PHYSICS TODAY

January 2021 • volume 74, number 1

A publication of the American Institute of Physics

SEISMIC DAMAGE

Fast radio bursts

Nuclear power in Canada

Color from nanostructure

SUPPORT SCIENCE

To friends and donors, please accept our best wishes for a happy—and healthy—New Year!

Thank you for your generosity in 2020 to programs of the American Institute of Physics including the Center for History of Physics, The Niels Bohr Library & Archives, and student scholarships and other programs administered through Sigma Pi Sigma and the Society of Physics Students.

To learn more about ways that you can make a difference in advocating for science in 2021, visit: **foundation.aip.org**

Looking ahead to 2021, please also join the AIP Foundation in congratulating and welcoming members of its inaugural Board of Trustees.

With best wishes for the New Year,

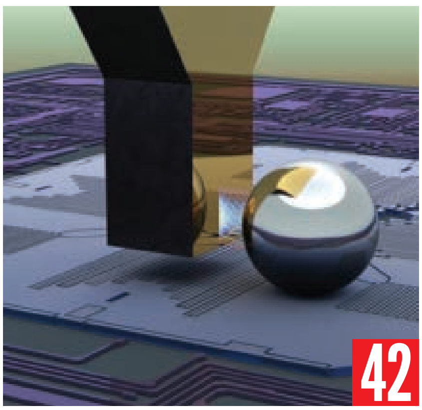
Tanya L. Easton, Ed.D.
Executive Director
AIP Foundation

Introducing the Inaugural Board of Trustees for the AIP Foundation:

Learn more about the AIP Foundation Board of Trustees, the AIP Foundation and ways to support programs of the Institute at: **foundation.aip.org**

PHYSICS TODAY

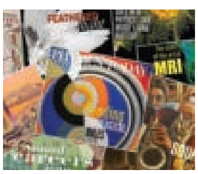
January 2021 | volume 74 number 1



ON THE COVER: Depicted in this woodblock print, the 1855 Ansei Edo earthquake caused widespread destruction in and around what is now Tokyo. Just how earthquakes damage buildings is the subject of the feature article by Koji Uenishi on **page 34**. The curious appearance of catfish in the print and others like it sprang from the myth that earthquakes and tsunamis are caused by the thrashing of giant, subterranean catfish. (Image from CPA Media Pte Ltd/Alamy Stock Photo.)

Recently on PHYSICS TODAY ONLINE

www.physicstoday.org



PADIAN/PAGANI/CUMMINGS

Best of 2020

Take a look at Physics Today's most popular articles from last year, including several available only online. Topics include graduate departments' move away from the GRE, the growing discrepancy between Hubble-constant measurements, and the prevalence of anti-Black racism in the physics community.

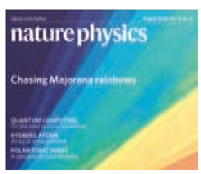
physicstoday.org/Jan2021a

SPRINGER; HARVARD U. PRESS

The year in books

Physics Today editors look back at 2020 and compile a list of recommended books for enthusiasts of physics and history of science. Selections include a biography of astronomer Cecilia Payne-Gaposchkin, a survival guide for researchers, and a unique work that is part popular science, part history, and part memoir.

physicstoday.org/Jan2021b



SPRINGER NATURE

Nature changes

Springer Nature recently announced policy changes for its *Nature* journals, including giving authors the option to make published papers freely available immediately. Dalmeet Singh Chawla examines the connection to Europe's Plan S open-access initiative and researchers' concerns over article fees.

physicstoday.org/Jan2021c

Physics Today (ISSN 0031-9228, coden PHTOAD) volume 74, number 1. Published monthly by the American Institute of Physics, 1305 Walt Whitman Rd, Suite 300, Melville, NY 11747-4300. Periodicals postage paid at Huntington Station, NY, and at additional mailing offices. POSTMASTER: Send address changes to Physics Today, American Institute of Physics, 1305 Walt Whitman Rd, Suite 300, Melville, NY 11747-4300. Views expressed in Physics Today and on its website are those of the authors and not necessarily those of AIP or any of its member societies.

PHYSICS TODAY

www.physicstoday.org

DEPARTMENTS

SUBSCRIPTION QUESTIONS? +1 800 344-6902 | +1 516 576-2270 | **ptsubs@aip.org**

Address
American Center for Physics
One Physics Ellipse
College Park, MD 20740-3842
+1 301 209-3100
pteditors@aip.org

PhysicsToday **@physicstoday**

THE UNIVERSITY OF ALABAMA AT BIRMINGHAM

Assistant Professor Position – Condensed Matter Physics

The UAB Department of Physics, https://www.uab.edu/cas/physics/, invites applications for an Assistant Professor tenure-track faculty position that will strengthen the Department's program in **Theoretical and Computational Condensed Matter Physics.** A qualified applicant will have a Ph.D. in Physics. Research areas of interest are broadly defined in theoretical physics, quantum materials science and computation, and quantum information science. They include, but are not limited to, high-performance computing, quantum computing and simulations, non-equilibrium dynamics, and data-driven simulations of quantum materials properties. We are looking for an innovative and inclusive new faculty member with an outstanding publication record and a strong commitment to excellence and diversity in research, teaching, outreach, and student research supervision at both graduate and undergraduate levels. This faculty member will also help us sustain departmental efforts for "data and digital literacy for all UAB students". These efforts include innovative distance-accessible STEM education focusing on Computational Modeling Instruction. We particularly welcome applicants from underrepresented groups in the physical sciences. Screening of applications will begin immediately and continue until the position is filled. The fullest consideration will be given to all applications received by January 31, 2021, that include: (i) short letter clearly explaining the applicant's research and extramural funding ideas and her/his experiences and qualifications relevant to this position, (ii) full curriculum vitae, (iii) statement of planned and past research projects, (iv) brief description of teaching and mentoring interests and diversity, equity, and inclusion philosophy, (v) three reference letters. All applications will be handled through http://uab.peopleadmin.com/postings/8028. For more information, please contact the search committee chair Cheng-Chien Chen, chencc@uab.edu

The University of Alabama at Birmingham (UAB) is a comprehensive urban university with the nation's third-largest public hospital, which has rapidly evolved into a world-renowned research university and health care center that ranks in the top ten nationally for student diversity. Times Higher Education has ranked UAB No. 1 young U.S. university for two years in a row, top 10 worldwide. UAB is Alabama's single largest employer and an engine of revitalization for Birmingham. With a record enrollment of over 22,500 students, over 2,200 full-time faculty members, and a campus covering more than 100 city blocks, UAB is focused on the future of teaching, research, health care, and community service. We are also a founding partner of Innovation Depot, the largest high-tech incubator in the southeast, whose economic impact between 2010 and 2015 was $1.38 billion. UAB research funding is at an all-time high of over $600M, while the Physics footprint continues to grow with the new state-of-the-art Science and Engineering Complex that will host the Department. The Department of Physics is experiencing growth fueled by its focus on Advanced Materials, Optics, and Computation, as well as using emerging technologies to remove existing barriers and provide equal opportunities for high-quality education across geographical, social, economic, and gender boundaries. Birmingham is the largest city in Alabama, noted for its vibrant music scene, fine dining, warm weather, excellent schools, and a culture embracing diversity within driving distance to Atlanta, Memphis, Nashville, and New Orleans

UAB is an Equal Opportunity/Affirmative Action Employer committed to fostering a diverse, equitable and family-friendly environment in which all faculty and staff can excel and achieve work/life balance irrespective of race, national origin, age, genetic or family medical history, gender, faith, gender identity and expression as well as sexual orientation. UAB also encourages applications from individuals with disabilities and veterans.

A pre-employment background investigation is performed on candidates selected for employment.

Wir fahr'n fahr'n fahr'n auf der Autobahn

Charles Day

One day in 1975 (I've been unable to track down the date), the BBC's science and technology TV show *Tomorrow's World* opened with the German band Kraftwerk playing the title track of their 1974 album, *Autobahn*. I was 12.

Even if I hadn't found the Kraftwerk clip on YouTube, I'd still remember much about the band's TV performance. It seems conventional at first. The two keyboardists, Ralf Hütter and Florian Schneider, play Minimoog synthesizers while twiddling knobs to adjust the sound. But then the camera pans to show Karl Bartos and Wolfgang Flür using what look like knitting needles to rhythmically tap metal disks the size of drink coasters.

Perhaps anticipating viewers' puzzlement, the show's presenter, Raymond Baxter, explains in a voiceover, "Last year they removed the last recognizable instrument, the violin, and built these synthetic drums. Each disk gives a different sound—rolls, congas, snares—just by completing the contact with the spring steel batons."

Besides synthesizers and electronic percussion, the band was notable for its demeanor. With their neatly groomed hair, conservative ties, and jackets, the band members looked more like middle managers than rock musicians. I was mesmerized!

Tomorrow's World made its debut on 7 July 1965 with the goal of introducing the British public to new technologies. The show's Wikipedia entry lists some of those technologies along with the year they appeared on the show. When Sony released the world's first commercial camcorder, the Betacam, in 1983, viewers of *Tomorrow's World* would have remembered seeing Baxter introduce the technology two years earlier.

Despite the impression that Kraftwerk made on me, I wasn't a devoted fan of *Tomorrow's World*. It was broadcast during the summer in the early evening when I preferred to play outside.

Another science show that could have influenced the young me but didn't was *Horizon*, which served as the blueprint for the PBS show *Nova*. Timothy Boon of London's Science Museum pored through the BBC's archives to discover the story of *Horizon*'s conception in the mid 1960s. His research, which appeared in 2015 in the *British Journal for the History of Science*, volume 48, page 87, revealed that it took four years of research and planning to devise an enduringly successful format: a documentary shot on location, based around interviews with scientists, and without an on-screen presenter.

What accounted for my lack of interest in science TV? It could have to do with what TV offered and what I chose to watch. Factual shows that weren't news or current affairs were relatively rare. Perhaps because I read so many books, I turned to TV for entertainment, not knowledge. The documentary series that transfixed me during my school years, *The World at War* (1973) and *All You Need Is Love: The Story of Popular Music* (1977), are, significantly, just two in number.

Without inspiration from TV, my interest in science grew anyway as I attended classes in biology, chemistry, and physics in secondary school. I didn't need a charismatic presenter or theatrical experiments to get me hooked. But I was lucky to have excellent teachers in my state school in North Wales. Without them, I might have devoured *Tomorrow's World* and *Horizon*.

On page 26 of this issue, historian of science Ingrid Ockert recounts the genesis of *3-2-1 Contact*, a children's science show that ran on PBS in 1980–88. My wife was an avid fan who can still sing the show's theme song. When I asked her what she liked about the show, she had a ready answer: "It taught me I could solve problems by asking questions. I could connect the dots myself. At school we pretty much just learned facts." PT

WHAT SCIENCE SHOWS DID PHYSICS TODAY'S EDITORS WATCH AS CHILDREN? HOW DID THE SHOWS INFLUENCE THEM?

Click on physicstoday.org/jan2021d to read their reminiscences.


Monitor Deposition in Real Time
Ellipsometry offers solutions that improve your process with live feedback.
+OPTIMIZE DEPOSITION PROCESS
Determine thickness and optical properties of films and multi-layer stacks for metals and dielectrics
+IMPROVE QUALITY CONTROL
Detect variations as they occur with live feedback during the deposition process
+MONITOR GROWTH KINETICS
Sub-angstrom thickness sensitivity provides additional information about film nucleation, surface conditions and other process conditions
J.A. Woollam

Nobels neglect fluid dynamics

I was surprised to see that Philip Anderson's obituary (PHYSICS TODAY, June 2020, page 59) did not mention how he viewed the belief held by some in particle physics that their field deserves more funding than other areas. Anderson had said, "There is a great arrogance and immodesty about the whole field." The sidelining of some disciplines of physics in preference to the contemporary, more exotic fields, especially when it comes to awards like the Nobel Prize, is not new.

Since the 19th-century publication of the Navier–Stokes equations, the governing equations in fluid dynamics, many scientists have attempted to solve them. And well-known physicists have worked in different aspects of fluid mechanics. Arnold Sommerfeld, the noted theoretical physicist, had a passion for it, and his "school" was well known for work in it.[1] Much of that work related to stability, transition to turbulence, and lubrication.

Sommerfeld is supposed to have said that before he died he wanted to understand two phenomena—quantum mechanics and turbulence. Theodore von Kármán recalled in his autobiography that Sommerfeld was somewhat nearer to an understanding of the quantum but no closer to the meaning of turbulence.[2]

Werner Heisenberg, a star of quantum mechanics, did his 1924 PhD thesis, "On the stability and turbulence of fluid flow," under Sommerfeld. After World War II, while he was interned at Farm Hall in the UK, Heisenberg contemplated the problem of turbulence stability and the transition to turbulence.[1] Three papers published in 1948 cover his work from that time period.

Outstanding efforts of stalwarts like Ludwig Prandtl, von Kármán, and G. I. Taylor provided the understanding and methodology to examine fluid flow, including turbulence and boundary layers. They thus laid the foundations of aerodynamics, and their work led to rapid development in aeronautics and astronautics.

The field of mechanics, especially fluid mechanics, has been routinely neglected in considerations for the physics Nobel Prize. The importance of the advances mentioned above and their benefit to society underscores the sidelining of the field. Taylor in 1935 privately complained about the Nobel Committee's preference for "atomic physics," owing to nominations being made by previous recipients. Believing that Prandtl should have been awarded a Nobel, Taylor wrote that the prize needed to be opened up to "non-atomic physicists."[3] Von Kármán expressed similar thoughts regarding Prandtl's deservedness.[4] The Nobel Committee's dismissive attitude toward fluid mechanics continues to this day.

Although innovative techniques have created great progress in addressing the problem of turbulence, the general solution to the Navier–Stokes equations remains elusive. The importance and the difficulty of solving the problem of turbulence in fluid mechanics is highlighted by the fact that the Clay Mathematics Institute lists the existence and smoothness of Navier–Stokes solutions as one of its unsolved millennium problems. Let us hope that the one who solves it will win not only the $1 million reward but also the Nobel Prize in Physics.

WAKE CREATED BY THE FERRY TO FANØ, DENMARK. Fluids are important to many processes, in nature and in human actions. Yet the study of fluid mechanics seems to garner few accolades. (Photo by Malene Thyssen, CC BY-SA 3.0.)

References

1. M. Eckert, *Annu. Rev. Fluid Mech.* **47**, 1 (2015).
2. T. von Kármán, L. Edson, *The Wind and Beyond: Theodore von Kármán, Pioneer in Aviation and Pathfinder in Space*, Little, Brown and Co (1967), p. 134.
3. G. Batchelor, *The Life and Legacy of G. I. Taylor*, Cambridge U. Press (1996), p. 185.
4. Ref. 2, p. 40.

Rajan Menon
(menonrajank@gmail.com)
University of St Thomas
St Paul, Minnesota

A memory of Mark Azbel

In their obituary for Mark Azbel in the October 2020 issue of PHYSICS TODAY (page 67), Bertrand Halperin, James Langer, and Roman Mints wrote that "Life in his presence was never dull." How right they are.

In the early 1980s, Mark spent several summers at Bell Labs, where he sat at the extra desk in my office. He was a friendly and soft-spoken man. One day I came into the office, said hello, and sat down at my desk, with my back to him. He picked up the telephone and tapped a few numbers, and I heard one side of an interesting conversation:

"Hello, operator? I would like to make telephone call to Soviet Union please.

"My name? Azbel.

"Azbel. A as in asparagus, Z as in Riemann zeta function, B as in Bogoliubov-Born-Green theory, E as in electron–phonon coupling, . . ."

At that point, I was walking out the door, hand over mouth, trying hard to stifle my laughter.

Azbel finished with ". . . and L as in Landau damping."

Paul Kolodner
(paulkolodner@alumni.princeton.edu)
Hoboken, New Jersey

Whiting's notes on induction-coil size

The article "Sarah Frances Whiting and the 'photography of the invisible'" (PHYSICS TODAY, August 2020, page 26) was fascinating. It was inspiring to learn of the important contributions she and her group made to x-ray science while using relatively modest laboratory facilities at Wellesley College.

I offer a different interpretation of Whiting's notes on an x-ray photography experiment that was "executed with a 6 in. coil"—the induction coil used to supply high voltage to the Crookes tube that produced the x rays. In the nomenclature of the day, the maximum voltage of an induction coil was measured in inches, referring to the maximum length of air-discharge spark it could make, the most reliable way to measure high voltage at the time. A six-inch coil would generate a pulse of about 130 kV. That was a key detail to record because it related directly to the x-ray energy. The coil diameter was much less important.

Fred E. Wietfeldt
(few@tulane.edu)
Tulane University
New Orleans, Louisiana

Isaac Newton was brilliant except when he was not

Andrew Odlyzko's article "Isaac Newton and the perils of the financial South Sea" (PHYSICS TODAY, July 2020, page 30) is more than just a fascinating read about Newton and financial speculation of the time. It is also, perhaps unintentionally, a commentary on society's assumptions about scientists.

Why would we expect Newton to excel in financial speculation? Because of his mastery of mathematics and complex natural systems and his work at the Royal Mint? Perhaps. Furthermore, as a culture we—and often scientists themselves—assume the portability of scientific wisdom: Because science is hard, scientists are considered to be qualified to master "less hard" nonscientific subjects. I have worked in communications at scientific and technical organizations for decades, and it is not uncommon to find PhDs who assume—and even say—"I could do your job better than you. I just don't have time." An exceptional few are good communicators to anyone outside their field; the vast majority are tolerable to dreadful despite their conviction otherwise.

Of course Newton would flunk the test. He had no financial models at the time, and even if he did, the motion of markets owes more to the unquantifiable forces of expectation and fear than to the quantifiable forces of nature that Newton knew so well.

James M. Kent
(jkent@thorntontomasetti.com)
Irvington, New York PT

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

A portable laser system fills the terahertz gap

With the right dimensions, a laser composed of a series of quantum wells emits hard-to-produce terahertz-frequency light without the usual need for cryogenic cooling.

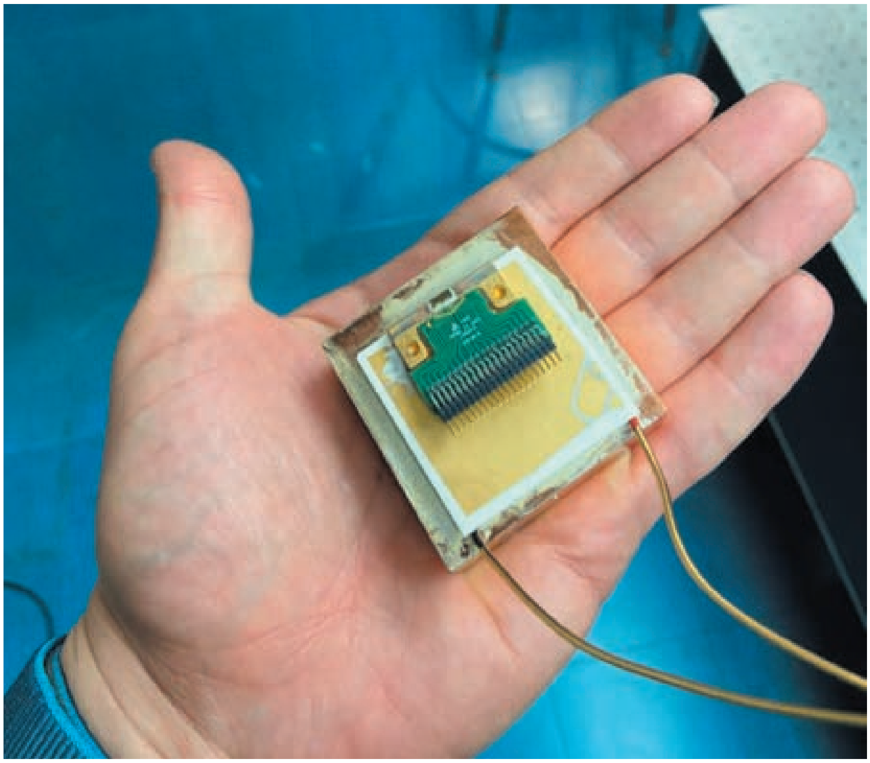


FIGURE 1. THE TERAHERTZ QUANTUM CASCADE LASER and thermoelectric cooler shown here are all the equipment necessary for the portable laser developed by Qing Hu and his colleagues. The compact design opens up potential applications, such as security scans for drugs and skin cancer screening. (Photo courtesy of Qing Hu and colleagues, MIT.)

Many illicit drugs, including methamphetamines and heroin, have distinctive spectral peaks at terahertz frequencies. Terahertz is a happy medium between microwave and IR: Characteristic molecular absorption features are present in the IR and terahertz ranges but largely absent in millimeter and microwave ranges, and many packaging materials that are opaque to IR frequencies are transparent to terahertz light. Such transparent materials include paper, cardboard, wood, textiles, and plastic.

A portable terahertz spectrometer would allow security personnel to nondestructively scan for illegal substances in luggage and other packages. And unlike x-ray screening, it can distinguish materials of similar densities and textures and even offer chemical identification. Researchers have already demonstrated terahertz spectroscopy's ability to distinguish the shape, position, and concentrations of baggies of methamphetamine, MDMA, and aspirin inside a sealed envelope.[1]

Drug scanning and other practical applications, such as skin cancer screening, have been held back, however, because researchers have trouble producing light from about 1 to 10 THz, the so-called terahertz gap. Quantum cascade lasers (QCLs) are a promising photonic method to bridge that gap. But terahertz QCLs typically operate at a maximum temperature of 210 K, which requires bulky, nonportable cryogenic cooling equipment.

MIT's Qing Hu and his colleagues have now developed a terahertz QCL that operates at 250 K. Their compact laser needs only a palm-sized thermoelectric cooler,[2] like that shown in figure 1. The system could broaden the application of terahertz spectroscopy to medical imaging, security screening, and quality inspection.

Bridging the gap

The terahertz gap lies between the frequencies accessible to photonic and electronic technologies. Microwave ovens, cell-phone towers, and walkie-talkies rely on alternating currents to produce electromagnetic waves. But currents can only go back and forth so fast, and that limitation puts an upper bound on how quickly the produced waves can oscillate. Electronic devices readily pump out radio waves and microwaves, but the power drops off above 1 THz as $1/f^4$ or faster in terms of the frequency f.

A semiconductor laser produces light through an electron transition from the conduction band to the valence band. In principle, it's possible to yield frequencies as low as 10 THz. But materials with the requisite small bandgaps are temperature sensitive and difficult to process. Nonlinear optical techniques can circumvent that limit—for example, through down-conversion—but a lot of power is lost.

Quantum cascade lasers create lower energy transitions through periodic layers of different semiconductors, sometimes called a superlattice (see the article by Federico Capasso, Claire Gmachl, Deborah Sivco, and Alfred Cho, PHYSICS TODAY, May 2002, page 34). The layers form quantum wells, and the electrons' spatial confinement splits the conduction band into discrete subbands with energy gaps in the IR or terahertz range. Because the widths of the wells—controlled by the thicknesses of the layers—determine the emission wavelength, researchers are not limited to the naturally occurring properties of semiconducting materials.

Over the years many terahertz QCL shortcomings, such as poor collimation, have been mitigated (see, for example, PHYSICS TODAY, February 2016, page 16). But improving the instruments' maximum operating temperature has been a long-standing challenge.

Cascading effects

Hu first heard about the concepts underlying QCLs at the American Physical Society's March Meeting in 1990, just before he joined the MIT faculty. At the meeting, Manfred Helm, now at Helmholtz-Zentrum Dresden-Rossendorf in Germany, presented his and his colleagues' observation of inter-subband spontaneous emission in the terahertz range from a semiconductor superlattice. A superlattice laser, he argued, should be possible. Even though Hu's background wasn't in laser development, he decided the topic was too interesting and potentially useful to pass up. Terahertz QCLs became a focal point of his research.

Lasing from superlattices was proved possible in 1994, when Bell Labs researchers produced the first QCL, which emitted in the IR. But the move from IR to terahertz laser took another eight years.[3] The difficulty lay in maintaining population inversion, a state in which a higher energy level is teeming with electrons while a lower energy level is relatively empty. Population inversion produces the optical gain necessary for a laser.

In its simplest form, a QCL works as shown in figure 2a. An electron in the nth set of quantum wells starts in the upper lasing level u_n. When the electron drops down to the lower lasing level l_n, a photon is emitted. The electron then scatters to the ground state, known as the injector level i_n, which is still in the conduction band. An applied electric potential offsets the modules energetically, so the electron tunnels from the injector level into the next module's upper lasing level, u_{n+1}. That cascade effect is responsible for the high power in QCLs.

When u_n and l_n are close in energy—as in terahertz QCLs, which have about 16 meV gaps to produce 4 THz photons—maintaining the requisite population inversion is difficult. To do so, researchers design devices that slow the rate of transfer from u_n to l_n to keep electrons in the upper level, increase the rate of transfer from l_n to i_n and i_n to u_{n+1} to quickly move electrons out of the lower level, or some combination. Those tactics hinge on the energetic and spatial relationship between the states' probability density functions.

Each repeating module of a QCL contains multiple quantum wells. The simplest case of two wells is shown in black in figure 2b, but many QCLs have far more wells in a module. To speed up the so-called injection rate—the transfer from i_{n-1} (red) to u_n (blue)—Hu and his group designed QCLs whose states have high spatial overlap.

To slow the transfer from u_n to l_n (yellow), the researchers determined quantum well dimensions that produced low spatial overlap for the lasing states; u_n is localized more in the left well of the nth module whereas l_n is localized more in the right well. That way, even though electrons could scatter between the states instead of making an optical transition, the effect will be small.

To counterbalance the slow rate of the optical transition from u_n to l_n across a barrier and get a decent signal, the device needs more electrons. High electron concentrations produce a charging effect, which changes the states' relative energies. The result is that i_{n-1} might be misaligned with u_n and that the energy spacing between l_n and i_n isn't guaranteed. An applied voltage can restore the injection alignment of i_{n-1} and u_n, but the uncertainty in the l_n to i_n transition limits the options for efficiently shuffling electrons out of l_n.

Direct-phonon scheme

In most terahertz QCL devices, electrons rapidly scatter out of l_n through an interwell transition resonant with a phonon. (The electrons typically move first to an intermediary energy level above i_n not shown in figure 2.) But that route depends on a specific and fixed energy difference between the two states. Hu and his colleagues instead moved to a direct-phonon scheme, in which electrons scatter directly to the injector state within the same well, with no specific energy spacing needed.

Those and other population inversion strategies have been developed gradually over the past 18 years since terahertz QCLs were introduced. In that time, the

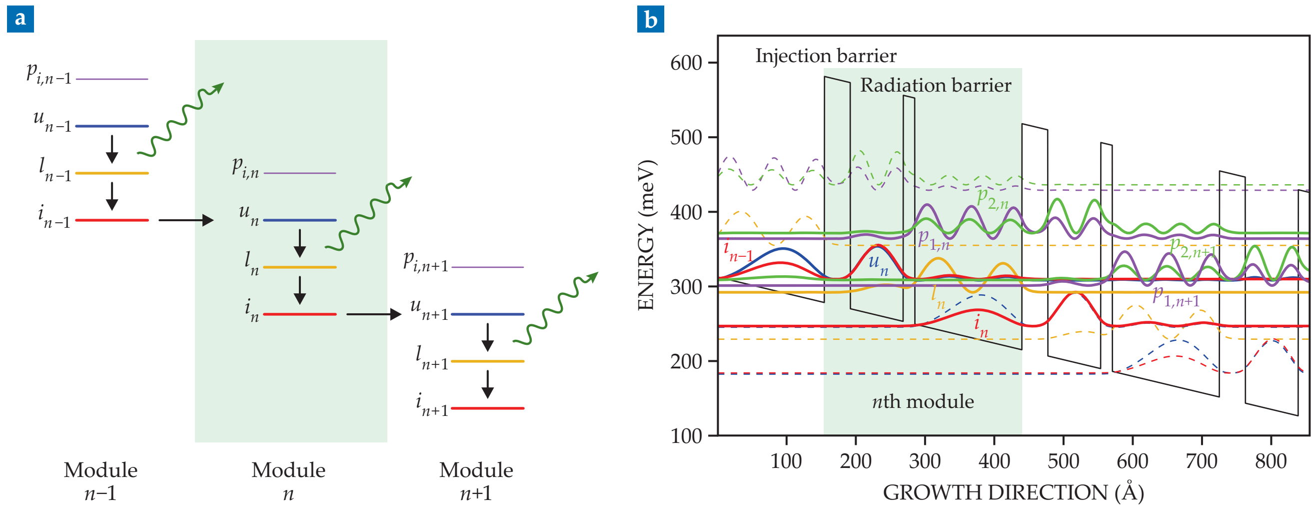


FIGURE 2. A CASCADE OF ENERGY LEVELS produces laser light. **(a)** Electrons in a quantum cascade laser follow the black arrows from module to module. Within each module n, an electron in the upper lasing level u_n moves to the lower lasing level l_n and emits a photon. It then quickly scatters into the ground state i_n and proceeds to the next module. With the right design, electrons never enter the higher-energy $p_{i,n}$ states, $p_{1,n}$ and $p_{2,n}$, which don't have available optical transitions. **(b)** Each module comprises a pair of quantum wells (black lines) defined by an injection barrier and a radiation barrier. The wells' dimensions determine how the energy states' probability density functions (colored lines) distribute. Transitions between levels with high spatial overlap are more likely to occur than between those with low overlap. (Adapted from ref. 2.)

maximum operating temperature T_{max}—the temperature at which thermal effects overwhelm lasing—initially increased rapidly from 50 K in 2002 to 164 K in 2005. Then progress stalled at 200 K from 2012 until 2019, when Jérôme Faist's group at ETH Zürich finally inched T_{max} up to 210 K.[4]

All terahertz QCL lasers except Faist's from 2019 required cryogenic cooling. To move to a portable thermoelectric cooler, which reaches 210 K to 235 K, T_{max} ideally needs to be higher than 235 K to ensure there's sufficient power for imaging. Many researchers argued that 200 K was a fundamental limit of T_{max} related to the point where thermal energy is comparable to the subband gaps. But Hu was never convinced that such a limit is relevant in a nonequilibrium system, such as a laser.

