and research. Desired areas of expertise for the positions are: Optimization and Life-Cycle Performance for Large-Scale Structural Systems; Geoengineering for Sustainable Urban and Off-Shore Development; Synthetic Biology for Environmental Solutions; Emerging Construction Materials for Buildings and Pavements; and Sustainable and Smart Infrastructure and Multimodal Transportation. Information about the Department may be found at: http://cee.illinois.edu. Please visit https://jobs.illinois.edu/ to view the complete position announcement and application instructions. Full consideration will be given to applications received by **November 24, 2017**. Applications received after that *date may be considered until the positions are filled. The University of Illinois conducts criminal background checks on all job candidates upon acceptance of a contingent offer. Illinois is an EEO Employer/Vet/Disabled -* http://www.inclusiveillinois.illinois.edu *and committed to a family-friendly environment:* http://provost.illinois.edu/faculty-affairs/work-life-balance/.

Faculty Position
Experimental Atomic/Molecular/Optical Physics
Columbia University

The Department of Physics at Columbia University seeks to appoint an assistant professor in the area of experimental atomic, molecular and optical physics, quantum optics, low-energy precision measurement or a related field starting on July 1, 2018. It is expected that the candidate will develop a vigorous independent research program, continuing the long Columbia record of forefront accomplishment in science. Applicants must possess a doctoral degree in Physics or a related field and have demonstrated the ability to do pioneering experimental research as well as the promise of excellence in teaching and mentoring at both the undergraduate and graduate levels. Candidates should submit with their application a cover letter, Curriculum Vitae (including a publication list), and brief statements of research plans and teaching philosophy. Candidates should arrange for three letters of recommendation to be sent on their behalf. Please visit our online application site for further information about this position and to submit your application. https://academicjobs.columbia.edu/applicants/Central?quickFind=65284. Review of applications and scheduling of interviews will begin on **December 1, 2017** and will continue until the position is filled. *Columbia University is an Equal Opportunity / Affirmative Action employer, and is committed to a working and learning environment supportive of its faculty and staff in their pursuit of a productive and fulfilling professional and personal life.*

Faculty Positions in Institute for Advanced Study Soochow University, China

苏州大学高等研究院
Institute for Advanced Study
Soochow University

About IASSU

The Institute for Advanced Study of Soochow University (IASSU) is a newly founded research center dedicated to fostering collaborative research between physicists, biologists, medical scientists, engineers, and material scientists. The 2016 Nobel Laureate in Physics, Prof. John Michael Kosterlitz, is the honorable director of the IASSU. IASSU plans to build two major research groups, a complex matter group working in the areas of nonequilibrium statistical mechanics and physical biology, and a quantum matter group working in the areas of exotic quantum properties of electrons in solids. The center has a total of 20 permanent faculty positions (tenured and tenure track faculty members, including 10 Principal Investigators) open for applications.

Positions and Qualifications

In 2018, we are seeking at least 4 PIs (2 in complex matter group and 2 in quantum matter group). Candidates should hold a doctorate degree and have a proven record of high quality research at an international level. They will be expected to lead a research group with students, postdoctoral fellows and research assistant professors. Exceptional candidates winning ``Thousand Talents Program for Distinguished Young Scholars" can be considered for full professorship with tenure.

Salary and Benefits

The salary and benefit are internationally competitive. For regular positions, annual salary of 350K RMB (1 US $=6.5 RMB), start-up funds of 2M RMB, and relocation cost allowance ranging from1.5M to 2.5M RMB are offered. The university also provides the assistance for children school enrollment. For distinguished professors, the salary and benefits are negotiable.

To Apply:

Applicants should send full curriculum vitae; a statement of research interest and a research plan (in 4 pages or less), copies of 3-5 key papers (in pdf) and three letters of recommendation (in pdf) to the **Director of IASSU, Professor Xinsheng Sean Ling**, at xsling@suda.edu.cn. Further inquiries of the positions can also be sent to:

Professor Xinsheng Sean Ling
Institute for Advanced Study (IASSU)
Soochow University
Suzhou, China
E-mails: xsling@suda.edu.cn

Penn Engineering

FACULTY POSITIONS
Materials Science and Engineering
University of Pennsylvania

The School of Engineering and Applied Science at the University of Pennsylvania initiated a period of significant growth in 2015 that has resulted in 30 new faculty hires of which four are in the Department of Materials Science and Engineering. The department is continuing this aggressive, multi-year hiring effort by seeking a tenure-track assistant professor. Exceptional applicants for tenured associate and full professor positions may also be considered.

Applicants from all materials-related research areas are invited to apply, especially those with expertise in (1) materials for health sciences, (2) electronic materials, and (3) structural materials. Additional descriptions of these research areas and the Penn Engineering's strategic plan are available (**www.mse.seas.upenn.edu**).

Applications must be submitted online **http://facultysearches.provost.upenn.edu/postings/1290** and include a cover letter, a complete curriculum vitae, a short (5 page limit) research statement, a teaching statement and the names of three references (with contact information) who could provide letters of recommendation. The cover letter should describe the applicant's most significant scientific accomplishment as a graduate student and as a postdoc, the applicant's overall goals/vision for a research program at Penn, and the experience and qualifications that make the applicant particularly well-suited to achieve those goals

Review of applications will begin immediately with a deadline of **January 2, 2018**.

The University of Pennsylvania is an affirmative action/equal opportunity employer. All qualified applicants will receive consideration for employment and will not be discriminated against on the basis of race, color, religion, sex, sexual orientation, gender identity, creed, national or ethnic origin, citizenship status, age, disability , veteran status, or any other characteristic protected by law.

Professor (Faculty Rank)
DEPARTMENT OF MECHANICAL SCIENCE AND ENGINEERING
College of Engineering
University of Illinois at Urbana-Champaign

The Department of Mechanical Science and Engineering at the University of Illinois at Urbana-Champaign invites applications for multiple faculty positions in all ranks. Candidates are sought in all technical subdisciplines of mechanical science and engineering including design, thermosciences, solid and fluid mechanics, and dynamics and control, with particular interest in the broad areas of manufacturing, energy and sustainability, and robotics and cyber-physical systems.

Qualified senior candidates will also be considered for a named appointment as part of the Grainger Engineering Breakthroughs Initiative, supported by a $100-million gift from the Grainger Foundation.

A doctoral degree is required, all opportunities are full-time, tenure or tenure-track, 9-month appointments paid over 12 months, with salary commensurate with qualifications and experience. Applications received by **December 1, 2017** will receive full consideration. Early applications are strongly encouraged. Interviews may take place before the given date; applications received after December 1, 2017 may be considered until positions are filled. The expected start date of a position offered/accepted through this search is August 16, 2018, but other start dates will be considered.

A full position description and information on how to apply can be found on the University of Illinois at Urbana-Champaign online jobsite **http://jobs.illinois.edu**. For further information regarding application procedures, please address questions to: mechse-facultyrecruiting@illinois.edu.

The University of Illinois conducts criminal background checks on all job candidates upon acceptance of a contingent offer.

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Max Planck Institute for the Physics of Complex Systems

mpipks

The Max Planck Institute for the Physics of Complex Systems in Dresden announces the opening of one or several

Postdoctoral Positions

in the area of condensed matter theory, to work with Roderich Moessner, Markus Heyl, David Luitz, Anne Nielsen, Takashi Oka and Inti Sodemann. The areas of research range from strongly correlated Fermions and Bosons in and out of equilibrium, frustrated systems and topological/fractionalized phases of matter, via computational many-body physics, to quantum computation and information theory.

The Institute provides a stimulating environment due to an active in-house workshop program and a broad range of other research activities. Strong experimental groups are nearby, in particular in the neighbouring Max Planck Institute for Chemical Physics of Solids.

