PHYSICS TODAY

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FEATURES

ON THE COVER: This month the American Meteorological Society celebrates its 100th anniversary. Physics Today's editor-in-chief, Charles Day, marks the momentous milestone, starting on **page 52**, by looking back at how the magazine has covered, or neglected to cover, progress in the science of climate and weather since the first issue was published in May 1948. (Detail from *Skyscape*, 1912, by Nicholas Roerich/Tretyakov Gallery, Moscow/Bridgeman Images.)

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LANL

▶ Secret physics

At Los Alamos National Lab, physicists Chris Fryer and Tess Light can pursue interdisciplinary research and take up tangential projects. But the secrecy around their work can get complicated. Sarah Scoles tells their stories to explore the advantages and drawbacks of a career in national security science.
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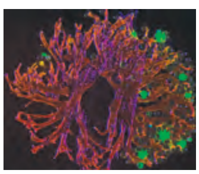

CORNEILE MINNAAR

▶ Quantum dots

To track pollen's movement between flowers, biologist Corneile Minnaar attached quantum dots to pollen and observed their fluorescence with a 3D-printed box that fits under a dissection microscope. Sarah Wild reports on how the method helped researchers probe an intriguing flower species.
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PRAD COLLABORATION

▶ Proton radius

The charge radius of the proton was thrown into question in 2010, when an experiment yielded an unexpectedly small value of about 0.84 femtometers. A pair of experiments now confirm that measurement. Physics Today's Heather Hill explains whether the results settle the decade-old mystery.
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DEPARTMENTS

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The margins of reproducibility

Charles Day

In 2016 *Nature* published the results of polling scientists about their views on a central tenet of science: reproducibility. Shockingly, 70% of the 1576 respondents said they had tried and failed to reproduce another scientist's experiments; 52% said that irreproducibility constituted a significant crisis.

Physicists and engineers were the most confident in the reproducibility of published results. Perhaps because of that confidence, they were also the least likely, at a rate of 24%, to have taken concrete steps to improve reproducibility. Given that some of the most notorious cases of irreproducibility in science have been perpetrated by physicists, it's important to examine the causes and propose remedies.

The most flagrant cases are the most straightforward to address. When Jan Hendrik Schön fabricated the results of experiments on organic semiconductors in the early 2000s, he surely knew that what he was doing was wrong. I doubt ethics training, even if he had received any, would have made a difference. What could have checked him is foreknowledge of the shame and sanctions he brought on himself.

Schön set out to deceive. Other researchers have sincerely believed in their theories or experiments—and then persisted in advocating their conclusions even after contrary evidence has convinced almost everyone else of the conclusions' invalidity. Forty years ago, Stanley Pons and Martin Fleischmann trumpeted their measurement of a temperature increase in an electrochemical cell, which they attributed to the fusion of deuterium to make tritium or helium-3. The widespread failure to reproduce the results or to plausibly explain them convinced most physicists that cold fusion is spurious. Pons, Fleischmann, and others who study low-energy nuclear reactions remain unswayed.

Sometimes mavericks are right. Alfred Wegener's theory of continental drift was eventually confirmed. Sincere belief in the face of opposing evidence is challenging to classify as unethical, except when attributable to the deliberate and dishonest mishandling or misinterpretation of data. A bitter dispute about supercooled water's structure just above the temperature at which it freezes came down to an unphysical assumption buried in a subroutine. (See "The war over supercooled water" by Ashley Smart, PHYSICS TODAY online, 22 August 2018.)

The largest number of cases of irreproducible research likely arise from scientists' pushing at the margins of what is technically and statistically feasible. In the July 2008 issue of PHYSICS TODAY (page 12), I reported on a survey of quasars that found evidence in their UV spectra of a hot phase of intergalactic plasma. The finding was newsworthy because the plasma could account for 40% of the baryons missing at low redshifts and suspected to lurk in filamentary structures connecting clusters of galaxies. What of the remaining 60%? Astronomers anticipated finding the baryons in even hotter, x-ray-emitting plasma. "New missions, such as NASA's *Constellation-X* and ESA's *X-ray Evolving Universe Spectroscopy,* are expected to find some of them," I wrote.