In 2015 Hu and former postdoc Asaf Albo, now at Bar-Ilan University in Israel, suggested that at high temperatures electrons jump over the potential barriers between quantum wells rather than dropping from upper to lower lasing levels and emitting photons. Higher barriers between wells should therefore improve T_{max}.

Physically, barrier heights depend on the materials in the layers of the QCL. The quantum wells are typically composed of gallium arsenide, and the barriers are aluminum gallium arsenide. Alloying GaAs with Al widens the bandgap, so the alloy's conduction band is at a higher energy. That energy difference provides the barrier height for the well.

Until now, the best-performing terahertz QCLs all used $Al_{0.15}Ga_{0.85}As$ barriers, and early studies on higher-aluminum-content devices found decreased T_{max}, despite the higher barriers. As a result, researchers have largely ignored the high-barrier strategy because they assumed the lower T_{max} was an unavoidable consequence of increased scattering from interface roughness, which scales with barrier height.

In their own experiment with high barriers from 2016, Hu and Albo noted an additional limiting factor on T_{max}: the introduction of higher-energy states, which electrons tunnel into without emitting light.[5] To avoid electrons jumping into nonlasing states in the devices in their new study, Hu's student Ali Khalatpour used numerical band-structure calculations, made easier by the device's simple two-well design, to optimize the dimensions with high barriers.

Reaching new heights

Previous models often assumed that the upper laser level was the highest subband. But higher barriers introduce other bound states, such as $p_{1,n}$ and $p_{2,n}$ in figure 2b. The Hu group's QCL design had to trade off minimizing leakage into such nonlasing states and maximizing the injection rate and optical gain. For example, increasing the radiation barrier thickness reduces leakage into the nonlasing states, but it also makes the radiative transition harder and thus reduces the gain.

In collaboration with Zbig Wasilewski's group at the University of Waterloo in Canada, the researchers produced four of their designs for QCLs made of $Al_{0.3}Ga_{0.7}As$ and GaAs. Creating terahertz QCLs takes high-quality growth with molecular beam epitaxy. Because the wavelengths are long in the terahertz range, the devices are thick, around 10 μm, and take around 15 hours to grow. Maintaining stable growth conditions over that long period is tricky. QCLs also depend on crisp interfaces, otherwise significant scattering will occur. The small subband energy gaps relative to IR devices make those effects even more important.

Paired with a room-temperature detector and camera, the team's best 4 THz laser, with a compact and portable thermoelectric cooler, produced power sufficient for real-time imaging. And future design tweaks and optimization should make room temperature operation possible.

Portable terahertz sources offer promising applications, including skin cancer screening.[6] To look for cancer now, doctors slice off and dye the affected skin and scan it under a microscope. "My mother was a pathologist," says Hu. "I used to peek through her microscope, and it really took trained eyes to identify cancer cells. I couldn't tell the difference between normal and cancer cells."

Water absorbs terahertz frequencies too strongly to do a full body scan, but surface penetration even up to a few millimeters is possible. Terahertz imaging wouldn't require the excision of skin, and it's sensitive to the increased blood supply and water content indicative of cancer in skin tissue.

Heather M. Hill

References

1. K. Kawase, *Opt. Express* **11**, 2549 (2003).
2. A. Khalatpour et al., *Nat. Photonics* (2020), doi:10.1038/s41566-020-00707-5.
3. J. Faist et al., *Science* **264**, 553 (1994); R. Köhler, *Nature* **417**, 156 (2002).
4. L. Bosco et al., *Appl. Phys. Lett.* **115**, 010601 (2019).
5. A. Albo, Q. Hu, J. L. Reno, *Appl. Phys. Lett.* **109**, 081102 (2016).
6. A. Rahman, A. K. Rahman, B. Rao, *Biosens. Bioelectron.* **82**, 64 (2016).

A galactic fast radio burst finally reveals its origin

Observations at multiple wavelengths provide compelling evidence that the first example of a fast radio burst detected in our galaxy came from a magnetized neutron star.

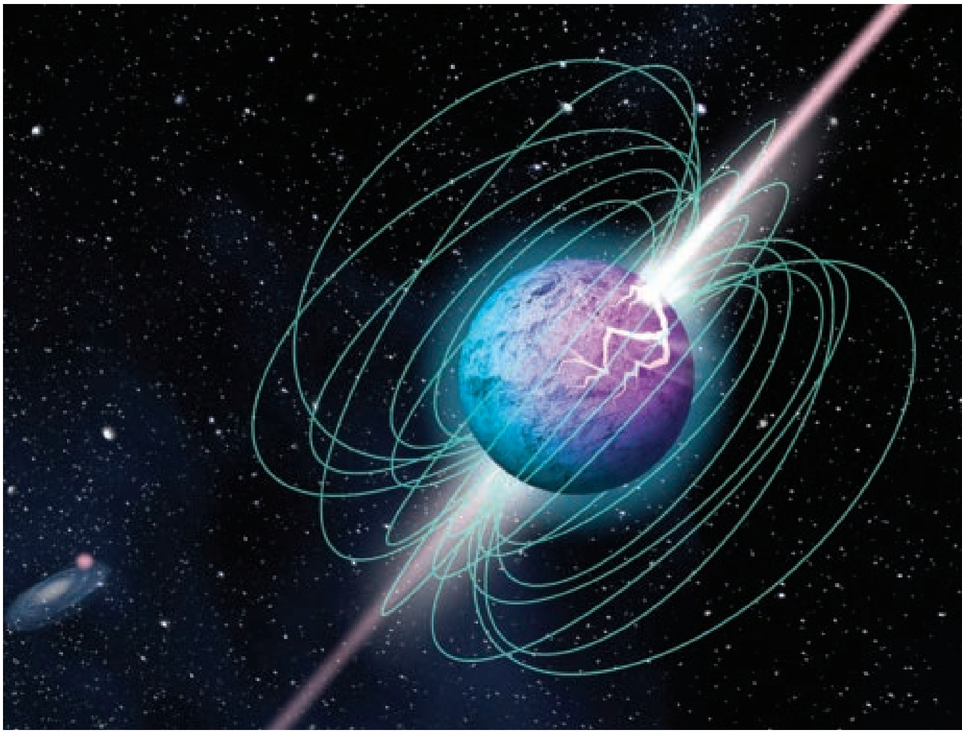


FIGURE 1. THIS ARTIST'S IMPRESSION OF A MAGNETAR represents the one now believed to be the source of the fast radio burst that was observed in April 2020. Shown here are the complex magnetic field structures (green lines) and radio, gamma-ray, and x-ray emissions that are produced from the magnetar's poles following a crust-cracking starquake episode. (Image courtesy of the McGill University Graphic Design Team.)

In 2007 a bright, brief burst of radio waves emanating from far outside the Milky Way captured the attention of astronomers. Short-duration pulses are not uncommon in radio astronomy. Pulsars in our galaxy produce intermittent, milliseconds-long flares of radio waves. The new phenomenon was orders of magnitude more luminous than those familiar signals and was spectrally different. The fast radio burst (FRB) was a perplexing new phenomenon.

Since that first discovery, radio telescopes have detected dozens of FRBs, some of them recurring sporadically from the same location. (See PHYSICS TODAY, March 2017, page 22.) Astronomers have pinpointed the galaxies that host just a few of them. To account for the signals, some theories invoke high-energy bursts of radiation emitted by compact stellar remnants—in particular, highly magnetized neutron stars called magnetars. But until now, observational evidence has not directly associated an FRB with a magnetar or other specific astronomical entity.

This year an international effort has identified the first known FRB from within the Milky Way and determined that the signal coincides with x-ray and gamma-ray emissions from the same location. The site corresponds to a magnetar in the constellation Vulpecula. The findings provide new observational constraints on FRB progenitor theories and a direction for future study.

Team effort

Magnetars are spinning neutron stars, each left over from the explosion of a star tens of times the mass of the Sun, and they have magnetic fields 100 trillion times stronger than Earth's. Strain induced by the intense magnetic field increases until it's abruptly relieved in a starquake, which gives rise to characteristic bursts of x rays and gamma rays, depicted in figure 1.

Of the 30 magnetars currently known in our galaxy and the Magellanic Clouds, five have exhibited faint, transient radio pulses coincident with what is presumed to be the magnetar's spin period. A leading model for repeating FRBs suggests that they come from extragalactic magnetars. However, for that model to hold, some magnetars must be capable of generating radio emissions that exceed

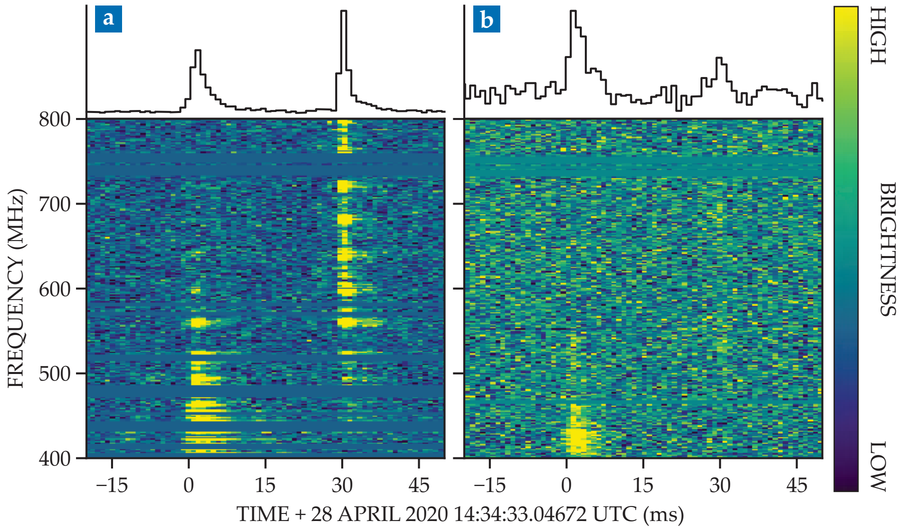


FIGURE 2. THE FAST RADIO BURST FROM SGR 1935+2154 was detected on 28 April 2020 by **(a)** the Canadian Hydrogen Intensity Mapping Experiment (CHIME) and **(b)** the Algonquin Radio Observatory. The ARO hosts a stationary 10-meter single-dish telescope that also observes the sky over the main CHIME antenna. The top panels show the total intensity of the milliseconds-duration burst, and the bottom plots show the intensity of the burst as a function of frequency. (Adapted from ref. 1.)

those of local, galactic ones by orders of magnitude.

On 27 April 2020, the Burst Alert Telescope aboard NASA's *Neil Gehrels Swift Observatory* detected multiple bursts of gamma rays and x rays coming from the magnetar SGR (soft gamma repeater) 1935+2154, which indicated heightened activity. The *Fermi Gamma-Ray Space Telescope* also reported multiple gamma-ray bursts from the same object.

By the next day, that region of the sky came into view of ground-based telescopes in the Western Hemisphere. The Canadian Hydrogen Intensity Mapping Experiment (CHIME) radio telescope in Penticton, British Columbia, detected an FRB coming from the direction of the signal. CHIME researchers posted a notice to the astronomy community reporting the detection of an FRB, dubbed FRB 200428, and included the data shown in figure 2a. The signal was well outside CHIME's field of view and was only detected because of its extreme brightness.[1]

Christopher Bochenek, a graduate student at Caltech, saw CHIME's notice when he began his daily inspection of data collected by the radio telescopes that make up the university's Survey for Transient Astronomical Radio Emission 2 (STARE2). "I saw the same burst in the STARE2 data, and I was so surprised I froze for a bit!" he says. The three STARE2 telescopes, in Utah and California, were designed explicitly to find an FRB in the Milky Way, which was expected to be rare but incredibly bright.[2] Bochenek confirmed that the signal was consistent with the one reported by CHIME. It was three orders of magnitude brighter than any observed radio pulse from known galactic magnetars.

Because of the *Swift* telescope's gamma-ray alert, several space telescopes had been keeping a close eye on the same location. Four of them reported an x-ray burst that simultaneously occurred with the radio bursts.

The Five-Hundred-Meter Aperture Spherical Radio Telescope (FAST) in China had also been observing SGR 1935+2154 in the preceding weeks, but the narrow-field telescope was not pointed toward the magnetar when CHIME and STARE2 reported their new finding. FAST did, however, report a lack of FRB-like events alongside 29 other x-ray bursts from SGR 1935+2154 in the days before FRB 200428 was announced.[3]

Bing Zhang of the University of Nevada, Las Vegas, explains, "The nondetection is significant because it indicates that an FRB's association with a gamma-ray repeater is unique and rare." That rarity could be because specific physical conditions required for FRB emission are difficult to satisfy or because FRBs have narrow beams that seldom point toward Earth. Two days after CHIME and STARE2 reported FRB 200428, FAST saw, from precisely the same location, another, weaker radio burst typical of a magnetar.

The observation of gamma-ray and x-ray emissions concurrently with an FRB allowed astronomers to make the first compelling link between FRBs and magnetars. Amanda Weltman of University of Cape Town says, "This is the first galactic FRB, our first FRB localized to an actual source and not just a host galaxy, and the first sign that a magnetar can produce bright enough bursts to be observed as FRBs."

Mulling magnetars

The discovery of FRB 200428 implies that active magnetars can produce FRBs that are bright enough to be detectable at extragalactic distances. Although the observed signal, when scaled for distance, was weaker than other extragalactic FRBs by a factor, the researchers estimated that if the signal had come from the location of other known FRBs, it would nonetheless be detectable. Figure 3 shows how the FRB's energy and duration compare with radio emissions from other known astronomical objects. Those comparisons led the CHIME, STARE2, and FAST researchers to conclude that magnetars like SGR 1935+2154 could indeed be a dominant source of FRBs.

How, exactly, a magnetar produces FRBs is still up for debate. One proposed mechanism for the link is that a starquake causes a magnetar to generate short-lived flares of electrons and other charged particles that collide with those emitted during previous flares, thus creating a shock front and huge magnetic fields.[4] Electrons swirling around the magnetic field lines emit bursts of radio waves, and the heated electrons emit x rays. Another possibility is that the starquake triggers disturbances in magnetic field lines near the magnetar's surface. Those disturbances induce relativistic particles to stream from the magnetosphere and generate radio emissions.[5]

Bochenek says, "We knew the source would need to be a compact object and have strong magnetic fields and that magnetars and neutron stars can create coherent radio emissions. But it's not like anyone expected magnetars to make such bright radio emission before the discovery of FRBs." Further study could help astronomers home in on the specific mechanisms and circumstances that drive

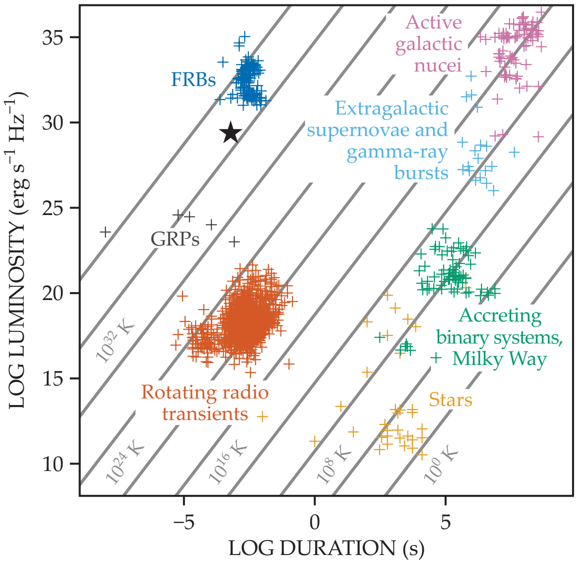


FIGURE 3. ASTRONOMICAL OBJECTS PRODUCE RADIO EMISSIONS that cover a wide range of energies (*y*-axis) and durations (*x*-axis). The radio burst that two telescopes detected simultaneously from the Milky Way magnetar SGR 1935+2154, indicated by the black star, could be a fast radio burst (FRB) and share some common features with giant radio pulses (GRPs) emitted by pulsars. (Adapted from ref. 2.)

magnetars to generate FRBs and, more generally, determine how coherent radio emission can be made under extreme conditions.

More observations are needed to fully understand the physics behind FRBs. Investigations should include searching nearby galaxies for similar events and seeking nonradio counterparts. For example, a coincident neutrino burst detected from the same locale as an FRB could provide evidence of another magnetar-driven FRB mechanism that involves an ultrarelativistic shock wave interacting with thermal synchrotron photons. So far, researchers combing through data from neutrino observatories have not found a corresponding signal.

From a theoretical point of view, determining the specific signatures of different physical mechanisms from distinct astrophysical objects will be vital to future FRB research. Zhang says, "Before the discovery, people had been talking about more than 50 possibilities of producing FRBs. I believe that a lot of models are no longer competitive." Still, there are likely multiple ways that repeating FRBs are created. It's also possible that rare, one-off FRB events could arise from catastrophic events such as merging neutron stars.

The FRB source in the Milky Way may also answer open-ended questions, such as how frequently the signals repeat over years to decades, how distant and energetic bursts are, and whether similar pulses can be used to identify specific objects in other galaxies. West Virginia University's Duncan Lorimer, who reported the first-ever detected FRB in 2007, points out that there has not yet been any evidence for rotational periodicity in repeating FRBs—as might be expected for a spinning source. He says, "I think ultimately FRBs could be, and are, produced by different sources."

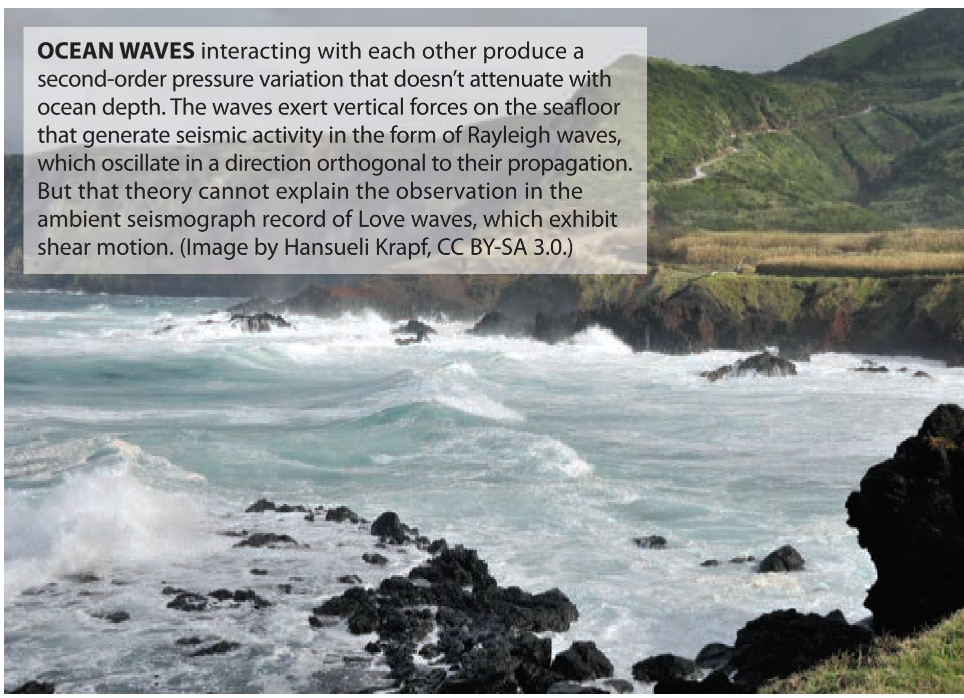
Rachel Berkowitz

References

1. The CHIME/FRB collaboration, *Nature* **587**, 54 (2020).
2. C. D. Bochenek et al., *Nature* **587**, 59 (2020).
3. L. Lin et al., *Nature* **587**, 63 (2020).
4. B. D. Metzger, B. Margalit, L. Sironi, *Mon. Not. R. Astron. Soc.* **485**, 4091 (2019).
5. W. Lu, P. Kumar, B. Zhang, *Mon. Not. R. Astron. Soc.* **498**, 1397 (2020).

Solving the century-old mystery of background Love waves

New simulations reveal that much of Earth's ambient seismic wave field arises from interactions with the planet's interior.



OCEAN WAVES interacting with each other produce a second-order pressure variation that doesn't attenuate with ocean depth. The waves exert vertical forces on the seafloor that generate seismic activity in the form of Rayleigh waves, which oscillate in a direction orthogonal to their propagation. But that theory cannot explain the observation in the ambient seismograph record of Love waves, which exhibit shear motion. (Image by Hansueli Krapf, CC BY-SA 3.0.)

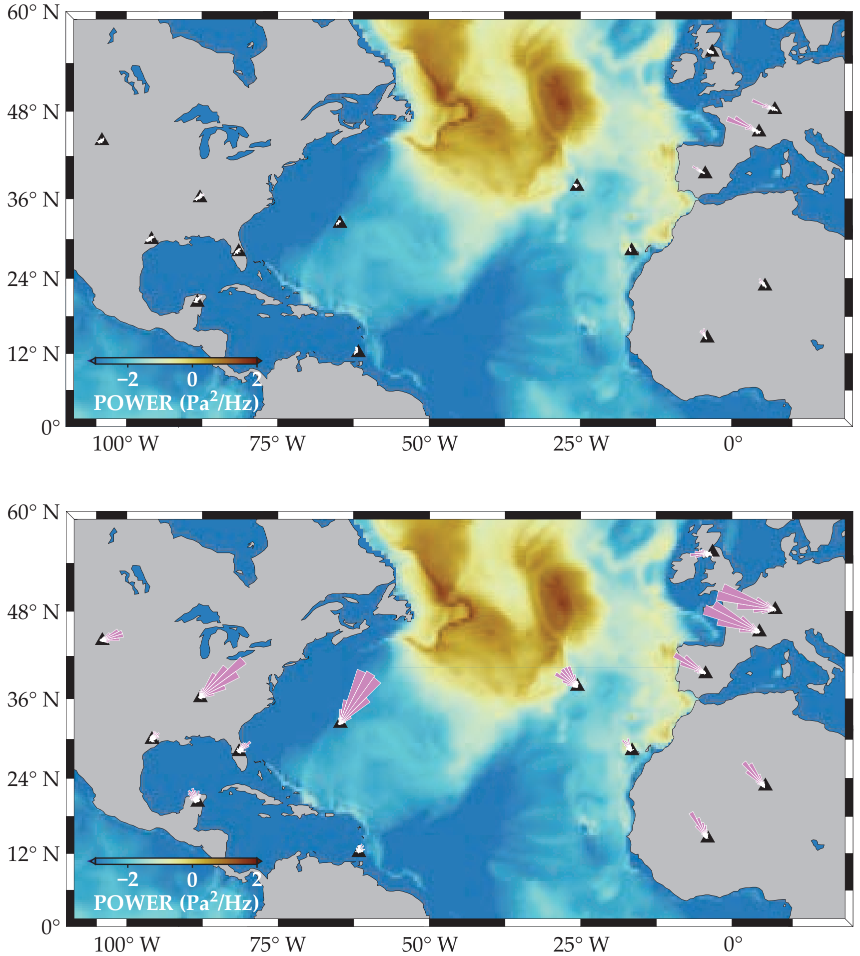
Earthquakes generate only a small fraction of the seismic energy that travels through Earth and on its surface. Most seismic activity arises from wind-driven ocean waves interacting with the solid ground. The background vibrations carry useful information about the exchange of energy between the ocean, the atmosphere, and Earth's subsurface, and seismologists extract that information to image the planet's internal structure and to conduct other geophysical investigations.

The strongest of those vibrations are known as secondary microseisms and are produced by pressure sources at the ocean surface that don't attenuate with the depth of water. Such fields arise when ocean waves interact nonlinearly with each other.[1] Most of the secondary microseisms, known as Rayleigh waves, oscillate in an up–down direction as they propagate across a surface. But some of the seismic energy takes the form of Love waves, which oscillate side to side.

Despite about a century of observations, the origin of those Love waves has puzzled seismologists. Some ocean waves, driven initially by atmospheric winds associated with hurricanes and other storms, form pressure sources that generate compressional waves. They propagate to the seafloor and can travel through Earth's interior. If the compressional waves interfere with each other, the interaction produces secondary-microseism Rayleigh waves but not Love waves.

For several decades, seismologists have pondered two hypotheses to explain the origin of the Love waves. One proposes that the ocean bathymetry—the inclined surfaces of seafloor ridges—splits the pressure sources into vertical and horizontal components, which can generate Rayleigh and Love waves, respectively.[2] The other hypothesis contends that the three-dimensional variations in seismic-wave velocities inside Earth scatter the seismic wave field in ways that generate Love waves.[3] But to date, the computational cost of 3D simulations has prevented researchers from comprehensively studying secondary-microseism Love waves.

Now Lucia Gualtieri of Stanford University and her colleagues at Princeton University have uncovered the waves' elusive source.[4] Using high-frequency numerical simulations, the researchers show that secondary-microseism Love waves form when seismic energy traveling through Earth's subsurface scatters haphazardly because of 3D heterogeneities in temperature, density, and rock and mineral composition. Besides answering a decades-old question, the finding may spur new tomographic methods and help improve existing ones.



A STATE-OF-THE-ART EARTH MODEL simulated secondary-microseism Love waves, the shear motion that arises when ocean waves interact nonlinearly with each other. The ocean color indicates the intensity of the pressure sources. The direction and strength of Love waves are indicated by the polar histograms at various detecting stations (black triangles). The top-panel simulation assumes a simple, layered Earth structure and shows only a few Love waves (pink bars) arriving at a handful of stations in Europe. The bottom panel shows results from a simulation that includes three-dimensional variations in seismic-wave velocity produced by a heterogeneous Earth structure. That distribution and number of Love waves better match observations. (Adapted from ref. 4.)

From 30 years to 8 hours

When researchers first started modeling seismic activity with computers in the 1970s, simulated waves were coarse approximations of the real thing. Those early models used a simple Cartesian coordinate system because of the limited computational capabilities available at the time, and the lowest period of a wave field that could be simulated was about 20 seconds. Secondary microseisms, however, have periods of 4 to 10 seconds.

To accurately capture the behavior of Love waves, Gualtieri and her colleagues used an Earth model with better frequency resolution. It has a geocentric coordinate system that incorporates various planetary parameters, including ellipticity, rotation, and the Coriolis effect.[5] The algorithm, a 3D spectral element solver, numerically calculates solutions to the differential equations that describe propagating waves as a sum of basis functions. Researchers first adapted the method for seismology studies in 1994, and since then the open-source code called SPECFEM3D Globe has been reviewed, revised, and validated by dozens of experts.

Still, using the venerable code to model secondary microseisms for the entire planet strains computational resources. The ambient-noise pressure sources of the waves are located across Earth's surface. A simulation of a portion of those places couldn't provide the insight that came from modeling all of Earth. The quantity of spatial cells the model used to resolve the Love waves numbered about 230 000.