To apply for a position, please fill the online application form (http://www.pks.mpg.de/CMpd18) and upload your application package (cover letter, curriculum vitae, list of publications, statement of research interests and publications) in one pdf file. Please arrange for at least two letters of reference to be sent by **January 15, 2018** preferably to be submitted in pdf format online (http://www.pks.mpg.de/reference/); or by email to visitors@pks.mpg.de with subject line **CMpd18**; or by regular mail:
Max Planck Institute for the Physics of Complex Systems, Visitors Program, Nöthnitzer Str. 38, 01187 Dresden, Germany.

The Max Planck Institute aims to increase the number of women in scientific positions. Female candidates are therefore particularly encouraged to apply.

In case of equal qualifications, candidates with disabilities will take precedence.

MAX-PLANCK-GESELLSCHAFT

Assistant Professor of Experimental Particle Physics
Texas Tech University

The Department of Physics and Astronomy at Texas Tech University, as part of its strategic growth plan, invites applications for a tenure-track position in experimental particle physics at the assistant professor level; exceptional candidates at a more senior level may be considered. The starting date is September 2018. The members of the experimental particle physics group at Texas Tech (Akchurin, Kunori, Lee, Volobouev, and Wigmans) actively participate in the CMS experiment at CERN and maintain a rigorous R&D program in advanced detector physics. In addition to the ongoing beyond Standard Model searches, we share significant responsibilities for the upgrade of the CMS calorimeters for the high luminosity LHC. The group enjoys strong infrastructure support: the Advanced Particle Detector Laboratory is well-suited for R&D and production of detectors based on scintillator and silicon systems, and the High Performance Computing Center allocates substantial resources in support of the group's analysis work. The university has recently been ranked in the Highest Research Activity category by the Carnegie Foundation. We expect the new experimental faculty member to strengthen and complement the ongoing research in CMS, particularly in detector upgrade effort, or to initiate a new and significant research program in any area of experimental particle physics. Candidate must have a Ph.D. in physics and at least two years of post-doctoral experience, possess an outstanding research record, and show promise of excellent teaching at both undergraduate and graduate levels. Candidate is expected to garner extramural funding to support his/her research. Service to the department, college, and university is also expected. Applicants should submit a vita, list of publications, statement of research interests and plans, teaching philosophy, and contact information for at least three references. Applications should be submitted online jobs.texastech.edu using requisition ID **11830BR**. Inquiries should be sent to **Professor Nural Akchurin** (nural.akchurin@ttu.edu). Applications will be reviewed starting **December 1st 2017** and will continue until the position is filled. *As an Equal Employment Opportunity/Affirmative Action employer, Texas Tech University is dedicated to the goal of building a culturally diverse faculty committed to teaching and working in a multicultural environment. We actively encourage applications from all those who can contribute, through their research, teaching, and/or service, to the diversity and excellence of the academic community at Texas Tech University. The university does not discriminate on the basis of an applicant's race, ethnicity, color, religion, sex, sexual orientation, gender identity, national origin, age, disability, genetic information or status as a protected veteran. Texas Tech welcomes consideration of dual career and professional couple accommodations.*

FACULTY POSITION
Theoretical Particle Physics
Florida State University

The Florida State University (FSU) Physics Department invites applications for a tenure track Assistant Professor position in theoretical particle physics, with starting date at the beginning of the Fall semester of 2018. We are seeking candidates who can strengthen the existing areas of interest of the theory group, which include collider phenomenology, with particular emphasis on higher-order perturbative calculations and the exploration of new observables and signatures, effective field theories, model building, and astroparticle physics and cosmology. The particle-physics theory group at Florida State University benefits from a fruitful synergy with members of the local experimental group who participate in the CMS experiment at the Large Hadron Collider. The FSU experimental group has extensive experience in top-quark, Higgs-boson, QCD, and electroweak physics; searches for physics beyond the Standard Model, and hardware development. The synergy extends to other strong groups within the FSU Physics Department, including: astrophysics, with specializations in star formation, supernovae, and the cosmic microwave background; nuclear physics, with overlapping interests in hadronic physics and neutron-star physics; and condensed matter physics, with strong expertise in field theoretical methods and strongly-correlated fermion systems of relevance to the experimental program at the FSU National High Magnetic Field Laboratory. Applicants should arrange for an electronic copy (PDF) of a cover letter, a curriculum vitae with a list of publications, a research plan, and at least three letters of recommendation to be sent to: hepsearch@hep.fsu.edu. Review of applications will begin on **November 27, 2017** and continue until the position is filled. *The Florida State University is an Equal Opportunity/Affirmative Action Employer and it especially encourages applications from women and members of minority groups.*

Tenure-track Assistant Professor
Boston University

The Department of Physics at Boston University (BU) is seeking candidates for a tenure-track Assistant Professor position in experimental high energy collider physics to join our effort on the CMS experiment at the Large Hadron Collider (LHC), pending budgetary approval. We encourage applications from the broad experimental particle physics community, but we are particularly interested in candidates whose expertise includes instrumentation and detector development, trigger and readout electronics, advanced simulation techniques and data analysis. The successful candidate is expected to collaborate effectively with the CMS group at BU and to develop an independent, internationally recognized research program. The successful candidate should have a Ph.D. degree or equivalent, and is expected to be an effective teacher and mentor in the undergraduate and graduate instructional programs of the Physics Department. Applications should be submitted via **AcademicJobsOnline**: https://academicjobsonline.org/ajo/jobs/9918, and should include a curriculum vitae, a list of publications, a statement of research interests, a statement of teaching experience and philosophy, and three letters of recommendation. The review of applications will start on **November 1, 2017** and continue until the position is filled. *Applications from women and underrepresented minorities are particularly encouraged. The University is committed to building a culturally, racially and ethnically diverse academic community dedicated to the highest level of excellence in teaching, research, and scholarship. BU is an equal opportunity employer and all qualified applicants will receive consideration for employment without regard to race, color, religion, sex, national origin, disability status, protected veteran status, or any other characteristic protected by law. We are a VEVRAA Federal Contractor.*

Assistant Professor, Tenure-Track
University of South Alabama

The Department of Physics at the University of South Alabama invites applications for a full-time (9 month), tenure-track assistant professor position to begin August 15, 2018. The successful candidate must have a Ph.D. in Experimental Physics and must show evidence of excellence in teaching and research with strong potential for external funding. Teaching duties include a wide spectrum of undergraduate physics lecture and laboratory courses (and may include introductory astronomy and astrophysics). Post-doctoral experience is desirable. The successful candidate will also be expected to conduct experimental research which will either strengthen the Department's current research in atomic-molecular-optical physics, condensed matter physics, high-energy physics or show promise of starting a strong program in experimental biological/medical physics or experimental astrophysics. Applications must be submitted online at https://www.governmentjobs.com/careers/usouthal/jobs/1853130. Deadline: **November 15, 2017**, 5:00 PM Central time.