Neither mission has launched. I was surprised, therefore, to encounter papers in 2018 and 2019 that claimed to have discovered the even hotter plasma in data gathered by two spacecraft, ESA's *XMM-Newton*[1] and NASA's *Chandra X-Ray Observatory*,[2] that were in orbit when I wrote the 2008 story. Both studies abutted the limits of statistical significance and relied on challengeable assumptions. They are not invalid, however. Both groups fully described their methods, and thanks to the widespread practice in space-based astronomy of making data publicly available, astronomers are free to repeat the analysis.

Ernest Rutherford's glib remark, "If your experiment needs statistics, you ought to have done a better experiment," is not helpful when the better experiment is years away. What's needed, I think, is better instruction in data analysis. Mine came indirectly from Allyn Tennant, then a postdoc, who urged me to buy and read Philip Bevington's book, *Data Reduction and Error Analysis for the Physical Sciences* (1969). The book remained my *vade mecum* throughout my career as an astronomer.

In their November 2004 PHYSICS TODAY article, "Ethics and the welfare of the physics profession" (page 42), Kate Kirby and Frances Houle cited a survey of physics graduate students and postdocs that was conducted by Roman Czjuko of the American Institute of Physics (publisher of PHYSICS TODAY). It found that only half had received training on acceptable ways to interpret and analyze data.

Physicists should continue to publish marginally significant results. But when they do so, the statistical analysis should be sound, transparent, and reproducible.

References

1. F. Nicastro et al., *Nature* **558**, 406 (2018).
2. O. E. Kovács et al., *Astrophys. J.* **872**, 83 (2019).

PT

Reading out qubits with quantum-noise-limited amplifiers

Phil Dooley

Over the past decade, quantum computing has evolved from a promising field into a race to demonstrate real prototypes. Researchers are experimenting with physical systems including supercooled ions, nitrogen-vacancy centers, and superconducting circuits to serve as qubits. The success of any qubit architecture is contingent on its ability not only to maintain and process delicate quantum states but also to pair with instruments that decipher its output.

Defense contractor Raytheon is on the way to creating a vital cog in that process: an amplifier that can read out the quantum signal from some superconducting qubit systems. Despite its small size, the amplifier has minimal quantum noise. And because it uses microwave technology and is compatible with silicon, it would be easy to manufacture in large quantities using existing infrastructure. "These amplifiers allow the scalable readout of multiple qubits with quantum-limited noise in a footprint that is small enough to integrate into the same package as the qubits themselves," says Andrew Wagner (pictured above), a lead scientist at Raytheon.

The kinetic inductance traveling-wave amplifiers that Raytheon is working on are not new, but they are a promising contender for early generations of quantum computers. Made from superconducting niobium, they consist of a resonant circuit that sits alongside the qubit circuit—close enough for the two to be coupled, but not so tightly bunched that reading out the amplifier circuit destroys the qubit's state. "Microwave engineering can become very complicated very quickly the instant you start chaining things together or cramming things into small spaces," Wagner says.

The amplifier leverages the nonlinearity in a thin layer of niobium nitride to convert the resonant signal of the superconducting circuit to a desired frequency via parametric amplification. To amplify the signal, the phase of the signal and that of a pump wave must match. That matching is achieved by including a band stop or dispersive feature with carefully engineered impedance in the transmission line. "The design of the amplifier requires careful modeling of thin superconducting metal layers in a nontrivial microwave geometry," Wagner says.