When Gualtieri first tested the code at Princeton, the local computer cluster could handle just one-sixth of Earth at a time. The supercomputer at Oak Ridge National Laboratory in Tennessee, however, made the full simulation possible. "When I was in grad school in 2011, people were saying this would take 30 years," says Gualtieri. "But my simulation took about 8 hours."

Dimensions matter

Once the model was running smoothly, the researchers tuned it with and without bathymetry and 3D heterogeneities, the features that were hypothesized to generate secondary-microseism Love waves. The top panel of the figure on page 18 shows results of a simulation that incorporates realistic bathymetry and a simple, layered Earth structure. Secondary-microseism Love waves, shown by the pink bars, appeared in just a few seismic stations in Europe.

The roughness of the seafloor did generate some Love waves, but Gualtieri and her colleagues found that at most locations, with the exception of a few areas, the bathymetry was not steep enough to significantly split the pressure sources. However, the simulation that includes the 3D heterogeneous structure, in the bottom panel of the figure on page 18, shows a distribution of Love waves that agrees more closely with the observations. "The major contribution is definitely due to heterogeneities," says Gualtieri.

Andrea Morelli, a professor of physics at the University of Bologna in Italy, says, "The results are enlightening. The discussion about the generation of Love waves by oceanic sources will not end here, of course, and further analyses will be needed to confirm this mechanism and improve the detail." Based on a wave's period, researchers could more precisely calculate the depth of a heterogeneity. The deeper structure of the mantle may also affect the reshaping of the entire ambient wave field, though researchers still need to explore that possibility further.

Refined tomography

The new findings may improve future efforts to image the subsurface. The classic approach to seismic tomography relies on data from earthquakes and their sources to reconstruct an image of the planet's interior. A different and more data-rich approach uses ambient seismic noise, but its sources are murky. So seismologists have relied on cross-correlation methods, which produce an image by assuming a homogeneous distribution of the sources to get information about the seismic-wave velocity variations between pairs of stations. (See the article by Roel Snieder and Kees Wapenaar, PHYSICS TODAY, September 2010, page 44.)

Love waves are recorded in the horizontal component of seismic activity. But previous imaging studies either did not use the horizontal components or assumed that they originated at the surface. "Our work could be a way of starting to do tomography with ambient noise in a classical way, using the information about the sources," says Gualtieri.

Without information about the ambient pressure sources, researchers have had to assume that they're uniformly distributed around Earth. But the figure on page 18 clearly shows a variable distribution of pressure sources. Gualtieri says, "There are errors we know are there but have been ignored. I think it's time to move beyond and introduce what we now know: where the sources are and what their mechanisms are."

Alex Lopatka

References

1. M. S. Longuet-Higgins, *Philos. Trans. R. Soc. London A* **243**, 1 (1950).
2. T. Saito, *Geophys. J. Int.* **182**, 1515 (2010).
3. T. Tanimoto et al., *Geophys. Res. Lett.* **42**, 2650 (2015).
4. L. Gualtieri et al., *Proc. Natl. Acad. Sci. USA* **117**, 29504 (2020).
5. D. Komatitsch, J. Tromp, *Geophys. J. Int.* **149**, 390 (2002); D. Komatitsch, J. Tromp, *Geophys. J. Int.* **150**, 303 (2002). PT

NSF launches funding schemes for medium-scale infrastructure

Funding across scientific disciplines could catalyze US competitiveness.

CORNELL UNIVERSITY

THE BLUE STRUCTURE is an artist's rendition of the housing for a high-magnetic-field beamline to be added to the Cornell High Energy Synchrotron Source. The adjacent brown structure represents the existing lab.

Does the research facility you want to build cost upwards of $100 million? Try lobbying Congress or chasing down the big money through NSF's major-facility awards or the Department of Energy. Need up to a few million dollars for lab equipment? Ask NSF or another funding agency. Those are the standard avenues for funding scientific infrastructure in the US. Until recently, however, scientists had few places to turn for medium-cost infrastructure.

Now NSF seeks to fill that gap with a pair of funding lines. Awards in the smaller midscale research infrastructure category (MidScale RI-1) are available for projects costing from $6 million to $20 million and can encompass design or implementation; the MidScale RI-2 line funds infrastructure costing from $20 million to $100 million. The two programs run in alternate years.

The funding gap had been recognized for a long time. Then in 2017, as part of the American Innovation and Competitiveness Act, Congress instructed NSF to address it. The agency came up with the specific approach as part of its 10 Big Ideas, an exercise for planning future investments. Medium-scale projects have been funded in a few divisions within NSF, but the new awards are open to all science and engineering fields. When the agency put out requests for proposals in late 2018, they poured in across all fields, says Allena Opper, NSF program director for experimental nuclear physics, who cochaired the working group for the MidScale RI-2 projects.

In late 2019 NSF announced the winners of the first round of MidScale RI-1 funding. Ten projects will receive a total of $121 million over five years. Then, on 29 October, NSF announced three awards totaling $125 million over five years for shovel-ready MidScale RI-2 projects: A high-magnetic-field beamline at Cornell University's synchrotron light source received nearly $33 million; a test bed for future power-grid architectures at the University of California, San Diego (UCSD), $39 million; and a network of global ocean-monitoring floats by a collaboration led by the Monterey Bay Aquarium Research Institute, $53 million.

A competitive edge

A MidScale RI-2 award will put a 20-tesla superconducting magnet on a new beamline at the Cornell High Energy Synchrotron Source (CHESS). It will be the strongest persistent magnet on any synchrotron worldwide. According to NSF division director for materials research Linda Sapochak, the project is part of a longer-term goal to keep the US competitive in high-magnetic-field science.

By combining it with strong magnetic fields, x-ray scattering can be brought to bear on phase changes induced in materials by magnetic fields. The prime science driver is to probe quantum materials such as spin liquids, frustrated magnets, and topological insulators. "Strong magnetic fields provide the most direct way to manipulate quantum states of matter," says Cornell physicist Brad Ramshaw. Jacob Ruff, director of the NSF-funded beamlines at CHESS, anticipates that scientists will also use the high-field beamline for structural biology, chemistry, and other studies.

Magnetic fields can induce big changes. "In some materials interesting behavior may occur at 2 T, while in others it takes 20 T or 200 T," says Ruff. Many synchrotron sources have beamlines equipped with magnetic fields of 2–7 T. The strongest persistent magnet used in structural studies is a 17 T solenoid that the UK's University of Birmingham dispatches to x-ray and neutron sources. Although a couple of synchrotron facilities have made "heroic measurements" with pulsed fields up to 30 T that have offered glimpses, Ruff says, "we have not yet been able to carefully study materials at those fields in detail."

The NSF award covers the cost to build a new beamline and install a commercial magnet, which partners at the National High Magnetic Field Laboratory (MagLab) will help choose. The partners will also work jointly on the experimental station so that it can eventually accommodate a 40 T magnet that the MagLab is developing.

To open in 2025 as planned, "we need to be in the dirt" by summer 2022, says CHESS director Joel Brock. Housing the magnet requires special infrastructure—

for example, the concrete cannot contain conventional rebar—for which Cornell needs to raise $24 million.

The high-field beamline team is collaborating with the University of Puerto Rico at Rio Piedras to bring doctoral students to Cornell. Starting in September, four students per year will come to design, test, and build instruments and parts for the new beamline. Ramshaw, the Cornell liaison for the partnership, sees "a lot of excitement on both sides." He notes a general need to train more people in x-ray instrumentation, and the collaboration gives students in Puerto Rico direct access to a world-class facility.

Flatter architecture

A team of engineers and computer scientists at UCSD won a MidScale RI-2 award to create a test bed to explore algorithms for controlling and monitoring energy use. To start with, the project will link existing applications, including 15 solar power generators, devices in a dozen classroom and administrative buildings, and roughly 300 electric-vehicle charging stations. A big chunk of the award will go to adding thousands of controllable light fixtures and hundreds of air-handling systems. "We have a large number of different types of devices and flexible loads," says John Dilliott, UCSD director of utilities and sustainability.

Today's power grids employ central communications systems, in which a single controller exchanges data with each device, says principal investigator Jan Kleissl, director of the university's Center for Energy Research. Future grid systems will have to deal with millions of devices—"every water heater, AC unit, electric vehicle, and so on," says Kleissl. A federated architecture, where responsibilities reside locally in neighborhood nodes and report only occasionally to a central entity, are expected to make communications in power systems—and ultimately power use—more efficient, he says.

Some 2000 devices will be connected by the test bed, which will make it the first of its kind in terms of size, device heterogeneity, number of devices, easy access for users, and the like. Sonia Martínez is a UCSD professor who researches distributed controls and coordination of power systems. "We have to break down decision making from top-down to a flatter architecture," she says. The facility's aim is to test ideas for the integration of renewable

UNIVERSITY OF CALIFORNIA, SAN DIEGO

ONE OF 15 SOLAR POWER GENERATORS that will be part of a set of 2000 devices linked to form a power-use test bed at the University of California, San Diego. The test bed will allow the exploration of algorithms to better manage power grids.

energy and load sharing using real loads and data. The team hopes that researchers from both academia and industry will use the test bed. "There is a barrier between the two worlds," she says. "It's hard for utilities to adopt new technologies. We hope that with the test bed they can be convinced that the power is reliable."

A longer-term goal, says Dilliott, is to expand to interactions with California's power grid. "What we do here can be extrapolated to grid stability and energy efficiency. We'll have granular control of buildings and employ algorithms to reduce energy use."

Float fleet

The third inaugural MidScale RI-2 award is for a network of 500 ocean floats known as the Global Ocean Biogeochemistry (GO-BGC) Array. The floats carry sensors for oxygen, chlorophyll, nitrates, pH, particles, and sunlight. They record data from the upper ocean, within about 300 meters of the surface, where phytoplankton grows. "The goal is to measure the ocean's metabolism," says principal investigator Ken Johnson, of the Monterey Bay Aquarium Research Institute. The University of Washington, Scripps Institution of Oceanography, Woods Hole Oceanographic Institution, and Princeton University are partners in the project.

Plankton plays a huge role in the globe's biological pump by taking carbon dioxide out of the air. How and where the microscopic plants do that is sensitive to ocean warming. "There are all kinds of questions about whether the mixing of deep water and warmer top water changes," Johnson says. "And if you reduce the plankton concentration in the upper ocean, will the ocean absorb less CO_2 from the atmosphere?"

The floats are to spend most of the time a kilometer below the surface. Every 10 days they automatically drop to 2 km and then rise to the surface. From there, they transmit data via satellite, and then sink again. "The data is offloaded in 15 minutes," says Johnson. "You don't want the floats at the surface for long, because things grow on them, or they could be crushed by ships." Parking them at 1 km prevents biofouling, he says. And the detour down to 2 km is useful for calibration, because measured variable values are stable there.

An extension of a pilot network in the Antarctic Ocean, the project is intended to form half of an international network. The best floats are made at the University of Washington, Johnson says, and the cost to acquire and deploy them is about $100 000 each; the team hopes to transfer those float-building skills to industry and bring down the price. Some countries deploy simpler floats with only an oxygen sensor, which cost about $30 000. But, says Johnson, "if you want the full carbon cycle, it helps to have all of the sensors.

"If we want climate signals, we will want to do this for decades," says Johnson. "But it's an NSF grant. We have to do cool science in five years and hit a home run." And, he says, few data exist about the open global oceans, "so there are plenty of home runs to hit." The "cool" areas of research that the team—and other scientists—may pursue, he says, include the effects on plankton of nonlinear interactions between the wind and ocean, the cycle of plankton production, the linkage between volcanic dust and plankton productivity, and the patchiness of uptake and outgassing of CO_2.

The first GO-BGC floats are scheduled to be deployed this spring. The data will be freely available.

GRETA SHUM

RESEARCHERS DEPLOY A FLOAT in the Antarctic Ocean. Starting this spring, a collaboration headed by the Monterey Bay Aquarium Research Institute will build and deploy 500 such floats, each carrying six sensors to monitor the carbon cycle and plankton growth. The project is one of the inaugural NSF midscale research infrastructure awards.

Smaller midscale infrastructure

Among the MidScale RI-1 awards for infrastructure is the neutron spin-echo spectrometer to be built at NIST in Maryland with $11.8 million. And for design, a team led by the Smithsonian Astrophysical Observatory won $12.7 million to plan an upgrade to the Event Horizon Telescope (EHT), the linked array of radio dishes that in April 2019 produced the first-ever image of a black hole. (See "What it took to capture a black hole," PHYSICS TODAY online, 11 April 2019.)

The spin-echo spectrometer takes advantage of an upgrade at NIST's neutron source that will more than double the flux. Combined with stronger and more controlled magnetic fields due to improved correction coils, the new instrument will "have better data and a 10 times better data acquisition rate," says Dan Neumann, director of the NSF-funded NIST Center for High Resolution Neutron Scattering.

Spin-echo spectrometry probes nanoscale dynamics—in both time and size—in systems such as soft matter, biological samples, colloidal systems, and nanomaterials. "It's an esoteric technique," says Neumann. Even so, the existing spectrometer is the facility's most oversubscribed instrument.

"The new instrument will let us look at slower processes, to over 300 ns for most samples, and 700 ns for others," says principal investigator Norman Wagner of the University of Delaware. The third partner on the award is the University of Maryland.

One company hopes to use the new spin-echo spectrometer to study the viscosity and longer-time-scale dynamics of a monoclonal antibody solution. The motivation is to understand the antibody solution at a molecular scale and then to adjust the interactions so that the monoclonal antibodies could be delivered by injection rather than intravenously.

The improved spin-echo spectrometer was on NIST's wish list, but in-house money was unavailable, says Neumann. "It would have taken many more years—if at all—if this money hadn't come through," he says. And the NIST instrument is an adaptation of one in Germany, which "makes it an easy sell. The risk is low and we know the costs rather accurately." The instrument will open to users in 2024.

Earth-sized video camera

Imagine making a movie of a black hole, says astronomer and EHT founding director Sheperd Doeleman. That's exactly what he and his collaborators are planning.

The extreme gravity of a supermassive black hole inexorably pulls in surrounding matter, which heats to billions of degrees. Magnetic fields are swept along by the gas and get caught up in the rotation of the black hole. The fields fling out jets of charged particles that can stretch for thousands of light-years. "If we could observe the orbits of gas around a black hole, we could devise new tests of Einstein's theory of gravity," says Doeleman. "We could see how the jets are formed and how matter and energy are redistributed on galactic scales." With the next-generation EHT, he says, "we aim to build an Earth-sized video camera to turn black holes into extreme cosmic laboratories."

The iconic image of a black hole was stitched together using data from eight radio telescopes scattered around the world and synchronized with atomic clocks. The award will be used to design new telescopes to increase the network to 20 dishes. The team will run simulations to determine the best dish size, radio frequencies, and locations for them.

A major part of the award will go toward outfitting the Large Millimeter Telescope near Puebla, Mexico, with a prototype superconducting receiver. The MidScale RI-1 award will put the team in a position to apply for the larger sums it will need to realize the next-generation EHT. Says Doeleman, "We want to make a black hole movie by the end of the decade."

Preliminary proposals for the next round of MidScale RI-1 grants are due this month; a new call for MidScale RI-2 proposals was issued in early December, with letters of intent due on 21 February.

Toni Feder

Canada's nuclear future brightens

Although the Canadian and US nuclear industries have shared origins in World War II, their paths soon diverged.

On a windswept field near the shores of Lake Ontario in mid-November, Canadian politicians and nuclear industry executives gathered to announce plans to build the country's first new nuclear reactor since the early 1990s. A month earlier US Department of Energy Secretary Dan Brouillette and Romania's Minister of Economy, Energy, and Business Environment Virgil Popescu signed an $8 billion agreement in Washington, DC, that paves the way for the construction of two new Canadian-origin reactors at a nuclear power plant on the Black Sea. Two Canadian reactors are already located there.

The two events highlight differences between the Canadian nuclear industry and its counterpart in the US. As competitive pressures have forced the closure of nuclear power stations and threaten many others south of the border, Canadians are in the midst of major refurbishments to extend the lives of a dozen reactors; another has already been updated. Six other aging reactors are due to be shut down by 2025, and it's likely that some new nuclear plants will eventually replace them.

Canada's 19 operating power reactors all have a markedly different design from the light-water reactors (LWRs) that predominate in the US and around the world. Known as CANDUs (Canadian deuterium uranium), they employ heavy water (deuterium oxide) as the neutron moderator and coolant. Should current plans proceed, however, the next Canadian reactor will be of a new type altogether.

Ontario Power Generation (OPG), the provincial government utility that owns the province's 18 reactors, is to select one of three competing designs for a single small modular reactor (SMR) to be built at its Darlington Nuclear Generating Station roughly 80 kilometers east of Toronto. GE Hitachi Nuclear Energy, X-Energy, and Terrestrial Energy are finalists in the competition, said Ken Hartwick, OPG's president and CEO. The target date for startup is 2028.

A RENDERING OF A SMALL MODULAR REACTOR design from SNC-Lavalin. The heavy-water-moderated reactor would produce 300 MW of electricity.

Additional SMR orders from Saskatchewan, New Brunswick, and Alberta will follow, predicted Greg Rickford, Ontario's minister of energy, northern development, and mines and of indigenous affairs. In a December 2019 memorandum of understanding, the four provinces agreed to cooperate on advancing development and deployment of SMRs.

Nuclear power in Canada has always been centered in Ontario, the most populous and industrialized of the 13 provinces and territories. Roughly 60% of the electricity consumed in the province is from nuclear. The only CANDU outside Ontario supplies about one-third of New Brunswick's electricity. British Columbia and Quebec have abundant hydroelectric resources, and Quebec, which exports power, closed its only CANDU in 2012, electing to forgo the expense of refurbishment. Alberta, Manitoba, Saskatchewan, and the maritime provinces are more sparsely populated and rely mainly on fossil fuels.

Heavy and light water

Canada's nuclear program dates to World War II, when the UK relocated its atomic bomb program from Cambridge University to its North American dominion. In Montreal and later at Chalk River Laboratories, about 180 kilometers upstream of Ottawa, British and Canadian scientists were focused on developing a heavy-water-moderated reactor to produce plutonium for the Manhattan Project. The British had brought along a large quantity of heavy water that had been smuggled out of occupied France. The Zero Energy Experimental Pile (ZEEP) at Chalk River, the world's second operating nuclear reactor—after Enrico Fermi's Chicago Pile-1—was a heavy-water design.

Ultimately, the US nuclear bomb development program chose graphite to be the neutron moderator for the reactors that made the plutonium for the Nagasaki bomb. But Canada's National Research Experimental (NRX) reactor, the successor to ZEEP, was the basis for the heavy-water plutonium and tritium production reactors at DOE's Savannah River Site, says historian Robert Bothwell, author of *Nucleus: The History of Atomic Energy of Canada Limited* (1988).

Some of the R&D in support of Hyman Rickover's nuclear propulsion program for the US Navy was done at the NRX, although the navy chose light water as the moderator and coolant for submarine reactors. President Jimmy Carter, who was then a navy lieutenant, was assigned to assist the cleanup of a 1952 partial meltdown of the NRX, the world's first major nuclear accident.

The National Research Universal (NRU) heavy-water research reactor began operating at Chalk River in 1957.

THE BRUCE NUCLEAR GENERATING STATION on Lake Huron is the largest nuclear power plant in North America. Its eight CANDU reactors produce 30% of Ontario's electricity. Four of the reactors are in the foreground; the others are visible in the background.

In addition to developing fuels for CANDUs and conducting materials research, the NRX and NRU produced medical radioisotopes. At times the NRU supplied more than half the world's molybdenum-99, the precursor to technetium-99m, the most widely used medical isotope. When it was permanently shut down in 2018, the NRU was the world's oldest operating nuclear reactor. Two dedicated replacement isotope-production reactors at Chalk River, completed by a public–private partnership, were plagued by design faults and were abandoned in 2008.

Canada never developed nuclear weapons, but Canadian mines and uranium processing facilities played key roles in the Manhattan Project and in the postwar US nuclear arms buildup. In Port Hope, Ontario, a former radium processing plant now owned by Cameco Corp was converted during World War II to refine high-grade uranium from the Belgian Congo. Today it exports uranium hexafluoride to enrichment plants for peaceful purposes only. It also produces uranium dioxide for CANDU fuel.

The Cold War arms race fueled a boom in uranium mining at Elliot Lake in northern Ontario. Joseph Hirshhorn, whose collection of art now populates the Smithsonian museum that bears his name, made much of his fortune from Elliot Lake. When the US Atomic Energy Commission began cutting back on uranium orders in the late 1950s, the boomtown went bust. Canada is today the world's second-largest exporter of uranium, all of which is now mined in Saskatchewan's Athabasca River basin, whose ore has a higher grade than Elliot Lake's.

As partner in the North American Aerospace Defense Command and a NATO member, Canada once fielded US nuclear warheads on surface-to-air missiles and aircraft, says Tim Sayle, assistant professor of history at the University of Toronto. Canada has been free of nuclear weapons since the early 1980s.

Enrichment not required

With encouragement from the government, the US Navy submarine reactor technology was adapted by US utilities for electricity production. All operating commercial reactors in the US are LWRs. But Canada continued to develop its heavy-water technology. In large part, the CANDU design stemmed from Canada's inability to manufacture large castings for the pressure vessels that encapsulate LWR nuclear fuel assemblies, says Colin Hunt, cochair of the government and regulatory affairs committee of the Canadian Nuclear Society.

The CANDU reactor core consists of a calandria, an unpressurized vessel of heavy water with hundreds of tubes running through it to contain the nuclear fuel. Whereas LWRs must be shut down every 12–18 months to be refueled, CANDUs were designed to allow on-line refueling. The reactors remain operating as fresh fuel bundles are inserted into the tubes and the spent ones are ejected. LWR uranium fuel must be enriched to around 4% in the fissile uranium-235 isotope, but the CANDU burns naturally occurring uranium fuel containing about 0.7% ^{235}U. That feature eliminates the need for costly enrichment plants or services. And the CANDU can burn other fuels, including thorium, plutonium, and even spent fuel from LWRs.

The first CANDU, at Douglas Point on the shores of Lake Huron, operated commercially from 1968 to 1984. Four larger CANDUs came on line at the Pickering Nuclear Generating Station near Toronto in 1971, and four more units were added there in 1983. Six remain in operation. Twelve more CANDUs were built in Ontario, eight at the Bruce Nuclear Generating Station at Douglas Point and the newest four at Darlington. Today, Bruce is the largest nuclear generating station in North America, supplying more than 30% of Ontario's electricity.

Outside Canada, CANDUs have been installed in Argentina (1), China (2), India (2), Pakistan (1), Romania (2), and South Korea (4). Following India's 1974 test of a nuclear weapon, Ottawa ended nuclear cooperation with New Delhi. India went on to build more than a dozen reactors of a CANDU-derived design. Canada's assertive efforts to sell CANDUs to the UK were unsuccessful. Had the UK bought any, Bothwell says, the CANDU likely would have become a joint venture between the two nations, and the technology might have become the world's dominant reactor model.

An uncertain future

The aging Pickering reactors, which supply about 15% of Ontario's power, are scheduled to be permanently closed by 2025. It's an open question what will replace them. The other major power source in Ontario, hydroelectric, has been fully tapped, says Hunt. Coal-fired generation in the province is prohibited by law, and a recently enacted federal carbon tax of Can$30 ($23) per ton of carbon dioxide, rising to Can$50 in two years, should discourage new natural-gas-fired plants.

Although the province's electricity demand isn't growing now, it will likely

CANADIAN NUCLEAR LABORATORIES

CREATED DURING THE MANHATTAN PROJECT, the Chalk River Laboratories north of Ottawa were home to CANDU heavy-water-reactor development and several research reactors. Now known as Canadian Nuclear Laboratories, the facility is operated by a consortium of companies led by SNC-Lavalin for the federal government.

increase as demand for electric vehicles and hydrogen grows, says William Fox, executive vice president for nuclear at SNC-Lavalin, an architect and engineering firm that holds the rights to CANDU technology.

At the federal level, the Liberal-led government of Justin Trudeau has begun considering legislation with the aim of reducing Canada's carbon emissions to zero by 2050. On 30 November the government announced its intention "to launch an SMR Action Plan by the end of 2020 to lay out the next steps to develop and deploy this technology." It's a sign that Liberal members of Parliament have recognized that nuclear power is needed if Canada hopes to meet its 2015 Paris Agreement pledge that by 2030 it will have cut greenhouse gas emissions by 30% from their 2005 levels, says John Barrett, a consultant and former Canadian ambassador to the International Atomic Energy Agency.

Increasing wind and solar energy seems an obvious option to meet Ontario's future needs. But its leaders have soured on renewables since the previous Liberal provincial legislature's heavy subsidization of wind energy led to enormous increases in electricity rates. From 2010 to 2016, average home electricity costs rose by 32%, despite a 10% decline in average household electricity consumption, according to Ontario's Financial Accountability Office. The price hikes, which also caused many industrial operations to flee the province, were a major contributor to the Liberals' historic rout in the 2018 elections. The current Progressive Conservative provincial government tore up the still-outstanding wind turbine construction contracts, says Hunt.

Importing power from neighboring provinces isn't an option, Hunt says. Purchasing power from electricity-rich Quebec would put Ontario in competition with New England and New York State and drive up electricity rates further. Quebec's transmission system was built to export power to the US, so new transmission lines would be required to accommodate interprovincial flow, Hunt says. A further complication is that Quebec's electricity grid is out of phase with the rest of North America's: The peaks and valleys of its alternating current flow are asynchronous with the rest of the continent's. As a result, the power imported by Ontario would need to be converted to DC and then converted back to in-phase AC once across the border.

Hunt believes that no more CANDUs will be built in Canada; he sees the future belonging to SMRs. (See PHYSICS TODAY, December 2018, page 26.) Though SNC-Lavalin has a large SMR design (see the figure on page 23), Fox believes that large reactors will be needed to replace the 2400 MW that Pickering's CANDUs now supply. Because the entirety of Canada's nuclear experience with large reactors has been with CANDUs, Fox is confident that the same technology will be chosen if new conventional-size reactors are ordered.

Smaller SMRs could be ideal for providing electricity to remote off-grid communities in the vast Canadian north. The diesel-generated power they use now is expensive, dirty, and vulnerable to cutoffs of fuel supply during severe winter weather. SMRs also would be an attractive option to provide power to remote mining operations and to produce the steam used in extracting oil from Canadian tar sands, Barrett says. Several 300-MW-sized SMRs could meet Saskatchewan's needs, he notes.

Compared with the US, Canada has made far more progress on the disposition of nuclear waste. The federal Nuclear Waste Management Organization expects to select the location for a geological nuclear waste repository in 2023. Unlike the US, where the now-abandoned Yucca Mountain location was unsuccessfully forced on Nevada, the waste authority invited site proposals from communities; 22 were received. After each was characterized, two Ontario sites were named finalists: one in farmland about 45 kilometers east of Lake Huron and the other in the exposed rock of the Canadian Shield about 246 kilometers northwest of Thunder Bay.

David Kramer PT

S is for Science: The making of 3-2-1 CONTACT

The beloved after-school show of the 1980s was the product of a then revolutionary idea: asking children what they wanted in a television science series.

Ingrid Ockert serves as an adviser to the American Archive of Public Broadcasting. She is a historian of science based in Berkeley, California.

Ingrid Ockert

From *Elinor Wonders Why* to *Emily's Wonder Lab*, a multitude of fresh, dynamic programs have recently premiered that encourage children to channel their inner scientists. Between streaming services and television, today's young people have more access to quality science programming than ever. But before there was *Cyberchase*, *Wild Kratts*, *The Magic School Bus*, or even *Bill Nye the Science Guy*, there was the show that started it all: *3-2-1 Contact*.

Premiering in 1980, *3-2-1 Contact* aired on PBS (Public Broadcasting Service) stations across the US and quickly became a beloved classic of Gen Xers and Millennials. Although it was not the first science series for children—*Watch Mr. Wizard* had entertained young people in the 1950s and 1960s—it broke new ground in several ways. It was the first children's science series to receive funds from NSF. It was the first to intentionally reflect the diversity of its young audience by introducing viewers to scientists of different ethnic backgrounds. And unlike previous science programs, which presented kids with straightforward experiments, *3-2-1 Contact*'s creators gave their show a freer format that combined skits, cartoons, and documentary shorts, grouped into loose themes. For example, one episode on the topic of "order and disorder" featured a visit to a sewage treatment plant, a skit about teamwork, and a quick lesson on programming computers. The show's writers had ample freedom to familiarize students with various scientific disciplines.