Faculty Position in Atomic, Molecular, and Optical Physics
Physics Department, Auburn University

The Physics Department at Auburn University is seeking a highly qualified individual for a tenure-track faculty position in theoretical/computational Atomic, Molecular, and Optical (AMO) physics. The AMO group at Auburn has active theoretical and experimental faculty with expertise in collision dynamics, spectroscopy, laser interaction, and massively parallel computer applications. The group benefits from strong collaborations between its experimental and theoretical members, and active participation in off-site experiments. Research subspecialties that are of interest include (but are not restricted to) laboratory astrophysics, electron and ion collisional processes with atomic and molecular systems, photon interaction with atoms and molecules, charge exchange processes, astrochemistry, and molecular spectroscopy. Applicants must possess a Ph.D. or equivalent degree in physics or a closely related field. Post-doctoral research experience is also highly desirable. Candidates at all faculty ranks will be considered. The successful candidate will be expected to: (1) develop a strong research program, (2) obtain external funding for their research, (3) provide high quality mentorship to undergraduate, graduate students and post-doctoral researchers, and (4) conduct excellent instruction at the undergraduate and graduate level in the physics curriculum. Excellent written and interpersonal communication skills are required. Candidates must apply online at: http://aufacultypositions.peopleadmin.com/postings/2445. Applications need to include a cover letter, curriculum vitae, teaching statement, research statement and the names and contact information for three professional references. Questions for further information can be directed to amosearch@auburn.edu. More information about the department can be found at: http://www.physics.auburn.edu. The review of applications will begin on **December 1, 2017** and will continue until the position is filled. The desired starting date is August 16, 2018. *Candidates selected for this position must be able to meet eligibility requirements to work in the United States at the time the appointment is scheduled to begin and continue working legally for the proposed term of employment. Auburn University is an EEO/Vet/Disability Employer.*

Faculty Position in Astronomy
Texas Tech University

The Department of Physics and Astronomy at Texas Tech University, as part of a continuing strategic expansion, has two open positions in the area of observational astronomy with an expected start date of September 2018. The positions are expected to be at the rank of assistant professor, but exceptional experienced candidates will be considered at higher ranks. We anticipate that one of these positions will be for gravitational waves (including data analysis, interpretation or experiment) and the other will be for electromagnetic astronomy. We particularly encourage candidates whose research areas expand upon and complement existing efforts, but outstanding candidates from any area of astrophysics will be considered. The department is concurrently conducting a search in experimental particle physics. The astrophysics group presently consists of three tenured/tenure-track faculty (Corsi, Maccarone and Owen), one research assistant professor, one long-term instructor, six postdoctoral fellows and a visiting Fulbright scholar. Research facilities at Texas Tech include a High Performance Computing Center with a 250 Teraflop cluster, and Texas Tech University is among the closest universities to Ft. Sumner and NRAO. Texas Tech is a member of the LIGO Scientific Collaboration and recently has been ranked in the Highest Research Activity category by the Carnegie Foundation. The successful candidate will have a Ph.D. in physics, astronomy or a related field, at least two years of post-doctoral experience, a strong research track record, and strong potential for excellence in teaching at both undergraduate and graduate levels. Candidate is expected to garner extramural funding to support his/her research. Service to the department, college, and university is also expected. Applicants should submit a curriculum vita, including a publication record, a statement of research interests with a plan for future research, and a statement of teaching philosophy. Candidates should also arrange for three letters of reference to be sent to thomas.maccarone@ttu.edu by the application deadline. Candidates who are primarily interested in the electromagnetic astronomy position should apply at jobs.texastech.edu position **11823BR** and candidates who are primarily interested in the gravitational waves position should apply to position **11816BR**. Inquiries should be directed to **Tom Maccarone** (thomas.maccarone@ttu.edu), the search committee chair, or **Ben Owen** (benjamin.j.owen@ttu.edu), the co-chair for gravitational waves. Review of applications will begin on **December 1, 2017** and continue until the positions are filled. *As an Equal Employment Opportunity/Affirmative Action employer, Texas Tech University is dedicated to the goal of building a culturally diverse faculty committed to teaching and working in a multicultural environment. We actively encourage applications from all those who can contribute, through their research, teaching, and/or service, to the diversity and excellence of the academic community at Texas Tech University. The university does not discriminate on the basis of an applicant's race, ethnicity, color, religion, sex, sexual orientation, gender identity, national origin, age, disability, genetic information or status as a protected veteran. Texas Tech welcomes consideration of dual career and professional couple accommodations.*

ASSOCIATE OR FULL PROFESSOR
SCHOOL OF ENGINEERING AND APPLIED SCIENCE
PRINCETON UNIVERSITY

The School of Engineering and Applied Science at Princeton University invites applications for a new faculty position in the area of Bioengineering, at the associate or full professor rank. We welcome applications from all areas in biological engineering, including but not limited to engineering approaches to controlling and understanding intracellular self-assembly, tissue-level biological organization, and/or biological networks, as well as critical bio-related technology development (computational methods, sensing and imaging, biofabrication). Applicants must hold a Ph.D. in Bioengineering, Physics, Engineering, or a related subject, and have a demonstrated record of excellence and leadership in research. We seek faculty members who will be instrumental to creating an ecosystem of excellence and diversity, with a strong commitment to teaching and mentoring. Princeton's School of Engineering and Applied Science has a strong core of faculty engaged in Bioengineering-related research, distributed in all engineering departments, particularly Chemical and Biological Engineering, Computer Science, Mechanical and Aerospace Engineering, and Electrical Engineering. These ongoing efforts also build on Princeton's historical strengths in interdisciplinary biology, focused in the departments of Molecular Biology and Ecology and Evolutionary Biology, together with the Lewis Sigler Institute for Integrative Genomics, and the Princeton Neuroscience Institute. We seek creative and enthusiastic candidates with the background and skills to build upon and complement existing strengths, while leading Princeton's expanding Bioengineering program into new and exciting research areas in the future. To ensure full consideration, applications should be received by **December 1, 2017**. Applicants should submit a curriculum vitae, including a list of publications and presentations, a 3-5 page summary of research accomplishments and future plans, a 1-2 page teaching statement, and contact information for at least five references online at **https://www.princeton.edu/acad-positions/position/3443**. *Personal statements that summarize leadership experience and contributions to diversity are encouraged. This position is subject to the University's background check policy.*

BRIGHAM YOUNG UNIVERSITY
Visiting Faculty Position

The Department of Physics and Astronomy at Brigham Young University (BYU) in Provo, Utah, invites applications for a one-year (but renewable up to three years) visiting professional faculty position to begin in 2018. The new faculty member will be expected to support existing research programs (see **https://www.physics.byu.edu/**), with particular emphasis on providing excellent mentoring at the undergraduate and graduate levels and on building connections with industry. Interested candidates should complete an online faculty application at **https://yjobs.byu.edu** (posting **66871**), with a cover letter outlining research and industrial experience as well as professional aspirations, a current CV, and provide the contact information for three references. For additional info, contact **physicsjob@byu.edu**. Completed applications received by **November 1, 2017** will be given full consideration. *BYU, an equal opportunity employer, requires all faculty members to observe the university's honor code and dress and grooming standards. Preference is given to qualified candidates who are members in good standing of the affiliated church, The Church of Jesus Christ of Latter-day Saints.*

BRIGHAM YOUNG UNIVERSITY
Faculty Position

The Department of Physics and Astronomy at Brigham Young University (BYU) in Provo, Utah, invites applications for a faculty position to begin in August 2018. The new faculty member will be expected to provide excellent teaching and research mentoring at the undergraduate and graduate levels. All new faculty members are also expected to develop externally-funded research programs of significance. We are seeking applicants in the fields of Acoustics, Atomic Molecular and Optical Physics, Astronomy, Condensed Matter Physics, Magnetic Resonance Imaging, Numerical Relativity, Physics Education Research/Astronomy Education Research, Plasma Physics, Quantum Information, or Theoretical Physics to strengthen and complement existing research programs (see **https://www.physics.byu.edu/**). Interested candidates should complete an online faculty application at **https://yjobs.byu.edu** (posting **66856**), with a cover letter outlining teaching and research experience and aspirations, a current CV, and provide the contact information for three references. For additional info, contact **physicsjob@byu.edu**. Completed applications received by **November 15, 2017** will be given full consideration. *BYU, an equal opportunity employer, requires all faculty members to observe the university's honor code and dress and grooming standards. Preference is given to qualified candidates who are members in good standing of the affiliated church, The Church of Jesus Christ of Latter-day Saints.*

Postdoctoral Position in Photodynamic Therapy and Spectroscopy
Perelman Center of Advanced Medicine, University of Pennsylvania

