PHYSICS TODAY

April 2020 • volume 73, number 4
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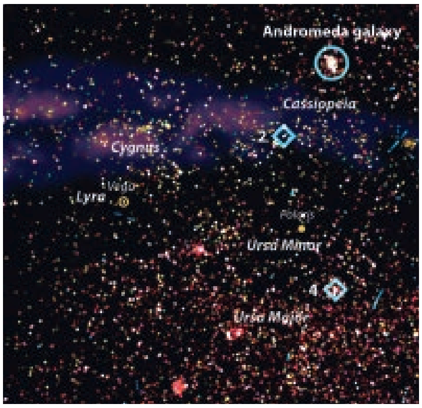

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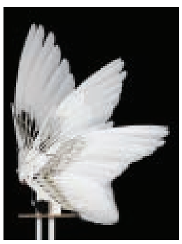
FEATURES



ON THE COVER: Birds change the shape of their wings for different flight maneuvers. A team of biologists and engineers studying the phenomenon discovered that interlocking microstructures keep the feathers together. When the researchers constructed a biohybrid robot with real pigeon feathers, shown here, the microstructures prevented gaps from forming and limiting the robot's mobility. See the story on **page 20** to learn more about the feather fasteners. (Photo by Lentink Lab/Stanford University.)

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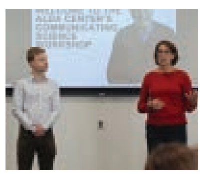

ALDA CENTER AT SBU

▶ Avoiding jargon

Jargon leads laypeople to distrust content about science and to conclude that they are not good at—and don't like—the broader subject area, according to a recent study. The results can inform the efforts of those who communicate with students and the general public.

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The economics of progress

Charles Day

On 9 February of this year, a British Airways Boeing 747-436 landed at London's Heathrow Airport 80 minutes ahead of schedule. Its flight from New York's JFK International Airport had taken just 4 hours and 56 minutes, thanks to a boost it received from Storm Ciara's powerful winds. No other subsonic airliner has crossed the Atlantic Ocean so quickly.

The previous fastest subsonic crossing, 5 hours and 1 minute, was made 41 years ago by a Vickers VC10 operated by BOAC. Granted, the plane took the shorter route from New York to Glasgow, Scotland. Still, the longevity of the VC10's record is remarkable, and it's due to the economics of air travel. Carrying more passengers in bigger planes is more profitable than flying a smaller number in faster planes.

The record for the fastest transatlantic crossing made by an ocean liner—an accolade called the Blue Riband—has lasted even longer. It was set in July 1952 by the SS *United States*, whose average speed was 34.51 knots (63.91 km/h, 39.71 mph). The voyage took 3 days, 12 hours, and 12 minutes.

A previous Blue Riband holder, the SS *Normandie*, entered service for Compagnie Générale Transatlantique in 1935. Passengers marveled at its grand Art Deco public rooms and sumptuous cabins. The ship's rival, Cunard's RMS *Queen Mary*, was just as luxurious, but because it had a higher fraction of public rooms and cabins devoted to the more numerous second- and third-class passengers, it made more money. The one true ocean liner sailing today, Cunard's RMS *Queen Mary 2*, made its maiden voyage from Southampton, UK, to Fort Lauderdale, Florida, in January 2004. Its maximum speed is 4.5 knots slower than that of the *United States*. Being faster was not worth the cost.

Economic considerations also play into the progress of science. Most basically, the total amount of money available constrains how much research gets done. When I visited physics departments in Hong Kong in 2008, I saw world-class experiments, all of which were being carried out in modestly sized facilities. The Hong Kong government supports curiosity-driven, peer-reviewed research, but not to the point that the territory's scientists can do big, expensive experiments. Individual countries balk at building a 30-meter-class optical telescope by themselves. They have to band together.

Most democracies dole out science funding using a combination of political priorities and community review. We like to think that the best science is, within reason, funded. But that's not always the case. As Jason Callahan wrote in his December 2019 Commentary for PHYSICS TODAY, when it comes to NASA's space missions, sometimes a politician's personal preferences enter the fray.

A subtler influence is what's in fashion. Some fields explode with activity after a momentous discovery. In 2004 Konstantin Novoselov and Andre Geim devised a cheap and convenient way to make graphene, whose exotic properties had been predicted by theorists. Nine years later, after more than 3000 papers on graphene had appeared in the journals of the American Physical Society *alone*, the European Union launched Graphene Flagship, a €1 billion ($1.1 billion) research initiative. I welcome the largesse, but I worry that it could be starving less fashionable fields.

Indeed, we should be especially concerned about fields that are currently unfashionable. Venerable classical electromagnetism spawned the vibrant field of negative refractive index materials. Dynamical astronomy was not a popular field when I was a grad student in the 1980s. Now it's revived, thanks to the discovery of other solar systems and the European Space Agency's astrometry missions, *Hipparcos* (1989–93) and *Gaia* (2013–). Few-body physics has also undergone a revival. Whoever kept funding those fields and—crucially—hiring researchers who practiced them during their dormancy deserves credit.

It's difficult, perhaps impossible, to predict what fields might be ripe for a revival, which means funders should continue to support curiosity-driven research regardless of fashion. And they should continue to support research that has yet to achieve its ultimate goal, despite decades of effort. I'm hopeful that physicists will eventually reconcile quantum mechanics and general relativity, formulate a microscopic theory of high-T_c superconductivity, and identify the nature of dark matter—to name just three. Continuing to fund those and other challenging quests will hasten their completion. PT

Albert Einstein's 1950 speech, "Physics, philosophy, and scientific progress," was reproduced in PHYSICS TODAY's June 2005 issue. Read it online at www.physicstoday.org

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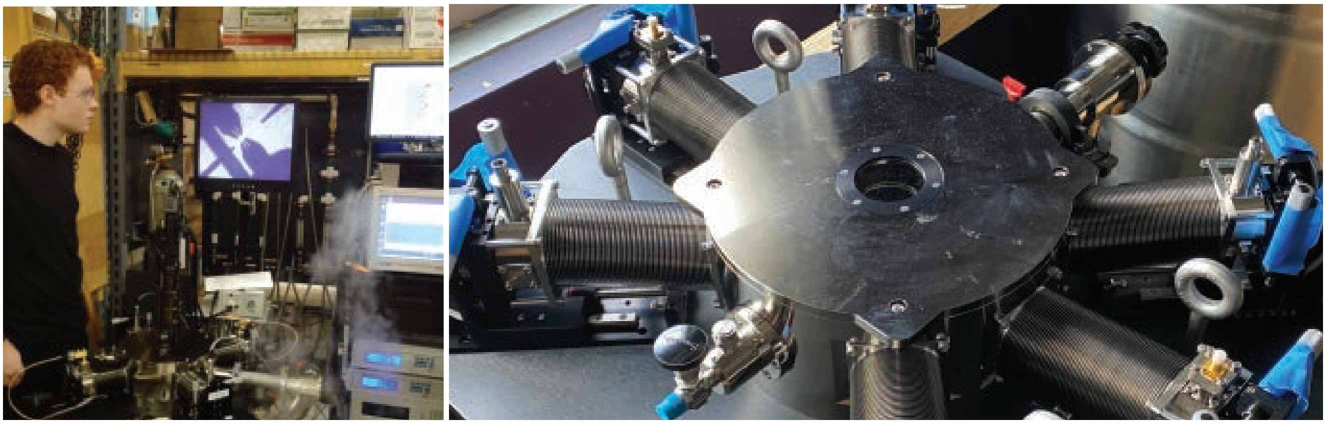

At left, University of Toronto PhD student Shai Bonen tests qubit structures. At right is the cryogenic probe station used in the experiments. (Photos courtesy of Sorin Voinigescu.)

Transforming transistors into qubits

Phil Dooley

Last year Google announced that its 53-qubit quantum computer had performed a task in 200 seconds that would take a classical supercomputer 10 000 years. The achievement was an important step for demonstrating the viability of quantum computing, says University of Toronto nanoelectronics researcher Sorin Voinigescu. But there are still major challenges ahead. "Most people in the industry can't see how the current technology can be scaled to thousands or millions of qubits," he says.

Voinigescu and colleagues are exploring one prospective path by attempting to turn the conventional transistors used in smartphones and computers into qubits. They reported last year in *IEEE Electron Device Letters* that, using the ubiquitous complementary metal oxide semiconductor (CMOS) manufacturing platform, they had successfully built a chip that contains both a potential qubit and its readout electronics. The goal is to demonstrate the effectiveness of transistors as qubits and then scale up the process so that many of them can be packed on a single chip.

The team used some of the smallest existing CMOS transistors, which, at 6 nm by 18 nm by 50 nm, are small enough to show quantum properties when cooled, much like a quantum dot. A qubit requires a system of two energy levels. The Toronto team hopes to create electron-spin and hole-spin qubits by cooling the transistors to 4 K and applying a 2.5 T magnetic field to split their lowest-energy state.

Along with leveraging existing manufacturing methods, the single-chip design cuts out several sources of noise. The Google machine's qubits are made from Josephson junctions operating below 20 mK; its control systems reside far away and operate at 4 K or higher. The connections between qubits and control introduce significant capacitance, delay, and loss, Voinigescu says. In contrast, the Toronto team's prototype integrates qubits and control and operates at the same 4 K temperature.

Transforming transistors into qubits won't be seamless. Because the transistors are designed for use in electronics operating at room temperature, the Toronto team must demonstrate that the cooled device can indeed operate as a qubit.

To perform such sensitive cryogenic measurements, Voinigescu and his colleagues have turned to a new probe station manufactured by Lake Shore Cryotronics, a 50-year-old company based in Ohio. Lake Shore's CPX-VF-LT device allows the Toronto team to cool its new chip, apply a magnetic field, and generate millimeter-wave signals to fully characterize electronic behavior.

In their recent study, the researchers addressed the qubit and profiled the performance of the readout system, repeatedly running their probe station to the limit of its 60-liter liquid helium capacity—about six hours' worth of investigation. "Measurements at such low temperatures take much longer than at room temperature," Voinigescu says. "You need to use very fine steps to capture the quantum effects."

The data obtained from cryogenic DC and S-parameter measurements are promising, Voinigescu says, but obstacles remain. For example, the spin-flip transition energy required to address the elevated-temperature qubit corresponds to radiation at 70 GHz, a challenging regime for electronics manufacturers. And although having the control and readout electronics on the same chip cuts out the capacitance from long cables, it means any heat generated by additional components could threaten the qubit's coherence. "It's the most complex and interesting thing I have ever worked on," Voinigescu says.

Phil Dooley is a freelance writer and former laser physicist based in Canberra, Australia.

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We need to rethink lower-division physics teaching

Over a 30-year teaching career, I have noticed some embarrassing gaps in basic physics understanding among faculty members and students. Those gaps, originating in the first-year calculus-based physics courses taken by science and engineering students, seem mainly due to choices of pedagogy and format made by lower-division textbook writers. When the writers were deciding how to write introductory textbooks, they understood almost nothing about human brain science or learning modalities. We need to take time now to reconsider those choices.

Introductory courses tend to teach from particular to general, which often means that instructors run out of time and general concepts are never presented. I believe the rationale for that choice was to retain weaker students by not overloading them. But the approach ignores the primacy effect: Social scientists have long known that people tend to remember information presented earlier better than that presented later. Students are therefore apt to lose the big, general picture.

Another problem is that textbooks and instructors cram too much information into introductory courses; they especially include new findings in an effort to provide exciting and relevant material. One motivation for the information overload is pressure from admissions departments and accreditation boards to finish a four-term course in three terms or less. Thus informative general introductions to and road maps of topics across chapters and semesters have been tossed under the bus.

An introductory course is the only opportunity many students have to compare subtopics and to gain a big-picture concept map of physics. Upper-division and graduate courses focus narrowly on specialized topics, and big-picture summative connections are rare. As a result, misconceptions about broad, basic concepts never get addressed and may remain once students have become professors.

The issue I see is with existing faculty misconceptions rather than with students. A self-sustaining feedback loop has been created: A student learns conditional and half-truths in lower-division courses and may not absorb the full truth in more advanced studies. That student later becomes a professor and is assigned to teach a lower-division course. The professor is presented with a supposedly authoritative, well-thought-out text and relapses to teaching the half-truths they were taught.

By perpetuating the cycle of misconceptions, we are letting our students down. Here are a few examples of ways in which introductory textbooks could change their presentations to help students build broad understanding and avoid misconceptions.

Rather than teaching Maxwell's equations in integral form, which hides some salient and important features, teachers should use differential form. It may be more challenging: Beginning students are far better at understanding and calculating with differentials than with integrals.

As a first example, introductory courses present Coulomb's law as the final truth even though it is not universally valid. I have always taught it from general to particular despite what appears in textbooks. Instead of the simplified version, I begin with

$$\vec{E} = \frac{q}{4\pi\varepsilon_0}\left[\frac{\vec{e}_{r'}}{r'^2} + \frac{r'}{c}\frac{d}{dt}\left(\frac{\vec{e}_{r'}}{r'^2}\right) + \frac{1}{c^2}\frac{d^2}{dt^2}\vec{e}_{r'}\right],$$

and I point out that for historical reasons and calculation difficulties, I will address the second and third terms through electric charge velocities and accelerations. I leave the details for higher-level courses.

I offer a second example: Instructors often use painfully anemic explanations when introducing waves. Simply put, waves have two basic properties: Their speed is dependent on environmental factors, and they travel at that speed in all moving observer reference frames.

I use the Doppler effect to introduce true relativity of observer experience. When I hear and measure a frequency while observing a moving sound source, that perceived frequency depends on both my vector location relative to the source's velocity and the relative velocity between the transmitter and myself.

For the sake of clarity, it is okay to bring up information that will be covered in a future term. I tell my students that, in principle, sound and light behave in the same manner, with both subject to wave restrictions.

Then I introduce speeds for light and sound: $c_{\text{light}} = c$(electromagnetic vacuum properties) $= c(\varepsilon_0, \mu_0)$, $c_{\text{sound}} = c$(air properties) $= c(T, m_{\text{molecules}})$. For first-semester students who have not yet encountered them, ε_0 and μ_0 can be described as the strengths of the electric and magnetic forces. Students can go back to what they know about the Doppler effect to understand that the reference frame transformation function, $\Gamma(v)$, is a function of the relative frame velocity v. However, be-

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cause the wave speeds for both light and sound are independent of v and because $c = \lambda f$, the factor $\Gamma(v)$ must appear reciprocally in both the frequency and wavelength transformations.

Then, when the same issue arises in special relativity for light, the groundwork has been done and students don't experience culture shock or feel betrayed.

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Tito's interest in science

The feature article "Physics in the former Yugoslavia: From socialist dreams to capitalist realities" (Physics Today, August 2019, page 30) mentioned the strong interest and encouragement the country's leader, Josip Broz Tito, gave to science in the then newly founded Federal People's Republic of Yugoslavia. I add one further account that shows his interest.

I was at the Princeton Plasma Physics Laboratory (PPPL) when Tito visited it in 1963 as part of his tour of the US. Why he chose to visit us was not clear to me at the time since the work at PPPL had, at best, only long-range applications to fusion power. However, I now see that it was a part of his general interest in both science and its applications in planning for the future of Yugoslavia. He was the only head of state to visit PPPL while I was there. I recall the event clearly because it was the first and only time I have ever shaken hands with such a notable.

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A scenario for getting rid of the bomb

Regarding Thomas Jonter's article "Getting rid of the Swedish bomb" (Physics Today, September 2019, page 40), I have a comment. Everyone in the world who might be considering building or using the atomic bomb should have as required reading the novel titled *Alas, Babylon* (1959) by Pat Frank. Although the story is fictional, it is not too far from what the ugly truth would be if means of mass destruction, such as the bomb, were to be used as weapons of war.

The book clearly approximates what things would be like if an accident involving nuclear weapons should ever happen. The only solution would seem to be that all nations simultaneously agree to stop production of such weapons and dispose of any that they have. Otherwise, a freak accident like the one depicted in *Alas, Babylon* could become a terrible reality.

I am 90 years old and don't have too much time left, so perhaps I should not worry about such a situation. However, I do have family members who will be around for many more years. I can only hope that they will not be faced with a terrible happening such as a nuclear war.

Robert Grayson
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[Editors' note: Alas, Babylon *is out of print but still available through used-book sellers and as an ebook. It was mentioned briefly in a review of* The Trinity Paradox *(*PHYSICS TODAY*, May 1992, page 64).]*

Charles Kittel's perseverance

I read with great sadness the obituary of Charles Kittel (PHYSICS TODAY, October 2019, page 73). I have something to add—namely, his incredible courage in the face of a major speech impediment. His example of not bowing to his disability but soldiering on was an inspiration to anyone lucky enough to hear him speak. I look back at my incredible fortune in having spent time with Professor Kittel, and my guess is that thousands of physicists around the world would say the same thing.

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Richter supported Stanford accelerator projects

The excellent obituary for Burton Richter by Roy Schwitters (PHYSICS TODAY, August 2019, page 64) does not cover the support, starting in the late 1960s, that Burt gave the Stanford Synchrotron Radiation Project (SSRP) to use synchrotron radiation from the colliding beam storage ring of SPEAR, SLAC's first electron–positron collider. Nor does it mention his support, starting in the early 1990s, for the Linac Coherent Light Source to use the SLAC linac to drive an x-ray free-electron laser. His advocacy for those projects has enabled SLAC to transform from a high-energy physics lab into a photon science lab. Without his contributions, it is doubtful that SLAC would be in existence today.

Perhaps the first and most critical decision Burt made was to install, as part of the original construction of SPEAR in 1972, a special vacuum chamber with a tangential spout that allowed a small swath of synchrotron radiation, from less than one degree of curved path in a modified bending magnet, to exit the ring.

The chamber made it possible to start synchrotron radiation experiments without having to modify a SPEAR magnet and vacuum chamber. It is hard to imagine that those modifications would have been made after the exciting colliding-beam results that were obtained at the start of SPEAR's operation, because they would have required that the ring be shut down and vented. The decision to design, construct, and install the chamber could not have been easy for Burt; SPEAR was significantly underfunded, and financing to cover the additional cost of the modifications to the vacuum system would have been hard to find.

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Corrections

December 2019, page 15—In the statement "He calculated that the radiation would have cooled from an initial temperature greater than 1010 K," the figure should have been 10^{10} K.

January 2020, page 50—Quartz was mistakenly listed as a carbonate mineral. PT

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An optical trap nudges a nanoparticle into its motional ground state

Cooling techniques borrowed from atomic physics bring a room-temperature speck of glass into the quantum regime.

Macroscopic objects tend to behave classically rather than quantum mechanically—unless they can be cooled to ultralow temperatures. With a macroscopic quantum system, physicists could elucidate both the transition from classical to quantum and the causes of decoherence, including the role of gravity. Such systems would also have potential sensor applications for small forces (see PHYSICS TODAY, October 2018, page 19).

A suite of laser-cooling techniques has successfully pushed the temperature of atomic gases down to within a fraction of a degree above absolute zero, where quantum mechanics dictates their behavior. But the gases are not in macroscopic superposition states. Another potential route to macroscopic quantum systems is quantum optomechanics, in which an optical cavity is paired with a mechanical resonator of dimensions up to hundreds of millimeters (see the article by Markus Aspelmeyer, Pierre Meystre, and Keith Schwab, PHYSICS TODAY, July 2012, page 29). Although researchers have cooled those systems to their ground state mechanical modes, the research applications are limited because the resonator is attached to a support and can't be manipulated as a single, isolated object.

Now Markus Aspelmeyer of the University of Vienna in Austria and his colleagues have demonstrated a strategy for an easily manipulated macroscopic quantum system.[1] They cooled a nanoparticle to its ground state, as depicted in figure 1, through a cooling technique that pairs an optical trap with an optical cavity.

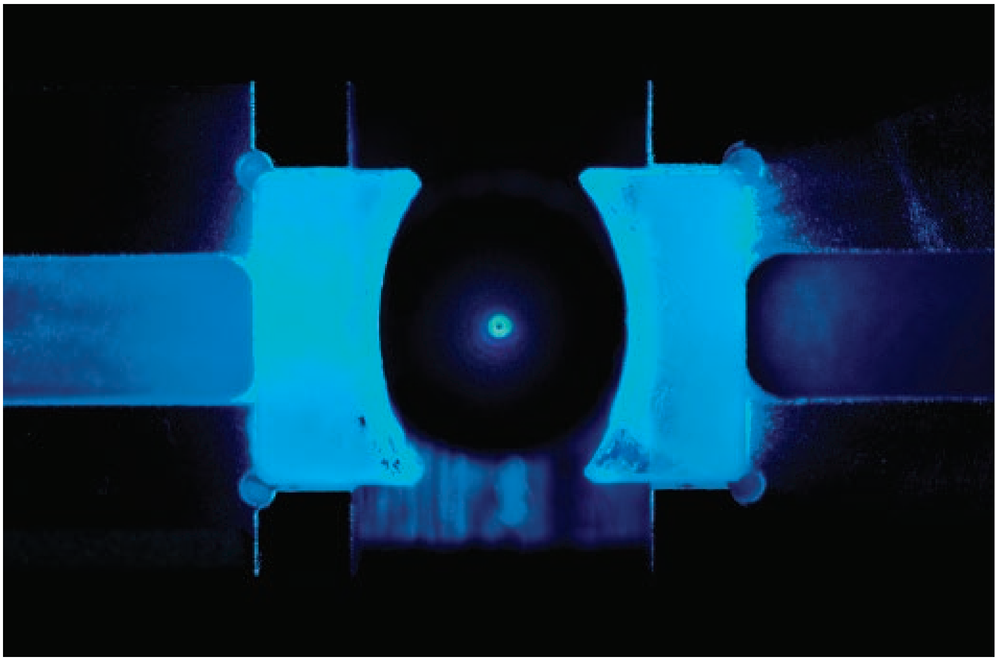

FIGURE 1. AN OPTICALLY TRAPPED NANOPARTICLE, shown here through its dipole scattering (blue dot), is cooled to its ground state inside an optical cavity about 1 cm wide. (Courtesy of the University of Vienna.)

From atoms to nanoparticles

Extending laser-cooling techniques to molecules and solids has proven tricky. The most common technique, Doppler cooling, irradiates the sample from all sides with laser light that is tuned slightly below the frequency of an atomic transition. When an atom moves in the opposite direction of a photon, the light is blueshifted into resonance and absorbed. The atom then slows down, reemits the light, and returns to its ground state.

Repeating that absorption and emission tens of thousands of times can cool a sample to temperatures as low as tens of microkelvins. But a molecule's rotational and vibrational degrees of freedom split the energy levels. Therefore, when a molecule reemits light, it can get stuck in a state other than the ground state and actually gain energy in the process (see PHYSICS TODAY, January 2010, page 9).

About 20 years ago, Helmut Ritsch and, independently, Vladan Vuletić and Steven Chu proposed a different method called cavity cooling.[2] It relies on coherent scattering in an optical cavity irradiated by a laser, which doesn't need to be tuned to an electronic transition. The cavity field traps the atom or molecule, and when the light in the cavity scatters off it, the particle is left in either a higher motional energy state, so-called Stokes scattering, or a lower motional energy state, anti-Stokes scattering. The driving laser is tuned such that the cavity enhances anti-Stokes scattering, and each photon scattered into the cavity lowers the energy of the particle one quantum of motion, or phonon, at a time.

In theory, that tactic should cool a nanoparticle to its motional ground state. As Uroš Delić finished his undergraduate thesis in preparation for grad school, he and Aspelmeyer were eager to try cavity cooling on a solid particle, an effort pursued by a few groups, including that of Lucas Novotny at ETH Zürich. But any effort to reduce the temperature below tens of millikelvin, or several hundred phonons, faces two hurdles. First, fluctuations in the laser's phase cause cavity-field fluctuations that jostle the particle and heat it. Second, cooling the nanoparticle further than tens of millikelvin requires more photons—that is, the laser intensity needs to be increased. But a strong cavity field pulls the particle into one of the field's antinodes, where the particle motion no longer interacts with the cavity field and thus isn't cooled.

After an internship in Vuletić's lab at MIT, Delić altered the cavity-cooling setup in Aspelmeyer's lab to remove those obstacles. In their cooling scheme, shown in figure 2a, he and Aspelmeyer incorporated an optical trap that they detuned by Ω from the cavity's resonant frequency ω_{cav}. The trap (green) holds the particle in a stable position in the cavity and provides photons for the cooling process; no driving laser, with its phase noise, is necessary. Because the photons come from the trap, the particle can be cooled at any position in the cavity. Positioning the trap in a cavity field node removes elastic scattering (dashed green arrows) to leave only Stokes and anti-Stokes scattering.

Otherwise, the process is similar to the usual cavity cooling: Photons from the trap scatter off the particle, and rather than enhancing Stokes scattering (smaller red arrows), the cavity enhances anti-Stokes scattering (blue arrows in figure 2b), which gradually lowers the particle's energy. Aspelmeyer's and Novotny's teams both implemented cooling with an optical trap,[3] and they found it is much more efficient: It takes four to five orders of magnitude fewer photons than cavity cooling to reach the same temperature.