Many viewers have credited *3-2-1 Contact* with helping to spark their scientific career aspirations. In an article she wrote for *Science*, Ainissa Ramirez, an engineer and science communicator, fondly recalled the series: "I have wanted to be a scientist ever since I was a little girl. I got the idea from a television program called *3-2-1 Contact*, where I watched a young African-American girl solve problems. I saw my reflection in her and was transfixed."[1] That effect wasn't an accident. The creators of *3-2-1 Contact* were determined to use their show to inspire a new generation of scientists. What was their secret? Science.

Strikingly, *3-2-1 Contact* was the first science television series to be designed by scientific study. The show's content and dynamic style were informed by two years of focus groups and audience evaluations. A close look into the origins of *3-2-1 Contact* offers a fascinating case study into the ways that scientists, researchers, and broadcasters can collaborate on educational projects to reach and inspire viewers.

Meet the Mod Squad

The innovative *3-2-1 Contact* was a product of the Children's Television Workshop (CTW, now the Sesame Workshop), the nonprofit production company that had created *Sesame Street* and *The Electric Company*. The CTW was founded in 1968 by producer Joan Ganz Cooney and a handful of other creative professionals who hoped to develop a new type of educational programming for American children. *Sesame Street*, with its colorful puppets and humans living together in a New York City neighborhood, premiered in 1969, and by 1972 it was watched by 80% of all preschoolers in the US.[2] But *Sesame Street* isn't just one of the most popular children's shows of all time; it was the first to be based on scientific research.

Breaking new ground, the CTW hired a full research staff.[3] Every television series the organization produced had its own research team that assessed the show's intended audience and determined the viewers' wants and needs. Cooney later recounted how her colleagues ridiculed her belief in sociological research. "'Researchers helping producers design a show? You must be kidding!'" she recalled being told by "practically everyone in TV willing to give an honest opinion."[4] The established television dogma held at the time that a successful show depended on the intuition of an experienced staff, not the facts and figures of audience surveys.

But the 1970s saw a flurry of new sociological studies about children and television. For the first time, social scientists started to observe children in classrooms, not laboratories. They began asking how television viewing affected children's views of society. Science helped producers like Cooney prove that badly scripted shows could damage children's worldviews, and prosocial programming could help children form more positive ideas about their environment.

The CTW's research department became the company's secret weapon in the battle to design wholesome educational

FIGURE 1. BRAINSTORMING THE IDEAS that would grow into *3-2-1 Contact* were students from Harvard University's Graduate School of Education, shown here in 1975, on the left. Several members of the class went to work on the show's research and production teams. On the right, Keith Mielke, Barbara Myerson Katz, and Milton Chen, three of the four research staff involved in the program's development, are shown together in 2005. (Photos courtesy of Barbara Myerson Katz.)

content for young minds. Shows were designed based on an informed feedback loop between writers, researchers, and directors. As a program was produced, department staff would test it in classrooms for appeal and comprehension by using a system of interviews and questionnaires. If children disliked a particular character, for instance, the writers would be notified, and the character might be rewritten or recast. Only when the show garnered the audience's approval would it be aired on national television.

In the early 1970s, buoyed by the success of *Sesame Street* and *The Electric Company*, Cooney tasked her researchers with a new challenge: to create a television series that would inspire children to become scientists. Over the next four years, several CTW producers brainstormed ideas for a "curiosity show" with students at Harvard University's Graduate School of Education, shown in figure 1 on the left. Their ideas became the seeds of a new science series.

The three research associates who worked to develop the new show were Milton Chen, Hylda Clarke, and Barbara Myerson Katz. Chen and Myerson Katz had studied at Harvard's Graduate School of Education, and Clarke held advanced degrees in psychology. Additionally, Chen focused on communications research and later pursued a doctorate at Stanford University. The three researchers worked on the third floor of the CTW office building in Manhattan, but they spent a lot of their time traveling to different elementary school classrooms, YMCAs, and community centers in the New York City area. As a diverse team (Chen is Chinese American, Clarke is African American, and Myerson Katz is Jewish), they dubbed themselves "the Mod Squad of research," a reference to the popular television show about a multiethnic trio of police officers. They worked under the CTW's head of research, Keith Mielke (shown on the right in figure 1 with Myerson Katz and Chen), a former university professor who proved a generous mentor for the young researchers.

The CTW was an exciting place for young creative professionals in the 1970s. Researchers and writers would frequently be hired on a temporary basis and then become permanent staff members as positions opened up. Although each CTW show had its own research team, members of different teams often met for lunch and strolled together through Central Park. The research staff spent long nights together tabulating data and graphing assessments by hand.

In 1977 Chen, Clarke, and Myerson Katz began designing studies to assess children's preexisting attitudes about science and how they were shaped by films and TV shows. They even had at their disposal a new interactive technology called the Program Evaluation Analysis Computer, a system of individual remotes that children could use to register their likes and dislikes and send them to a central console.[5] The researchers could then view the data within minutes on a computer monitor—a step up from hand tabulation!

That summer, the cinema release of *Star Wars* captivated the CTW's core audience. Myerson Katz remembers the first time she heard about the movie: She, Mielke, and Chen were walking down Broadway when they spotted a striking billboard advertising it. "Keith pointed to the sign," she recalls, "and said, 'That's what we're competing against. We have to get the attention of an audience that's going to see that in the movies.'" The CTW, which lacked the budget for talking robots and fast-moving spaceships, had to convince children that real science could be just as cool as the Force.

The squad in action

One of Chen, Clarke, and Myerson Katz's first studies gathered qualitative data on children's bias toward scientists. Two hundred children in grades 4–6 at an elementary school in western New York were asked to write essays either describing the reasons why they might want to be a scientist or imagining the average day in the life of a scientist.

Discouragingly, boys and girls alike overwhelmingly believed that science was an intellectually exhausting, dangerous, and demanding career. Their perceptions reflected the way scientists were portrayed in movies and cartoons: as older men wearing white lab coats, hunched over their laboratory equipment. Most saw scientists as "very narrow human beings who spend their lives in labs and have little social interaction." One boy wrote, "I would not like to be a scientist because I would not like to do what they do. They get up early in the morning." The children understood the importance of scientific research—and some expressed an interest in learning about the human body—but they didn't feel comfortable imagining themselves as future scientists.

The team's magnum opus, "The Television Interest Survey,"[6] came in 1978. More than 4000 children in five states completed the survey, which asked their opinions on a range of popular television programs, including *The Six Million Dollar Man*, *The Muppet Show*, and *ZOOM*. The researchers hoped that the selection of states—Massachusetts, Mississippi, Virginia, Illinois, and California—would encompass not only geographic but also ethnic and economic diversity. To make the questionnaire as accessible as possible, they designed it to be completed in just 20 minutes, with minimal literacy required. The study confirmed what the researchers had long suspected: Current television programs were not meeting the needs of scientifically minded children.

Commercial stations featured a few documentary programs about wildlife, and they were popular. Almost 90% of the survey participants were avid viewers of *Wild Kingdom*, a nature series on NBC. Children also reported watching the technicolor series *The Undersea World of Jacques Cousteau*.

But for children with budding interests in engineering, physics, chemistry, or astronomy, there weren't a lot of television options. In 1978 PBS had been around for less than a decade, and its producers had largely focused on arts and culture programs. *NOVA*, the only nationally aired PBS program that featured scientists at all, was billed as a show "for curious grown-ups." Understandably, then, only 30% of the children surveyed reported having even heard of it.

Unfortunately, the content gap in astronomy and other physical sciences was partially filled by the pseudoscientific show *In Search Of*. Hosted by former *Star Trek* actor Leonard Nimoy, *In Search Of* covered tantalizing subjects such as UFOs, psychic plants, and Bigfoot. The show was quite popular: Two thirds of boys and around half of girls surveyed reported watching it. But the show's entertaining approach conflated fact and fiction, much to the dismay of science educators and researchers.

FIGURE 2. HOSTING THE FIRST SEASON of *3-2-1 Contact* were Lisa (Liz Moses), Marc (Leon W. Grant), and Trini (Ginny Ortiz). In a series of segments shot individually on location and together in their studio clubhouse, the three presenters showed the many ways that science is part of everyday life. (Photo © PBS/Courtesy of the Everett Collection.)

Overall, girls and boys reported watching different genres of programs. Many more boys than girls watched science and science fiction shows. Girls, on the other hand, enjoyed scripted shows that centered on female characters and the importance of community, such as *Little House on the Prairie* and—surprisingly—*Charlie's Angels*, a show aimed at teenage boys. But girls told the researchers that they loved how the Angels solved puzzles and showed confidence. Young girls, it seemed, were looking for role models on television. For a science show to attract girls, it would need to feature strong female cast members solving challenges. Furthermore, noting that Latino and Black viewers reported enjoying shows featuring same-ethnic-group actors, the researchers suggested the potential appeal of an ethnically diverse cast.

Additional, separate studies conducted by the team confirmed that both boys and girls seemed to like shows with dramatic narratives. Children were also intrigued by action-filled footage, such as oil spills and exploding volcanoes. Documentaries with strong visuals and clear narration could hold their attention.

But the characters and action needed to be realistic. Surprisingly, a television short featuring science fiction hadn't fared well in CTW's classroom tests. "While *Star Wars* was extremely popular," the researchers noted, "the phony appearance of a space station and its cast in another program was rejected by kids." Children were a fickle audience; they were eager for new

FIGURE 3. DIZZY GILLESPIE showed off his jazz skills in the *3-2-1 Contact* clubhouse during an episode on noisy and quiet sounds. (Photo © PBS/Courtesy of the Everett Collection.)

material but picky about production quality. As the researchers summarized, "This audience is quite sophisticated in their television viewing and relatively unsophisticated in their scientific knowledge, which is what makes them a fascinating and challenging audience for this series."

Researchers in the writers' room

As the writers collected and developed ideas for the new show, Chen, Clarke, and Myerson Katz continued to have seats at the table. They were joined by several more scientific advisers; early in the process, Cooney had recruited a wide variety of well-regarded science educators and professors to join *3-2-1 Contact*'s advisory committee. Charles Walcott, a biologist from the State University of New York at Stony Brook who had been involved with the first season of *NOVA*, served as the scientific content director of the series. MIT physicist Philip Morrison and his wife Phylis Morrison, a science educator, urged the writers to focus on how science was a part of a child's daily experience beyond the classroom. Sheldon White, a psychologist at Harvard, suggested that the show could give children the conceptual tools to recognize patterns in their own lives. He proposed organizing episodes around simple binaries, such as "hot and cold" and "big and little," rather than conventional scientific disciplines. That thematic structure became the foundation to *3-2-1 Contact*'s novel approach.

The next conceptual building block was Chen's idea. He proposed dividing the show between two settings: A TV studio home base and a roving remote unit that would provide daily documentary pieces. Segments in both settings would be presented by actors between 20 and 30 years old, whom Chen imagined would be like the docents in a science museum: "Their main purpose is to make everything on the show as clear as possible to viewers. . . . They are not professional scientists but are intensely curious and serve as role models. For now, imagine them as Lindsay Wagner [*The Bionic Woman*], Clifton Davis [*That's My Mama*], or Ron McNair [one of NASA's first Black astronauts]."[7] Young viewers wanted to see youthful, hip students, the team concluded, not space warriors or cutesy Muppets. The show's realism would set it apart from other children's television programs.

Gradually, the structure of *3-2-1 Contact* took shape. The show's three main characters—Marc, a Black man; Lisa, a white woman; and Trini, a Latina woman, shown in figure 2—would take turns traveling to locations such as laboratories, volcanoes, and the ocean. In between those documentary shorts, they'd hang out in their clubhouse to discuss what they'd learned. The clubhouse setting was the show's connective tissue and provided viewers with a relatable, on-screen community.

With that premise in place, some of the show's consultants and writers wondered about other ways to make the series "cool." With the popularity of *Mork & Mindy* and its zany star in mind, they thought about finding a host with similar appeal. Perhaps a teen idol such as Shaun Cassidy? Or Alan Alda, the star of *M*A*S*H*? For a while, they joked about approaching Henry Winkler, "the Fonz" from *Happy Days*.

But research had shown that children wanted multifaceted scientific role models, not talking heads. So instead of hiring one main celebrity, the producers decided to sprinkle cameo appearances throughout the show. Tennis pro Arthur Ashe appeared in one segment to talk with Marc about the mechanics of his sport. Dizzy Gillespie, shown in figure 3, and the members of KISS were featured in episodes about sounds. Most of the first season's guests, however, were plucked from scientific and everyday life: graduate students, university professors, a surfer, a race-car driver, a veterinarian, and the *Guinness Book of World Records* record holder for making the world's largest pizza.

With its eclectic mix of guests, *3-2-1 Contact* projected the idea that anyone could be a scientist. The show never lost sight of its commitment to racial and ethnic diversity. In one episode, Marc was building a model of the solar system and wanted to learn more about the Sun. So he invited Joseph Martinez, a Mexican American physicist from the Department of Energy, to visit the clubhouse and talk about the physics of light. Martinez and the gang sat down on beanbag chairs, and the conversation soon turned from science to his career path. After listening to Martinez recount how he'd gotten his start in science, Trini asked him why there were so few Hispanic scientists. Martinez explained that Mexican American children didn't have many role models in the sciences and didn't know that they could be scientists. Further, he explained, some teachers falsely believed that their Spanish-speaking students couldn't excel in science. The hosts expressed their disappointment. "It shouldn't really make any difference," replied Lisa, "because science is science, and the Moon affects everyone on Earth, no matter what language you speak."

Contacting a new generation of viewers

In late 1979, after three years of production led by executive producer Kathy Mendoza, *3-2-1 Contact* was approaching its final form. All the CTW staff were pleased with the first season of episodes, written by physicist Ted Ducas and science writer Boyce Rensberger. At the last minute, Sid Fleischman, the Newbery Medal–winning author of *The Whipping Boy*, was hired to write a detective serial to be aired as a "show within a show" on the series. The result, *The Bloodhound Gang*, featured a trio of crime-solving kids foiling the plots of a revolving cast of zany villains. The stars of the segment, shown in figure 4, were as diverse as those of the main series.

When *3-2-1 Contact* premiered on 14 January 1980, one reviewer called it "zippy, hip, and the kind of show that would interest adults as well as 8- to 12-year-olds." During its premiere run, Nielsen estimated that the show had been viewed by 23% of all children between the ages of 6 and 11. The research team's follow-up studies indicated that many children who'd watched the program felt more positively about science—and were more likely to agree that women could be scientists and that scientists were normal people. Some of the show's young viewers, such as Ainissa Ramirez, would go on to pursue science as a career. Just as the CTW researchers had hoped, African American and Hispanic children saw themselves reflected in the characters of *3-2-1 Contact*.

Chen was promoted to the CTW's director of research and oversaw the studies that guided *3-2-1 Contact*'s subsequent seasons. For the first season, the *3-2-1 Contact* research team had designed more than 50 studies and surveyed 10 000 children. For the second season, which aired in 1983, Chen led his team in generating 60 additional reports. That season was even more successful, reaching almost 40% of school-age children. To accompany the series, the CTW published a popular companion magazine, featuring games, activities, and articles about science, that saw a yearly circulation of 300 000 copies. The Girl Scouts partnered with the CTW to produce a series of *3-2-1 Contact* merit badges that rewarded girls for watching the program and completing activities inspired by particular episodes. In the Washington, DC, area alone, almost 10 000 of the badges were awarded.

New seasons of *3-2-1 Contact* continued until 1988, with several changes in actors and format along the way. The show's success encouraged the NSF program officers to fund more children's television series, including *Bill Nye the Science Guy* (1993) and *The Magic School Bus* (1994). Samuel Gibbon Jr, one of the leading visionaries of *3-2-1 Contact*, was inspired to create a narrative-driven science series, *The Voyage of the Mimi*

FIGURE 4. THE BLOODHOUND GANG—Zach (Kelly Pease), Ricardo (Marcelino Sánchez), and Vikki (Nan-Lynn Nelson)—starred in scripted segments that rounded out most *3-2-1 Contact* episodes. The trio of young sleuths used principles of logic and observation to bring wrongdoers to justice. (Photo © PBS/Courtesy of the Everett Collection.)

(1984), which followed the adventures of children on a marine biology expedition. (That series, incidentally, marked Ben Affleck's television debut.) In the mold of *3-2-1 Contact*, the CTW-produced *Square One Television* (1987) featured an eclectic assortment of sketches about mathematics. George Tressel, the former head of NSF's Public Understanding of Science program, credited *3-2-1 Contact* with laying the foundation for many of the organization's informal science education initiatives in the 1980s. (See the article by George Tressel, PHYSICS TODAY, November 1990, page 24.)

The success of *3-2-1 Contact* proved the value of formative research studies in television production. No previous television program had thoughtfully asked its audience, "What sort of science would you like to watch on TV?" The CTW embraced the unusual perspective that collecting audience data would help to create a better series. Today, creators of many children's science shows conduct similar research to evaluate their programming. Producers like Cooney showed their colleagues that scientists could be trusted members of production teams.

But *3-2-1 Contact* also demonstrated something much more important. It was the first science television series to take diversity seriously. Recognizing the need for children to see diversity reflected in scientific and technological fields, the *3-2-1 Contact* researchers, writers, and actors intentionally created inclusive narratives of science. The CTW listened to the voices of underrepresented children and invited them to dream about their own future in science. The ultimate message was that science is for everyone—especially viewers like you.

Thanks to Milton Chen, Ted Ducas, Barbara Myerson Katz, Sam Gibbon, and Charlie Walcott for sharing their memories with me. Also, special thanks to the Library of American Broadcasting and to David Cohen at Sesame Workshop for allowing me to access their collections.

REFERENCES

1. A. Ramirez, *Science* **348**, 726 (2015).
2. F. Bruning, *Newsday*, 23 October 1972, p. 1A.
3. For more about the early history of the CTW, see R. W. Murrow, *Sesame Street and the Reform of Children's Television*, Johns Hopkins U. Press (2006).
4. S. M. Fisch, R. T. Truglio, eds., *"G" Is for Growing: Thirty Years of Research on Children and "Sesame Street,"* Lawrence Erlbaum Associates (2001), p. xi.
5. M. Chen, *A Review of Research on the Educational Potential of 3-2-1 Contact: A Children's TV Series on Science and Technology*, rep. prepared for the Children's Television Workshop and the National Science Foundation (January 1984), available at https://files.eric.ed.gov/fulltext/ED265849.pdf.
6. K. Mielke, M. Chen, in *Learning from Television: Psychological and Educational Research*, M. Howe, ed., Academic Press (1983), p. 31.
7. M. Chen to Science Show Production and Research, "Strategy and Guesses Leading to Format Idea Stressing Viewer Participation Strategy and Guesses" (8 September 1978), folder 34, box 103, Children's Television Workshop Records, Library of American Broadcasting, University of Maryland. PT

Koji Uenishi is a professor in the department of advanced energy and the department of aeronautics and astronautics at the University of Tokyo in Japan.

OVERLOOKED MECHANISMS BEHIND SEISMIC DAMAGE

Koji Uenishi

Photographs of aboveground and underground structural failures after earthquakes uncover simple but not widely recognized physics.

On 17 January 1995, a devastating earthquake struck the port city of Kobe in southern-central Japan and the densely populated surrounding area. The quake, officially named the Hyogo-ken Nanbu earthquake, had a moment magnitude of 6.9. The seismic rupture initiated at a shallow depth of 16 km and propagated to the northeast and southwest along the crust's local geological fault system (figure 1a). It released tectonic energy stored on and near the fault system and converted part of that energy into seismic waves.

What made the Kobe event unusual was that seismic rupture—the slipping in Earth's crust—propagated along a fault that ran directly through a developed area with a population of more than three million. The distance between the city center and the earthquake's epicenter was only about 20 km; often it's hundreds of kilometers or more because most cities are located farther from geologic faults. The Kobe area was therefore directly hit by strong seismic waves that hadn't yet attenuated through propagation. The quake totally or partially destroyed approximately 640 000 buildings throughout the area.

The photograph in figure 1b was taken near Kobe's Rokkomichi railway station and shows archetypal seismic disaster: Wooden houses were completely destroyed, whereas those made of reinforced concrete (RC) were left standing, seemingly unharmed. It agrees with an intuitive image of seismic disasters in which similar structures experience comparable amounts of damage.

That wasn't the case everywhere, though. Surprising structural damage was found in

A 1976 earthquake in Friuli, Italy, produced a periodic structural failure pattern in adjacent, mechanically similar buildings. (H. P. Rossmanith, Vienna University of Technology, Austria.)

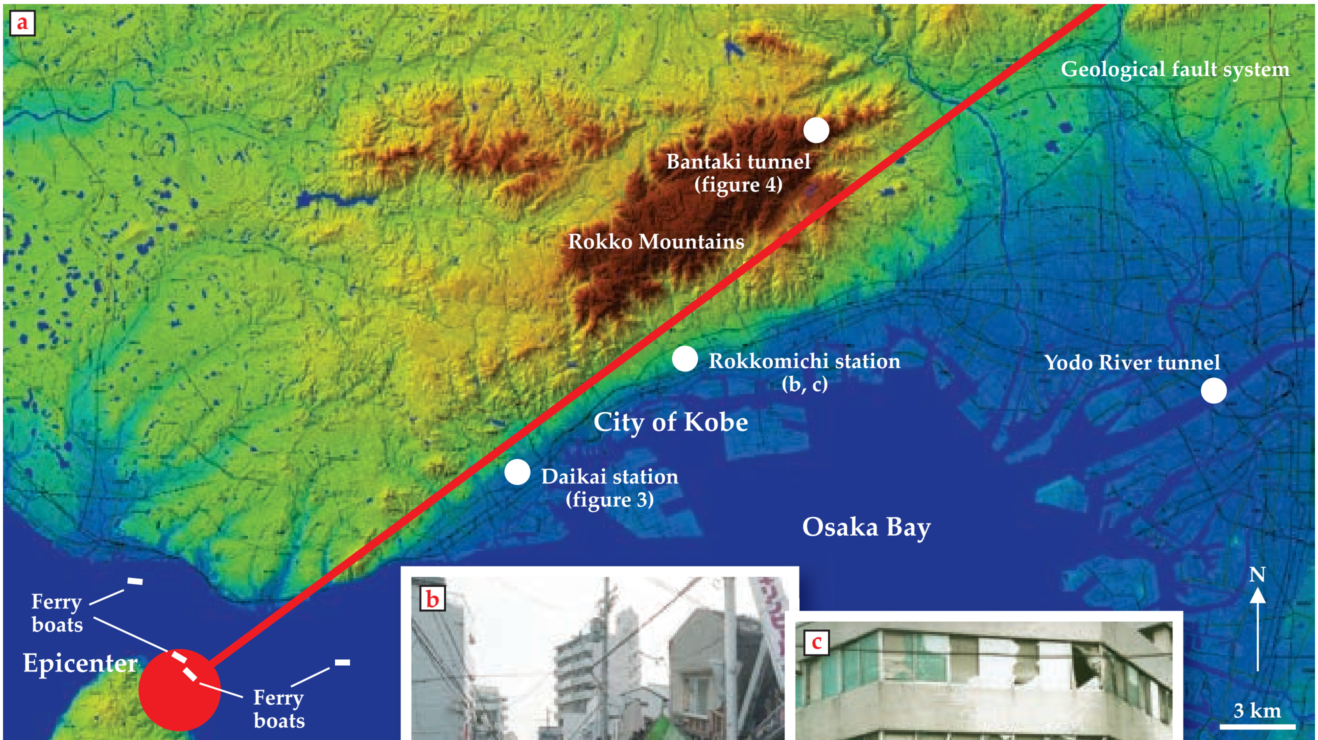


FIGURE 1. (a) THE 1995 HYOGO-KEN NANBU EARTHQUAKE near Kobe, Japan, produced structural failures throughout the area and at the specific locations indicated. (Adapted from topographic map provided by Geospatial Information Authority of Japan and ref. 3.) **(b)** Mechanically similar structures normally suffer similar levels of damage during an earthquake. In this image taken near Rokkomichi railway station, wooden houses have collapsed while reinforced concrete buildings remain standing. (Courtesy of the City of Kobe.) **(c)** Despite being built from reinforced concrete, a nearby building had its second story vertically compressed so that it completely disappeared. High-frequency seismic waves can account for such localized damage. (Courtesy of Shunsuke Sakurai, Kobe University.)

RC buildings around Kobe. Figure 1c shows another area in the Rokkomichi district. At first sight, the RC building seems structurally undamaged by the quake. However, a careful look at the picture reveals that the second story is compressed and perfectly flattened. Surprisingly, the signboards remained unaffected, and the upper floors shifted vertically with almost no horizontal movement or deformation. Similar structural damage was observed in other RC buildings near the city center.

Seismic waves and structural vibrations

To understand how the Kobe earthquake caused such damage to supposedly earthquake-resistant RC buildings, we first consider the basic characteristics of typical seismic waves. In a linear elastic solid like Earth's crust, the force per unit area, or stress, in the material is linearly proportional to the local deformation per unit length, or strain.[1] Continuum mechanics accommodates two types of body waves, primary longitudinal (P) and secondary shear (S) waves. P waves propagate the fastest, and they cause the ground to move parallel to the direction of the wave's propagation (figure 2a). If they approach the surface from below, they produce vertical shaking with compressive and extensional forces. P waves can also travel through fluids. On the other hand, S waves exist only in solids. They cause motion normal to the wave's propagation direction, so if they come from below, they cause horizontal shaking with no volumetric change (figure 2b).

In addition to body waves, earthquakes also generate surface waves, typically Rayleigh (R) waves. R waves moving along a stress-free boundary like Earth's surface induce both horizontal and vertical shaking at the surface. They also attenuate more slowly than body waves as they propagate: The amplitude of an R wave decreases as $1/r^{1/2}$ with distance r from its origin, whereas a body wave's amplitude dies off as $1/r^2$ along the surface and $1/r$ in the bulk.[1]

A wave's attenuation is also affected by its frequency. Lower-frequency waves propagate farther and with less attenuation than higher-frequency ones. High-frequency P and S waves should therefore be more abundant in seismological recordings near an earthquake's focus. On the other hand, if a seismograph is installed far from the focus, lower-frequency R waves dominate the recorded shaking.

Seismologists have used the fundamental characteristics of waves described above to derive relationships between the shaking recorded by seismographs and the invisible waves that radiate from earthquake hypocenters. (See the article by Hiroo Kanamori and Emily E. Brodsky, PHYSICS TODAY, June 2001, page 34.) A primary objective has traditionally been to shed light—or, more precisely, waves—on the inner structures of Earth through which seismic waves propagate. That study has focused on the far-reaching low-frequency waves that travel thousands of kilometers from hypocenters to seismological recording stations worldwide. For earthquakes, low frequency means less than 1 Hz. A 1 Hz *P* wave travels at about 6 km/s in granite, so its wavelength would be 6 km. That is sufficiently small to resolve the details of the geological structures, which are on the order of tens or hundreds of kilometers, by analyzing wave interactions such as refraction, reflection, and diffraction.

Engineers, on the other hand, are often concerned with earthquakes' effects on natural and artificial structures like slopes and buildings, whose relevant length scales range from a few to hundreds of meters—far smaller than Earth's interior structures. Low-frequency seismic waves are much longer than those structures, so their detailed features are usually not considered when designing buildings and testing their earthquake readiness. Instead, the vibrations recorded at nearby seismological stations are low-pass filtered, and target structures under test are subjected only to low-frequency horizontal vibrations. Both vertical shaking from *P* and *R* waves and dynamic interactions between incoming waves and the target are neglected.

The insights gained from that sort of conventional engineering have been invaluable. However, localized structural failures whose length scales are on the order of meters or tens of meters, like that in figure 1c, can't be straightforwardly explained by low-frequency horizontal vibrations alone. Consider a 1 Hz *S* wave that propagates at 1 km/s. Its wavelength is 1 km. If it strikes a 10-m-diameter underground tunnel from below, the phase difference between the tunnel's floor and ceiling is negligibly small. The tunnel should therefore move like a rigid body, and the wave shouldn't generate localized damage. According to that picture, a tunnel is perfectly earthquake resistant. Although that may be true if the epicenter is far from the structure and low-frequency seismic waves prevail, the situation isn't necessarily the same for structures near epicenters where high-frequency seismic waves can be dominant.