Applicants are sought for a POSTDOCTORAL FELLOWSHIP in the Department of Radiation Oncology. The related research will employ modern biomedical optics techniques to carry out PDT dosimetry, develop light delivery systems, and develop schemes for treatment planning. This project is funded by NIH grants for 1 year, with possibility of renewal to 2nd year based on funding. Current projects include light dosimetry in intra-cavitary conditions, development of innovative light blanket for pleural PDT treatment, development of a treatment planning system for pleural PDT with real-time image guidance, and reactive oxygen species (ROS) modeling. **QUALIFICATIONS:** A Ph.D. degree in engineering, physical sciences or equivalent is required. Preference will be given to applicants with a proven track record in biomedical research, especially in optical spectroscopy and in finite-element analysis. Experience in the following is highly desired: programming in Matlab, photon transport in tissue, medical imaging, fiber optics and lasers, small animal handling, and optical instrumentation design. Salary and benefits will be commensurate with the applicant's experience. To apply, submit a CV and the names of three references to **Prof. Timothy C. Zhu, tim.zhu@uphs.upenn.edu**. *The University of Pennsylvania is an equal Opportunity / Affirmative Action Employer. Women and Minorities are encouraged to Apply.*

Faculty Position in Theoretical Nuclear Physics
University of Minnesota

The School of Physics and Astronomy at the University of Minnesota, Twin Cities, invites applications for a tenure-track position in the area of Theoretical Nuclear Physics. Candidates are expected to hold a Ph.D. in physics, astrophysics, or other related fields and should have demonstrated the potential to conduct a vigorous and significant research program as evidenced by their publication record and supporting letters from recognized leaders in the field. The ability to teach physics effectively at both the graduate and undergraduate levels is required. The appointment is expected to be at the Assistant Professor level, although a more senior appointment will be considered for a candidate with exceptional qualifications. The University of Minnesota has a strong and well-supported theoretical nuclear physics group pursuing topics that include heavy ion collisions at RHIC and LHC, AdS/QCD, finite temperature field theory, neutron stars, neutrino astrophysics, supernova explosions and gamma-ray bursts, evolution and nucleosynthesis of massive stars, and chemical evolution of galaxies. The group also has significant overlap in interests with members of the Fine Theoretical Physics Institute and the Minnesota Institute for Astrophysics. Applications are encouraged from researchers working on the above or any other topics in theoretical nuclear physics. The expected starting date for this position is August 27, 2018, although an earlier or later start can be arranged. Candidates for this position (**Job ID 320296**) must go to (**https://z.umn.edu/TheoreticalNuclearPhysicsFaculty2017**) and submit an application online. Application materials, which must be submitted as a single PDF file, should include a cover letter, a current C.V. with a list of publications, a statement of research interests, a statement of teaching interests, and the names of at least three references with complete address and contact information. Candidates should arrange to have letters of reference (signed and on official letterhead) sent directly to **jjmurphy@umn.edu** as PDF files no later than **December 15, 2017**. Alternatively, letters of reference may be sent to **Professor Ronald Poling, School of Physics and Astronomy, University of Minnesota, 116 Church St. SE, Minneapolis, MN 55455.** All materials including letters of reference must be received by **December 15, 2017** for full consideration. Review of applications will begin on **December 16, 2017**, and continue until the position is filled. *The University of Minnesota shall provide equal access to and opportunity in its programs, facilities, and employment without regard to race, color, creed, religion, national origin, gender, age, marital status, disability, public assistance status, veteran status, sexual orientation, gender identity, or gender expression.*

Faculty Position in Theoretical Physics
William I. Fine Theoretical Physics Institute
University of Minnesota

The School of Physics and Astronomy at the University of Minnesota, Twin Cities invites applications for a tenured position in the area of Theoretical Physics. The appointment is expected to be at the Associate or Full Professor level in the Fine Theoretical Physics Institute. Current interests within the Institute include High Energy Physics, Condensed Matter Physics, and Cosmology. Candidates are expected to hold a Ph.D. in physics and should have demonstrated the potential to conduct a vigorous and significant research program as evidenced by their publication record and supporting letters from recognized leaders in the field. The ability to teach physics effectively at both the graduate and undergraduate levels is required. The start day for this position is negotiable and could be as early as July 1, 2018. Candidates for this position (Job ID **320295**) must go to **https://z.umn.edu/FTPI_TheoreticalPhysics**) and submit an application online. Application materials, which must be submitted as a single PDF file, should include a cover letter, a current C.V. with a list of publications, a statement of research interest, a statement of teaching interests, and the names of at least three references with complete address and contact information. Candidates should arrange to have letters of reference, signed and on official letter, sent directly to **bieve008@umn.edu** as PDF files no later than **December 15, 2017**, though the search is expected to continue until the position is filled. Alternatively, letters of reference may be sent to **Professor Ronald Poling, School of Physics and Astronomy, University of Minnesota, 116 Church St. SE ,Minneapolis, MN 55455.** *The University of Minnesota shall provide equal access to and opportunity in its programs, facilities, and employment without regard to race, color, creed, religion, national origin, gender, age, marital status, disability, public assistance status, veteran status, sexual orientation, gender identity, or gender expression.*

Assistant Professor of Experimental Physics, Tenure Track
Hofstra University

The Hofstra University Department of Physics and Astronomy invites applications for an anticipated tenure track faculty position in experimental condensed matter physics, atomic physics (AMO) or laser physics. The department is looking for faculty committed to developing a vibrant research program, teaching and working with undergraduates. In particular, the candidate must demonstrate a willingness to involve undergraduates in research or to generate advanced projects for physics majors. The department now offers the BA and BS in Physics, the BS in Applied Physics and the MS in Medical Physics. It currently has eight faculty members with strong records in research and teaching. Startup funding is available for new faculty. Hofstra University is a selective private university with 11,000 students (6,900 undergraduates), located 25 miles from New York City and provides excellent benefits and sabbatical support. The scheduled start date for this position is September 1, 2018; review of applications will begin **January 2, 2018**. Interested candidates should submit a CV, a research statement, copies of up to three recent/significant publications and a description of one or two potential projects for advanced undergraduates as a single unprotected pdf file to the search committee at the email address below. The applicant should also arrange for three letters of recommendation to be sent before **January 2, 2018** to **PhysicsSearch2017@Hofstra.edu**. We welcome any questions about the Physics Department, startup funds, experimental facilities or the research environment at Hofstra University. *Hofstra University is an equal opportunity employer, committed to fostering diversity in its faculty, administrative staff and student body, and encourages applications from the entire spectrum of a diverse community.*

Associate/Full Professor of Physics
University of Miami

The Department of Physics at the University of Miami invites applications from highly qualified persons for a faculty position focusing on experimental Energy/Materials research. This appointment will be made at the Associate or Full Professor rank to begin Fall 2018. Targeted research topics include, but are not limited to, energy harvesting, storage, conversion, and optoelectronics, encompassing hard and/or soft matter. Candidates must have a Ph.D. in physics or a related discipline, a demonstrated record of research and funding achievements, and a strong commitment to teaching and mentoring students at the undergraduate and graduate levels. The physics department is located on the University's attractive Coral Gables campus in the greater Miami area, and has wide-ranging research expertise and an established Ph.D. program. Application materials, including curriculum vitae with list of publications and statement of research plans, should be sent electronically (as a single PDF) to physics.energysearch@miami.edu or to **Energy Search Committee Chair, Department of Physics, University of Miami, Knight Physics Building, Coral Gables, FL 33124.** Applicants should arrange for three letters of recommendation to be emailed or mailed to the same address. Review of applications will begin on **November 1, 2017** and continue until the position is filled. *The University of Miami is an Equal Opportunity Employer — Females/Minorities/Protected Veterans/Individuals with Disabilities are encouraged to apply. Applicants and employees are protected from discrimination based on certain categories protected by Federal law.*

Post-Doctoral Position in Theoretical Condensed Matter Physics
National High Magnetic Field Laboratory at Florida State University

The National High Magnetic Field Laboratory (NHMFL) at Florida State University has an opening for a post-doctoral position in Condensed Matter Theory, beginning September 1, 2018. The successful candidate will have opportunities to collaborate with all faculty members of the theory group, including N. Bonesteel, V. Dobrosavljevic, E. Manousakis, O. Vafek, and K. Yang. Current areas of active research within the group include (but are not limited to): Quantum Hall Effect, Graphene and Topological Insulators, Topological Quantum Computation, Unconventional Superconductivity, Quantum Criticality,Theory of Metal-Insulator Transitions, Complex Behavior of Correlated Electrons, Many-body Physics in Cold Atom Systems. More detailed information about the NHMFL Condensed Matter Science program can be found at: http://cms.magnet.fsu.edu. This position will remain available until filled. Applicants should provide a Curriculum Vita that includes a list of publications, a statement of research interest, and have at least three reference letters provided separately. The application materials should be submitted in electronic (PDF) format through email, to **Mr. Arshad Javed**, Coordinator Research Program Services at ajaved@magnet.fsu.edu. Inquiries should be addressed to **Prof. Efstratios Manousakis** at manousakis@magnet.fsu.edu. Screening of application will start as they arrive, so early applications are encouraged.