Fine tuning

The nanoparticle's temperature is the sum of the phonons' energies. To measure the number of phonons, Aspelmeyer and his team collect the scattered light and identify the frequency peaks from Stokes and anti-Stokes scattering. The evolving asymmetry of those peaks indicates the average number of phonons $\bar{n}$. The cavity enhancement leads to a much larger anti-Stokes peak when there are many phonons. But a particle in its ground state can't reduce its energy further—that is, anti-Stokes scattering is no longer possible. As the temperature approaches that of the ground state, the anti-Stokes peak therefore shrinks, whereas the Stokes peak stays relatively constant.

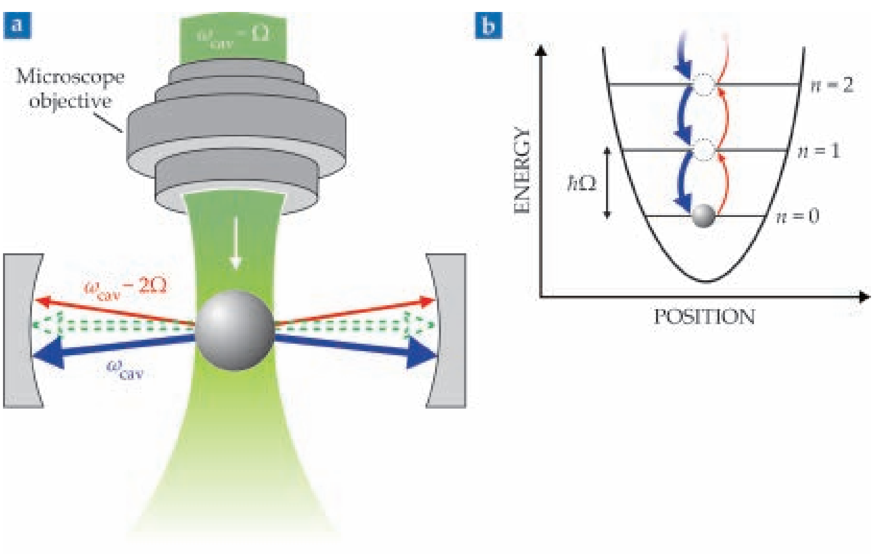

FIGURE 2. IN THE OPTICAL COOLING SCHEME, a nanoparticle reaches its ground state through coherent scattering. **(a)** An optical trap (green) holds the particle (gray sphere) inside an optical cavity with resonant frequency ω_{cav}. Photons scatter off the particle, and the cavity enhances anti-Stokes scattering (blue arrows) over Stokes scattering (red arrows). The nanoparticle's position in the cavity suppresses elastic scattering (green dashed arrows). **(b)** Anti-Stokes scattering lowers the energy of the particle one phonon at a time, whereas Stokes scattering increases it. Each phonon has a frequency of Ω and an energy of $\hbar\Omega$. (Adapted from ref. 1.)

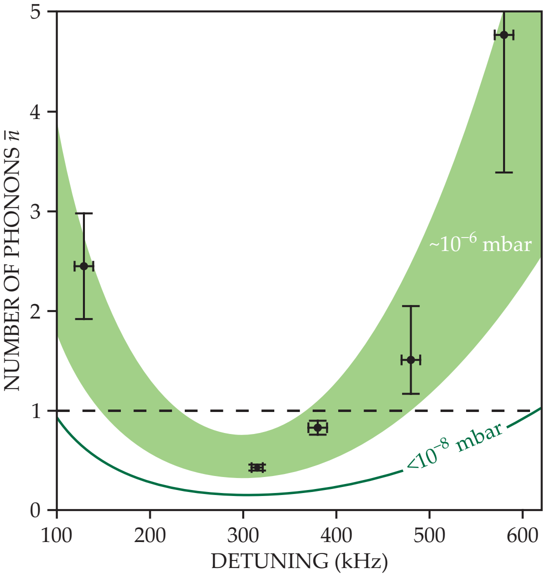

FIGURE 3. THE AVERAGE NUMBER OF PHONONS $\bar{n}$ for the nanoparticle reaches a minimum when the optical trap is detuned from the cavity resonance by about 315 kHz. A value below $\bar{n} = 1$ indicates that the particle is in its ground state. The experimental data (black dots) match theoretical predictions (light green band). Even better cooling is predicted at ultra-high-vacuum pressures below 10^{-8} mbar (dark green line). (Adapted from ref. 1.)

In the experiment, the team members cooled a 143-nm-diameter silica nanoparticle down to its ground state, which corresponds to a temperature of about 12 μK. The lowest value of $\bar{n}$ they measured was 0.43; any value below 1.0 indicates the ground state. Previous cavity cooling studies reported nanoparticles with hundreds of phonons, and Novotny and his team reached four phonons using an optical tweezer with an active feedback loop.[4]

To optimize the cooling, Aspelmeyer's group members detuned the optical trap by different frequencies relative to the cavity resonance, as shown in figure 3. They found that detuning by about 315 kHz produced the minimum average number of phonons. But detuning by 380 kHz also dropped the particle to the ground state.

Room for expansion

Now that Aspelmeyer has cooled a nanoparticle to its ground state, he says, "What I would really love to see is a wavepacket that is the size of the object." In the current experiment, the nanoparticle's wavepacket is localized to a few picometers. But a wavepacket as big as the particle itself would allow researchers to examine its properties in the macroscopic quantum regime.

Expansion of the wavepacket is possible by swapping the trap's beam profile from a harmonic potential to a double well or any number of nonlinear potentials. Engineering particle dynamics quickly and on the fly through the beam profile is something the cold-atom and biophysics community has been doing successfully for years with optical tweezers. The particle stays trapped, and the potential landscapes evolve around it.

Another method to expand the wavepacket is turning off the optical trap and letting the particle fall. With the current setup, a freely falling wavepacket would have time to expand by only a factor of three before it decohered. Lowering the pressure to 10^{-11} mbar and the surrounding temperature below 130 K would preserve coherence for long enough, about 10 ms, for the wavepacket to expand to a size on the order of the particle radius.

Aspelmeyer's long-term vision is to apply his technique to particles that are large enough to produce a measurable gravitational field. In that regime, questions about how the gravitational field looks for an expanded wavepacket can be answered. But Aspelmeyer says those experiments are still a decade or two away.

Heather M. Hill

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A novel liquid-crystal phase is ferroelectric

Molecular dipoles in a liquid don't usually spontaneously align. The secret to getting them to do so may be the molecules' shape.

Three years ago chemist Richard Mandle and colleagues at the University of York in the UK published a surprising observation.[1] They'd created a new organic molecule, now known as RM734. Because of its elongated shape and large electric dipole moment, they thought it might be useful in liquid-crystal applications.

Cooling a hot sample of RM734 molecules below 188 °C transformed it, as expected, from an ordinary isotropic liquid into a nematic liquid-crystal phase, characterized by its orientational order without positional order. But as the researchers cooled the liquid further and monitored its heat capacity, they saw the clear signature of a second phase transition, at 133 °C, that they were unable to explain. Above and below the transition temperature, the material looked exactly the same.

Now, in collaboration with Mandle and others, physicists Nerea Sebastián and Alenka Mertelj, both at the Jožef Stefan Institute in Ljubljana, Slovenia, have figured out what's going on.[2,3] Through a combination of measurements, they found that the high-temperature phase is indeed the usual uniform nematic one, in which the asymmetric elongated molecules all align along, say, the *z*-axis, but with a homogeneous mix of molecules pointing in the +*z* and −*z* directions. The lower-temperature phase, however, is something that had never been seen before: It comprises a series of stripes, as shown schematically in yellow and blue in figure 1, of +*z*- and −*z*-oriented molecules, respectively.

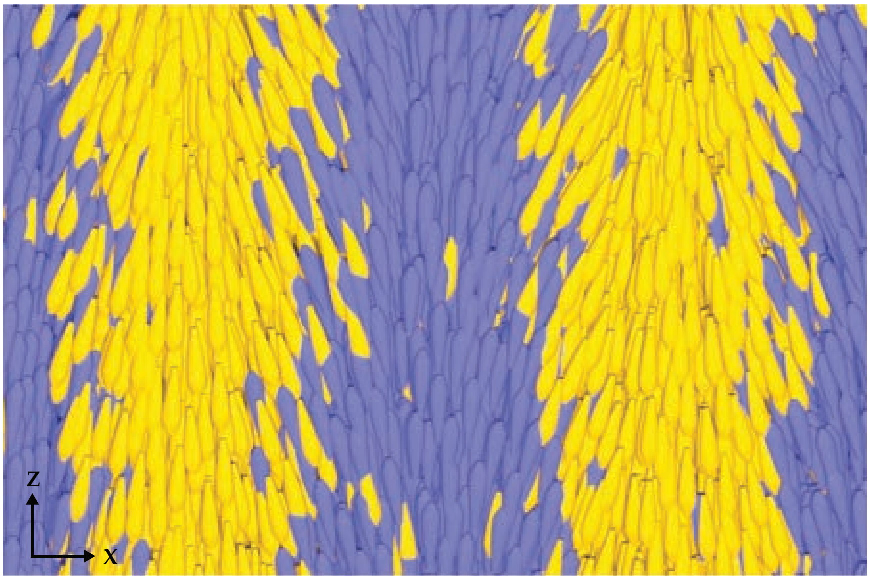

FIGURE 1. THE SPLAY NEMATIC PHASE in a liquid crystal is made up of polar wedge-shaped molecules. Aligned along the *z*-axis, the molecules segregate into slightly splayed stripes of molecules with their narrower end pointing toward +*z* (yellow) and –*z* (blue). (Adapted from ref. 2.)

Because the RM734 molecules are slightly wedge shaped—a bit wider at one end than the other—the stripes are also splayed in alternating directions. And they're surprisingly wide, at several microns, or thousands of times the width of a single molecule.

Long molecules with large electric dipole moments, like RM734, don't usually seek out such parallel, ferroelectric arrangements in the liquid phase. Rather, they energetically prefer to form antiparallel pairs. So as useful as a ferroelectric liquid might be—its spontaneous polarization could enable molecular orientations to be switched quickly and with low power—ferroelectricity in liquid crystals has until now been limited to smectic phases, which, because of their partial positional order, aren't fully fluid.

It's not yet clear exactly what makes RM734 different. The researchers are still working to get a handle on which specific molecular features give rise to the ferroelectric phase, in the hope of being able to tune properties such as the stripe width and the transition temperature. But from what they've seen so far, they've concluded that a subtle interplay is at work between the molecule's charge distribution and its shape. Apparently, neither one alone is enough to produce the unusual molecular arrangement, but together they are.

Bend and splay

The polarity–shape interaction is related to the flexoelectric effect, a phenomenon first described in liquid crystals by Robert Meyer half a century ago.[4] Similar to the piezoelectric effect in solids, in which mechanical strain produces an electric potential or vice versa, the flexoelectric effect is the coupling between an electric potential and a strain gradient.

Figure 2 illustrates two ways it can work. The top panel shows a liquid crystal of banana-shaped molecules with electric dipole moments perpendicular to the molecular length. In the normal nematic phase, shown on the left, all the molecules align horizontally, but with the dipole moments pointing in random directions. But when the liquid-crystal layer is bent, the molecules reorient so their curves conform to the bend, and the dipoles align.

The bottom panel shows a similar reorientation of wedge-shaped molecules with dipoles parallel to their length. This time, the dipoles are aligned by a splay strain gradient: squeezing the liquid crystal at one end and stretching it at the other.

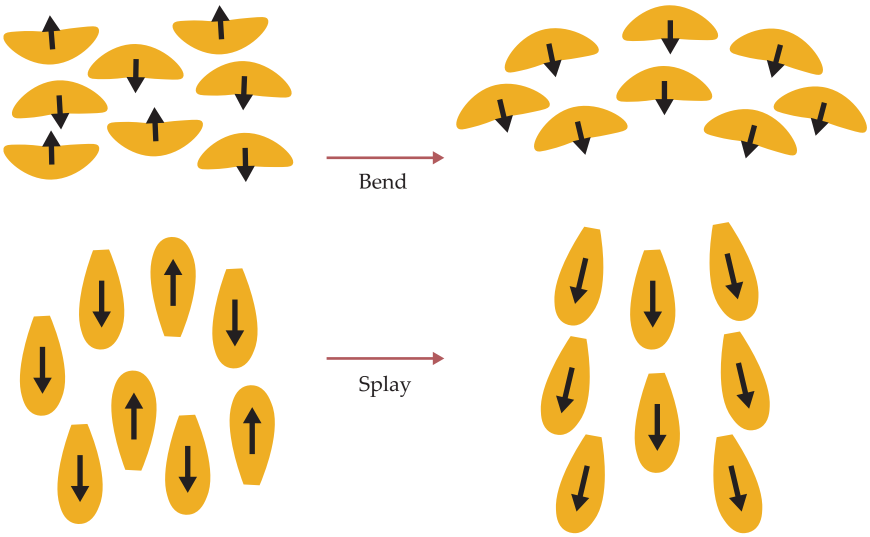

FIGURE 2. THE FLEXOELECTRIC EFFECT in a nematic liquid crystal describes the coupling between molecular dipoles (black arrows) and strain gradients. Banana-shaped molecules are polarized by an applied bending strain, and wedge-shaped molecules by splay strain. (Courtesy of Nerea Sebastián.)

Flexoelectricity is not ferroelectricity; external forces are required to align the dipoles. But in 2001 Ivan Dozov showed theoretically that molecules might align spontaneously under some circumstances, at least over small length scales.[5] Specifically, in a liquid crystal of banana-shaped particles, if the mechanical resistance to bending strain were to somehow go to zero, the molecules would tend toward the bent configuration all by themselves.

However, it's impossible for a uniformly bent arrangement of curved molecules to fill three-dimensional space: Even in a thin bent layer, the curvature is tighter on the inner surface than the outer one. Dozov proposed that the molecules could overcome that problem by adding a twist—by arranging into loosely wound helical structures that look locally like the bent configuration. Because the helix is turning every few nanometers, there's no large-scale ferroelectric alignment of molecular dipoles. Still, when the twist–bend nematic phase was experimentally discovered, a decade after Dozov's prediction, it took the liquid-crystal world by storm.[6] It was the first new kind of nematic phase to be discovered in almost a century.

Wide stripes

Mandle and colleagues weren't thinking about the flexoelectric effect, or about the twist–bend phase, when they designed RM734. "We were interested in molecules with large electric dipole moments," explains Mandle. "But our only motivation to make them wedge shaped was to reduce the material's melting point"—a molecule that's bulkier at one end than the other would have a harder time organizing into an ordered, solid crystal lattice—"and make it easier to study." When they saw the unexpected phase transition, though, they were immediately reminded of the twist–bend phase. So was Mertelj, when she heard about the work at a conference and offered to study the unusual liquid crystal in her lab.

The exact relationship to the twist–bend phase, however, was far from clear. "Initially we believed that the second nematic phase was due to the formation of antiparallel pairs of molecules," says Mertelj, "and unconnected to the material's mechanical properties." Later she and her colleagues wondered whether they might be seeing a version of the twist–bend phase itself—but the bend elastic constant showed no unusual behavior at the phase transition. The splay elastic constant, on the other hand, dropped sharply at the transition temperature. "That was a big surprise," says Mertelj. "We had to remeasure it several times to be certain of what we were seeing."

Just like the bent arrangement of banana-shaped molecules, though, the splay arrangement of wedge-shaped molecules can't uniformly fill space. If the RM734 molecules were spontaneously splaying, there had to be something more to the phase structure to compensate.

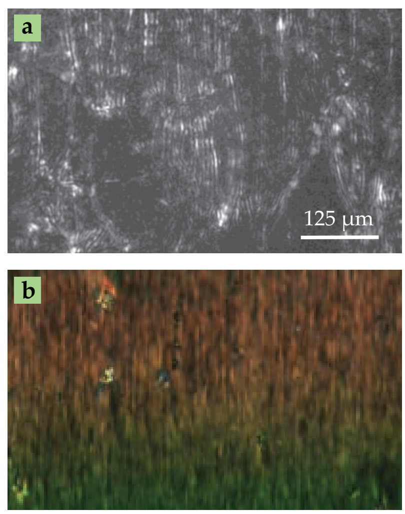

FIGURE 3. THE STRIPE MODULATIONS shown in figure 1 are visible in **(a)** second harmonic generation microscopy and **(b)** polarized optical microscopy. Although the schematic in figure 1 depicts stripes on the order of 10 molecules wide, the observed stripe widths, at 4–5 µm, are thousands of times the width of a molecule. (Panel a adapted from ref. 3; panel b courtesy of Nerea Sebastián.)

With a little more detective work, the researchers arrived at the modulated structure—the alternating stripes—shown in figure 1.

At first, they supposed that the modulation period, or width of the stripes, would be on the order of nanometers, similar to the pitch of the helices in the twist–bend phase. The splayed phase was optically identical to the ordinary nematic phase, so any structural features seemingly had to be smaller than the wavelength of visible light. And if the phase transition was driven purely by molecular shape, as it seemed to be, the modulations couldn't be much larger than the dimensions of the molecule itself.

But second harmonic generation (SHG) microscopy told a different story. SHG can occur only in structures that lack inversion symmetry. The interfaces between stripes don't qualify because they contain about as many molecules pointing one way as the other. But the interior of each stripe, where all molecules point in the same direction, is potentially visible in SHG imaging. "In fact, as we cooled the sample through the phase transition, the signal was so strong that we nearly burned out our detector," says Mertelj. The SHG image, seen in figure 3a, shows clearly delineated stripes 4–5 μm wide at the phase transition.

As it turns out, the stripes show up in optical images too, such as the one in figure 3b. Mandle and colleagues hadn't seen them before because they're visible only at the cusp of the phase transition. Below the transition temperature, the phase structure reorients, so the modulation direction (the x-axis in figure 1) is perpendicular to the imaging plane, and the stripes are rendered invisible to both SHG and optical microscopy.

Ferroelectric potential

The stripe modulations are too wide to arise from the mechanical effects of molecular shape, but what else could be causing them? If the phase transition was driven by molecular polarity, it would be revealed in the material's dielectric susceptibility—similar to the critical behavior of the magnetic susceptibility at a ferromagnetic phase transition. But labs equipped for broadband dielectric spectroscopy measurements on liquid crystals are scarce, and Mertelj's isn't one of them.

Fortunately, the lab where Sebastián had done her PhD—with María Rosario de la Fuente at the University of the Basque Country in Bilbao, Spain—specializes in just such dielectric measurements. Sebastián took a sample of RM734 back to Bilbao, measured the susceptibility, and found that it diverged at the phase transition. It was a clear signature of ferroelectricity.

From the dielectric measurements and stripe widths, the researchers concluded that the mysterious phase transition is driven primarily by molecular polarity, with shape playing only a bit part. But it must play some role, because most polar liquid-crystal molecules don't tend toward ferroelectric order. The nature of the polarity–shape interplay is not yet understood.

There's still a lot of work to do. Experiments so far have focused on the immediate vicinity of the phase transition, and little is known about how RM734 behaves as it's cooled deeper into the splay nematic phase. Do the stripes, although reoriented, stay more or less the same? Or do more complicated textures form? And how does the behavior change when the molecular features are subtly altered?

An eventual goal is to design a molecule that forms a homogeneous ferroelectric phase: all the molecular dipoles pointing in the same direction, without any splay or stripes. "We strongly believe it is likely that such a material can be found," says Mertelj. "Everything is possible."

Johanna Miller

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Barbs of a feather lock together

When a bird extends its wings in flight, microscopic fasteners stick to each other to prevent gaps between the feathers and improve the bird's macroscopic maneuverability.

FIGURE 1. THIS BIOHYBRID ROBOT combines mechanical parts with pigeon feathers. During real-world flight tests with high and low turbulence, PigeonBot controlled the position of its 40 feathers using four wing-mounted motors. The feathers' fasteners prevented any gaps in the wings from forming that would have otherwise limited the robot's mobility. (Lentink Lab/Stanford University.)

Airplane wings trade off some of their efficiency for stability. Their shape is fixed and rigid except for the flaps and slats that pilots can tune during takeoffs and landings to attain the desired level of lift and drag. Birds approach flying a bit differently: They take off, glide, turn, and land more efficiently and nimbly than airplanes by changing the shape of their flexible wings to various configurations (see PHYSICS TODAY, June 2007, page 28).

The feathers that make such morphing possible are made of a few basic parts. Each feather consists of a central shaft that's lined with branching barbs. The many hook-like barbules on each barb easily fasten together to form an individual feather with a pliable and gapless surface. Based on several detailed observational studies, biologists have assumed for decades that simple friction causes feathers to cling together during flight.[1]

Scientists could use computational fluid dynamics simulations to test, in principle, whether frictional forces are strong enough to keep feathers together. But the research is complicated by the morphable wings, which deform as they interact with air. More recently, engineers have begun applying dynamical systems analysis to better understand how individual structures in bird anatomy, including the neuromuscular and sensory systems, integrate to control wing shape and flight.[2]

A group of biologists and engineers that recently teamed up has now uncovered the biophysical mechanism that makes morphing feasible. Graduate student Laura Matloff, her adviser David Lentink (both at Stanford University), and their colleagues determined that adjacent feathers on the wings of common rock pigeons are held together by microstructures similar to barbules.[3] Field tests with a biohybrid flying robot, shown in figure 1, confirm that the microstructures fasten together in one direction and unlock in the other to prevent wings from getting bent out of shape in flight.

Prime mover

The researchers first measured the skeletal kinematics of pigeon wings and their relative flight positions using cameras and microcomputed tomography scanning. They couldn't observe each configuration of the bird's fingers, arms, and wrist bones in an active, living bird, so three pigeon cadavers were used for the experiment. The wings of each cadaver were positioned in various

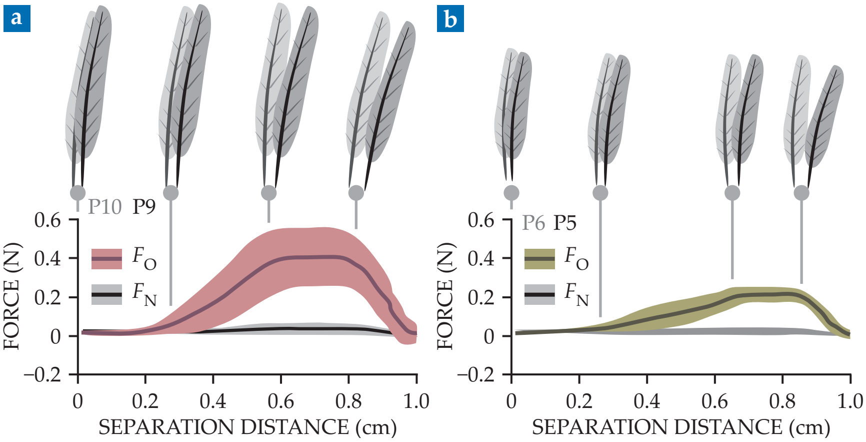

FIGURE 2. THE OPPOSING FORCE F_O between adjacent feathers of rock pigeons rapidly increases as the feathers slide apart. (Shaded regions show the standard deviation.) The magnitude varies between feather pairs P9–P10 **(a)** and P5–P6 **(b)**. The normal force F_N for both pairs is too small for frictional forces to keep the feathers together. (Adapted from ref. 3.)

glide poses to collect the necessary data.

Biologists already know that the distribution of feather positions arises from bone movements that are mediated by a series of muscles and elastic ligaments. The scans and images of the wings supported that view, but the group found another correspondence between feathers and bones: As the pigeon's wings morph for flight by extending the angle of the wrist bone, the angle of the feathers relative to the forearm bone increases linearly.

The transfer functions—that is, the translation of a bird's wrist bone angle to each of the individual feather angles—can be generally described as an underactuated system. Computer scientists, mathematicians, and roboticists use the term for mechanical systems that contain fewer actuators than degrees of freedom. In the case of birds, the lower arm, hand, and a finger bone actuate 40 flight feathers to position them collectively rather than individually. Lentink says, "It's an ingenious system that greatly simplifies feather position control."

Show of force

When Matloff and other graduate students presented the research at the annual meeting of the Society for Integrative and Comparative Biology in 2016, researcher Teresa Feo with the Smithsonian National Museum of Natural History suggested that they measure the friction between the feathers. "Laura Matloff and I decided to simply slide some pigeon flight feathers over each other in the lab during an afternoon and expected nothing beyond a little friction," says Lentink. "Instead we suddenly felt the feathers lock together with a force that was something else."

The force was not caused by friction alone: The calculated coefficient of friction for even the lowest measured normal force was far greater than the theoretical limit based on the feathers' material properties. Some other mechanism was clearly causing, or at least contributing to, their resistance to separation.

To look at the feathers in more detail, Feo and Lentink's graduate student Lindsie Jeffries used x-ray and scanning electron microscopy. They found microstructures that fasten together and apply a directional, opposing force, as shown in figure 2. The structures interlock when overlapping feathers—for example, the P9–P10 and P5–P6 pairs—are extended for flight. Because the microfasteners are directional, a pigeon can easily change the shape of its wings by unlocking them so that the feathers overlap more.

The discovery of directional fasteners prompted Matloff and Feo to look for the mechanism in 15 other bird species. They found that 12 of them use the fasteners to control wing shape and prevent feathers from separating in flight. Barn owls, barred owls, and chuck-will's-widows lack them. The evolutionary loss does have a benefit: Barn owls can fly some 40 dB more quietly than pigeons, which makes them adept nocturnal hunters.