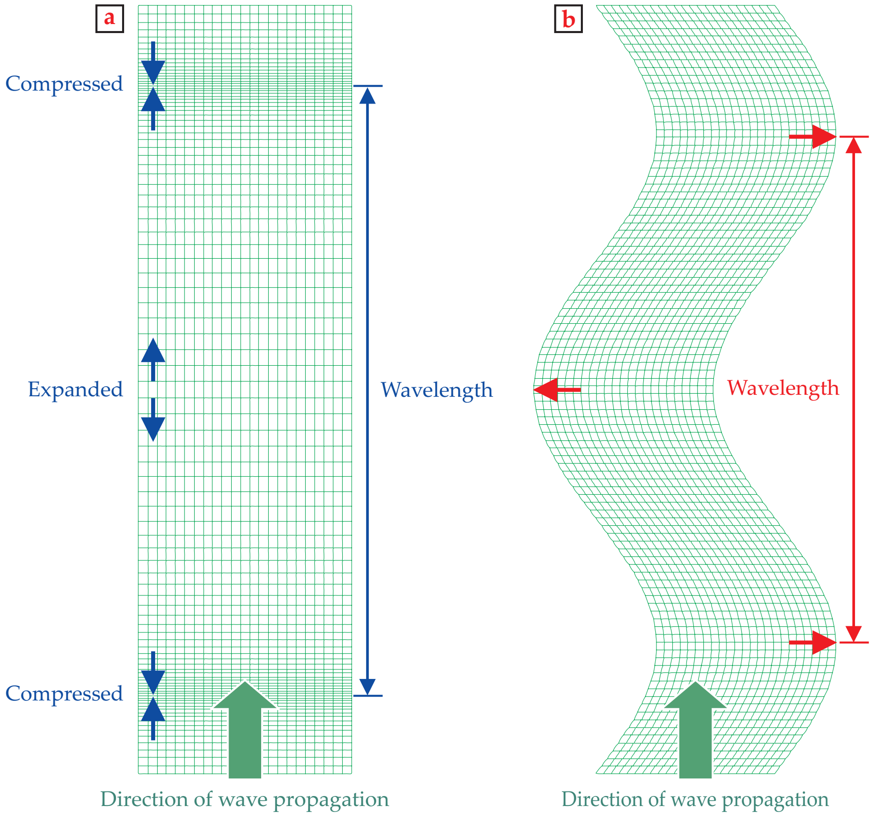


FIGURE 2. (a) A LONGITUDINAL (*P*) WAVE MOVING THROUGH A SOLID MEDIUM generates compressive and extensional motions that cause local volumetric changes in the medium. The wave moves at a constant speed through the medium. **(b)** A shear (*S*) wave, which travels at a constant speed smaller than that of a *P* wave, produces transverse or shearing motion that doesn't cause volumetric change.

Unexpected, then forgotten

Underground structures are generally believed to be sufficiently strong against earthquakes. And usually they are. But in 1995, the Daikai railway station in downtown Kobe catastrophically failed. At the station, about 5 m below ground, vertical collapse of the reinforced concrete columns supporting the roof (figure 3a) resulted in the failure of the roof and the sinking of the street above (figure 3b).

The central section of the approximately 1750-m-long Bantaki road tunnel through the Rokko Mountains was also damaged. The concrete wall, which was reinforced with steel bars, fractured from compressive force, and the road surface jumped up from the underlying concrete, known as the invert (see figure 4). Strangely, however, the ceiling, the invert, and the surrounding ground sustained no damage. The geological faults crossing the tunnel hadn't moved.

The unexpected failures at the Daiki station and the Bantaki tunnel were the first that could not be attributed to, say, instability near the portal of the tunnel; they may have been directly induced by seismic waves. Then, in 2004, a failure pattern similar to that in Bantaki was observed after the magnitude 6.6 Niigata-ken Chuetsu earthquake. The damage was observed in the near-epicenter Uonuma tunnel, which is part of the Shinkansen high-speed train system. Together, the observations support the idea that structural failures should be expected in underground structures sufficiently close to an earthquake's epicenter.

To understand the mechanism behind the Bantaki failure, consider a *P* wave causing vertical shaking and an *S* wave causing horizontal vibrations, both propagating up toward the tunnel (figure 4). If the *P* wave has a wavelength twice the height of the tunnel—20 m for the approximately 10-m-high Bantaki tunnel—the wave has opposite phases at the tunnel's floor and ceiling. In that case, the wave can leave the top and bottom of the tube intact while generating a large compressive stress in its midsection that destroys the concrete and bends the steel bars reinforcing the wall (figure 4). If the *P* wave's speed is

FIGURE 3. THE UNDERGROUND DAIKAI STATION in Kobe, Japan, collapsed during a 1995 earthquake. **(a)** The reinforced concrete columns supporting the roof gave way and **(b)** the street above the station sank in a 100 m × 20 m area; in some places, it fell as much as 2.5 m. The failure disproves the myth that underground structures are safe against earthquakes. (Photographs courtesy of Shunsuke Sakurai, Kobe University.)

2 km/s in the already-fractured surrounding rock, then the frequency of the incident wave would be 100 Hz, which is well into the high-frequency range.

Simple but rigorous elastodynamic analyses confirm that if 100 Hz *P* waves interacted with the tunnel, the compressive vertical stress acting on the concrete lining could become more than three times as large as that in the incident wave, and the vertical acceleration would be doubled at the tunnel's floor.[2] That stress and acceleration can explain why the tunnel's concrete lining failed in compression and why the road surface detached in response to the earthquake. On the other hand, high-frequency *S* waves and conventional low-frequency waves produce much smaller vertical compressive stress on the wall and acceleration at the bottom. Hence, it seems unlikely that they generated the failures in Bantaki. High-frequency *P* waves are also a likely culprit for the flattened second floor in figure 1c and the collapsed Daikai station in figure 3.[3,4]

The question of detection

Although the unusual structural failure patterns observed after the 1995 Kobe earthquake suggest the existence of higher-frequency vertically oscillating seismic waves, the seismographs widely installed at that time had sensitivities that fell drastically for frequencies above 20 Hz. Additionally, shaking over 10 Hz was filtered out in seismic analyses because of contamination by scattering off inhomogeneities. Strong high-frequency vibrations were therefore scarcely detected at Kobe (figure 5a) despite multiple accounts from people who experienced strong vertical shocks near the earthquake's epicenter.

Vertical shocks were even felt on ferries (identified in figure 1a) and fishing boats that were at sea during the seismic event.[3,5] Vertical disturbances at sea, known as seaquakes, are felt only near earthquake epicenters. Thousands have been reported, but few are listed in reports like Lloyd's List, which tracks maritime incidents. Thus the study of the vertical shocks near epicenters is difficult.[3]

The failure of the concrete lining in Bantaki was nearly forgotten, and the potential importance of higher-frequency seismic waves largely ignored, until a pair of earthquakes occurred in Kumamoto in 2016. A magnitude 6.2 quake struck the city on the island of Kyushu at 9:26pm on 14 April and was followed by an even-stronger magnitude 7.0 main shock at 1:25am on 16 April. The events were enlightening because they produced clear and significant evidence of dominant higher-frequency vertical shaking near their epicenters.

As usual, horizontal vibrations prevailed below 1 Hz. But seismograms of the main shock that were recorded with upgraded seismographs in Uki some 20 km away displayed a peak in vertical shaking just below 10 Hz (figure 5b), which indicates that vertical rather than horizontal shaking dominated in the high-frequency range. Although the exact geological situation in Uki differs from that in Kobe, the clear detection of dominant high-frequency waves near the epicenter of a seismic event of similar magnitude and focal depth gives credence to anecdotal accounts from Kobe more than 20 years after the quake.

Evidence is still lacking for the 100 Hz waves estimated from the Bantaki failure. Even upgraded seismographs are not sensitive to seismic waves of 100 Hz, and signals become contaminated by scattering above 10–20 Hz. The signals are not impossible to record: Sensors that detect vibrations from blasting can capture frequencies up to 1 kHz. But to capture an earthquake's signal without undue noise, specialized sensors appropriate for the frequency range and duration still need to be developed. Even though such high frequencies generated by earthquakes have not yet been recorded, it's conceivable they exist.[4,6]

Dynamically deformed town

Small-scale earthquake-induced failures point to a need for seismographs that are more sensitive to high frequencies. However, even horizontal vibrations well within the range being recorded can cause unusual damage on the scale of a single structure. A building or tunnel can be deformed by seismic waves, but so can an entire town.

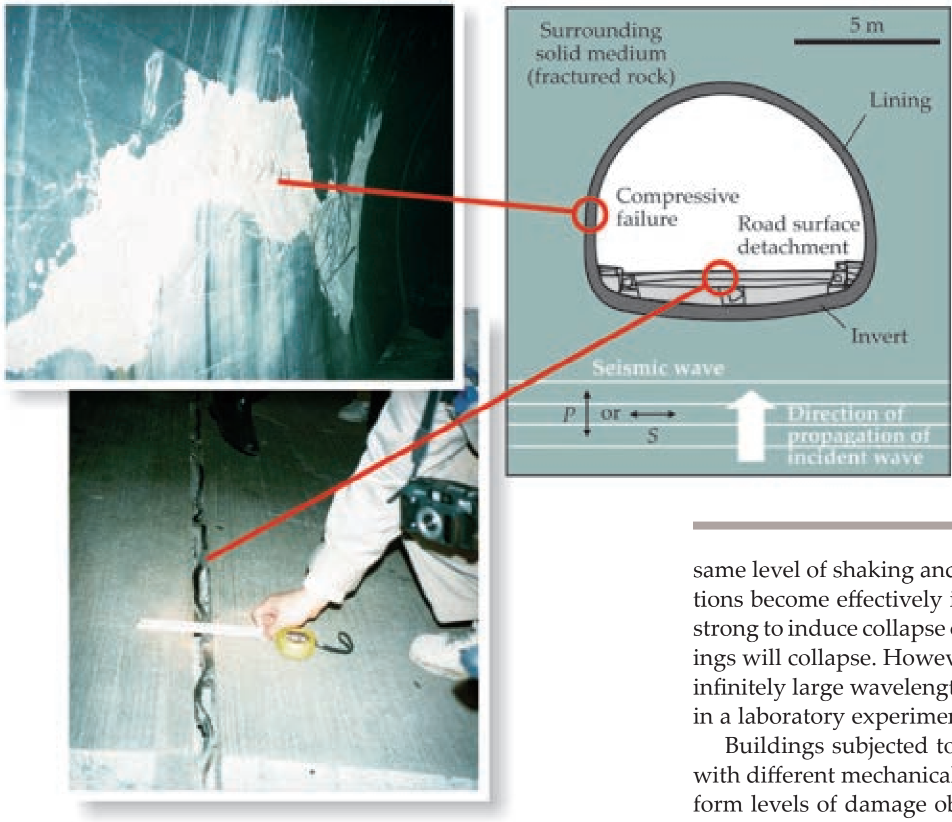


FIGURE 4. THE BANTAKI TUNNEL experienced unfamiliar structural damage during the Hyogo-ken Nanbu earthquake. A high-frequency *P* wave impinging on the tunnel could have caused vertical shaking that dynamically compressed the tunnel and caused the failure observed in Bantaki—namely, the fracture of the concrete wall and the detachment of the road from the tunnel's underlying concrete. An *S* wave with horizontal vibration could not have produced the necessary compressive force in the tunnel's wall. (Photographs courtesy of Shunsuke Sakurai, Kobe University.)

Nearly half a century ago, an astonishingly periodic structural failure pattern was seen in Italy after the magnitude 6.5 Friuli earthquake (see opening figure). The quake produced an alternating pattern of collapsed and undamaged buildings near the epicenter. In a traditional seismic model, if mechanically and geologically similar buildings are densely packed and subjected to the same seismic waves, they all experience the same level of shaking and damage. Buildings at different locations become effectively identical: If a vibration is sufficiently strong to induce collapse of a single building, then all the buildings will collapse. However, that assumes unrealistic waves of infinitely large wavelength, akin to the rigid shaking of a table in a laboratory experiment (upper panel of figure 6).

Buildings subjected to identical vibration can be endowed with different mechanical characteristics to model the nonuniform levels of damage observed in real earthquakes. But that doesn't explain the regularly alternating damage to similar structures in the opening image. The surprising failure pattern arises naturally, however, if waves with wavelengths on the order of a few buildings are accounted for. Even if only conventional *S* waves with horizontal shaking are assumed, the inclusion of higher-frequency waves and the dynamic interaction between waves and the buildings results in individual buildings in a densely built town experiencing totally dissimilar vibrations.

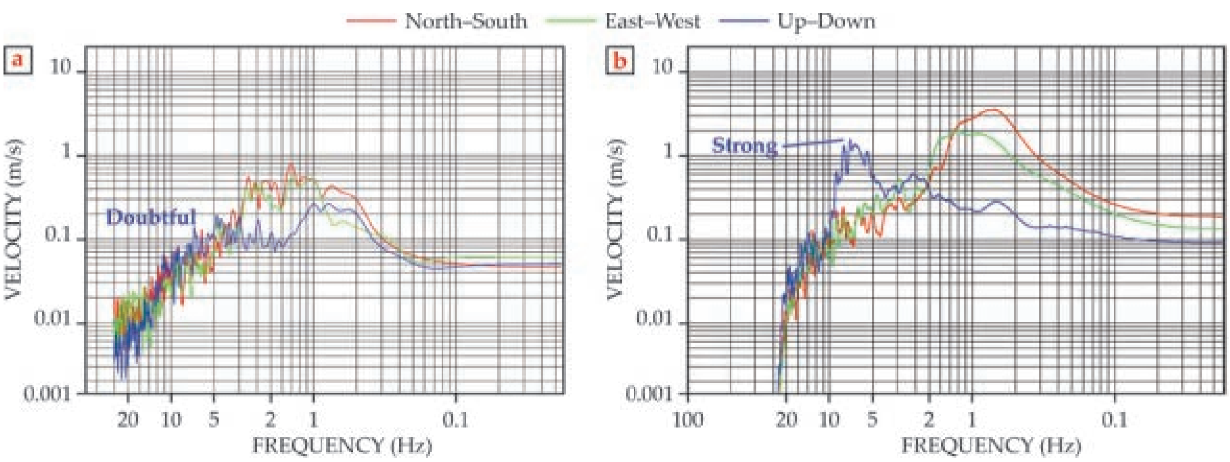


FIGURE 5. THE FOURIER SPECTRA OF SEISMOGRAMS show the vibrations recorded for **(a)** the 1995 Hyogo-ken Nanbu earthquake and **(b)** the 2016 Kumamoto earthquake. Contrary to verbal anecdotes of vertical shocks during the earliest stage of seismic shaking in the 1995 event, a seismogram recorded in Kobe, just 16 km from the epicenter, suggests that the up and down vibrations from *P* waves were weak and that horizontal shaking was dominant. However, it's not clear that seismographs at the time would have been able to detect high-frequency vibrations. Upgraded seismographs deployed during the 2016 quake captured the arrival of stronger *P* waves. Dominant high-frequency vertical motion was recorded in Uki, 14 km from the epicenter. (Based on online data provided by the Japan Meteorological Agency, https://www.data.jma.go.jp/svd/eqev/data/kyoshin/jishin. Site is in Japanese.)

In a town's fundamental vibrational mode, illustrated in the center panel of figure 6, the buildings at the center of the town vibrate the most whereas those at the edges experience no translational motion. In a higher mode, depicted in the lower panel, every other building may vibrate strongly while the others remain at rest. That disparity in the mechanical behavior of each building is called the town or city effect.[7] In Friuli, where the speed of an *S* wave through the soft soil is about 225 m/s, generating damage by that mechanism would require a wave with a frequency of about 4 Hz and a wavelength of about 60 m. Those parameters are consistent with the dominant frequencies recorded at the nearby Tolmezzo-Ambiesta dam during the Friuli 1976–77 earthquake sequence. The magnitude 6.2 Dinar earthquake in Turkey in October 1995 produced a similar periodic failure pattern.

The idea that urban areas might interact differently with seismic waves was theoretically developed in France. It appeared after the 1985 Michoacán earthquake that generated severe damage in Mexico City.[8] Classical computational methods could not explain seismic records, and researchers wondered whether some of the seismic energy transmitted to the buildings could still affect neighboring buildings through interactions between vibrating structures and waves in the ground.

It's hard to imagine the ground under one's feet dynamically deforming on such short length scales. But during the 1995 Kobe event, a surveyor working in a straight, flat section of a railway tunnel 40 m below the Yodo River in Osaka, more than 40 km from the epicenter (figure 1a), reported just that. He saw the tunnel horizontally winding with apparent amplitude of about 1 m and wavelength of 40–50 m, which supports the idea of town-scale dynamic ground deformation.[5]

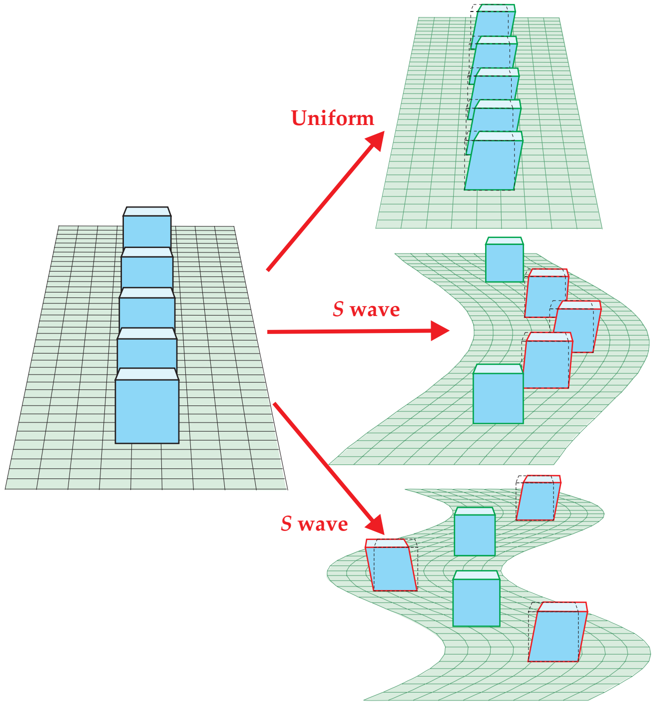


FIGURE 6. THE TOWN EFFECT challenges the conventional idea that earthquakes generate rigid-body shaking of unbending ground. Uniform shaking (top right) should cause the same level of vibration and damage to mechanically identical buildings; it can't generate the alternating failure pattern in the opening image. However, *S* waves propagating through a densely built town can deform the ground and deliver dissimilar vibrations and damage to identical buildings (center and lower right). The frequency of the vibration determines the damage pattern. (Adapted by Donna Padian from the author's original.)

Higher or lower?

The now-dated photographs of Kobe and Bantaki point to the possibility that high-frequency seismic waves have had previously unrecognized effects on structures near earthquake epicenters. The images show damage that cannot be explained systematically using conventional low-frequency approaches. In their foundational textbook *Quantitative Seismology: Theory and Methods* (1980), Keiiti Aki and Paul Richards summarized classical, low pass–filtered seismology,[9] which is now intensively employed in seismic research. However, in a 2005 historical overview of the field, Aki noted that even with the improved quality and quantity of seismological data and associated computational processing capabilities, it's hard to incorporate waves above 1 Hz into traditional low-frequency seismology models.[6]

Some earthquake scientists have long acknowledged the significance of including higher frequencies in their studies. A stochastic approach to seismology developed in the 1980s incorporates Earth's smaller-scale seismic inhomogeneities and accepts the presence of so-called coda waves, which decay slowly relative to other seismological signals. The scattering of high-frequency coda waves is used to study geological inhomogeneities.[10]

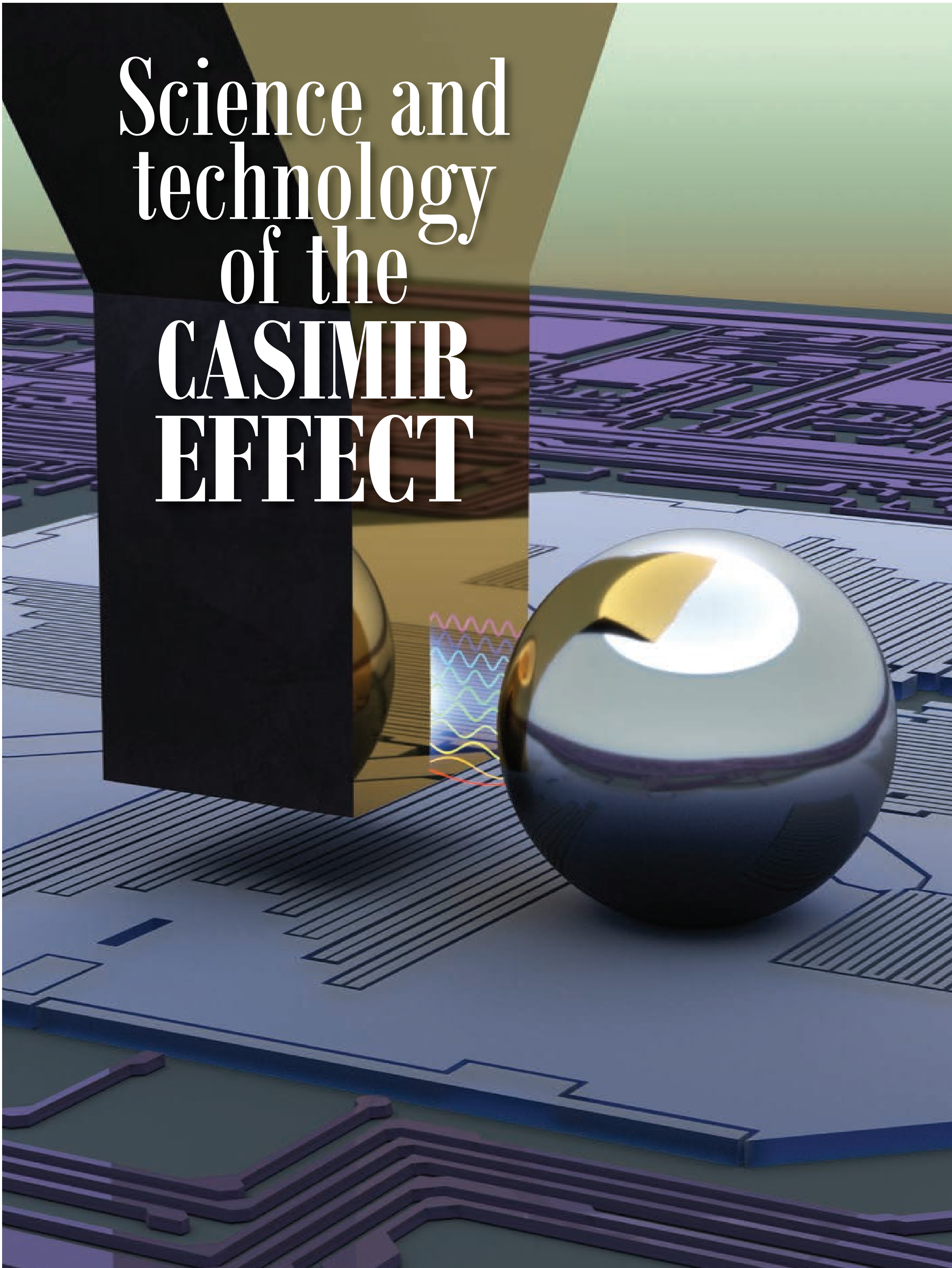
Research in engineering seismology is advancing in the opposite direction—to even lower frequencies. In 2011 long-wavelength vibrations from a magnitude 9.1 earthquake off the Pacific coast of Tohoku in northeastern Japan delivered long-lasting and large-amplitude shaking to the higher stories of skyscrapers in Osaka, about 700 km from the epicenter. Accounting for increasingly lower frequencies would certainly be useful in such cases. But although low-frequency analyses can teach us many meaningful things, they cannot tell us everything. The importance of higher-frequency seismic waves should also be recognized in engineering research. Waves both above and below the normal frequency range are needed to better understand the mechanisms behind the wide variety of earthquake damage.

REFERENCES

1. K. F. Graf, *Wave Motion in Elastic Solids*, Clarendon Press (1975).
2. K. Uenishi, *ASME J. Appl. Mech.* **79**, 031014 (2012).
3. K. Uenishi, *Annu. Rev. Earth Planet. Sci.* **46**, 387 (2018).
4. S. Sakurai, K. Uenishi, *J. Jpn. Soc. Civil Eng.* **90**(6), 48 (2005; in Japanese).
5. Y. Kawata, *Kagaku* **66**, 70 (1996; in Japanese).
6. K. Aki, *J. Seism. Soc. Jpn. 2nd Ser.* **57**, 317 (2005).
7. K. Uenishi, *Rock Mech. Rock Eng.* **43**, 811 (2010); M. Ghergu, I. R. Ionescu, *Int. J. Eng. Sci.* **47**, 342 (2009).
8. A. Wirgin, P.-Y. Bard, *Bull. Seismol. Soc. Am.* **86**, 914 (1996); P. Guéguen, P.-Y. Bard, F. J. Chávez-García, *Bull. Seismol. Soc. Am.* **92**, 794 (2002); C. Boutin, P. Roussillon, *Bull. Seismol. Soc. Am.* **94**, 251 (2004).
9. K. Aki, P. G. Richards, *Quantitative Seismology: Theory and Methods*, W. H. Freeman & Co (1980).
10. H. Sato, M. C. Fehler, *Seismic Wave Propagation and Scattering in the Heterogeneous Earth*, Springer-Verlag (1998).

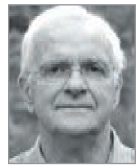
PT

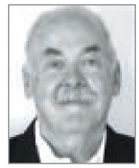
Science and technology of the CASIMIR EFFECT



ALEXANDER STANGE

Alex Stange is a research scientist in materials science and engineering, **David Campbell** is a professor of physics, and **David Bishop** is a professor and head of the division of materials science and engineering, all at Boston University.





Alexander Stange, David K. Campbell, and David J. Bishop

Caused by simple fluctuations in space, the Casimir effect may validate theories of the cosmological constant and allow for measurements of ultrasmall magnetic fields.

In its simplest form, the Casimir effect is an attractive interaction between two uncharged and perfectly conducting plates held a short distance apart—usually less than a micron. Classically, the only attractive force acting between such plates should be gravity. But that's vanishingly small for microscale objects. In 1948 theorist Hendrik Casimir predicted the existence of the now eponymous force on the scale of a few hundred piconewtons when the plates are held 100 nm apart.[1] Seen experimentally many times,[2–7] the force is a nanoscale phenomenon that arises from quantum fluctuations of the electromagnetic vacuum. For a short survey of the first 60 years of research on the Casimir effect, see the article by Steve Lamoreaux, PHYSICS TODAY, February 2007, page 40.

Since the late 20th century, the miniaturization of sensors, actuators, and other electronic components has become routine. Integrated electronics on a chip are now pervasive—in our computers, cell phones, and all kinds of common devices. That ongoing miniaturization inevitably brings quantum mechanical effects to the fore. Fortunately, those effects can also be exploited. The development of microelectromechanical systems (MEMS) devices allows for precision measurements to be conducted in the deep submicron regime. In the past 20 years, the field of Casimir science has exploded. This article surveys current progress and the outlook for nanotechnical applications, including metrology in physical and biomedical contexts.

First, let's step back and review the foundations of the field. To conceptually appreciate the origins of the Casimir effect, see figure 1. In a quantum vacuum, electromagnetic fluctuations appear and disappear as intermittent electromagnetic modes that span an infinite range of wavelengths in free space. But when two perfectly conducting plates are brought close together, the long-wavelength modes get "frozen out." That is, the optical cavity formed by the proximity of the two plates restricts the number of modes that can exist inside the cavity to those with wavelengths that are half-integral divisors of the separation. The number of modes that resides in free space has no such constraint. And that higher density of modes outside the plates produces an effective net force that pushes them inward.

More formally, the force can be determined by summing over all cavity modes. Although that quantity diverges, one can obtain a finite result by taking differences in the energy between plates at different separations. Using that method, in 1949 Casimir predicted[1] an attractive force per unit area at a separation a given by $-\hbar\pi^2 c/240a^4$. In the classical limit, $\hbar$ goes to zero and the Casimir force vanishes. The inverse quartic dependence with distance is most unusual in physics and sharply different from the familiar inverse quadratic dependence of gravitational and electrostatic forces.

Experimentally, it's difficult to place two large plates less than a micron apart. Doing so requires that they be strictly parallel. A now common geometry whose separation is easier to tune is that of a plate and a sphere whose radius R is much greater than a. For that configuration, the force is $-\hbar R c\pi^3/360a^3$.