Niobium is a conventional superconductor, with properties that are fully described by the Bardeen-Cooper-Schrieffer (BCS) theory. To simulate the layers, Wagner turned to COMSOL's finite elements simulator package, which accommodates BCS theory. COMSOL's package allows Wagner to incorporate the BCS sheet resistance and the superconducting transition temperature so that the kinetic inductance can be accurately calculated.

Wagner says the flexibility of COMSOL's software is crucial in enabling the precise simulation of the complicated circuits without supercomputing infrastructure. The software maximizes efficiency by having meshing strategies that allow both fine sampling of the solution space around complicated nanoscale components and coarser sampling in less complex, larger-scale areas of the circuit. "That's important," Wagner says. "It saves you a ton of memory."

If Wagner's designs prove successful, he aims to integrate them into the readout chain of existing qubit circuits. "It's thrilling to take something you've made, cool it down, and make it behave like an atom," he says.

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

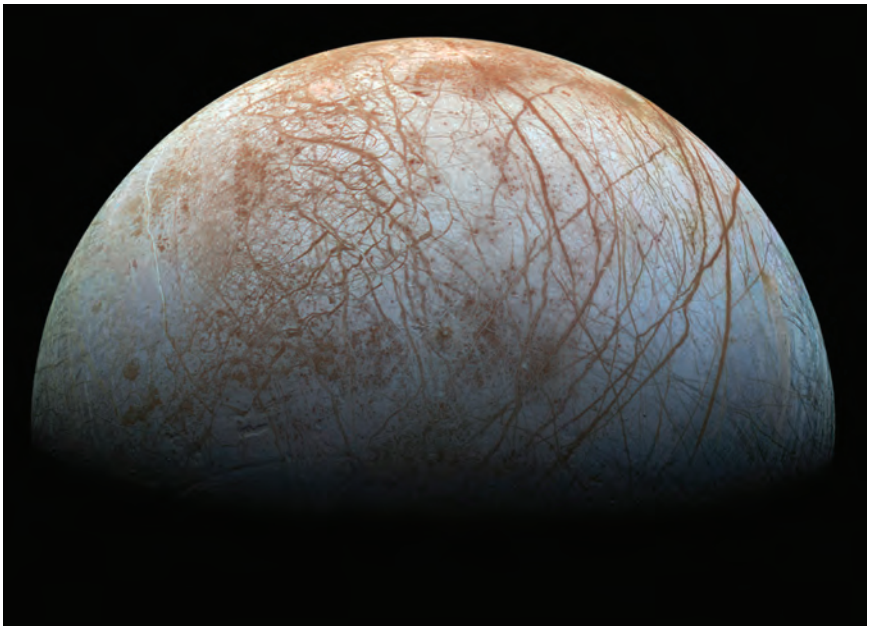
Commentary

Beyond the decadal surveys: Establishing policy for US space science

Even though the US government's fiscal year 2020 budget is subject to a continuing resolution through at least late November that keeps federal spending at FY 2019 levels, the annual budget process is well underway. Federal agencies are putting the finishing touches on their FY 2021 requests, which then go through negotiation with the Office of Management and Budget (OMB) before delivery to Congress in February.

Many in the space science community are aware of the budget process. However, having spent roughly a decade working in space policy, primarily in planetary science, I have often encountered a disconnect between space scientists' understanding of how policy is formed and of the activities that affect budgets in their field.

Since 2005 Congress has instructed NASA to use the decadal surveys from the National Academies of Sciences, Engineering, and Medicine in determining what missions it selects. Many in the space science community assume that the surveys are binding. In fact, Congress and the executive branch view the decadal surveys as a particularly useful tool for two reasons: First, they are a tangible indication that the space science community is cohesive; second, the community has done the work to enumerate its priorities by vetting options, eliminating those of lesser science value, and prioritizing those viewed as central to progress. There are, however, additional factors affecting the decision-making process.



JUPITER'S MOON EUROPA has received attention in recent federal budgeting. A series of flybys has received the go-ahead for its next step. But a mission to place a lander on Europa's surface has been scrubbed, in part because its major champion in Congress, Representative John Culberson (R-TX), lost his seat. (NASA/JPL-Caltech/SETI Institute.)