Learning to fly

The team applied the underactuation results and the fastener discovery to build PigeonBot—a biohybrid robot.[4] Rather than attempt to mimic bird feathers with synthetic materials of carbon and glass fiber, the researchers used the real thing. The prototype employed four motors mounted on the wings to control the movement of synthetic ligaments and the position of 40 feathers, which lock together when extended.

During real-world test flights under both calm and turbulent conditions, PigeonBot's wings morphed and extended at frequencies similar to those observed in pigeons. With fully extended wings, PigeonBot glided at realistic speeds and angles of attack. The directional fasteners easily unlocked so that PigeonBot could, for example, flex its wings to a tucked position for turns, like real birds do. In wind-tunnel experiments without the underactuated ligaments and fasteners, the angles of the feathers were purposefully extended and gaps formed between the feathers, which would have made the robot fly unreliably in the turbulent atmosphere.

"I think this research by the Lentink group is an excellent example of a general trend that's starting to happen," says Simon Sponberg, a biophysicist at Georgia Tech. "This fastener mechanism is showing the deeper physics understanding underneath the interesting biological structure that we've appreciated." The microscopic dynamical properties of the feathers influence the macroscopic shape and kinematics of wings. Sponberg says, "I'm really excited about this idea that you can take interesting observations done in biology and connect the emergent dynamics with the functions that make biological systems so cool." The insights from the new results may help guide designers toward improving aircraft, especially low-speed drones.

Alex Lopatka

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PT

Opening a new university offers opportunities to try new approaches and reach new populations

Brand recognition, funding, and language barriers are common challenges.

In late 2014, some months after Tadeusz Patzek was approached about heading up a new petroleum institute at the King Abdullah University of Science and Technology (KAUST), he moved to the young research university in Saudi Arabia. Patzek had been at the University of Texas at Austin for about seven years, with no intentions of leaving. "I went for the sense of adventure, the sense of creating something new and unique," he says.

As an astronomy professor at Pomona College, Bryan Penprase got involved with plans to launch a sister college in Asia. "It was so exciting to get a group of dreamers together to say, 'What is possible?' The idea was to take best practices and liberate from less relevant things." Innovation at existing institutions can be "pretty impossible," he adds. The plan fizzled due to the 2008 global financial crisis, but was later taken up by Yale University in collaboration with the National University of Singapore. The new institution opened in 2011 as Yale-NUS. Penprase helped hire the inaugural faculty and design the curriculum. He is currently dean of faculty at Soka University of America, a small private school in southern California that focuses on global citizenship and a humanistic liberal arts education.

New universities differ in the reasons for starting them, the models they adopt, and the degrees they offer. Adequate funding is a must—whether from public sources, tuition, or an endowment. But funding aside, from Abu Dhabi to England and from Japan to Canada, the challenges new universities face, their goals, and the ingredients for success overlap.

"Whatever is needed"

KAUST was launched to great fanfare in 2009 (see PHYSICS TODAY, November 2009, page 24). The main goal was to bring world-class research to Saudi Arabia as a means to diversify the economy, staunch brain drain, and tackle regional problems. Ten years on, it has achieved name recognition, admissions to its programs are highly competitive, and it is amassing patents and spin-off companies. The 158 faculty members, 476 postdocs, and roughly 1100 PhD and master's students hail from more than 100 countries.

Like KAUST, the Okinawa Institute of Science and Technology (OIST) in Japan stresses interdisciplinarity and confers only graduate degrees. It, too, is gener-

RESEARCHERS AT THE KING ABDULLAH UNIVERSITY OF SCIENCE AND TECHNOLOGY (KAUST) use the instrumented yellow glider to study currents, temperatures, and other properties of the Red Sea as a function of depth. Much research at KAUST addresses regional problems.

KING ABDULLAH UNIVERSITY OF SCIENCE AND TECHNOLOGY ously funded, which frees researchers from the grant-writing mill and affords them the opportunity to pursue risky, curiosity-driven projects; its high level of funding and direct line to the prime minister's cabinet generates envy at other Japanese institutions. Japan created OIST in 2011 with the dual aims of conducting world-class research and education and economically boosting the country's poorest region, and thus contributing to internationalizing its science enterprise. Okinawa's main industries are fishing and tourism. The island is an hour's flight from Taipei, two from Hong Kong, and three from Tokyo.

Integration with the Japanese research community is an ongoing challenge for OIST. "We are still exotic in Japan," says faculty member Matthias Wolf, who works on virus structures. "When it comes to the best students, they tend to go to the top universities on the main islands." Only about 15% of OIST's roughly 200 students are Japanese. To come to OIST, he explains, "they have to leave the safety of their traditional educational system."

Evolving environments

"All new institutions have the same challenges," says David Frost of Georgia Tech. "What's important is the manner in which the people and the institutions respond." In 1999 Frost served as founding director for Georgia Tech's new satellite campus in Savannah. "You have to hire engaged people who step up and do whatever is needed. You need people who are comfortable in a dramatically evolving environment," he says. "Even for me as director, it was like sitting on a balloon that was getting bigger and bigger."

Faculty at new institutions have to be flexible, creative, and willing to do the extra work of program building, says Ajay Gopinathan, physics chair at the University of California's newest campus, which opened in Merced in 2005. It was created to serve the state's growing population. "Injecting higher education and economic opportunity into this community in the San Joaquin Valley generated a lot of political will to putting the campus here," says Gopinathan. Even when the UC budget was cut during the financial crisis, UC Merced continued to grow, he says.

"When I got here, there were pristine facilities but essentially no established programs or students," Gopinathan says. He was one of four junior physics faculty tasked with setting up the undergraduate and graduate curricula and recruiting students and faculty. It was both a challenge and an opportunity, he says. "We had no institutional inertia. We could be agile in our educational programs and our research." Among the strategic decisions he and his colleagues made was to focus on select interdisciplinary subfields: biological and soft-matter physics and quantum materials for sensing, computing, and renewable energy. The department has grown to 17 faculty members, he says, and is now building strength in computational and data-science astrophysics. It also plans to increase its focus on preparing graduates for careers in industry.

Being born into a well-respected system with public funding, the new campus was somewhat shielded from the challenges of recruiting students and faculty that campuses with no brand recognition face. In 15 years, UC Merced has grown from an initial 875 under-

NMITE

IN PREPARATION FOR OPENING, officials at NMITE (New Model Institute for Technology and Engineering) worked with 25 stand-in students to test-drive everything from the school's curriculum to the design and architecture of classrooms to relations with the host city, Hereford in the UK. Here, some of that cohort visit a Heineken cider bottling plant to explore ways to reduce the amount of plastic in its bottling operations.

graduate and 37 graduate students to 8000 undergraduate and nearly 700 graduate students, and counting. Of the undergraduates, 65% are underrepresented minorities and 75% are first-generation college attendees.

Similarly, the University of Northern British Columbia (UNBC) in Prince George and the Singapore Institute of Technology (SIT) were created by their governments to meet demand. In the case of the now three-decades-old UNBC, the demand came from local communities, says past president George Iwama. "People were seeing their children migrate south and not returning. UNBC provided an opportunity to get an education closer to home. It also produced doctors and other much-needed professionals in the north." From 2014 to 2017 he was at OIST, and he is now president of Canada's only private, secular, not-for-profit liberal arts university, Quest University (see PHYSICS TODAY, June 2017, page 28).

An experimental undergraduate engineering school is set to open this fall in Hereford, UK. NMITE (New Model Institute for Technology and Engineering) is intended to boost the local economy and implement modern pedagogical approaches. Courses will be project based with heavy industry involvement. Students will take one course at a time. NMITE is taking the "bold step" of waiving the usual high school math and physics engineering prerequisites, says founding trustee Karen Usher. "We say if you have grit, curiosity, passion, and work hard, you can learn engineering." A new higher-education institution is not like a startup company, she says. "Everything has to be in place on day one. What do you do if a student gets sick? What are the learning outcomes of each course? The breadth and variety of requirements are rigorous."

The Singaporean government launched SIT in 2009 as part of its plan to achieve 40% university attendance and a diversified knowledge-based economy. SIT offers applied degree programs in such areas as nutrition, aircraft systems engineering, and information security. "One of our biggest concerns is that students get the right jobs," says Yong-Lim Foo, the university's assistant provost of applied learning. "The government holds us accountable if our employment data looks bad. So far it looks good."

At the start, low name recognition made recruiting students tough, says Foo. It was also a challenge to get companies on board. "We introduced compulsory internships, and it has taken time for industries to see themselves as part of the training process."

Ashesi University in Ghana is finding success by embodying some of the same ideas that work elsewhere, notably a limited course selection, training in entrepreneurship, and an interdisciplinary approach. It also introduced community service and a student-written honor code. US-educated Ghanaian Patrick Awuah founded the university in the country's capital, Accra, in 2002, with the conviction that "a liberal arts education is critical to forming true leaders, because it builds decision-making skills, an ethical framework, and a broad vision," as he says in a TED talk. "Ashesi" means "beginning" in the Akan language.

Obtaining accreditation for Ashesi "was a huge battle," says Suzanne Buchele, who stepped down as provost in 2018. "The venture was seen as a condemnation of existing universities." But, she says, the institution is gaining visibility. "In 2014 people had not heard of it. Now, if you get asked for a bribe at a police checkpoint and say 'we can't because we work at Ashesi,' they accept it." And these days, she adds, parents ask how they can get their kids in.

Challenges and incentives

In the 1990s and 2000s, American and European universities opened offshoots, mainly in Asia and the Middle East. Many of them failed, says Georgia Tech's Frost, who cited as a common cause the reluctance of the established partner to cede control. "Separating authority and accountability is a disaster. The best people to make decisions are the ones who live in the community every day. You need agility to adjust to local conditions." In some cases expectations were unrealistic. For example, the parent university may have wanted to make money and then pulled out if that didn't happen on the anticipated time scale.

Still, some partnership models have worked, and new universities continue to crop up. Fulbright University Vietnam opened its doors in Ho Chi Minh City last fall. The main objectives are to spread a western educational philosophy and "for Vietnam to compete on an international level," says Ryan Derby-Talbot, who until late last year was the university's chief academic officer. Seed money comes from the US; the sources are USAID and the Vietnam Debt Repayment Fund, created in a 1997 agreement between the US and Vietnam to repay Vietnam's wartime debts. Eventually the private, nonprofit university will have to rely on tuition. The

ASHESI UNIVERSITY

ASHESI UNIVERSITY IN GHANA graduated 167 students in 2019.

university is setting up career services for students. "That matters a lot in that part of the world," says Derby-Talbot.

A challenge with new institutions, says Derby-Talbot, who previously taught math at Quest University, is "mission drift." To be successful, an institution has to have a clear mission and stick to it. "Higher education in general is under pressure," he says. "It's helpful to send a message to the public that resonates, and to be known for what is important to the particular place."

New York University started NYU Abu Dhabi as an independent satellite campus in 2010. Joseph Gelfand and Ingyin Zaw were attracted by the pioneering spirit required of new faculty. Since they are a couple, it helped that they both landed jobs in the physics department. Until recently, faculty hires and promotions were approved by both the local and parent campus. After a while, "we no longer needed as much help," Gelfand says, "and in some cases—though not physics—the home department wanted to shed the extra work." The campus adheres to NYU standards and answers to the NYU provost, he adds.

Denis Simon is executive vice chancellor of Duke Kunshan University, just west of Shanghai, China. The university is one of nine institutions started jointly by a Chinese university and a foreign one between 2004 and 2017 with the aim of internationalizing the country's higher education system. "These are pilot experiments in an attempt to produce world-class universities," says Simon. "The idea is to see what kinds of pedagogical approaches work best here." Duke Kunshan opened its doors in 2013. Students earn degrees from both Duke and Duke Kunshan universities; the Duke degree is accredited by the same organization as at Duke University in North Carolina. Simon says it's easier to recruit faculty in the humanities and social sciences because "many of them are interested in China or Asia," but in science and math, faculty sometimes "have to be incentivized to come." He lists as incentives superb infrastructure, research support, and high-caliber students.

Among the challenges, Simon says, is learning to simultaneously uphold US principles and be respectful of Chinese customs and regulations. "We are trying to get our students to think critically and to challenge their instructors; this is not always easy in a society where respect for teachers is a core value." Another example is cross-cultural integration of the three communities on campus: Chinese, American, and others. "That requires constant attention and nurturing."

For institutions that recruit internationally, language and cultural differences can challenge faculty and students. OIST researchers benefit from the 2009 decision in Japan to accept grant applications in English. At KAUST, the foreigners and many of the Saudis live in an onsite enclave. For some, human rights, political issues, and the country's links to terrorism can be tough to square with the university's vibrant research environment. Isolation is a challenge at many of the new campuses, whether because of a time difference, far-flung location, or other reasons. "If you like living in big cities, Merced doesn't have as much to offer," says Gopinathan. But his campus, KAUST, and others got a leg up in hiring during the global recession. And, says Gopinathan, the UC Merced physics department has a high faculty retention record.

Toni Feder

Take your pick: A new warhead or a "new program of record"

Administration officials say a proposed new weapon for the US Navy won't require nuclear testing.

The Trump administration announced in February that it was initiating a program to develop the first new nuclear warhead since the late 1980s. That action reversed the Obama administration's policy to neither develop new nuclear weapons nor enhance the military capabilities of existing weapons systems. But the W93, as the warhead is called, won't be entirely new: Its nuclear explosive package will be borrowed from an existing weapons system.

The W93 was unveiled as a line in the Department of Energy's fiscal year 2021 budget request for the National Nuclear Security Administration (NNSA). DOE is asking for a stunning increase of 25%, or $3.1 billion, for the agency's nuclear weapons programs, to a level of $15.6 billion. The $53 million included for the W93 will support conceptual studies of potential warhead architectures and system requirements, the first stage of a seven-step process that has been followed in the past for new warhead development. Although the W93 isn't scheduled to enter the nuclear arsenal until 2034, NNSA budget documents show its out-year costs ballooning to $1.1 billion in FY 2025.

NNSA administrator Lisa Gordon-Hagerty and Charles Richard, the commander of the Defense Department's Strategic Command, shared few details of the W93 in recent open congressional testimony. At a 27 February hearing before the strategic forces subcommittee of the House Armed Services Committee, Richard repeatedly refused to call the W93 a warhead, referring to it instead as a "new program of record." He said the W93 will be a payload for a new missile to be carried aboard *Columbia*-class ballistic missile submarines. The new subs are scheduled to begin replacing the US Navy's fleet of *Ohio*-class SSBNs in 2031. (The navy denotes a class of ships by the name of the first one to enter service.)

The two officials insisted the W93 will use an existing nuclear explosive package and thus won't need nuclear testing before deployment. Many experts have said that a warhead built with new nuclear components would have to be tested underground before it's approved for deployment. The US has observed a moratorium on nuclear tests since 1992.

Today, two warhead types top submarine-launched Trident II D5 missiles. The W76, the more numerous of the two, underwent a life extension that was completed last year. It is now designated W76-1. The W88, the higher-yield but less plentiful warhead, underwent a modernization that was delayed a year after a faulty capacitor was discovered. The first refurbished W88 is slated for delivery to the navy later this year. Because the changes made to it will be less extensive than those of a full life extension, the updated warhead will retain its original designation. In the parlance of US nuclear weapons, a warhead's number denotes approximately the year that the first one

DEPARTMENT OF DEFENSE

A RENDERING OF A *COLUMBIA*-CLASS BALLISTIC MISSILE SUBMARINE (SSBN), which will carry ballistic missiles to be armed with the W93 warhead. The boats will replace the existing *Ohio*-class SSBN fleet. The first *Columbia*-class sub is scheduled to begin patrols in 2031.

enters the stockpile. It isn't clear why the W93 will depart from that tradition.

Richard said the W93 would "address an imbalance in a strategic leg" of the so-called nuclear triad of delivery systems: land-based missiles, submarine-launched ballistic missiles (SLBMs), and aircraft. The warhead will "wind up initially being a third [SLBM] warhead." He said the W93 could replace the W76-1, the W88, or both, or it could become a third SLBM system alongside the other two. But a senior defense official told reporters in a briefing last month that the W93 will replace the W88.

"We have an opportunity to address the imbalance between the W76-1s and the W88s," Richard noted, in an apparent reference to the much higher yield of the W88—an estimated 455 kilotons, compared with the W76-1's 90 kilotons. The W93 will not add to the stockpile. According to the NUKEMAP simulator built by Alex Wellerstein of Stevens Institute of Technology in Hoboken, New Jersey, a W88 detonated above a city would vaporize everything within a radius of 0.7 km and collapse most residential buildings within a radius of 5.4 km. The corresponding radii for the smaller W76-1 are 0.5 km and 3.3 km.

New security features

One likely improvement in the new warhead, experts say, is the use of insensitive high explosive (IHE), which is much less likely to detonate in a fire or other accident and disperse plutonium and other nuclear materials. Unlike the majority of US weapons, the submarine warheads contain more volatile conventional high explosive. The decision to eschew the use of IHE was made at the height of the Cold War, when nuclear war planners called for packing eight warheads on each D5. That wouldn't have been possible with the less energetic IHE because of the greater volume of the material required. Today four or five warheads are carried on each missile, which provides room for bulkier designs.

Gordon-Hagerty said the W93 will incorporate modern technologies to improve safety, security, and flexibility to address future threats and will be designed for ease of manufacturing, maintenance, and certification.

Hans Kristensen, a nuclear weapons expert at the Federation of American Scientists, says a variable, "dial-a-yield" option might be added. The B-61 bomb, some of which are deployed in NATO countries, offers such a range of yields, as does the W80 warhead for the air-launched cruise missile. Controlling the yield can be accomplished by deactivating the weapon's fusion–fission secondary stage, which produces the most destructive blast, or by varying the amount of tritium–deuterium gas used to boost fission in the primary.

Since 9/11, the NNSA has been upgrading safety and security features as each warhead system undergoes refurbishment, with a goal to prevent a warhead's use if one should get into terrorist hands. All warheads have been certified to be one-point safe, meaning that a detonation of their high-explosive component at a single point, whether by a bullet or some other method, can't produce a nuclear yield. According to Kristensen, the weapons labs have been striving for two-point safety. Although extremely improbable, in theory a precisely timed detonation at two exact points might result in an implosion that produces a nuclear yield.

Other safety and security features that could be added to a new weapon include improved self-destruct systems, lightning arresters, and optical firing systems. The labs had hoped to introduce optical firing to the B-61 gravity bomb as part of a life extension that is now underway, but officials concluded the technology wasn't ready to meet the production schedule, Kristensen says.

DOE has not yet determined which of the two national weapons design labs, Los Alamos or Lawrence Livermore, will be responsible for developing the W93, Los Alamos director Thomas Mason told reporters in February. In the past, one or the other lab has been given responsibility for birthing a specific weapons system. The other lab reviews the design process.

At the 27 February hearing, Richard warned that US weapons upgrades can't be delayed: "The entire triad is reaching the end of its useful life. Either we replace what we have now or we start to divest almost on a path to disarmament." Russia and China are developing new weapons systems, he said, and although "Russia will tell you exactly what they're doing and why, China does not."

There were some inconsistencies in Richard's and Gordon-Hagerty's testimonies. The NNSA administrator said the refurbishment of the submarine warheads will extend their lives by 30 years or more. But Richard said the W76-1 and W88 life extensions were "modest" and didn't alter their nuclear components. "If you want to replace those weapons or life-extend them in the 2030s, based on historical timelines, we need to start now," he said.

Richard blamed a lack of new pits for limiting the extent of refurbishments. (The pit is the plutonium core of the primary stage of nuclear warheads.) He told lawmakers that pits to be built at Los Alamos beginning in 2023 will be used to "refurbish the entire stockpile." DOE budget documents, however, show that all 141 pits that the NNSA plans to build through 2030 are earmarked for a replacement warhead series for Minuteman III intercontinental ballistic missiles. Designated W87-1, it will replace the W78 that tops most ICBMs today (see PHYSICS TODAY, February 2020, page 23). The NNSA proposes to establish additional pit production at its Savannah River Site and increase total output at the two sites to 80 pits per year post 2030.

A very full plate

At a 4 March hearing of the House Appropriations energy and water development subcommittee, Gordon-Hagerty said that the multibillion-dollar increase proposed for NNSA weapons activities in FY 2021 is essential to carrying out life extensions of four warhead types as the agency rebuilds its crumbling infrastructure, 30% of which dates to the Manhattan Project. In addition to the W88, W87-1, B-61, and W93 programs, the agency is in the throes of planning a modification to the W80 air-launched cruise missile. The US Air Force is procuring a replacement cruise missile that it calls the long-range standoff weapon.

During the hearing, chair Marcy Kaptur (D-OH) called the $15.6 billion request "unrealistic" and questioned the NNSA's capacity to spend it. Last year the NNSA projected a need for $12.8 billion in FY 2021, Kaptur said, and noted that as of last October, the agency had accumulated $8 billion in unspent funding from previous years. "This request is simply sprinting toward failure," she said. "We need to give NNSA more breathing room before it falls off the cliff."

Gordon-Hagerty insisted that the NNSA is up to the task. "We're to the point of throwing good money after bad" with regard to the weapons complex infrastructure, she said. "Yes, we are seeking to do things in 10 years that would traditionally take 15."

Gordon-Hagerty didn't respond directly when asked why the NNSA had moved up initiation of the W93 program from its previously planned date of 2023. Until this year the W93 was referred to in planning documents as the next navy warhead.

Stephen Young, a nuclear expert with the Union of Concerned Scientists, believes the military wants to ensure the new warhead program is formally established while President Trump is in office. "A Democratic president would be less inclined to support it," Young says.

Kristensen says the NNSA has too much on its plate. "Everybody not in an official position says they are already overstretched in their ability to manage all of their life extensions. And here comes Trump and throws a bunch of extra systems and work onto the pile."

David Kramer PT

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Reading through others' work can inspire new directions in my own work, even if it is relatively unrelated to my research.

Physics Today exposes me to ideas outside of my specialty. It has led to some interesting applications of ideas that have resulted in new research.

PHYSICS TODAY

Figures and quotes obtained from a *Physics Today* reader survey.

Vladimir Shiltsev is a Distinguished Scientist and researcher in the accelerator division at Fermi National Accelerator Laboratory in Batavia, Illinois. He led the Tevatron collider department and the Fermilab Accelerator Physics Center from 2001 to 2018 and was chair of the American Physical Society's division of physics of beams in 2018.

Particle beams behind physics discoveries

Vladimir Shiltsev

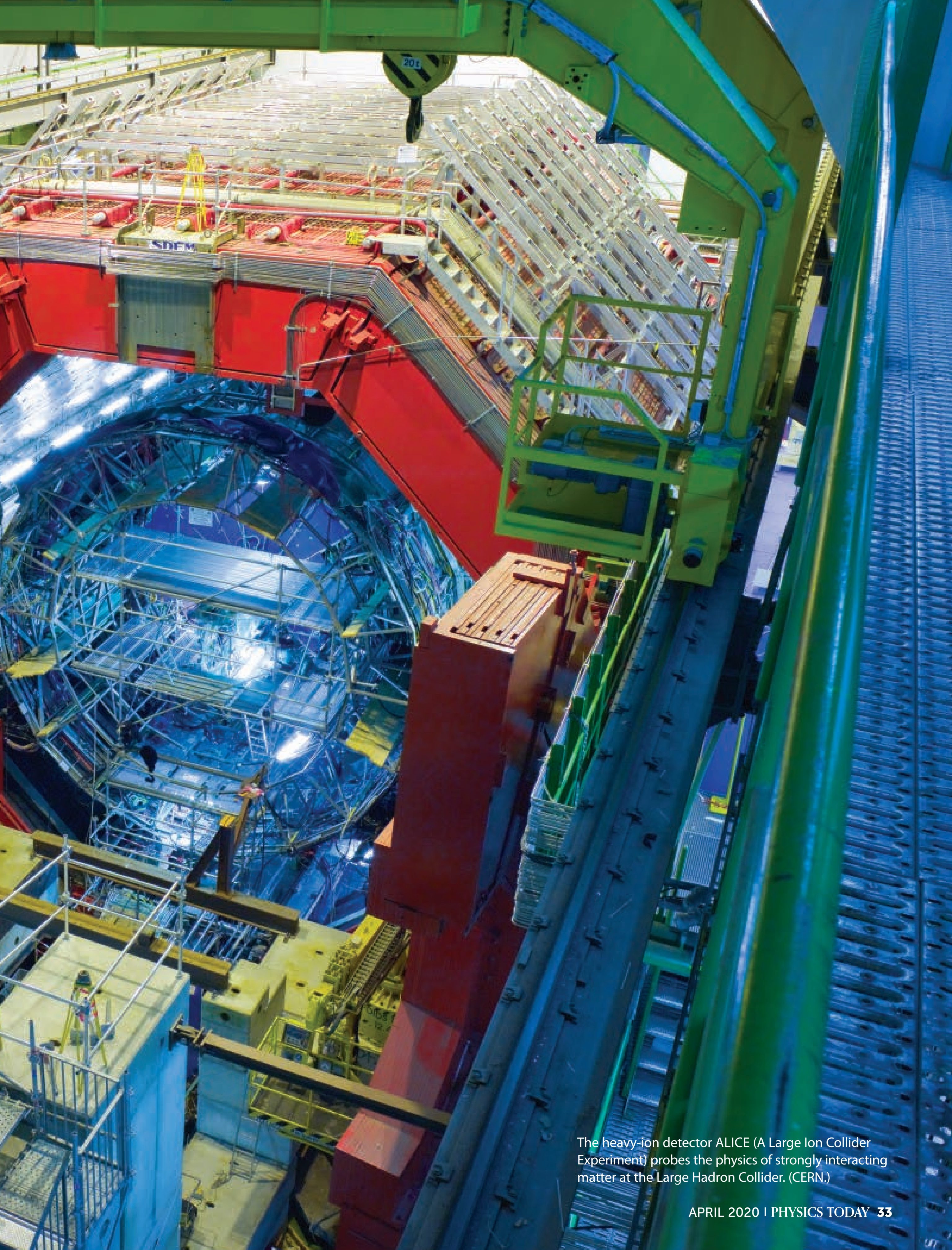
Advances in accelerator technology are enabling discoveries in particle physics and other fields.

