PHYSICS TODAY

April 2017 • volume 70, number 4

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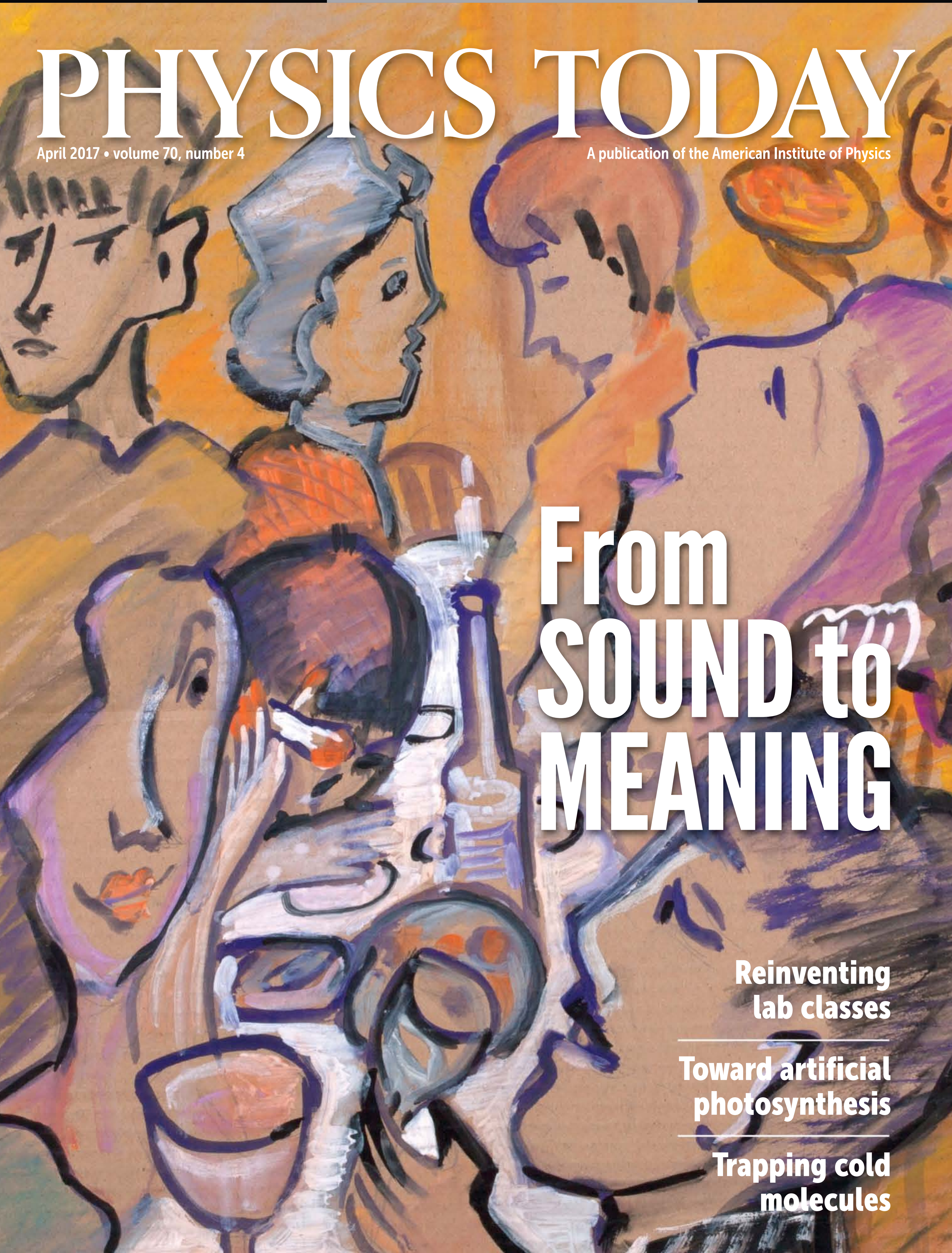

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Trapping cold molecules


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PHYSICS TODAY

April 2017 | volume 70 number 4

FEATURES

ON THE COVER: When the silver-haired woman talks to her red-haired friend, she transmits a complicated pressure wave whose intensity varies with time and frequency. What is perceived, though, is a message such as "The music's really good." The path from sound to meaning involves numerous physical and psychological processes. Although much remains to be understood, several sections of the path have been well surveyed. In her article beginning on **page 34**, Emily Myers describes some fascinating details scientists have uncovered. (Image by vvoe.)

Recently on PHYSICS TODAY ONLINE

www.physicstoday.org

HARVARD–SMITHSONIAN CFA

▶ No physics GRE

Several astronomy graduate programs, including the one at Harvard (above), no longer require applicants to submit scores from the physics Graduate Record Exam. Three astronomers explain why that's a good idea and what might replace the test in evaluating candidates.

USGS

▶ Quake risks

The US Geological Survey has released a short-term assessment warning that the risk of damage remains high from human-induced earthquakes in Oklahoma and Kansas. PHYSICS TODAY reports how recent regulations and economic trends have altered the most at-risk areas.

ROSHNI PATIL

▶ Women in science

Despite overall progress worldwide in narrowing the gender gap in the sciences, women continue to be particularly under-represented in physics, astronomy, and related fields, according to a new Elsevier report. PHYSICS TODAY examines the numbers and what is likely driving them.

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FROM THE EDITOR

Hearing from you

Charles Day

In July 1989 Anne Cutler and her collaborators published a letter to *Nature* entitled "Limits on bilingualism." The paper reported the results of an ingenious experiment to determine whether people who are fluent in two languages nevertheless favor one over the other.[1]

The two languages in the study, English and French, were chosen in part because French has much clearer boundaries between syllables than English does. Being able to segment words into syllables helps in the comprehension of spoken French but not spoken English.

In a previous study, Cutler and her collaborators played recordings of unrelated words to monolingual French speakers. The subjects' task was to listen for sounds at the start of words that were either consonant-vowel, such as the *ba* in *balance*, or consonant-vowel-consonant, such as the *bal* in *balcon*. As soon as they recognized the specified sound, they pressed a button. Consonant-vowel syllables are far more common in French than consonant-vowel-consonant syllables are. The subjects recognized *ba* tens of milliseconds faster than they did *bal*. When English speakers were given the same test with English sounds and words, they exhibited no difference in recognition time. Evidently, syllable segmentation is an acquired ability.

GROUP CHAT 2001 by Diana Ong

For the 1989 study, Cutler and her collaborators repeated the experiment on English–French bilinguals. But first they asked their subjects the question, "If you had to lose one of your languages to save your life, which would you keep?" The ones who would keep English performed like English monolinguals on both tests. But the ones who would keep French performed like English monolinguals on the English test and like French monolinguals on the French test.

The researchers concluded that the concept of a mother tongue is valid: People do have a dominant language. Their second conclusion was that syllable segmentation is not only acquired; it can be acquired only if your mother tongue uses it.

Cutler's paper was not reported in PHYSICS TODAY in 1989, but it could have been. Linguistics is a field that rests partly in acoustics, which rests partly in physics. Just as important, members of the Acoustical Society of America have been receiving PHYSICS TODAY since the magazine's first issue in May 1948. If you browse the table of contents of the March 2017 issue of the *Journal of the Acoustical Society of America*, you'll find papers on such subjects as hearing loss in humans, a photoacoustic method for taking fingerprints, big brown bats' response to loud noise, and vibration damping using an acoustic black hole. And if you turn to page 34 of this issue you'll find an article by Emily Myers on how humans process sound into meaning.

In the sense that speech perception would not typically be covered in a university physics course, the topic lies outside mainstream physics. But it very much belongs in PHYSICS TODAY. If you know of other nonmainstream subjects that PHYSICS TODAY should cover, I'd like to hear from you. My email address is cday@aip.org.

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1. A. Cutler, J. Mehler, D. Norris, J. Segui, *Nature* **340**, 229 (1989). PT

READERS' FORUM

Commentary

In defense of Crazy Ideas

Unless we change direction,
we are likely to wind up
where we are headed.

—Ancient Chinese proverb

Like many of you, I get unsolicited manuscripts that make startling and revolutionary claims. In years past they arrived by snail mail and were often handwritten or typed with copious use of capital letters, exclamation marks, and hand-drawn diagrams. More recently they come by email and look more like conventional scientific literature. (Even crackpots know how to use word processors and PowerPoint.) Denials of Einstein's special relativity seem especially popular.

Although the shortcomings of those efforts are often readily apparent, there is much to admire about the passion and dedication with which they are constructed. Occasionally they merit attention, if only because their authors' thought processes are not fettered by conventional thinking. Sadly, their deficiencies are often fundamental and betray a lack of understanding of the nature of science and its interconnectivity. They are what I call Crazy Ideas of the First Kind—the most common and least interesting.

Most published science is mundane. It is the easiest to get published and the easiest to get funded at a modest, sustainable level—though no funding is easy to get these days. It is also more likely to be right, precisely because it is incremental. Just as rock-solid financial investments are an important part of any balanced portfolio, so the mundane science is an important part of the science portfolio. But I suspect many scientists, even some who are recognized as leaders in their field, are unwilling to acknowledge their lack of adventurousness. They will protest that they are inventive, innovative scientists, but their measure of that is probably quite constricted because of the fine-scale partitioning that characterizes the modern scientific world. In the landscape of scientific knowledge, most of us are digging deeper holes and maybe an occasional trench to link up with a neighboring hole, but few are venturing across the ridges to the next valley.


RICHVINTAGE

Crazy Ideas of the Second Kind come when well-established scientists venture out from their holes and up to the ridges and peaks to survey the landscape. Inevitably, such excursions can look like the actions of a dilettante since it takes less effort to dash up a ridge than to dig a really deep hole. One is then accused of speculation. I occasionally sense from colleagues some disdain for scientific speculation, perhaps because it is cheap: It seems to require relatively little effort and commitment. Indeed, bad speculation is easy, and you can do it at the local bar or Starbucks or while riding a bike. Poor experimental or observational work also often requires less effort than good work. In fact, good speculation is hard, judging by the evident rarity of examples. Good speculation is also not always easy to recognize immediately, because part of what makes it good is something that may be hidden: the failures of alternative speculations, the crumpled sheets of paper in the wastebasket.

Richard Feynman once said that the essence of science is (or should be) "the belief in the ignorance of experts."[1] I think he meant that outsiders may provide an important breakthrough because they are unfettered. The "ignorance" that he refers to, though, must not be complete. It still must allow an appreciation of how science works and the rules that apply, and so it is the ignorance of areas of science other than your own. Residents of deep holes know very well the stuff they have excavated and the walls that surround them but know less well what novelty may lie elsewhere.

And then there are Crazy Ideas of the Third Kind, the most interesting and least common. They arise from a leading

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eminence in some field who has decided that something is rotten in that field's fundamentals. In essence, they have decided that their hole is a false claim or has been mined out, even though it may be capacious and well populated.

Importantly, good crazy ideas do not have to be true to be valuable. Distinguished astrophysicist Fred Hoyle and colleagues had the crazy idea that influenza came from space.[2] The more general concept of panspermia—of which Hoyle's idea is a special case—is, however, of considerable interest.

Perhaps an even better example of that line of thinking is Hoyle's wonderful science fiction novel *The Black Cloud* (Harper, ca. 1957), wherein an intelligent life-form exists as a dispersed but organized globule that wanders into our solar system. That is a truly engaging though crazy idea: Could life take the form of something that we normally think of as having high entropy? Indeed, some fluid dynamical systems display order—consider Jupiter's Great Red Spot—and the question of what form life could take remains an open one.

Another distinguished astrophysicist, Thomas Gold, had the crazy idea that natural gas was part of Earth's starting material rather than arising from biological processes much later in Earth history.[3] Geochemists might laugh (some did), and yet the possible delivery of large amounts of reduced carbon to Earth at formation is not such a ridiculous idea. We still do not know Earth's total reservoir of carbon, since some of it may be very deep. Gold was wrong about natural gas, but the idea is provocative, and that's good.

More famously, Lord Kelvin had the crazy idea that you could figure out the age of Earth by solving the diffusion equation for heat conduction in a half-space. He knew that Earth is a sphere, but the diffusion time for the whole Earth is so large that a half-space suffices. (For more on Lord Kelvin's mistake, see my letter, PHYSICS TODAY, November 2010, page 8.)

Kelvin's idea is a particularly interesting example because it was not regarded as crazy at the time but would be viewed as crazy now, for reasons that could have been explained to him back then. He was ignoring the geological evidence for the great expanses of time that must have passed, but there were as yet no good clocks for geologic time. He was also ignoring the possibility of convection, and that should not have been acceptable. Crazy ideas are often ephemeral: What was crazy then can be "natural" now and vice versa.

As for Crazy Ideas of the Third Kind, opinions will vary, but perhaps one is the idea that gravity is an emergent phenomenon, an idea often attributed to Andrei Sakharov. The extension of a rubber band, which roughly obeys Hooke's law, is purely entropic and has nothing to do with the forces between the atoms that make up the material, so one could say that in that case a force law emerges from Boltzmann's definition of entropy. Or perhaps Roger Penrose and his fundamental discretization of spacetime would be one of the Third Kind. Many great developments in physics began encumbered with ideas that we have now shed—for example, Maxwell's molecular vortices.

My thesis adviser, Ed Salpeter, would occasionally say to me, "Is it crazy enough to be true?" I think what he meant is that when you're attempting to explain something important and it has resisted solution for a significant time, then the mundane explanation is unlikely to work, so you should be seeking the "crazy" answer. Although Salpeter almost invariably wrote papers of great solidity and impact, he did coauthor a paper with Carl Sagan on life in the atmosphere of Jupiter.[4] It was a good crazy paper, I think. Life in the atmosphere of Jupiter figures prominently in a science fiction novel, *The Algebraist* (Orbit, 2004), by Iain Banks.

In a somewhat similar spirit, Niels Bohr, responding to a lecture by Wolfgang Pauli, said, "We are all agreed that your theory is crazy. The question which divides us is whether it is crazy enough to have a chance of being correct." The hard part lies in figuring out what is crazy enough.

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LETTERS

Meghnad Saha and the contemporary scene

I much enjoyed Soma Banerjee's article "Meghnad Saha: Physicist and nationalist" (PHYSICS TODAY, August 2016, page 38), particularly for its bringing attention to Saha's English translation, with Satyendra Nath Bose, of Albert Einstein's and Hermann Minkowski's papers. Their translation was published by the University of Calcutta in 1920.

Many English-language readers of the papers found them in a later translation, first published in 1923 by Methuen in London. A paperback edition of that translation, *The Principle of Relativity* (Dover Publications), is still in print today.

In a letter to Einstein posted from Dacca University on 4 June 1924, Bose, then unknown internationally, introduced himself:

> I do not know whether you still remember that somebody from Calcutta asked your permission to translate your papers on Relativity in English. You acceded to the request. The book has since been published. I was the one who translated your paper on Generalised Relativity.

That letter also contained a copy of Bose's own English-language manuscript on the statistics of photons, which had been rejected for publication by the *Philosophical Magazine*. As aficionados of Bose–Einstein condensation know, Einstein, then already a world-famous scientist, soon arranged for Bose's paper to be translated into German and published in *Zeitschrift für Physik*.

The rest is history—though seemingly lost in its mists is the English original of Bose's famous paper. I've sought it for some time. Do any readers know its location?

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Soma Banerjee has provided a thoughtful and sensitive account of Meghnad Saha as a physicist and nationalist in India and his rise to international fame as an astrophysicist. I have a large collection of letters, given to me by Saha's family, between him and other scientists and between other scientists about him. I wanted to share some of the insights and knowledge I gathered from those letters and from other publications.

The notion persisted that Saha owed the idea of his groundbreaking work in astrophysics, the Saha equation, to Alfred Fowler, with whom he worked in England in 1920. Saha was particularly offended by a talk in 1946 in which Harry Plaskett discussed Saha's work on the thermal ionization theory. Saha found the discussion "entirely gratuitous and misleading" and wrote Plaskett a long letter discussing how and where the ionization theory was developed and describing his career in India. Plaskett's response was remarkable:

> What was quite new to me was the fact that the early part of your work had been done in India, not Germany, before you came to Fowler's laboratory. The knowledge that you had done so much without help and backing in India only serves to increase the admiration I have always felt for your great contribution to astrophysics. I only regret that I did not know about this at the time of my presidential address, and can only ascribe my ignorance to a probably incorrectly remembered statement of [Henry Norris] Russell on his return from England in the early 1920's. . . . Your place in the history of astrophysics is secured for all time. So much so indeed, that it seemed to me worthwhile to correct a tendency (prevalent in some quarters of the United States) to regard astrophysics stemming from the work of [William] Pickering and yourself, forgetting the indispensable contributions from [Ralph] Fowler and [Norman] Lockyer.

At the Calcutta School of Physics, Saha belonged to a generation of stellar physicists[1] that included Jagadish Bose, a pioneer of radio-wave communication, semiconductor junctions, and plant biophysics; Chandrasekhara Venkata Raman and Kariamanickam Srinivasa Krishnan, who also made major contributions to the discovery of the Raman effect;[2] and Satyendra Nath Bose of Bose–Einstein statistics, Bose–Einstein condensation, and bosons. That group emerged quickly in an almost barren field that had not yet produced internationally acclaimed scientists. Subrahmanyan Chandrasekhar, according to a biography by Kameshwar Wali, speculated that this remarkable assembly was probably associated "with the need for self-expression, which became a dominant motive among the young during the national movement. . . . We could show the West in their own realm that we were equal to them."[3]

The nationalistic spirit surely had played a major role in the emergence of that extraordinary group, but somehow the city of Calcutta was also fortunate to have visionaries and mentors like distinguished mathematician Asutosh Mukherjee, who was also a judge of the Calcutta High Court and later a vice chancellor of the University of Calcutta, and Prafulla Chandra Ray, a distinguished chemist and industrialist. Both were able to identify talents among the younger generation and tried to provide them with a nurturing environment and as much support as possible.

The Saha and S. N. Bose translation of the relativity papers of Albert Einstein and Hermann Minkowski in 1919, which represents the first translation of those papers, grew out of a program of self-study of relativity and quantum mechanics. Mukherjee, then vice chancellor, mandated that work for the newly hired young lecturers in the university so they could teach the new subjects to their students (see PHYSICS TODAY, September 2006, page 10). Saha and Bose were relieved of any teaching responsibility in their first year. Both the Saha equation and Bose–Einstein statistics followed soon after the self-study and marked the birth of theoretical physics research in India. Scientific research in India received very little financial or infrastructural support at the time of Saha and the others. Saha struggled to generate modest funding from different courses, including the US, but without much success.

In addition to his prolific scientific contributions, Saha also led various organizational aspects and coordination of scientific work in India. Chandrasekhar, then a student at Cambridge University, characterized those efforts as "beyond all praise"; he sought Saha's help for the release of Pyotr Kapitsa from his native country, the Soviet Union.

Later in his career, Saha got involved in national politics, as he thought he must put his knowledge of science to use in contributing to society. Although born into a Hindu family, his activism put him on a collision course with some Hindu religious leaders.

Meghnad Saha was twice nominated for the Nobel Prize by Arthur Compton, in 1937 and in 1940, but without success.

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3. Ref. 2, p. 246.

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Science is indeed special

This letter is in response to Charles Day's editorial "Science is special" (PHYSICS TODAY, July 2016, page 8). Obviously, there is an objective truth regarding the universe that exists external to the human mind. However, all of our scientific theories are products of the human mind and therefore not the same as the real universe. To what extent is the progress of science discovering the truth about the universe, and to what extent are humans simply inventing new theories to match current observation? It is human nature to want to believe that our theories are true, so in the debate over discovering versus inventing, our impulse is to skew in the direction of claiming that we are discovering something that was true before we discovered it.

In his book *Constructing Quarks: A Sociological History of Particle Physics* (University of Chicago Press, 1984), Andrew Pickering discusses the flaw in this way of looking at the history of science. Obviously, we discover individual facts that are objectively true, but is our entire view of the universe, based on our current scientific theories, true? Is it even close?

Throughout history, scientists have assumed that their view of the universe was close to being true. Each time, they were proven wrong. It is probably equally wrong to make the same assumption today. We can't even assume that we are making substantial progress toward knowing the truth about the universe, because we don't know how far our current theories are from the truth. Our progress to date might be negligible compared with the distance we have yet to go. However, we can measure the extent to which our present theories explain what we can currently examine. We observe natural phenomena, try to fit them into the framework of current theories, and try to think up explanations for them. Making new observations leads to new theories, which leads to technological advancements, which are applied to building new experimental tools, which enable us to observe natural phenomena that we could not detect previously, which means we have to revise our theories. The process continues in a never-ending feedback loop.

Let me pose a question: Can you arrive at the truth by a method other than science? My answer: That depends on what you mean by "science." We consider Western science to be motivated by natural philosophy going back to the ancient Greeks, which includes a framework of logical reasoning and the scientific method. That approach has been very successful. However, for centuries, the Chinese were able to make scientific progress without that Western tradition, which proves that it is possible, even though their science later stagnated compared with the West's.

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In his July 2016 editorial, Charles Day asks readers to imagine what extraterrestrial science might look like. Here's my response:

Planet Q is cold and dark by our standards, but it is teeming with life. Its inhabitants are microscopic; so small, in fact, that their tiny eyes can see one photon at a time. With their hands they can feel a single atom. They experience a world of quantum jumps, where nothing is gradual or smooth. They do not think of time as a continuously flowing quantity because the only way they can detect its passage is through some kind of change, and all the changes they see are spontaneous and unpredictable. For them, time lurches forward in fits and starts.

Their advanced understanding of quantum mechanics has enabled them to produce sophisticated technology—what we would call nanotechnology. But their science is based on discrete mathematics and number theory; they would be puzzled by our concept of a smooth, differentiable curve. They would be surprised to learn about our Schrödinger equation because it leaves out the quantum jump, the most prominent feature of the physical world.

It would be hard to convince the inhabitants of Planet Q that such things as electromagnetic waves exist, although, of course, they have analogues of diffraction and interference in their own equations. It would be like telling a couple of ants crawling across a pointillistic painting that they are actually standing on a drawing of an umbrella. That would seem unnecessarily abstract to them: Why would you group together those dots and call them something else? If you understand photons, you have no need of an electromagnetic field.

And the residents of Planet Q really would not recognize our ray optics. Even terrestrial physicists agree that such a thing as a light ray does not exist, yet they nevertheless calculate its displacement and direction as it goes through a lens. Earth-bound scientists might patiently explain that the light ray is a convenient fiction, a calculational tool; however, the beings from planet Q have brains that work like quantum computers, so they have no need of such mental crutches.

By contrast, the Shadow people are unimaginably large, each blood cell larger than a solar system, their bodies the size of a galaxy. They move slowly, think slowly, and pay no attention to us. Their physics describes their kind of matter, dark matter, and does not include any details about our familiar electrons, protons, and neutrons, since they hardly interact with those particles.

Zooming out from our galaxy, we see our whole universe, and then a myriad of other universes, coming into existence and expanding like the bubbles in a pot of water that has just come to a boil. That is the multiverse. It was created as a science fair project by an alien being whose name roughly translates to Timmy. He mixed together what we might call—in a very crude analogy—chemicals and heated them on the stove. (The secret, his mom said, is to add just the right amount of inflatons.)

As the pot started to boil, Timmy's eyes grew wide with delight. He leaned forward to take a closer look, and as our universe floated up, he said, "Wow!"—an exclamation that took, by our reckoning, 100 billion years.

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Footnote on femtochemistry

Marcos Dantus commented on the femtosecond bond formation by bringing readers' attention to his and others' early contributions in the 1990s (PHYSICS TODAY, November 2015, page 10). I would like to add to the discussion an interesting interview comment by Yuan T. Lee, who shared the 1986 Nobel Prize in Chemistry for his work on molecular beams.[1]

When Lee was asked, "Do you think that what is called femtochemistry has overtaken what you had been doing?," he replied,

> Not really. The people doing femtochemistry always say that for studying the molecular beams they have to go to femtochemistry. However, when we do chemical reactions, we already have the rotational period as a clock. In the reaction of potassium and methyl-iodide, what Dudley Herschbach was doing, it was possible to see the product bouncing backward in the time period of one rotation. That clock is a picosecond clock. It made it possible to tell how fast that chemical reaction took place. One of the reactions was particularly interesting. It was a charge transfer reaction between potassium and oxygen. At a long distance there is an electron transfer and the oxygen starts vibrating. Then at some point the electron jumps back to potassium. By looking at the angular distribution, it was possible to see the oscillation of electron jump probability based on the molecular vibration. It is a femtosecond phenomenon. In the beam experiments, there is a lot of information provided on a femtosecond timescale. Of course, when you use spectroscopy, you can see electronic excited states and how they decay on a femtosecond scale. However, it won't tell you anything about approach and molecular alignment and other spatial characteristics. Neither will it give information about angular momentum and the conservation of angular momentum.

Lee's arguments about the pico- and femto-clocking capability of molecular rotations and vibrations can be traced back to his Nobel lecture, in which he referred to more detailed expositions in the lecture by Herschbach, his co-laureate. In molecular-beam studies, the intrinsic clocking capability and insights gained from angular distributions of reactants and products are admittedly powerful and revealing. But rather than overshadowing traditional molecular-beam achievements, femtochemistry has contributed fundamentally to our understanding of molecular-reaction dynamics. Even for the seemingly simple bond-formation mechanisms mentioned by Dantus, there is still much more to discover. But that will happen only as we welcome more innovative theoretical and experimental advancements, following the legacy of Lee, Manfred Eigen, Ronald Norrish, Herschbach, Ahmed Zewail, and more.

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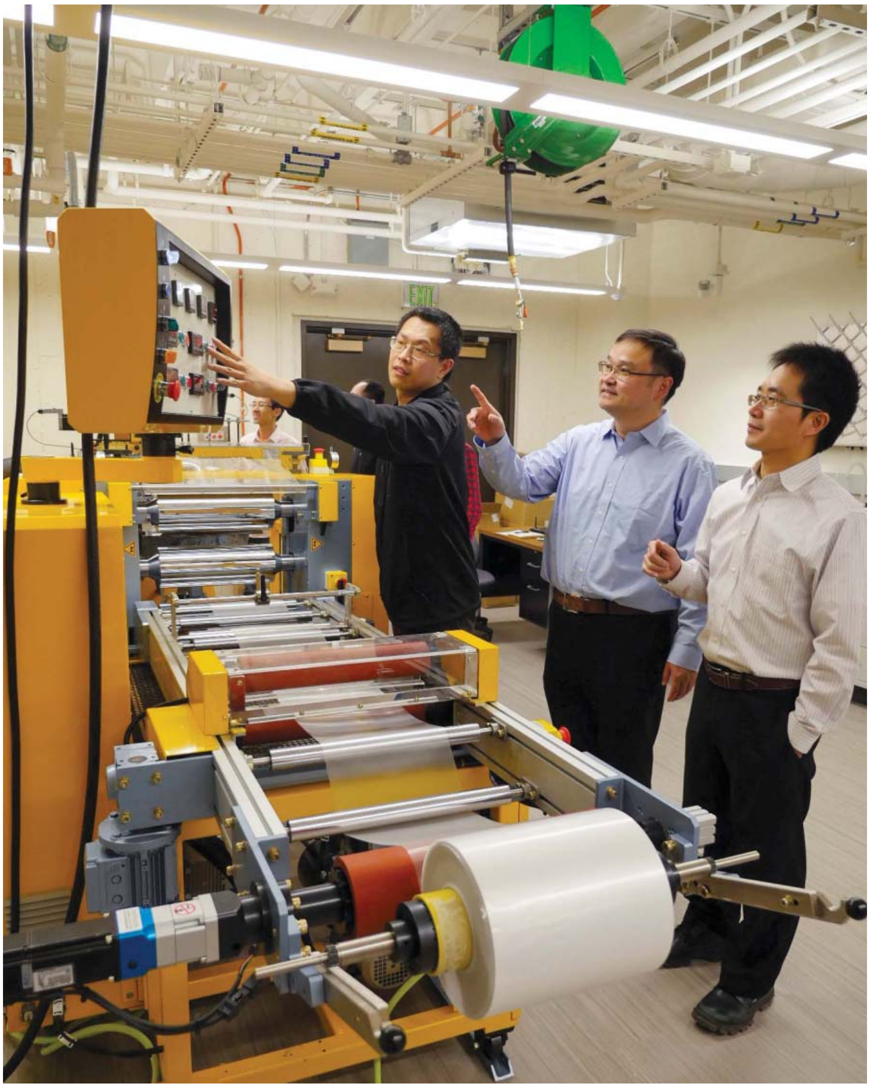
SEARCH & DISCOVERY

Passive cooling doesn't cost the planet

Inexpensive ingredients and scalable processes yield a material that can emit more energy than it absorbs, even under direct sunlight.



GLENN ASAKAWA, UNIVERSITY OF COLORADO

FIGURE 1. YAOGUANG MA, XIAOBO YIN, AND RONGGUI YANG (left to right) oversee the roll-to-roll production of the glass–polymer film used in their radiative cooling experiments.

Just over 10% of the electricity in the US is generated by the mechanical energy of wind and water. Almost all the rest is produced from heat: from fuel combustion, nuclear fission, geothermal energy, or concentrated sunlight.