The force originally calculated by Casimir applies to perfectly conducting metal plates with electrostatically hard boundaries. A little more than a decade later, Evgeny Lifshitz extended the calculation to nonideal metals and dielectrics,

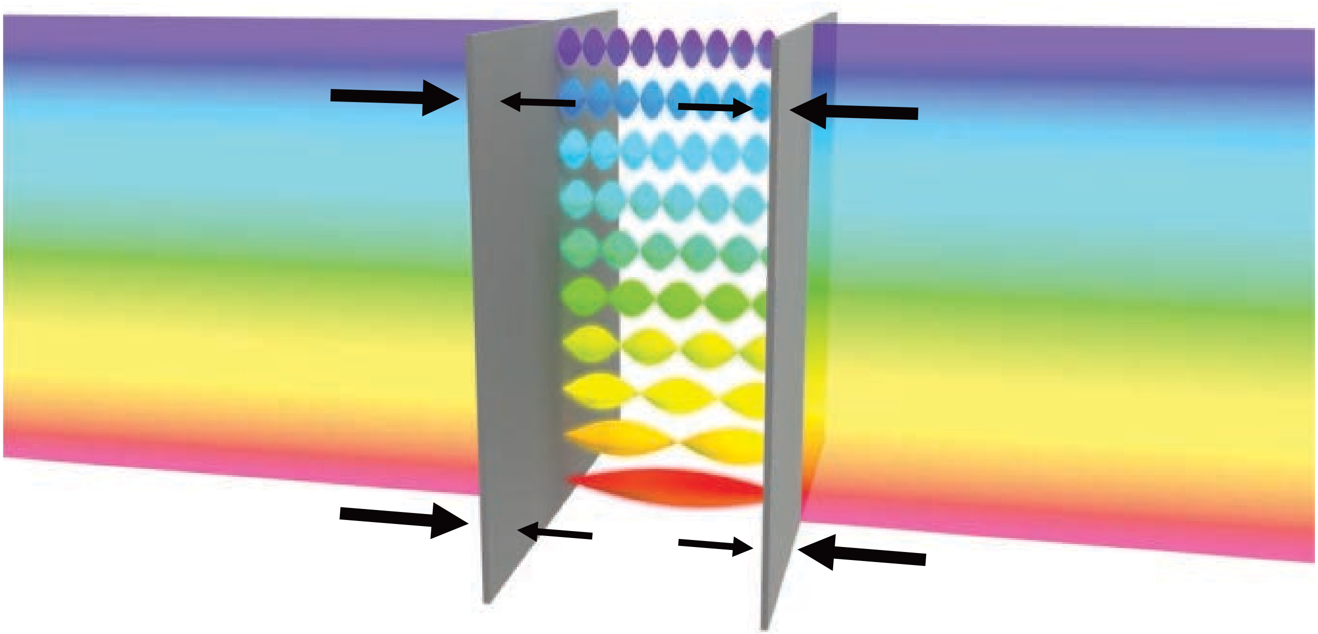


FIGURE 1. IN A QUANTUM VACUUM, free space is filled with electromagnetic fluctuations at all wavelengths. But in a Casimir cavity, typically composed of two perfectly conducting plates, boundary conditions allow for the existence of fluctuations only at half-integer wavelengths. That constraint lowers the energy density in the cavity relative to the energy density outside it and produces a net attractive interaction between the plates—provided the plates are made from the same material. For a special combination of materials, the Casimir force can be repulsive. (Figure created by Alex Stange, David Campbell, and Dave Bishop.)

including those that have rough surfaces and allow some penetration by electric fields.[8] Dutch physicist Marcus Sparnaay provided qualitative evidence as early as 1958 that the Casmir effect is real.[2] But the first unambiguous quantitative observations[3] came from experiments that Lamoreaux conducted using a torsional pendulum almost 40 years later, in 1997.

To appreciate the high precision and sensitivity of the Casimir force, see figure 2, which shows an early measurement using the same kind of torsional pendulum, but mounted on a far smaller MEMS device.[5] Taking into account correction factors for real metallic surfaces,[6] those data agree quantitatively with theoretical predictions to within a few percent.

Today, measurements of the attractive Casimir force between metals, especially spheres and plates, are routinely seen in a wide range of geometries and experiments. Research concerns itself with details such as the finite conductivities of the metals, surface roughness, subtly varying “patch” potentials, and detailed calculations of plate–sphere geometries that are not amenable to simple, closed-form solution.

Repulsion, torque, and dynamical effects

The simple mode-variation model shown schematically in figure 1 yields an attractive force when gold films are deposited on plates that have air or a vacuum between them. But as Lifshitz and his collaborators predicted early on,[8] a repulsive force should also be achievable. One needs to separate the plates

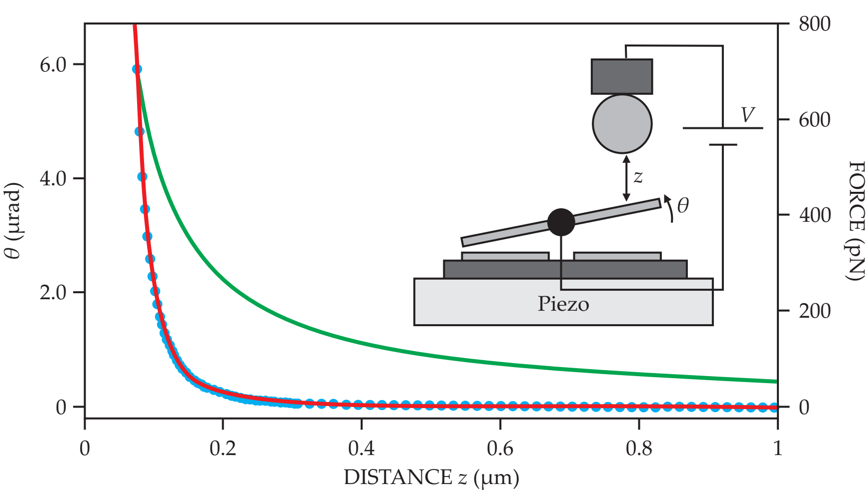


FIGURE 2. A MICROELECTROMECHANICAL TORSIONAL OSCILLATOR, sitting atop a piezoelectric stage, is positioned near a 100-μm-radius gold-coated sphere. An attractive Casimir force (the blue data points, fit to the red curve) causes the oscillator plate to rotate by an amount θ that scales with $1/z^3$, where z is the distance between the oscillator and the sphere. At separations greater than 300 nm, no tilt was detectable; below that, the attractive force increased rapidly. The voltage V on the sphere was set to a value that eliminated electrostatic contributions to the attractive force. The green curve plots the electrostatic force, whose range is much longer. (Adapted from ref. 5, H. B. Chan et al., *Science* **291,** 1941, 2001.)

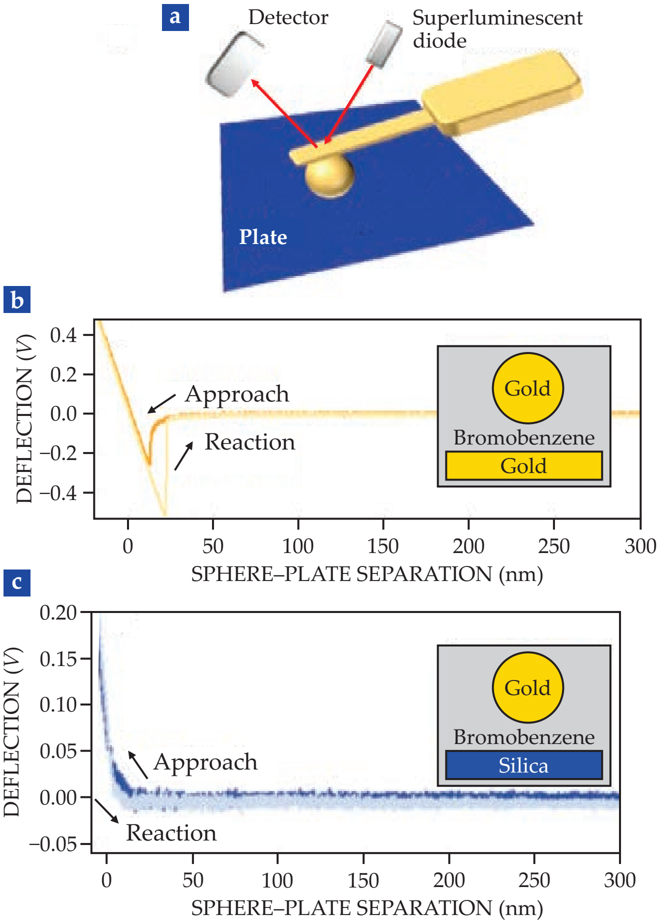


FIGURE 3. WHETHER A CASIMIR FORCE IS ATTRACTIVE OR REPULSIVE depends on the dielectric properties of the two interacting objects. **(a)** An atomic force microscope (AFM) can discern which sign is at work. In two cases, a 40 µm gold sphere attached to the end of an AFM cantilever is lowered onto a plate—either gold or silica. Sphere and plate are both inside a fluid cell containing bromobenzene. The sign of the force on the sphere is determined by the position of a light signal reflected from the cantilever into a photodetector as the cantilever is moved toward or away from the plate. **(b)** In the case where gold interacts with gold, the region of negative deflection implies that the approaching sphere is attracted to the surface and "jumps" to make contact; the attraction arises from the equal permittivities ε_1 of the sphere and plate. **(c)** In the case where gold interacts with silica (permittivity ε_2) in liquid bromobenzene (permittivity ε_3), the deflection is positive, signifying a repulsive force, because the three permittivities satisfy $\varepsilon_1 > \varepsilon_3 > \varepsilon_2$. (Adapted from ref. 9.)

with a fluid, not a vacuum or air, and use a nonperfect conductor or dielectric as one of the plates. The trick is to choose materials for the plates and surrounding fluid such that the product of their permittivity differences, $-(\varepsilon_1 - \varepsilon_3)(\varepsilon_2 - \varepsilon_3)$, is positive over a wide range of frequencies.

If $\varepsilon_1 = \varepsilon_2$ the product is always negative, regardless of the value of ε_3, producing an attractive force. If, however, one chooses materials such that $\varepsilon_1 > \varepsilon_3 > \varepsilon_2$, then the product is positive and thus produces a repulsive force. An experiment performed by Jeremy Munday, Adrian Parsegian, and Federico Capasso demonstrated the different signs of the forces[9] using an atomic force microscope (AFM) 12 years ago (see PHYSICS TODAY, February 2009, page 19). Figure 3 outlines their experiment. When a gold sphere glued to the tip of the AFM approaches the gold plate inside a fluid cell of bromobenzene, the Casimir effect pulls the objects together and the cantilever is deflected downward, a measure of an attractive force. But when the gold plate is swapped out for silica in the bromobenzene bath—a case in which the permittivities of all three materials differ and satisfy the above inequality—the cantilever deflects upward as it approaches the surface, which signifies a repulsive force.

Attractive and repulsive are not the only two kinds of forces produced by the Casimir effect. In the 1970s researchers realized that when the materials that make up the plates were optically anisotropic, they would generate a torque with respect to each other. That's because the total free energy, which normally depends just on the separation between two parallel plates, also depends on the angle that defines their relative orientation. The conceptually obvious way to demonstrate the effect would be to rotate two birefringent crystals relative to each other and measure the torque as a function of distance between the crystals. But the difficulty of keeping two large plates parallel complicates the measurement, as does the presence of dust and surface roughness.

Munday's group attacked the problem more cleverly, by replacing one of the birefringent plates with a liquid crystal.[10] Munday and his students took a solid birefringent crystal, capped it with a layer of aluminum oxide a few tens of nanometers thick, and then placed a liquid crystal atop that. The liquid crystal wets the stack, forming a trilayer structure, and the aluminum oxide film behaves much like the vacuum gap in conventional Casimir-force experiments. The Casimir torque caused the orientation of the liquid-crystal birefringence to rotate until its optical axis aligned with the underlying solid crystal to minimize the free energy.

The coupling between the two different birefringent materials was varied by making multiple samples with differing thicknesses of aluminum oxide. The researchers then measured the extent of the rotation by shining polarized light through the stack and found that the magnitude of the torque decayed with a power-law dependence and had a $\sin 2\theta$ dependence on the angle. (See the Quick Study by Munday, PHYSICS TODAY, October 2019, page 74.)

Those experimental and theoretical results are more than just demonstrations. They point to future work in which the Casimir force can be used to manipulate nanoscale objects. In MEMS devices, high surface-to-volume ratios often result in unwanted stiction that could be mitigated with a repulsive Casimir interaction. What's more, by producing attractive and repulsive forces and torque at the nanoscale, one can create, at least conceptually, a micro-tractor beam for moving quantum dots, nanowires, bacteria, viruses, and other minuscule objects.

In the dynamic Casmir effect (DCE), photons are created by a rapid change in a system parameter, such as an electromagnetic boundary condition. For example, a mirror in an optical cavity moving rapidly at a frequency f generates pairs of photons with frequency $f/2$ from the vacuum. Moving a mirror at relativistic speeds is no mean feat, and researchers have relied on changing another system parameter such as the index of refraction instead. The effect has been seen in superconducting circuits, a Josephson metamaterial, a Bose–Einstein condensate, and photonic crystal fibers.[11]

How is this related to the static Casimir effect? Imagine a mirror moving slowly. The quantum fluctuations can easily keep up with the mirror, and their energy, stored in the modes of a cavity, can give rise to attractive or repulsive forces. If the mirror is accelerated to relativistic speed, the virtual particles that pop into existence get separated from their partners and produce real photon pairs. The dynamic analogue is a way to essentially mine the fluctuations by stripping photons from the pairs. In the static Casimir effect, the fluctuations produce a force; in the DCE, they produce photons.

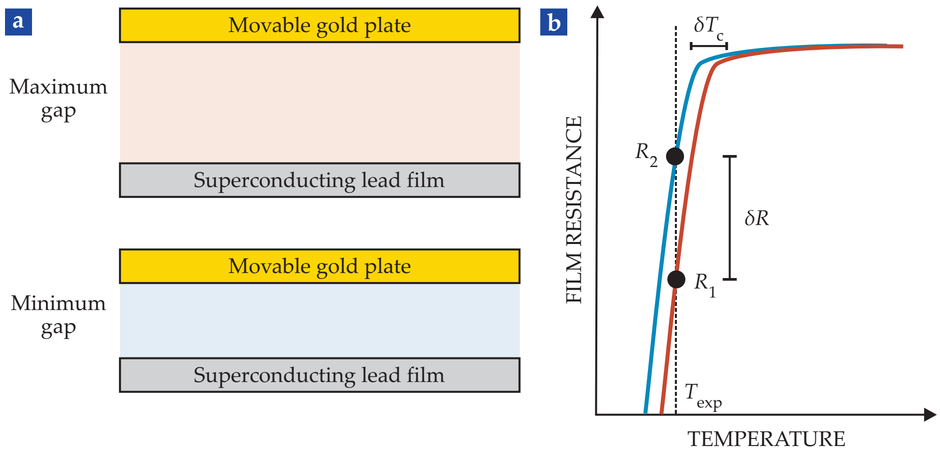


FIGURE 4. CAN A CASIMIR CAVITY CHANGE the critical temperature of a superconductor? We set out to answer that question experimentally this year. **(a)** A microelectromechanical system with a thin superconducting lead film deposited near a movable gold plate forms a tunable Casimir cavity. Theory predicts that a change in the Casimir free energy—via a change in size of the cavity—will produce a change in the condensation energy of the Pb superconductor and therefore in the critical temperature T_c of its superconducting transition. **(b)** With the temperature T_{exp} of the system set in the middle of that transition, we modulate the cavity size and search for small shifts in δT_c by monitoring any changes δR in the film's resistance. (Adapted from D. Pérez-Morelo et al., *Microsyst. Nanoeng.* **6**, 2020, doi:10.1038/s41378-020-00221-2.)

Searching for the Casimir energy

The Casimir effect emerges from fluctuations of the quantum vacuum, but its details depend directly on the nature of the materials that make up the Casimir cavity. Those details thus involve the coupling between the electromagnetic field and the walls. In the conventional Casimir effect between two perfect conductors separated by a vacuum, the positive energy density of the modes inside the cavity is less than that outside the cavity. An important question is, Can that difference in energy—the Casimir energy—be directly detected, and if so can it be exploited to reveal any novel physical phenomena?

In 1988 Michael Morris, Kip Thorne, and Ulvi Yurtsever speculated that this Casimir energy vacuum could be used to stabilize the existence of a wormhole and thus lead to the possibility of superluminal travel.[12] The Casimir force also has been invoked in connection with the cosmological-constant problem—the so-called vacuum catastrophe—and dark energy in the universe. But the wide discrepancy between the estimates of the background energy density of the universe and the energy density that would result from naïve calculations of the quantum vacuum energy fluctuations remains unresolved.

Furthermore, the Casimir effect can be formulated and Casimir forces computed without reference to zero-point fluctuations.[13] Hence, experimentalists hope to be able to measure a physical effect that can be attributed unambiguously to the existence of the Casimir energy in order to confirm the existence of what has to date simply been used as a theorist's tool.

One possibility recently investigated is a test of whether a Casimir cavity can shift the zero energy and alter the features of well-known phase transitions such as superconducting, melting, freezing, or magnetic transitions. Theorist Giuseppe Bimonte and others have argued along those lines to suggest that one can use a Casimir cavity to shift the critical field of a superconductor.[14] The sharp change in resistance that accompanies the superconducting transition could, at least in principle, detect the small changes caused by Casimir-induced variations in energy. Bimonte argues that a Casimir cavity introduces an extra free-energy term, E, such that the new critical magnetic field $H_c(T)$ required to destroy the superconductivity becomes

$$H_c(T)^2/8\pi = E_{cond} + E,$$

where E_{cond} is the condensation energy of the superconductor. In addition to developing the theory, Bimonte and his colleagues have conducted an extensive series of experiments looking for the effect by comparing the critical magnetic fields and temperatures of many similar superconducting aluminum thin films, either inside or outside a Casimir cavity. To date, however, they have not observed any unambiguous signs of a shift in the critical field, at least in experiments performed with sub-millikelvin temperature resolution.

Figure 4 outlines a different approach that we've recently taken to detect the shift. The experiment consists of a MEMS device with a lead thin film underneath a suspended gold plate. The two surfaces make a Casimir cavity, in which the bottom plate is a superconductor held fixed and the top is an oscillating gold surface. That arrangement allows one to vary the cavity size and simultaneously probe changes in the critical temperature of a single Pb film; that is, it lets us avoid having to compare several samples piecemeal.

In the experiment, we cool the system to the superconducting transition temperature T_c and then oscillate the gold plate and thus the size of the Casimir cavity. By monitoring the lead's resistance, we're able to search for small shifts in T_c with a resolution of a few tens of microkelvin. Like Bimonte and collaborators, we've also not yet detected any shifts. However, it is probably possible to extend the experiment's resolution into the nanokelvin regime using existing technologies. What's more, experimental null results of this kind constrain the effects we

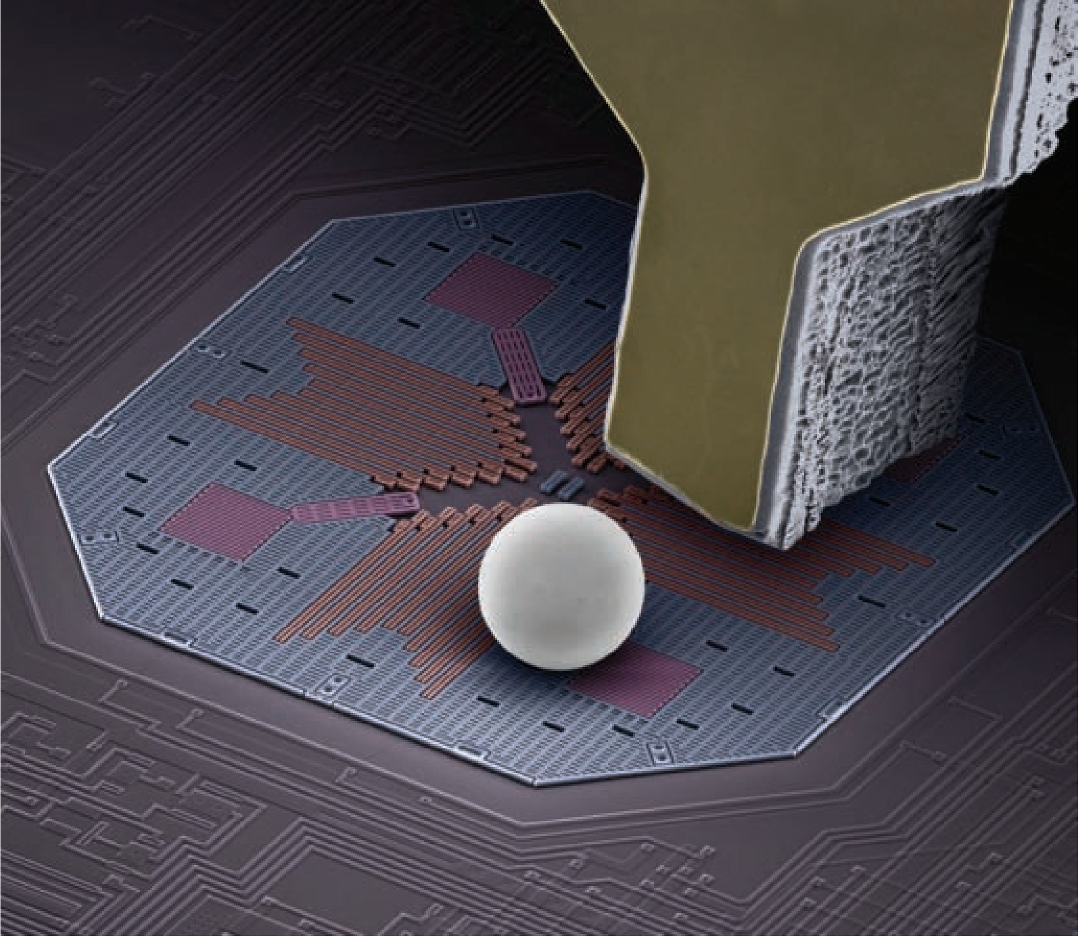


FIGURE 5. CASIMIR METROLOGY, DEMONSTRATED. A microsphere is glued to the platform of a commercial microelectromechanical-system accelerometer using a few picoliters of adhesive. It forms one half of a Casimir cavity. The other half is formed by moving the gold-coated electrode close to the sphere. The Casimir force is detected and measured using electronic sensors (orange) on the accelerometer, which pick up any motion caused by the electrode nudging the movable plate to which the sphere is attached. This device, with all the electronics integrated onto a chip, opens the door to Casimir-based metrology. (Adapted from ref. 15, A. Stange et al.)

are seeking, and refining the theories to better guide the search for the Casimir energy is an active area of research.

Although daunting, such experiments may bear on other unresolved issues of fundamental physics. Indeed, if the Casimir energy exists and can alter phenomena such as the temperature at which a phase transition occurs, then an entirely new range of devices and technologies may emerge.

Casimir metrology

Quantum metrology refers to the use of quantum mechanical phenomena for measurements well beyond what can be accomplished with classical systems. Examples abound: Superconducting quantum interference devices (SQUIDs), cold-atom interferometers, and squeezed atomic states have revolutionized high-precision measurements, but they tend to come at a substantial cost in terms of size, weight, and power requirements (SWaP). For example, SQUIDs require bulky cryogenic hardware. Cold-atom systems are similarly complex and require that a significant collection of optical components be miniaturized. Unfortunately, no current approach will allow for few-millimeter, chip-scale solutions in the foreseeable future.

Casimir-enabled quantum metrology might change that. Chip-scale devices could harness the Casimir effect and exploit it for widely applicable, room temperature, low cost, low SWaP measurements. As an example, biological systems almost never use quantum-enabled metrology given the difficulty of bringing all the measurement hardware into operation in a typical biological research or clinical setting. Yet researchers dream of having a single, millimeter-scale chip to do the job for both *in vitro* and *in vivo* applications. Breakthrough applications include magnetocardiography, measuring the magnetic fields produced by electrical currents in the heart, and magnetoencephalography, noninvasively measuring ongoing brain activity using sensitive magnetometers.

The platform one needs for such a sensor requires that the electronics of an existing technology be placed on a chip-scale Casimir system. Figure 5 shows one such system developed by two of us (Stange and Bishop) and our collaborators.[15] It essentially modifies a MEMS accelerometer by incorporating a Casimir cavity. We bonded a micron-sized sphere to the accelerometer platform with picoliters of glue, so that it would be held fixed as a mobile electrode is brought close and the sphere–electrode pair behaves as a Casimir sensor. The accelerometer, which detects forces as small as piconewtons, is thus modified to a Casimir metrology device, an important first step in moving Casimir physics from the lab to the commercial world.

The Casimir effect can be used in various ways for metrology. One approach is to create a parametric amplifier that is modulated by the Casimir force. Such a device leverages the inverse quartic or cubic dependence on distance, as discussed earlier. In a sphere–plate geometry, one would oscillate the sphere at one frequency f and modulate the plate position at $2f$. The Casimir force couples the two objects and pumps energy into the primary resonance. Another set of electrodes controls the distance between the objects with an applied voltage. A few years ago two of us (Campbell and Bishop) demonstrated how the coupling can produce a system in which the resonant amplitude depends on the tenth power of the applied voltage.[16] That approach is reminiscent of an earlier 2001 experiment that used Casimir coupling to an oscillating sphere to create a nonlinear response in the system.[5]

Nanopatterning

So far, this article has dealt with planar surfaces and with sphere–plane systems. In either case, surface roughness has been treated as an imperfection that needs to be measured and accounted for using Lifshitz theory.[8] However, it can become a feature in some situations—something deliberately added to the surface that makes the coupled system more interesting to study.

Nanopatterning metallic surfaces can yield a rich palette of advantageous effects. Applications such as extraordinary light transmission, surface-enhanced Raman scattering, and single-molecule spectroscopy made possible by plasmonic enhancements are a few well-known examples, although they work over a narrow range of frequencies. (See the articles by Katrin Kneipp, PHYSICS TODAY, November 2007, page 40, and by Mark Stockman, PHYSICS TODAY, February 2011, page 39.)

With metamaterials, engineers can control the local electric and magnetic properties of a material and endow it with optical properties that cannot be obtained with conventional films. Nanopatterning, a common method for forming a conventional material into a metamaterial, allows the customization of surfaces in a vast variety of ways. Whether a Casimir force is attractive or repulsive, as we've seen, is determined by the dielectric response of materials that make up the Casimir cavity. Researchers are using plasmonics and metamaterials to modify the Casimir force in ways that can't be done using planar surfaces with conventional materials. Nanopatterning may become a powerful tool to explore many new phases and states of matter that emerge from interactions between the plates.[17]

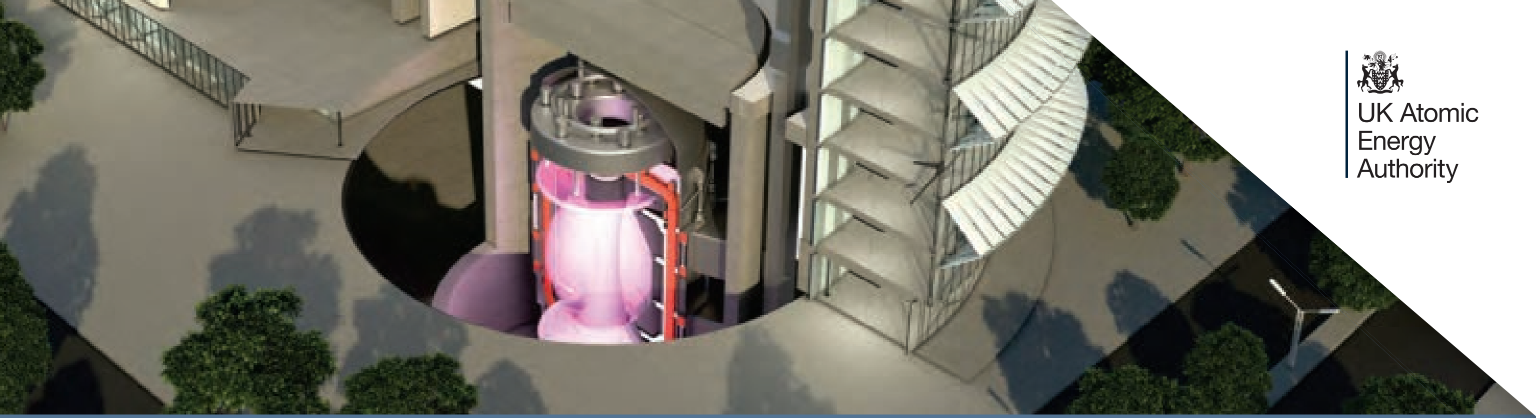
Because the Casimir effect is a room-temperature, nanoscale phenomenon, its use for practical measurements is a real possibility in the near future. We are particularly enthusiastic about the prospects for its biological and medical applications. SWaP considerations are particularly acute in those fields, and chip-scale, room-temperature devices could, among other advances, be able to detect ultrasmall magnetic fields. We believe that the Casimir effect may someday save lives through technologies like quantum-enabled magnetometers for ultrasensitive cancer detection.