Criminal Background Check
This position requires successful completion of a criminal history background check.

Tobacco Free Campus
Effective January 1, 2014, tobacco use, including simulated tobacco use, is prohibited on property, interior and exterior owned or managed by Florida State University. This policy applies to all Florida State University students, employees, consultants, contractors, visitors, and external individuals.

Equal Employment Opportunity
An Equal Opportunity/Access/Affirmative Action/Pro Disabled & Veteran Employer. FSU's Equal Opportunity Statement can be viewed at: http://www.hr.fsu.edu/PDF/Publications/diversity/EEO_Statement.pdf.

The Department of Physics and Astronomy at the **University of Alabama** invites applications for an **interdisciplinary tenure-track position** in atomic, molecular, and atomic physics related to precision timing at the full or associate professor level. We are especially interested in candidates who specialize in one of the following areas: (1) atomic clock development, including both microwave and optical clocks and related technologies such as ultra-high vacuum systems; (2) metrology for precise timing applications, including measurement systems, modeling of noise processes, and associated statistical methods; and (3) realization and optimization of time scales based on aggregating ensembles of atomic clocks. Highly-qualified candidates with specialization in closely-related fields will also be considered. This position is intended to start a new program in precision timing. The appointment will begin August 16, 2018. In addition to faculty working in experimental and theoretical particle and condensed matter physics, we have related research groups in Electrical and Computer Engineering and the Materials for Information Technology, as well as an opportunity to interface with UA's growing Transportation Center. Tuscaloosa is also home to Microsemi Corporation's hydrogen maser research and development center. More information about the department can be found on the department's website physics.ua.edu. The minimum qualifications for this position are a Ph.D. or equivalent, postdoctoral experience or equivalent, scholarly publications, and experience with physics related to precision timing. Candidates for this position are expected to have an outstanding research record and exhibit potential for effective teaching at the undergraduate and graduate levels. The successful candidate is expected to develop a high quality, externally funded research program, as well as teach and mentor at the undergraduate and graduate levels. Applicants with academic, industrial, or government experience are encouraged to apply. We will begin reviewing applications on **1 November 2017**, and the review process will continue until the position is filled. Applications should consist of a resume, including descriptions of the applicant's accomplishments, a complete list of publications including citations, a research statement, and a statement of teaching philosophy. Applicants should also arrange for at least three letters of recommendation to be sent electronically to **Prof. Adam Hauser** at ahauser@ua.edu, or by mail to **Prof. Adam Hauser, Department of Physics and Astronomy, Box 870324, Tuscaloosa, AL, 35487.** Applications must be submitted online at the University of Alabama website https://facultyjobs.ua.edu/postings/41903. *The University of Alabama is an Equal Opportunity Affirmative Action Employer and actively seeks diversity among its employees. Women and minorities are strongly encouraged to apply.* For additional information, contact the search committee chair, **Prof. Adam Hauser**, at ahauser@ua.edu or **(205)348-4557**.

Baylor University

Baylor University is a private Christian university and a nationally ranked research institution, consistently listed with highest honors among The Chronicle of Higher Education's "Great Colleges to Work For." The university is recruiting new faculty with a deep commitment to excellence in teaching, research and scholarship. Baylor seeks faculty who share in our aspiration to become a tier one research institution while strengthening our distinctive Christian mission as described in our strategic vision, Pro Futuris (www.baylor.edu/profuturis/). As the world's largest Baptist University, Baylor offers over 40 doctoral programs and has almost 17,000 students from all 50 states and more than 80 countries.

Baylor seeks to fill the following tenured faculty position at the rank of full professor within the College of Arts and Sciences:

Chair of the Physics Department

We are seeking exceptionally qualified candidates to lead the Physics Department and contribute to the University's focus on developing materials research. The chair is expected to maintain active and internationally recognized research efforts in advanced materials and foster collaboration between STEM programs at Baylor. The successful applicant will build upon the physics department's commitment to undergraduate and graduate education and research. The department currently consists of 20 teaching and research faculty, 80 undergraduates, and 40 graduate students. Current research areas include nano/quantum optics and surface physics of various materials, high energy and elementary particle physics, complex plasma physics, gravitation and cosmology, and nonlinear dynamics.

Qualifications: Applicants will hold an earned doctoral degree in Physics or a related field and possess a continuing track record of high level interdisciplinary research and scholarly accomplishments, characterized by a strong record of external research funding and publications as well as demonstrated professional leadership. Salary is commensurate with experience and qualifications. Application material may be submitted online at https://academicjobsonline.org/ajo/jobs/9763. Applicants will be asked to provide the following: a cover letter describing their experience, qualifications, and goals for the position; curriculum vita; official transcripts, and contact information for three references. Review of applications will begin immediately; for full consideration applications are encouraged to be submitted by **December 1, 2017.** Please visit the appropriate URL to learn more about the above position https://jobs.baylor.edu/, the Department of Physics http://www.baylor.edu/physics, the College of Arts and Sciences http://www.baylor.edu/artsandsciences/ and Baylor University http://www.baylor.edu/.

Baylor University is a private not-for-profit university affiliated with the Baptist General Convention of Texas. As an Affirmative Action/Equal Opportunity employer, Baylor is committed to compliance with all applicable anti-discrimination laws, including those regarding age, race, color, sex, national origin, marital status, pregnancy status, military service, genetic information, and disability. As a religious educational institution, Baylor is lawfully permitted to consider an applicant's religion as a selection criterion. Baylor encourages women, minorities, veterans and individuals with disabilities to apply.

Assistant Professor of Physics
Coe College

The Physics Department at Coe College invites applications for a tenure track faculty appointment beginning Fall 2018. Applicants with expertise in all areas related to glassy materials are encouraged to apply. A Ph.D. with a focus in glass research, evidence of strong teaching skills, and the ability to teach undergraduate physics courses are required. For position details and application process, visitwww.coe.edu/aboutcoe/employment. The review of applications will begin on **November 1, 2017**, we will continue to accept applications until the position is filled.