The conversion from thermal to electrical energy is inevitably inefficient, so thermal power stations must dispose of a lot of waste heat. Usually that's done by cooling their turbines and reactors with water. But water is a finite resource that's not always plentiful around the ideal sites for power plants. An alternative is dry cooling with air instead of water, but those systems are expensive to build, and the large fans that circulate the air consume around 1% of the generated power.

Furthermore, discharging heat into the environment, whether by air or water, means that cooling can't go below the ambient temperature. Because a thermodynamic cycle's efficiency is a function of its temperature range, power plants generate significantly less power on hot days—when the demand for electricity is greatest—than they do on cold ones.

Motivated by the challenge of cooling power plants in hot weather, Ronggui Yang, Xiaobo Yin (both of the University of Colorado Boulder), and their colleagues have created a material capable of round-the-clock cooling to below the ambient temperature.[1] The material, a 50-μm-thick glass–polymer film backed with a 200-nm-thick silver coating, can be cost-effectively manufactured by standard industrial roll-to-roll methods, as shown in figure 1. Its cooling power is on the order of 100 W/m^2, so around a square kilometer of it could meet the cooling needs of a power plant, and 10–20 m^2 could rival the power of a residential air conditioner. A lot of work remains to be done before either of those applications can be realized. But obtaining enough of the material isn't expected to be a limiting factor.

Balance of power

The second law of thermodynamics dictates that heat can't spontaneously flow from a cooler object to a warmer one, all else being equal. Air conditioners and refrigerators therefore require energy to create and maintain an inside temperature lower than that of the outside air. But the Boulder group's material, astonishingly, is completely passive. It can cool itself and its surroundings to below the ambient temperature with no power input.

Key to the operation is the atmospheric window: the band of IR wavelengths between 8 and 13 μm over which the atmosphere, greenhouse gases and all, is nearly transparent. As shown in figure 2, the window coincides with the peak range of thermal radiation at typical terrestrial temperatures. It thus creates a thermal link that allows heat to flow directly between outer space and objects on Earth, bypassing the atmosphere. Space, with notably rare exceptions, is colder than Earth, so it acts as a thermal sink.

A material's temperature drops if it can shed more heat than it absorbs. Figure 3 shows the major sources that can contribute to that absorption: sunlight, thermal radiation from the atmosphere outside the 8–13 μm window, and nonradiative heat exchange with the immediate environment. The ideal cooling material, then, should emit strongly across the atmospheric window while absorbing little at other wavelengths.

The mechanism of passive radiative cooling has been understood for a long time, and demonstrations of cooling to below the ambient temperature[2] date back to the 1970s. But nearly all of those experiments were performed at night, when solar heating is not an issue. That made the proof of principle much easier, but in practice, the demand for cooling is greatest during the day. So despite some prototype designs for radiatively cooled rooftop panels, the idea never gained much traction.

Something new under the Sun

Adding sunlight to the mix makes cooling considerably harder. Absorption of just 10% or so of the Sun's radiation can negate all of a material's IR cooling power. A daytime cooling material must therefore be almost perfectly transparent to the solar spectrum. In a simple configuration, in which the cooling material is used as a coating to lower the temperature of an object underneath, a layer of reflective metal under the material can reflect away the sunlight. But then the sunlight must pass through the material twice, so it has two chances to be absorbed.

In 2014 Stanford University's Shanhui Fan and his colleagues demonstrated daytime radiative cooling to 5 K below the ambient temperature.[3] To get the necessary combination of solar reflection and IR emission, they used a nanophotonic material with alternating layers of silicon dioxide and hafnium dioxide. A phonon resonance in SiO_2 causes strong IR absorption and emission at around 9 μm, and the layering with HfO_2 creates interference effects that broaden the resonance to encompass the entire atmospheric window. To make the layers with

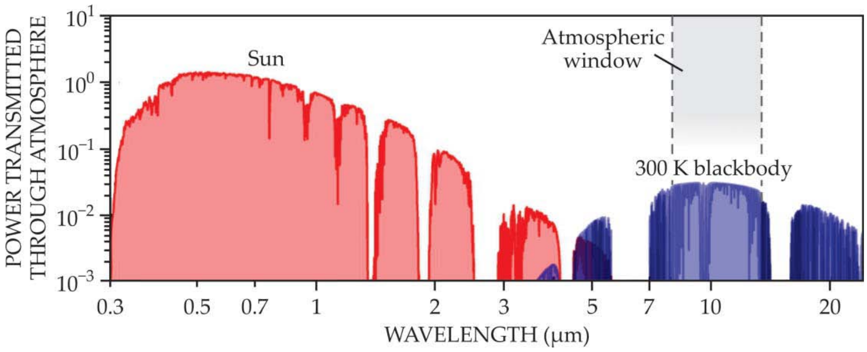


FIGURE 2. THERMAL RADIATION from the Sun and from a room-temperature object on Earth have little spectral overlap, as shown by these logarithmic plots of the radiative power transmitted through the atmosphere. It's possible, therefore, to design a material that emits strongly into the 8–13 μm atmospheric-transparency window while being transparent to sunlight. (Adapted from ref. 1.)

precise thicknesses ranging from 13 nm to 688 nm, Fan and company fabricated their material using electron beam evaporation under cleanroom conditions—a process that doesn't easily lend itself to mass production.

The Boulder group achieved a similar effect with a much less precisely structured material: SiO_2 microbeads dispersed in a transparent polymer film. (For their demonstration, the researchers used polymethylpentene, a polymer widely used in medical products. But, they say, any optically transparent polymer should work.) The basis of the IR absorption is the same SiO_2 phonon resonance, enhanced and broadened by the beads' surface modes and collective interactions.

Crucially, no effort was made to control the beads' exact positions, and their overall arrangement was random—the beads' diameter (8 μm) and concentration (6% by volume) turned out to generate the required spectral properties by themselves. "We usually think of photonic structures as having to be periodic," says Yin, "so we were surprised that this random optical structure could work." That structural freedom allowed the researchers to use scalable production techniques to fabricate their material at a rate of 1.5 m^2 per minute, or hundreds of square meters over the course of their experiment.

To measure the material's cooling power, the researchers connected it to a feedback-controlled electric heater; the rate at which energy was shed into space would match the rate of heating required to keep the system at exactly the ambient temperature. Over three days, they found an average cooling power of 93 W/m^2 at midday and well over 100 W/m^2 at night.

Inconvenient truths

An air-conditioner replacement that consumes no power is an exciting prospect. "But that's a long-term goal," Yang stresses. "We will have to do a lot of thermal system engineering." Simply placing the cooling material on the roof won't cool an entire building if the roof is insulated. And most places don't need constant cooling at night and in the winter, so there would have to be a way to turn the cooling on and off. For example, the material could cool a reservoir of water that's then circulated through the building as needed. But the details have yet to be worked out.

Another challenge is in limiting or mitigating heat exchange with the environment. As the glass–polymer film drops below ambient temperature, heat flows conductively and convectively in proportion to the temperature difference, and the cooling power drops. In effect, the film cools the atmosphere above in addition to whatever's below. Because the Boulder researchers used the feedback heater to keep the film at ambient temperature, their measurements don't account for that efficiency drop. They did do a test without the feedback heater, in which they cooled some water to 8 K below the ambient temperature. But that was at night, without the complication of solar heating.

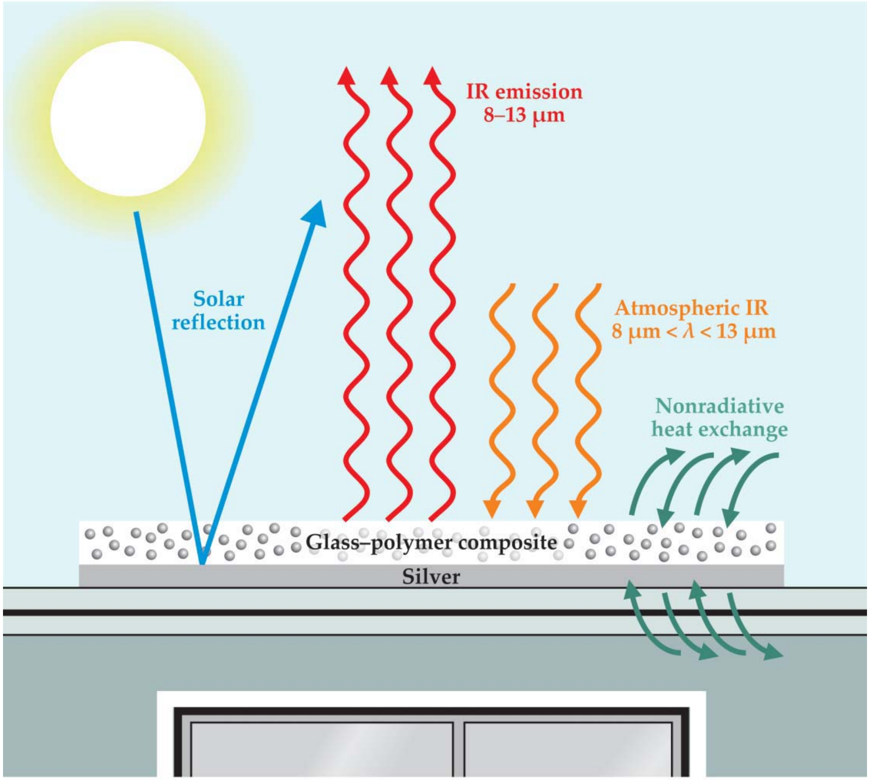


FIGURE 3. A GLASS–POLYMER COOLING PANEL, depicted here on the roof of a house, must emit more energy into space than it absorbs from other sources: from the Sun, from atmospheric thermal radiation, and from the environment via conductive and convective heat exchange. To keep the sunlight from warming the underlying roof, a film of silver reflects it away.

To best discharge heat into space, the film needs to face a clear, unobstructed patch of sky. Surrounding buildings, trees, clouds, and dirt on the film's surface could all compromise the cooling efficiency by emitting their own thermal radiation that the film then absorbs. Humidity, too, diminishes the atmosphere's transparency in the 8–13 μm window and reduces the cooling effectiveness. The Boulder researchers did their tests under nearly ideal conditions: on a series of clear, dry days in an open space in Arizona. "We want to get a better understanding of how atmospheric and geological conditions affect cooling," says Yang, "but that's not our area of expertise. And we're just starting to study the effects of dirt on the film."

A more immediate application could be adhering the film (without the silver backing) to the surfaces of photovoltaic cells, which can lose efficiency when they get too hot. The researchers expect that the material could be ready for market in as little as a year or two. Beyond radiative cooling, they emphasize the potential to draw on the existing body of research on photonics and spectral engineering to create inexpensive, mass-producible materials. Says Yin, "You don't need a cleanroom to make a photonic structure."

Johanna Miller

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Magnetic trap snares methyl radicals

The ability to isolate the important reaction intermediates at subkelvin temperatures could be a boon to cold chemistry.

By and large, physicists have succeeded in their quest to tame the atom. These days, atoms can be laser cooled to their ground states, stored in traps for minutes, and switched between internal states virtually at will. (See the article by Ignacio Cirac and Peter Zoller in PHYSICS TODAY, March 2004, page 38.)

Molecules, however, are wilder beasts. They are all but impervious to laser cooling, which demands a closed optical loop—that is, a sequence of photoexcitation and decay that can be repeated ad infinitum. Due to the additional degrees of freedom afforded by rotational and vibrational modes, molecules tend to decay unpredictably, often to states that can't be optically addressed. Inevitably, the loop breaks.

Over the years, experimenters have devised strategies to overcome the optical-loop problem: creating cold molecules *in situ* from cold, trapped clouds of reactive atoms (see the article by Debbie Jin and Jun Ye, PHYSICS TODAY, May 2011, page 27); cooling molecules "sympathetically" by letting them thermalize with cold atoms; closing optical loops by using RF fields to periodically reset molecules' internal states (see PHYSICS TODAY, January 2010, page 9). But those methods generally either work only in limited cases or yield gases that are too dilute for investigations of cold-molecule collisions, Bose–Einstein condensation, and other quantum phenomena of interest.

A fourth way to cool molecules into the quantum realm is simply to let them escape from a pressurized container into a vacuum. If the initial pressure is suitably high and the escape orifice suitably small, the temperature of the exiting molecules will fall to well below 1 K, cold enough that they behave more like waves than particles. For the experimenter set on interrogating them, however, there's a complication: The molecules will shoot from the orifice at roughly the speed of a rifle bullet.

In 2000 Gerard Meijer and his colleagues at the University of Nijmegen in the Netherlands showed that such beams could be slowed to a standstill using pulsed electric fields, provided the molecules had sufficiently strong electric dipoles.[1] Now researchers led by Takamasa Momose (University of British Columbia, Vancouver, Canada) and David Carty (Durham University, UK) have pulled off an analogous feat on a molecule that has no electric dipole at all: They used pulsed magnetic fields to decelerate and trap a beam of methyl radicals cooled to their rotational ground state.[2] The new trapping technique can be applied not only to CH_3 but to any molecule with a magnetic moment—a class that includes essentially the entire family of reactive intermediates known as radicals.

Zeeman deceleration

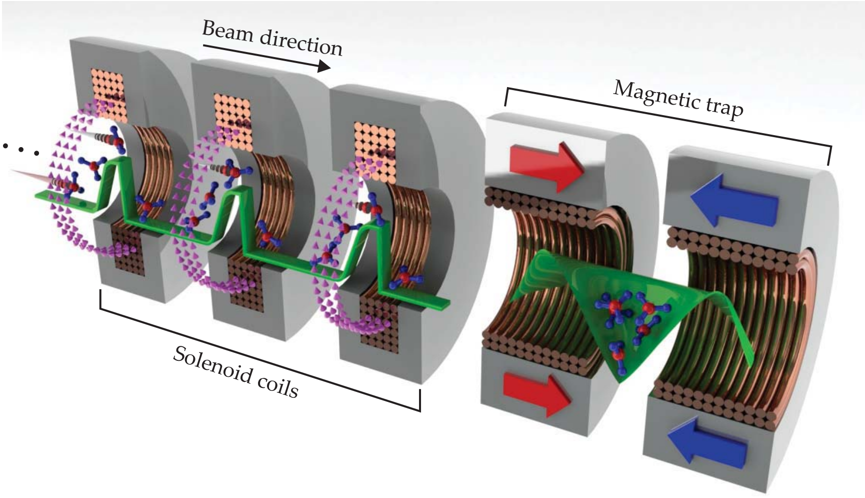
The concept behind the new decelerator and trap is nearly a decade old, developed by Frédéric Merkt and coworkers at ETH Zürich as a way to corral beams of paramagnetic atoms. When such beams are directed through the magnetic field of a solenoid coil, about half the atoms have their unpaired electron spin aligned antiparallel to the field. Those atoms are weakly repelled by the field due to the Zeeman effect, whereby the energy of an antiparallel state grows in proportion to an external field.

But that repulsion alone doesn't suffice to slow an atomic beam. A fast-moving atom's encounter with a localized magnetic field is like a fast-rolling ball's encounter with a mound: The atom expends kinetic energy climbing the magnetic potential but regains it during the ensuing descent. The trick with Zeeman deceleration is to switch the coil off just as the atoms arrive at the field's peak, so that the expended kinetic energy is permanently lost. By repeating that process with a succession of a dozen coils, each delivering 1 T pulses, Merkt and his coworkers could stop atoms entirely.

For nearly a decade now, Merkt's group has been using the approach to trap atomic hydrogen and deuterium. But stopping the heftier CH_3 radicals called for considerably greater braking force. Momose and his colleagues needed coils that could deliver pulses exceeding 4 T, on par with the strongest magnets in laboratory use. And they needed 85 of them.

The team's instrument, a meter-long cylinder lined with 4-mm-diameter solenoid coils, is partially illustrated in the figure on page 20. (The design is a modified version of an atom decelerator built by a University of Texas at Austin group led by Mark Raizen.[3]) At the outlet is a pair of opposing permanent magnets that serve as the trap. Near the inlet, a nozzle spouts CH_3 radicals in cold, bunched beams. The appropriate timing for each pulse could be calculated based on the gas's initial velocity, around 320 m/s. But coordinating the coils to fire with the requisite precision took considerable technical know-how. "We have to send 700 amps to each of the 85 coils for just a few microseconds at a time," Momose explains. "And we have to do it inside a vacuum. There are always dielectric breakdowns."

In all, it took six years to get the instrument working—three to decelerate molecules and another three to stop them. In a typical run the team captures some 50 000 molecules in the 1 mm^3 magnetic trap, where they can be held for about a second. The trapped gas is sufficiently dense to allow precise measurements of cross sections for collisions between CH_3 and assorted background gases; those measurements are already under way.



A FAST BEAM OF METHYL RADICALS can be slowed to a near standstill with a series of well-timed magnetic pulses from solenoid coils. Each pulse exerts a braking force on molecules with magnetic moments oriented antiparallel to the magnetic field. (The green curves indicate effective potentials for such a molecule as it travels, from left to right, through the device; purple triangles indicate the direction of the electric current.) As molecules exit the final coil, they can be trapped in the field of two ring-shaped permanent magnets, whose polarities are indicated by the red and blue arrows. The real-life implementation uses 85 4-mm-diameter coils, as opposed to the three shown here. (Adapted from ref. 2.)

"It would have been extremely difficult to trap methyl radicals using any other method," comments Edvardas Narevicius, whose group at the Weizmann Institute of Science has been developing a magnetic decelerator to simultaneously trap lithium and molecular oxygen.[4] "This is really a big step forward expanding the number of species that we can address."

Interstellar chemistry

On occasion, Momose cadges time at the Nobeyama Radio Observatory's 45 m telescope in Nagano, Japan. There he combs the space between stars for spectral lines produced by small hydrocarbon molecules, which are puzzlingly abundant in the interstellar medium. A possible explanation is that the rates of hydrocarbon-forming reactions are boosted by quantum tunneling through activation-energy barriers.

That's one reason Momose is especially excited about the newfound ability to isolate cold CH_3. He previously worked with researchers at Kyoto University in Japan to detect tunneling contributions to the methane-forming reaction $CH_3 + H_2 \rightarrow CH_4 + H$ in cryogenic hydrogen crystals. Now that CH_3 can be more comprehensively isolated from environmental influences, he hopes to measure those tunneling rates with far greater precision.

The ability to trap CH_3 also presents opportunities for fundamental physics. With the molecule in its rotational ground state, the researchers can make precise measurements of hyperfine transitions and parity-violating interactions. (See the article by David DeMille, PHYSICS TODAY, December 2015, page 34.) Ultimately, however, they hope to create a molecular gas that's cold enough and dense enough to form a Bose–Einstein condensate.

Momose thinks they should be able to cool their gas to submillikelvin temperatures via sympathetic cooling, "and then evaporative cooling should get us much lower, down to 1 microkelvin. Then the only missing part would be the density."

A BEC requires a phase space density of order 1, which would translate to a volumetric density about three orders of magnitude higher than the 5×10^7 cm^{-3} that Momose and company have achieved so far. "We'd probably need to build another decelerator," he muses. "So that would mean another three years."

Ashley G. Smart

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Why the ocean's carbon sink has gotten stronger

The past decade's slowdown of overturning boosted the ocean's ability to take up carbon dioxide, but the enforcement may not last.

In just over a century, the atmosphere's carbon dioxide concentration has risen from around 280 ppm to 400 ppm. That increase is a consequence of the burning of fossil fuels, conversion of forests into farm lands, and other human activities. Yet if all anthropogenic carbon stayed in the atmosphere, the rate at which atmospheric CO_2 concentration is presently increasing would be more than double its actual value. Instead, terrestrial plants, soils, and the ocean have taken up a significant tranche of the anthropogenic CO_2. (See the article by Jorge Sarmiento and Nicolas Gruber, PHYSICS TODAY, August 2002, page 30.) Some 30–40% of all anthropogenic CO_2 emitted since the late 18th century is thought to have been absorbed by the ocean.

The net flow of CO_2 across the air–sea boundary depends on the relative concentrations of the greenhouse gas in the ocean and the atmosphere. Attention has understandably focused on rising CO_2 levels in the atmosphere, but the ocean is no passive bystander. The 1990s saw a weakening of the ocean's carbon sink, which was attributed to the strengthening of westerly winds over the Southern Ocean, the waters encircling Antarctica.[1] Those winds combine with the Coriolis force to drive the northward flow of surface waters, which in turn draws carbon-rich deep waters to the surface. Puzzlingly, the ocean's carbon sink recovered in the 2000s even though the westerly winds remained strong.[2]

To tease out what other factors might be at play, Timothy DeVries at the University of California, Santa Barbara, Mark Holzer at the University of New South Wales in Australia, and François Primeau at the University of California, Irvine, took a look below the ocean surface. The researchers ran model simulations of the global ocean overturning circulation—the transport of surface waters downward and deep waters upward—for the 1980s, 1990s, and 2000s and then fed the results into an ocean carbon-cycle model. Their findings identify changes in the pace of circulation in the upper 1000 m of the global ocean as the primary driver of the observed trends in the ocean's net carbon uptake.[3]

The ups and downs

Global ocean overturning circulation involves water at all depths—from the surface down to the abyss some 4000–6000 m below—and operates at 1000-year time scales. (See the article by Adele Morrison, Thomas Frölicher, and Jorge Sarmiento, PHYSICS TODAY, January 2015, page 27.) For decadal variability in the ocean carbon sink, though, DeVries and his colleagues focused on the upper 1000 m of ocean, because deeper waters are unlikely to reach the surface in those time frames.

Ocean general-circulation models typically start with an at-rest ocean with some initial distribution of temperature and salinity. Turning on hydrodynamic and thermodynamic processes gets the waters moving, and then the model is stepped through time, often for thousands of simulated years, until an equilibrium circulation pattern emerges. Observational data serve mostly to set reasonable initial conditions.

DeVries and his colleagues opted for a different approach that places at center stage observational data for temperature, salinity, naturally occurring carbon-14, and chlorofluorocarbon distributions, each of which helps to reveal when a parcel of water last contacted the ocean surface. Chlorofluorocarbons, the ozone-depleting gases once widely used as refrigerants (see the article by Anne Douglass, Paul Newman, and Susan Solomon, PHYSICS TODAY, July 2014, page 42), are a particularly good tracer because their history in the atmosphere is well known and their distribution in the ocean has been extensively measured.

Rather than relying solely on simulated ocean dynamics, the group iteratively minimized the differences between simulated and measured tracer distributions to reach a solution that's consistent with observations. "Essentially, we give the model the data," explains DeVries, "and ask it to find the circulation that best matches the data."

"In some sense you get the best of the underlying physical theory, and you get the best of the observations," says Galen McKinley of the University of Wisconsin–Madison. "This is definitely a new approach, and I think it's a really great addition to the toolkit of being able to understand the ocean carbon cycle," she adds.

DeVries and Primeau debuted their model six years ago to determine the long-term average ocean circulation.[4] What's new this time around is that the researchers have accounted for data from the 1980s, 1990s, and 2000s separately to examine how the circulation changed over time.

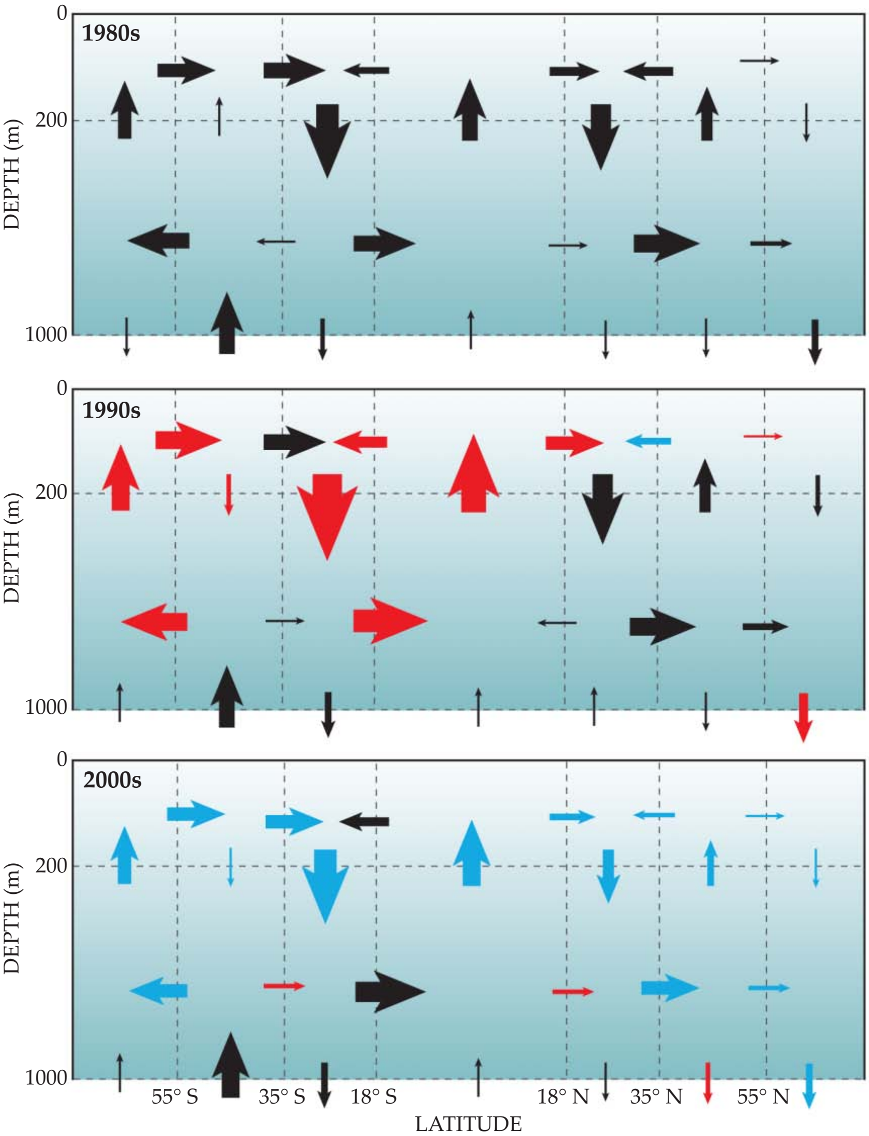

FIGURE 1. OVERTURNING IN THE UPPER 1000 m of the ocean in the 1980s (top), 1990s (middle), and 2000s (bottom). The arrows indicate the directions and magnitudes of longitude-summed fluid transport rates across various latitude and depth boundaries. They range from less than 1 sverdrup (1 sverdrup $= 10^6$ m^3/s) for the thinnest arrows to 37 sverdrup for the thickest. Red arrows indicate that the magnitude of volume flow has increased relative to the previous decade, and blue arrows indicate a decrease. (Adapted from ref. 3.)

Figure 1 shows the upper-ocean overturning circulation for the three decades, obtained by DeVries and his colleagues. In the 1990s the circulation strengthened relative to the 1980s primarily in the Southern Hemisphere, in line with previous analyses. In the 2000s that trend reversed; both Northern and Southern Hemispheres exhibited reduced overturning.

The computational cost for getting that decade-resolved view meant foregoing a strictly realistic continuous evolution of the ocean circulation. The model simply computes a mean steady-state circulation for each of the three decades.

In addition, measurements at many locations have been infrequent, in some cases only once every 5 or even 10 years. The use of robotic instrumentation in recent years has led to improved data coverage for temperature and salinity. But for chlorofluorocarbons, "we still have to go out on ships and do those measurements the hard way," DeVries says. "Unfortunately, we can't go back in time and fill in the gaps we have."

Still, DeVries is hopeful that in the future he and his colleagues will be able to capture circulation changes not from just one decade to the next but from one year to the next. They could then see how quickly the changes took place and perhaps figure out what physical processes drove them.

What's circulation got to do with it?

Once they established the decadal circulation patterns, DeVries and his colleagues used them in an ocean carbon-cycle model to see how changing circulation would affect the ocean's ability to absorb CO_2. As illustrated in figure 2, the vigorous overturning in the 1990s enhanced the transport of surface waters to the deep. If that were the only effect, one might expect that the ocean's ability to uptake anthropogenic CO_2 would increase, as it indeed did according to the researchers' model.

However, the overturning also brought carbon-rich deep waters to the surface. Once there, the abundant carbon in the upwelled water could escape into the atmosphere. The overall balance tipped toward a weakening of the ocean's net carbon uptake from 1.7 Pg C/year in the 1980s to 1.3 Pg C/year in the 1990s

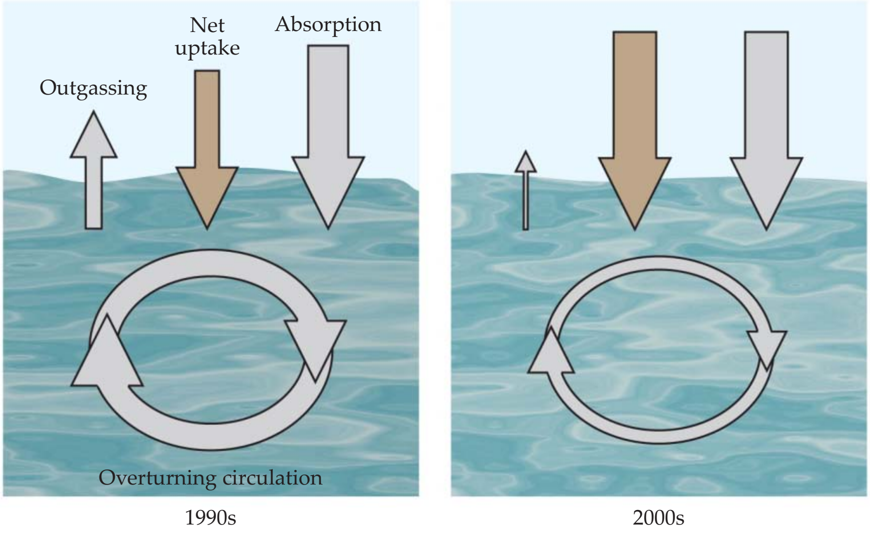

FIGURE 2. CIRCULATION'S ROLE in the ocean's carbon dioxide uptake. The overturning circulation in the upper 1000 m of the ocean transports absorbed atmospheric CO_2 downward but simultaneously brings up natural CO_2 from the deep. Combined with increased atmospheric CO_2 concentrations, weakening overturning circulation in the 2000s resulted in greater net uptake (brown) of CO_2 in that decade. (Adapted from ref. 3.)