Hendrik Casimir passed away in 2000. He lived long enough to see his prediction quantitatively verified but not to appreciate the current explosion of activity. Those of us who work in the field like to think he would be extremely proud of what he created.

Our work in this field has been supported by NSF grants.

REFERENCES

1. H. B. G. Casimir, *Proc. K. Ned. Akad. Wet.* **51**, 793 (1948); H. B. G. Casimir, *J. Chim. Phys.* **46**, 407 (1949).
2. M. J. Sparnaay, *Physica* **24**, 751 (1958).
3. S. K. Lamoreaux, *Phys. Rev. Lett.* **78**, 5 (1997).
4. U. Mohideen, A. Roy, *Phys. Rev. Lett.* **81**, 4549 (1998).
5. H. B. Chan et al., *Science* **291,** 1941 (2001); H. B. Chan et al., *Phys. Rev. Lett.* **87**, 211801 (2001).
6. R. Decca et al., *Ann. Phys.* **318**, 37 (2005).
7. D. Dalvit et al., eds., *Casimir Physics*, Springer (2011).
8. E. M. Lifshitz, *Sov. Phys. JETP* **2**, 73 (1956); I. E. Dzyaloshinskii, E. M. Lifshitz, L. P. Pitaevskii, *Adv. Phys.* **10**, 165 (1961).
9. J. N. Munday, F. Capasso, V. A. Parsegian, *Nature* **457**, 170 (2009).
10. D. A. T. Somers et al., *Nature* **564**, 386 (2018).
11. S. Vezzoli et al., *Commun. Phys.* **2**, 84 (2019).
12. M. S. Morris, K. S. Thorne, U. Yurtsever, *Phys. Rev. Lett.* **61**, 1446 (1988).
13. R. L. Jaffe, *Phys. Rev. D* **72**, 021301 (2005).
14. G. Bimonte, *Phys. Rev. A* **99**, 052507 (2019) and references therein.
15. A. Stange et al., *Microsyst. Nanoeng.* **5**, 14 (2019); for a related system, see J. Zou et al., *Nat. Commun.* **4**, 1845 (2013).
16. M. Imboden et al., *J. Appl. Phys.* **116**, 134504 (2014).
17. F. Intravaia et al., *Nat. Commun.* **4**, 2515 (2013). PT



UK Atomic Energy Authority

If you are a plasma physicist and want to be part of an exciting programme that aims to demonstrate fusion as a net-zero carbon energy source, we need you!

Do you want to work at the forefront of research and technology, solving one of humanity's biggest problems?

Do you want to be part of a unique international environment?

Come and join us on the Spherical Tokamak for Energy Production (STEP) programme, an exciting and ambitious national endeavour, working in a vibrant team in conjunction with industry to deliver a multi £bn prototype fusion energy plant by the early 2040s. Successful delivery of the prototype will pave the way for a commercial fleet of fusion reactors.

STEP is funded by the UK government for an initial five-year phase, through to 2024, and our key objective is to define a concept tokamak design in that timeframe. To help us achieve this aim, we are now seeking to recruit physicists to work in the following areas of tokamak plasma modelling:

- **Gyrokinetic simulations of core plasma turbulence** (2 positions)
- **Fast particle physics**
- **Plasma disruptions**
- **Runaway electron physics**
- **Radiofrequency (RF) physics**

Further vacancy details can be found here:
www.ccfe.ukaea.uk/jobs

While each of these positions will be primarily focussed on plasma modelling in the high beta burning plasma domain of STEP, successful candidates will also work on plasma modelling and experiments in other tokamak devices at Culham and internationally. UKAEA operates the new MAST-U spherical tokamak, one of the two largest spherical tokamaks in the world, which will help to develop the physics basis for STEP. UKAEA also operates JET, the world's largest tokamak, and is strongly involved in ITER and the European fusion programme. Further details of the STEP project can be found at ***www.step.ukaea.uk*** and more information about UKAEA's wider work is available here: ***www.ccfe.ukaea.uk***

In all cases applicants should hold, or be about to hold, a PhD in plasma physics or possess equivalent experience.

EVERETT COLLECTION INC/ALAMY STOCK PHOTO

HOLLYWOOD'S MELODRAMATIC reworking of a 1963 Czech B movie envisions the universe's end.

A brief history of the future

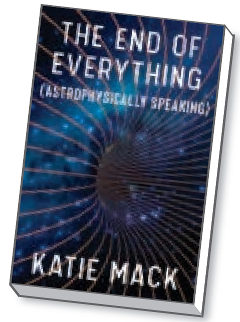
The End of Everything (Astrophysically Speaking), by Katie Mack, is a lively antidote to our otherwise cheerful times. Instead of agonizing over a pandemic, political polarization, and economic upheaval, why not fret over the end of the entire universe?! All jokes aside, why bother studying our universe's demise? Well, as Mack says, contemplating our end helps us "understand the fundamental nature of reality itself."

Known as AstroKatie to her legions of followers on Twitter, Mack is a theoretical astrophysicist and an assistant professor of physics at North Carolina State University. She contemplates such cosmological catastrophes as the Big Rip, the heat death of the universe, and, most terrifyingly, vacuum decay—the possible transition from the false "metastable" vacuum state we may currently be enjoying into its true minimum, or ground state, which would cause the instantaneous disintegration of baryonic matter, among other day-ruining effects. In her skillful hands, we learn that although our cosmic comeuppance won't be pretty, we at least have billions of years before it will occur. That is, unless vacuum decay—discussed with the perfect blend of academic rigor and poetic license—is the ultimate culprit of our doom, in which case cosmic catastrophe may occur as you read this sentence.

Following Yogi Berra's dictum that "it's tough to make predictions, especially about the future," Mack warns us that how the universe will end is much less certain than how it began. Although she largely eschews the typical approach of

The End of Everything (Astrophysically Speaking)

Katie Mack
Scribner/Simon & Schuster, 2020. $26.00



recapitulating cosmology's vast history, she does note that our knowledge of the origin of the universe also was once more nebulous. Well into the 20th century, there were many rival cosmogonies, including the cosmic egg, Lemaître's primeval atoms, and even the biblical book of Genesis. Nevertheless, cosmic eschatology has gotten short shrift.

The End of Everything was published exactly 100 years after the famous debate between astronomers Harlow Shapley and Heber Curtis over whether the Milky Way galaxy was the entire universe or other galaxies were in the cosmos. The so-called Great Debate was resolved three years later when Edwin Hubble demonstrated that the object then known as the "great spiral nebula" in Andromeda was not a nebula at all but an entirely separate galaxy. Further observations by Hubble proved that the universe was expanding, which prompted speculation about what happened when its expansion began. Scientists eventually settled on the Big Bang theory accepted today. All the while, attention to the opposite end of the timeline—if there is one—has been sparse, and speculation reigns.

Mack's surprisingly lively account of the Big Bang's end-of-time counterpart is uplifting, with a wry wit permeating its 240 pages. It is meticulously researched, nicely illustrated, and copiously footnoted. Although footnotes are usually the bane of the reading experience, that is not so with Mack's: Her joke-per-footnote ratio is near unity.

Comparable books aimed at a popular science audience are Stephen Hawking's epochal *A Brief History of Time: From the Big Bang to Black Holes* (1988) and Sabine Hossenfelder's *Lost in Math: How Beauty Leads Physics Astray* (2018). The latter similarly blends first-person expert perspective, wit, and interviews with other experts, including some of the same scientists Mack conversed with. Unlike Hossenfelder, though, Mack is more optimistic about possibilities for scientific progress in realms of astroparticle physics that are currently untestable, such as multiverse theories, vacuum decay, and the large-extra-dimensions model.

My only (minor) qualm with this otherwise masterful work is that it lacks the vantage point of an experimental astrophysicist. Had Mack surveyed a few of us alongside the many theorists and high-energy experimentalists she interviewed, it would have added another dimension to her book: Instrument builders can and should act as assayers of the theories they test.

Amidst Mack's humor is beautiful prose. Contemplating future end-times research, she writes, "Someday, deep in the unknown wilderness of the distant future, the Sun will expand, the Earth will die, and the cosmos itself will come to an end. In the meantime, we have the entire universe to explore, pushing our creativity to its limits to find new ways of knowing our cosmic home. We can learn and create extraordinary things, and we can share them with each other. And as long as we are thinking creatures, we will never stop asking: 'What comes next?'"

In *The End of Everything*, eschatology meets cosmology, evoking in this reader an aphorism from Ecclesiastes: "Better is the end of a thing than its beginning." Mack's brief history of the future is bound to inspire minds young and old not to deny the eventual death of the universe but rather to embrace it while there's still time.

Brian Keating
University of California, San Diego
La Jolla

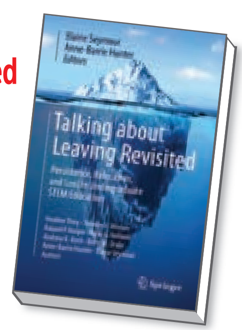
STEVE FU/ALAMY STOCK PHOTO

POSTERS FOR ACTIVITIES and student groups at MIT, March 2020.

A landmark study reconsidered

Students, especially women and minorities, continue to leave science, technology, engineering, and mathematics, or STEM, disciplines in large numbers. Who are those students, and why do they leave? That is the topic of a new volume edited by Elaine Seymour and Anne-Barrie Hunter titled *Talking About Leaving Revisited: Persistence, Relocation, and Loss in Undergraduate STEM Education*. (Full disclosure: I am a part-time research associate at the University of Colorado Boulder's Center for STEM Learning; both Seymour and Hunter are also affiliated with the university.) The extensive study discussed therein reevaluates the findings of a landmark 1997 study that Seymour wrote with Nancy Hewitt called *Talking About Leaving: Why Undergraduates Leave the Sciences*, which prompted a reform movement when it revealed that poor teaching and negative classroom cultures were pushing students out of STEM disciplines.

Talking About Leaving Revisited
Persistence, Relocation, and Loss in Undergraduate STEM Education
Elaine Seymour and Anne-Barrie Hunter, eds.
Springer, 2019. $149.99



How has the situation changed after 20 years? Spoiler alert: Many of the same problems remain. The findings will be of interest to advisers, those teaching introductory courses, department chairs, and education researchers in general.

Authored by a strong team of qualitative and quantitative researchers, the book is a compendium of detailed research reports about the current comprehensive study, which had two major components. First, the researchers surveyed 7800 STEM students across the US to gain quantitative insight into broad patterns of switching and persistence. Second, to explore the qualitative factors driving those trends, the team revisited six of the seven institutions that participated in the 1997 study and conducted 346 interviews of STEM switchers and persisters.

Talking About Leaving Revisited begins with a review of the prior investigation and then moves to a discussion of the first portion of the current study—namely, the quantitative national survey of switching and persistence. That chapter should be required reading for all institutional research personnel, as it is a blueprint for conducting similar analyses. The authors found that the rate of switching has reduced over the past 20 years: Of students who begin college as STEM majors, 28% switch to a non-STEM major today compared with 47% in the 1997 study. However, they also found that 20% of STEM majors leave college altogether—meaning that only 52% of students who begin college in a STEM major complete a STEM degree. Early retention efforts appear to be crucial: 80% of switchers make their decision by the end of their second year.

Women and minority students remain more likely to leave STEM fields. Even controlling for other background variables, women switch out of STEM majors 7% more frequently than men. Students from underrepresented backgrounds also switch more frequently, which the authors argue is statistically explained by their incoming standardized math test scores and GPAs. This suggests that improving high school STEM teaching is critical for retaining minority students.

The next chapter enumerates the factors influencing switching and persistence that were found in the qualitative interviews. As in the 1997 study, the factors include poor teaching, difficult transitions to college, poor curriculum design, and loss of confidence. Not only are those problems still present today, but according to the current study, both switchers and persisters experience them *more* than they did 20 years ago. The authors emphasize that the same underlying factors affect all students, not just the switchers. One bright spot is that women are now less likely to experience hostile, sexually inappropriate behaviors from male colleagues.

The rest of the book explores issues affecting persistence, such as choosing a major, high school preparation, problematic teaching methods, weed-out classes, and feelings of not belonging. Those chapters provide a valuable narrative of student experiences in STEM fields. Most include a crisp and readable literature review, and many (but, sadly, not all) include a useful summary of the findings. The final chapter by Seymour provides a summary and recommendations for reform.

The issues raised by *Talking About Leaving Revisited* are important, so it is disappointing that the book is not more accessible to those not well read in education research. A summary of the main findings in the first chapter, for example, would have been highly beneficial. Similarly, it would be useful if each chapter had an abstract, introduction, and conclusion. Moreover, the index is incomplete and not as practically oriented as I hoped.

I also felt that the study lacked guidance on how to interpret the many percentage comparisons. It would be useful to know, for example, the total sample size for a particular comparison and how large a difference in percentages the researchers consider to be meaningful. It would also be helpful to understand the impact on those percentages of the specific institutions selected for the qualitative study, which had lower switching rates than the national sample, and of the sampling strategy, which oversampled women, minorities, and life-science students.

That said, I highly recommend this book to anyone concerned about improving student persistence. It has many suggestions for how departments should emphasize career opportunities in physics, improve pedagogy in introductory courses, examine grading policies, provide support to those with inadequate high school preparation, and improve STEM preparation at the high school level. The past 20 years have seen great improvement, but work remains to be done to cultivate a physics discipline welcoming to all.

Stephanie Chasteen
University of Colorado Boulder

NEW BOOKS & MEDIA

Fireball

Visitors from Darker Worlds

Werner Herzog and Clive Oppenheimer

Apple TV+, 2020

Fireball: Visitors from Darker Worlds, directed by Werner Herzog and Clive Oppenheimer, is a unique documentary focused both on the scientific aspects of meteorites, shooting stars, and deep impacts and on their influence in human culture. We learn that one of the most talked about events in November 1492 in European chronicles was not Christopher Columbus landing in the Americas but a fireball that landed in Ensisheim, France; that micrometeorites can be collected from the roof of a stadium in Oslo, Norway; and that dogs can be trained to sniff out meteorites because of their distinct smell. The movie is available now on Apple TV+. –PKG

The Right Stuff

Mark Lafferty

Disney+/National Geographic Studios, 2020 (Season 1)

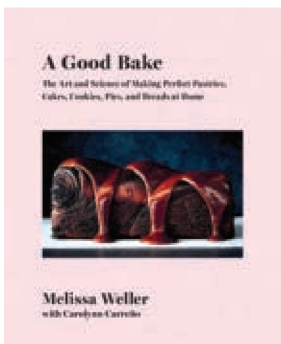
The Right Stuff on Disney+ is a highly dramatized account of the first US astronauts. Based on Tom Wolfe's seminal 1979 book of the same title, the eight-episode TV series is significantly different from the 1983 movie (also of the same name), which focused more on the exploits of Chuck Yeager, the first person to break the sound barrier. This time, the competition between the astronauts, the strain on their wives, the temptations of fame, and the risky enterprise of putting a human into space are front and center. The rivalry between John Glenn (Patrick J. Adams) and Alan Shepard (Jake McDorman) is portrayed well. A companion documentary, *The Real Right Stuff*, based on hundreds of interviews with former NASA employees, is also available to stream on Disney+. –PKG

A Good Bake

The Art and Science of Making Perfect Pastries, Cakes, Cookies, Pies, and Breads at Home

Melissa Weller and Carolynn Carreño

Knopf, 2020. $40.00



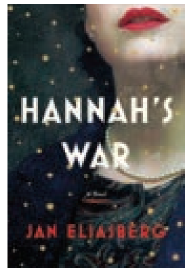
With recipes for such offerings as strawberry jam and hazelnut rugelach, kale and cheese khachapuri with zhoug, and pumpkin layer cake with salted caramel buttercream and brown sugar frosting, this cookbook is less Betty Crocker and more *Great British Baking Show*. Nevertheless, chemical engineer and professional baker Melissa Weller claims that the recipes are written in a way that even a novice home baker can follow. In addition to the detailed instructions, Weller and coauthor Carolynn Carreño include master classes, tutorials, and explanations of some of the chemistry involved. The book is beautifully illustrated with photographs by Johnny Miller. –CC

Hannah's War

A Novel

Jan Eliasberg

Back Bay Books/Little, Brown and Co, 2020. $16.99 (paper)



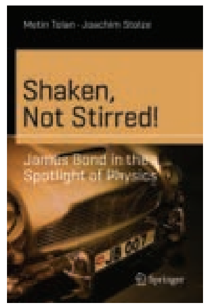
Written by Hollywood screenwriter Jan Eliasberg, *Hannah's War* is loosely based on the life of Austrian Jewish theoretical physicist Lise Meitner, who should have shared with Otto Hahn the 1944 Nobel Prize in Chemistry for the discovery of nuclear fission. "Loosely based" is a stretch, for the book's relationship to historical reality is quite tenuous: Unlike Hannah, the book's protagonist, Meitner never worked on the Manhattan Project (she refused to participate in nuclear weapons research), her father did not die fighting for the Austro-Hungarian Army in World War I (he did not serve at all), and she certainly would never have called the Kaiser Wilhelm Institute for Chemistry the "Kaiser Wilhelm" in conversation. Historical nitpicking aside, the book captures the spirit of a fascinating time in physics. –RD

Shaken, Not Stirred!

James Bond in the Spotlight of Physics

Metin Tolan and Joachim Stolze

Springer, 2020. $24.99 (paper)



Shaken, Not Stirred!, authored by two German physicists who are fans of the James Bond franchise, provides physics-based explanations of gadgets and stunts in the series, such as the titular villain's infamous laser beam from *Goldfinger*, Bond's jet pack from *Thunderball*, and various death-defying jumps out of and onto aircraft. Metin Tolan and Joachim Stolze even provide a scientific foundation for Bond's martini preferences: When a cocktail is shaken, granular convection causes the larger, more flavorful molecules to rise to the top. The authors write entertaining depictions of Bond's seemingly gravity-defying stunts followed by outlines of the physics calculations they made. Written with a light-hearted, winking tone worthy of 007 himself, the fun book is unfortunately hampered by its awkward English translation and lack of copyediting. –RD PT

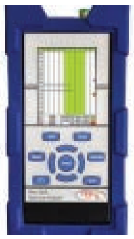
NEW PRODUCTS

Focus on photonics, spectroscopy, and spectrometry

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 product submissions to ptpub@aip.org.

Andreas Mandelis

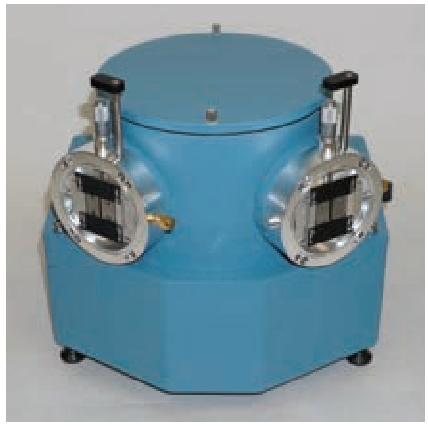
Optical spectrum analyzer



The FTE-8100-C optical spectrum analyzer (OSA) from Terahertz Technologies is one of the most cost-effective mini-OSAs on the market, according to the company. The full-featured instrument offers such functions as "power tilt" for dense wavelength division multiplexing channel equalization, "gain tilt" to adjust erbium-doped fiber-amplifier gain flatness, and file-based user configurations. The rugged unit is available with up to 98 channels in the C band with 50 GHz or 100 GHz channel spacing. Its touch screen and twice-a-second scan capability make it fast and simple to use. The one-button auto-test feature and full set of selectable scale limits and thresholds let users easily zero in on channel measurements. For flexibility, the channel numbers are selected in wavelength or frequency. Users can set pass/fail thresholds and store up to 1000 tests that can be downloaded via the USB PC port. ***Terahertz Technologies Inc****, 169 Clear Rd, Oriskany, NY 13424, www.teratec.us*

UV Raman spectrometer

Wasatch Photonics has added a compact, cost-effective UV Raman spectrometer to its family of modular Raman spectroscopy products for research and industry. The use of UV excitation makes the WP 248 suitable for fluorescence-free Raman and UV resonance Raman (UVRR) spectroscopy to enhance sensitivity and selectivity. Applications include gas detection, materials analysis, and UVRR studies of structure and dynamics in biomolecules such as proteins and nucleic acids. The stand-alone WP 248 covers a 400–3200 cm^{-1} range with 14 cm^{-1} resolution and uses a UV-enhanced CCD for detection. It offers free space input and an f/2.0 numerical aperture for superior signal collection and high-throughput detection. Designed for use with a compact 248.6 nm neon–copper laser, it comes with a triggering cable to synchronize acquisition with the laser. ***Wasatch Photonics****, 808 Aviation Pkwy, Ste 1400, Morrisville, NC 27560, https://wasatchphotonics.com*



Monochromator for UV spectroscopy

McPherson has upgraded its compact model 234/302 monochromator for UV spectroscopy: The internal surfaces now have an optimized ultrablack low-scatter finish, the range of masterpiece gratings has been expanded, and spectrograph accessories and an improved turret are available. The enhancements improve efficiency and spectral resolution from the deep UV and vacuum UV (VUV) to the visible and near-IR. The model 234/302 can be equipped with a grating turret that allows users to broaden the accessible wavelength range without breaking vacuum or purge. With a digital grating drive for precise wavelength selection and positioning, the compact VUV spectrometer is easy to use as a scanning monochromator or as a spectrograph with a microchannel plate intensifier or a CCD detector. ***McPherson Inc****, 7A Stuart Rd, Chelmsford, MA 01824, https://mcphersoninc.com*

Near-IR Raman spectrometer

Optimized for performance in the near-IR region, the TPIR-785 Raman spectrometer from Teledyne Princeton Instruments has ultrahigh sensitivity and is suitable for use in such areas as biological, medical, and life sciences research. The system uses an f/2 spectrograph with lens optics designed to provide high light throughput and imaging quality. Users can tailor the instrument's performance for an optimal spectral resolution up to 5 cm^{-1} or an optimal spectral range up to 80–3650 cm^{-1}. The system includes a 785 nm Raman probe, a universal fiber adapter, a manual adjustable slit, and a high-power, temperature-stabilized 785 nm laser. A proprietary CCD delivers near-IR quantum efficiency greater than 70% at 1000 nm. The "super-deep-depletion" sensor has a 1340×400 array composed of 20 μm^2 pixels. It can be thermoelectrically cooled to −90 °C for ultralow dark current, which allows integration times from 10 μs to hours. The detector provides spectral rates higher than 1 kHz, offers readout speeds up to 16 MHz, and uses two readout ports. ***Teledyne Princeton Instruments****, 3660 Quakerbridge Rd, Trenton, NJ 08619, www.princetoninstruments.com*

Shortwave-IR laser

Beyond Photonics has launched its compact piezo-tunable Swift single-frequency short-wave IR (SWIR) laser. The rugged, solid-state laser is suitable for lidar and laser spectroscopy applications that require very stable high-power reference and seed lasers. It is initially offered in the range of 2050 nm, but it can be adapted to many other near- and shortwave-IR wavelengths. The Swift is optimized for use in coherent and direct-detection eye-safe lidar systems or other SWIR applications that require ultralow short-term frequency stability and broad, fast tunability. With its high CW output power—greater than 35 mW standard and up to 100 mW optional—and less than 10 kHz/ms short-term frequency jitter, the Swift is suitable for use as a master and local oscillator source in lidar systems. Fast and broad mode-hop-free frequency tuning enables next-generation spectroscopic applications, such as pollution monitoring and greenhouse gas measurements that use differential absorption lidar techniques. ***Beyond Photonics LLC****, 6205 Lookout Rd, Ste B, Boulder, CO 80301, www.beyondphotonics.com*

Positioning stage for photonic applications

Physik Instrumente (PI) now offers a compact, modular, five-axis stage with closed-loop motors for precision alignment and positioning of photonics and optics components, such as fibers, waveguides, and lenses. The F-122 5DOF stage consists of a three-axis linear module with linear encoders for direct position measurement and PI's WT-85 and WT-100 goniometers. The goniometers are combined with a shared pivot point to perform high-precision angular motion with resolution to 3.5 μrad. Submicron precision is ensured by highly accurate mechanical components and encoder feedback for closed-loop operation. A multiaxis controller and software with automated alignment functionality are available. With programming interfaces, including LabVIEW and MATLAB, users can integrate a PI controller into their own programs. ***Physik Instrumente LP****, 16 Albert St, Auburn, MA 01501, www.pi-usa.us*

Multispectral *in vivo* IR imaging

According to Photon Etc, its IR VIVO preclinical imager provides noninvasive spectral imaging in the first (NIR) and second (NIR-II) biological windows, from 900 nm to 1620 nm. It combines micron-scale spatial resolution, real-time imaging, and full multispectral coverage for *in vivo* research on small animals or other living organisms. With fast acquisition speed, multicolor imaging, and good penetration depth—10 times as great as traditional visible optical systems, the company claims—the IR VIVO captures both structure and function. Because it uses near- and shortwave-IR, the imager benefits from reduced scattering and minimal tissue absorption and autofluorescence, which allows deeper, clearer imaging than can be achieved with standard optical systems. Emission of several fluorophores can be isolated with a high-efficiency tunable filter and ultralow-noise scientific-grade indium gallium arsenide camera. ***Photon Etc***, *5795 Ave de Gaspé, #222, Montreal, QC H2S 2X3, Canada, http://photonetc.com*

Spectrophotometer for turbid media

The novel SphereSpectro 150H system from Gigahertz-Optik simultaneously discriminates and quantifies both the spectral absorption coefficient and the spectral effective scattering coefficient of scattering media. The spectrophotometer uses an integrating sphere to measure the total reflected and transmitted light of an illuminated sample. From those two quantities, the absorption coefficient and the effective scattering coefficient are calculated based on the radiative transfer equation. The SphereSpectro 150H covers the wavelength range between 200 nm and 2150 nm, with modular versions available for subranges within that spectral range. The compact tabletop device offers fast, precise, and absolute measurements; simple operation; and a large sample chamber with an optimized sample holder. Applications include materials analysis, biophotonics, and quality assurance. ***Gigahertz-Optik Inc***, *Boston North Technology Park, Bldg B, Ste 205, Amesbury, MA 01913, https://light-measurement.com*

Compact Q-switched laser

Hübner Photonics has introduced the Cobolt Tor XE compact Q-switched laser at 1064 nm and with 0.5 mJ/pulse. It delivers short pulse lengths of less than 3.5 ns at kHz repetition rates and high pulse-to-pulse stability—jitter is less than 2 μs—in a TEM_{00} beam. The advanced, integrated control electronics use external or internal signals to trigger the emission from single pulses up to 1 kHz pulse trains or bursts of pulses. The Cobolt Tor XE is manufactured using proprietary HTCure technology; according to the company, the resulting hermetically sealed package improves the laser's reliability under varying environmental conditions. It can be used in laser marking, laser-induced breakdown spectroscopy, micromachining, and photoacoustic microscopy applications. ***Hübner Photonics Inc***, *2635 N 1st St, Ste 202, San Jose, CA 95124, https://hubner-photonics.com*

HÜBNER Photonics

Tube-below WDXRF spectrometer

Due to its tube-below optics, the ZSX Primus IVi wavelength-dispersive x-ray fluorescence (WDXRF) spectrometer from Rigaku optimizes the measurement of typical gravity-loaded samples such as liquids and analyzes alloys and plated metals. According to the company, the new model improves on previous systems by having the smallest footprint in its class and an efficient new drive sequence that decreases the time between multiple high-speed, precision measurements. It includes new sample film corrections, and a redesigned control system optimizes movement sequences. The ZSX Primus IVi spectrometer has a patented vacuum partition system for analyzing liquids. Because the spectroscopic chamber is separated from the sample chamber when the helium gas is being changed, the conversion from vacuum to helium atmosphere can be completed in less than 2 minutes. ***Rigaku Americas Corporation***, *9009 New Trails Dr, The Woodlands, TX 77381-5208, www.rigaku.com*

High-speed camera

According to Vision Research, its Phantom T1340 high-resolution camera doubles the capabilities of other 4 MP cameras in its class. It captures images up to 13 GP/s. Its 2048 × 1952 pixel low-noise sensor and compact size make the camera suitable for demanding measurement applications such as object tracking, flow visualization, and microscopy and for modern imaging techniques such as digital image correlation. A binned mode provides higher throughput and a sensitivity boost at 1 MP and below. Because the T1340 includes Phantom CineMag V compatibility for an ultrafast, secure workflow and for direct recording of long-duration events, the camera can be used in outdoor environments. A 10 GB ethernet option is available for fast file downloads, so users can continue shooting with reduced downtime. ***Vision Research Inc***, *100 Dey Rd, Wayne, NJ 07470, www.phantomhighspeed.com*

Programmable IR spectrometer

The PEAK XNIR, a novel high-throughput OEM spectrometer from Ibsen Photonics, combines Ibsen's high-efficiency fused-silica transmission gratings with DLP Pico technology from Texas Instruments. It provides a dimension of spectral programmability that, according to the company, has not been possible with other available spectrometer technology: Users can control the relative power and exposure time independently for each wavelength in a spectrum. The PEAK XNIR's retroreflective advanced optical design allows for a compact form factor with high resolution, sensitivity, and environmental ruggedness. It features a wavelength range of 1650–2400 nm, 10 nm resolution, and a high numerical aperture of 0.22. The PEAK XNIR is suitable for process analytical technology because it offers real-time in-line monitoring and measurements for near-IR spectroscopy. ***Ibsen Photonics A/S***, *Ryttermarken 17, DK-3520 Farum, Denmark, https://ibsen.com* PT

Yuri Fyodorovich Orlov

Yuri Fyodorovich Orlov was an inspiration to many people worldwide through his unrelenting pursuit of science in difficult circumstances, his many contributions to accelerator physics, his courageous sacrifices for human rights in the USSR, and his dedication to the free, international exchange of ideas. Born on 13 August 1924 near Moscow, he died on 27 September 2020 in Ithaca, New York.