A team of accelerator physicists came to the CERN Control Center, shown in figure 1, on the night of 30 June 2017. Some members came from departments and groups throughout CERN; others, like me, even came from across the ocean. Our aim was to test a new collimation idea for the Large Hadron Collider (LHC) beam that would be critical for the future of the world's most powerful accelerator. An eight-hour shift was scheduled for beam-physics studies. As is often the case at large accelerator facilities, beam physicists get full control of their machines overnight to minimize the inconvenience to users and high-energy physicists and to avoid numerous daytime distractions.

One night in the life of an accelerator physicist

We were scheduled to get beam access at 10:00pm, but due to last-minute problems with the collider's cryogenics, we had to wait until well beyond midnight. Stefano Redaelli, head of the LHC collimation group and my close long-term collaborator, had been planning the night's study for months. He and I repeatedly reviewed the detailed step-by-step procedures of the study over several cups of coffee from the control center's famously great espresso machine.

The LHC has more than a hundred collimators—1.2-m-long fiber-reinforced graphite plates—to intercept stray protons.[1] They protect the machine's 8 T superconducting magnets and other sensitive equipment from damage by any of the central beam's 6.5 TeV protons that get kicked away from their orbit. That happens when protons collide with either residual gas molecules inside the high-vacuum beam pipe or the opposite-direction proton



The heavy-ion detector ALICE (A Large Ion Collider Experiment) probes the physics of strongly interacting matter at the Large Hadron Collider. (CERN.)

MAXIMILIEN BRICE/CERN

FIGURE 1. THE CERN CONTROL CENTER is made up of four "islands" in one big room. Each island has a circular arrangement of consoles and displays. They control the Large Hadron Collider (above), the Proton Synchrotron and Super Proton Synchrotron in the collider injection chain, and the technical infrastructure of the CERN accelerator complex.

beam at an interaction point inside one of the massive particle detectors.

The collimator jaws are the closest objects to the 500 MJ 0.2-mm-diameter beams; they come within just a few millimeters of each other. Although the graphite jaws are very robust—they can absorb the power from the stray beam and survive—their electrical conductivity is relatively low, which means that acquired charge can't easily dissipate. After its next major upgrade, the LHC will produce much higher beam currents, and graphite collimators, if not modified, would lead to unstable transverse oscillations of the proton beams. The night's plan was to test a new type of collimator that would mitigate the issue by covering the graphite surface with a 5-μm-thick layer of much-higher-conductivity material. We had prepared three 10-mm-wide parallel strips of molybdenum carbide, titanium nitride, and pure molybdenum. By placing the LHC beam next to each strip in turn, we expected to see up to threefold improvement in the beam stability.

As soon as we got the beams from the LHC injectors, we slowly accelerated them for more than 20 minutes until they reached the operational energy of 6.5 TeV. Then the fun began. In a controlled fashion, we moved the proton beams toward and away from each strip in an attempt to observe changes in the frequency of the beams' transverse oscillations. We established the best procedures relatively quickly and began the planned tests. By about 5:00am we were done, and the next team of accelerator physicists started to appear in preparation for their beam time, which was scheduled to start at 6:00am. We reviewed the preliminary results of our measurements with delight: The effect was within 10–15% of what was anticipated, and the beam was most stable near the pure Mo strip, which had the best conductivity.

I left Geneva on a 7:00am flight to Chicago. Over the next several months, the data we collected were analyzed, compared with computer models, presented at a major international conference, and published. Most importantly, our approach was found to be viable, and Mo-coated collimators were approved as part of the billion-dollar High-Luminosity LHC (HL-LHC) project scheduled for implementation by 2026.

Innovation leads to improvement

The LHC is the most complex scientific instrument of our time, but its life cycle is the same as that of previous frontier machines (see figure 2). They all were designed, constructed, and commissioned, and then they underwent many years of incremental improvements in luminosity. The early and middle years of a facility's life are dominated by the quest for ever higher luminosity and are often characterized by a repeating cycle of problems and solutions. The Tevatron proton–antiproton collider at Fermilab had the longest tenure at the energy frontier of particle physics, from October 1985 to September 2011. More than 40 improvements in beam physics and technology during that time enabled the Tevatron's peak luminosity to reach 430 times its original design value.[2] A few of the improvements resulted in gains of as much as 25–40%, although many added as little as 5%.

Many upgrades can be done during operation and usually at a limited cost to the physics program. More significant gains, like the factor-of-three increase in the LHC's performance expected during the forthcoming HL-LHC era, require years of preparation and hardware installation to either increase beam currents, tighten the beam's focus at interaction points, or both. Notably, there are remarkably long periods of sustainable exponential growth in luminosity L, indicated by near-linear segments of data seen in figure 2. The performance of energy-frontier colliders has increased by a factor of 10^4 from the 1970s until now with an average doubling time $\tau_L = dt/d\log_2(L)$ of approximately 4 years. For comparison, Moore's law says that the number of transistors per microprocessor chip should double every two years. Given the complexity and size of modern accelerators, such a fast pace is astounding.

Beam physicists are the people who make that increase happen. In addition to supporting constant accelerator operation, they continuously invent and implement new ideas and methods while also improving existing ones. In the 21st century alone, beam physicists have developed a dozen advanced tools for high-energy hadron and electron–positron colliders, some with strange-sounding names like "crab waist," "electron lenses," "nanobeams," and "crab cavities."

Beyond particle physics, accelerators are major tools for basic and applied research worldwide (see the box on page 35). They generate electromagnetic radiation from terahertz waves to x rays by moving high-energy electrons in magnetic fields. The ability of an x-ray source to probe molecules' atomic structures for biology and materials research scales with its brilliance, which embodies not only the photon flux but also the beam's collimation.[3] Brilliant beams are intense and tight. Figure 3 shows how the brilliance of radiation sources has increased over time. Modern synchrotron light sources are 10^{11} times brighter than those used to generate x rays in hospitals, and free-electron lasers offer an additional 10-orders-of-magnitude increase in brilliance. The increase by a factor of about 10^{22} from the mid 1960s to the present gives the average doubling time of about eight months—three times as fast as for transistors and six times as fast as the luminosity of colliders.

The origin of that dramatic improvement is the sustained evolution of technology for producing radiation from moving electrons. First- and second-generation synchrotron radiation sources used the by-product light from electron ring accelerators. However, in the past two decades, some 40 dedicated third-generation facilities known as storage rings have been built worldwide with the deliberate purpose of generating high-brilliance x rays. They use specially designed insertion devices called undulators that shake the beam to increase the emission of electromagnetic radiation and can simultaneously deliver x-ray beams to many, often several dozen, experimental stations.[4]

A radiation source's brilliance can be increased by the optimal design of its underlying technology: the electron beam in the storage ring. In the past decade, beam physicists have developed numerous improvements, such as cutting-edge superconducting undulator magnets and advanced systems to stabilize beam orbits down to as small as a few nanometers. One impressive recent invention is the so-called multibend achromat focusing lattice, which optimizes the arrangement and strengths of the dipole, quadrupole, and sextupole magnets used to guide a beam. The lattice can make electron-beam sizes and angular divergences so small that the phase space of radiated photons is limited only by diffraction. That upgrade increases the brilliance of fourth-generation sources, also known as diffraction-limited storage rings, by two to three orders of magnitude over the previous generation.

The most recent revolution in radiation production has been the self-amplified spontaneous emission in linear-accelerator-

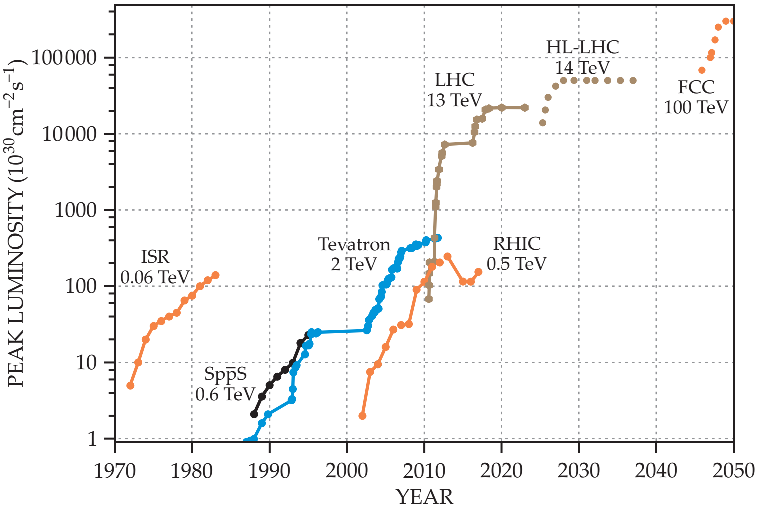


FIGURE 2. A COLLIDER'S LUMINOSITY quantifies its ability to generate new particles via high-energy collisions. The production rate for a particle of interest is the product of the beam luminosity and the cross section for the desired reaction. Producing high luminosity generally requires high-intensity beams to be compressed so they collide with the smallest possible overlap area. For reference, at the Large Hadron Collider's 2019 luminosity, about one Higgs particle is born every second when two 6.5 TeV proton beams collide inside the ATLAS and CMS detectors (see the article by Joe Lykken and Maria Spiropulu, Physics Today, December 2013, page 28). All luminosities shown are for proton–proton and proton–antiproton colliders. (Courtesy of Vladimir Shiltsev.)

THE INFLUENCE OF ACCELERATOR SCIENCE ON BASIC RESEARCH

In 2011 SLAC researchers Enzo Haussecker and Alexander Chao set out to evaluate accelerator science's impact on the physics community.[12] They analyzed all of the Nobel Prize–winning research in physics from 1939—the year Ernest Lawrence received his for inventing the first modern accelerator, the cyclotron—until 2009. Updating the numbers to account for the 2010–18 awards does not change their main conclusion: Accelerator science has been integral to physics research. It inspired or facilitated work by 25% of physicists working between 1939 and 2018; on average, accelerator science contributed to a physics Nobel Prize every three years. Two more prizes for accelerator science were awarded after Lawrence's in 1939: John Cockcroft and Ernest Walton won in 1951 for inventing the linear accelerator, and half of the 1984 prize went to Simon van der Meer for developing the method of stochastic cooling. Several other developments are widely recognized as Nobel caliber. One is the 1952 discovery of the principle of strong focusing, in which a beam of charged particles passes through alternating magnetic field gradients and converges. It is now used in the majority of accelerators. Another is the invention of free-electron lasers, and particularly self-amplified spontaneous emission FELs, which revolutionized x-ray-based research.

Accelerator-based synchrotron radiation sources have also been instrumental to the work of several scientists who were awarded a Nobel Prize in Chemistry: John Walker in 1997 for revealing the structure of F1-ATPase, Roderick MacKinnon in 2003 for demonstrating the structure of cellular ion channels, Roger Kornberg in 2006 for determining the structure of RNA polymerase, Ada Yonath in 2009 for discovering the structure and function of the ribosome, and Brian Kobilka and Robert Lefkowitz in 2012 for studying G-protein-coupled receptors.

The US Department of Energy's Office of Science is a major supporter of 28 user facilities for basic research; for more information see www.science.osti.gov/user-facilities. Of those facilities, 16 are accelerators—colliders, light sources, and neutron sources. The annual budget for their operation and construction exceeds $2 billion. They support about 20 000 users from academia, industry, and government laboratories. Some 400 scientists and students carry out beam-physics research at a dozen dedicated accelerator R&D facilities.

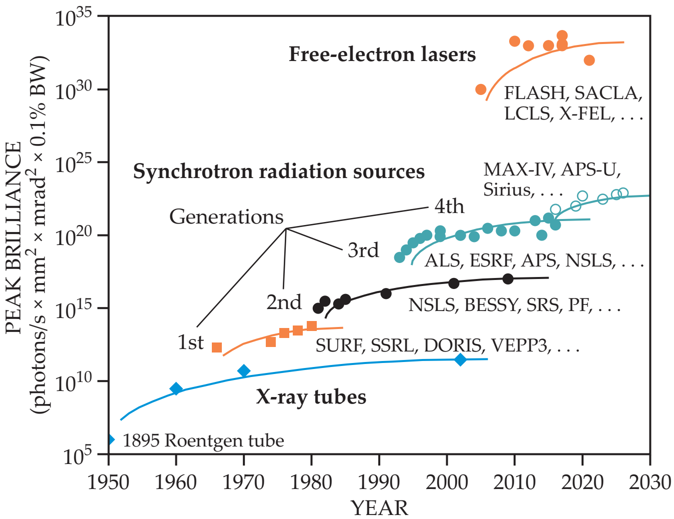


FIGURE 3. THE PEAK BRILLIANCE OF VACUUM-UV AND X-RAY SOURCES has grown tremendously since Wilhelm Roentgen's discovery of x rays in 1895. Electron storage rings are centerpieces of the first-, second-, third-, and fourth-generation synchrotron radiation sources. High-current electron linear accelerators drive free-electron lasers. (Adapted from ref. 10.)

driven x-ray free-electron lasers. The lasers' higher brilliance relative to the storage-ring-based sources is due to their extremely short and intense light pulses, which are generated by a small, relativistic electron beam passing through an alternating magnetic field in a long undulator array and coherently pumping its own radiation. Proposals are under consideration for high-efficiency x-ray sources based on energy-recovery linear accelerators, or linacs. Those sources would combine the advantages of both ring- and linac-based schemes.

Secondary particles can be generated in abundance when high-energy beams hit solid or liquid targets. Those particles can subsequently be used in such applications as muon spectroscopy, neutrino physics, and neutron scattering. A secondary particle beam comes from either a linac, cyclotron, or synchrotron, and its intensity is proportional to the power of the primary beam. Over the past decades, scientists have been able to increase that power by about three orders of magnitude (see figure 4) by improving technology and addressing problems with beam pulse structures, beam losses, and the lifetimes of beam targets.

Technology push

The mid 20th century saw a burst of accelerator construction because accelerators could finally produce beams with energies per particle exceeding those of nuclear reactions and lasers by many orders of magnitude.[5] Even so, over the past 50 years the record-high beam energy has advanced at a slower pace than total beam power, luminosity, and peak brilliance. The energy frontier progressed from about 60 GeV at CERN's Intersecting Storage Rings accelerator in the early 1970s to 13 TeV at the LHC in 2019, for a doubling time of approximately 6 years. The main cause of high-energy accelerators' relatively slow progress is their cost, which depends strongly on their core technologies. Figure 5 shows the present snapshot of the "accelerator menu."

The cost and affordability of accelerators accounts for the spectrum of their types: 99% of the more than 30 000 accelerators in operation worldwide are relatively small with low beam energies. They are used for commercial production of radionuclides and radiopharmaceuticals, ion implantation, energy and environmental applications, neutron generation, lithography, studies of material interfaces, and other production issues in the semiconductor industry. (See the article by Robert Hamm and Marianne Hamm, PHYSICS TODAY, June 2011, page 46.) Even research facilities have more x-ray and light sources—about 60 worldwide—than particle colliders, of which there are only 7. Just two have energies over 100 GeV, the Relativistic Heavy Ion Collider at Brookhaven National Laboratory and the LHC at CERN.

Frontier particle accelerators often cost more than $1 billion, and the aspirations of high-energy-particle physicists require even larger facilities estimated to cost 10 times that. Such expenses become nonnegligible on the scales of national economies. All kinds of measures are taken to cut costs, including reuse of existing accelerators as injectors for new ones, other utilization of existing infrastructure, and burden sharing among several laboratories or countries, as with CERN. Major opportunities for new facilities come from better technological performance, reduction of cost, or, ideally, both.

Current core technologies employ normal and superconducting magnets and normal and superconducting RF cavities to accelerate particles (see figure 6). The magnets either focus or bend beams in circular accelerators, and the time-varying electric fields in RF cavities accelerate the charged particles. Tunnels, electrical infrastructure, and facilities' other technical subsystems can be quite expensive; however, the cost of core accelerator components, magnets, and RF structures usually dominates construction costs for high-energy and high-power accelerators. Over the past quarter century, the accelerator community has successfully worked to bring those costs down. Peak magnetic fields in operational accelerators grew from

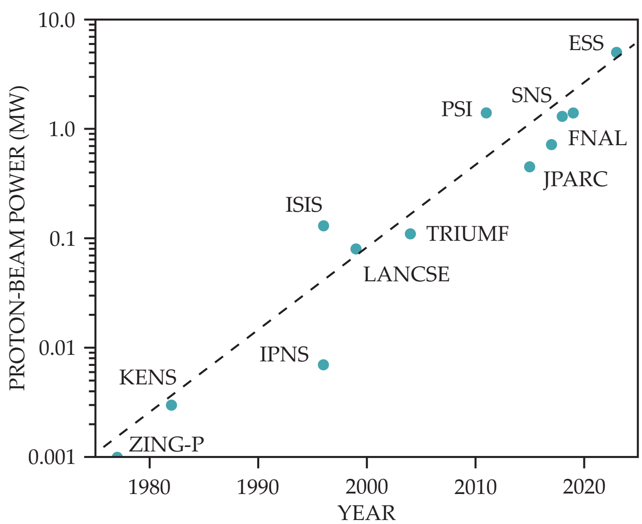


FIGURE 4. BEAM POWER IN LEADING PROTON ACCELERATORS has increased dramatically over the past few decades. The dashed line corresponds to the doubling time of about four years. (Adapted from ref. 11.)

about 4 T to 12 T. Accelerating electric gradients have reached record highs, increasing by a factor of three or so to more than 30 MV/m in superconducting RF cavities and to more than 100 MV/m in normal-conducting RF structures. Without improvements in magnet and RF technologies, costs would have grown linearly with beam energy E; instead, the costs of modern facilities[6] have grown approximately as $\sqrt{E}$. Still, the growing demand for higher-energy beams has outpaced the progress of traditional accelerator technologies, so researchers continue to pursue new ideas and technological advances.

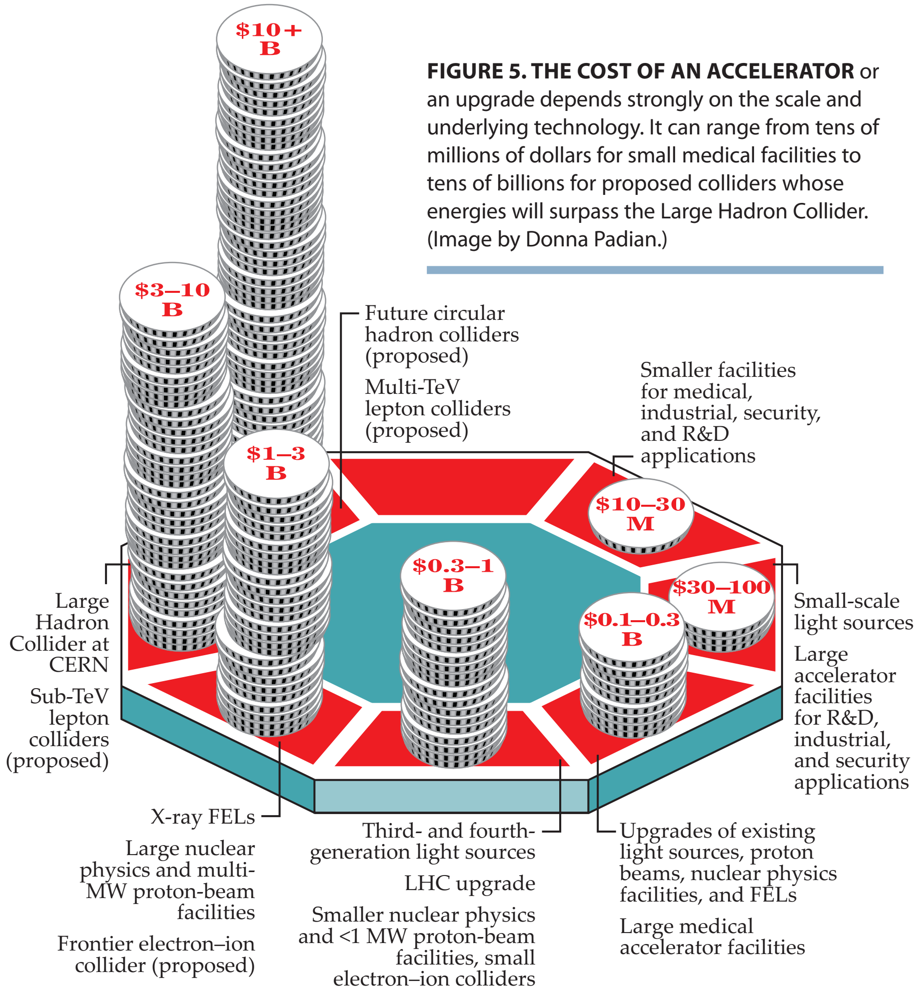


FIGURE 5. THE COST OF AN ACCELERATOR or an upgrade depends strongly on the scale and underlying technology. It can range from tens of millions of dollars for small medical facilities to tens of billions for proposed colliders whose energies will surpass the Large Hadron Collider. (Image by Donna Padian.)

Beams as science

Today, around 4500 accelerator scientists and engineers work in more than 50 countries. They collaborate with a pool of approximately three times as many technical experts. Although most of us are deeply involved in operations and ongoing upgrades, the career of an accelerator scientist also includes design and construction of new facilities, beam-physics research, development of critical technical components, and project leadership. It also often involves technology transfer, industrial applications, education and training of the next generation of accelerator experts, and outreach to both the public and academia.

Over the past 20 years, the science of beams has evolved into a distinct discipline with its own subject matter and methods of study, a series of annual International Particle Accelerator Conferences with a typical attendance of about 1500, almost two dozen other regularly held conferences and workshops on topics ranging from computer modeling to accelerator technologies, and dedicated peer-reviewed journals—the leading one, *Physical Review Accelerators and Beams*, reached its 20-year anniversary in 2018.

Several thousand people, including nearly 1400 in Europe and approximately 400 in the US, receive some training in accelerator and beam physics annually.[7] About 40 academic programs at universities worldwide, including a dozen each in the US and Europe, provide that training. However, education for accelerator physicists and engineers also includes on-the-job training supplemented with intensive courses at numerous locations, through programs such as the US Particle Accelerator School and the CERN Accelerator School. Approximately 100 PhDs are awarded each year globally in accelerator and beam physics.

Accelerator scientists are well represented in many scientific societies, councils, and groups worldwide. The International Union of Pure and Applied Physics Working Group 14 has been promoting the exchange of information and views among the members of the accelerators and beams community since 2015, and the International Committee for Future Accelerators has been facilitating collaboration on the construction and use of high-energy accelerators since 1976.

In the US, funding for accelerator science and technology totals approximately $120 million per year from the Department of Energy's Office of Science—which includes programs for high-energy physics, basic energy sciences, and nuclear physics—and from NSF. The high-energy-physics program is by far the largest sponsor, with about 5% of its annual budget going to general accelerator R&D. Large, dedicated beam-research facilities are hosted by major national laboratories, including Fermilab, SLAC, Lawrence Berkeley, Argonne, and Brookhaven, and several universities, including Cornell, UCLA, the University of Michigan, and the University of Maryland. Those facilities play pivotal roles in the progress of accelerator science.

The biggest challenge for us accelerator physicists is developing energy-frontier beams. If we were to use current technology, however, the cost of constructing colliders with substantially higher energy would be prohibitive. We're unlikely to find the money, or find a site where labor, land, and raw materials are cheap, to pursue that route.