(1 Pg = 10^{15} g). The largest reduction occurred in the subantarctic (latitudes 55° S to 35° S), where newly risen deep water in the Southern Ocean encounters the atmosphere.

When the overturning circulation weakened in the 2000s, less anthropogenic CO_2 was sent down to the depths, but even less deep-ocean carbon escaped into the air. On balance, therefore, the ocean took up more CO_2 than before. That might sound like good news; after all, it means less CO_2 accumulated in the atmosphere. However, coral bleaching and other consequences of ocean acidification make increased CO_2 uptake by the ocean a mixed blessing at best.

Besides, says DeVries, "we think that the effect is going to gradually wear off." The amount of deep ocean CO_2 rising to the surface will eventually plateau even as ever more fossil-fuel CO_2 makes its way into the atmosphere. The balance will tip in favor of reduced ocean CO_2 uptake. Then the slowing ocean overturning circulation will seem to be bad news all around.

Sung Chang

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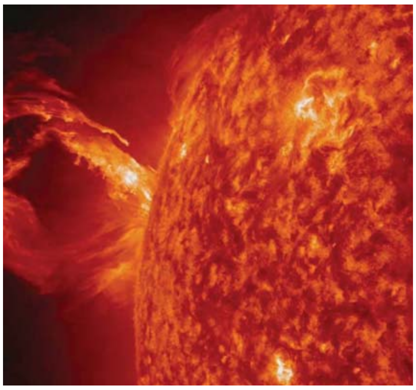
PHYSICS UPDATE

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

THE UPPER ATMOSPHERE'S NATURAL THERMOSTAT

Occasionally, our sun belches massive plumes of plasma from its corona that stream Earthward. When a fast coronal mass ejection (CME) arrives, it compresses Earth's magnetosphere and can reconfigure the planet's magnetic field lines. The reconfiguration enhances electric currents and energizes charged particles. Those currents and particles heat the tenuous atmosphere—hundreds of kilometers in altitude—which then expands outward. Low-orbiting satellites should thus experience more drag. But measurements of their orbital decay reveal that the drag from CMEs isn't always as great as expected. Researchers led by Delores Knipp (University of Colorado Boulder) now explain why. Under some circumstances, the same CME that heats the upper atmosphere also triggers chemical reactions that quickly cool it. Charged particles with energies greater than about 10 keV split molecular nitrogen, and the free N atoms react with oxygen to produce nitric oxide. The NO molecules, often created in a vibrationally excited state, spontaneously radiate in the IR. The upshot is that they remove energy from the heaving atmosphere and thereby cool and contract it.

From an archive of satellite data, the researchers analyzed the IR flux from NO as it responded to nearly 200 isolated CMEs that struck Earth between 2002 and 2014. They found that the fastest CMEs—ones whose speeds exceeded 500 km/s and produced shock waves ahead of the ejected plasma—led to early and copious NO production and emission. The shock-led CMEs transferred so much energy into the upper atmosphere that they generated more than twice the IR flux as non-shock-led storms. Knipp and her colleagues are hopeful their analysis will offer new insights for atmospheric modelers and satellite-drag forecasters trying to plan and track orbits that avoid collisions with space debris. (D. J. Knipp et al., *Space Weather*, doi:10.1002/2016SW001567.) —RMW



NASA/GODDARD/SDO

HELIUM COMPOUND MAY FORM UNDER PRESSURE

Helium doesn't play well with others. Beyond its noble gas designation on the periodic table, it has the lowest electron affinity—zero—among the elements, and the highest ionization energy. Scientists have managed to mechanically pack He atoms with other elements, but the He has little effect on those compounds' characteristics.

Now an international team has presented evidence for a compound whose electronic structure and thus its physical properties are influenced by its He components. Researchers led by Artem Oganov ran a crystal structure prediction algorithm to play matchmaker for He and found that the compound Na_2He should form at high pressures. The researchers shared their prediction with Alexander Goncharov and colleagues, who loaded He gas and solid sodium into a diamond-anvil cell at the Carnegie Institution for Science. After increasing the pressure to 140 GPa and heating the sample, Goncharov's team noticed a marked shift in material properties. New peaks appeared in x-ray diffraction patterns, and the sample's melting point rose to more than 1500 K; pure Na melts at about 550 K.

The scientists say they have created a novel insulating ionic crystal in which He atoms take residence inside cube-shaped voids present in the lattice of Na atoms; in doing so, the He atoms force Na electrons out into neighboring voids. Though the He atoms do not form bonds, they facilitate a new stable arrangement in which each non-He-occupied cube shares a pair of electrons.

Andreas Hermann, a materials scientist who was not involved in the research, is impressed by the theoretical analysis but says that "follow-up experiments seem necessary" to confirm the Na_2He interpretation. He notes that the x-ray diffraction pattern includes the peaks predicted for Na_2He but also some unexplained extra ones. And Hermann would like to see more details supporting the researchers' claim that the compound Na_2HeO should also prove stable.

Assuming Na_2He has formed between the diamond tips at Carnegie, scientists will want to explore the possibility that helium is crushed into compounds inside the cores of gas giant planets. (X. Dong et al., *Nat. Chem.*, in press.) —AG

A GRAVITATIONAL-LENSING MEASUREMENT OF THE HUBBLE CONSTANT

In 1929 Edwin Hubble confirmed that galaxies are receding from us with a speed proportional to their distance: $v = H_0 d$. As late as the mid 1990s, the value of the proportionality constant H_0, the Hubble constant, was known only to be somewhere between 50 and 90 km/s per megaparsec (see the article by Mario Livio and Adam Riess, PHYSICS TODAY, October 2013, page 41). With the help of space-based observatories, H_0 can now be determined with a precision of about 1%. The value obtained from a detailed map of the cosmic microwave background (CMB) is 66.93 ± 0.62 km/s/Mpc. But that determination is in tension with the value of 73.24 ± 1.74 km/s/Mpc derived from standard candles (Cepheid variables and type Ia supernovae, whose luminosities are known).

Now the H0LiCOW (H_0 Lenses in COSMOGRAIL's Wellspring) collaboration has presented a comparably precise measurement based on its observations of three gravitationally lensed quasar systems. The H0LiCOW result, $H_0 = 71.9 + 2.4 - 3.0$ km/s/Mpc, agrees with the standard-candle determination, but it is about 2 standard deviations distant from the CMB-derived value.

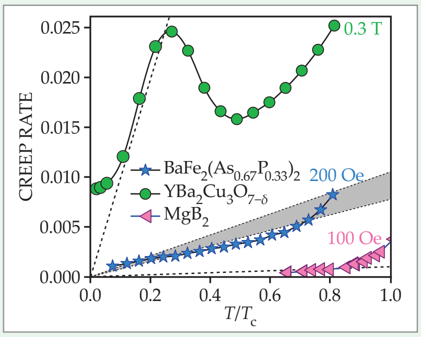
When light traveling from a quasar to Earth passes by a sufficiently massive galaxy, the galaxy can act as a lens that bends the quasar light. As a result, Earthbound astronomers see multiple images of the quasar as shown in the figure. At times the brightness of the quasar flickers, and those fluctuations at the source are observed in the lensed images too. But since each image corresponds to a slightly different path length from quasar to telescope, the flickers appear at slightly different times for each image. The H0LiCOW team carefully measured those time delays, which are inversely proportional to H_0.

ESA/HUBBLE, NASA, SUYU ET AL.

The Hubble constant determination from the CMB assumes, among other things, that the universe is flat and that dark energy is characterized by Einstein's cosmological constant. If the conflicting values suggested by standard candles and lensed quasars hold up, some of the assumptions of cosmology's now-standard model may need to be revised. (V. Bonvin et al., *Mon. Not. R. Astron. Soc.* **465**, 4914, 2017.) —SKB

UNIVERSAL LOWER BOUND ON THE DISSIPATION OF SUPERCONDUCTORS

Despite their name, not all superconductors have zero resistance below their transition temperature T_c, at least when placed in a sufficiently strong magnetic field. For so-called type 2 superconductors—a class that includes high-temperature cuprate, iron-based, and magnesium diboride superconductors—the field penetrates and forms a lattice of vortices. Each vortex is an eddy of supercurrent that encircles a quantized amount of magnetic flux. Crystal defects, often intentionally introduced, will tend to pin the vortex lattice in place, but a sufficiently high current will force the vortices to move. That motion dissipates energy and manifests itself as a finite resistance. For currents slightly below the threshold, thermal fluctuations can provide the extra kick needed to knock the lattice free. Known as creep, thermally activated vortex motion can limit the operating range in applications such as high-field magnets and power transmission. The discovery of iron-based superconductors a decade ago challenged the understanding of vortex creep: The materials' observed creep rate was significantly higher than expected. Serena Eley (Los Alamos National Laboratory) and colleagues now report on their study of $BaFe_2(As_{0.67}P_{0.33})_2$. The research did not explain the high creep rates in iron superconductors—indeed, the team observed the lowest rate yet seen for those materials. But the researchers did find a universal lower bound for the low-temperature creep rate, one that depends only on the ratio of temperature to T_c and on the square root of the Ginzburg number, which parameterizes the scale of thermal fluctuations with respect to the superconductor's magnetic properties. The figure shows how the derived limits (dashed lines) compare with measured creep rates for different superconductors. The researchers conclude that any new high-T_c superconductor will have high creep; the work may also help guide materials design for superconductor applications. (S. Eley et al., *Nat. Mater.*, in press, doi:10.1038/nmat4840.) —RJF PT



ISSUES & EVENTS

Undergraduate labs lag in science and technology

Grants, prizes, and new experiments aim to bolster the status and stature of lab instruction.

Undergraduate physics laboratory instruction in the US is in disarray: Equipment is dilapidated, experiments are not up to date, many schools don't offer labs beyond the first year, faculty get scant credit for investing time in the labs, and funding for maintaining and updating labs is lacking. "There is a problem, there really is, at every level," says Randolph Peterson, a physicist at Sewanee University in Tennessee.

A host of intertwined efforts are emerging to combat the problems facing undergraduate laboratory teaching. Those efforts include conferences, training sessions, and other activities organized by the Advanced Laboratory Physics Association (ALPhA), a decade-old professional organization of which Peterson is president. Two years ago physicist Jonathan Reichert created a foundation to promote and support undergraduate physics laboratory instruction. TeachSpin, the company he started more than two decades ago, now belongs to the foundation and continues to create and disseminate new experiments for advanced lab instruction.

The latest thing to hit the streets is TeachSpin's 44-foot trailer, dubbed the Food Truck for the Physics Mind. It debuted in January, with a mission of hauling a suite of hands-on experiments for one- and two-day visits to physics departments around the country.

Tight funding, low status

Among the roughly 750 institutions in the US that offer a physics bachelor's degree, "there has been a collapse" in lab courses in recent decades, says Illinois Wesleyan University's Gabriel Spalding, an ALPhA board member and vice president of the Reichert Foundation. The traditional physics curriculum is made up of labs, lectures, and computational work, he says. At ALPhA, "we are trying to promote covaluing the hands-on labs." In terms of laboratory equipment, poor institutions are more challenged, he notes, but adds that "it's surprising how little some top-ranked institutions are doing."

One reason that laboratory instruction is suffering is that money for updating equipment has shrunk and become harder to obtain. In 1985 NSF established the Instrumentation and Laboratory Improvement (ILI) program, which made matching grants available for lab equipment in many fields of science. In its first decade, according to NSF program records, ILI awards were made to 1185 institutions in amounts from $5000 to $100 000 and totaling $158.6 million.

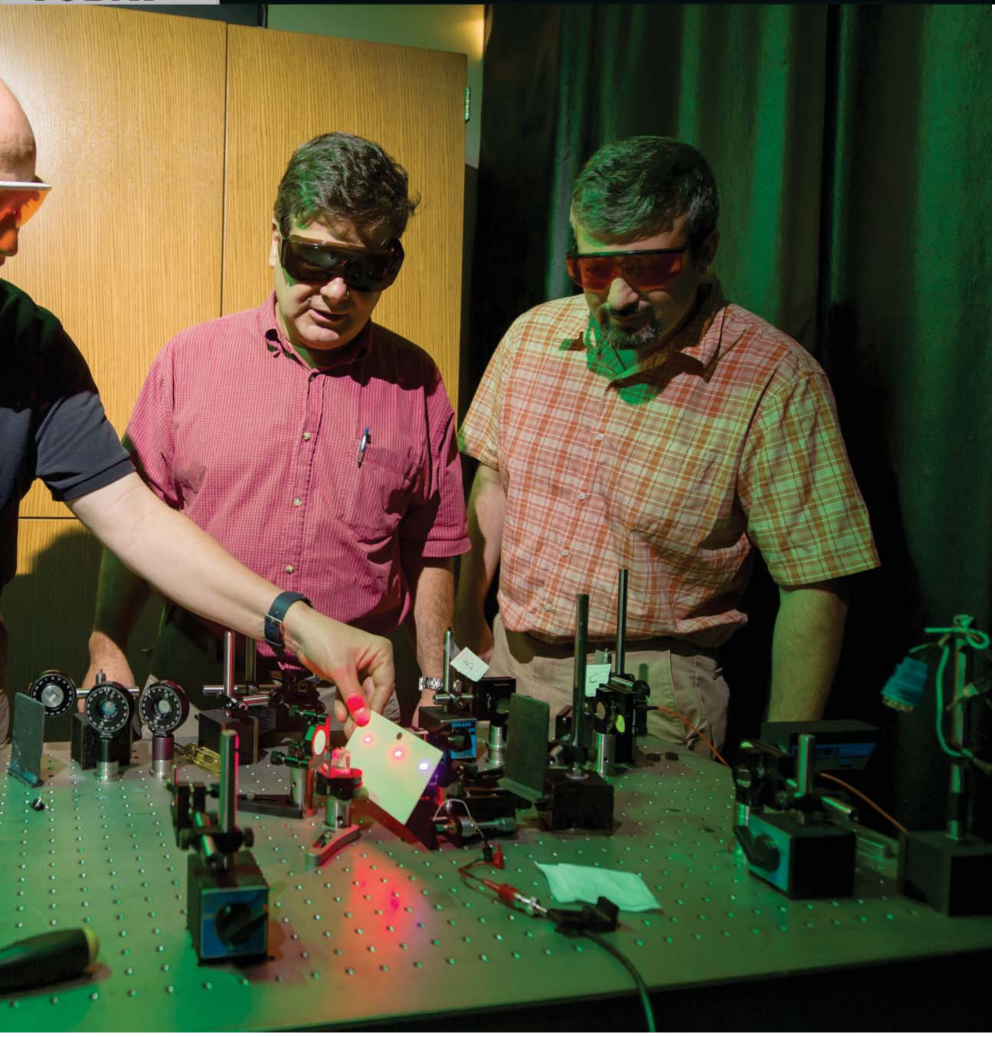
Over the years the ILI program has been transformed and repackaged several times. "Initiatives that once focused largely on equipment have adopted broader educational missions," says NSF spokesperson Robert Margetta. Tracing the funding level through those incarnations is nearly impossible, he says, but it's definitely less than was available in earlier years. Moreover, the directions for the current program require applicants to "be clear about the knowledge generating aspects of their proposal."

That's an unreasonable barrier, says Peterson. "If I want money for equipment, I don't want to do physics education research [PER]. And if someone else wants to do PER, they don't want to approach developing an experimental lab the way I go about it." He notes that departments typically allocate about $1000 a year for laboratory equipment and supplies. Sometimes scientists can get money for laboratory experiments by including them as outreach in a proposal for research money. But, says Spalding, "there really is no significant federal money for instructional lab equipment anymore."

A. DADDIO

In July 2015 some 365 physicists, including many of ALPhA's roughly 250 members, signed a petition calling on NSF to "immediately begin focused discussion of ways to re-energize its commitment to instructional laboratory education for a next generation of students who must be more adequately prepared to address the nation's STEM [science, technology, engineering, and medicine] needs." Spalding sent the petition to NSF again on 28 February of this year. Two days later acting chief operating officer Joan Ferrini-Mundy responded that undergraduate education of the next generation of STEM students "is of very high priority to the NSF. . . . I look forward to ongoing opportunities to work together."

At many institutions, students are still doing the Millikan oil-drop experiment, the Cavendish gravitational force experiment, and other decades- or even centuries-old experiments. "We see stagnation in what is offered," says Lowell McCann of the University of Wisconsin–River Falls. With so many advances in both scientific understanding and technologies, "we need new ideas to flow into this part of the curriculum," he says.



ENRIQUE GALVEZ (center) regularly mentors other physics instructors on how to set up and run the quantum optics experiment he developed. Greg Severn (left) of the University of San Diego and Joshua Grossman of St Mary's College of Maryland attended an immersion workshop in August 2012 organized by the Advanced Laboratory Physics Association.

Financial stress is not the only hindrance. Maintaining labs takes time and requires knowledge beyond any one person's research expertise. "It's hard work to maintain a piece of equipment inherited from a previous faculty member, and even more challenging to create a new lab experiment," says Colgate University's Enrique Galvez.

Typically one to two faculty members in a given department take on the job of maintaining labs. "The instructors like what they do and are committed," Galvez says. But it's hard to attract young faculty to instructional labs, partly because maintaining them doesn't go far toward winning tenure.

Two new prizes are intended to boost recognition for undergraduate lab instruction. The $5000 Jonathan F. Reichert and Barbara Wolff-Reichert Award of the American Physical Society (APS) goes to faculty who have developed and sustained an outstanding advanced laboratory instruction program. A TeachSpin-funded $4000 award, which ALPhA and the American Association of Physics Teachers (AAPT) will bestow for the first time this summer, recognizes undergraduate physics students for developing an advanced laboratory apparatus.

Grassroots dedication

To promote communication among laboratory instructors, AAPT in 2006 started an electronic mailing list to foster discussion and interaction. Then, in 2009, ALPhA, which has ties to both AAPT and APS, held the first of what has become a triennial Beyond the First Year (BFY) of College laboratory conference to showcase lab experiments.

The most recent BFY conference, in July 2015 at the University of Maryland in College Park, took over every available corner of instructional lab space for 60 workshops, says Spalding. "People brought lasers, radioactive sources, and

LOADED WITH 17 HANDS-ON EXPERIMENTS, this truck began making the rounds of US physics departments in January.

SUE LEIGH/TEACHSPIN INC

so on. It's a smorgasbord for faculty and staff to see what they may want to teach."

The BFY experience, which gives attendees brief exposure to many experiments, led ALPhA to launch two-and-a-half-day workshops to train instructors on a particular experiment. The first dozen "immersions" took place in 2010. In 2016 some 27 immersions were held around the country on topics such as multiphoton microscopy with a compact fiber laser, plasma-physics spectroscopy, and galactic rotation as evidence for dark matter. The immersions to date have attracted a total of 385 participants, says McCann, who coordinates the workshops. Participants come away with a list of parts, including vendors and prices, to get them started back at their home campus. Attending an immersion costs $350 plus lodging. An NSF grant to ALPhA helps with costs and fully covers participants from minority-serving institutions.

About five years ago Carl Grossman, a Swarthmore College physicist who is the driver and host of the TeachSpin physics food truck, participated in an immersion on quantum optics and "walked away having doubled my knowledge about Bell's inequality." There were a half dozen participants, he recalls, and "we had everything from people like me who had already built experiments in the topic but still had trouble to others who hadn't done anything." More recently he led an immersion on experiments that investigate noise. In an experiment with Johnson noise, Boltzmann's constant is extracted from thermal fluctuations across a resistor, and in one using Schott noise, the electron charge is deduced from fluctuations in the current from a lamp.

A survey of participants from 2010–14 showed that 18 months after their immersion, 60% of respondents—43% of the participants—had already introduced the experiment back home. "We are happy that a large number are able to go and implement," says McCann.

Experiments for undergraduate labs can run from a few hundred dollars to tens of thousands of dollars. ALPhA offers a range of immersions, says McCann, from ones on experiments that use Arduinos, programmable devices that cost tens of dollars, to one using x-ray diffraction, for which the equipment can cost up to about $25 000. The most popular immersion has been a quantum optics experiment with single photons that Galvez and colleagues developed, which from scratch costs around $18 000.

To make it easier for campuses to afford the photon optics experiment, ALPhA arranged with Excelitas Technologies to provide an education-grade version of its commercial photon detector at a deep discount. With money borrowed from AAPT, ALPhA buys the detectors in bulk and then sells to schools at cost plus shipping. So far, the organization has delivered more than 400 detectors to around 100 institutions.

In more of a one-off, ALPhA found homes in undergraduate laboratories for 40 new vacuum pumps donated by Kimball Physics Inc. "We posted on our webpage, and it took us 30 minutes to give them away," says Peterson.

"I got the bug"

Reichert, whose fingerprints show up on many of the efforts to bolster undergraduate labs, became a player more than two decades ago when he noticed that "more and more advanced labs were disappearing." Now 85 years old, he remembers how he and his peers would "take old research equipment and make experiments" for undergraduates. That was standard, he says, "but faculty today know less and less about building instruments. They are not going to take a lock-in amplifier and spend a week trying to get it to work."

During a sabbatical year in 1992, he and two former students designed a tabletop pulsed NMR apparatus for undergraduates. In 1994 they sold the first one to Carnegie Mellon University, where, says Reichert, the original instrument is still in regular use. "I got the bug," he says. A few years later he left his faculty position at the University at Buffalo and founded TeachSpin. "We build instruments to optimize thinking, experimental skills, analysis of data, and so forth," he says.

SUE LEIGH/TEACHSPIN INC

INSIDE THE TRUCK. Students from a mathematical methods class at the State University of New York at Fredonia visited the Food Truck for the Physics Mind this past February.

As an example, he describes how he and others at TeachSpin used interferometry to measure the tiny change in the length of a nickel rod caused by an applied magnetic field. "We noticed the fringe pattern was drifting like crazy," he says. "We figured out that it was a combination of thermal expansion and magnetostriction. For research, you would thermally isolate the sample, but for teaching, we left it so students could figure out for themselves what was going on."

TeachSpin now markets more than a dozen advanced undergraduate experiments. But, says Reichert, profit is not the aim—"last year we netted $3500," which in any case was plowed back into the parent foundation. Rather, it works to build up instructional laboratories. Starting two years ago, the foundation began awarding equipment grants to laboratory instructors who had attended an ALPhA immersion workshop. The foundation puts in 40% of an apparatus's cost, up to a maximum of $7500. So far, it's paid out more than $100 000.

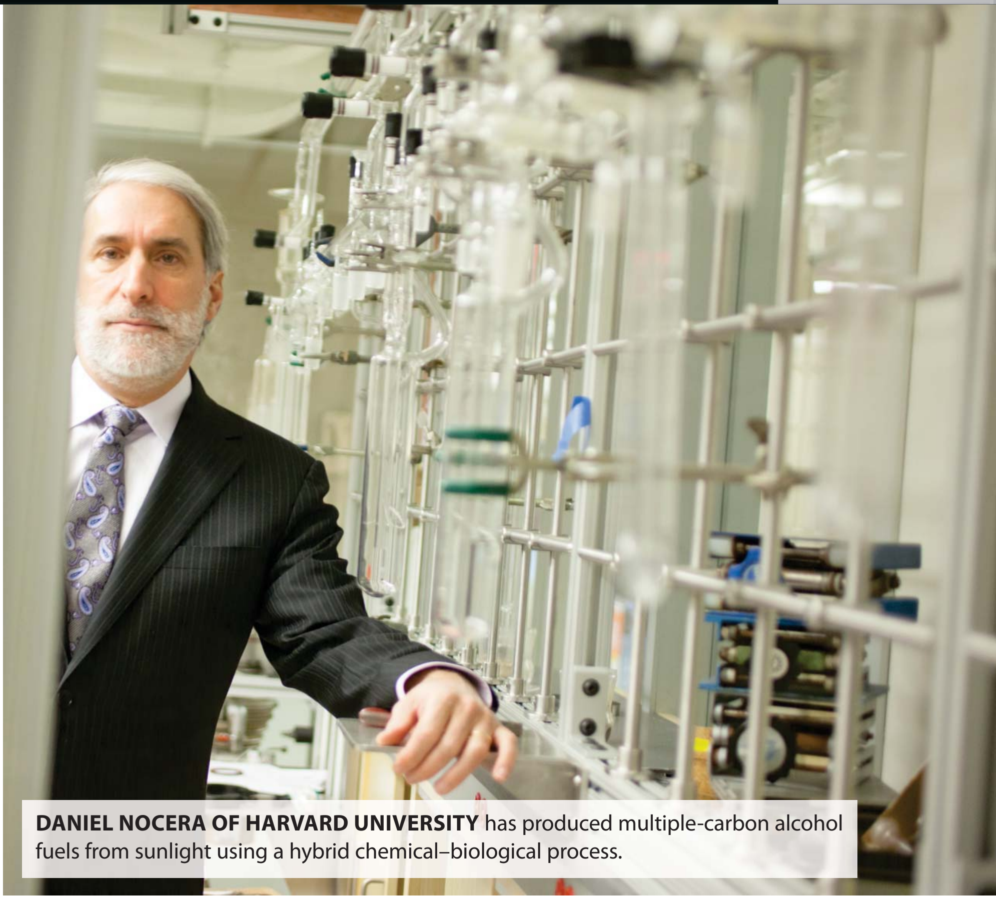
The aim of the Food Truck for the Physics Mind is to excite students and faculty. The truck is equipped with 17 undergraduate experiments, currently all TeachSpin inventory. Up to a dozen people at a time can come in and try out the equipment. "We are hoping to hit two or three schools a week," Grossman says.

The big picture is that "we want to bring back the advanced lab," says Reichert. It's a "central part of undergraduate education, and we will support it in every way we can." **Toni Feder**

ISSUES & EVENTS

Biology leads the race to turn sunlight into fuels

A bacterium can be harnessed to do the job, but can that process be scaled up?



DANIEL NOCERA OF HARVARD UNIVERSITY has produced multiple-carbon alcohol fuels from sunlight using a hybrid chemical–biological process.

ROSE LINCOLN, STAFF PHOTOGRAPHER, HARVARD UNIVERSITY

Now in its seventh year, a Department of Energy–funded effort to produce liquid fuels from sunlight, water, and carbon dioxide continues to hinge on finding an inexpensive and abundant catalyst. Meanwhile, a separate project led by Harvard University's Daniel Nocera already has produced isobutanol and isopentanol fuels using a hybrid chemical–biological process.

Founded in 2010 by former energy secretary Steven Chu and managed by Caltech, the Joint Center for Artificial Photosynthesis (JCAP) is the largest of many initiatives that aim to convert sunlight's energy into chemical fuel. Others include Nocera's project, a collaboration based at Sweden's Uppsala University, and a collaboration led by scientists from Technion–Israel Institute of Technology. All begin by splitting water into hydrogen and oxygen in photoelectrochemical cells. The next and far more difficult step is to reduce carbon dioxide to end up with hydrocarbon fuels.

Supported at $15 million annually, JCAP in 2015 achieved its initial five-year goal: producing compact prototype cells that split water using inorganic catalysts and have better than 10% efficiency. Harry Atwater, JCAP's director, expects efficiency will approach the 20% attained by today's best commercial solar panels in five years or so. Now JCAP has moved on to the CO_2 reduction challenge set forth by the five-year grant extension that began in 2015. JCAP brings together more than 100 graduate students, postdocs, and faculty members at Caltech, Lawrence Berkeley National Laboratory (LBNL), SLAC, and the University of California's Irvine and San Diego campuses.

Although reducing CO_2 counts as a success, the type of fuel produced is not fixed. Compounds could range from one-carbon molecules such as methanol or even carbon monoxide to the more energy-dense multiple-carbon alcohols such as ethanol or isobutanol.

The most basic fuel from CO_2 reduction is CO. It has a low energy density and is toxic but can be converted to liquid fuels via the well-established Fischer–Tropsch process. Methanol is more energy-dense and could be used directly as a fuel or converted to gasoline via another well-known chemical pathway. But Atwater notes that JCAP's premise is building compact fuel generators that don't require refineries to produce finished fuels.

The hydrogen from water splitting could be used in fuel-cell vehicles. But despite their efficiency, Atwater says, JCAP's solar devices can't compete economically today with the CO_2-emitting commercial plants that convert methane into the hydrogen being sold at California filling stations.