The relationship between federal agencies and the OMB can seem fairly opaque. I have often heard frustrations—even from individuals high in NASA's chain of command—about the onerous and seemingly arbitrary funding limits imposed by the small group of OMB bureaucrats. Those frustrations are not always unwarranted, but I have found that the motivations behind the office's decisions, at least toward space science, can often be misconstrued. Part of the executive branch, the OMB is charged with ensuring that the entire federal budget request complies with the president's policy directives. In most administrations, the OMB works closely with the Office of Science and Technology Policy to establish policies and budget priorities for science, though that isn't always the case and generally reflects the administration's views on science as a means to further its broader policy goals.

A surprisingly small number of individuals at the OMB are involved in space science: the director of the OMB and the associate director for natural resource programs, both of whom are political appointees; the deputy associate director for the energy, science, and water division; and the fewer than 10 individuals who make up the division's science and space branch. Space science is, for the most part, handled by just a few career civil servants.

I've not come across anyone in Congress or the executive branch who simply did not want to fund space-science missions. I have, however, encountered government officials who are vividly frustrated with cost overruns, and I have found that bureaucrats tend to value flexibility. The folks I met at the OMB and on Capitol Hill were sensitive to unforeseen occurrences or prescriptive options that placed undue limits on future actions, particularly if they interfered with agreed-on courses of action or involved a time frame beyond which policies—or politicians—might experience turnover.

Such considerations certainly affected the 2012 decision to end NASA's Mars

Astrobiology Explorer-Cacher (MAX-C) rover project. Although it was included in the 2013–22 planetary science decadal survey and aligned with the Obama administration's goal of increasing participation in international space science, MAX-C came on the heels of cost overruns on the *Curiosity* rover and the *James Webb Space Telescope* (*JWST*) and was intended as the first of three large-scale missions to return samples from the surface of Mars.

OMB leadership and staff sought to avoid having NASA embark on a new large-scale project while still covering cost overruns for the *JWST*. They were also concerned that agreeing to fund three large missions over a decade or more posed too tight a constraint on other projects during that period. In the end, the OMB would not allow NASA to start the MAX-C project, and NASA's potential participation in the European Space Agency's ExoMars program was reduced to providing a communications instrument on ESA's *Trace Gas Orbiter*.

As with the OMB, the number of people in Congress involved in space science is limited. Between the two authorization subcommittees—the space and aeronautics subcommittee of the House Committee on Science, Space, and Technology and the aviation and space subcommittee of the Senate Committee on Commerce, Science, and Transportation—fewer than 30 members of Congress deal directly with space science policy. On each chamber's Commerce, Justice, Science, and Related Agencies (CJS) appropriations subcommittee, the number is similar. The chairs of those congressional committees and subcommittees wield significant power; they control the agenda of their respective groups and direct a majority of the staffs, generally 7–10 for committees and 2–6 for subcommittees, with a smaller contingent reporting to the ranking member. Regardless of the support an issue may have, the chair determines whether legislation on it will move forward.

In the 2017–18 Congress, House CJS chair John Culberson (R-TX) provided funding for two projects that NASA had not included in its budget requests: a multiple flyby and a lander mission to the Jovian moon Europa. The planetary decadal survey listed the flyby as the second priority among large-scale projects behind a mission to Mars and recommended further study for the lander mission. Nevertheless, Culberson was able to appropriate more than $1.2 billion over six years for the two.

When Culberson lost his seat in the 2018 election, the Europa missions lost a powerful advocate. His support had been particularly idiosyncratic in that the missions had no direct ties to his district; he simply believed that the science was of benefit to the nation. The multiple-flyby mission, now called Europa Clipper, survived due in part to its being included as a second-tier option in the decadal survey and in part to its being far enough along in its development cycle that NASA had "confirmed" it, meaning that officials had signed an agreement with Congress establishing the mission's cost, schedule, and technical milestones.