Instead, we are exploring several avenues for development. One approach is using traditional superconducting magnets and RF cavities to accelerate nontraditional particles—namely, muons. Unlike protons, which share energy between constituent quarks and gluons, muons are point-like particles that effectively deliver their entire energy to the collision. The center-of-mass energy in muon–muon collisions will be 6–10 times that in proton–proton collisions at the same beam energy, so a 14 TeV muon collider would be approximately equivalent to a 100 TeV hadron collider. Circular electron–positron colliders at

EUROPEAN SYNCHROTRON RADIATION FACILITY FERMILAB

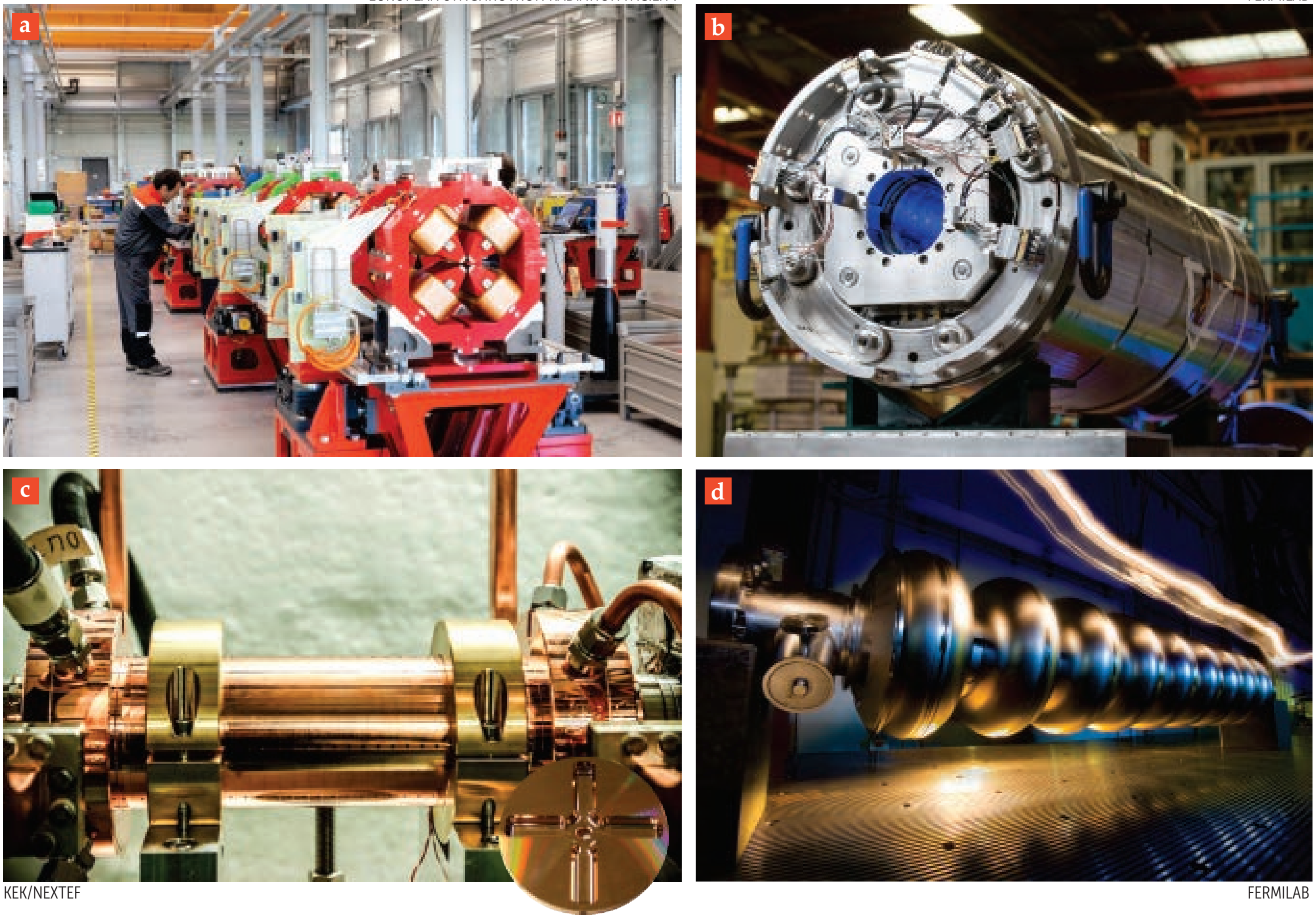


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FIGURE 6. STATE-OF-THE-ART CORE ACCELERATOR TECHNOLOGIES enable scientists to control beams. **(a)** Sophisticated normal-conducting magnets for the European Synchrotron Radiation Facility's multibend achromat upgrade include combined-function dipoles with quadrupolar components to simultaneously bend and focus the electron beam. Quadrupoles, sextupoles, and octupoles control the beam's size and other properties. **(b)** A 12 T superconducting large-bore niobium–tin quadrupole magnet, shown on a test stand at Fermilab, is a prototype for the High-Luminosity Large Hadron Collider upgrade. **(c)** A 12 GHz conducting copper RF cavity, shown at the KEK accelerator research facility in Japan, was developed for the CERN Compact Linear Collider project; the inset shows one damped accelerating cell. **(d)** A superconducting 1.3 GHz accelerating structure with nine cell cavities was developed for the International Linear Collider. It produces a 31.5 MeV/m beam-accelerating gradient.

such energies are impractical because they would lose tremendous energy as synchrotron radiation, but much heavier muons avoid that problem. Researchers have been developing that strategy for the past 20 years (see the article by Andrew Sessler, PHYSICS TODAY, March 1998, page 48) and have now proved the conceptual feasibility of an energy-frontier muon collider. One necessary advance—ionization cooling of the initially dispersed muons—was experimentally demonstrated in 2019. Still, many formidable challenges remain before we can definitively assess the technical and cost feasibility of such a collider; most of those challenges involve the effective and economical production of high-brightness muon beams.

Continuing to improve existing technologies is a less revolutionary approach, but it also has some promise. Assuming that next-generation energy-frontier beams are 15–20 years away and the rate of progress will not slow down, doubling or even tripling current energy records seems possible. Many ideas already exist for achieving 20–24 T magnetic fields with high-temperature superconductors and reaching 60–90 MV/m accelerating gradients with superconducting RF cavities. Experimental proof-of-principle demonstrations of such techniques must be undertaken to establish their potential to make future machines feasible and affordable. Long-standing collaborations with the solid-state physics and industrial technologies communities will greatly help with those developments.

One of the biggest advances may come from the novel technology of particle acceleration by plasma waves, which are excited by either lasers or particle beams. The field has advanced and expanded in the past two and a half decades with the influx of methods and ideas from plasma and laser scientists;[8] Gérard Mourou and Donna Strickland were awarded the 2018 Nobel Prize in Physics for related work (see PHYSICS TODAY, December 2018, page 18). The total electron energy gain in a 1-m-long plasma cell has progressed from a few MeV to 9 GeV with an energy-doubling time of about 2.5 years.[9]

At the same time, researchers have developed a better understanding of what would be required to build a collider based on plasma acceleration (see the article by Wim Leemans and Eric Esarey, PHYSICS TODAY, March 2009, page 44). The current focus of plasma acceleration R&D is less on developing record-breaking accelerating gradients and more on addressing mundane but critical issues such as energy-transfer efficiency, multistage acceleration, preservation of high brightness and energy in electron and positron beams traveling through dense plasmas, and cost-efficient drivers for plasma waves. We have not yet devised a reliable technical design for an affordable high-luminosity, multi-TeV electron–positron plasma wakefield collider. However, there is reason for optimism: More than a dozen research groups are building and operating test facilities to systematically explore various options and regimes.

The bottom line

For the January 2001 issue of PHYSICS TODAY (page 36), Maury Tigner, a foundational and pivotal figure in modern accelerator physics, wrote an article entitled "Does accelerator-based particle physics have a future?" He made many observations remarkably close to those outlined above and called on other scientists, particularly particle physicists, to help explore new ideas and improve the cost-effectiveness of our accelerators.

The answer to Tigner's question was and is resoundingly yes. Beam physics has evolved into a scientific discipline of its own, and the accelerator community has developed outstanding advances such as fourth-generation synchrotron light sources, x-ray free-electron lasers, and megawatt-power proton-beam facilities like spallation neutron and neutrino sources. World records have been set as the performance metrics of major accelerator technologies have doubled or tripled. Improvement of the maximum beam energy has been less dramatic, but the LHC expanded that frontier by a factor of seven and facilitated the discovery of the Higgs boson—the last missing piece of the standard model—in 2012 (see PHYSICS TODAY, September 2012, page 12).

Many advances, breakthroughs, and discoveries lie ahead. The push for improved methods of particle acceleration continues in several directions, including the use of exotic particles like muons, more advanced magnets and RF cavities, and compact high-gradient plasma accelerators. Applications of advances in solid-state physics, lasers, plasmas, and high-energy physics are being explored through collaborations with experts in those disciplines. Accelerator and beam physicists expect that developments currently underway will lead to more effective and economical beam-based research facilities in the coming decades.

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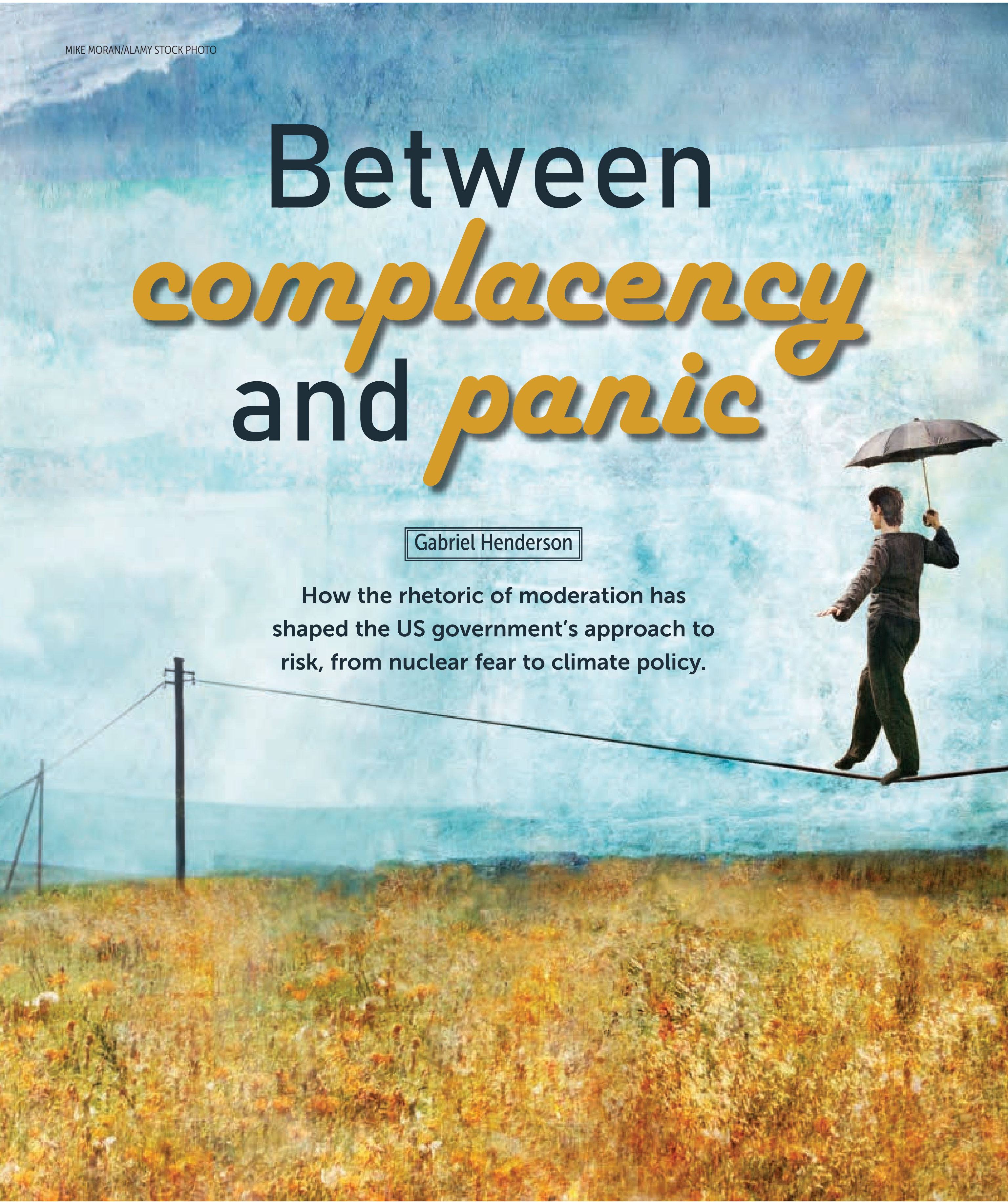


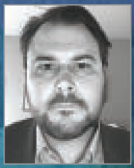
MIKE MORAN/ALAMY STOCK PHOTO

Between *complacency* and *panic*

Gabriel Henderson

How the rhetoric of moderation has shaped the US government's approach to risk, from nuclear fear to climate policy.

Gabriel Henderson is an associate historian at the American Institute of Physics in College Park, Maryland.



Current debates in the US about the risks of climate change boil down to a struggle between two warring camps: those who argue that our current course is fine, and those who insist that we are in a moment of crisis. But a third stance seeks to split the difference. "We cannot afford to be complacent, but there is no need to panic," wrote Lloyd Dumas, a professor of public policy and political economy at the University of Texas at Dallas, in 2006. "We still have the time to take a measured approach, to roll up our sleeves and build the political will to take sensible, pragmatic actions that will make global warming a problem of the past, rather than a threat to our future."[1]

Dumas's language about charting a course between complacency and panic appears in many other areas of risk management, from environmental science to epidemiology. For example, Jay Lund, a professor of civil and environmental engineering at the University of California, Davis, told the California State Assembly Select Committee on Water Consumption and Alternative Sources that when it comes to climate change, "we need to always be between complacency and panic. Either extreme isn't right, and either extreme doesn't help us to address real problems, but being in the middle allows us to attack problems rationally and determine the best solutions."[2] In April 2017 Northeastern University convened a symposium entitled "Between Complacency and Panic: Legal, Ethical, and Policy Responses to Emerging Infectious Diseases." The following year, global health specialists Lawrence Gostin and Katharina Ó Cathaoir cautioned that nations' tendency to continually "lurch" or "careen" between complacency and panic stymied efforts to manage global pandemics.[3]

The rhetoric of moderation seems to have acquired a special power in specialists' discussions of how to manage the risks of events like climate change, water management, and global pandemics. Such rhetoric portrays an in-between course of action as pragmatic, sensible, rational, and stable. But where did the frequently used phrase about complacency and panic come from? How did it acquire value to technical specialists in such diverse fields? Although it is difficult to trace the lineage of individual uses of the phrase, we can trace a broader ancestral story, one that begins with efforts by US civil defense officials to manage public anxieties during the early Cold War.

Origins of the phrase

During the 1950s, officials in the Eisenhower administration sought to manage public anxiety about the risks of nuclear war, nuclear waste, and radioactive fallout (see figure 1). Drawing on social-scientific research about the psychological consequences of extreme emotional states, the administration established what historian Guy Oakes has called a "comprehensive system of emotion management."[4] Civil defense authorities arrived at two conclusions about the risks of emotional extremes: one, that unmitigated public hysteria would undermine citizens' capacity to act reasonably in the event of an attack, and two, that excessive complacency about the possibility of a Soviet attack would undermine the public's incentive to monitor and respond to emerging Soviet threats. Either emotional extreme could jeopardize the integrity of US institutions. As President Dwight Eisenhower himself warned while giving remarks at the 42nd Annual Meeting of the US Chamber of Commerce in April 1954, "We must, of course, prevent ourselves always from overexaggerating danger, just as we refuse to become complacent because of our historical position of geographic isolation."[5]

Many scientists agreed that extreme emotional states posed a serious challenge to national preparedness, and they occasionally incorporated the administration's middle-road logic into their own assessments of emergent risks. Beginning in the mid 1950s, Herman Kalckar, a biochemist at Johns Hopkins University, advocated for measuring the amount of strontium-90 transmitted to the human population by nuclear testing. He recognized that any resulting knowledge of radioactive contamination could cause a massive public outcry. In a 2 August 1958 article for *Nature*, he wrote that experts had an obligation to convey knowledge "to the public without interpretations which might give rise to either complacency or fear, but rather in a spirit that would encourage sober, continued, active concern."

Around the same time, Roger Revelle, director of the Scripps Institution of Oceanography and chair of the National Academy of Sciences Panel on the Biological Effects of Atomic Radiation, released a report on whether nuclear waste posed a hazard to the world's oceans. Intimately familiar with the public's apparent tendency to misinterpret scientific information about the risks of nuclear waste, Revelle argued that "our present knowledge should be sufficient to dispel much of the over-confidence [in nuclear technology] on the one hand and much of the fear [of it] on the other."[6] Along similar lines, Dwight Chapman, chair of the psychology department at Vassar College, wrote in 1953 that the task of protecting the American public was possible "only if people in time of a disaster are neither too paralyzed nor too frenzied to carry out the necessary activities."[7]

Such examples show that scientists and policymakers were building a strategy of nuclear governance premised on mediating between complacency and panic (see figure 2). Their statements of moderation served as convenient heuristics to induce desired levels of vigilance, prudence, judiciousness, emotional maturity, and informed judgment in the general public. To inform the public without creating either excessive complacency or alarm was to, in effect, manage the inherent dilemmas and insecurities of a modern state.[8] But could those rhetorical standards be adapted and applied to other political challenges?

The phrase in changing times

As citizens began to learn of scientists' close alignment with national security interests during the 1950s and 1960s, many started to question scientists' commitment to the well-being of humanity. The bomb had inaugurated a new age of anxiety, so what other technologies resided in the shadows, waiting to destroy the human race? Members of the ascendant US counterculture protested universities' roles as agents of destruction in Vietnam and highlighted the potentially undemocratic implications of too much collusion between experts and their patrons. Meanwhile, many students challenged the pro-moderation assumptions guiding national affairs. After all, how responsible were appeals to a moderation that seemed to support the status quo and the so-called military–industrial complex?

Critics of the alliance between science and government were not wrong. Universities did collude with the government to maintain their commitments in Vietnam, especially regarding the use of the herbicide Agent Orange. And federal agencies did keep secrets about the health effects of radioactivity, including concealing the government's role in conducting human radiation experiments during and after World War II. As details of those collaborations and cover-ups emerged, administrators of the US's most elite scientific institutions grew increasingly concerned about their declining credibility. "Scientists cannot expect to live in a world in which they are universally loved and admired. But the change in climate from that of a decade ago has been drastic," observed Philip Abelson, editor of *Science* and president of the Carnegie Institution of Washington,[9] in the early 1970s.

FIGURE 1. A CIVIL DEFENSE ADVERTISEMENT from the early 1950s urges citizens to learn how to protect themselves from nuclear fallout. (Courtesy of the Michigan Civil Defense Museum.)

Distrust of US institutions increased as the public became more concerned about the deterioration of the natural environment. To defend the role and credibility of high-level scientists in navigating such debates, prominent representatives once again reached for the language of moderation. In 1973, for instance, Philip Handler, president of the National Academy of Sciences (NAS), and Alexander Zucker, physicist and chair of the Environmental Studies Board of the NAS and the National Academy of Engineering, published a brief article in the proceedings of the Federation of American Societies for Experimental Biology. Entitled "Between complacency and panic," the article declared the importance of developing "generalized approaches to the problems of the environment" that could accommodate the interests of private industry and of environmentalists.[10]

Did scientists know all the answers? Absolutely not, and scientists like Abelson, Handler, and Zucker acknowledged as much. But they were concerned about the potential long-term consequences of the US becoming distrustful of expert knowledge, and they worried that the public was increasingly unable to distinguish genuine experts from charlatans. They believed there was room for genuine disagreement about the direction of US society but did not want the substance of those disagreements to evaporate in a heated maelstrom of public paranoia and hyperbole. It was crucial, Handler and Zucker argued, to identify and interrogate genuine problems confronting humankind without abandoning the ethics of moderation that had guided decision making in previous decades.

Policymakers also seemed eager to prove their *bona fides* as stalwart defenders of moderation by capitalizing on growing public support for environmental protections (see figure 3). Even those who opposed environmental regulation adopted familiar-sounding language about action without panic. Pres-

EDITORIAL AND FEATURE PAGE

Neither Complacency Nor Panic Has Any Place Among Americans

We Americans don't often think of ourselves as a mercurial people. That is a tag often hung on Frenchmen, whereas the French are among the world's most practical, down-to-earth race.

Currently you hear a great deal of talk, and see a great leal of writing, about how our loss of leadership to the Russians in the guided missiles field frightened us, undermined our faith in our country and inclined us to go riding off in all directions.

As often as not, the same person who expresses this opinion in talk or writing will branch off suddenly and declare the American people are too complacent about this thing.

Well, we couldn't very well be scared and complacent at the same time, could we? Still, we venture to say if any people could, it would be us Americans.

With respect to the current hullabaloo, we can see no cause for riding off in all directions, or going round like a chicken with its head chopped off. We are still the mightiest nation on earth—the mightiest nation the world has ever seen—and we have the means, the genius and the will to meet this latest Russian challenge.

But we will have to eschew panic and complacency, both, to do it. Fright and over-confidence are equally dangerous to our nation. We have known since the late 1940s that we were entering a long period of world unrest and uncertainty, of accelerated science and invention. We know who our enemy is. We know he couples an ability to solve scientific problems with a ruthlessness and determination that brook no consideration of morality or principle.

We must dedicate ourselves to the proposition that our system of government and our way of life are the best ever devised, and that whatever it takes to preserve them is worth fighting for.

We must realize, and act accordingly, that sacrifices may be necessary — sacrifices of the things of the flesh that we have become accustomed to, and which we have developed and enjoyed to a greater extent than any people ever achieved before.

We do not believe our people are afraid. Anyone who tries to soft-soap them with sweet talk on the theory they are panicky is doing a national disservice. Anyone who tries to frighten them out of an attitude of complacency that doesn't exist would be equally in error.

We more than any people on earth can be trusted with the facts. If our leaders will just give us the facts minus the soft soap and the hyperbole, we have no fear of the American people's reaction to whatever may betide.

FIGURE 2. A 15 NOVEMBER 1957 EDITORIAL FROM THE *PARIS NEWS* in Paris, Texas, advocates moderation when considering nuclear war. (Courtesy of the *Paris News*.)

ident Richard Nixon, for example, spoke in 1973 about what he called an environmental awakening:

> Some people have moved from complacency to the opposite extreme of alarmism, suggesting that our pollution problems were hopeless and predicting impending ecological disaster. . . .
>
> I reject this doomsday mentality, and I hope the Congress will also reject it. I believe that we can meet our environmental challenges without turning our back on progress. . . .
>
> I believe there is always a sensible middle ground between the Cassandras and the Pollyannas. We must take our stand upon that ground.[11]

Behind the scenes, however, Nixon had become increasingly hostile to environmental interests since his reelection in 1972. But his speech shows that by the 1970s, the language about a path "between complacency and panic" had found its way into the increasingly polarized world of environmental politics. Nixon's use of the language of moderation shows how it could suit a wide range of interests. Nixon, like Abelson, Handler, and Zucker, understood that appeals to such language signified proper stewardship of the nation. Those who proclaimed themselves stalwart advocates of moderation seemed to understand its political significance in times of instability.

The power of a call for moderation would endure, and it would be adapted to new risk landscapes and new political challenges. And there was perhaps no greater political and scientific challenge than one that began to appear on the national agenda in the 1970s: climate change.

New applications

The week of 7–11 July 1977 was a busy one for geophysicist Frank Press (see figure 4), director of the Office of Science and Technology Policy under President Jimmy Carter. On 7 July, he wrote a memo to the president declaring that the threat of climate change was real and urgent and that if the US did not make significant changes to national energy policy, it could induce large-scale catastrophic changes to global agricultural output, economic markets, and migration patterns. After consulting with his colleagues and high-level executives in the administration, Press had concluded that those risks required serious political consideration. The challenge was to integrate climate into national planning and to determine whether the threat level was high enough to justify a national or global response. Although climate change could be catastrophic if left unchecked, Press and others reasoned that there was enough time over the next decade to engineer a scientific consensus that would justify a more substantive response. In his memo to the president, he advocated for a policy that was "neither complacent nor panicky."[12]

Press understood that the phrase had long been engineered to manage two things: public perceptions of risk and public expectations that the government could address complex challenges in the near term. He and many others were skeptical that immediate action to curb reliance on fossil fuels would be possible, and the administration's approach to climate governance was often to simply continue funding for scientific research. "Neither complacent nor panicky" was the rhetorical equivalent of a stopgap measure, a way to buy time until more meaningful solutions could be devised or until greater scientific certainty could be achieved about the effects of climate change.

The scientific community was already conducting a campaign to do those two things. The basis of Press's cautionary memo to the president was a report released under the auspices of the NAS entitled *Energy and Climate*. The report, compiled by a panel chaired by Revelle, was as much about communicating technical knowledge as about public relations. The NAS convened a press conference when *Energy and Climate* was released in July 1977. Building on the report's argument that the document should "lead neither to panic nor to complacency," high-level NAS officials Abelson and Thomas Malone used the metaphor of a yellow stoplight, an image that, in their minds, encapsulated the importance of caution.

The summer of 1977 was crucial in the history of US climate politics. Despite increasing pressure from Congress to quickly develop a national climate program, the Carter administration appeared uninterested in managing the negative consequences of climate change in the near term. The administration's alternative position was that carefully laying the groundwork for a long-

FIGURE 3. US POSTAGE STAMPS FROM 1970 reflected the growing power of the environmental movement. (Via Wikimedia Commons, PD-USGov.)

term research strategy was both politically prudent and scientifically justified, and that the nature of climate change itself required a long-term management strategy rather than immediate policy action.

The vast majority of scientists and policymakers believed that countering climate change was different from managing the risks of an immediate crisis like a polluted river or an oil spill; it needed, in officials' estimations, to be treated with a more delicate, steady hand. Society was not moving quickly in the direction that many would have preferred, but that did not mean movement was not taking place. The government was interested in continued research to evaluate the risks, but it was not willing to make large-scale, immediate decisions about climate change given the potential ramifications that immediately abandoning fossil fuels would have for the global market system. Portraying the administration's guiding principle as a flashing yellow light was meant to convey the virtue of caution.