The hybrid artificial photosynthetic method developed by Nocera and his fellow Harvard researcher Pamela Silver combines an inorganic catalyst for water splitting with the hydrogen-feeding bacterium, *Ralstonia eutropha,* for CO_2 reduction. Nocera says that if he uses pure CO_2, the process yields a general solar-to-fuel conversion efficiency of 5–7% for liquid fuels. Even with CO_2 from ambient air, the process beats the 1% efficiency of natural photosynthesis.

Using inorganic catalysts rather than a bacterium, JCAP has so far succeeded, with 10% efficiency, in reducing CO_2 to formic acid (HCOOH) in a device similar to a solar cell, says Atwater. Although formic acid isn't combustible, it is used in fuel cells. And the ability to selectively produce it is an early indicator that with the right catalysts it should be possible to direct the CO_2 and hydrogen to form a single compound while preventing formation of diatomic hydrogen and other potential reduction byproducts.

String of pearls

Most CO_2 reduction schemes produce compounds containing a single carbon atom. "What's hard to do is stringing a bunch of carbon atoms together to make C_2, C_3, C_4 molecules, like pearls on a necklace," says Nocera. Compounding the challenge of making carbon–carbon bonds is the large number of transferable protons and electrons that need to be managed lest they participate in competing hydrogen-producing reactions.

Biology manages that process "beautifully," says Nocera. "It knows how to make carbon–carbon bonds and not make hydrogen and do it selectively. And it can manage lots of protons and electrons." The other advantage to the bacterial reduction process is that it requires no sunlight; only the water-splitting reaction requires the sun. That separation eases the design constraints on scaling up the process, he says. Last year, he and Silver announced an improvement to their process—a water-splitting catalyst that doesn't produce reactive oxygen species toxic to the bacterium.

Each of Nocera's bench-scale 1-liter reactors can produce fuel from 1200 liters of air at ambient conditions per day. He has granted the rights to use the proprietary process to India's Institute of Chemical Technology, which is scaling up the technology for use in the developing world. Neither he nor Atwater expects any artificial photosynthesis technology to compete against fossil fuels—at least absent a carbon tax. But Nocera says his method could make sense in the developing world, where refineries, chemical plants, and other infrastructure are scarce and where solar fuel plants could be sized to fit in a backyard.

Although the biological approach offers reduction-product selectivity, it's difficult to speed up the management of copious protons and the formation of carbon-carbon bonds. Speed is the potential selling point of the chemical approach, provided that it can meet the challenges biology has already tackled.

Atwater is careful not to oversell expectations for JCAP. "The most important thing we'll have at the end of five years is an understanding of the criteria for activity and selectivity for catalysts for carbon dioxide, informed by theory and validated by experiment," he says. "It's not wise or appropriate to claim that we're within a couple years going to have a complete manufacturable device that works with high activity and high selectivity."

Caltech performs high-throughput screening of potential catalyst compounds using combinatorial synthesis in ways analogous to the pharmaceutical industry's screening of small molecules for new drug candidates. A parallel theory effort uses the high-performance computing assets at LBNL's National Energy Research Supercomputing Center to rule out most of the millions of potential candidate compounds and thus dramatically lower the need for synthesis and testing.

Ian Sharp, a JCAP researcher at LBNL, says the center draws on expertise at the lab's Molecular Foundry to find catalysts and materials for thin-film semiconductors used in the photovoltaic part of the cells. "We are at a stage now where materials prediction is sufficiently good that we can use that with some degree of reliability for targeting the compounds we want to use."

But trying to fabricate devices that will both oxidize water and reduce CO_2 won't be easy. "The problem is that in terms of semiconductors, there are no materials that can all at the same time exploit high efficiency and [that] are chemically stable in reaction environments and are composed of elements that can be scalably deposited," he says. So while the search for materials with the necessary properties continues, researchers are taking a parallel path in seeking ways to protect traditional semiconductor materials such as silicon, gallium arsenide, and indium gallium phosphide from the corrosive environment.

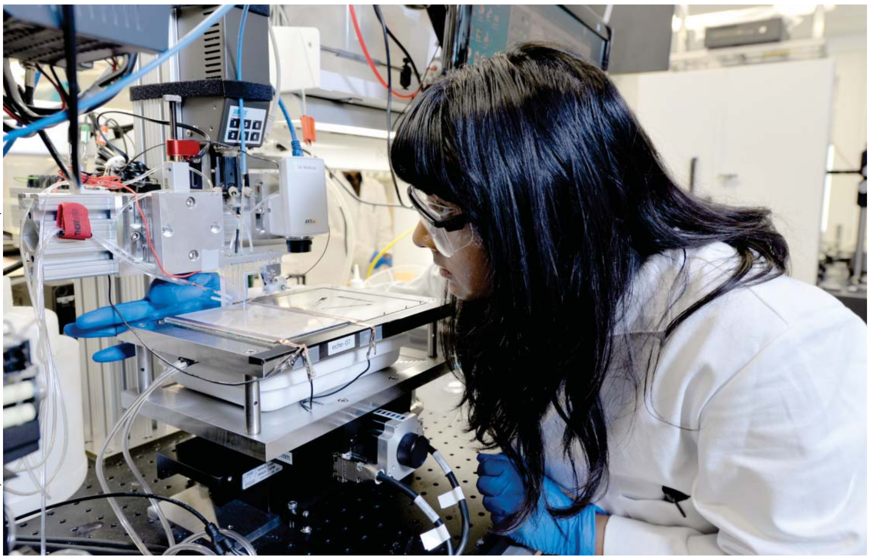
The theorist contingent at JCAP has increased from about 5% of staff in the initial five years to 25% today; that switch reflects the difficulty facing CO_2 reduction. The influx of theorists has improved the understanding of catalytic mechanisms. Although it was known that there were heterogeneous or inorganic metal catalysts such as silver or gold that could produce CO, for example, the mechanism by which, say, copper could produce more complex fuels remained a mystery. "We have developed a lot more understanding of that," Atwater says.

A secret (so far) process

Among other solar fuels research projects is an Israeli collaboration that envisions hydrogen as the end product. Avner Rothschild of the Technion favors combining the hydrogen from water splitting with plentiful atmospheric nitrogen to produce ammonia for fertilizer or fuels. He notes that extracting sufficient amounts of CO_2 at its atmospheric concentration of 400 ppm for reduction to fuels will be very challenging. Ammonia can't be produced in a photoelectrochemical cell, however; that requires a chemical plant.

Rothschild and Technion chemical engineer Gideon Grader are working with metal oxide catalysts to develop efficient photoelectrochemical water-splitting

JCAP, CALIFORNIA INSTITUTE OF TECHNOLOGY, PHOTOGRAPHY BY ROBERT PAZ



SCIENTIST ANIKETA SHINDE works on the rapid screening of materials for solar-fuels generators in the high-throughput experimentation laboratory at Caltech.

cells. "Most of us realize we're not going to split water with some simple material like metal oxide powder in a solution," Grader admits. Why not just use well-established photovoltaic-powered electrolysis? Grader and Rothschild's analysis finds that the photoelectrochemical process has the potential to increase water-splitting efficiency by 30–40% relative to PV electrolysis. And the catalysts that are developed will be less costly than the rare earths and platinum group metals currently used in electrolysis.

As PHYSICS TODAY went to press, the Technion team was days from publishing its novel approach for generating hydrogen from the millions of photoelectrochemical cells that would be needed to produce large quantities of hydrogen. They would not describe the concept in detail pending its publication, except to say that the hydrogen would be generated at a central location.

The Swedish collaboration's investigation of catalysts draws on resident expertise in the mechanisms for proton-coupled electron-transfer reactions that occur in inorganic catalysts and in enzymes such as photosystem II, which participates in photosynthesis in cyanobacteria, algae, and plants. "We make cells but we don't promise to solve the world's problems within the next granting period," says Stenbjörn Styring, the Uppsala University chemist who heads the 75-person consortium. "We study how protons and electrons couple in the very complicated reactions, and we drive the idea that molecular systems have a future in the field."

The consortium has focused on developing water-splitting catalysis based on ruthenium, cobalt oxide, and cobalt-containing molecular complexes. Although ruthenium is expensive, it is "amazingly efficient," Styring says. Citing Nocera's approach, he favors biological pathways for reducing CO_2 to long-carbon-chain fuels. Photosynthetic algae and bacteria can make almost any compound from CO_2, water-derived electrons, and solar energy, he notes.

Atwater mentions another challenge: durability. Rooftop solar panels make economic sense because they will last 25 years. "To date we don't have any demonstration that these relatively efficient water-splitting devices are able to last for more than a few hundred hours." Efforts to improve device lifetimes are under way at JCAP.

David Kramer

Theory institute opens residence hall for visitors

The aim is for informal interactions to stimulate creativity and collaborations.

PATRICK PRICE

NEW GUEST HOUSING opened in January at the Kavli Institute for Theoretical Physics at the University of California, Santa Barbara.

Visitors to the Kavli Institute for Theoretical Physics (KITP) at the University of California, Santa Barbara, can now lodge together in a sleek new residence hall. Before the hall opened in January, visitors were scattered across town in hotels, rental quarters, and campus housing. The new building is named for Charles T. Munger, who gave $65 million for its construction. Munger is the vice chairman of Berkshire Hathaway, the conglomerate founded by Warren Buffett.

Some 700 visitors come to KITP each year for three weeks or longer, and another 600 come for shorter visits. Roughly half of the visitors come from outside the US. The institute hosts about 10 topical programs each year, on everything from the mysteries of massive stars to the

MICHAEL GRAHAM/UNIVERSITY OF WISCONSIN–MADISON

ON A FRIDAY EVENING IN JANUARY, participants in a program on turbulence hang out in one of the new KITP residence's bar areas.

physics of hearing. Two or three 10- to 12-week programs run simultaneously.

The main goal of the new residence "is to create an environment that allows people to keep interacting day and night and weekends," says KITP director Lars Bildsten. "We expect it to have an impact on collaborations. We wanted to construct a facility that would transform the lives of our visitors."

A couple of kilometers from the main KITP building, the residence can house up to 61 people in single and double units and seven-room suites, each with its own kitchen. There is also a large communal kitchen, a formal drawing room, a children's playroom, exercise rooms, and more. "There is privacy and space to congregate," says Bildsten. And, he says, "there are chalkboards everywhere. Yes, chalk."

Paula Szkody was among the first visitors to stay in the residence. The University of Washington astronomer was there for six weeks for a workshop on magnetohydrodynamics of accretion disks. "We had a couple of gatherings and barbecues," she says, and there was some cross-talk with people from the concurrent workshop on turbulence. "The ambience was great."

"Typically, I spend hours with colleagues in a work environment and don't get to know them outside of work," says Ehsan Moravveji, a postdoc at the Institute of Astronomy at KU Leuven, Belgium. The KITP residence "will enhance communications and let scientists connect and live together outside the academic environment. I find it wise and clever."

As PHYSICS TODAY went to press, Moravveji, who is Iranian, was waiting to see if his visa would come through so he could present an invited talk on massive stars at a conference at KITP in late March. If not, he planned to give his talk from Leuven by either prerecording or live-streaming it over the internet.

Toni Feder PT

PHYSICS TODAY Previous Page | Contents | Zoom in | Zoom out | Front Cover | Search Issue | Next Page PHYSICS TODAY

CYNTHIA CUMMINGS

Emily Myers is an associate professor in the department of speech, language, and hearing sciences and the department of psychological sciences at the University of Connecticut in Storrs.

From SOUND to MEANING

Emily B. Myers

Culture and experience contribute to the process that translates a complex acoustic stimulus into an intelligible message.

A man waits on a crowded train platform. His cell phone buzzes, and he recognizes his daughter's number. He answers, she reminds him to pick up milk on the way home, he says OK, and they chat briefly. The interaction might take only a minute and would be unremarkable for both father and daughter. Yet the transmission of even a simple message requires a multitude of physical and psychological processes that are phenomenally complex and as yet not fully understood. During the past decade or so, psychologists, neuroscientists, and acousticians have made tremendous strides in understanding the quasi-magical process of putting your thoughts into someone else's head.

The get-milk message began miles away from the train platform, when the daughter drew in a breath of air and began to speak. Speech production is an invisible ballet that requires precise and rapid coordination of the many muscle groups that control the lips, tongue, jaw, larynx, and respiration. The daughter's coordinated muscle movements, called speech gestures, result in an acoustic signal containing multiple acoustic cues that ultimately enable her father to decode the signal. The acoustic signal is transmitted via a cell phone, which compresses and filters it; the phone especially distorts the higher frequencies that allow listeners to distinguish the "s" sound in *sack* from the "sh" sound in *shack*. Back at the train station, the signal emerges from a cell phone, travels through the air, enters the father's ear, and impinges on his cochlea. He must sort the signal emanating from the cell phone from the screech of train brakes and the conversations of other commuters on the platform.

Next, the speech message is processed by the father's nervous system. Neural signals that represent the sound with high fidelity are transmitted along the auditory nerve, ascend through the brain stem, pass through the thalamus, and arrive in the cerebral cortex, where the language centers of the brain are located. There the message is further processed. The sounds in the speech stream are compared with the sounds that the father has learned over the course of his lifetime; the brain's task is to match the speech stream with words in the father's lexicon, or mental dictionary. Further transformations are required to turn strings of words into meaningful sequences such as "Don't forget to pick up milk."

What does the father actually perceive during the conversation? Most likely he is aware of only a few pieces of information—for example, that he is listening to his daughter's voice and that he's going to have to make a detour on the way home. Perception is built on such knowledge, and each step in the complex chain leading to that knowledge is worthy of

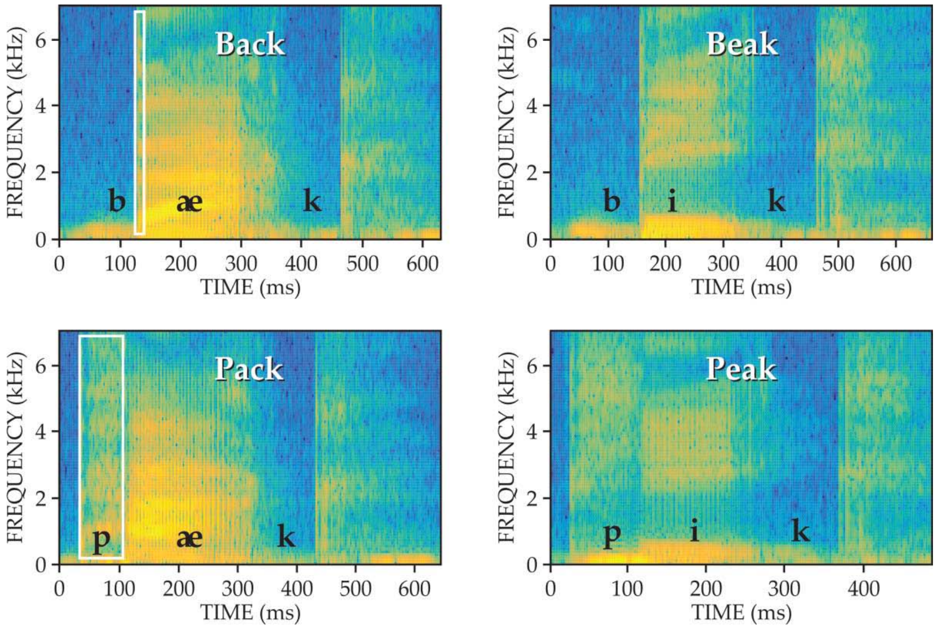


FIGURE 1. THE TIME SEPARATING the vowel sound from the burst of the initial consonant—the voice onset time (VOT)—is distinctly different for words like *back* and *pack* or *beak* and *peak*. The four spectrograms show the frequencies that are most intense at a given time (yellow is most intense; blue, least). The VOT is indicated by the width of the rectangles in the *back* and *pack* panels; it's about 20 ms for the "b" sound and near 80 ms for "p."

discussion. In this article, though, I concentrate on what happens once the signal arrives in the brain—that is, on how a listener takes a processed auditory signal and maps it to a meaningful message.

When light sounds right

Speech is made up of units that linguists call phonemes, abstract units of perception and production that, when swapped, produce a change in the word. Linguists use forward slash marks to denote phonetic symbols: For example, /l/ denotes the beginning sound in the word *light*. In the English language, /l/ and /r/ are different phonemes because replacing the /l/ sound in *light* with an /r/ sound results in a new word, *right*. Japanese, by contrast, has no instances in which changing an /l/ phoneme to an /r/ will result in a new word. For that reason, many Japanese listeners find it difficult to hear the difference between words like *lock* and *rock*.

Some languages have distinct phonemes that are not distinguished in English. Hindi, for example, has two /d/-like sounds: one, the dental /d̪/, made with the tongue placed behind the teeth and the other, the retroflex /ɖ/, made with the tongue curled back along the hard palate. In Hindi, those two sounds, when swapped, can change the meaning of a word. People who use English as their native language simply perceive them as two slightly different varieties of /d/. Therefore, the dental and retroflex sounds make up a phonemic contrast in Hindi but not in English, whereas the /l/ and /r/ sounds are contrasting in English but not in Japanese.

Speech sounds are differentiated with the help of multiple acoustic cues. For instance, the stop sounds that begin words like *pack* and *back* are distinguished primarily in terms of the timing of two articulatory movements. Both sounds are made with an initial closure of the lips. What differs is the time—on the order of tens of milliseconds—between the pop open of the lips and the beginning of the vowel sound. Figure 1 illustrates that lag, which is called voice onset time (VOT). The same type of time lag enables listeners to distinguish between words like *duck* and *tuck* or *goal* and *coal*.[1]

Different acoustic properties distinguish other speech sounds. For instance, vowels are primarily determined by the patterns of energy maxima, or formants, in the frequency spectrum. Fricative speech sounds such as the /s/ in *sack* and the /ʃ/ ("sh") in *shack* are determined by a combination of factors that include their duration, their amplitude, and the concentration of energy across the frequency spectrum (see figure 2). In fact, most of the time people like the father on the train platform have to assemble multiple pieces of information to determine the identity of the sounds they are hearing, a process known as cue weighting.[2]

The lack of invariance problem

Even after the father has extracted the acoustic cues in his daughter's request that he pick up milk, his task is hardly over. His next major challenge is that no two utterances of a particular phoneme—for example, the /p/ in *pick*—are identical. His daughter might sometimes produce her /p/ sound with a VOT of 70 ms, sometimes with a VOT of 90 ms. His wife might produce /p/ with relatively shorter VOTs, even as her sister tends to pronounce the sound with longer VOTs.[3] Add to that the fact that the sounds abutting the /p/ will bleed into the consonant; the /p/ sound in *pick*, for example, is acoustically different from the /p/ sound in *poke*. An infinite number of acoustic patterns can map into a single speech sound. Ostensibly, that "lack of invariance" problem presents an enormous challenge to the father. It is not enough for him simply to note the acoustic cues of speech. He also must figure out how to categorize the sound he is hearing on the basis of what he knows about the talker (she's his daughter), speech rate (she's speaking quickly), coarticulatory context (the /p/ in *pick* is next to an /I/ sound), and other information (*pick* makes sense in context, whereas *bick* does not).

To convince yourself of how difficult it can be to translate acoustic cues into words, try any commercially available speech-recognition interface such as Apple's Siri or Amazon's Alexa. Say a single, monosyllabic word such as *pack* clearly and slowly, and the system is reasonably likely to identify it correctly. However, if you repeat the word *pack* quickly, you may get a multitude of responses; in different tries, Siri thought I was saying *back*, *beck*, *talk*, and *part*.

As noted earlier, the human speech system does not deliver the entire auditory content to the point of conscious awareness. Rather, we usually can perceive only acoustic differences that matter for meaning. Consider, for example, a series of sounds that lie along a continuum between two speech categories in English—say, /d/ and /t/. People whose native language is English will easily perceive the difference between sounds that fall into one class or the other. Those same listeners, however, will struggle to hear a difference between two examples of the same sound—for example, two types of /d/ sound—that have the same degree of acoustic distinctiveness as /d/ and /t/ sounds that are readily distinguished. The tendency of listeners to perceptually collapse sounds in the same category leads to difficulties in distinguishing the Hindi /d̪/ and /ɖ/, two phonemes that fall into the /d/ category in English. (Native English listeners can confirm this for themselves with the sound files available online.) That phenomenon, known as categorical perception, may be in place to help our brain's limited resources focus on only the most important aspects of the speech signal—what is the message, and who is doing the talking.[4]

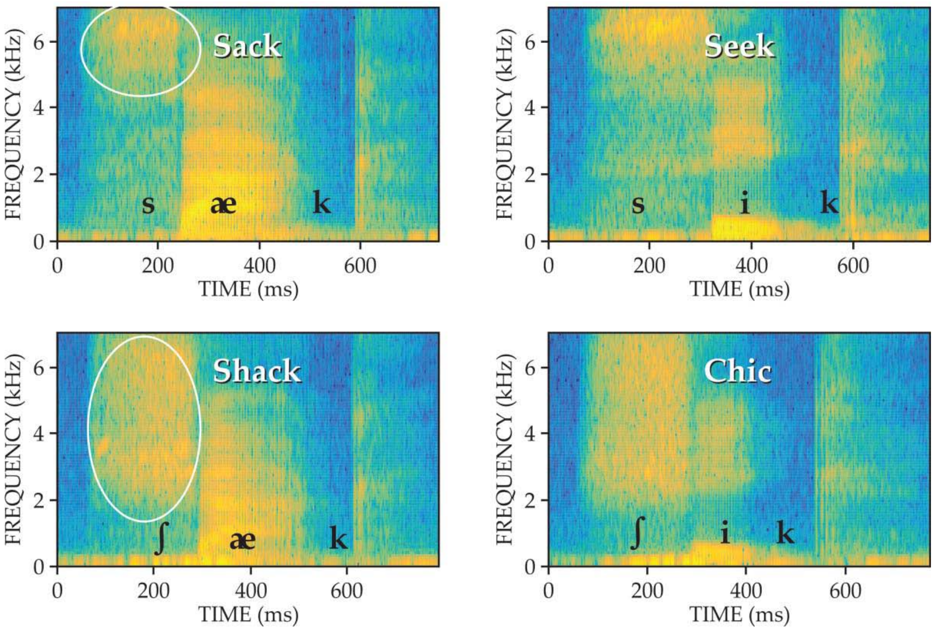


FIGURE 2. FREQUENCY RANGE influences phoneme perception. The four spectrograms show the frequencies that are most intense at a given time (yellow is most intense; blue, least). As the ovals indicate, for the "s" sound in *sack*, the average frequency is higher and the distribution is narrower than for the "sh" sound in *shack*. Those features persist when the vowel sound is changed, but as the right panels comparing the words *seek* and *chic* attest, altering the vowel sound significantly changes the details of the acoustic cues.

So what we hear is not what we perceive. The pressure waves that impinged on the commuting father's cochlea were full of details that he couldn't tell you if you asked him—how long was the VOT for that stop sound? Were the formants for the vowel close together or spaced far apart? Studies suggest that the brain encodes both the fine-grained acoustic details of the speech signal and the information about the identity of the speech sound itself (Is it a /p/ or is it a /b/?).

Regions in the superior temporal gyrus, a part of the brain that specializes in auditory processing, respond to the complex acoustic landscape of speech sound. They also show sensitivity to tiny acoustic differences that the father may not be able to consciously perceive and that may not even be important for understanding the message.[5,6] As the neural processing advances away from his superior temporal gyrus to other areas in the temporal lobe and toward left frontal brain areas, the representation of sounds appears to lose some of the fine-grained acoustic detail. Instead, it seems to represent something closer to what he actually is aware of hearing.[7] Figure 3 shows the locations in the brain of both the temporal-lobe system that can access all the acoustic complexity in the signal and the frontal system that discards that detail in favor of preserving the things that are important for meaning. Having both those systems may allow us to ignore the minute acoustic variation in the signal while still processing that information in case it is relevant for other purposes.

Entrenchment and flexibility

Newborn infants, as psychologist Peter Eimas and others showed, can detect differences between most, if not all, of the sound contrasts in the world's languages.[8,9] Yet over the first year of life, babies begin to ignore sound contrasts that are not represented in their native language and to preserve those that are found in their language. Patricia Kuhl and other scientists have called that process "perceptual narrowing." By the time they reach adulthood, people in an English-speaking environment will struggle to hear the difference between sounds like the dental and retroflex speech contrast that is used in Hindi, a contrast that poses no problem for adults who were raised in India by Hindi-speaking parents. For reasons that are not fully understood, by adulthood we have become perceptually entrenched—that is, we do not appear to show the flexibility in learning new speech sounds that we had as children.

Perceptual entrenchment is easy to observe. Many of us, for example, are acquainted with excellent speakers of English who learned the language late in life and retain strong traces of their native language. It is rare to speak any language like a native speaker if you have learned that language after some critical juncture sometime around puberty. In addition to perceptual entrenchment, a second obstacle to speaking a new language like a native is so-called motor entrenchment: It may be difficult for an adult to learn the movements of the lips, tongue, and larynx that are necessary for new speech sounds. The same phenomenon observed in accented speech production is present in speech perception as well; we also "listen with an accent," meaning that we often cannot distinguish sounds that

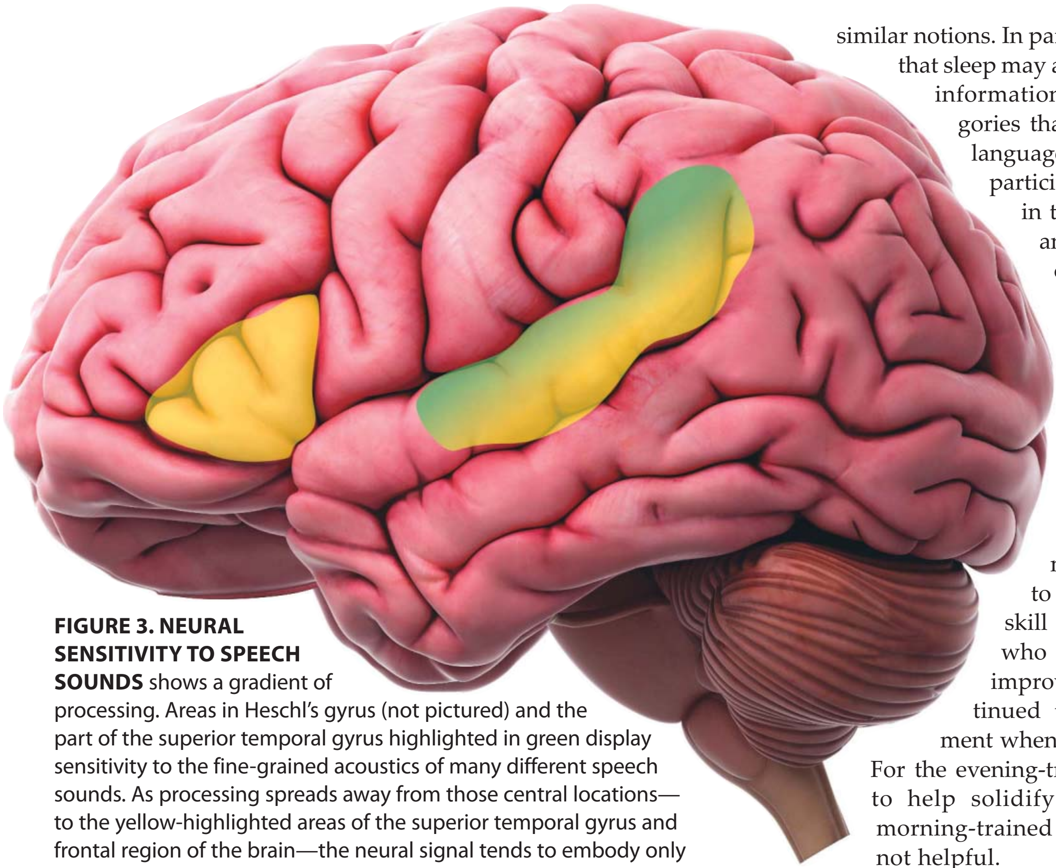


FIGURE 3. NEURAL SENSITIVITY TO SPEECH SOUNDS shows a gradient of processing. Areas in Heschl's gyrus (not pictured) and the part of the superior temporal gyrus highlighted in green display sensitivity to the fine-grained acoustics of many different speech sounds. As processing spreads away from those central locations—to the yellow-highlighted areas of the superior temporal gyrus and frontal region of the brain—the neural signal tends to embody only the acoustic differences that listeners use to distinguish between words. (Adapted from an image by Sebastian Kavlitski.)

aren't part of our native language's repertoire. It may be that our binning of sounds into distinct speech categories is itself an obstacle to learning new sounds.

Adults can learn the sounds of a new language, but with highly varying degrees of success. Attempts to train motivated learners on difficult sound contrasts—for example, efforts to teach native speakers of Japanese to hear differences between /l/ and /r/ sounds—usually show modest gains after many hours of training.[10] Some people learning a new language reach native-like performance, but most fall short of that goal, even after a lifetime's immersion.[11]

Many factors make it hard to learn the sounds of a new language. For instance, as adults, we have many demands on our personal time that make language learning a lower priority than it is for an infant. Differences in motivation, in auditory acuity, in ability to remember speech sounds that we've heard before, and in neural plasticity likely affect how well we will do in picking up a new language. New data from my lab, the Language and Brain Lab at the University of Connecticut, hint at two less-explored factors that may explain some of the variability in adults' speech-sound learning—sleep, and interference from sounds from the native language.