The lander project was less fortunate. Without support from its influential patron or the decadal survey, the project is in limbo, with enough funding to continue low-level studies but not enough to begin building the spacecraft. Robust policies tend to benefit from strong coalitions of stakeholders with varying interests, and the lander's supporters may have been overly reliant on a single individual.

None of the handful of people in Congress or at the OMB who deal with space science—or even with NASA—do so exclusively. They view NASA as part of a portfolio of responsibilities they must balance, and they receive finite resources to do so. They invariably require justification for budget requests. On many occasions I have encountered individuals or groups asking Congress to increase NASA's budget by some percentage or dollar amount, or by "adding a penny of every dollar of tax revenue" to the space agency's top line. The inevitable response from congressional or OMB staff is, "For what purpose?" They are not asking for grand philosophical answers or "imagine what we could do" rhetoric. They are looking for hard analysis on the projected cost of a program or mission, for evidence of agreement on its necessity from the relevant expert community, and for justification for choosing that investment over others. Pie-in-the-sky wish lists or attempts to bypass a consensus-building process leave government stakeholders without justification to present to their constituencies for expending tax dollars.

Another disconnect between science communities and policy is temporal. The federal government operates on a different time scale than the "march of science." The current and next fiscal years are the glaring priorities, and anything beyond a two-year time frame is an abstraction. That is a function of the political cycle, and it can be maddening to scientists with projects that can last a decade or more. Such is the price of relying on taxpayer funding in a representational democracy.

In years to come, space science will encounter growing budget competition from expenses related to climate change, an aging population, growing national debt levels, deteriorating infrastructure, and other issues that will increasingly demand government attention. Rather than trying to impart to lawmakers and bureaucrats the values important to the space science community, perhaps the community will be better served by evaluating the pressures to which policymakers respond and finding ways to describe how space science already contributes to congressional, executive, and broader national objectives, such as economic growth, international relations, education, workforce sustainability, and national security.

Each decadal survey includes sections describing the scientific field's contributions to the nation, but the information is often qualitative rather than quantitative. Detailed workforce information, economic impact analyses, student and graduate data, and other, nonscience information that chronicles the many ways in which space science supports broader priorities could be included not only in decadal surveys but also in mission descriptions and other public documents. Scientists should also communicate regularly with their political representatives to discuss the value of their work. As a Senate committee staffer once told me, "If you show up in my office the day your budget is cut, you're a year too late."

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LETTERS

Respect for a master's in physics

With regard to Toni Feder's story about physics master's degrees (PHYSICS TODAY, April 2019, page 22), I am glad that the degree finally seems to be getting some respect. I received my master's 30 years ago from a PhD-granting research university. Although I had been accepted to continue toward my PhD, I intended from the beginning to pursue only a master's and then look for teaching positions. I remember being told, "That and a dime will get you a cup of coffee," and I often received unsolicited advice that I would be useless to the profession without a PhD.

Partly on the suggestion of my adviser, who counseled me to think about the goals I'd had when I entered graduate school, I accepted a one-year position as a visiting lecturer at a nearby branch campus. That job led to a tenure-track position at a nearby community college the next year. There I had a professionally and materially satisfying 27-year career teaching and doing research.

For reasons mostly my own, I did eventually complete a PhD and a postdoc and have recently found myself as a lecturer back where I got my MS. I hope to stay until I retire. I have no regrets about what I've done and how I did it and perhaps just a bit of pride in how much I accomplished with my master's degree, despite what I was told.

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Notes on a brilliant failure

The article "Ernest Lawrence's brilliant failure" by Joshua Roebke (PHYSICS TODAY, March 2019, page 32) gives a historical account of early work by the Nobel recipient and his associates at the University of California, Berkeley, to invent color TV. An alumnus of both Berkeley and the TV industry (1964–2006), I was surprised and pleased to learn of that work. I had not realized that Sony's Trinitron technology traces its origin back to Berkeley and Lawrence.