The pro-caution message trickled down quickly into other agencies. "The general scientific opinion is that our understanding of climate and climate variability is far too meager to warrant serious pronouncement. The important task at present is rather to give an accurate picture of what we know and what we don't know, and to develop a program for advancing our knowledge," cautioned Patsy Mink, assistant secretary of state for oceans and international environmental and scientific affairs.[13]

Although most observers were unaware of the tangled history of the phrase "between complacency and panic," the message was clear to experts and policymakers: Watch out, but don't despair. Monitor the situation, but don't run headfirst into action. Slight variations on the rhetorical motif also began to appear in various forums. "Being alert is wise," eminent climatologist Helmut Landsberg wrote in 1979 in a draft policy paper for an energy working group at the University of Maryland, but "being alarmist is foolish."[14] Along similar lines, planners for a fall 1978 climate symposium in Aspen, Colorado, wrote that "the first goal" of their meeting would be "to focus on steps needed to raise the public consciousness of the problem in a way that is not alarmist, but still appropriately urgent."[15] For many, practicing a state of vigilance was the most responsible path forward. That approach accommodated scientists' desire to increase scientific knowledge while providing policymakers the space to devise a long-term strategy.

The same rhetoric appeared again and again in other scientific and government publications. "The picture [of climate change] here may not be a gloomy one, but complacency would be ill-advised," noted a 1979 workshop report from the Department of Energy.[16] The decision to privilege caution was clearly not rooted in ignorance or disinterest in the implications of climate change. It stemmed instead from the habits of thought that had defined experts' ideas about their roles in managing complex problems since the 1950s. Officials were, quite simply, using the rhetorical tactics passed down from one generation to the next, one political challenge to another.

Employing such reasoning was not necessarily a rational decision or an ethically sound one. Some analysts in and outside the administration believed that a moderate pathway constituted a breach of responsibility to the welfare of future generations who would have to live with the effects of present decisions. Precisely because climate change differed in kind from a polluted river or an oil spill, more proactive policies were required. Waiting too long, a vocal minority of scientists and advocates argued, would invariably make the problem harder to solve.

FIGURE 4. GEOPHYSICIST FRANK PRESS served as director of the Office of Science and Technology Policy under President Jimmy Carter. (Courtesy of the American Geophysical Union and AIP Emilio Segrè Visual Archives. Photograph by Ivan Massar; © Massar Studios.)

In the meantime, many institutions grew increasingly interested in the social, political, and economic effects of climate change during the 1970s; those organizations included the International Federation of Institutes for Advanced Study, the MITRE Corp, DOE, Friends of the Earth, the US Council on Environmental Quality, and the Aspen Institute for Humanistic Studies. Many specialists began to organize around a common belief that robust interdisciplinary research would be necessary to tackle the immense dilemmas associated with global warming.[17]

The realization of those broader and deeply salient agendas, however, would have to wait for another day. The overriding ethos of the late 1970s and early 1980s was to maintain a posture of tempered engagement calibrated to steer society between the extremes of complacency and panic, in the expectation that science would soon produce answers.

Enduring legacy of the phrase

The most curious element of those numerous expressions of caution is their subliminal nature. They appeared in reports but were rarely highlighted. They appeared in correspondence but were rarely explained or elaborated on. Yellow-light metaphors were used to guide the public's understanding of climate risk but failed often to make national headlines. The phrases that appear ubiquitous in the historical record also remain hidden and undervalued in histories of science and politics.

When asked about the origins of his own knowledge of the phrase, for instance, Lund responded with a tone of mild bemusement: "[I] may have picked up the phrase carelessly from someone else, or it might be originated independently in my mind." His response is understandable. After all, scientists do not learn such phrases formally in school, nor do they appear to learn them formally from advisers or colleagues. Perhaps they acquire them in the marketplace of ideas or, as Lund suggested, in the course of interacting with their colleagues.

The significance of Lund's reflection is not that he used the phrase without knowing its origin story. It's that the phrase itself has acquired meaning independent of any obvious history. Changes in scientific rhetoric are not as splashy or newsworthy as the discovery of a new phenomenon or the establishment of a new scientific theory, and the stories of such changes can often be discounted as tangential meta-history that merely swims along on the currents of real history. But perhaps there is room to ask why the language of caution was deemed responsible by scientists and policymakers in nuclear, environmental, and climate debates. It is also worth asking now whether rhetorical strategies designed during the early years of the Cold War are suited to humankind's efforts to manage our contemporary challenges.

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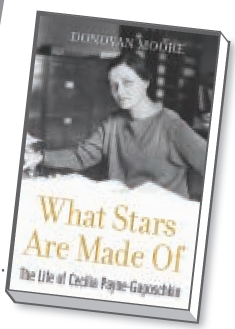
Cecilia Payne-Gaposchkin (1900–1979)

Breaking the glass ceiling of 20th-century astronomy



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Donovan Moore
Harvard U. Press, 2020. $29.95

Cecilia Payne-Gaposchkin was one of the most gifted astrophysicists of the 20th century. But as Donovan Moore shows in *What Stars Are Made Of: The Life of Cecilia Payne-Gaposchkin*, her career was hindered by what was at the time an almost insurmountable handicap: her gender. Payne-Gaposchkin pounded on astronomy's glass ceiling, and she was the first to put major cracks in it. But in many places, the ceiling was impervious to her effort and intellect. She deserves more praise for her accomplishments than she has received, as she is far less well known than figures like Annie Jump Cannon and Henrietta Leavitt, who came just a bit before her, and Margaret Burbidge and Vera Rubin, who came after. Fortunately, Moore's new biography of this brilliant scientist is a must-read.

Payne-Gaposchkin left the UK for Boston in 1923 with one family heirloom, her father's violin, which she was forced to pawn while a graduate student. She should have been Harvard University's first female recipient of a PhD in astronomy. Harvard had no astronomy department, however, and the physics department refused to admit women as degree candidates, so she was awarded her doctorate through Radcliffe College in 1925. Later, when starting her job as a technical assistant at the Harvard College Observatory, she was given a lower salary than the male fellows. To make ends meet between the end of her graduate fellowship and her first professional paycheck, she had to pawn her jewelry.

Yet her determination to learn about the universe led Payne-Gaposchkin to uncover one of its fundamental truths: that most of it is made of hydrogen. In doing so, she overturned the principle of uniformity, long held up as a law of physics, which stated that the universe was composed primarily of the same elements that dominated Earth's crust. Her accomplishments were initially pooh-poohed by her field's most eminent scientists, including her external PhD adviser Henry Norris Russell, who forced her to change the conclusion of her dissertation and say that her results must be spurious. But, as we now know, she was right.

Four years later Russell would conclude, in a paper in which he took credit for the discovery, that the stars and the universe are indeed made almost entirely of hydrogen. Well into the 1970s, Russell's 1929 paper was regularly cited as the one that established the dominance of hydrogen in the universe. Payne-Gaposchkin's work was important enough that a Nobel Prize should have been hers, but because of Russell, that was not to be—she was never even nominated.

Other important rewards did come her way, though often not as soon as she deserved them. Payne-Gaposchkin became the first tenured female professor of astronomy at Harvard, but only after serving three decades in the lesser position of technical assistant. That lengthy period of underemployment was no accident. Harvard president Abbott Lawrence Lowell had declared, according to Harvard College Observatory director Harlow Shapley, that "Miss Payne should never have a position in the University as long as he was alive." Lowell, who stepped down as president of Harvard in 1933 and died in 1943, was unfortunately right: Payne-Gaposchkin was only promoted to the faculty in 1956. In 1976 she became the first woman to receive the American Astronomical Society's most prestigious honor, which, ironically for Payne-Gaposchkin, is called the Henry Norris Russell Lectureship.

Payne-Gaposchkin's autobiography

was Moore's most important source, and so he uses her own words to tell much of her story, almost as if he wrote from a series of extended interviews with his late subject. *What Stars Are Made Of* flows like a historical novel, and Moore has a particular gift for weaving details about the cultural richness of early-20th-century Cambridge, Massachusetts, into his prose. Moore explains both the scientific details and the overall significance of Payne-Gaposchkin's work clearly, and he does so without jargon. His descriptions of Payne-Gaposchkin's Forrest Gump–like habit of running into some of the greatest physicists of the 20th century adds to the readers' fun; her mentors and teachers included such luminaries as Niels Bohr and Ernest Rutherford.

But reading about the sacrifices Payne-Gaposchkin made, and the burdens under which she suffered, was often painful. How could my predecessors have worked so hard to undermine the work of one of the greatest minds in 20th-century astrophysics? The book also prompts uncomfortable questions about the modern scientific community. In the year 2020, women have softened most of the barriers for participation in astrophysics, but that progress is recent, and it is far from complete. Who is our modern Payne-Gaposchkin? Is that person undervalued and denied opportunities because of their gender or gender identity? Their skin color or country of birth? A disability?

Most of us in science can probably relate to one part of Payne-Gaposchkin's story: She became a scientist because she was encouraged and inspired to do so by dedicated teachers. At age 12 her path led her to Dorothy Daglish's science classroom at St Mary's Catholic school. Next, at St Paul's School for Girls, she had the good fortune of finding another inspiring and caring teacher, Ivy Pendlebury. Most, or perhaps all, of us chose a path into science because we had similar experiences. We should pause and say thank-you to all of the Miss Daglishes and Miss Pendleburys we've been lucky enough to meet. This, then, is my chance to say thank-you to Chris Tellefson, my high school physics teacher in State College, Pennsylvania, in the early 1970s, who has no idea how important her teaching, guidance, and advice were to me.

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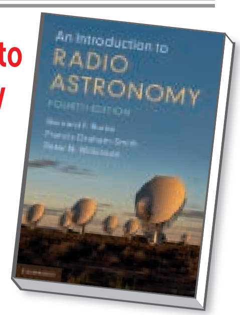
A radio astronomy classic, updated

An Introduction to Radio Astronomy

Bernard F. Burke, Francis Graham-Smith, and Peter N. Wilkinson
Cambridge U. Press, 2019 (4th ed.). $79.99



Radio astronomy has a reputation in the scientific community as a mature field, given that nearly nine decades have passed since Karl Jansky and Grote Reber made the first measurements of the sky outside the optical regime. But that description is hardly appropriate today, as the field is enjoying a remarkable period of discovery driven by an impressive range of technical innovations. The Event Horizon Telescope's imaging of the black hole shadow in M87 and the discovery of mysterious fast radio bursts are just two recent examples.

The publication of a fourth edition of the classic text *An Introduction to Radio Astronomy*, therefore, could not be timelier. Lead author Bernard Burke sadly passed away in 2018; Burke's coauthor Francis Graham-Smith is joined in this edition by new coauthor Peter Wilkinson, an expert in radio interferometry and a longtime participant in the Square Kilometre Array project. The book has been significantly revised and reorganized following input from the astronomical community. However, the fourth edition remains true to its original audience: graduate students and astronomical researchers who seek a comprehensive introduction to the field.

The first part of the book is devoted to the basic physics of radio wave emission, how radio waves are affected by the interstellar medium and our atmosphere, and how they are detected using modern receivers. In the second part the authors delve into the theory and operation of single-dish radio telescopes and interferometers; they have added considerable new material on observational techniques. The third and final section covers the large variety of phenomena studied by radio astronomers, starting with our solar system, the Milky Way, and other galaxies out to very distant quasars. The book concludes with a primer on cosmology and covers how radio observations of the cosmic microwave background and gravitational lenses are vital to our understanding of the structure and evolution of our universe.

Authors attempting to cover in a single volume a field as vast as radio astronomy will have to make choices between depth and scope; Burke and coauthors have clearly opted for the latter. *An Introduction to Radio Astronomy* is impressively comprehensive in addressing the basic theory, techniques, telescopes, and astrophysics in the radio regime—no small feat in 500 pages. The only important areas that need more in-depth treatment are astrometry and geodesy, molecular cloud and star formation, and radio transients, all of which have significant research communities.

The authors adopt a lecture-like writing style that is easy to read, and the text is interspersed with relatively clean, simple figures. Students looking for detailed derivations of equations may be disappointed, however, as many equations are not presented from first principles. The authors do include numerous references to more in-depth works. Professors interested in adopting the textbook for a graduate course should be aware that it has no end-of-chapter problems and very few worked examples or calculations involving actual astronomical data, omissions that are atypical among popular astrophysics textbooks.

Other texts published in the past few years fill different niches from *An Introduction to Radio Astronomy*. James Condon and Scott Ransom's *Essential Radio Astronomy* (2016) places more emphasis on equations and worked examples but omits detailed material on observer techniques and individual radio telescope facilities. Those looking for an undergraduate-level text appropriate for students who don't have an astronomy background will want to check out *Fundamentals of Radio Astronomy* (2015) by Ronald Snell, Stanley Kurtz, and Jonathan Marr.

Overall, the fourth edition of *An Introduction to Radio Astronomy* is a pleasure to read and has only a few flaws. Given that the field straddles both astronomy and electrical engineering, it is not surprising that no uniform system of units is used throughout, although nonexperts will likely be baffled when mks and cgs units sometimes appear in the same equation.

The publishers also make an odd choice to use a footnote-size font for all text that involves a list, even when such a list takes up a whole page. The index uses an even smaller font and is incomplete: It omits many italicized terms in the text such as scattering, starburst galaxy, and photodissociation region. Some of the figures, such as that showing the Milky Way's rotation curve, could be replaced with more recent data, and very few of the spectacular images recently obtained by the Atacama Large Millimeter/Submillimeter Array are included. The authors appear to have recognized some of those shortcomings, and they provide continuously updated supplementary material on the publisher's website.

The relatively minor issues aside, I highly recommend the book for graduate students and other astronomers looking for an up-to-date, comprehensive introduction to the exciting and rapidly advancing field of radio astronomy. As a reference work it merits a prominent place on the bookshelf of every radio astronomer.

Matthew L. Lister
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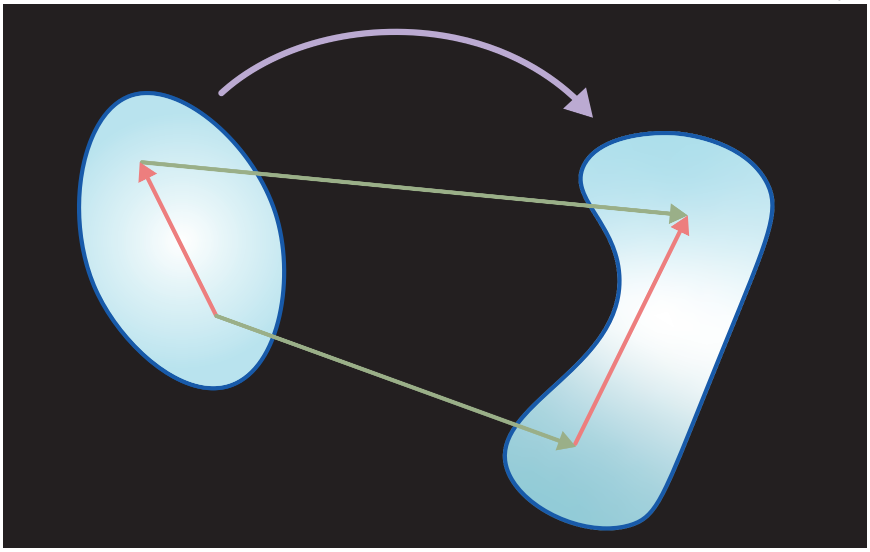
FREDDIE PAGANI



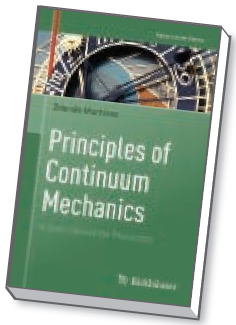
A quick reference for continuum mechanics

Continuum mechanics, arguably the crown jewel of classical physics, is a framework for modeling arbitrary material deformations that are subject to constraints for a motion to be physically possible. A course in continuum mechanics might be an undergraduate's first exposure to tensor analysis and analytical geometry, so a text for such a course requires plentiful figures, in-text examples, and end-of-chapter exercises. *Principles of Continuum Mechanics: A Basic Course for Physicists* by Zdeněk Martinec lacks those crucial components and therefore is best regarded as a quick reference for mathematically adept readers who are already familiar with the subject. For that audience, the book is useful and content rich.

As is typical of continuum mechanics treatises, *Principles of Continuum Mechanics* mentions only the general character of laboratory data. The book omits any discussion of the spatial scale at which discrete components can be well modeled as a continuum; instead, it focuses on formulations unified in the 1950s and 1960s by Clifford Truesdell, Walter Noll, Bernard Coleman, Morton Gurtin, Ahmed Eringen, and their contemporaries.

Rather than starting with the customary chapter on tensor notation, *Principles of Continuum Mechanics* opens by employing multivariate mappings to describe the time-varying deformation of a

Principles of Continuum Mechanics
A Basic Course for Physicists
Zdeněk Martinec
Birkhäuser/Springer, 2019. $49.99 (paper)



body from one geometrical configuration to another. The book proceeds at breakneck pace, and it often uses terms or symbols before they are defined. Topics include large-deformation kinematics, field equations, and a better-than-average description of contemporary entropy principles and linearization with prestress. Constraints and expectations applicable to all constitutive models are discussed, and some specific models are presented. Although the book offers below-average instruction on Cartesian tensor analysis, it does include appendices on curvilinear surface geometry and orthogonal curvilinear coordinates.

Principles of Continuum Mechanics is mostly error free and fastidiously rigorous, with some unfortunate exceptions. The book's discussion of mappings, for example, perpetuates the myth that having local invertibility—a positive Jacobian—at every point ensures global invertibility of a deformation mapping. If that were true, finite-element codes wouldn't need contact detection schemes to prevent nonphysical material interpenetration. The book often invokes smallness of a physical quantity without stating a standard of comparison; it even nonsensically asserts the smallness of stress, a dimensional quantity, in comparison to unity, a dimensionless quantity.

Rigor, elegance, and clarity fall short in some respects. Mass is incorrectly referred to as an intrinsic property of a body. After stating that "an arbitrary non-singular tensor $\boldsymbol{T}$ is positive definite if $\vec{v} \cdot \boldsymbol{T} \cdot \vec{v} > 0$ for all vectors $\vec{v} \neq 0$," the book goes on to spread the myth that positive eigenvalues of $\boldsymbol{T}$ are sufficient for $\boldsymbol{T}$ to be positive definite; the 2×2 matrix $\boldsymbol{T} = \{\{4,9\},\{1,4\}\}$ with $\vec{v} = \{1,-1\}$ is a counterexample. One of the book's proofs invokes positive definiteness of a decidedly nonpositive definite tensor, strain. The book refers to "Lagrangian" and "Eulerian" variables, potentially confusing word choices that fail to emphasize the distinction between a tensor and the tensor's various functional representations.

When presented with the equations of thermodynamics, readers will ask—but not find answers to—some reasonable questions: What exactly is energy? What is temperature? Heat? Entropy? What motivates or proves their existence? Although the equations of thermodynamics are properly stated and analyzed, explanations of their physical interpretations are absent, weak, or wrong. For example, radioactive decay and chemical reactions are incorrectly cited as examples of heat supply in the first and second laws. There is no discussion of the role of internal variables, such as plastic work or chemical species fractions, as additional independent variables in the energy potential function.

The book has a few unexpected omissions and questionable choices in terminology. For example, Martinec claims the phrase "small deformation" means "small displacement gradients," which is misleading because the two are not equivalent. The book also refers to the symmetric part of the spatial velocity gradient as "the strain rate" even though it is not the rate of any path-independent function of the deformation gradient. More broadly, the book needs stronger emphasis on the distinction between state variables and path-dependent variables.

Martinec does not offer a satisfying definition of objectivity; some tensors are confusingly identified as being scalars or vectors. The concept of fundamental potentials is not mentioned, nor is the role of different thermal constraints in purely mechanical constitutive models. Lie rates, which are common in finite-element codes, are not discussed. The book's index is missing entries for corotational, curl (and "rot," a nonstandard abbreviation for curl), deviator, double dot, isotropy, Newtonian fluid, objectivity, and other key terms.

Many books on the subject share the shortcomings of *Principles of Continuum Mechanics*. The book might therefore be seen as a retelling of an old story, one that does not address fundamental gaps or the need for clarity in the existing literature. *Principles of Continuum Mechanics* can nevertheless serve as a useful quick-reference summary of major results and analysis methods in continuum mechanics.

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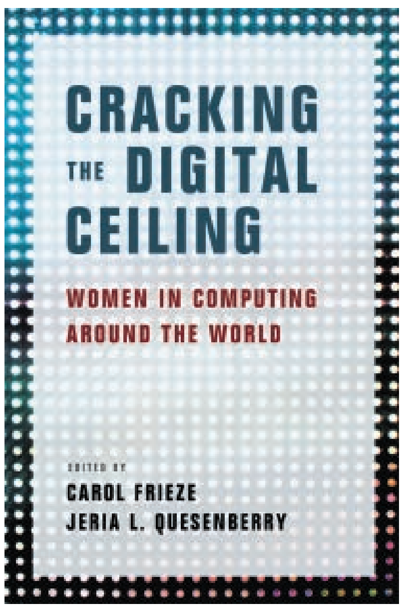
NEW BOOKS & MEDIA

Cracking the Digital Ceiling

Women in Computing Around the World

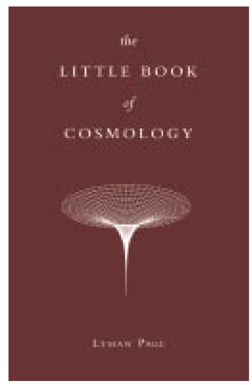
Carol Frieze and Jeria L. Quesenberry, eds.
Cambridge U. Press, 2019. $29.99 (paper)



Cracking the Digital Ceiling addresses the stereotype that women are intellectually inferior in the field of computer science. Editors Carol Frieze and Jeria Quesenberry collected perspectives from experts across the globe to show how culture and social constructions shape people's view of women's capabilities. For example, the chapter on education in Israel reports that women face strong work–family conflicts that men do not. Women in different cultures and countries face that problem too, and other factors, including unbalanced institutional support and the culture of startup companies, also affect their participation. The editors argue that the problem's complexity precludes simple solutions: Local and global remedies will need to be implemented in tandem so more women are welcomed into the field of computer science. —AL

The Little Book of Cosmology

Lyman Page
Princeton U. Press, 2020. $19.95

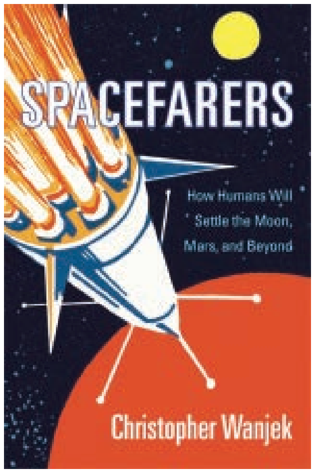


At just 152 pages, including appendixes and the index, *The Little Book of Cosmology* covers a lot of ground in a relatively short space. Aimed at readers with some knowledge of physics concepts, the primer starts off with a few basics about the cosmos, including the size and age of the universe, and then moves to such topics as its composition and evolution, the cosmic microwave background, matter and dark matter, and the cosmological constant. All those components come into play in a chapter on the standard model of Big Bang cosmology. The author, observational cosmologist Lyman Page, tops off the discussion with some intriguing questions yet to be answered, such as whether the cosmological constant is really constant. —CC

Spacefarers

How Humans Will Settle the Moon, Mars, and Beyond

Christopher Wanjek
Harvard U. Press, 2020. $29.95



Although Earth has its share of extreme environments—for example, Antarctica and the top of Mount Everest—its warmth, water, atmosphere, magnetosphere, and gravity make it the best place in the solar system for humans to live. So why leave? asks science journalist Christopher Wanjek. In *Spacefarers*, Wanjek provides a thought-provoking discussion of the history of the space program, the pros and cons of space travel, and the economic, physical, and biological issues involved. Chapters about living on the Moon, Mars, and other solar objects serve as launching points to discuss current and future technologies and missions and what setting up camp on those worlds would entail.

—CC

Time to Eat the Dogs

A Podcast About Science, History, and Exploration

Michael Robinson, 2019–present

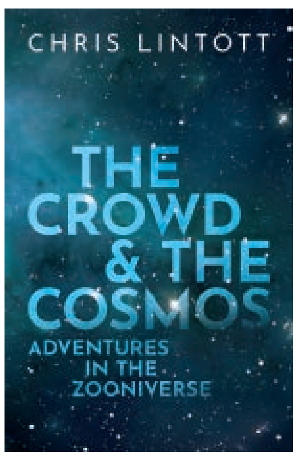
Historian Michael Robinson hosts this program to tell stories about science and exploration under extreme conditions and in remote locations. Robinson and his guests cover a remarkable cross section of history of science and recent scientific findings. Historian Paige Madison visited the podcast in February to talk about the discovery of *Homo floresiensis* fossils in the Liang Bua cave in Indonesia. Robinson also has a gift for highlighting interesting new books; in January, for example, historian Kim Walker told listeners about *Just the Tonic: A Natural History of Tonic Water*, a book she wrote with Mark Nesbitt. Episodes are released weekly and are roughly 30 minutes in length.