Experimental Condensed Matter Physics Assistant Professor
Purdue University

The Department of Physics and Astronomy at Purdue University (www.physics.purdue.edu) seeks applications for a faculty position at the level of Assistant Professor in the field of experimental condensed matter physics. We envision a junior hire to complement existing strengths in the condensed matter group. Areas of current research interest in the Department include non-Abelian fractional quantum Hall physics, nanoscale phenomena, novel topological phases of matter, quantum computing and information processing, and exotic superconductivity. The experimental condensed matter group also makes frequent use of the state-of-the-art facilities available in Purdue's Birck Nanotechnology Center (http://www.purdue.edu/discoverypark/birck). Individuals pursuing novel experimental techniques to probe condensed matter systems are particularly encouraged to apply. Candidates are required to have a doctoral degree in physics or related field and a documented record of research accomplishments. A successful candidate is expected to develop a vigorous research program, supervise graduate students, and teach undergraduate and graduate level courses. Applicants should send a curriculum vita, a brief statement of present and future research plans, a statement of teaching philosophy and arrange for three letters of recommendation. Electronic submission is preferred: https://www.physics.purdue.edu/searches/app/. Questions regarding the position and search should be directed to **Prof. Michael Manfra** (mmanfra@purdue.edu). Applications completed by **January 11, 2018** will be given full consideration, although the search will continue until the position is filled. A background check will be required for employment in this position. *Purdue University's Department of Physics and Astronomy is committed to advancing diversity in all areas of faculty effort, including scholarship, instruction, and engagement. Candidates should address at least one of these areas in their cover letter, indicating their past experiences, current interests or activities, and/or future goals to promote a climate that values diversity and inclusion. Purdue University is an EOE/AA employer. All individuals, including minorities, women, individuals with disabilities, and veterans are encouraged to apply.*

Assistant Professor Position
University of Pennsylvania

The Department of Physics and Astronomy at the University of Pennsylvania invites applications for an Assistant Professor position, to start July 1, 2018. We are looking for an astrophysicist with expertise in data science, numerical simulation, or computation. The first three years of this tenure-track position at Penn will include a joint (50/50%) appointment with the newly created Simons Center for Computational Astrophysics (CCA). At the CCA, the appointment will hold the position of Associate Research Scientist. Associate Research Scientists develop algorithms and codes for computational astrophysics and/or for the analysis of large astronomy data sets. Applicants are expected to have a PhD and to have established an independent program of research that they will expand at Penn and CCA. Penn hosts a collegial department with a vibrant research enterprise, and strong programs in undergraduate and graduate teaching and public outreach. The Department is actively involved in a number of data-intensive projects including AdvACT, DES, HERA, SDSS IV, LSST, WFIRST, and the Simons Observatory. The CCA, part of the Flatiron Institute in New York City, aims to become a focal point for computational astronomy around the world and plans to play a leadership role in developing the computational tools needed for calculations, simulations and data analyses. Candidates should submit materials online at http://facultysearches.provost.upenn.edu/postings/1289 and include: a curriculum vitae (including list of publications); a description (4 pages maximum) of past and planned research and of teaching interests; and the names and contact information for at least three references. Recommenders will be contacted by the University with instructions on how to submit a letter to the website. Review of applications will begin **December 1, 2017** and continue until the position is filled. *The Department of Physics and Astronomy is strongly committed to Penn's Action Plan for Faculty Diversity and Excellence and to creating a more diverse faculty (for more information see: http://www.upenn.edu/almanac/volumes/v58/n02/diversityplan.html). The University of Pennsylvania is an equal opportunity employer. Minorities, women, individuals with disabilities, and protected veterans are encouraged to apply. The Simons Foundation is an Equal Opportunity Employer, M/F/D/V.*

FACULTY POSITION
EXPERIMENTAL CONDENSED MATTER PHYSICS
UNIVERSITY OF ILLINOIS, URBANA-CHAMPAIGN

The Department of Physics invites applicants for a full-time tenured or tenure-track faculty position in Experimental Condensed Matter Physics, beginning as early as August 16, 2018. The University of Illinois Department of Physics has strong programs in experimental and theoretical condensed matter physics. Scientists from all subfields of condensed matter physics are encouraged to apply. The successful candidate is expected to teach effectively at both the undergraduate and graduate levels, have a strong record of publication, and to lead a vigorous research program at the cutting edge of the field. For full consideration, application materials must be received by **November 20, 2017**. Please visit http://jobs.illinois.edu to view the complete position announcement and application instructions. The University of Illinois conducts background checks on all job candidates upon acceptance of a contingent offer. *The University of Illinois is an EEO Employer/Vet/Disabled* www.inclu.

Open Rank Astronomy/Astrophysics Tenure/Tenure Track Faculty Position
Missouri University of Science & Technology

Missouri University of Science & Technology Open Rank Faculty Position Astronomy/Astrophysics The Physics Department at Missouri University of Science & Technology (Missouri S&T) is expanding its research portfolio by launching a new emphasis area in astronomy and astrophysics. We are seeking a highly qualified individual to lead this effort. Applications from both experimentalists and theorists are encouraged. Appointment rank will be determined by the candidate's qualifications and their alignment with the school's promotion and tenure policy. The successful candidate must have a Ph.D. in Physics or an equivalent degree and have demonstrated outstanding research accomplishments, a commitment to excellence in teaching at all levels, and excellent communication skills. More information is available at http://physics.mst.edu. Enquiries about the position may be directed to **Prof. Michael Schulz, Chair of the Search Committee** (schulz@mst.edu). Applications, including curriculum vitae, complete publications list, names of at least three references, a brief description of research interests, and a statement of teaching philosophy should be submitted electronically to the **Missouri University of Science and Technology's Human Resource Office** at http://hraadi.mst.edu/hr/employment/. All submitted application materials must include the position reference number **00070376** in order to be processed. Acceptable electronic formats that can be used for email attachments include PDF and Word; hardcopy application materials will not be accepted. Applications will be considered until the position is filled; review of applications will begin **Jan. 1, 2018**. The final candidate is required to provide official transcript(s) for any college degree(s) listed in application materials submitted. Copies of transcript(s) must be provided prior to the start of employment. In addition, the final candidate may be required to verify other credentials listed in application materials. Failure to provide official transcript(s) or other required verification may result in the withdrawal of the job offer.

Graduate Research Assistantship/Fellowship in Physics

Graduate research assistantship/fellowship in physics master degree program are available for application at **Southern University** and **A&M College, Baton Rouge, Louisiana, USA.** This program is designed to foster entry into physics research and education for highly motivated graduates or undergraduates with a strong interest in Physics or related disciplines. To Apply: Please check the web site of Graduate School Admissions of Southern University and A&M College, or www.phys.subr.edu/PhysicsCurrent. Complete the required application forms. Select the Graduate Degree Program in Mathematics and Physics - Physics Concentration. *Minorities are welcome to apply.* For any queries, please contact Guang-Lin_Zhao@subr.edu or bagayoko@aol.com.

Department Chair, Department of Physics, Geology, and Engineering Technology
Northern Kentucky University

The Department of Physics, Geology, and Engineering Technology at Northern Kentucky University invites applications for the position of Chair. This is a twelve-month tenured position at the rank of Associate or Full Professor and begins July 1, 2018. The department offers baccalaureate degrees in physics, geology, and in engineering technology, as well as pre-engineering transfer programs, and operates a planetarium. NKU is located in the metropolitan Cincinnati area. Screening of applications will begin **December 1, 2017**, and continue until the position is filled. More information is available at http://jobs.nku.edu/postings/6285.

Tenure Track Faculty Position
Theoretical AMO Physics
Missouri University of Science & Technology

The Physics Department at Missouri University of Science & Technology (Missouri S&T) invites applications for a tenure track faculty position at the Assistant Professor level in the area of theoretical AMO physics to begin in August 2018. Particular consideration will be given to candidates with expertise in optics. The successful candidate must have a Ph.D. in Physics or an equivalent degree and have demonstrated outstanding research accomplishments, a commitment to excellence in teaching at all levels, and excellent communications skills. More information is available at http://physics.mst.edu. Applications, including curriculum vitae, complete publications list, at least three letters of recommendation, a brief description of research interests, and a statement of teaching philosophy should be submitted electronically to the Missouri University of Science and Technology's Human Resource Office at http://hraadi.mst.edu/hr/employment/. All submitted application materials must include the position reference number **00030917** in order to be processed. Acceptable electronic formats that can be used for email attachments include PDF and Word; hardcopy application materials will not be accepted. Applications will be considered until the position is filled; review of applications will begin **Jan. 1, 2018**. The final candidate is required to provide official transcript(s) for any college degree(s) listed in application materials submitted. Copies of transcript(s) must be provided prior to the start of employment. In addition, the final candidate may be required to verify other credentials listed in application materials. Failure to provide official transcript(s) or other required verification may result in the withdrawal of the job offer. *Missouri S&T is an AA/EO Employer and does not discriminate based on race, color, religion, sex, sexual orientation, national origin, age, disability, or status as Vietnam-era veteran. Females, minorities, and persons with disabilities are encouraged to apply. Missouri S&T is responsive to the needs of dual-career couples. Missouri S&T participates in E-Verify.* For more information on E-Verify, please contact DHS at **1-888-464-4218**.