Sleep has various effects related to memory. One is that it facilitates the transfer of learned information from the hippocampus to cortical regions, a move that allows learners to generalize from concrete experiences to abstract categories and also protects learned information from being confused with similar notions. In particular, recent studies suggest that sleep may also help learners "lock down" information about speech-sound categories that are not part of their native language.[12,13] In those investigations, participants came to the lab either in the morning or in the evening and were trained in the Hindi dental–retroflex speech-sound contrast that English listeners usually hear as two varieties of the /d/ sound (see figure 4).

Participants who came in the morning appeared to retain what they had learned over the course of the day, but as tests the following morning revealed, they seemed to have lost their newly acquired skill overnight. In contrast, those who were trained in the evening improved overnight, and they continued to show increased improvement when tested the following evening. For the evening-trained group, sleep appeared to help solidify training, whereas for the morning-trained group, sleep apparently was not helpful.

My colleagues and I speculated that the difference in the two groups' performance lay in participants' exposure to sounds that are similar to the trained sounds. For our specific experiment, we reasoned that participants who were trained in the morning likely were exposed to many examples of the English /d/ sound before they went to sleep, whereas participants who were trained in the evening heard many fewer English /d/ sounds before bed.

We tested our hypothesis by training two groups of participants in the evening. One group was exposed to many examples of the /d/ sound after training; the other group heard many examples of the /b/ sound. As predicted, listeners who heard many /d/ sounds showed less benefit from sleep than those who heard the /b/ sounds. In fact, the evening-trained /d/ group did a poor job of discriminating the new Hindi sounds, much as the morning group had in our previous study. A good deal remains to be learned about the process that led to our results, but our findings hint that learners of a new language pay a real perceptual price when they switch between languages. English-speaking adults who take an Italian class to prepare for a vacation may lose ground when they leave the class and listen to English for the rest of the day—particularly if they hear their native language before the protective effects of sleep.

You hear what you expect to hear

If the above story about the difficulties in perceiving the sounds of a new language painted a pessimistic picture, here's a sunny antidote: In the context of our native language, we have a remarkable ability to use knowledge about what words and sounds are likely to appear to solve difficult perceptual prob-

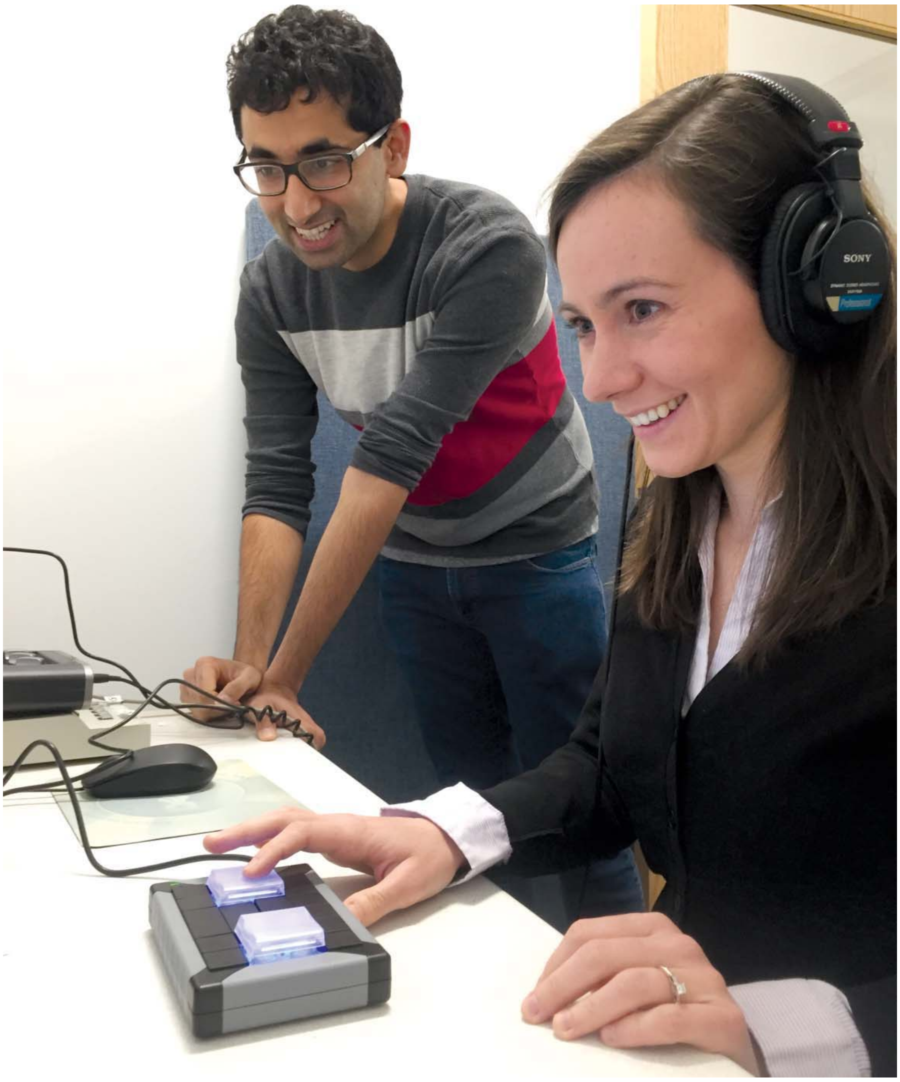


FIGURE 4. BEFORE TRAINING there is troubleshooting. Sahil Luthra and Pamela Fuhrmeister, University of Connecticut graduate students and members of the Language and Brain Lab, make sure that the equipment for a speech perception experiment functions properly. In the study, people are trained to associate Hindi speech sounds with novel objects on a computer screen. The participants then return to the lab several times to measure how well they remember what they have learned.

lems. Consider the father on the train station platform, chatting with his daughter. Cell-phone service being what it is, his connection may have dropped a few times and cut out bits and pieces of the conversation. Further, noises from the approaching train and the conversations of passengers around him probably obscured certain sounds. The speech perception system is built to fill in those gaps. Even if a whole speech sound such as the /s/ in *Tennessee* is replaced with a cough, listeners will report hearing the full word along with a superimposed cough; interestingly, they don't report the cough as overlapping with the restored sound.[14] The phenomenon, discovered in 1970, is called phoneme restoration.

Listeners attempting to understand ambiguous speech sounds lean heavily on their expectations about which sounds and words are likely to appear. For instance, when they hear an ambiguous sound between a /g/ and a /k/ at the beginning of the syllable *ift*, they will assume that the sound is a /g/, which corresponds to the real word *gift*. In contrast, if that same sound is inserted into the syllable *iss* they will come to the conclusion that they are hearing a /k/ sound, completing the real word *kiss*.[15] Other work shows that people can learn to adapt to speech sounds that are out of the norm. For example, researchers Ann Bradlow and Tessa Bent have demonstrated that with the right kind of experience, listeners can improve their ability to understand accented speech, and they can even generalize what they have learned about an accent to new talkers with the same accent.[16]

The process of mapping speech to meaning is laden with contradictions. On the one hand, understanding speech seems effortless to the listener. On the other, a lot is going on under the hood before the message is delivered. The speech system is plastic, able to adapt to various listening conditions. Yet it is also rigid in the sense that adults struggle to learn the sounds of a new language. Speech scientists have made progress in mapping the brain architecture that allows people to take sound vibrations and turn them into meaning, but we still have much to learn.

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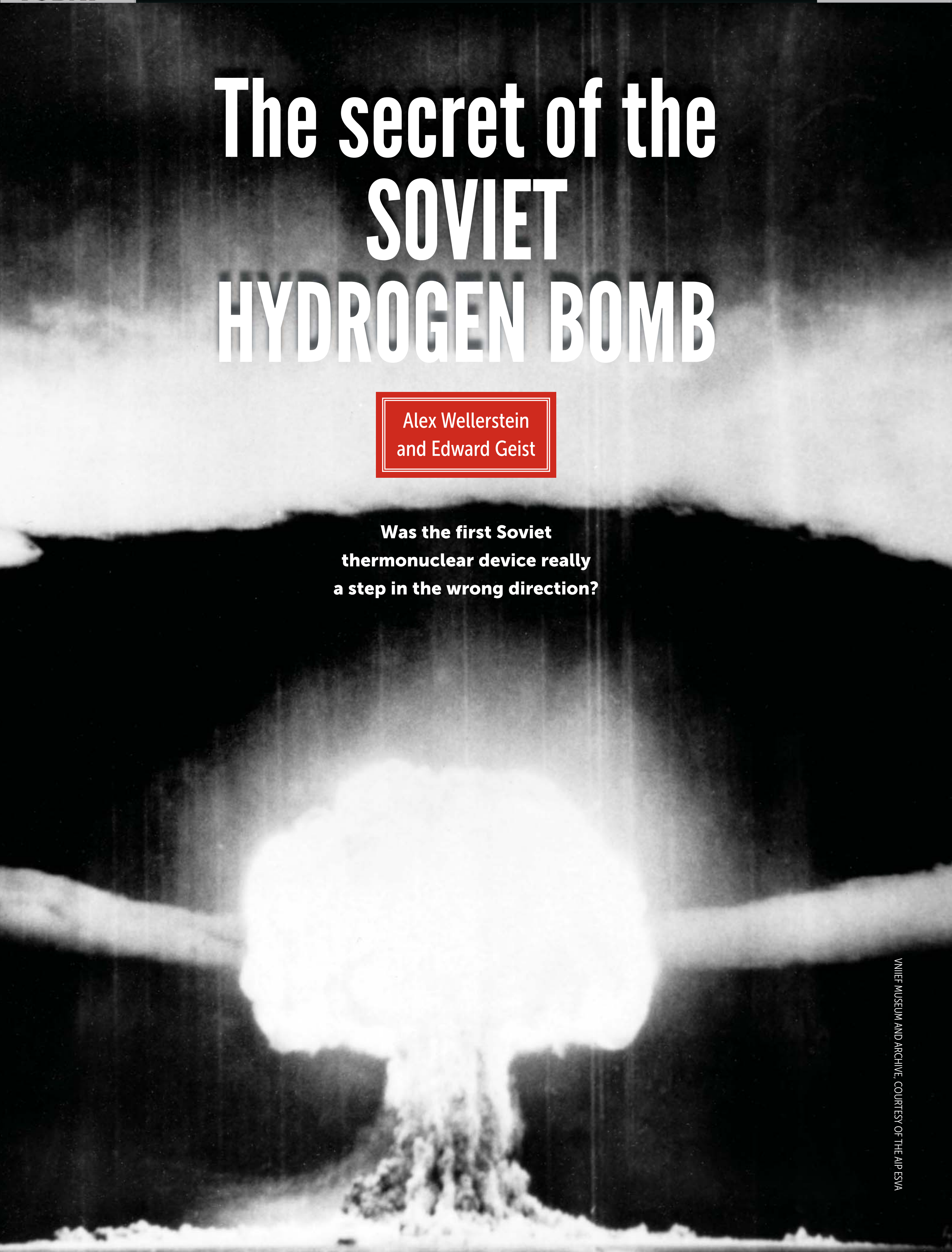
The secret of the SOVIET HYDROGEN BOMB

Alex Wellerstein and Edward Geist

Was the first Soviet thermonuclear device really a step in the wrong direction?



VNIIEF MUSEUM AND ARCHIVE, COURTESY OF THE AIP ESVA

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No bomb design has been as much maligned or otherwise disparaged as the first Soviet thermonuclear weapon. Detonated in August 1953, the bomb, officially tested under the name RDS-6s but usually known as *Sloika* or "layer cake" (the name Andrei Sakharov coined for it), was nothing to sneeze at. Shown in figure 1 and able to be dropped from aircraft, it released the explosive equivalent, or yield, of almost half a megaton of TNT. The result was a blazing fireball with 20 times the power of the bomb that leveled Nagasaki, Japan.

But when discussed today, the Sloika is almost immediately qualified by US experts as not a "true" hydrogen bomb. The downgrading is a curious reflex, one with interesting cultural and nationalistic origins. At one level, it is a technical determination: The bomb's design did not allow it to be scaled up to near unlimited explosive yields that true hydrogen bombs would allow, and it differed from what has become the foundation for all modern thermonuclear weapons, the famous US-developed Teller–Ulam design.

Historically, there was also a political reason to downplay the weapon. In the 1950s a lot was at stake for a US government official to say exactly when the Soviets first had true thermonuclear capability or that their first H-bomb was a militarily useless weapon and a dead end from a design standpoint. Decades later, the downplaying of the Sloika remains emblematic of how that phase in nuclear history is spoken of by US historians.

But a perusal of Soviet-era sources released in the past decade and of several new and obscure publications that have come from the Russian weapons establishment has convinced us that the disparaging view is incomplete. The new sources seem to point to two contrary views: First, the Sloika was, in fact, seen as a useful weapon in its own right, even if it was inefficient; it was not "cobbled together" just to make a statement, as some American scientists thought at the time. Second, it was also not as much of a nuclear dead end as it was perceived and is still claimed to be: Rather, it appears to have been absolutely crucial in helping to solve the riddle of how the Soviets developed their later, multistage, multimegaton thermonuclear weapon designs. Indeed, the Sloika is possibly the answer to the most curious question about the Soviet thermonuclear program: How did it develop a form of the Teller–Ulam design only a year after developing the Sloika?[1]

Why do we care?

The origins of the reflexive diminishing of the Sloika are found, in part, in an earlier debate in the US over whether to develop an H-bomb at all. In the fall of 1949, after the first Soviet atomic bomb test (labeled Joe-1 by the US, RDS-1 by the Soviets), a polarizing debate took place among US scientists and policymakers about whether a crash program to develop the H-bomb was the appropriate response to the loss of the nation's nuclear monopoly. The debate became public by the end of the year, and the resulting publicity prompted President Harry S. Truman in late January 1950 to issue a mandate to the US Atomic Energy Commission to develop thermonuclear weapons. The problem was that nobody knew how to do such a thing. The H-bomb, which would use the power of nuclear fission to initiate substantial reactions of nuclear fusion, was then still an uninvented technology, an idea without an implementation.[2]

A few days after Truman's mandate, the UK announced that physicist Klaus Fuchs had confessed to being a Soviet agent. Fuchs had been a key member of the UK nuclear program and had worked at Los Alamos during and slightly after World War II, before the US had stopped all classified cooperation with the British. Newspapers reported that Fuchs may have passed on information about the H-bomb to the Soviets as well. Now the American narrative was a new one: The Soviets had stolen the design for an atomic bomb, not independently developed or reinvented it, and they were possibly galloping ahead. For Edward Teller and others who had argued in favor of developing the H-bomb, the story was a vindication.[3]

Thermonuclear research in the US revolved primarily around one design, later called the Classical Super. The Classical Super was Teller's idée fixe and posed difficult technical problems. The basic idea involved using a high-yield nuclear fission bomb to ignite fusion reactions in a mixture of deuterium and tritium, which would generate enough heat to propagate further fusion reactions. The appeal was that arbitrarily large explosions could be generated that way; just add more deuterium. The problem—aside from the fact that it would require large amounts of scarce tritium and a very large fission stage to set the bomb off—was that it didn't seem to work.

In the spring of 1951, US scientists Teller and Stanislaw Ulam, shown in figure 2, made their famous breakthrough. Instead of a reaction that propagated relatively slowly down a tube of material, one fission bomb (the "primary") would detonate inside a heavy chamber that reflects its radiation to compress another, separate fusion capsule (the "secondary") inside a heavy chamber. That scheme, based on the concepts of staging (keeping the primary and secondary physically separated) and radiation implosion (the use of radiation to compress the secondary), became known later as the Teller–Ulam design. From the perspective of most weapons designers at the time, it was a radical departure from the approach taken with the Classical Super.[4]

The first prototype of the Teller–Ulam design was tested in November 1952 and was known as shot "Mike" of Operation Ivy. Yielding an equivalent of more than 10 million tons of TNT, the prototype vindicated the concept, though Mike was not designed to be used as a weapon. Its extensive cryogenic equipment, designed to keep deuterium in liquid form, meant that it weighed some 80 tons.

Just before the test, a fierce, secret debate about the importance of Fuchs's information began in the weapons laboratories. Fuchs's last contact with the US thermonuclear program was in 1946. Was information he could have gleaned from the program at that time valuable to the Soviets? On one side was Hans Bethe, who argued that the successful Teller–Ulam design differed so much from the original Classical Super design that anything Fuchs could have given them would be at best irrelevant and at worst completely misleading. Poised against him was Teller, who argued that the theoretical distance between the Classical Super and the Teller–Ulam design was not as large as Bethe thought. Furthermore, he pointed out, Fuchs had himself been involved with working on certain lines of research that eventually proved crucial: Fuchs, along with John von Neumann, had worked on a hydrogen bomb design that involved a version of the concept of radiation implosion.[5] (See the articles by German Arsen'evich Goncharov, PHYSICS TODAY, November 1996, pages 44, 45, 50, and 56.)

FIGURE 1. THE SLOIKA, or "layer cake," is the informal name for the Soviet Union's first thermonuclear bomb. Although its casing was roughly similar in shape and size to Fat Man, the US atomic bomb dropped on Nagasaki, Japan, in World War II, the Soviet bomb was 20 times as powerful: It detonated with the explosive equivalent of 400 kilotons of TNT. (Courtesy of the Russian Federal Nuclear Center, VNIIEF.)

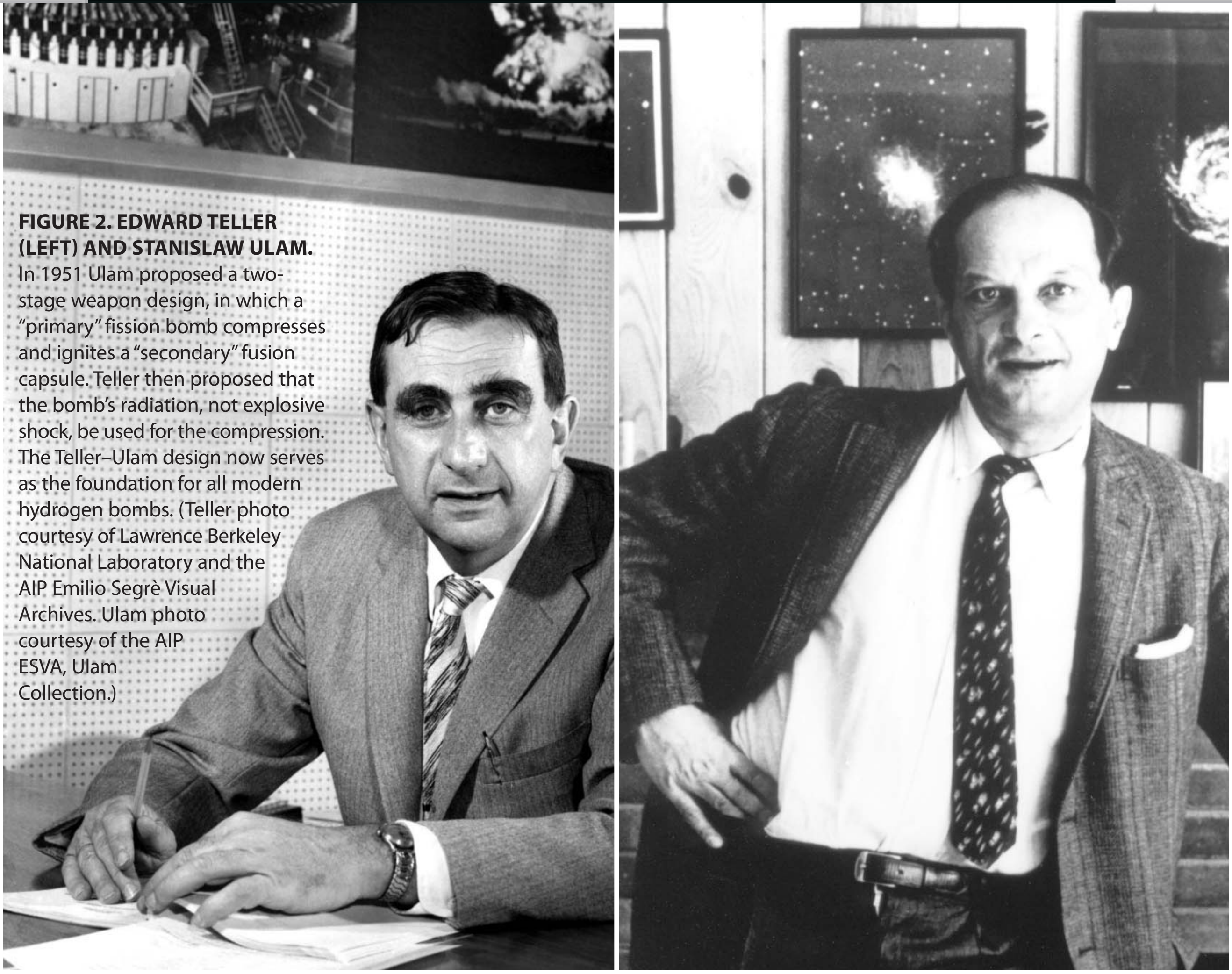


FIGURE 2. EDWARD TELLER (LEFT) AND STANISLAW ULAM. In 1951 Ulam proposed a two-stage weapon design, in which a "primary" fission bomb compresses and ignites a "secondary" fusion capsule. Teller then proposed that the bomb's radiation, not explosive shock, be used for the compression. The Teller–Ulam design now serves as the foundation for all modern hydrogen bombs. (Teller photo courtesy of Lawrence Berkeley National Laboratory and the AIP Emilio Segrè Visual Archives. Ulam photo courtesy of the AIP ESVA, Ulam Collection.)

The content of the debate was technical, but the reasons for it were clearly political. If Teller was correct, then the US was potentially behind the Soviets in weapons development. In Teller's eyes, it was because people such as J. Robert Oppenheimer stood in the way of his work on the H-bomb in the years after World War II and squandered a potential lead. If Bethe was correct, though, then not only would Fuchs be unable to pass on useful information about later US H-bomb design (since he did not know anything about it), but Oppenheimer would be vindicated for not supporting Teller's early, wrong-footed schemes. That debate started in the spring of 1952, even before the Mike test, and versions of it arguably continue today in any history of the thermonuclear program.

The Soviet Sloika entered the story in the middle of the debate and before the US had tested deliverable versions of the Teller–Ulam design. On 8 August 1953, Soviet premier Giorgi Malenkov gave a speech to the Supreme Soviet in which he declared that "the United States has no monopoly in the production of the hydrogen bomb." On 12 August, the fourth Soviet nuclear test, dubbed Joe-4 in the US, was detonated over the Kazakh steppe. On 20 August, *Pravda* published a statement proclaiming that "within one of the last few days an explosion of one of a variety of hydrogen bombs was carried out for experimental purposes" and attributed its "great strength" to a "mighty thermonuclear reaction."[6]

It looked, then, as if the Soviets might be keeping pace with the US, if not beating it: If the Joe-4 test was of a deliverable thermonuclear bomb, then the Soviets could be seen as ahead in the H-bomb race in one sense, because the US Mike device was an experimental apparatus, not a weapon. More than US pride was in the balance: A leading Soviet program might be a vindication of those who said that the US program had been needlessly stalled.

By September 1953, however, there were reasons to doubt that the Soviets were, in fact, ahead in the race for a deliverable H-bomb. A panel consisting of physicists Bethe, Enrico Fermi, Richard Garwin, and Lothar Nordheim conducted an analysis of the fallout residues from the August test. Their full conclusions are still redacted more than six decades later, but from what has been released, we can see they found that the Joe-4 test used highly enriched uranium, not plutonium, and that it involved "a substantial thermonuclear reaction." They were able to estimate the amount of uranium in the device and the amount of energy release attributable to fusion reactions, and they could speculate on the geometry of the device. They concluded that it was not a Teller–Ulam design but a weapon that had achieved "a high-yield, high-efficiency [fission] reaction with the help of the boosting principle." Bethe would later call the device "a big boosted fission weapon" and "a glorified booster," and he would say that it was clear from the analysis that it was a "single stage" weapon that involved "alternating layers of uranium and lithium deuteride."[7]

The Soviet bomb was therefore not really an H-bomb, if by H-bomb one means something along the lines of the Teller–Ulam design. Instead, it shared characteristics with two other thermonuclear designs the US had pursued. One design, Booster, involved a fission weapon that had a small amount of deuterium–tritium gas injected into its core at the moment of its detonation, which generated enough fusion neutrons to cause extra fission reactions.

The other design was one Teller had proposed in 1946 as the Alarm Clock—a weapon that would use spherical layers of fissionable and fusionable fuel in a matryoshka-doll arrangement, one sphere inside the other. The design had serious negatives: Its fusion yield would necessarily be limited, primarily serving to enhance fission reactions, like Booster; the various layers would interact in complex ways that were extremely difficult to calculate with the computing technology of the time; and to increase the Alarm Clock's yield to the megaton scale meant increasing a bomb's radius so much that it would not fit inside a bomber. For Teller, the fact that Alarm Clock's yield could not be increased indefinitely made it less interesting. Like the Booster, it was considered an auxiliary approach to what was then still the main show, the Classical Super.

If Joe-4, the Sloika, was just an Alarm Clock, then it wasn't the main show. If it was a glorified Booster, it definitely wasn't an H-bomb. But the Soviets saw it somewhat differently.

The Soviet view of Sloika

The Soviets called their H-bomb design the Sloika in reference to a layered Russian pastry similar to a napoleon. The code name hints at the bomb's internal geometry: layers of highly enriched uranium, fusion fuel made of solid lithium deuteride, lithium deuteride tritide, and uranium tamper materials, all of which would be compressed by high-explosive lenses. Many details, such as the number of layers, their order, and their relative masses, remain classified.

Declassified documents and imagery indicate that the test device was roughly a sphere, 1.5 meters in diameter, and that it weighed about 4.5 tons. The test device apparently fit into the same casing as the original Soviet atomic bomb and differed from the production-line (military) version of RDS-6s mainly in that the latter used two to three times as much tritium and uranium-235 as the test version and thus would have likely had a substantially larger yield.[8] In terms of weapons design, that size is not extreme (see figure 1)—it would be roughly the same shape and weight as the US Fat Man bomb dropped on Nagasaki, Japan, in World War II, though with a far more powerful explosion.

The basic problem with the Sloika, from a weapons designer's viewpoint, is that chemical high explosives simply lack the power to compress the entire mass sufficiently for substantial fusion reactions to occur. Such a weapon would also be extremely expensive in terms of enriched uranium usage.

As tested in 1953, the Sloika detonated with an explosive yield of 400 kilotons, of which around 80% of the energy came from fission reactions and 20% came from nuclear fusion. That ratio of fission-to-fusion reactions is less useful in determining a true H-bomb than it might seem: The Mike design, like practically all US H-bombs, relied heavily on a final uranium fission stage to increase its yield, and it had the same fission/fusion ratio as the Sloika. As J. Carson Mark, one of the few US weapons designers not to quibble about the status of the Sloika, argued in an interview: "They managed to get 400 kilotons without going to an unreasonable or even a heavier size. And, they did it by using thermonuclear reactions. Want to call that a hydrogen bomb? Well, why not?"[9]

Where Sloika really loses is in terms of the yield-to-weight ratio, the amount of energy release divided by the total bomb weight, which is the preferred method by which weapons designers gauge weapon sophistication. At 0.08 kilotons of energy per kilogram of bomb weight, the Sloika was an order of magnitude better than Fat Man, but still an order of magnitude less efficient than the first deliverable US H-bomb designs.

Documents declassified in the past decade give us some insight into how the RDS-6s device was viewed by those who made it. Although privately the Soviet designers also would consider it a glorified booster, they had grand plans for the Sloika. Contrary to US analyses that insisted those weapons could never achieve yields much greater than the 1953 test, the Soviets originally envisioned it as a megaton-range weapon.

But the multimegaton Sloika proved more difficult to develop than Soviet nuclear scientists, including Andrei Sakharov, originally envisioned. Serious problems emerged because a Sloika of a particular diameter could only make efficient use of expensive materials such as uranium–235 and tritium up to a certain yield. By mid 1954 it became clear that within the 1.5-m radius dictated by the size of delivery vehicles, constructing a Sloika with a yield greater than 0.5–1.0 megaton without using costly tritium would be difficult.

Over the next year, some of the Soviet Union's most brilliant technical experts devoted their attention to constructing a cost-effective, multimegaton Sloika. They also explored developing a design with a focus on economy rather than yield. That effort resulted in a new budget-friendly design that was the same size as the multimegaton Sloika but with a yield of only 350 kilotons. Soviet nuclear scientists, however, insisted that the seemingly inferior weapon exploited the full potential of the Sloika concept for maximizing yield while minimizing the need for scarce nuclear materials such as lithium-6, making it vastly more cost-effective.

In September 1953 the Bethe panel produced a lengthy analysis, in which it asserted that weapons on the Sloika principle would scale poorly even if "the yield they have achieved is certainly enough to cause concern." How are we to account for the contrast between Bethe's dismissal of the RDS-6s design and the Soviets' ambitious plans for the Sloika? One possibility is that Bethe's conjectural reconstruction of the weapon's internal geometry was in error, but we cannot be sure, as both Bethe's analysis and the design details of the Soviet device remain classified.