—MB

The Crowd and the Cosmos

Adventures in the Zooniverse

Chris Lintott
Oxford U. Press, 2019. $24.95



The vast amount of data that needs to be crunched is a challenge for researchers. The citizen-science initiative Zooniverse harnesses large numbers of people to analyze that data. Chris Lintott, an astrophysicist and the principal investigator behind the initiative, describes in his new book *The Crowd and the Cosmos* the various scientific achievements those curious people have helped make possible. Examples include cataloging craters on the Moon, transcribing written weather observations from historical ship logs, and hunting for supernovae in telescope images. You can participate in the latest projects at www.zooniverse.org.

—AL

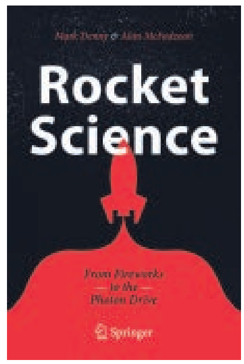
The Art of Electronics

The x Chapters

Paul Horowitz and Winfield Hill
Cambridge U. Press, 2020. $59.99

This companion to *The Art of Electronics* (3rd edition, 2015) covers, as the authors put it, material that is "advanced, important, novel, or just plain fun" but that is not in a typical electronics course. Topics include switches and relays, bipolarity current mirrors, low-voltage switching, and fast LED pulsers—to name just a few. Paul Horowitz and Winfield Hill recommend the book to professors, students, and dedicated self-taught electronics enthusiasts.

—MB



Rocket Science

From Fireworks to the Photon Drive

Mark Denny and Alan McFadzean
Springer, 2019. $29.99 (paper)

Explaining rocket science doesn't have to be as difficult as it may sound. In their book *Rocket Science*, physicists Mark Denny and Alan McFadzean cover the field's history from the introduction of fireworks to more recent space efforts of NASA, SpaceX, and Blue Origin. With jargon kept to a minimum, the authors describe how modern satellites and spacecraft get to space and navigate once they're there and how engineers bring them back to Earth. Because the book is aimed at both laypeople and scientists, the mathematical derivations are in the appendix for interested readers.

—AL PT

NEW PRODUCTS

Focus on lasers, imaging, and microscopy

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 its description. Please send all new products submissions to ptpub@aip.org.

Andreas Mandelis

Short-wave IR camera

The latest addition to the Teledyne Princeton Instruments short-wave IR (SWIR) camera portfolio, the NIRvana HS, uses the advantages of the second near-IR window (NIR-II) to meet scientific, industrial, and medical needs. According to the company, the NIRvana HS provides a combination of features not previously offered in a high-performance SWIR camera: It runs at 250 frames/s in 16-bit mode and offers both integrate-then-read and integrate-while-read modes for low noise and high duty cycle. The thermal design includes deep cooling to −55 °C and incorporates a state-of-the-art vacuum-sealed chamber to provide long-term maintenance-free operation. Advanced image correction ensures high image quality. The NIRvana HS has applications in fluorescence microscopy, nanomaterials, *in vivo* imaging, astronomy, agriculture, and semiconductors. ***Teledyne Princeton Instruments***, *3660 Quakerbridge Rd, Trenton, NJ 08619, www.princetoninstruments.com*

Optical spectrum analyzer

Bristol Instruments has announced a fast, cost-effective optical spectrum analyzer (OSA) for testing optical transceivers used in applications of wavelength-division multiplexing. The model 750 measures and reports the side-mode suppression ratio (SMSR) in less than 0.07 s. Compared with traditional grating-based OSA systems, that speed reduces testing times, according to the company. The model 750 optical spectrum analyzer uses Michelson interferometer-based technology with FFT analysis to generate a laser's spectrum over the entire 1260–1680 nm wavelength range. Spectral resolution of 0.15 nm and wavelength accuracy of ±0.01 nm provide a detailed analysis of the main peak and side modes of most optical transceivers. A high dynamic range of greater than 40 dB ensures an accurate SMSR measurement. ***Bristol Instruments Inc***, *770 Canning Pkwy, Victor, NY 14564, www.bristol-inst.com*

Light-sheet microscope

Bruker developed its Luxendo LCS SPIM light-sheet fluorescence microscope for fast 3D imaging of large, optically cleared samples. The versatile LCS SPIM features a removable standard quartz-crystal cuvette that allows gentle sample mounting, easy access, and compatibility with all types of clearing solutions. The cuvette comes in different lengths to enable imaging of various sample configurations up to 40 mm long. Filled with the clearing solution and specimen, the cuvette is positioned on the sample stage. The motorized stage and programmable optics for fast 3D scanning of the light sheet through the sample lessen mechanical stress on the sample. The design minimizes motion-induced sample distortions, while its novel optical configuration enables high acquisition speed. ***Bruker Optics Inc***, *40 Manning Rd, Billerica, MA 01821, www.bruker.com*

Enhanced laser driver

PicoQuant has expanded the capabilities of its Taiko PDL M1 picosecond diode laser driver. Because of Taiko's smart, flexible power control and monitoring, pulse energy and shape are almost perfectly constant and calibrated at any repetition rate. The Max Power mode, now available as a free firmware update, lets the driver operate existing and new laser heads with increased power and run each laser diode at the highest possible pulse energy. The company has also extended the range of laser heads for the Taiko PDL M1: It now includes modules emitting at 530, 560, and 595 nm and high-powered multimode diodes that cover the spectral range from the visible to the near-IR. The diodes provide access to average optical output powers up to 150 mW in pulsed mode or up to 200 mW in continuous mode. ***PicoQuant***, *Rudower Chaussee 29, 12489 Berlin, Germany, www.picoquant.com*

Low-vibration laser shutter systems

Stanford Research Systems has introduced two optical shutter systems, the SR470 and the SR474, built around a novel shutter head designed to minimize vibration on optical tables. Unlike conventional solenoid-based shutters, the SR475 shutter head contains a control system with a closed-loop digital signal processor that precisely guides the shutter blade between open and closed positions. Because the shutter blade never encounters a physical stop, the SR475 minimizes vibration and mechanical noise. The shutter blade is mounted between sapphire jewel bearings that lessen friction, which results in a long head lifetime in excess of 10 million cycles. The SR470 laser shutter controller provides timing signals to a single shutter head; exposure time can be set between 4 ms and 10 000 s with 0.1 ms resolution. The multichannel SR474 drives up to four shutter heads and is controlled by external timing signals. ***Stanford Research Systems***, *1290-D Reamwood Ave, Sunnyvale, CA 94089, www.thinksrs.com*

Digital microscope cameras

Zeiss has completed its Axiocam portfolio with the introduction of four CMOS cameras—the Axiocam 705 color, 712 color, 705 mono, and 712 mono—for digital imaging in light microscopy. According to the company, the Axiocam 705 color and 712 color microscope cameras deliver optimal image quality for histology, pathology, and materials research and analysis. The cameras' small 3.45 μm pixels and low noise levels, combined with the USB 3.0 platform, ensure fast imaging and excellent signal quality. Their global shutter architecture allows dynamic samples to be captured without creating motion artifacts. Suitable for fluorescence live-cell imaging, the Axiocam 705 mono and 712 mono offer extended near-IR sensitivity that yields deeper insights into sample structures. The 5 MP Axiocam 705 color and 705 mono cameras are optimized for speed and high dynamic range. With 12 MP, the 712 color and 712 mono cameras can be used to acquire large samples, which reduces the need for stitching. ***Carl Zeiss Microscopy GmbH***, *Carl-Zeiss-Promenade 10, 07745 Jena, Germany, www.zeiss.com*

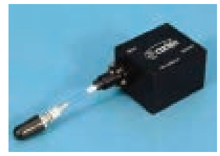
Positioner for nanoscale-motion microscopy

The Nano-F100 focusing-element nanopositioner from Mad City Labs offers subnanometer accuracy under closed-loop control. According to the company, the Nano-F series features very low off-axis motion, so microscope images remain stable throughout the entire 100 μm range of vertical motion. The Nano-F100 can be used alone or in conjunction with other Mad City nanopositioning systems. Quick-mount adapters with various threads allow the Nano-F series to be used on all microscopes. The adapter screws directly into the microscope turret; the nanopositioner can then be clamped onto the adapter without having to rotate the entire assembly with the attached cable. Applications for the Nano-F100 nanopositioner include photoactivated localization, stochastic optical reconstruction, and superresolution microscopy, as well as confocal and fluorescence imaging. ***Mad City Labs Inc***, *2524 Todd Dr, Madison, WI 53713, www.madcitylabs.com*

Supercontinuum white-light laser

NKT Photonics has brought to market its SuperK Fianium range of pulsed supercontinuum lasers. Based on the company's SuperK Extreme laser, the Fianium features upgraded electronics and new fiber technology for improved performance and reliability. According to NKT, it represents a cost-effective and user-friendly alternative to titanium:sapphire lasers, and its monolithic all-fiber architecture makes it stable and robust. The Fianium covers the UV, visible, and near-IR wavelength ranges from 390 nm to 2400 nm. It offers broadband output; users can also tune to the line needed by means of tunable filters or expand further into the UV with the spectral extension unit. The diffraction-limited spot size ensures a high resolution. The Fianium can be operated either from the front panel or via a graphical interface on a PC. ***NKT Photonics Inc***, *23 Drydock Ave, Boston, MA 02210, www.nktphotonics.com*

Pulse compressor and peak-field booster



The pulse compressor and peak-field booster accessory from OZ Optics uses nonlinear effects from an optical fiber to surpass peak electric-field limitations from an ultrafast optical source. After the compact device is attached to the output of a pulsed laser source, only minor adjustments are needed to increase the peak electric field by a factor of more than two. The pulse exiting the device contains more frequency content than the optical source and has a shorter pulse duration, which allows for significant broadening of the bandwidth of output terahertz radiation. The pulse compressor and peak-field booster features tunable pulse-width compression and spectral bandwidth expansion. Applications include use in terahertz generation and detection, optical microscopy, and nonlinear optics. ***OZ Optics Ltd***, *219 Westbrook Rd, Ottawa, ON K0A 1L0, Canada, www.ozoptics.com*

Continuous-wave 266 nm laser

The compact model FQCW266-10-C CW laser from Crystal Laser Systems delivers 10 mW of output power at a wavelength of 266 nm, linewidth less than 300 kHz, and coherence length greater than 1000 m. Based on a patented design, the diode-pumped, frequency-quadrupled laser is a self-contained, conduction-cooled, sealed plug-and-play device. Its control unit can be operated either directly via push button or remotely via serial RS232 or USB interface. According to the company, the FQCW266-10-C is low noise, highly reliable, and very stable. Applications include use in photoluminescence, UV Raman spectroscopy, laser-induced fluorescence, optics testing, and metrology. ***Crystal Laser Systems GmbH***, *Ostendstrasse 25, 12459 Berlin, Germany, www.crylas.de*

Camera for ultrasensitive microscopy

Andor Technology, an Oxford Instruments company, has added a new model, the Sona 4.2B-6, to its Sona back-illuminated microscopy camera series. The series' high sensitivity allows for an optimized signal-to-noise ratio under reduced illumination, low fluorophore concentrations, and decreased exposure times. It accurately preserves the biology of living cells during extended measurement periods. According to the company, the Sona 4.2B-6 balances sensitivity with speed and resolution to achieve up to 74 fps for full-range 16-bit images. When combined with the commonly used 60× and 40× objective lens magnifications, the Sona's 4.2 MP sensor format with a 6.5 μm pixel size obtains maximum resolution. A low-noise mode uses correlated multisampling to improve image detail while maintaining frame rates and low exposure times. Applications include Förster resonance energy transfer, ion signaling, and localization-based superresolution. ***Andor Technology Ltd***, *Springvale Business Park, 7 Millennium Way, Belfast BT12 7AL, UK, https://andor.oxinst.com*

Hyperspectral camera

HERA, a compact hyperspectral camera from Nireos, can create a hyperspectral data cube by capturing in a few seconds a continuous spectrum, in the 400–1000 nm region, of each image pixel. Based on a patented Fourier-transform technology, HERA uses an ultrastable interferometer with a 1 cm clear aperture. It dispenses with filters and gratings, which typically limit the light throughput. With less than 1 nm resolution at 400 nm wavelength, HERA can accurately characterize all types of materials in the visible region. The camera's software allows users to capture an image more quickly, although spectral resolution may be diminished. HERA is suitable for use in fluorescence imaging, cultural heritage conservation, and other low-light applications; onsite material sorting; and plant analysis. ***Nireos SRL***, *Via Giovanni Durando, 39, 20158 Milan, Italy, www.nireos.com* PT

Gloria Becker Lubkin

The physics community lost a treasured citizen when Gloria Becker Lubkin died of colon cancer on 26 January 2020 in Raleigh, North Carolina.

Gloria was a journalist extraordinaire. Her network of friends and acquaintances was unparalleled: luminaries from essentially every major field of physics and a vast circle of researchers in academia, government, and industry. Her friendships were international, springing from scientific visits to the Soviet Union in 1968, Japan in 1975, and China in 1979, and numerous visits to Europe. Her understanding of physics and her skills as a writer and journalist, together with her enormous circle of friends and contacts, uniquely qualified her for her five-decade career at PHYSICS TODAY and her legendary reputation as writer, editor, and editor-in-chief.

Born in Philadelphia on 16 May 1933, Gloria received her AB in physics from Temple University in 1953. She then pursued graduate work at Boston University, where she earned an MA in nuclear physics in 1957 for a thesis supervised by Fay Ajzenberg-Selove. A week after Gloria received her degree, she married Yale Jay Lubkin. To support her graduate studies, she took a series of short-term positions in industries—often nuclear related—and as an interim professor. That pattern continued after graduation but stopped abruptly when she was fired for pregnancy, as was legal at the time.

In 1963 Gloria switched careers. She enjoyed writing and had reported for her college newspaper. A great conversationalist with a natural gift for explaining physics, she phoned the editor of PHYSICS TODAY (PT), Robert Davis. Their conversation ended abruptly when Davis exclaimed, "You're hired! Come on over."

Gloria was associate editor from 1963 to 1970. In 1964 she was fired again for pregnancy; she returned to PT part time six weeks after giving birth. In 1968 she divorced and resumed full-time work at PT. Two years later she was appointed senior editor. Her career flowered, and over the decades she helped mold the magazine. She was editor-in-chief from 1985 to 1994, editorial director from 1994 to 2000, and editor-at-large from 2001 to 2003. She was editor emerita from 2003 to 2009, when she retired.

In 1974–75 Gloria received a Nieman journalism fellowship at Harvard University, where she attended classes and formed links with journalists. When Peter Kapitza, a 1978 physics Nobelist, visited the US in the 1970s, the only journalists he agreed to talk with were Walter Sullivan of the *New York Times* and Gloria.

Gloria read everything published in PT, edited many of the articles herself, and wrote about 450 articles over the years. She built a staff of editors and meticulously mentored them. She transformed much of the magazine. The Search and Discovery department grew from a series of brief reports to substantive articles by a well-informed staff. Her scientific knowledge and her reputation for integrity were powerful assets in her roles both as editor and writer.

In 1986 Gloria created Reference Frame, a department of personal, thought-provoking essays by writers she selected. Her enthusiasm, scientific credibility, and charm enabled her to enlist a bravura group of authors, including Philip Anderson, David Gross, Herman Feshbach, Leo Kadanoff, James Langer, Leon Lederman, David Mermin, Helen Quinn, Vera Rubin, and Frank Wilczek. Also, both of us. (Gloria would insist on total transparency.)

Throughout her career, Gloria was seriously concerned about the problems faced by women in physics. In 1971 she coorganized a session on the situation at an American Physical Society meeting and became a founding member of the Committee on the Status of Women in Physics.

In the 1980s real estate developer William I. Fine proposed funding and establishing a world-class theoretical institute at the University of Minnesota. The physics department turned to Gloria for advice. She knew several Russian physicists who were distressed by the collapsing economy in their country. As a result, the Fine Theoretical Physics Institute (FTPI) was created with a critical number of first-rank Russian theorists forming its faculty. The FTPI is now a leader among such international institutes. Gloria cochaired its Oversight Committee from the beginning to 2014. In 1990 the FTPI honored her by establishing the Gloria Becker Lubkin Chair in Theoretical Physics.

Gloria Becker Lubkin

COURTESY OF SHARON LUBKIN

In 2013 Gloria was appointed visiting senior research scholar at the University of Maryland department of physics. She was working on a memoir when in 2014 a health crisis halted her writing.

Frank Wilczek, Herman Feshbach Professor of Physics at MIT, spoke for many in the physics community when he commented about Gloria: "She laughed both often and infectiously. She loved physics and she loved its community. She had a story for every occasion. I'll miss her. We all will miss her."

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Boston University
Boston, Massachusetts
Harvard University
Cambridge, Massachusetts
Daniel Kleppner
Massachusetts Institute of Technology
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Amy Lang is a professor in the department of aerospace engineering and mechanics at the University of Alabama in Tuscaloosa.

The speedy secret of shark skin

Amy W. Lang

The outward flaring of a shark's scales removes drag-producing eddies that otherwise form in the animal's wake.

Shortfin mako sharks are the cheetahs of the open ocean, with some estimates putting their top speeds at more than 100 km/hr. That swiftness may be the result of more than just powerful muscles and a streamlined shape. All sharks have enamel-coated scales, known as dermal denticles, that resemble tiny, translucent teeth, and on fast swimmers like the mako the scales are small—about 0.2 mm, as shown in figure 1. Not only do those scales act as a suit of armor, they also reduce the shark's hydrodynamic drag.

Friction and pressure

A swimming animal experiences two dominant sources of drag. The retarding force is largely due to viscosity, which in the reference frame of the shark causes water passing over its body to stick to the surface—a phenomenon in fluid dynamics known as the no-slip condition. That condition is responsible for a boundary layer, a thin region of fluid across which the velocity difference between the free stream and the body of the shark is sustained.

One source of drag is skin friction from the shear stress of viscous fluid rubbing against the surface. Scientists have known for decades that small riblets—stream-wise grooves on top of the scales—reduce skin-friction drag in a turbulent boundary layer by almost 10%.

The second source, known as pressure drag, has the potential to slow the animal to a much greater extent. It is the net force due to pressure around the entire body. Jutting your hand out the window of a moving car illustrates the effect: With your hand held against oncoming air, you can feel high pressure on your palm and low pressure on the back of your hand, with the net force due to pressure against the direction of motion. Streamlining its body—elongating and smoothing out the sharp, angular features—is the mako's first line of defense against pressure drag.

Pressure drag increases dramatically when the flow separates from the body—that is, when the high-momentum flow of water follows a path that no longer adheres to the shark's

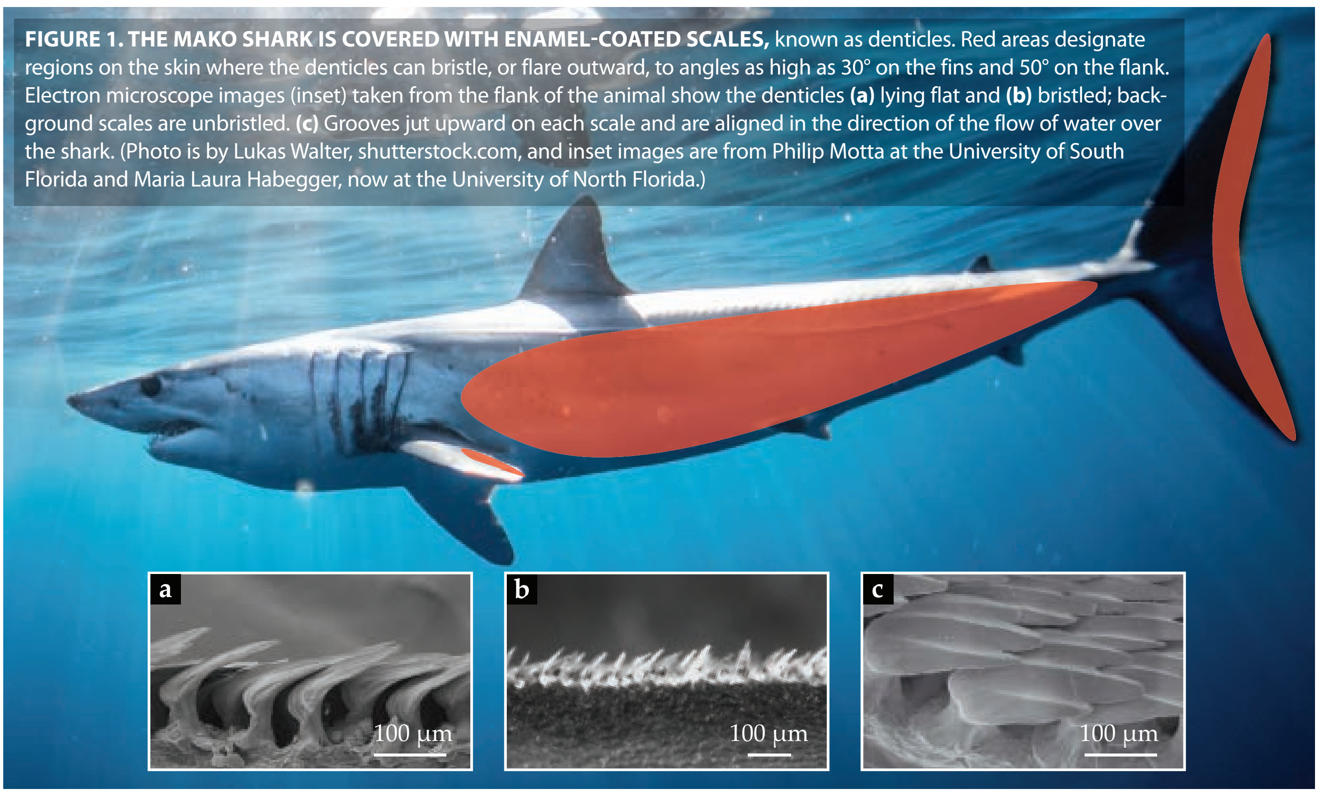

FIGURE 1. THE MAKO SHARK IS COVERED WITH ENAMEL-COATED SCALES, known as denticles. Red areas designate regions on the skin where the denticles can bristle, or flare outward, to angles as high as 30° on the fins and 50° on the flank. Electron microscope images (inset) taken from the flank of the animal show the denticles **(a)** lying flat and **(b)** bristled; background scales are unbristled. **(c)** Grooves jut upward on each scale and are aligned in the direction of the flow of water over the shark. (Photo is by Lukas Walter, shutterstock.com, and inset images are from Philip Motta at the University of South Florida and Maria Laura Habegger, now at the University of North Florida.)

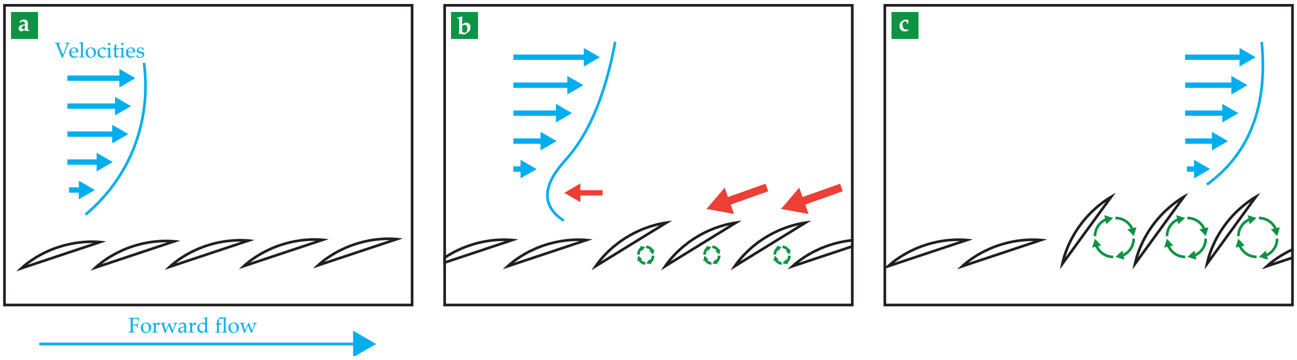

FIGURE 2. BRISTLING IN ACTION. Consider a single location on the shark's flank. **(a)** As water flows (blue) over the body, from nose to tail, the scales (black) lie flat. **(b)** But as the turbulent boundary layer experiences a higher-pressure gradient, the flow begins to reverse direction (red), which causes the scales to flare outward. **(c)** That bristling intermittently stops the flow reversal, as the vortices (green) from the flow's wake are shielded in the scales' cavities. As forward flow redevelops, the scales lie back down again. That dynamic motion repeats on the scale of milliseconds to minimize pressure drag on key locations of the shark's body. (Figure by Amy Lang.)

streamlined shape. A wake, or low-pressure region, forms in the gap created by the separation and is accompanied by a reversal in flow direction along the surface. The earlier the flow separates from the body, the larger the wake and the higher the drag. A golf ball has dimples to ameliorate just that effect: Dimples help to keep the flow attached farther around the back side of the ball; the attachment delays the point of separation and reduces the size of the wake. Indeed, a dimpled golf ball can be hit 30% farther than a smooth one. (See the Quick Study by John Eric Goff, PHYSICS TODAY, July 2010, page 62.)