However, I was shocked by several inaccuracies. The article is misleading regarding the basic principles of the color

CRT (cathode-ray tube), and it does not present an accurate account of the pre-flat-panel display industry.

The article claims that Sony's Trinitron CRT was the best-selling television in the world and was the color TV most Americans grew up with. That is incorrect. From the beginning of color broadcasting in 1954 to the mid 2000s, RCA's color CRT was the dominant one.

Sony's Trinitron was commercially introduced in 1968, 14 years after the start of the color TV industry. Virtually no other company manufactured color TVs with Trinitron displays. During the pre-flat-panel color TV era, Sony sold fewer than 300 million color TVs with Trinitrons; the rest of the industry globally sold well over 10 times as many sets with the RCA color CRT. Although RCA only manufactured in the US, it licensed its technology abroad; in several cases RCA provided direct engineering support for licensees' manufacturing plants. All color TV manufacturers worldwide, including Sony, were RCA licensees.[1]

The fundamental physical principles of the Sony and RCA color CRTs were identical. Both used three intensity-modulated electron guns to carry the three-color image information. Contrary to the article, the Trinitron did not use a single source for the three beams.

The beams were scanned by a common magnetic deflection system. In both the Sony and the RCA devices, a metal mask with small openings was placed at a precise distance between the screen and the electron guns. The beams emerged from each opening at slightly different angles and landed on the screen at three slightly displaced, nonoverlapping locations, where a trio of red, green, and blue light-emitting phosphor elements were positioned. To prevent the excitation of adjacent phosphor elements, the mask transmission is necessarily restricted to less than ⅓.

The Sony and RCA approaches used differently shaped masks. Sony's was made of tensioned metal strips forming a vertical standing cylinder. RCA's mask was best described as spherical. Thus the Sony guns were arranged horizontally, whereas the RCA ones had a triangle configuration. Both systems worked well. The price of color TVs was determined by the cost of the CRTs, which was mainly driven by the cost of their glass bulbs. Because the RCA approach was somewhat less expensive, it dominated the consumer market.

Reference

1. J. A. Castellano, *SID Symp. Dig. Tech. Pap.* **30**, 356 (1999); A. Monchamp et al., *Cathode Ray Tube Manufacturing and Recycling: Analysis of Industry Survey*, Electronic Industries Alliance (2001).

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▶ **Roebke replies:** I'm thankful that Istvan Gorog read my article until its end; he was, he confessed, pleased rather than shocked until its final paragraphs.

I did not write a history of the color television industry. My article told the story of one unheralded company and the physicists who worked on its color televisions, in their spare time, while building particle accelerators for both national defense and empirical pleasure. It was the story of the Chromatron, not RCA and the Trinitron.

Gorog was not just an alumnus of the TV industry. He was a director at RCA. So he objected when, in my denouement, I mentioned that the Trinitron was the best-selling television when most of us were growing up. In the 1990s, when I was growing up, it was.

In his letter, Gorog conflated tubes and televisions. But the first was mere synecdoche for the second. Sony built televisions from its tubes. RCA often licensed those components to other television manufacturers, so as not to manufacture all those televisions itself.

Gorog also demurred when I noted that the Trinitron had a single beam source. But it originally had a single electron gun. In the 1970s Sony even advertised "The Beauty of One Gun" as the Trinitron's distinctive feature. The veracity of my supposed inaccuracies is well documented.

Gorog then recapitulated what I wrote about grids and masks, albeit more technically and for the Trinitron rather than the Chromatron, which was the subject of my article. He distinguished the specifications of the Trinitron and RCA's tubes fluently. But he was an expert on such tubes when I was still sitting at home and watching television.