However, given the extreme difficulty the Soviets experienced developing the megaton-scale version of the RDS-6s (dubbed the RDS-6sd), it is also possible that their ultimate design differed very substantially from the weapon tested in 1953. For a predicted yield of 1.8 megatons, it may have incorporated a dissimilar internal geometry, different materials, and counterintuitive features that never occurred to Bethe or other US scientists who lacked hands-on experience with weapons of the Sloika type. Bethe's dismissal of the Sloika may also have been based on the analysis that had been done in the US on the Alarm Clock; although it shared a similarly layered design with the Sloika, it may also have differed in several ways.

By August 1955 both the RDS-6sd and its budget version were ready for testing, but the imminent arrival of a more advanced rival delayed their debut. After struggling to improve the Sloika, the Soviets had finally hit on their version of the Teller–Ulam design. They called it Sakharov's Third Idea, and gave the prototype the code name RDS-37. A two-stage weapon employing radiation implosion to produce a multimegaton yield, the RDS-37 used about a quarter of the nuclear explosive materials the RDS-6sd used and had the capacity for a much greater yield in a package that the Soviet Union's bombers and missiles could carry. Soviet leaders decided to wait to test the costly multimegaton Sloika until after the performance of Sakharov's new invention could be verified in a live test.

The successful airburst of the RDS-37 on 22 November 1955 sounded the death knell of the RDS-6sd and, in time, all other Sloikas. Deliberately detonated at half its total predicted power, the weapon fit into the same case as the Sloika but released 1.6 megatons of energy. Assuming its weight was similar to the Sloika's, it was a full order of magnitude more efficient and, more importantly, much more flexible for scaling weapon output both up and down. The handful of RDS-6sd devices were promptly dismantled so their precious lithium-6 and enriched uranium could be incorporated into more modern weapons. The Sloika had passed into history.

The Sloika's legacy

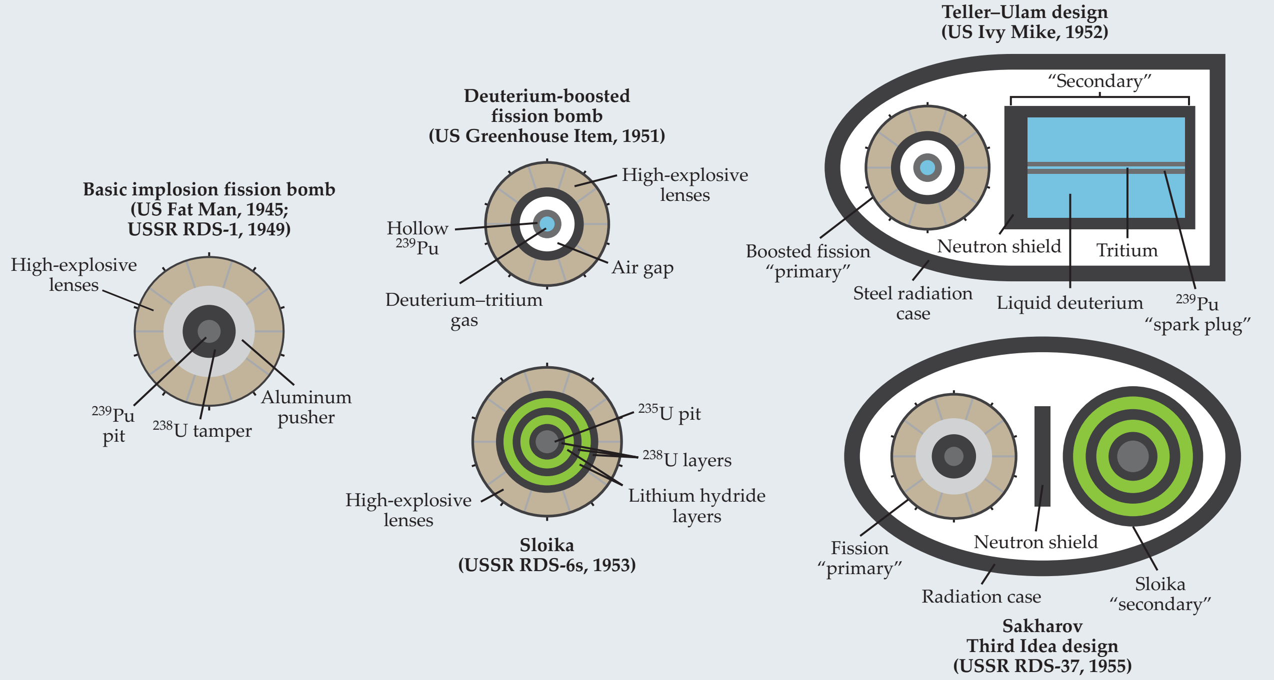
Was the Sloika merely a dead end? The Soviet records suggest not. For Soviet weapons designers, Sloika served as a means of exploring thermonuclear concepts while still producing deliverable weapons that though not as powerful as later developments were large enough to be considered serious city busters. Moreover, reading between the lines of the secret Soviet histories, there are reasons to suspect that Sloika was more important to their program than one might expect.

No doubt the Soviet fission bomb program owed much to

TWO APPROACHES TO THERMONUCLEAR WEAPONS

In a basic implosion bomb, like the one dropped on Nagasaki, Japan, a solid-metal plutonium core is compressed using high-explosive lenses and an aluminum pusher to around 2.5 times its original density. In the deuterium-boosted design, a hollow core of plutonium is injected with deuterium–tritium gas at the moment of detonation, which causes a small number of fusion reactions. Those reactions produce high-energy neutrons that enhance the efficiency of the fission reactions in the core. In the *Sloika* design, alternating layers of lithium hydride and uranium-238 surround a uranium-235 core. The high-explosive lenses compress the entire core and set off of a fusion reaction that in turn compresses the fusion fuel. The fusion reactions produce high-energy neutrons that induce further fissioning.

These bomb designs are the basic ingredients that the US and the Soviet Union adapted into thermonuclear weapons—also known as H-bombs. In the original US Teller–Ulam design, a boosted fission bomb sits at one end of a heavy radiation case. At the other end sits the thermonuclear charge, a cylinder with a neutron shield on one end, liquid deuterium inside it, and a thin "spark plug" of plutonium mixed with tritium. At detonation, the radiation from the fission bomb reflects off the inside of the radiation casing and compresses the thermonuclear charge to many times its original density. The compression, in turn, begins a fission reaction in the "spark plug," which compresses the fusion fuel from the other side simultaneously. Thus compressed, the fusion fuel is primed for fusion reactions, which contribute significantly to the explosive yield. The reactions produce high-energy neutrons that induce further fissioning in a uranium-238 tamper. Sakharov's "Third Idea" adopts a similar scheme, except the neutron shield is integrated into the overall design, and the Sloika is stripped of its high-explosive components.



espionage. The work of spies such as Ted Hall and David Greenglass allowed the Soviet Union to have a reasonably good understanding of what went into the construction of plutonium-implosion nuclear weapons, and its first fission bomb, RDS-1, was a "Sovietized" copy of the weapon dropped on Nagasaki.[10]

The Soviets also received some information on US thermonuclear work from Fuchs. Declassified documents from the Soviet archives show that Fuchs gave them extremely detailed accounts of the state of US work as of 1946 and of the work he did with von Neumann. The Soviets did have a research program for the Classical Super design, which they dubbed the *Truba*, or "Tube," that ran parallel with the Sloika work.[11,9]

As noted earlier, the Soviets eventually hit upon the two-stage, radiation implosion design known in the US as the Teller–Ulam idea. Although the Soviets called it Sakharov's Third Idea (see figure 3), internally they noted that exact authorship was difficult to determine. As Lev Feoktistov, a scientist on the project, recalled, "New ideas dawned upon us suddenly like light in a dark kingdom, and it was clear that the instant of truth had come. Rumors ascribed these fundamental thoughts in Teller's spirit now to [Yakov] Zel'dovich, now to Sakharov, now to both, or to someone else, but always in some indecisive form: likely, possibly, and so on."[12] The first two ideas were, in order, the Sloika's layering scheme and the use of lithium deuteride as a fusion fuel; both had been well-documented by 1949.

Both the Third Idea and the Teller–Ulam design differentiate themselves from earlier H-bomb designs in their use of radiation energy as a means of achieving extremely high densities in a thermonuclear assembly (see the box on page 45). As

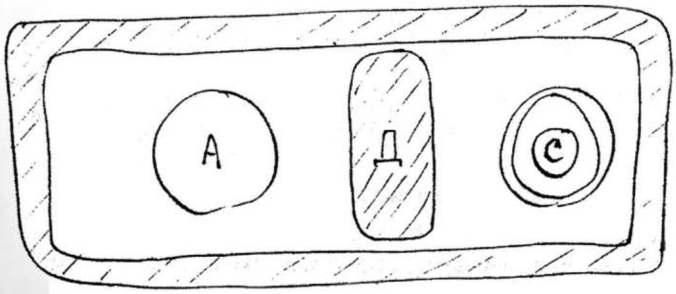


FIGURE 3. ANDREI SAKHAROV is pictured next to the first formulation of the "Third Idea," a heavy box containing an atomic bomb (A), a neutron shield or diaphragm (Д, the Cyrillic letter for "D"), and a Sloika (C, the Cyrillic letter for "S"). (Sakharov photo from the Russian Federal Nuclear Center, VNIIEF Museum and Archive, courtesy of the AIP Emilio Segrè Visual Archives; diagram adapted from ref. 8, doc. 56, p. 128.)

Soviet designers drew it, the weapon was a heavy box with an atomic bomb at one end and the thermonuclear capsule at the other. In the earliest US Teller–Ulam designs, the capsule was a cylinder with multiple layers: on the outside a heavy tamper, then liquid deuterium or lithium deuteride, and in the center a "spark plug" of plutonium and tritium.[13]

The first record of that idea from the Soviet archives dates from January 1954, a brief memo from Zel'dovich and Sakharov titled "On the use of a gadget for implosion of supergadget RDS-6s."[14] The memo describes a heavy box inside which an atomic bomb (labeled "A") sits at one end, a neutron shield (labeled the Cyrillic character for "D") sits in the center, and what looks like a Sloika (labeled with a Cyrillic "S") sits at the other end (see figure 3). Along with the title of the paper, the sketch suggests a plausible genealogy of the Third Idea: The Sloika became a second stage of a two-stage thermonuclear weapon, the "supergadget" imploded by the fission "gadget."

Much remains missing in our knowledge of Soviet thermonuclear developments, but the path to the Third Idea may have been paved in part by the intensive work on the Sloika. The chief practical problem of that device is achieving the high compressions one needs for fusion. If high explosives can't cause them, what can? A new approach appeared to answer the question: using a fission bomb to compress the entire Sloika, first imagined as a compressive shock, later as radiation implosion. The Sloika, minus its high explosives and simplified a bit, is essentially a high-performance thermonuclear secondary: layers of fusion fuel, tamper, and fission material.

Over the decades many authors have asserted that the Soviet Union somehow learned of radiation implosion from the US rather than developing it independently. In more recent decades, a few accounts have asserted that the Soviets could not have discovered radiation implosion on their own and that a still-unidentified mole must have given away the secret of the H-bomb.[15]

Declassified Soviet documents contradict those views. They reveal that the thermonuclear information the Soviets got from spies was of limited value and not responsible for the work on either the Sloika or the later RDS-37 device. There is simply nothing to suggest that the Soviet scientists had insight into US weapons designs; even after they developed their own two-stage design, Soviet nuclear scientists remained uncertain whether the American bombs operated on the same principle.[16] And if the Russian security services could have taken credit for the Soviet H-bomb, which would serve to delegitimize the dissident Sakharov, it seems likely they would have done so by now.

If just one lesson were to be taken from the history of the Sloika, it may be that in the journey toward invention there is no single path to a right idea. Too often the American case is taken to be the default path of technological development, often because the US did it first and perhaps because it is much easier to document than other countries' programs. But the secrecy involved meant that each national program, to various degrees, reinvented the bomb, and finding some national variances should not be so surprising.

The Sloika, rather than just being a relic, sheds much light on alternative approaches toward a similar technological end.

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PT

ON 23 MARCH 1983 President Ronald Reagan announced his Strategic Defense Initiative on television. The first three-quarters of the speech was spent justifying dramatic increases in the US defense budget, "to make America strong again after too many years of neglect and mistakes." The photograph behind the president shows a Soviet MiG-23 fighter-bomber base in Cuba.

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Sakharov, Gorbachev, and nuclear reductions

Frank N. von Hippel

Two years before his death in 1989, Andrei Sakharov's comments at a scientists' forum helped set the stage for the elimination of thousands of nuclear ballistic missiles from the US and Soviet arsenals.

The great Soviet dissident physicist Andrei Sakharov and Soviet Union leader Mikhail Gorbachev met for the first time in January 1988. That was a little more than a year after Gorbachev had given Sakharov permission to return to Moscow from the closed city of Gorky, to which Sakharov had been exiled for seven years.

When Sakharov returned, US–Soviet nuclear arms control was at an impasse; Gorbachev was insisting that the US commit to keeping its ballistic missile defense (BMD) program within the constraints of the 1972 Anti-Ballistic Missile (ABM) Treaty, and President Ronald Reagan was refusing to do so. Sakharov publicly argued that Reagan's program, ridiculed as "Star Wars" by its US critics, would never produce militarily significant capabilities and that Gorbachev therefore should seize the opportunity for nuclear arms reductions. Two weeks later that view was endorsed by the Soviet leadership and opened the path to deep cuts in Soviet and US nuclear forces.

In 1987 I coorganized a scientists' forum in Moscow on nuclear disarmament, where Sakharov went public with his views, and I was present at his first meeting with Gorbachev a year later. I also took part in a private discussion with Sakharov in his apartment before the forum. Five years later I received a copy of a partial transcript of that discussion, which had been delivered to Gorbachev by the head of the Soviet secret service, the KGB.

For the younger generation, many of whom may know little about Sakharov, I start this article with a brief summary of the man's remarkable career.[1] I then describe how he helped delink nuclear reductions from the issue of BMD at that key moment in the history of nuclear arms control; the meeting in his apartment; his meeting with Gorbachev; and finally how relinking arms reductions and BMD has now returned to hobble progress on nuclear disarmament.

Andrei Sakharov

Sakharov (1921–89) was recruited into the Soviet Union's nuclear weapons program in 1948, a year after he completed his doctorate. In 1949 the US detected the first Soviet test of a fission bomb, and the two countries embarked on a desperate race to design a thermonuclear hydrogen bomb that was a thousand times more powerful. The race ended in a rough tie five years later. (See the article by Alex Wellerstein and Edward Geist on page 40 of this issue.)

Sakharov made key contributions to the Soviet effort and was awarded the honorary title Hero of Socialist Labor three times, in 1953, 1956, and 1962. During the same period, he coinvented the tokamak (see PHYSICS TODAY, December 2005, page 15), a toroidal magnetic plasma confinement device that is still the main focus of international efforts to develop a fusion reactor.

Like his US counterparts, Sakharov justified his H-bomb work by pointing to the danger of the other country's achieving a monopoly. But also like some of the US scientists who had worked on the Manhattan Project, he felt a responsibility to inform his nation's leadership and then the world about the dangers from nuclear weapons.

Sakharov's first effort to influence policy was stimulated by his concern about possible genetic damage from long-lived radioactive carbon-14 created in the atmosphere from nitrogen-14 by the enormous fluxes of neutrons released in H-bomb tests.[2] In 1961 he urged Soviet leader Nikita Khrushchev to maintain the bilateral Soviet–US testing moratorium that had begun in 1959. Khrushchev told him that tests were required to show the US that the Soviet Union could not be intimidated. In the subsequent final spasm of Soviet and US atmospheric testing, the Soviet Union exploded a 50-megaton bomb, by far the highest-yield nuclear explosion ever set off. (Yield refers to the amount of TNT needed for an equivalent explosion.) The next year the Cuban Missile Crisis sobered both sides, at least temporarily, and in 1963 they agreed on an atmospheric test ban.

In 1968 a friend suggested that Sakharov write an essay about the role of the intelligentsia in world affairs. Samizdat (self-publishing) was the method at the time for spreading unapproved manuscripts in the Soviet Union. Many readers would create multiple copies by typing with multiple sheets of paper interleaved with carbon paper. One copy of Sakharov's essay, "Reflections on Progress, Peaceful Coexistence, and Intellectual Freedom," was smuggled out of the Soviet Union and published by the *New York Times*. More than 18 million reprints were produced during 1968–69. I still remember my excitement on reading that call for cooperation between East and West coming from the heart of the closed Soviet nuclear weapons complex. It was also a call, as Sakharov put it, for "freedom to obtain and distribute information, freedom for open-minded and unfearing debate and freedom from pressure by officialdom and prejudices."

After the essay was published, Sakharov was barred from returning to work in the nuclear weapons program and took a research position in Moscow. With his political views known, however, dissidents began to ask him to lend his name to their appeals for more freedom—requests he could not refuse. His status as coinventor of the Soviet H-bomb protected him, but as other dissidents were sent to prison, he became more and more outspoken and joined vigils outside the courtrooms where they were being tried.

In 1980, after an interview with the *New York Times* in which he denounced the Soviet invasion of Afghanistan, the government's patience finally ran out. To put him beyond the reach of Western journalists, the Soviet Union exiled Sakharov and his wife, Elena Bonner, to Gorky (now known as Nizhniy Novgorod). There he undertook prolonged hunger strikes. The longest, which lasted for about a year, was to get permission for Bonner to go abroad for heart-bypass surgery. During that period he was repeatedly force-fed before the government finally relented. (See the article by Sidney Drell and Lev Okun, PHYSICS TODAY, August 1990, page 26.) Under the stress, Sakharov suffered three heart attacks.

Foreign supporters—including Jeremy Stone, president of the Washington-based arms-control group the Federation of American Scientists—campaigned tirelessly to keep Sakharov's case in the spotlight of public and government attention. As chairman of the federation, I was a supporting character in that effort.

In March 1985 Gorbachev became general secretary of the Soviet Communist Party. More than a year and a half later, he persuaded the Politburo, the party's executive committee, to allow Sakharov and Bonner to return to Moscow. (For more details about Sakharov's life and work, see the special issue of PHYSICS TODAY, August 1990.)

The US–Soviet nuclear impasse

Reagan's election in 1980 led first to the intensification of the nuclear arms race and then to the largest ever public uprising against it. A powerful advocacy group, the Committee on the Present Danger (CPD), had convinced Reagan that the US was falling behind in the nuclear arms race and was in mortal danger of a Soviet first nuclear strike. Many of its members obtained high-level positions in the administration, including in the Department of Defense, where they proposed to add almost 10 000 ballistic and cruise missile nuclear warheads to the US arsenal. The new weapons would threaten Soviet intercontinental ballistic missiles (ICBMs) in their hardened underground silos in the same way that the CPD claimed Soviet ballistic missiles already threatened US silos. (See the article by Harold Feiveson and me, PHYSICS TODAY, January 1983, page 36.)

The proposed buildup and public statements by some middle-level DOD appointees that it might be possible to win a nuclear war led to huge public demonstrations in the US, Europe, and elsewhere against the nuclear arms race.[3]

In March 1983 President Reagan announced the Strategic Defense Initiative (SDI), which would focus on developing technology to make Soviet ballistic missiles "impotent and obsolete." The initiative communicated a less threatening image than the CPD buildup to the US public and allies. In Moscow, however, it suggested a scenario in which the US could threaten to destroy most of the Soviet Union's missiles in a first strike and then use its BMD to block the ragged counterattack by the surviving Soviet missiles.

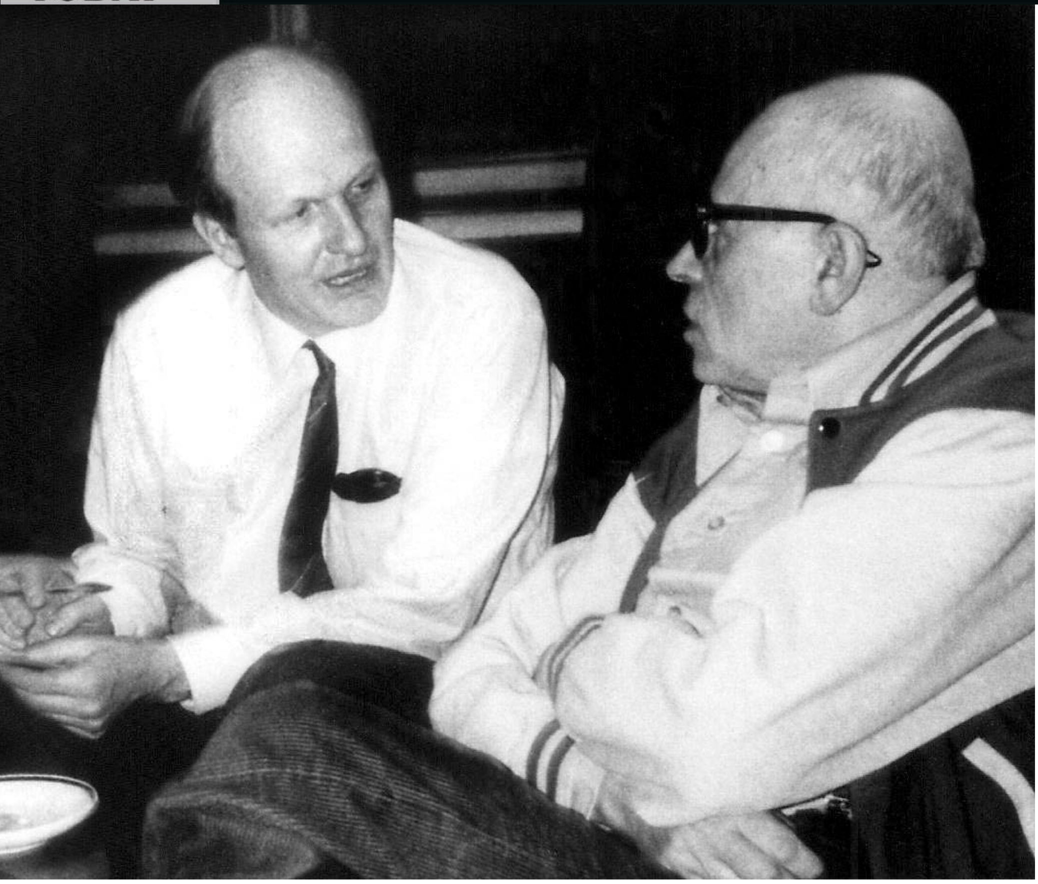

FIGURE 1. ANDREI SAKHAROV (RIGHT) AND I speak in his Moscow apartment on 11 February 1987, three days before a scientists' forum at which he made public his proposal to delink Soviet–US negotiations on nuclear reductions from the Reagan administration's Star Wars program. (Photo by Jeremy Stone.)

In early November 1983 the Reagan administration created a severe nuclear crisis with a NATO exercise, Able Archer, that Soviet intelligence mistook for preparations for an actual nuclear attack. Two years later the situation finally began to diffuse. At the recommendation of UK prime minister Margaret Thatcher, Reagan in November 1985 had a get-acquainted meeting in Geneva with Gorbachev, who had just become general secretary after two elderly predecessors, in quick succession, had died in office.

In their legendary October 1986 Reykjavik summit, Reagan and Gorbachev agreed on the goal of nuclear disarmament. But they could not agree on a first tranche of cuts because Gorbachev insisted that Reagan commit to remaining within the constraints of the ABM Treaty for 10 years. The treaty limited both sides to 100 ground-based interceptors at a single site. At the time, the Reagan administration was focused on a concept in which hundreds of orbiting, high-power lasers would burn holes in Soviet booster rockets as they rose out of the atmosphere.

Arms controllers on both sides, meanwhile, had found each other and were brainstorming about how to end the nuclear arms race. Stone and I had become involved in such discussions in November 1983. We met with a group headed by Evgeny Velikhov, a vice president of the Soviet Academy of Sciences. After Gorbachev came to power in March 1985, we learned that Velikhov and his colleagues had been advising Gorbachev (see my article, PHYSICS TODAY, September 2013, page 41).

Gorbachev's first move, in August 1985, was to declare a unilateral moratorium on nuclear testing, now underground because of the 1963 atmospheric test ban. The Reagan administration disparaged the initiative, but the Democrats, who controlled the House of Representatives until 1995 and the Senate during 1987–95, were impressed. In 1992 they were able to force the Bush administration to end US testing on the condition that other countries not test either. In 1996 the Clinton administration negotiated the Comprehensive Nuclear-Test-Ban Treaty (CTBT). Although that treaty has not yet been ratified by the US, China, India, Pakistan, or North Korea, only North Korea has tested since 1998 (see the article by Pierce Corden and David Hafemeister, PHYSICS TODAY, April 2014, page 41).

In February 1987 Velikhov and I organized the scientists' forum on nuclear disarmament in Moscow. Sakharov's release from Gorky may have been timed so that his exile would not become an issue at the forum. Stone and I arrived with our wives in Moscow a few days early, and Stone arranged a meeting with Sakharov and Bonner in their apartment (see figure 1). Now that he was able to speak out again, we knew the world was eager to hear what Sakharov had to say. We saw the forum as an opportunity for him to lay out his views on nuclear disarmament at that critical time.

Stone started the discussion by suggesting that Sakharov urge Gorbachev to ignore the SDI and seize the opportunity for arms reductions. He argued that Reagan's successors would abandon the program as unaffordable and that the US would not break the ABM Treaty if progress was being made on nuclear reductions. Sakharov responded that he had been thinking along the same lines.

My part of the discussion was not so easy. I told Sakharov that my colleagues and I were publishing estimates of the civilian consequences of US and Soviet nuclear "counterforce" attacks on each other's nuclear forces. We had found that the direct consequence would include tens of millions of civilian deaths. I argued that both sides should settle for "minimum deterrence" or what McGeorge Bundy, President John F. Kennedy's national security adviser, called "existential deterrence," a situation in which just the fact that a country has nuclear weapons instills caution—like a policeman's holstered gun—in other countries.

Sakharov argued that persuading both countries' military leaders to abandon counterforce strategies would be virtually impossible. In the two decades since our conversation, the numbers of warheads deployed on Russian and US strategic missiles have come down by a factor of about five, to less than 2000 each, but the two missile forces' highest-priority targets remain each other.

During our discussion, the apartment doorbell rang every 10 minutes or so. Bonner told us to ignore it, saying, "It's just the KGB." It turned out that the KGB was also recording our conversation.

The KGB transcript

In 1992, after the collapse of the Soviet Union, the new Russian government made public a collection of Communist Party documents, including a KGB transcript of parts of our conversation in Sakharov's apartment. Matthew Evangelista, a historian at Cornell University, obtained a copy and shared it with me.

Certain passages of the transcript were underlined. If that was done by Gorbachev—or by the KGB for his benefit—they indicate that he was interested in learning more about the nuclear balance. Among the underlined parts were my statements that Soviet warheads had higher explosive yields than US warheads and that the Soviet Union was about five years behind the US in reducing the weight of its warheads per unit of explosive power. That information may have been relevant to the debate within the Soviet leadership over Gorbachev's unilateral nuclear testing moratorium, which was about to end.

Sakharov's statement that silo-based ballistic missiles accounted for a much larger fraction of Soviet than US strategic warheads also was underlined, as was his response when Stone conveyed an invitation from Senator Edward Kennedy for Sakharov to visit the US. Sakharov said he would not be allowed to travel abroad in the absence of "very strong pressure" from "foreign political leaders and organizations," and he added that an effort of such magnitude would be "disproportionate to the goal."

Delinking missile defense from nuclear reductions

Sakharov argued at the scientists' forum that the Soviet Union should delink its objections to Reagan's SDI from the issue of bilateral nuclear cuts. He was heavily criticized for that by some Soviet nuclear strategists at the meeting. Later, at an event at the Kremlin, in a speech summarizing the conclusions of the scientists' forum for Gorbachev and a large audience, I presented Sakharov's recommendations.[4] In his book *Perestroika*, published later that year, Gorbachev recounted,

> At the Moscow International Forum "For a Nuclear-Weapon-Free World and the Survival of Humanity"—a meeting unprecedented in the number of participants and their authority—I had the opportunity to feel the moods and hear the thoughts and ideas of an international intellectual elite. My discussions with them made a great impression on me. I discussed the results of the congress with my colleagues in the Politburo and we decided to make a major new compromise—untie the Reykjavik package and separate the problem of medium-range missiles in Europe from the other issues.[5]

Sakharov was not the only one arguing for delinking. The day before the crucial 26 February 1987 Politburo meeting, Alexander Yakovlev, a close adviser, sent Gorbachev a memo arguing passionately for the delinking; his argument was based primarily on an analysis of European and US public opinion. Also, Velikhov's group had convinced Gorbachev that any SDI system could be handled with countermeasures. As Gorbachev said it, "A tenth of the US investments would be enough to create a counter-system to frustrate SDI."[6]

FIGURE 2. SAKHAROV SPEAKS as Mikhail Gorbachev presides at the new Congress of People's Deputies in June 1989. The proceedings were carried live on television and radio and riveted a public that had never heard a real democratic debate.[14] Sakharov fought for many reforms, including a repeal of the Soviet Constitution's Article 6, which gave the leading role in government to the Communist Party. He died on 14 December, after speaking again for that reform, which was adopted three months after his death. (*Priroda* magazine and Nauka Publishers, courtesy of the AIP Emilio Segrè Visual Archives, Physics Today Collection.)