Tenure Track Assistant/Associate Professor in Computational Physics
California State University, Fresno

Duties include teaching graduate and undergraduate physics courses; mentoring students; and developing an externally funded research program in computational physics. Expertise in condensed matter or high-energy physics and postdoctoral experience is preferred. An earned doctorate (Ph.D.) in physics from an accredited institution or international equivalent is required. Exceptionally qualified candidates may be considered for appointment at the Associate Professor rank. The position is open until filled. For full consideration, please apply online at http://jobs.csufresno.edu by **December 11, 2017**. *California State University, Fresno is an affirmative action/equal opportunity institution.* Inquiries: **Professor Gerardo Munoz, Search Committee Chair; Department of Physics, 2345 E San Ramon Ave M/S MH37, California State University, Fresno, CA 93740; 559.278.4020;** gerardom@csufresno.edu.

Tenure Track Assistant Professor - Marquette University

The Physics Department at Marquette University invites applications for a full-time, tenure track position as an assistant professor to begin on August 16, 2018. The department offers a Bachelor of Science degree in physics, and is seeking candidates with a Ph.D. in Physics or a closely related field. Applicants must have a strong interest in undergraduate teaching and engaging undergraduate students in research. There is considerable opportunity for collaborative research on and off campus. Please apply to this position at http://employment.marquette.edu/postings/8565. *The Physics faculty especially encourages candidates from underrepresented groups to apply.* For more information about the Physics Department at Marquette, please visit our webpage at www.mu.edu/physics.

ASSISTANT PROFESSOR -- The Department of Physics at Oakland University is seeking a gravitational physicist for a tenure track Assistant Professor position starting on August 15, 2018. A Ph.D. in physics or closely related discipline, and capability for excellent teaching at the undergraduate and graduate level are required. Our preference is for a numerical relativist, but applicants in any area of gravitational physics will be considered. The department offers a B.S. and M.S. in Physics and a Ph.D. in Medical Physics. A Ph.D. program in Applied and Computational Physics is under consideration. Applicants should submit a cover letter, curriculum vitae including list of publications, a description of research interests, a statement of teaching philosophy and experience, an unofficial transcript, and provide name and contact information for three professional references to http://jobs.oakland.edu/postings/12234. Questions and inquires may be directedto the search committee at physics@oakland.edu or to **David Garfinkle** at garfinkl@oakland.edu. To receive full consideration, applications should be received by **December 1, 2017**. For further information about the department, see http://www.oakland.edu/physics. *Oakland University is an ADVANCE institution, one of a limited number of universities in receipt of NSF funds in support of our commitment to increase diversity, and the participation and advancement of women and underrepresented minorities in the STEM fields. Oakland University is an Affirmative Action/Equal Opportunity Employer and encourages applications from women and minorities.*

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QUICK STUDY

Philip Richardson (prichardson@whoi.edu) is a scientist emeritus at the Woods Hole Oceanographic Institution in Massachusetts.

Da Vinci's observations of soaring birds

Philip L. Richardson

More than half a millennium ago, the great polymath Leonardo da Vinci sketched and described a maneuver that birds use to extract energy from a gradient in wind speed.

With only a minimal flapping, the wandering albatross can circumnavigate the globe. During its peregrinations over the Southern Ocean, the seabird exploits wind shear—the gradient of wind speed—to extract energy for its sustained flight. That same maneuver, called dynamic soaring, is used by pilots of radio-controlled gliders. In flights that take advantage of the shear associated with wind blowing over mountain ridges, the gliders reach air speeds of an astonishing 500 mph. Engineers are currently developing autonomous unmanned vehicles that can use the technique to supplement different sources of energy for sustained flight over the oceans. Possible applications include environmental monitoring, surveillance, and search and rescue.

The answer is blowin' in the wind

Dynamic soaring, as exemplified by the flight of the wandering albatross and other seabirds, typically has several phases, as illustrated in figure 1. The bird, flying near the ocean surface, turns into the wind and then climbs upwind, crossing the wind-shear layer at a shallow angle. Once above the shear layer, the bird turns downwind and descends across the wind shear into the region of calm air. There it turns around to again head in the windward direction.

As the figure shows, an albatross can gain air speed as it executes a climb-and-descent cycle across the wind-shear layer. The step that imparts kinetic energy to the bird is the banked downwind turn executed high up, where the wind is relatively strong. In essence, the albatross is reflecting off a massive wall moving toward it. The wall of wind transfers some of its kinetic energy to the bird but is essentially unaffected by the interaction. In actual soaring flight, much or all of the bird's kinetic-energy gain is dissipated by drag forces, so the flight is energy neutral.

The albatross in figure 1 is circling in a schematic hover mode. With a slight alteration in its flight path, it can travel in any direction relative to the wind. Indeed, albatrosses often use dynamic soaring to fly across the wind and can sustain speeds of 20 m/s doing so. Typically, as they climb and descend across the wind shear, their horizontal velocity component is tilted at an angle relative to the across-wind direction. When albatrosses and other seabirds fly directly upwind, they do so in a manner analogous to a tacking sailboat.

Leonardo da Vinci (1452–1519) studied bird flight while attempting to develop human-powered flying machines. He was particularly interested in understanding how birds soar without flapping their wings. Leonardo sketched numerous birds, added comments about patterns of flight, and carefully studied the movement of air and water. Although many people know him for his studies of aerodynamics, few realize that Leonardo was the first to document the dynamic soaring flight maneuver.

A brief history

Lord Rayleigh is generally credited with the first realistic description of how a bird can extract energy from wind shear for sustained soaring. In a paper from 1883, he analyzed a two-layer geometry as illustrated in figure 1, but recognized that the bird could equally well gain energy from a continuous gradient in wind speed.

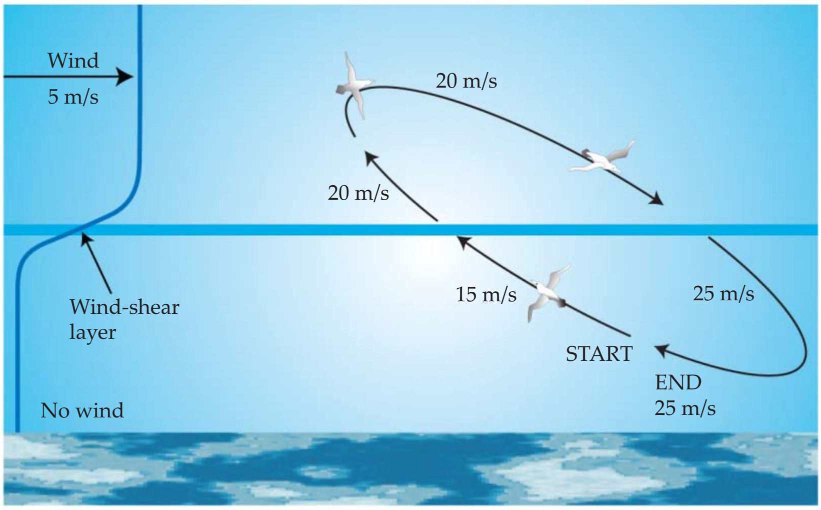

FIGURE 1. ALBATROSSES AND OTHER SEABIRDS can circle almost effortlessly by passing through a gradient in wind speed. In the idealization of dragless flight, they can even pick up speed, as this schematic shows. The zero wind speed in the lower layer represents weak wind located in wave troughs, and the 5 m/s wind in the upper layer represents the stronger wind above wave crests. All the specified albatross speeds are air speeds. In particular, as the albatross crosses the shear layer from below, its ground speed does not change, but its air speed increases by 5 m/s. Similarly, as the bird crosses the shear from above, its speed relative to the high-altitude wind does not change, but air speed increases by an additional 5 m/s. During the banked downwind turn, ground speed increases from 15 m/s to 25 m/s. Thus one cycle through the wind-shear layer increases the ground speed and air speed by 10 m/s.