Controlling the flow

Unlike a golf ball, a shark has a preferred flow direction—from nose to tail. Figure 2 illustrates how the scales control, at least to some extent, flow separation in the high-speed and turbulent-flow regime. As water passes over a shark's maximum girth at the gills, the Bernoulli effect forces it to accelerate to maximum velocity and minimum pressure. (The effect also sucks water through the gills.)

Downstream of that point of minimum pressure along the flank, where the shark undulates in order to swim, the flow experiences an adverse pressure gradient, in that the pressure increases as the flow slows. But because a fluid always moves toward a region of low pressure, the fluid nearest the surface in the boundary layer reverses direction and starts flowing upstream. It is that reversing flow that initiates flow separation. A passive mechanism that inhibits the flow from reversing would prevent, or at least delay, the separation and thus decrease pressure drag.

The scale orientation and bristling capability of the denticles exhibit just that kind of influence. The scales do not bristle as water passes over the skin from nose to tail when the flow is attached. However, on certain body locations—on the flank and trailing edges of the fins and tail, which correspond to regions of high adverse-pressure gradient—the scales sit loosely in the skin and are capable of bristling to angles as high as 50°, but only in the direction of reversed flow, from tail to nose.

In 2012 a collaboration between my group at the University of Alabama and biologists Philip Motta and Laura Habegger (both at the University of South Florida) discovered that the mako's scale-bristling capability was much larger than anyone had realized. As the flow in the boundary layer begins to reverse (red arrows in figure 2), it forces the denticles to bristle—flow-actuated, passive behavior that prevents the reversing flow from further developing into a state of large-scale flow separation. The bristling denticles effectively shield the animal from drag-producing eddies.

A secondary mechanism may also be at work. When scales bristle, they create cavities, whose presence induces turbulent mixing in the boundary layer. That mixing forces higher-momentum fluid in the layer's upper part (blue velocity vectors in figure 2) toward the surface, thereby increasing the speed of that near-surface boundary layer and, in effect, delaying flow reversal. Experiments imaging mako skin scales from the flank region have shown that the bristling caused by flow reversal is dynamic and rapid: The denticles took just 1 ms to flare outward from a reversed flow and were just as quick to lie back down when the stream-wise flow resumed.

For a description of our experiments to document the ability of mako skin to control flow separation, see the online supplement to this Quick Study.

We hope these findings will inspire the design and manufacture of surfaces that could be applied to submarines and aircraft alike. Flow separation not only produces higher drag; it can also cause airfoil surfaces, such as wings and helicopter blades, to lose lift. Covered with synthetic shark skin, submarines and aircraft would experience reduced fuel consumption, higher speeds, and greater maneuverability.

Additional resources

▶ F. Afroz et al., "Experimental study of laminar and turbulent boundary layer separation control of shark skin," *Bioinspir. Biomim.* **12**, 016009 (2017).

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▶ M. Gad-el-Hak, *Flow Control: Passive, Active, and Reactive Flow Management*, Cambridge U. Press (2006).

▶ K. Du Clos et al., "Passive bristling of mako shark scales in reversing flows," *J. R. Soc. Interface* **15**, 20180473 (2018).

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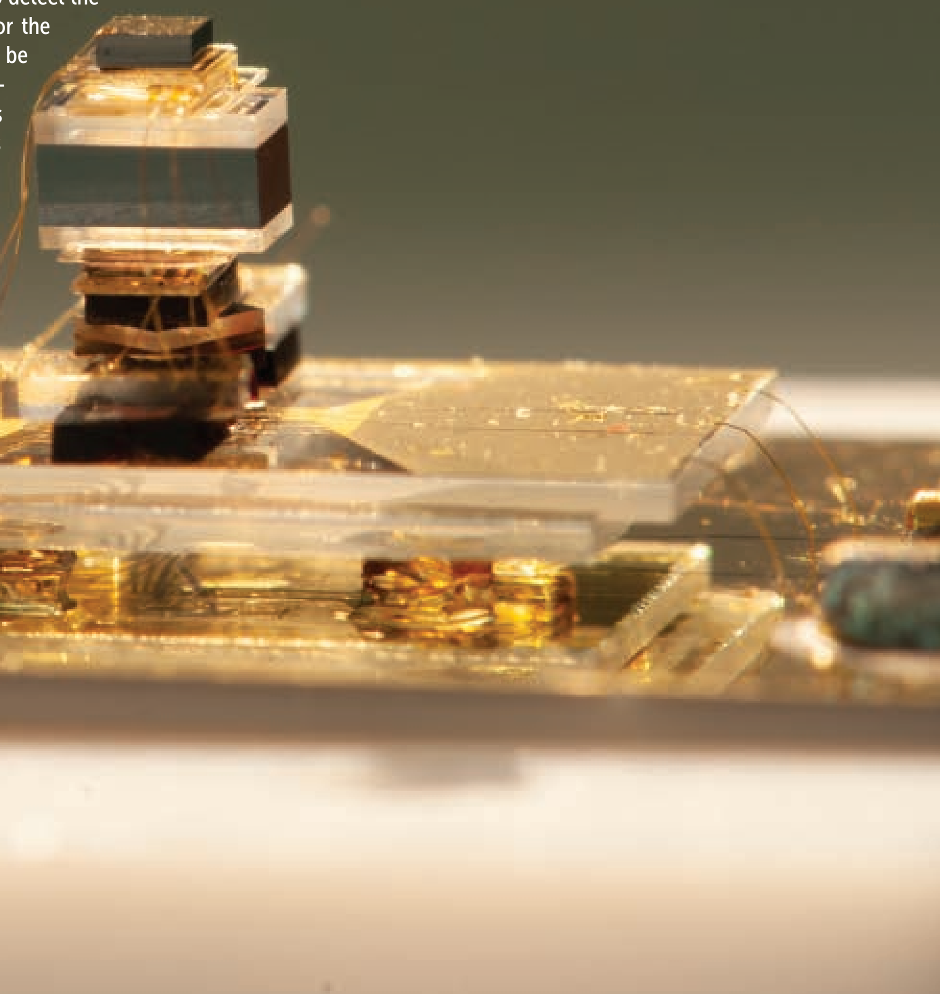
BACK SCATTER

NIST on a chip

A lab has traditionally been the preferred place to make small, detailed physical measurements. But sometimes a user needs to collect data *in situ*—for example, precisely measuring ionizing radiation that a human body may be exposed to during certain medical treatments. To help with that effort, researchers are designing microscale photonic radiometers. Accurate, quantum-based measurements also are increasingly important for other applications, including in navigation, security, and transportation. Scientists at NIST in Gaithersburg, Maryland, and in Boulder, Colorado, are working to meet that demand through the NIST on a Chip program.

Chip-scale magnetometers, such as the one pictured here, are fabricated with silicon micromachining techniques. They are about the size of a grain of rice. Inside is an atomic vapor cell that contains alkali atoms. When a pump laser shines through the cell, the spins of the atoms' unpaired electrons orient in the same direction. An applied, external magnetic field changes that orientation, which is then measured with the same light used to pump the atoms. The applications span many field strengths. Such a magnetometer could be placed aboard a low-cost cube satellite sent to detect the 25 000- to 65 000-nanotesla magnetic field of Earth or the magnetic fields of other planets. The device could also be implanted in a medical instrument to record the femtotesla-scale magnetic signal that transmits from human organs such as the heart or brain; that signal is about a billion times fainter than Earth's magnetic field at the planet's surface. (Image courtesy of John Kitching.) —AL



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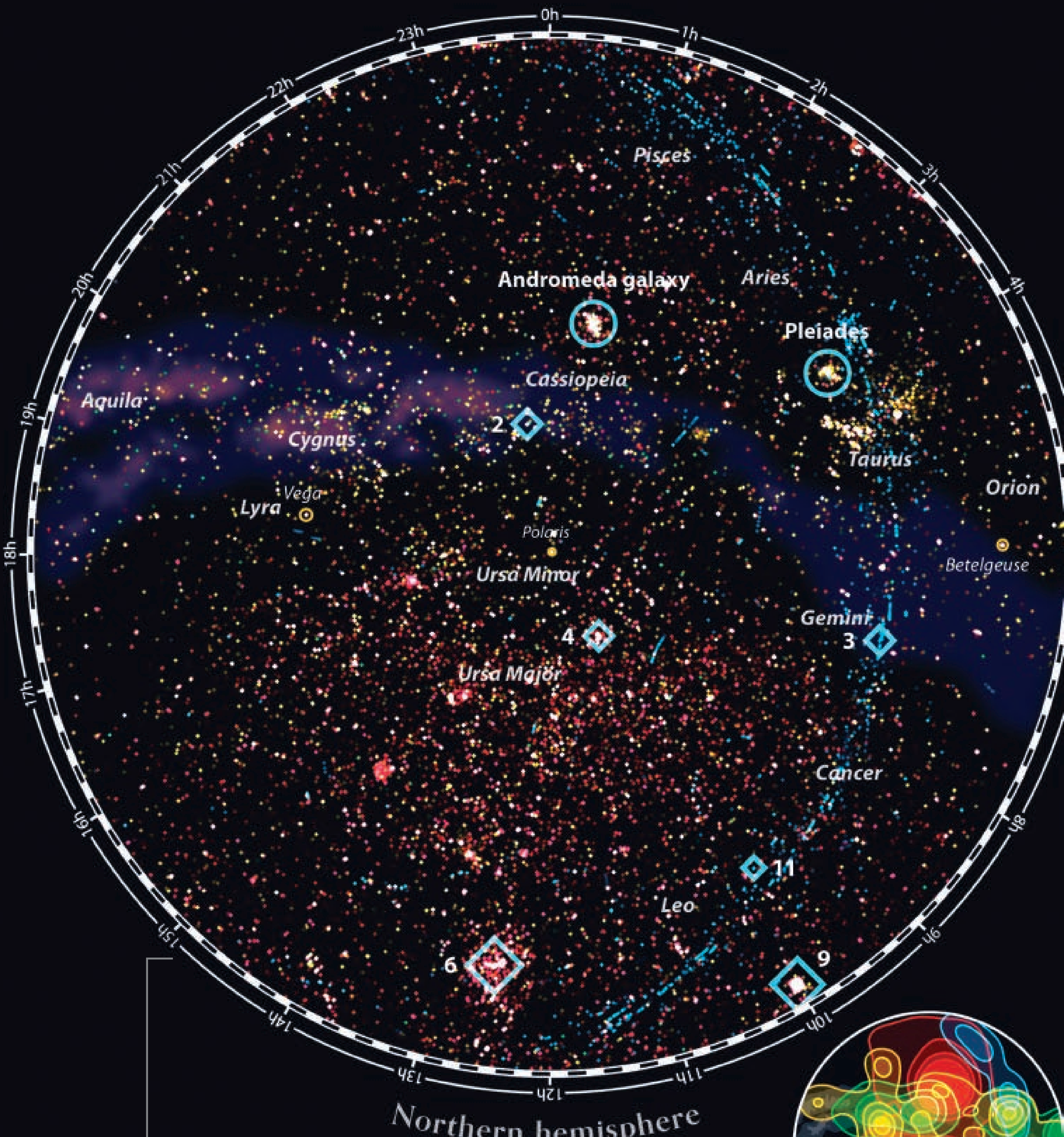

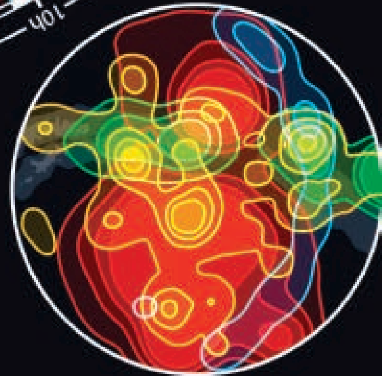

Hubble's observations

Each point on this map represents a *Hubble* scientific observation in the telescope data archive. The color signifies the main category of the observation target: ***Star*** and ***Stellar cluster***, which include extra-solar planets; ***Galaxy*** and ***Cluster of galaxies***, which include quasars and clusters that serve as gravitational lenses; interstellar medium, or ***ISM***, which includes planetary nebulae and supernova remnants; and ***Solar system***. Other observations are tagged as ***Unidentified***, such as the Hubble Deep Field surveys, or as ***Calibration***.

NASA

HUBBLE's 30-year legacy

In the three decades since the space shuttle *Discovery* carried it into orbit on 24 April 1990, the *Hubble Space Telescope* has changed the way both astronomers and the general public understand the cosmos. Incorporating some 550 000 scientific observations from the Space Telescope Science Institute's comprehensive Barbara A. Mikulski Archive for Space Telescopes, this stereographic map charts the diverse astronomical objects that *Hubble* looked at from 1990 to 2019. The callouts link specific observing proposals with the celebrated images and discoveries they produced. With its instruments working well and demand for observing time as high as ever, *Hubble* is primed to continue exploring the universe through at least 2025.

1

Ultra Deep Field

Proposals 9978–81 | 2003 | The Ultra Deep Field

By staring at a dark spot of sky for a cumulative 11.3 days, *Hubble* returned this view of about 10 000 galaxies, some of them dating back to when the universe was less than a billion years old.

Unidentified | *Blank field, High-latitude field*

2

Bubble Nebula

Proposal 14471 | 2016 | Hubble Heritage 2016

Hubble has returned multiple images of a young, massive star whose stellar wind has created a glowing bubble of heated gas that spans 7 light-years.

Unidentified | *Shell*

3

Jupiter

Proposal 13631 | 2014 | Dynamical change in Jupiter's Great Red Spot

Hubble has tracked the slow, steady diminution of the solar system's most famous anticyclone, the Great Red Spot (GRS).

Solar system | *Planet Jupiter, GRS dynamics*

4

Spiral galaxy M81

Proposal 2227 | 1991 | Determination of the extragalactic distance scale

Measurements of Cepheid variable stars in M81 helped establish one rung of the cosmic distance ladder that has been used to estimate the age of the universe.

Galaxy | *Spiral galaxy*

5

V838 Monocerotis

Proposals 9587–88 and 9694 | 2002 | HST imaging polarimetry of the light echo around V838 Monocerotis

Polarization measurements of light bouncing off a cocoon of dust helped scientists pin down the distance from Earth to the central red supergiant star, which briefly was one of the most luminous stars in the Local Group.

Star | *Nova-like*

6

Elliptical galaxy M87

Proposals 5267 and 5634 | 1994 | Velocity dispersions in the nucleus of M87

A quarter century after *Hubble* gazed at M87 to confirm whether supermassive black holes at the centers of galaxies exist, a network of radio telescopes directly imaged the galaxy's central black hole.

Galaxy | *Elliptical galaxy, Nucleus*
ISM **(extragalactic)** | *Coronal gas*

PHOTOS COURTESY OF NASA AND ESA. ADDITIONAL CREDITS: S. BECKWITH/STSCI AND THE HUDF TEAM (TOP); A. SIMON/GODDARD SPACE FLIGHT CENTER AND C. GO (MIDDLE); AND H. E. BOND/STSCI (BOTTOM).

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For more *Hubble* visualizations, history, and analysis, visit www.physicstoday.org.

Visualization by Nadieh Bremer • Text by Andrew Grant

7

Fomalhaut b

Proposal 9862 | 2004 | ACS detection of substellar companions around Vega, Fomalhaut, and beta Pic via parallax and proper motion

The first exoplanet to be directly imaged follows a long, highly elliptical orbit around its host star.

Star | *A0–A3 V–IV*

8

Eagle Nebula

Proposal 10393 | 2004 | Hubble Heritage observations of Eagle Nebula

Among *Hubble*'s most captivating cosmic subjects, first imaged in 1995, are the Pillars of Creation: billowing towers of cold gas and dust in a stellar nursery.

ISM | *Planetary nebula*

9

COSMOS

Proposal 9822 | 2003 | The COSMOS 2-Degree ACS Survey

Capturing more than 2 million galaxies over a 2-square-degree field, the Cosmic Evolution Survey is *Hubble*'s largest-ever sky survey.

Cluster of galaxies | *Blank sky*
Unidentified | *Parallel field*

10

NGC 3603

Proposal 10602 | 2005 | A complete multiplicity survey of galactic O2/O3/O3.5 stars with ACS

Astronomers have analyzed some of the young, massive stars clustered in the nebula to help evaluate theoretical limits of stellar mass.

Stellar cluster | *Star-forming region, OB association*

11

Comet 2I/Borisov

Proposal 16009 | 2019 | Interstellar object C/2019 Q4

Over the past three years, *Hubble* has observed two objects in the solar system that are likely interstellar visitors, including this active comet.

Solar system | *Comet, Interstellar comet*

12

Antennae galaxies

Proposal 10188 | 2004 | In-depth study of the Antennae with NICMOS and ACS

The pair of merging galaxies offers a possible preview of the Milky Way's future merger with the Andromeda galaxy.

Galaxy | *Interacting galaxy*

PHOTOS COURTESY OF NASA, ESA, AND THE HUBBLE HERITAGE TEAM (STSCI/AURA). ADDITIONAL CREDITS: ESA/HUBBLE COLLABORATION (MIDDLE); AND ESA/HUBBLE COLLABORATION AND B. WHITMORE/STSCI (BOTTOM).

Charles Day

Hatching HUBBLE

The advantages of placing a telescope above Earth's turbulent, absorbent atmosphere were apparent well before German V-2 rockets reached space in the 1940s. But what were the main technological hurdles to be surmounted? In an 11-page report for the think tank RAND, astronomer Lyman Spitzer Jr, then at Yale University, laid them out.[1] He also outlined what research might be accomplished with two sizes of extraterrestrial orbiting telescope: a 10-inch reflector and a 200-inch reflector.

On the need to steadily point instruments at stars and other targets, Spitzer was optimistically brief: "Orientation might be accomplished in principle by reducing the angular momentum of the satellite to zero by means of external jets; thereafter the satellite could be rotated by internal means to any particular direction." On the need to telemeter data back to Earth, he acknowledged that it "would involve many problems." Undaunted, Spitzer predicted that a large space telescope would not so much supplement ground-based instruments. Rather, it would "uncover new phenomena not yet imagined, and perhaps to modify profoundly our basic concepts of space and time."

In 1990, the year NASA launched the *Hubble Space Telescope*, Spitzer added a postscript to his 1946 RAND report.[1] He noted that the report did not appear in the astronomical literature and it had not been widely distributed as a preprint. Its influence on astronomers was negligible, he concluded. "Its chief effect," he wrote, "was on me."

Convinced that a large space telescope was feasible, he championed the concept. Congress approved $36 million to fund its development in 1978. Spitzer recounted in his postscript that one of the crucial technologies that convinced Congress of the success of a large space telescope was the vidicon. Developed at RCA in the 1950s, the vidicon is a type of video camera tube. Focused photons strike and excite a photoconductor, whose charge distribution—the image—is read out by low-energy electrons and converted to a telemeterable electrical signal.

Four UV-adapted vidicons made by Westinghouse flew aboard *Orbiting Astronomical Observatory 2* (*OAO-2*), which was launched in 1968 and is recognized as the first successful optical space telescope.

That same year Spitzer wrote a paper for *Science* that updated his 1946 report.[2] One of the biggest challenges that remained was how to hold the telescope's gaze. For the four 12-inch telescopes that focused light onto *OAO-2*'s vidicons, a pointing accuracy of 0.1 arcseconds sufficed. For the 120-inch *Large Space Telescope* that Spitzer envisioned, reaping the gain in resolution from observing in space would require far greater steadiness. He calculated that a pointing accuracy of 0.004 arcseconds would be needed when observing at 500 nanometers, the middle of the visible spectrum. *Hubble* ended up with a primary mirror of 2.4 meters, or 95 inches. The spacecraft's attitude control achieved a pointing precision of 0.007 arcseconds over an entire day.

Among the observations Spitzer anticipated in 1968 were of Cepheid variable stars. Distances to that class of variable stars can be derived thanks to a relation between their absolute luminosity and the period of their brightness fluctuations. Galactic and extragalactic Cepheids constitute the first rungs on the extragalactic distance ladder. The *Large Space Telescope*, Spitzer predicted, could extend the range of Cepheid observations by an order of magnitude.

At the time of *Hubble*'s launch, the current value of the Hubble constant H_0 was so uncertain that cosmologists used a dimensionless variable, h, to represent the factor by which H_0 differed from an upper limit of 100 km/s/Mpc. Before *Hubble*'s advent, h could conceivably be as small as 0.5. By the time *Hubble* had completed its first set of Cepheid observations in 2005, H_0 was determined to be 72 ± 8 km/s/Mpc. Last year, a team using *Hubble* images of gravitationally lensed quasars derived a value of 73.3 + 1.7 − 1.8 km/s/Mpc.

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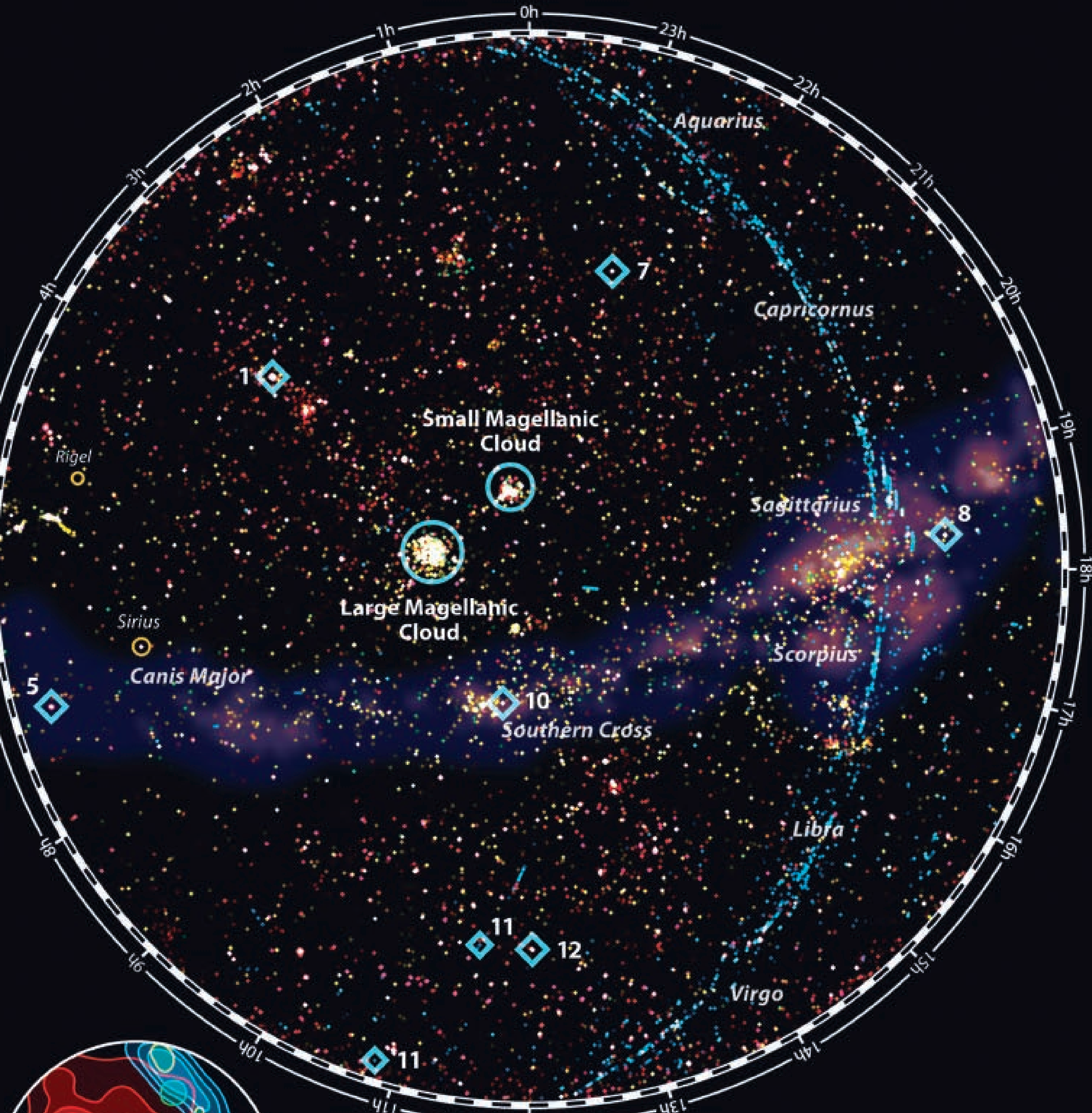
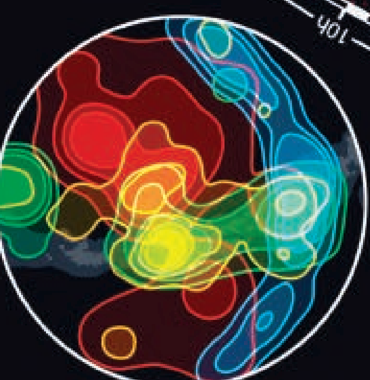
Charles Day is Physics Today's editor-in-chief.



Southern hemisphere



Hubble hot spots

The contours in this small map reveal roughly where the bulk of each category of target has been observed. Most stellar and ISM targets are in the disk of the Milky Way, so the observations cluster along the galactic plane. Many galaxy and galaxy cluster observations are made in the northern hemisphere because of the extensive catalog of targets already compiled by ground-based projects such as the Sloan Digital Sky Survey. Planets, moons, and other solar-system objects have been viewed at various positions along the ecliptic.