Later that year Gorbachev and Reagan signed the Intermediate-Range Nuclear Forces Treaty, which eliminated about 2700 medium- and intermediate-range nuclear missiles. The two men also agreed in principle on 50% cuts of strategic warheads, which laid the basis for the Strategic Arms Reduction Treaty (START) that entered into force in 1994. In the meantime, with both houses of Congress under solid Democratic control, Senator Sam Nunn, the chairman of the Senate Armed Services Committee, informed Reagan that if his administration reinterpreted the ABM Treaty to allow testing of a space-based BMD, funding for SDI would be cut deeply.

Meeting with Gorbachev

Sakharov's meeting with Gorbachev in January 1988 came about because of another Velikhov initiative, the establishment of an independent, international foundation in Moscow to work on global problems. Velikhov invited Sakharov to be on

the foundation's board, along with several foreign luminaries and me. The foundation's creation was announced at the scientists' forum, and the board was invited to meet with Gorbachev in the Kremlin.

I sat with Sakharov on the bus to the Kremlin. He told me about Gorbachev's call to Gorky to inform him that he was free to return to Moscow. Sakharov said that his immediate response to Gorbachev had been that freeing him was not enough. It was necessary to free all political prisoners.

At the Kremlin, there was first a reception outside Gorbachev's office. Gorbachev greeted Sakharov, who thanked him for "restoring my freedom and responsibility" (someone translated the exchange for me). Gorbachev responded that he was happy to hear Sakharov connect those two words.

Then the foundation board members sat down with Gorbachev around a conference table, and each of us had an opportunity to address him. According to my recollection, when it was Sakharov's turn, he started, "Mikhail Sergeyevich, when we spoke during your call, I raised the issue of other political prisoners. Today I have brought with me a list." Gorbachev responded, "Andrei Dmitrievich, we can't go too quickly. Remember what happened with the Red Guards in China," referring to the chaos that resulted when Mao Zedong unleashed young activists on China's establishment during the late 1960s. Gorbachev did, however, have an aide take Sakharov's list. A year later Sakharov could say, "The majority of prisoners of conscience have been freed."[7]

The foundation operated for a few years, which gave me an opportunity to get to know Sakharov better. He was absolutely uncompromising, starting with the foundation's name. He insisted that it be called the International Foundation for the Survival and Development of Humanity. I commented that was a rather long name but Sakharov responded, "What do you want to leave out? Humanity? Development? Survival?" I surrendered. On another occasion, he suggested that members of the board personally pay half of their travel expenses to make sure that we weren't being motivated by the opportunity to travel. That idea did not attract support from any other board member.

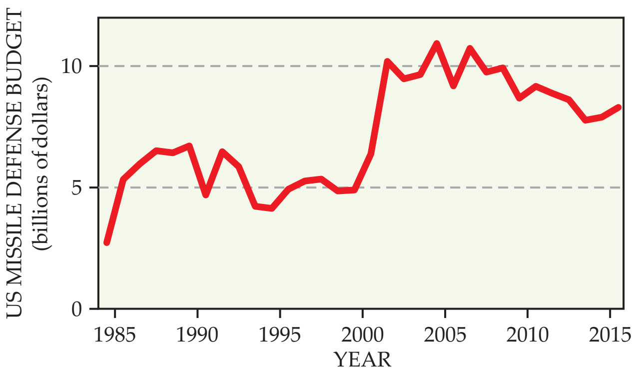

FIGURE 3. BUDGET OF THE US MISSILE DEFENSE AGENCY and its predecessors, the Strategic Defense Initiative and Ballistic Missile Defense Organizations. The initial rise followed President Ronald Reagan's Star Wars speech in 1983. The second major increase followed President George W. Bush's announcement in 2002 that he was taking the US out of the 1972 Anti-Ballistic Missile Treaty, which had limited ballistic-missile defenses. (Data from ref. 15, converted to constant 2016 dollars.)

I had the opportunity to see another side of Sakharov when I accompanied him to a lunch with Sweden's ambassador to the Soviet Union. The subject was Raoul Wallenberg, a heroic Swedish diplomat who in 1944 saved thousands of Jews in Budapest from being shipped to Nazi extermination camps. After the Soviet Union occupied Hungary, Wallenberg was sucked into the KGB's prison system. The KGB said that he died in 1947, but from time to time released prisoners reported having seen him. Sakharov had come to discuss the latest rumor. I was moved to see how, in the midst of his battle for democracy in the Soviet Union, this great man was still pursuing the cases of individual political prisoners.

Sakharov was elected as an opposition member to the Soviet Congress of People's Deputies in 1989 (see figure 2). Later that year he had a heart attack and died in his apartment. He left behind a draft of a new Soviet constitution that emphasized democracy and human rights. In a poll taken shortly thereafter, Sakharov was found to be the most revered person in Soviet history.[8]

Sakharov stood up for the principles that he had enunciated in "Reflections on Progress, Peaceful Coexistence, and Intellectual Freedom," and for that he was recognized with the 1975 Nobel Peace Prize. The European Parliament honored him by establishing the Sakharov Prize for Freedom of Thought in 1988. The American Physical Society created a Sakharov Prize in 2006 for physicists who uphold human rights.

Relinking

US presidents George H. W. Bush and Bill Clinton did not have the same enthusiasm for BMD as Reagan did. But weapons programs are difficult to kill, and its funding continued at about $5 billion per year, as shown in figure 3.

In 1996 a new Republican majority in both houses of Congress established the Commission to Assess the Ballistic Missile Threat to the United States, chaired by Donald Rumsfeld. The commission reported back in 1998 that within five years Iran and North Korea could have intercontinental ballistic missiles armed with weapons of mass destruction. It also said that Iraq could do the same within 10 years or, if it used ship-based ballistic missiles, "within a very short time" and that those capabilities might emerge with little warning.[9]

After his election in 2000, President George W. Bush appointed Rumsfeld to be his secretary of defense. In 2002 they took the US out of the ABM Treaty and committed to fielding missile defenses by the end of Bush's first term in 2004. The annual budget for BMD was quickly doubled to $10 billion (in 2016 dollars), a level from which it dropped only slightly during the Obama administration. Currently the US has 30 land-based interceptors deployed in Alaska and California and 33 Aegis cruisers and destroyers equipped with missile-detection radars and launchers for interceptor missiles (see figure 4). The most advanced Aegis interceptor, the Standard Missile 3 Block IIA, which was first tested in 2015, has sufficient speed, if launched from ships near the continental US, to intercept intercontinental ballistic missiles sent from Russia or China. The same system is being deployed on land in Romania and Poland. Designed to intercept missiles above Earth's atmosphere, the systems could be defeated by lightweight decoys and other countermeasures.

FIGURE 4. THE LAUNCH OF AN INTERCEPTOR MISSILE from the rear vertical launch magazine of a US Aegis cruiser. The cruiser's phased-array radars can detect incoming warheads at a range of about 300 kilometers. To defend the US against long-range missiles, the Aegis missiles would have to be given their interception points by more powerful early-warning radars. (Courtesy of the US Navy.)

The ABM Treaty came about in part because US physicists in the late 1960s explained the many obvious countermeasures to both Congress and their Soviet counterparts. Sakharov's 1968 essay cites a key article that informed the debate:

> . . . the practical impossibility of preventing a massive rocket attack. This situation is well known to specialists. In the popular scientific literature, for example, one can read this in an article by Richard L. Garwin and Hans A. Bethe in the *Scientific American* of March 1968.

When Garwin and Bethe wrote their article, the proposed US interceptor missiles were nuclear tipped. That was one reason for public interest in the issue. Suburbanites did not want nuclear-armed interceptors in their backyards. Today the interceptors are terminally guided with IR sensors. But the problem of decoys and other countermeasures remains.[10]

Both Russia and China have expressed concern about the US deployments. Russia cites US BMD as a principal reason why it is not interested in negotiating further reductions in strategic nuclear weapons.[11] And although it would make it easier for Russia and the US to further reduce their arsenals if China committed to not build up, China is increasing its small force of intercontinental ballistic missiles, in part because of its own concerns that US BMDs could neutralize its deterrent.[12]

The original justification by the Bush administration in 2002 for deploying a BMD was the imminent threat of weapons of mass destruction carried by missiles launched by Iran, Iraq, and North Korea. Today there are no such threats from Iran or Iraq. But the US BMD program goes on, including the provocative deployments in Poland and Romania. A North Korean threat of a nuclear-armed intercontinental ballistic missile has materialized, but there are alternative, potentially more effective defenses that would not threaten the deterrents of large countries such as China and Russia. Specifically, North Korean missiles still in their boost phase could be within reach of interceptors based off the country's shores or to the north in China or Russia.[13]

Gorbachev had the wisdom to ignore the Reagan administration's fantasies about space-based BMD. But this time, the US should take responsibility for weighing the questionable advantages of exo-atmospheric missile defense against the obstacles that it poses to further nuclear reductions. Physicists could again make an important contribution by explaining the technical issues in the debate.

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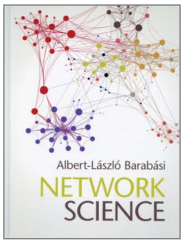

Network Science

Albert-László Barabási

Cambridge U. Press, 2016. $59.99 (456 pp.).
ISBN 978-1-107-07626-6

Networks pervade virtually every aspect of our lives, from how we engage with one another socially to the ways our cells interact to provide biological functionality. Networks of interacting entities can be found from the quantum world of fundamental particles to the cosmic-web structure of the known universe, and at virtually every level in between. The science of networks seeks to understand how the patterns and dynamics of interactions between the elements of a system contribute to the behavior of the system as a whole, how networks form and break down, and how they can be controlled.

Complex systems can often be represented with the help of graphs—diagrams that show discrete objects linked by a relationship, usually drawn as points with line segments between them. Mathematical graph theory goes back as far as Leonhard Euler's solution to the puzzle of Königsberg's bridges in 1735. However, graph theory does not equate to network science; physical network science came into being only in the past two decades. Network science is fundamentally data-centric; collecting the data that encode a map of interactions became possible only with the advent of powerful data-centric computational technology.

Once researchers looked at several real-world networks, they found surprising commonalities in the graph-theoretic properties of their representations, even for systems as seemingly disparate as the internet and protein interaction networks. Those mathematical similarities raised the possibility of common organizational principles behind the emergence of networked systems.

Network science came into existence with the goal of capturing those common principles. As a young and explosively growing field (aided by its widely interdisciplinary nature), it needs textbooks to cement its foundations. However, writing one is harder than it sounds due to the huge range of domains amenable to network analysis.

To meet the challenge, Albert-László Barabási, in his new book, *Network Science*, focuses on a select set of fundamental concepts that can be applied across many fields. He has written a hands-on and engaging textbook suitable for both graduate and advanced undergraduate courses.

Network Science introduces the reader to basic graph-theory notions, elements of data analysis, statistics, and some of the computational and modeling methods that allow us to interrogate network data sets. Throughout, the book illustrates those ideas with concrete and intuitive examples that also help achieve its main purpose, which is to instill network-based thinking in the reader. The writing is engaging, peppered throughout with stories, anecdotes, and historical connections.

Barabási is the director of the Center for Complex Network Research at Northeastern University and one of the founding figures of network science. He is also well known for his successful popularization *Linked: The New Science of Networks* (Perseus, 2002). *Network Science* is by no means a complete survey of everything in the field. The author makes that clear in the preface, in which he states that his choices of material are biased by his and his collaborators' experience. Although he discusses several network measures, he centers most of the material on degree-based notions and their applications.

The book starts with Barabási's inspirational personal history of his journey into network science. After that motivational introduction, it presents basic graph-theory concepts, followed by notions of randomness, models of random graphs, and random-graph ensembles. The following chapters focus on scale-free networks and their properties, degree correlations, and the implications of those correlations for real-world networks such as power grids and social networks.

The final three chapters of the book are particularly interesting and thought-provoking. Chapter 8, a nice exposition devoted to the question of network robustness, makes connections to percolation theory and cascading failures. Chapter 9 is devoted to the perennial issue of network communities—that is, it addresses the difficult problem of detecting clusters in networks. Communities can appear at various scales, can be node based or link based, can be overlapping, hierarchically nested, or all these at once. The last chapter both applies earlier material to the study of spreading phenomena and brings the reader up to date with the latest findings on the topic. Its discussion of the spread of disease in particular clearly illustrates the necessity of network thinking in solving a fundamental and practical problem that affects us all.

The book is carefully structured and visually pleasing, with lots of colorful diagrams, figures, tables, and schematics to help convey fundamental concepts and ideas. Its pedagogical value is significantly enhanced by a Tufte-style exposition that recognizes and works with the nonlinear character of learning. The wide margins contain bits of information—including figures, explanatory boxes, math derivations, and historical asides—that expand on the main text. When no annotations are present, the white margins invite the reader to jot down comments, questions, and observations.

Network Science is more than a book; it is also an online resource. The text is freely available at http://barabasi.com/networksciencebook in a version that includes embedded movies—for example, animations of dynamic network models. The book's webpage contains links to software, visualization tools, data sets, data sources, and teaching materials. The book even has its own Facebook page containing additional interactive resources, discussions, edits, and news updates. Within four months of the book's release, it was translated into Hungarian. Translations into Chinese, Japanese, Spanish, Russian, Portuguese, Italian, and German are on the way.

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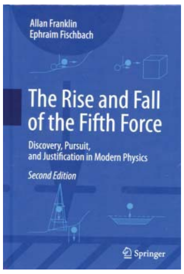
PHYSICS TODAY Previous Page | Contents | Zoom in | Zoom out | Front Cover | Search Issue | Next Page PHYSICS TODAY

The Rise and Fall of the Fifth Force:

Discovery, Pursuit, and Justification in Modern Physics

Allan Franklin and Ephraim Fischbach
Springer, 2016 (2nd ed.). $109.00 (249 pp.). ISBN 978-3-319-28411-8



"Hints of fifth force in universe challenge Galileo's findings," proclaimed a front-page headline in the *New York Times* on 8 January 1986. Written by highly regarded science reporter John Noble Wilford, the article under it revealed that Purdue University's Ephraim Fischbach and colleagues had just published a paper revisiting early 20th-century torsion-balance experiments by Hungarian physicist Roland von Eötvös. Those experiments had helped establish the equivalence of gravitational and inertial mass. Fischbach and coauthors argued that the experiments also revealed subtle evidence for a new intermediate-range force supplementing the fundamental four: gravity, electromagnetism, and the strong and weak nuclear forces.

This "fifth force," as Wilford dubbed it, was about 1% as strong as gravity, extended roughly 100 meters, and could be carried by a light "hyperphoton" that coupled to baryon number. Because that force depended on a material's composition, it would have slightly altered the acceleration rates of the objects Galileo is said to have dropped from the Tower of Pisa.

Fischbach and University of Colorado historian of physics Allan Franklin independently relate the story of the fifth force in the second edition of Franklin's original book, *The Rise and Fall of the Fifth Force: Discovery, Pursuit, and Justification in Modern Physics*. Exposure in the nation's leading newspaper likely catapulted the new result into a prominence it would not have otherwise enjoyed. Wilford's article quickly elicited critical reactions from other physicists. Within days Richard Feynman and Sheldon Glashow had weighed in with disbelief. Others soon pointed out an omission in the authors' reasoning: Such composition-dependent forces could not have arisen unless there were large horizontal asymmetries in the local mass distribution near where the Eötvös experiments had occurred.

Those qualms, however, did not dissuade the experimenters who rose to the challenge of testing a new hypothesis some considered plausible. Within a year three teams reported in with conflicting results. In one, Peter Thieberger of Brookhaven National Laboratory set a hollow copper sphere adrift in a temperature-controlled, magnetically isolated tank of water placed next to the Palisades in New Jersey. The sphere drifted steadily away from the cliffs, seeming evidence for a slight difference between the forces on water and copper. But a University of Washington experiment led by Eric Adelberger yielded null results. Using an extremely sensitive torsion balance, the Washington physicists suspended beryllium and copper cylinders pivoting about a central axis. Any composition-dependent force would have generated a tiny but measurable torque about that axis, but none was observed. Another University of Washington torsion-balance experiment gave positive results, but they disagreed numerically with Thieberger's conclusions.

In part, the experimental confusion reflected the limited understanding in the late 1980s of any deviations—which had been insufficiently measured—from Newton's inverse-square law at distances from 1 to 1000 meters. Only a few relevant experiments had been conducted, and they did not rule out deviations of up to a few percent. Some results had unattributed errors due, for example, to unaccounted-for mass asymmetries. But that area of experimentation rapidly improved during the late 1980s. By 1990, according to the authors, the fifth force was on its knees. A year later it was dead, with the great preponderance of evidence weighing against its possible existence.

So was all the experimental—and theoretical—effort a waste of time? Not at all, says Franklin in his new discussion. For one, the search for small intermediate- and short-range deviations had an effect on particle-physics theory, particularly on theories of charge conjugation–parity violation and string theories that required such discrepancies. It especially honed physicists' abilities to design and interpret the increasingly precise experiments needed to evaluate such theoretical work.

For scholars of science, argues Franklin, the search also provided a laboratory in which to study what he calls the "context of pursuit." That kind of research activity arises when a hypothesis is sufficiently plausible, and the experimentation costs sufficiently modest, for interested physicists to pursue appropriate measurements despite the likelihood of obtaining a null result. Appearance in the *New York Times* helps, too.

The publication of this revised edition, which includes updates on theory developments and experiments performed since 1991, is very welcome. Fischbach's section gives a detailed, subjective account of his work from 1985 to 1991, the period of his most intense activity on the fifth force. The revised edition serves as a valuable counterweight to Franklin's original account, included in the book, which was dense, compact, and difficult for the uninitiated to follow. I just wish the publisher had kept the book's cost below $100, for only the fervid few will judge its contents worth its high price.

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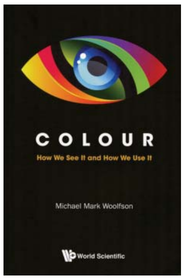
Colour

How We See It and How We Use It

Michael Mark Woolfson
World Scientific, 2016. $34.00 paper (239 pp.). ISBN 978-1-78634-085-6



Michael Mark Woolfson, a professor emeritus at the University of York in the UK, has had a long and distinguished career researching x-ray crystallography, the formation of stars and planets, and biophysics. He has also written more than 20 books on topics ranging from imaging to probability and statistics—an ambitious scope.

Woolfson clearly intends his latest book, *Colour: How We See It and How We Use It*, as a popularization. He hopes to cover his topic, he writes, in "a general broad-brush way without getting involved in the fine details that would only be of interest to professional engineers and scientists." Although that is a worthy goal, the book contains serious factual errors. Furthermore, the wide-ranging material is disorganized and the topics seem haphazardly chosen, which leaves me wondering why some phenomena were included while others were left out.

Here are a few of the factual errors. In figure 4.1, Woolfson draws an International Commission on Illumination *xy* chromaticity diagram that includes a line from white (W) to 520-nm green (A). He then says, "The point M, midway between A and W, would roughly correspond to a mixture of spectral green and white with the same intensity." In fact, a chromaticity diagram is a central projection from a three-dimensional color space, called tristimulus space, that is related to the sensitivity of the eye's three types of cone cells. There is no physical significance to the distance ratio AM/AW.

In chapter 6, Woolfson discusses retinal photopigment bleaching, the process by which retinal pigment absorbs a photon and is rendered temporarily unable to absorb another one. In the discussion, he makes an incorrect connection between bleaching and the visual process. He appears to equate the eye's visual response to the "proportion of active pigment"—that is, the remaining fraction of unbleached pigment. In fact, small light-induced fluctuations of intermediate and bleached photopigment are what initiate an electrical response in the eye. The unbleached pigment is like the charge in a battery—available for light stimulation but not itself part of the response.

The core of Woolfson's error is in figure 6.10, which shows "curves of rhodopsin decay" after a light is turned on. Here, decay is the same as bleaching. However, if active photopigment decayed as quickly as Woolfson indicates, we would essentially be blind after less than a second in daylight. In reality, the photopigment in a normal eye is almost never appreciably bleached when exposed to common illumination. A secondary error in figure 6.10 is that, contrary to its caption, not all visual receptors have rhodopsin as a photopigment. Only the rods, responsible for vision at low light levels, use rhodopsin.

Other errors are simply matters of terminology. For example, Woolfson recounts the classic demonstration that a white object in a scene looks green through a small green filter, but it looks white if the filter is brought close enough to the eye to cover the whole scene. Then he says, "The light entering the eye in both cases has the same chromatic content." He should have said "spectral content" because the chromatic (perceived color) content is not the same.

I was surprised that in a book on color, no mention is made of metamerism, a phenomenon in which two light spectra viewed under the same conditions can be perceived to have the same color. In particular, the trichromacy of vision implies that only three primary colors are required to make a match. For that reason, metamerism underlies color-reproduction systems from television to printed photographs, a fact that seems important to a popularization about color.

The style is also disappointing. Woolfson offers no overriding motif or question to launch his book and engage the reader. Color perception occupies several chapters, including chapters 6 and 10, but it is curiously absent from chapters 7–9, which present historical sketches of artistic uses of pigments, dyes, and pottery. At times, ideas jump around from sentence to sentence; for example, a discussion of nonvisual structures in the eye is interrupted by the out-of-context sentence, "The eye operates best at moderate light levels." There are no references or photo credits to lead a reader to further information. That said, the author provides a good index and includes with each noted innovator that person's dates of birth and death, nationality, and profession.

One high point in the book is figure 1.10. There, and in its associated discussion, Woolfson presents a retinal-processing model that captures three important visual effects. First, the light-gathering area for a retinal cell increases at low light intensities, which averages out noise. Second, the area decreases at high light intensities, thus increasing spatial resolution. Third, the contrast in neighboring bands of gray appears to be enhanced when the bands are touching, a phenomenon called the Mach band effect. I have seen such a model in technical papers but never in a popularization.

Although I don't view the book as successful, I respect the author's courage in writing about fields—from evolutionary teleology to cinematography—that are far from where he began.

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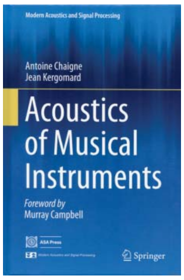
Acoustics of Musical Instruments

Antoine Chaigne and Jean Kergomard

Springer, 2016. $279.00 (844 pp.). ISBN 978-1-4939-3677-9



Our experience of sound is created by the motion of the air around us. That motion arises from the movement of nearby objects, whether machines, mosquitos, or musical instruments. Many authors have collected and organized the mathematical equations that predict the motions of the air. Perhaps the first to do so comprehensively was Lord Rayleigh. His *Theory of Sound* (1877, 1894) included everything he could find on the topic, organized in a logical development of ideas and math and largely rendered in the language of differential calculus. It was a singular achievement in its day, and so acute that physicists can still learn much from it.

One of Rayleigh's distinctive contributions was his careful demonstration of the construction of his mathematical models, revealing the assumptions and compromises that limited their predictive abilities. Some of his derivations were unambiguously solid; others employed compromises significant enough to invite the reader's consideration. With characteristic candor, he prefaces the second edition with a confession to his readers: "The pure mathematician will complain, and (it must be confessed) sometimes with justice, of deficient rigour, [but] the physicist may occasionally do well to rest content with arguments which are fairly satisfactory and conclusive from his point of view."

In *Acoustics of Musical Instruments*, Antoine Chaigne and Jean Kergomard have applied mathematical rigor with comprehensive scope, and the result is remarkable. The authors show the readers how each model of musical instrument acoustics is constructed and discuss the effects of assumptions and approximations. The level of detail they provide gives readers greater confidence in what each model can do—and a firmer understanding of what it cannot. Their observations drive them to build ever more effective models, many using ideas that were not available in Rayleigh's time.

Since musical instruments usually depend on vibrations to generate sound, the authors begin with the simplest equations describing bound motion and oscillation. They expand into traveling waves, modes of vibration, and damping and coupling, and they incorporate nonlinear and discontinuous behaviors. Finally, they model the complexities of design and operation of typical musical instruments, including wood and brass winds, violins, guitars and pianos, and various percussion instruments.

Each kind of instrument is given close attention, as is the listener's orientation with respect to the instrument, since musical instruments often drive different air motions in different directions. The authors' attention to wind instruments is necessarily more extensive in order to encompass those instruments' wider variety of input and output. Unlike string and percussion instruments, whose vibrating parts are made of solids that are relatively unchanging, wind instruments do not themselves vibrate significantly. Instead, they contain air that vibrates. Those vibrations are driven by motions of air inside the performer and are deeply affected by interactions with the air surrounding the instrument. The necessary models predicting the vibrations are developed over several dedicated chapters.

The authors use Newtonian mechanics for their initial simple models, then refine them by incorporating concepts from finite math, thermal and fluid dynamics, structural analysis, and dynamic systems. Although other books take a similar approach, Chaigne and Kergomard distinguish themselves by patiently introducing their topics, developing and assessing the math, and explaining their subject in a way that prevents any confusion or misunderstanding.

Readers also benefit from the authors' substantial investment in the book, which they have improved through several editions; this is the first English edition of the valuable text, which had earlier appeared in French. Chaigne and Kergomard have drawn from an immense collection of both theoretical and experimental sources, which has yielded a resource that is current, thorough, and packed with citations that can lead readers to deeper exploration.