Orlov graduated in 1952 from the Physical-Technical Institute in Moscow. He earned his first doctoral degree from the Yerevan Physics Institute in 1958 and his second from the Budker Institute of Nuclear Physics in 1963. Following his arrival in the US in 1986, he taught both physics and human rights at Cornell University until he retired at the age of 91.

Here we mainly address Orlov's scientific accomplishments. Additionally, his work in human rights made him "one of the most important figures of our last century," according to Scott Horton of the Andrei Sakharov Foundation. Detailed in many texts and obituaries and in Orlov's fascinating *Dangerous Thoughts: Memoirs of a Russian Life* (1991), those achievements included his cofounding the Soviet section of Amnesty International and, most importantly, establishing the Moscow Helsinki Group. That organization, created in 1976 to monitor Soviet compliance with the Helsinki Accords, is still active. It served as the model for similar groups throughout the USSR, inspired Solidarity in Poland and the Charter 77 initiative in Czechoslovakia, and is the grandparent of many of today's human-rights-monitoring groups. It was the main reason that Orlov was arrested in 1977, interrogated for months in a KGB prison, and sentenced, after a show trial, to years of hard labor followed by Siberian exile.

Orlov's formal scientific employment in the USSR, which began in the 1950s, was interrupted in 1956 when he was fired from the Institute of Theoretical and Experimental Physics (ITEP) for making a pro-democracy speech and was permanently blocked after 1973 when he was fired for joining the dissident movement. However, even from a labor camp he continued to do science; he smuggled out several articles, written on cigarette papers, that were published in the West. After being stripped of his citizenship and deported to the US in 1986, he resumed his scientific work.

ROBERT PALMER

Yuri Fyodorovich Orlov

Throughout his time in the USSR, Orlov mostly worked in accelerator physics. A theoretical-physics education with teachers such as Lev Landau and Peter Kapitza allowed him to pioneer some of the theoretical methods that are cornerstones of accelerator development today. He applied Hamiltonian perturbation theory to nonlinear oscillations around an accelerator's design orbit and analyzed nonlinear dynamics in terms of betatron and synchro-betatron resonances. Additionally, he established radiation sum rules in electron accelerators with E. K. Tarasov and described polarization dynamics and depolarization in storage rings, including contributions from quantum effects, with V. N. Baier. Orlov developed his groundbreaking work while designing ITEP's proton synchrotron and the 6 GeV synchrotron in Yerevan, Armenia. In addition, he proposed a 200 GeV electron–positron collider long before CERN's Large Electron–Positron Collider reached that energy.

Orlov also published articles on the foundations of quantum mechanics. In his eighties he wrote about gravitational physics, in part to consider small effects that can disturb stored beams in experiments on the electric dipole moment (EDM).

While at CERN in 1988–89, Orlov and D. Möhl independently invented "beam shaking" to eliminate ions from the antiproton beam, a method that has since been used at the Tevatron to increase antiproton intensity, at the German Electron Synchrotron's HERA particle accelerator to eliminate the coasting beam, and for various electron beams to eliminate accumulated ions. For the Muon $g-2$ experiment at Brookhaven National Laboratory, Orlov contributed elegant breakthrough ideas that were meant to eliminate background contributions while preserving the integrity of the important parameters. And as an initiator of the storage-ring EDM studies, he made essential contributions to identifying the main sources of systematic errors and worked out the precise theory describing many nonlinear effects essential for the method to succeed.

Orlov had a profound understanding of the relevant experimental issues and exceptional abilities to address them. He would go out of his way to give credit to people he worked with, including those whose solutions to scientific problems differed from his. And his humor, modest demeanor, intelligence, and creativity made it a pleasure to interact with him.

Days before his death, Orlov received the 2021 Robert R. Wilson Prize from the American Physical Society "for pioneering innovation in accelerator theory and practice . . .; deep understanding of beam and spin dynamics; consistently unique and fruitful ideas, ranging from the practical to the visionary; and embodying the spirit of scientific freedom." We rejoice that APS awarded this extraordinary physicist such a fitting and important prize just in time.

Georg Hoffstaetter
Cornell University
Ithaca, New York

Yannis Semertzidis
IBS Center for Axion and
Precision Physics Research
KAIST
Daejeon, South Korea

Vladimir Litvinenko
Stony Brook University
Stony Brook, New York

Nigel Oscar Weiss

Astrophysicist and applied mathematician Nigel Oscar Weiss, who made many fundamental contributions to our understanding of magnetohydrodynamics (MHD) and the Sun's magnetic field, died on 24 June 2020 in Cambridge, UK.

Nigel was born on 16 December 1936 in Johannesburg, South Africa. He was educated at Hilton College in Natal (which he hated) and then Rugby School in the UK (which he loved). He studied natural sciences at Clare College, Cambridge University. His graduate work at Cambridge was supervised by geophysicist Edward Bullard. Nigel began with fieldwork in seismology but soon switched to theoretical work in MHD. His dissertation examined variable hydromagnetic motions.

After receiving his PhD, Nigel joined the newly opened Culham Laboratory in Oxfordshire. There he wrote his classic paper showing that the combined effects of advection and diffusion in an array of cellular eddies expel magnetic flux from the eddies' cores and produce a concentrated magnetic field along their boundaries. That groundbreaking work involved the development of stable numerical discretization schemes, which he used extensively in his later research.

In 1965 Nigel returned to Cambridge as a lecturer in the department of applied mathematics and theoretical physics (DAMTP). One of us (Thomas) was a postdoctoral fellow in DAMTP in 1966–67 and benefited from Nigel's sage advice on numerical methods for solving the MHD equations. Nigel remained at DAMTP for the rest of his career, becoming a reader in 1979, professor of mathematical astrophysics in 1987, and emeritus professor in his retirement.

A problem of continued interest to Nigel throughout his career was magnetoconvection—that is, thermal convection in an electrically conducting fluid in the presence of a magnetic field. He and his students and collaborators advanced our knowledge of magnetoconvection with new theoretical ideas, some derived from the then active subject of chaos theory, and numerical simulations of increasing sophistication. They added nonlinear effects and fluid compressibility, which led to applications of magnetoconvection to the Sun's near-surface magnetic field. That work culminated in Nigel's 2014 monograph *Magnetoconvection*, with one of us (Proctor) as coauthor. Nigel's work led to great progress in understanding the complex dynamical interaction between strong intermittent magnetic fields organized into "flux tubes" and the surrounding convection.

Nigel was particularly interested in sunspots, which are perhaps the best "laboratory" for observing magnetohydrodynamic behavior under astrophysical conditions. His work in the 1970s with Friedrich Meyer, Hermann Schmidt, and Peter Wilson examined the influence of convection on the formation and decay of a sunspot. For one of us (Thomas), sunspots were the subject of several collaborations with Nigel: We organized a NATO workshop on them, wrote review articles, and published a monograph, *Sunspots and Starspots* (2008). With Nicholas Brummell and Steven Tobias, we showed that magnetic flux pumping by the solar granulation can explain many features of sunspot structure and evolution. Although a theoretician at heart, Nigel kept in close touch with solar observations, often through visits to Sacramento Peak Observatory and interactions with Alan Title and his group at Lockheed, who were conducting observations from space.

Nigel also contributed significantly to dynamo theory, the study of the way in which motions of a conducting fluid can produce and sustain a magnetic field. Using low-order mathematical models, he was one of the first to explore the chaotic behavior of dynamos, and he related the behavior to that of the solar dynamo and the 22-year solar magnetic cycle, especially concerning the occurrence of the Maunder minimum (from 1645 to 1715) and other periods of reduced solar magnetic activity. With Jürg Beer and Tobias, he investigated the historical record of cycle modulations—with radioisotope variations in tree rings and ice cores as data—and showed that those

JOHN H. THOMAS

Nigel Oscar Weiss

irregularly modulated cycles could be interpreted theoretically through chaotic behavior of the models. Nigel and his wife, Judy, a scholar in English and fellow of Robinson College, wrote a paper on a poem by Andrew Marvell that contains one of the earliest references to the disappearance of sunspots in the late 17th century.

Nigel was an active participant in the academic and social life of his Cambridge college, Clare, and he served the university as chair of its School of Physical Sciences from 1993 to 1998. He was president of the Royal Astronomical Society in 2002 and was awarded its Gold Medal in 2007 for his research contributions to solar astrophysics.

A man of exceptionally broad interests, Nigel read and traveled widely, loved music, collected modern art, and served on a scientific advisory board for the UK's National Gallery. He and Judy established an educational trust in Cape Town, South Africa, to support students from underprivileged backgrounds. He was a kind mentor to many students and colleagues, exuded a quiet authority, and was modest about his own achievements.

Michael Proctor
Cambridge University
Cambridge, UK

John H. Thomas
University of Rochester
Rochester, New York

LOOKING FOR A JOB?

Job ads are now located throughout the magazine, alongside the editorial content you engage with each month. Also find hundreds of jobs online at physicstoday.org/jobs

LOOKING TO HIRE?

Enjoy the power of print plus online bundles any time as well as impactful exposure packages & discounts for our special Careers issue each October. Post online-only jobs anytime at physicstoday.org/jobs

Questions? Email us at ptjobs@aip.org

PHYSICS TODAY | JOBS

QUICK STUDY

Vinothan Manoharan is a professor of chemical engineering and physics and **Annie Stephenson** is a graduate student of applied physics at Harvard University's John A. Paulson School of Engineering and Applied Sciences in Cambridge, Massachusetts.

A field guide to angle-independent structural color

Vinothan N. Manoharan and Anna B. Stephenson

The hues of blue birds come from constructive interference, but scattering and refraction also matter.

"The world is blue at its edges and in its depths," writes Rebecca Solnit in *A Field Guide to Getting Lost* (Penguin Books, 2005). "This blue is the light that got lost." That comment is, on the one hand, a pithy statement about the physics of color: The ocean and sky are blue because they preferentially scatter blue light. On the other hand, it is a metaphor, and an apt one for us. While studying the physics of color, especially blue, we've found that it's easy to get lost. And that is not a bad thing.

Consider the blue jay, a common sight in our home state, Massachusetts. Is it blue like the ocean or blue like the sky? In the ocean, red light is absorbed, leaving blue to be scattered back to us. In the sky, blue light is scattered more than red by the atmosphere, a process known as Rayleigh scattering. According to numerous field guides by Stan Tekiela, blue jays are like neither ocean nor sky. "Feathers lack blue pigment," he says. "Refracted sunlight casts the blue light."

Feather features

Wander with us while we puzzle over that explanation. It's true that blue jays have no blue pigment. Instead, the feathers display structural color, which comes from a mechanism other than absorption (see the article by Ross McPhedran and Andrew Parker, PHYSICS TODAY, June 2015, page 32). But a blue jay's feather isn't a prism; it's a protein matrix containing tiny pores. So scattering must be important to the color. But refraction? Surely that is a misconception.

If so, it wouldn't be the first. For most of the 20th century, Rayleigh scattering was thought to be responsible for a bird's blue color. Because the feather's pores are smaller than visible wavelengths, the argument goes, they should scatter more blue light than red. The isotropy of Rayleigh scattering would also explain why blue feathers, unlike iridescent opals or beetle shells, cast a structural color that depends only weakly on the viewing angle.

But constructive interference, not Rayleigh scattering, is the dominant effect in blue feathers. The matter was settled by ornithologist Richard Prum and colleagues studying another blue-colored bird, the plum-throated cotinga (figure 1), in 1998. Unlike opals or beetle shells, whose components display crystalline order, a cotinga feather has pores with short-range correlations and long-range disorder, like the molecules of a liquid. And just as x rays scattered from a liquid can constructively interfere when the wavelength is close to the interparticle distance, so too can visible-light waves scattered from a feather. Prum and colleagues showed that the characteristic distance between the pores leads to constructive interference for blue light but not for other colors.

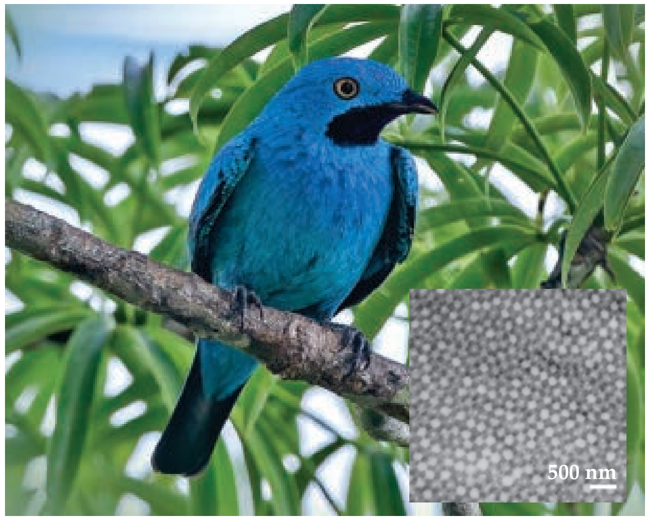


FIGURE 1. THE COLOR OF THE PLUM-THROATED COTINGA comes from constructive interference of blue light scattered from disordered pores in the feathers. A transmission electron micrograph of those structures in a cotinga feather is shown in the inset. (Photo by Wang LiQiang/Shutterstock.com. Inset adapted from E. R. Dufresne et al., *Soft Matter* **5**, 1792, 2009.)

A decade later, Jason Forster and colleagues at Yale University showed that when 200 nm polymer spheres aggregate, they show a similar blue. Importantly, the color appears only when the particles—proxies for the pores in the cotinga's feathers—are densely, though randomly, packed. The results underscored the point that birdlike blues come from constructive interference.

Manipulating color

Nevertheless, Rayleigh scattering—or, more broadly, the tendency of small particles to scatter more blue light than red—can affect the color. Our research group discovered that fact during an experiment, inspired by Forster's, when we tried to make particle packings that were red. At first the task seemed simple: Just increase the particle size, thereby redshifting the interference condition. But instead of red we got purple, a mixture of red and blue.

To make sense of that result, we developed a simple model. It assumes that light scatters just once inside the material—a crude approximation, but reasonable under certain conditions. The scattered intensity is the product of a structure factor, which describes the correlations between particles, and a form factor, which describes the scattering from individual particles (see figure 2a). Both are functions of the wavevector $q = 4\pi \sin(\theta/2)/\lambda$,

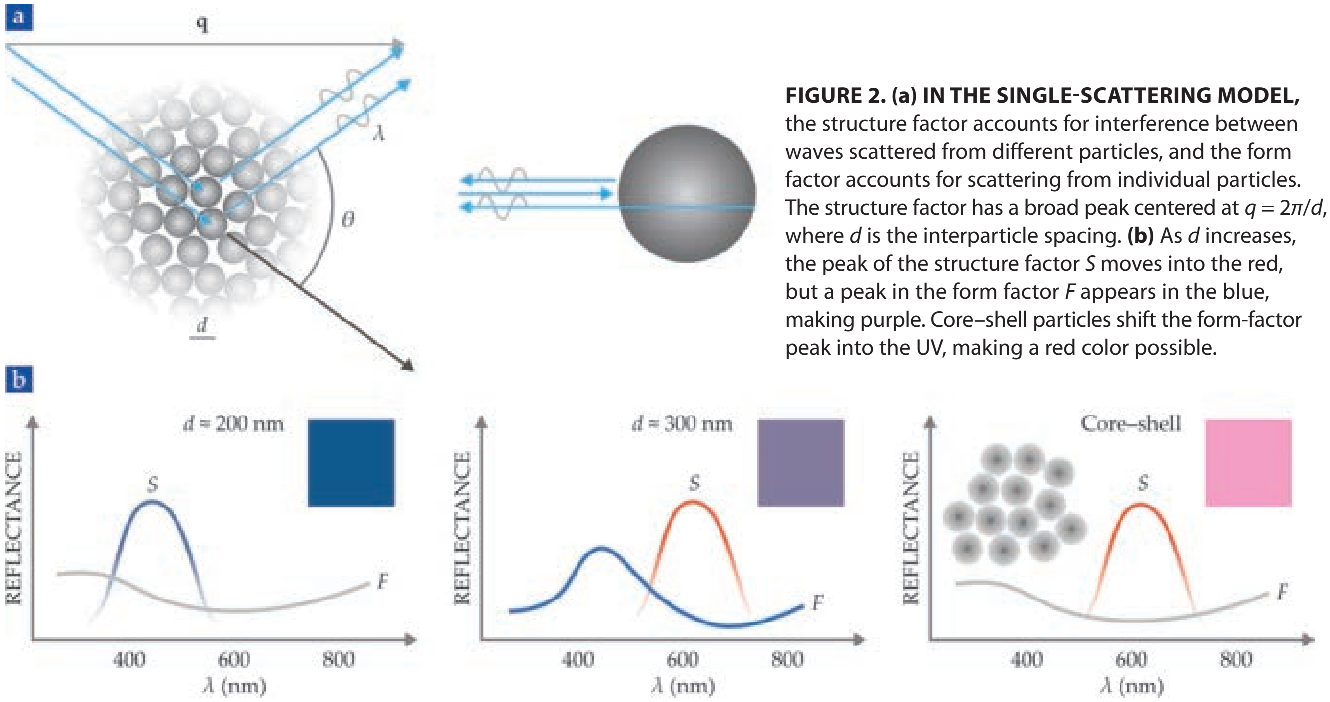


FIGURE 2. (a) IN THE SINGLE-SCATTERING MODEL, the structure factor accounts for interference between waves scattered from different particles, and the form factor accounts for scattering from individual particles. The structure factor has a broad peak centered at $q = 2\pi/d$, where d is the interparticle spacing. **(b)** As d increases, the peak of the structure factor S moves into the red, but a peak in the form factor F appears in the blue, making purple. Core–shell particles shift the form-factor peak into the UV, making a red color possible.

where θ is the scattering angle and λ is the wavelength in the material. The structure factor can be calculated by assuming the particles pack as atoms do in a simple liquid. The form factor can be calculated from Mie theory, the solution to Maxwell's equations for light interacting with a sphere.

The structure factor has a broad peak centered at $q = 2\pi/d$, where d is the average interparticle distance. Constructive interference should happen when the scattering wavevector is comparable to wavevectors near the peak. Equating the two expressions for q yields a constructive interference condition $\lambda = 2d\sin(\theta/2)$. When d is about 200 nm, as it is in the bird feathers and in the blue packings, the model correctly predicts that we should see blue light (about 450 nm wavelength) in reflection.

The model also explains the weak dependence on the viewing angle. Our constructive interference condition is actually Bragg's law—disguised, perhaps, by our definition of θ. Typically Bragg's law is derived for a crystal, in which case d takes on discrete values. But for a disordered material, d has a continuous distribution. Thus the constructive interference condition can be met for a continuous range of angles. Because of the lack of long-range order, the interference is only partially constructive, so the color is subdued rather than brilliant.

So why did our red structural colors become purple? When the particles are 300 nm, the structure factor is peaked in the red, as expected. But the form factor has a peak in the blue (see figure 2b) that arises from interference in a single particle. We realized that if we could shift the blue peak to the UV, where it would not be seen, we could make something that doesn't occur in nature: a red structural color with weak angular dependence. To do that, we'd have to make the particles smaller while keeping the spacing between them constant. Our plan was to pack particles with small polymer cores and transparent shells. The polymer cores would scatter the light and the shells would act as spacers.

The plan worked—at least partly. The packed core–shell particles showed a reflection peak in the red and no peak in the blue. But they looked pink. That's because light of all wavelengths can scatter more than once. Mix some of that white light with the red and you get pink. We're now trying to reduce the multiple scattering to make a more saturated red. That might be useful for applications like reflective color displays; imagine, for example, a smartphone that is readable in direct sunlight.

Edge effects

There's one important detail. Our model assumes that each particle is embedded in a homogeneous medium with an average, or effective, refractive index. That effective-medium approximation makes perfect sense—and can be justified by Maxwell's equations—when the particles are tiny, as they are in a molecular mixture. It's harder to justify when the particles are bigger, but it works well when the refractive indices don't differ greatly.

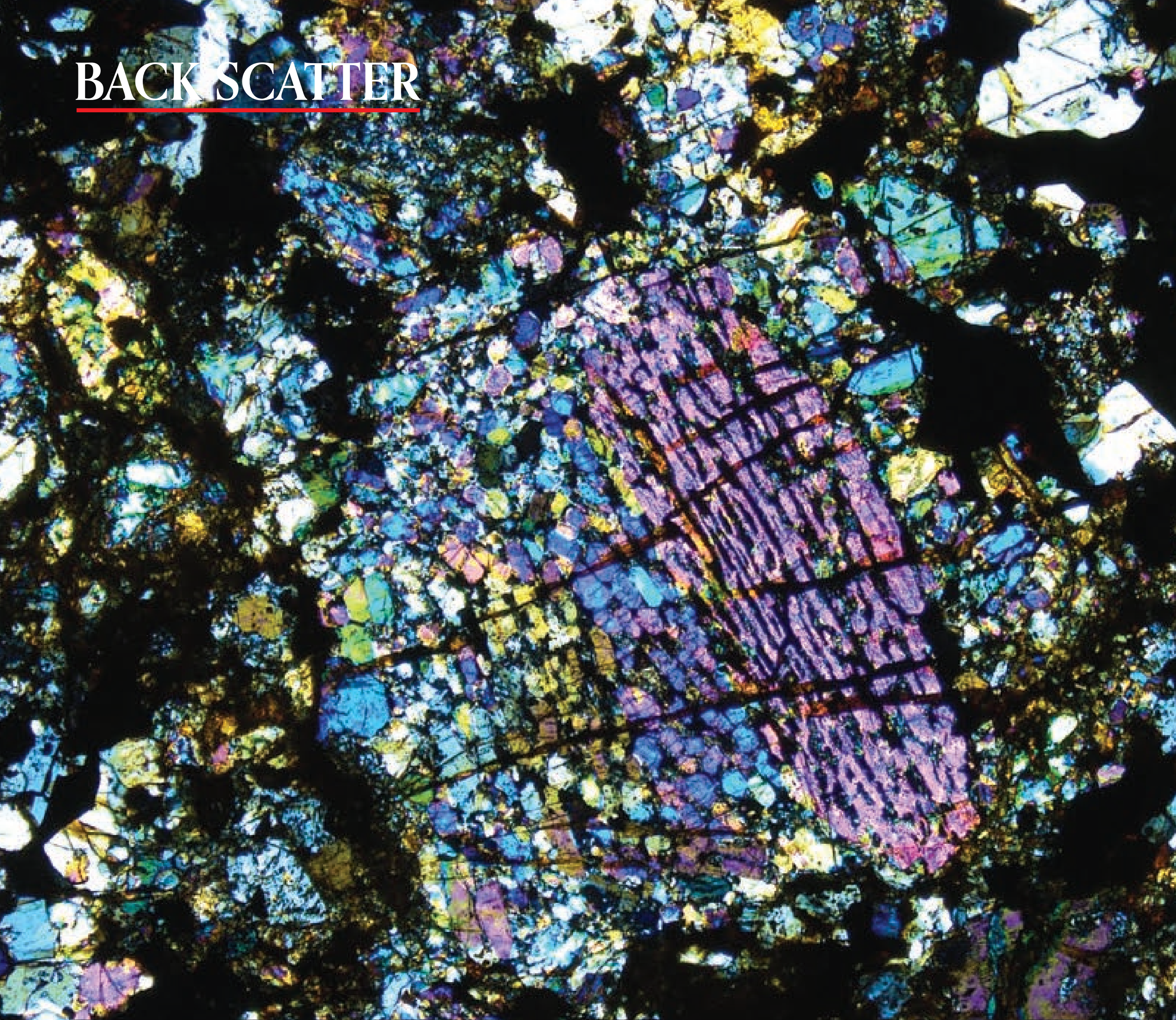
Why is that detail important? For the model to be consistent, we must account for what happens when light hits the boundary of the effective medium. There it can reflect and—you guessed it—refract.

Stan Tekiela's explanation wasn't quite correct: Refraction alone doesn't explain blue structural color. But the absence of refraction at certain angles—that is, total internal reflection—leads to some wavelengths being suppressed. And the presence of refraction alters the angular dependence of the colors that aren't suppressed. So the guide didn't exactly lead us astray either.

On our meandering journey, ideas that first seemed to be misconceptions—refraction and Rayleigh scattering—have become useful concepts. Like those who are lost, we go in circles. But as Rebecca Solnit writes, "Never to get lost is not to live." Indeed, each time we circle back, we have gained new understanding.

Additional resources

▶ R. O. Prum et al., *Nature* **396**, 28 (1998).
▶ J. D. Forster et al., *Adv. Mater.* **22**, 2939 (2010).
▶ S. Magkiriadou et al., *Phys. Rev. E* **90**, 062302 (2014).
▶ J.-G. Park et al., *Angew. Chem. Int. Ed.* **53**, 2899 (2014).
▶ L. Maiwald et al., *Opt. Express* **26**, 11352 (2018). PT



A meteorite's rocky start

This cross-polarized light image magnified about 100 times shows an olivine-rich grain in the 21-kilogram Artracoona meteorite, which was discovered in South Australia in 1914. The meteorite is an ordinary chondrite belonging to the L group, an astronomical family of thermally metamorphosed meteorites that are likely fragments of a planetary body from the early solar system. One clue about the meteorite's origin comes from its thermal history. Previous investigations, however, have found large ranges of cooling rates too imprecise for testing competing evolution models. Now Michael Lucas of the University of Tennessee, Knoxville, and his colleagues have used a suite of geochemical thermometers to determine the thermal rate of change over the geologic history of the ordinary chondrite's parent body.

The researchers determined that the chondrite samples reached a peak temperature of about 900 °C and then cooled at least 0.3 °C per year. That thermal evolution is inconsistent with the canonical onion-shell model in which the outer layers of an ordinary chondrite's parent body cool more rapidly than the insulated inner layers. Instead, the data point toward a process that cooled material rapidly at high temperatures and then more slowly at lower temperatures. That evolution is more consistent with the fragmentation–reassembly scenario: Parent bodies initially resembled an onion shell that had a catastrophic collision, broke apart, and then accreted to form a body of jumbled fragments. (Image courtesy of Michael Lucas and Nick Dygert; M. P. Lucas et al., *Geochim. Cosmochim. Acta* **290**, 366, 2020.) —AL

TO SUBMIT CANDIDATE IMAGES FOR BACK SCATTER VISIT https://contact.physicstoday.org.