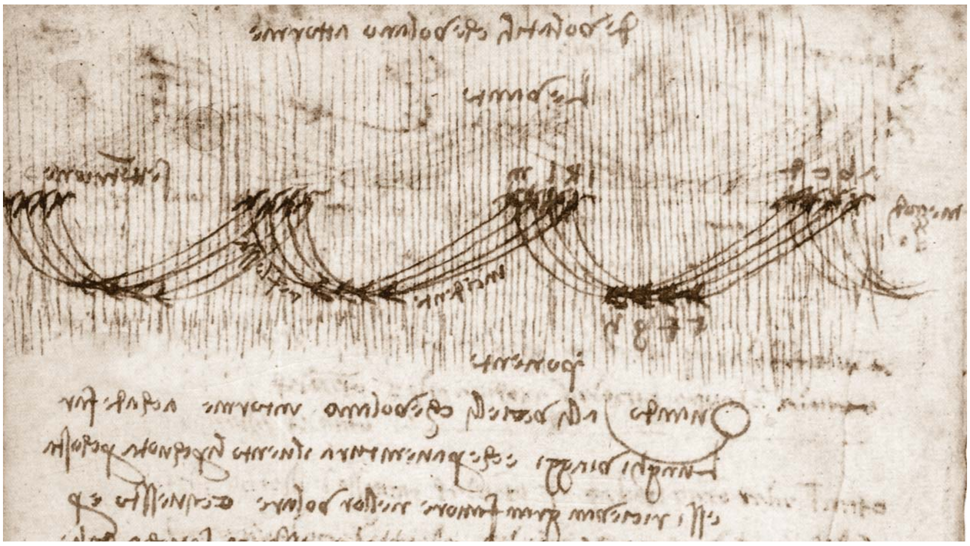

FIGURE 2. ACROSS-WIND dynamic soaring, as illustrated by Leonardo da Vinci in the early 1500s. The nearly straight vertical lines indicate the direction of the horizontal wind, which is blowing from top to bottom in the figure. Reading from right to left, the first phase of the birds' motion involves an ascent that has components out of the plane of the page and against the flow of the wind. The ensuing descent is partially with the wind. The wind direction and the details of the maneuver are described in Leonardo's notes, written in his characteristic reversed, right-to-left style.

In 1900 Rayleigh summarized bird soaring as part of a review of the mechanical principles of flight. It was an important review, because at the time Rayleigh was one of the few respected scientists to promote human flight. His work included an examination of dynamic soaring of albatrosses and other seabirds. It also had discussions of soaring in wind gusts, soaring in updrafts of warm air currents, and the phenomenon of wind striking sloping land and being deflected upwards.

Nowadays, the principal bone of contention concerning seabird soaring is what primary source of energy powers their flight: Does the energy come from wind shear as described above, or do updrafts deserve the credit? The consensus in the community, in part informed by accurate computer modeling, seems to be that dynamic soaring explains most albatross soaring, at least over the windy Southern Ocean.

Leonardo's notebooks

Leonardo wanted to discover how birds continuously soar so that he could use the information for developing human flight. Most of his observations of soaring birds were made near Florence, circa 1500–06. A summary of those observations and a description of dynamic soaring can be found in his "Manuscript E," which is dedicated to bird flight and the science of winds. The manuscript was compiled in 1513–15, while Leonardo was living in Rome.

In his manuscript, Leonardo drew pictures of both downwind and across-wind soaring. Figure 2, a reproduction from Manuscript E, folio 40 verso, shows across-wind dynamic soaring by a small flock of migrating birds. In his notes, Leonardo wrote that thrushes and similar birds fly in droves using the maneuver shown in the figure. Here is how he described the undulating motion (translation by John Venerella):

> When it happens that birds flying in flocks make long journeys, and the wind, by chance, strikes them on the side, these receive a great favor in their flying. And this is because the flying is done by bounds [undulations] and without the aid of the wings since their incident motion is made beneath [the course of] the wind, with their wings somewhat narrowed, and along the direction of the destined journey. But the reflected motion is made above the [course of the] wind, and with the wings opened, it rises upward, against the approach of the wind and so this wind penetrates beneath the bird, lifting it toward the sky, like a wedge that penetrates under a heavy object placed on top of it.

The "reflected motion" terminology Leonardo used is reminiscent of the hard-wall-reflection picture described earlier, though evidently his preferred simile for the wind's action on the birds was a wedge.

In Manuscript E, folio 40 recto, Leonardo illustrated downwind dynamic soaring. Although he mentioned several land birds in the manuscript, he did not name the downwind-soaring species he drew. Indeed, he identified only one bird with a specific time and place: a "cortone," a bird of prey he saw on his way to Fiesole, near Florence, on 14 March 1505.

Leonardo did not mention an increase of wind speed with altitude in his notes accompanying the dynamic soaring sketches, so he may not have recognized wind shear as being crucial to soaring. But in another notebook entry, he did recognize that wind speed increases with altitude. As he observed, "Birds always fly low when the course of the wind is contrary to their path and this teaches us how the wind is more powerful at a height than low down." Of course, at the beginning of the 16th century, Leonardo could not have conceptualized dynamic soaring with the precision of modern science. He was the first, though, to illustrate and describe an energy-harvesting maneuver important to seabirds and engineers alike.

Additional resources

▶ Biblioteca Leonardiana, "e-Leo: History of Science and Technology Digital Archive," www.leonardodigitale.com/index.php?lang=ENG.

▶ L. Rayleigh, "The Wilde Lecture: The mechanical principles of flight," *Mem. Proc. Manch. Lit. Philos. Soc.* **44**, memoir no. 5 (1899–1900).

▶ J. D. Anderson Jr, *A History of Aerodynamics and Its Impact on Flying Machines*, Cambridge U. Press (1997).

▶ L. da Vinci, *The Manuscripts of Leonardo da Vinci in the Institut de France*, J. Venerella, trans., Ente raccolta vinciana (1999–2007).

▶ D. Laurenza, *Leonardo on Flight*, J. M. Reifsnyder, trans., Giunti (2004).

▶ P. L. Richardson, "How do albatrosses fly around the world without flapping their wings?," *Prog. Oceanogr.* **88**, 46 (2011). PT

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BACK SCATTER

Ship tracks

Since the 1960s it's been known that the aerosol particles emitted in the engine exhaust of large ships can seed the formation of clouds: The particles form the nuclei around which water vapor condenses into cloud droplets. Aerosols' effect on cloud physics doesn't stop there—they influence clouds' size, density, lifetime, altitude, albedo, dynamics, and more. The report on page 20 highlights one consequence: a near doubling of lightning frequency in the sky above two of the world's busiest shipping lanes.

Clouds produced by ship emissions are also observable from above. Back in 2002, the MODIS (Moderate-Resolution Imaging Spectroradiometer) instrument aboard NASA's *Terra* satellite captured this image (color enhanced) of a stretch of the northern Pacific Ocean just below the Gulf of Alaska. Amid the large clouds are several bright, narrow streaks—ship tracks. The tracks become undulated in the wind yet they maintain their brightness due to their small droplet sizes.

—RJF

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