Chaigne and Kergomard's magnum opus sets a high standard for logical and mathematical rigor in musical-instrument acoustics. The text and math are lucid throughout and should be easily understood by readers with a basic grasp of mechanics. The authors are justified in recommending the book to "students at master's and doctorate levels [and] researchers, engineers and other physicists with a strong interest in music"—each of those groups will find the information they need in *Acoustics of Musical Instruments.*

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NEW PRODUCTS

Focus on lasers and imaging

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

Multiwavelength tunable diode lasers

Toptica Photonics has added 1050 nm, 1320 nm, and 1470 nm wavelengths to its continuously tunable laser (CTL) platform, thereby enabling continuous, mode-hop-free wavelength tuning up to 110 nm. Available at wavelengths ranging between 915 nm and 1630 nm, the CTL diode lasers can achieve ultrawide motorized wavelength scans with high absolute accuracy, subpicometer resolution, and output powers up to 80 mW. Piezo tuning allows for higher resolutions down to 5 kHz. With its novel resonator design and versatile, low-noise, all-digital DLC pro laser controller, the CTL reaches low drift values and a linewidth below 10 kHz. The controller offers functions such as zooming into spectra, frequency locking, and power stabilization. The CTL's new wavelengths support applications such as spectroscopy, waveguide characterization, ytterbium amplifier seeding, studying microresonators, and testing ytterbium fiber components. ***Toptica Photonics Inc,*** *1286 Blossom Dr, Victor, NY 14564, www.toptica.com*

Picosecond pulsed laser

PicoQuant has rounded out its LDH and LDH-FA series of picosecond pulsed laser sources with the release of a fiber-amplified laser head that pulses at 560 nm. The series is used in time-resolved microscopy and spectroscopy applications such as fluorescence spectroscopy, fluorescence lifetime imaging, and fluorescence lifetime correlation spectroscopy. The 560 nm light emitted by the new LDH-P-FA-560 is suitable for exciting molecular probes used in the life sciences, including fluorescent proteins such as mCherry and red fluorescent protein and dyes such as CY3 and Atto565. The new laser head can also be used in bioanalytics, biochemistry, genetics, semiconductor characterization, and quality control applications. The LDH-P-FA-560 delivers average optical powers of more than 3 mW at a repetition rate of 40 MHhz, with pulse widths down to 40 ps. The collimated free beam output can optionally be coupled to an optical fiber. ***PicoQuant,*** *Rudower Chaussee 29, 12489 Berlin, Germany, www.picoquant.com*

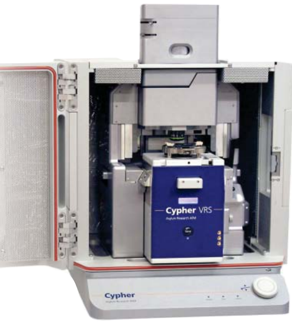
Near-IR line scan camera

Princeton Infrared Technologies now offers an OEM version of its indium gallium arsenide line scan camera. Designed for demanding imaging applications such as Raman spectroscopy and those in which objects are moving quickly, the USB3.0 SWIR OEM LineCam12 operates from 0.4 to 1.7 μm in the shortwave IR and visible spectra. It has USB3 Vision and Camera Link digital outputs and can be powered by USB3.0 in most applications. According to the company, the LineCam12 is the only SWIR line scan camera with USB3 Vision currently available, and the only USB3 camera that can image SWIR and visible light simultaneously. The 1024-element linear array can image over 37k lines/s. It comes in two models: One has 250-μm-tall pixels for spectroscopy, the other 12.5-μm-square pixels for machine vision tasks. They can be customized, including for high-temperature operation at 70 °C or very cold at −40 °C. ***Princeton Infrared Technologies Inc,*** *9 Deer Park Dr, Ste J-5, Monmouth Junction, NJ 08852, www.princetonirtech.com*

Pulsed-laser wavelength meter

Bristol Instruments has improved its 871 series pulsed-laser wavelength meter. It now has a wavelength accuracy as high as ±0.75 ppm (±225 MHz at 1000 nm), and an integrated proportional-integral-derivative controller that permits active regulation of laser frequency. The meter has a sustained measurement rate of 1 kHz—the fastest available, according to the company. A novel Fizeau etalon design is used to measure the wavelengths of both pulsed and CW lasers; automatic calibration with a built-in wavelength standard ensures optimal performance. The 871 system can operate from 375 nm to 1700 nm. Prealigned fiber-optic input provides for easy alignment and high accuracy. Automatic pulse detection triggers data collection for asynchronous operation. The model 871 operates with a PC running Windows via USB and Ethernet interface. Measurement data can also be displayed on a tablet or smartphone using a web-based application. ***Bristol Instruments Inc,*** *50 Victor Heights Pkwy, Victor, NY 14564, www.bristol-inst.com*

NEW PRODUCTS



Video-rate atomic force microscope

The Cypher VRS video-rate atomic force microscope (AFM) from Oxford Instruments Asylum Research enables high-resolution imaging of dynamic events at up to 625 lines/s, corresponding to about 10 fps. According to the company, that is about 300 times as fast as typical AFMs and 10 times as fast as current "fast-scanning" AFMs. The modular, versatile Cypher VRS can be switched between video-rate and conventional scan speeds. It is suitable for researching nano-events such as biochemical reactions, membrane studies, and self-assembly, and for other materials and life sciences applications. Compatible with the environmental accessories for the company's Cypher ES AFM, the Cypher VRS can be used for experiments with heating, cooling, and gas or liquid perfusion. Ease-of-use features include Asylum's blueDrive photothermal excitation, designed to make tapping mode simpler and more stable and quantitative. ***Oxford Instruments Asylum Research Inc,*** *6310 Hollister Ave, Santa Barbara, CA 93117, www.asylumresearch.com*

Optical power, energy, and position sensors

The versatile PEPS series of optical power, energy, and position quad-cell thermopile sensors from Newport can measure laser power, single-shot energy, and the position of a laser beam. When connected to a compatible Newport power meter—the 1919-R, 843-R series, and 841-PE-USB models—the detectors can track beams with 0.1 mm positional accuracy. They provide beam-tracking information such as the minimum and maximum X/Y positions, average position, and standard deviation. The PMManager software included with the detector allows for beam stability measurement. It produces a visual representation of the laser-beam drift over time in a 2D histogram. The data for the X and Y positions and the optical power can be logged and downloaded for further analysis or recording. ***Newport Corporation,*** *1791 Deere Ave, Irvine, CA 92606, www.newport.com*

Camera with back-illuminated sensor technology

Princeton Instruments has introduced its Kuro:1200B scientific CMOS camera system with back-illuminated sensor technology. According to the company, that technology has been used almost exclusively by CCD camera systems. Though very sensitive, CCD systems cannot match CMOS frame rates, and front-illuminated CMOS cameras cannot meet the high-sensitivity needs of ultralow-light scientific imaging and spectroscopy. Princeton Instruments claims the Kuro delivers the fast frame rates and high sensitivity required for applications such as astronomy; hyperspectral, cold-atom, and quantum imaging; and fluorescence and high-speed spectroscopy. It also eliminates the drawbacks associated with front-illuminated sCMOS cameras. The Kuro does not require performance-limiting microlenses. It features ultralow-level read noise of 1.3 e^- rms median and frame rates of 82 fps at full 1200 × 1200 resolution. ***Princeton Instruments,*** *3660 Quakerbridge Rd, Trenton, NJ 08619, www.princetoninstruments.com*

Wavelength-paired solid-state laser

Qioptiq, an Excelitas Technologies company, has added a 488/647 nm wavelength pairing to its iFLEX-Gemini dual-wavelength laser series. The 647 nm wavelength enables the use of specific fluorescence dye sets for superresolution microscopy and cancer research. The iFLEX-Gemini can be modulated internally. Each wavelength can be individually adjusted for output power and modulation repetition rate, and wavelengths will emit alternately or simultaneously on demand. The solid-state iFLEX-Gemini is one-tenth the size of equivalent argon–krypton gas lasers; the robust optomechanical design eliminates the need for laser realignment. It poses no toxic gas risk, requires no water-cooling or fans, and has a prolonged useful lifetime. Applications include DNA sequencing, flow cytometry, microscopy, optogenetics, and metrology. ***Excelitas Technologies Corp,*** *200 West St, Waltham, MA 02451, www.qioptiq.com*

Lasers for materials and life sciences

Coherent has extended the performance of its Monaco series of femtosecond lasers by increasing the adjustable pulse repetition rate to a maximum of 50 MHz. The company has also launched a high-energy Monaco that provides up to 60 μJ/pulse in the near-IR (1035 nm) or, optionally, 30 μJ in the green (517 nm) region. The improvements are designed to enhance performance in precision materials processing applications, particularly for delicate and tough materials, and to deliver increased frame rates in demanding multiphoton microscopy imaging applications. The Monaco lasers produce a beam with a high collimation factor of M2 less than 1.2; the beam enables tight focusing for high brightness and spatial resolution. Users can set the pulse width from under 400 fs to over 10 ps. In bioimaging applications, the new IR Monaco 1035-60 and green Monaco 517-30 enable high frame rates for applications such as photoactivation in optogenetic experiments. ***Coherent Inc,*** *5100 Patrick Henry Dr, Santa Clara, CA 95054, www.coherent.com*

Software for scanning microscopies

WITec's Suite Five software offers advanced functionality, accelerated workflow, and enhanced hardware control to help researchers perform Raman, atomic force, scanning near-field optical, and WITec correlative microscopy measurements. The Suite Five software wizard guides users from initial settings and data acquisition through data and image post-processing. Presets and highlighted analytical paths accelerate the generation of high-quality images. TrueComponent analysis, a novel post-processing function for confocal Raman imaging measurements, automatically establishes the number of components in a sample, locates them in the image, and differentiates their individual spectra. The EasyLink handheld multifunction controller provides a tactile, intuitive interface to direct motorized stages, white light illumination, laser power, autofocus, cantilever positioning, and objective selection with an automated turret. ***WITec GmbH,*** *Lise-Meitner-Str 6, 89081 Ulm, Germany, www.witec.de* PT

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.

Jacques Isaac Pankove

Jacques Isaac Pankove, one of the great 20th-century innovators in materials science and semiconductors, died in his home in Princeton, New Jersey, on 12 July 2016.

Jacques was born in Chernihiv, Ukraine, on 23 November 1922. A year later he and his family immigrated to Constantinople, and the following year they moved to Marseilles, France. After the Nazis occupied the city in 1942, he and his family immigrated to the US and settled in Oakland, California. He attended the University of California, Berkeley, where he received his BS in 1944 and his MS in 1948, both in electrical engineering. Between getting the two degrees, Jacques enlisted in the US Army Signal Corps and served in the Philippines. He earned his PhD from the University of Paris in 1960 for his work on IR emission in germanium.

From 1948 to 1970, Jacques was a member of the technical staff at RCA Laboratories in Princeton, and he was an RCA fellow from 1970 to 1985. Among the seminal contributions he made while there were prototypes of the first commercial transistor, the first gallium arsenide IR LED, and the first gallium arsenide phosphide visible injection laser. Most notably, he pioneered the semiconductors based on the gallium nitride family and in the 1970s was the first to develop a GaN blue LED. In that decade he studied most of the physical properties of GaN, and his works helped launch the worldwide scientific exploration of its family of semiconductors for the next 30 years. That research has led to novel devices with multiple applications in such areas as solid-state lighting, information storage, and high-power and high-frequency electronics.

Among the awards Jacques received for those discoveries were IEEE's J. J. Ebers Award in 1975, the 1998 Rank Prize in Optoelectronics, and the Distinguished Engineering Alumni Award from Berkeley in 2000. In 1997 the Materials Research Society dedicated its fall symposium on nitride semiconductors to him.

Jacques Isaac Pankove

When RCA decided to terminate the GaN program in the mid 1970s, Jacques redirected his energy and creativity to the fields of amorphous and crystalline silicon. Among his many contributions to those fields are his detailed investigations of the role of hydrogen in the materials; in particular, he discovered in the early 1980s how hydrogen deactivates p-type dopants in crystalline Si. Ten years later researchers discovered that deactivation of p-type dopants in GaN by hydrogen was responsible for the difficulty in generating p-type conductivity in it. Resolving that problem and employing improved heteroepitaxial techniques led to the first efficient blue LED by Shuji Nakamura and the device's subsequent commercialization by Nichia Corp.

Jacques was a Visiting MacKay Lecturer at Berkeley in 1968–69, a visiting professor at the University of Campinas in Brazil in 1975, and a Distinguished Visiting Professor at the University of Missouri in 1984. From 1985 until his retirement in 1993, he was the Hudson Moore Jr Endowed Chair in the electrical and computer engineering department at the University of Colorado Boulder with a joint appointment as a distinguished scientist at the National Renewable Energy Laboratory in Golden. At Boulder, in revisiting GaN, he invented the high-gain SiC/GaN heterojunction bipolar transistor, with good performance up to 500 °C. Later, as a professor emeritus, he founded the research company Astralux, where he continued to develop the transistor and other potential applications of GaN.

A prolific inventor, Jacques had more than 90 US patents. In 1962 he made an educational film called *Energy Gap and Recombination Radiation*. In 1971 he wrote the classic textbook *Optical Processes in Semiconductors* (Dover). Additionally, he served as an editor of several influential books, including two volumes—*Electroluminescence* (1977) and *Display Devices* (1980)—of Springer's Topics in Applied Physics series, and was a member of the editorial boards for several research journals.

Jacques was a passionate teacher who was insatiably curious and creative. When not teaching or writing, he loved being active; he could be found playing tennis, skiing, hiking, gardening, or working on a home-improvement project. He was a generous supporter of the arts in Princeton and enjoyed taking painting, sculpture, and print-making classes. He is deeply missed by his family, friends, and colleagues across the world.

Theodore D. Moustakas
Boston University
Boston, Massachusetts
Bo Monemar
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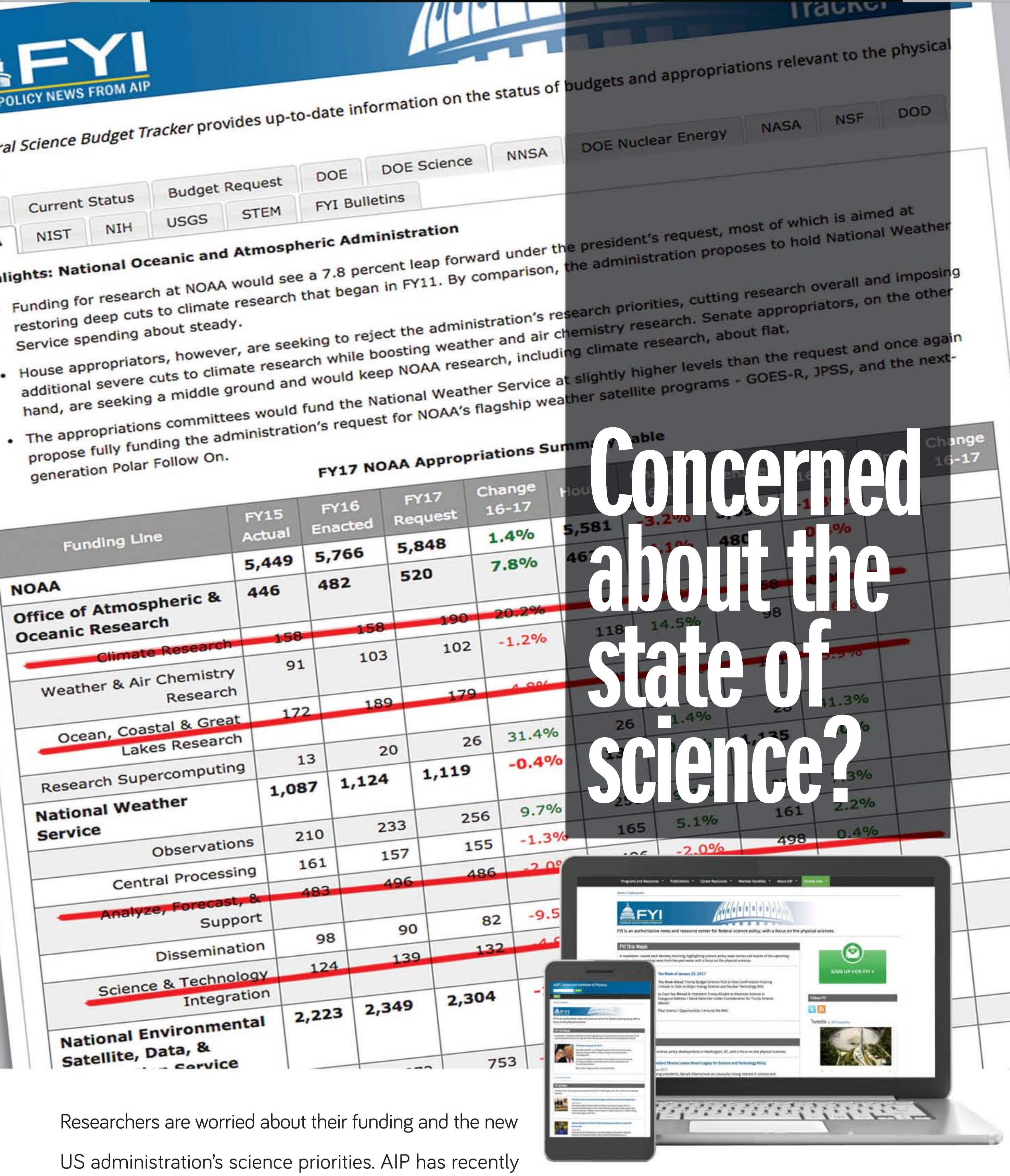
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In view of his/her role that presides over the business of KEK as a representative of the Inter-University Research Institute Corporation, nominees shall be:
1) persons of noble character, with relevant knowledge and experience and having abilities to manage its educational and research activities properly and effectively.
2) persons expected to promote with long-term vision and strong scientific leadership, the highly advanced, internationalized, and inter-disciplinary research activities of KEK by getting support from the public.
3) persons expected to establish and carry out the medium-term goals and plans.

The term of appointment is three years until March 31, 2021 and shall be eligible for reappointment only twice. Thus, he/she may not remain in office continuously over a period 9 years. We widely accept the nomination of the candidates regardless of their nationalities.

We would like to ask you to recommend the best person who satisfies requirements for the position written above.

Nomination should be accompanied by: 1) letter of recommendation, 2) brief personal history of the candidate, and 3) list of major achievements (publications, academic papers, commendations and membership of councils, etc.). The nomination should be submitted to the following address no later than **May 31, 2017**:
• Documents should be written either in English or in Japanese.
• Forms and details are available at :
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Inquiries concerning the nomination should be addressed to:

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QUICK STUDY

Phil Hopkins is an associate professor of theoretical astrophysics at Caltech in Pasadena, California.

Supernovae, supercomputers, and galactic evolution

Philip F. Hopkins

The stars in a galaxy emit radiation and solar winds, and they sometimes die in fantastic explosions. Supercomputer simulations are now beginning to assess how those energy releases affect the galaxy's life.

Perhaps the oldest question confronted by humanity is, "Where do we come from?" Philosophers pondered the issue thousands of years ago, and many people continue to ask the question today. For a modern scientist, the problem might be posed as, "How did we get from the Big Bang to the present day?," and the answer would be couched in terms of cosmology, astrophysics, and biology. The first step, at least for an astrophysicist, is to understand how our galaxy, the Milky Way, was formed.

A star is born

Galaxies are tremendously complex systems comprising normal matter, radiation, and dark matter, the nonluminous stuff that for practical purposes interacts only gravitationally. Fluid dynamics is influenced by gravitation, and plasma physics and nuclear physics come together inside stars—two hundred billion of them in a galaxy like the Milky Way. Moreover, galactic processes play out over an enormous range of scales. For example, the diameter of the Milky Way and the gravitationally bound spherical "halo" of dark matter surrounding it is about 200 000 light-years, whereas the diameter of a single star is just a few light-seconds. The complexity means the system is chaotic and nonlinear; the equations that describe it can be solved only numerically. The dynamic range means that numerical solutions push the world's premiere supercomputers to their limits.

Despite the challenges, physicists have arrived at a basic consensus as to how galaxies form (see the article by Tom Abel in PHYSICS TODAY, April 2011, page 51). Tiny fluctuations in the density of matter arise in the early universe during an "inflationary" epoch of rapid expansion. Those fluctuations grow as gravity attracts ever more material toward the denser bits. Eventually the dense regions become gravitationally bound. Dark matter, like regular matter, is captured. But since it essentially interacts only gravitationally, it forms an extended halo. On the other hand, as a region becomes more dense, its hydrogen and helium gases can interact with each other and with stray electrons. The photons emitted in those interactions escape and carry away kinetic and thermal energy; the cooled gas is pulled ever more strongly by gravity. The gas has some angular momentum, so it spins faster as it contracts, until its rotation halts further gravitational contraction.

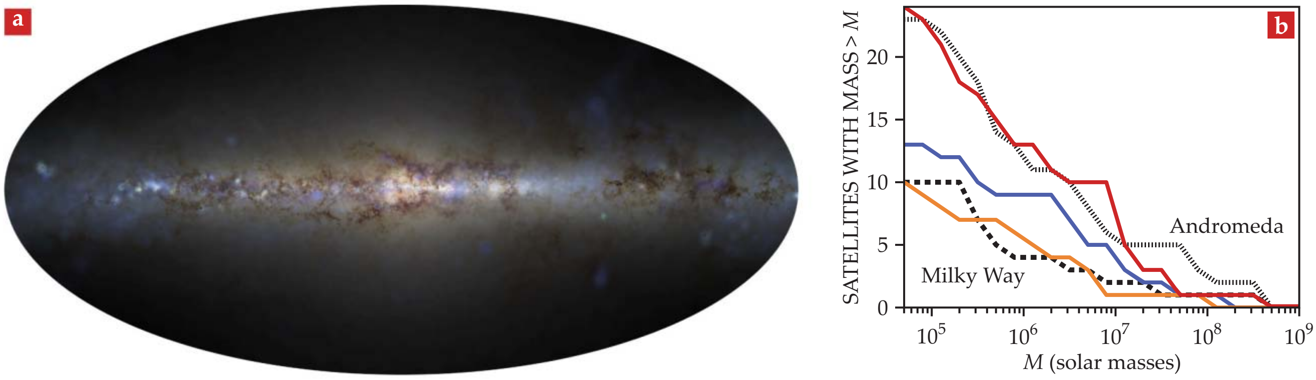
At that point, the galactic disk has formed. Within it, the concentration process repeats: Denser regions of gas pull together under the influence of gravity and continue to accumulate matter. Clumps of material break away, and in time, one of them gets so dense and massive that nuclear fusion ignites. A star is born.

A star is not to be ignored

As always, the devil is in the details. Simulations based on the above picture do a remarkably good job of obtaining the distribution of matter on large scales in the universe; we understand well why galaxies live where they live. But the simulations fail to reproduce the galaxies we actually see. Inevitably, they predict that almost all the normal matter in the universe should end up in stars, whereas only a small amount, perhaps a few percent, actually does. Moreover, they predict that the stars should have formed early in the history of the universe, when it was just a tiny fraction of its present size. However, we know that our sun, for example, formed when the universe was something like 75% of its current size.

By the 1990s astrophysicists realized that influences of the stars themselves simply cannot be ignored. After a star is born, its nuclear furnace emits energy in the form of radiation and stellar winds that can push on and heat up matter. Some of the most massive stars will explode as supernovae, thereby expelling a tremendous amount of energy in a cataclysmic event. In fact, the kinetic energy released by the supernovae that have exploded in the Milky Way is an order of magnitude greater than the gravitational potential energy holding the galaxy's normal matter together.

Advances in computer power, in computational algorithms, and in theories of stellar evolution have inspired a new generation of galaxy-formation simulations, including those of the Illustris and EAGLE projects and our own collaboration, the FIRE (Feedback in Realistic Environments) project. Our international collaboration comprises 16 institutions. Experts in supernova explosions come together with experts in gravitational dynamics, because the interactions between those processes are so critical. We are now able to simulate a galaxy like our own Milky Way over the whole of cosmic time, with a billion or so resolution elements for each time step (see panel a of the figure). Such resolution is short of that needed to model individual



REALISTIC GALAXIES with few satellites. **(a)** This Milky Way–mass galaxy, simulated by the FIRE (Feedback in Realistic Environments) project, includes filamentary molecular cloud complexes and young star clusters. **(b)** The plotted lines show the number of satellite galaxies whose mass *M* in stars (as opposed to dark matter) is greater than that given on the horizontal axis. The differences in the colored curves representing three FIRE simulations of Milky Way–mass galaxies reflect statistical variations. For comparison, the black curves show observations for the Milky Way (coarse dashes) and Andromeda (fine dashes), which has a similar mass. Unlike simulations that ignore effects of supernova explosions, the FIRE runs give a realistic population of satellites.

stars, but it's close. And it allows us to resolve key scales so that we can track, for example, the bubbles of hot gas generated when a supernova explodes and violently shocks the gas around it.

In the new generation of models, the above star-is-born story is just the beginning. Once the first stars form, they influence the larger-scale medium. Radiation, stellar winds, and kinetic energy from supernova explosions heat gas and sweep it out of large swathes of the galaxy. If a sufficient number of stars are formed, gas will be rapidly expelled from the galaxy, launched out in galactic superwinds with speeds of hundreds or thousands of kilometers per second. Such superwinds have been observed in many star-forming systems, and now models are able to follow, on galactic scales, the generation and impacts of those winds.

When feedback effects from stars are included, galaxy formation emerges as a competition between gravity pulling gas together and violent explosions blowing it apart. It is not an accident that the energy released by supernova explosions in the Milky Way is a reasonably small multiple of the gravitational potential energy of the stars in our galaxy. If fewer stars had formed, their energetic input would have been unable to stave off gravity; the result would be further collapse and additional star formation. If more had formed, they would have blown away material needed for the next generation of star formation. This realization has led to a new class of equilibrium models of galaxy formation wherein feedback loops regulate the cosmic cycle of inflow, star formation, and galactic outflow.

Stars as terminators

In recent work, we and other groups have shown that stellar feedback resolves one of many outstanding mysteries of galaxy formation, the so-called missing satellites problem. (See the article by Jeremiah Ostriker and Thorsten Naab in Physics Today, August 2012, page 43.) In short, the simple models that ignored feedback predicted that the Milky Way would be orbited by a swarm of thousands of small, luminous galaxies called dwarf galaxies. In fact, only a couple dozen such systems are seen. Theorists speculated that dwarf galaxies, with their relatively small gravitational binding energy, would be profoundly altered by feedback processes. For the smallest dwarfs, a single supernova explosion might be enough to terminate star formation forever; the tiny galaxies would be mostly dark. The new simulations of Milky Way–mass galaxies, with their resolution and physics sufficient to capture the evolution of the dwarf satellites and their stars, demonstrate that, indeed, stars shut down their own siblings' formation (see panel b of the figure).

Much work remains to be done. Galaxies smaller or larger than the Milky Way present their own challenges. For example, theory suggests that in the most massive galaxies, the dominant source of feedback energy comes not from stars but rather from matter falling into the supermassive black holes at the galactic centers. Limitations in modelers' understanding of the basic radiation and plasma physics mean that our treatment of radiation–matter coupling, magnetic fields, and cosmic rays is either oversimplified or nonexistent. Such entities almost certainly will present a rich, new phenomenology to explore, and once they are properly accounted for, the story of galaxy evolution might change again. But without a doubt, feedback is here to stay and the small and large scales of the universe will remain inextricably linked.

Additional resources

▶ P. F. Hopkins et al., "Galaxies on FIRE (Feedback in Realistic Environments): Stellar feedback explains cosmologically inefficient star formation," *Mon. Not. R. Astron. Soc.* **445**, 581 (2014).
▶ M. Vogelsberger et al., "Properties of galaxies reproduced by a hydrodynamic simulation," *Nature* **509**, 177 (2014).
▶ R. A. Crain et al., "The EAGLE simulations of galaxy formation: Calibration of subgrid physics and model variations," *Mon. Not. R. Astron. Soc.* **450**, 1937 (2015).
▶ A. R. Wetzel et al., "Reconciling dwarf galaxies with ΛCDM cosmology: Simulating a realistic population of satellites around a Milky Way–mass galaxy," *Astrophys. J. Lett.* **827**, L23 (2016).
▶ Phil Hopkins' Research Group, "Animations," www.tapir.caltech.edu/~phopkins/Site/animations. PT

BACK SCATTER

Graphene visualized

Graphene is at the atomic limit of thinness: a single layer of crystalline, hexagonally bonded carbon. Yet real-world samples usually contain defects, which are challenging to visualize. For graphene layers grown on or transferred to a transparent substrate, conventional light microscopy achieves an image contrast of only 2%. Ke Xu and his group at the University of California, Berkeley, have developed a new visualization approach based on interference reflection microscopy (IRM), a label-free optical technique originally developed for cell biology. When applied to graphene on a transparent substrate, the technique can distinguish layers with a contrast greater than 30% and allows *in situ* monitoring at up to 100 frames per second.

This image, generated by IRM using filtered green light from a broadband lamp, shows a 62 µm x 77 µm section of a graphene layer grown by chemical vapor decomposition and deposited on glass. Voids (white regions), cracks (white lines), wrinkles (thin dark lines), and folds (dark regions) are among the nanoscale defects that are readily seen. Better characterization and monitoring of such defects should help advance commercial applications of graphene in transparent and flexible electronics. (W. Li et al., *Nano Lett.* **16**, 5027, 2016. Image submitted by Wan Li and Ke Xu.)

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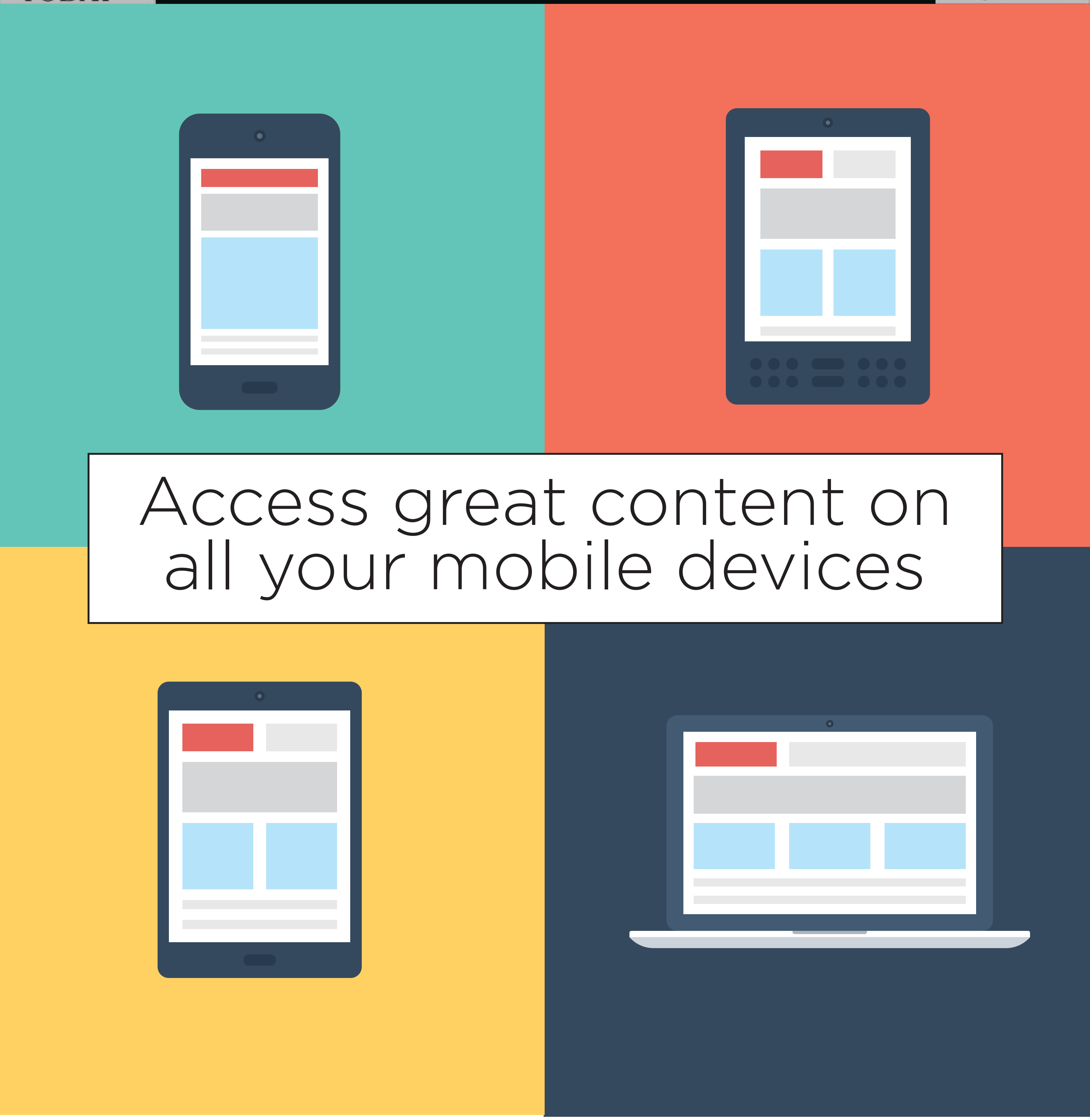
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