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Physical cosmology wins a share of the Nobel Prize in Physics

James Peebles developed a mathematical framework that describes how the universe evolved. Decades of empirical evidence later, it still holds up.

PRINCETON UNIVERSITY, OFFICE OF COMMUNICATIONS, DENISE APPLEWHITE

James Peebles

How and when did the universe begin? How has it evolved? What will be its fate? Albert Einstein and others pondered those questions in the early part of the century. But not until 1929, when Edwin Hubble observed that galaxies were moving away from ours in every direction, did solid empirical evidence begin to support any postulated answers. And not until the second half of the century did cosmology transition from a highly abstract discipline to a field in which accepted theories had to conform to measurements.

After World War II, cosmology discussions revolved around two competing theories. Relativistic evolution, which became known as Big Bang theory, postulated that the universe is expanding from an ultra-dense point that contained all the matter in today's universe. The alternative steady-state theory rejected the concept of a moment of creation and postulated that although the universe is expanding, matter is continuously created so that the average density of the universe remains unchanged. (See the article by Geoffrey Burbidge, Fred Hoyle, and Jayant Narlikar, PHYSICS TODAY, April 1999, page 38.) But in the academic world, "the discussion was really a sideshow. The topic just was not part of the mainstream of physics research," says David Kaiser, science historian at MIT.

James Peebles, at Princeton University, changed that. Beginning in the 1960s, he laid out a framework of precise mathematical theories about the universe's evolution that have continued to be verified by empirical observations. He posed questions that coupled mathematical analyses to potential physical consequences; for example, he asked what patterns of galaxies should be observable today based on different possible conditions in the earliest moments of the universe. This year, the Royal Swedish Academy of Sciences recognized Peebles with the Nobel Prize in Physics for his "theoretical discoveries in physical cosmology."

Off the beaten path

Apart from Hubble's, the lack of observations with which to test theories meant that cosmology had long been regarded as more of a speculative endeavor than a quantitative science. Only 30 to 40 cosmology papers per year appeared in the scientific literature in the 1950s. When Peebles moved from Manitoba to New Jersey to begin graduate studies at Princeton in 1958, most newly minted physics PhDs would never have had the opportunity to take a course that covered the then arcane theory of general relativity.

Princeton was the exception. John Wheeler brought general relativity to the physics department in 1954 and promoted academic discourse on how to model phenomena in our galaxy and beyond. (See the article by Charles Misner, Kip Thorne, and Wojciech Zurek, PHYSICS TODAY, April 2009, page 40.) Robert Dicke, who had worked at MIT's Radiation Laboratory during World War II and then focused on quantum optics at Princeton, decided that gravitational physics was "too interesting of a problem to ignore," according to Peebles. (See Dicke's obituary by William Happer, James Peebles, and David Wilkinson, PHYSICS TODAY, September 1997, page 92.) Peebles joined the "Dicke-birds" as a graduate student, conducting theoretical and experimental work to test fundamental ideas about gravity and its implications for the universe's large-scale evolution. Outside Princeton, however, Peebles says, "there was a general feeling that cosmology was a rather dismal subject. Although I never received criticism, I got the feeling that others thought it 'better me than them' to be working on those questions."

By his own admission, Dicke was not then aware of work by Soviet American theorist George Gamow and colleagues that, in hindsight, defined contemporary cosmological theory. Gamow had argued in 1948 that a big-bang universe would at first be dominated by high-energy radiation. (See the Reference Frame by Michael Turner, PHYSICS TODAY, December 2008, page 8.) As the universe expanded, most of that energy would be converted to matter but some radiation would remain throughout all space, cooling to near absolute zero. In 1964 Dicke proposed that a remnant of that early thermal energy would remain as cosmic background radiation. He suggested that new professor David Wilkinson develop a way to detect the radiation and that Peebles, who stayed on as a researcher after completing his PhD, consider the theoretical implications of finding, or not finding, it. That guidance from Dicke set the course of Peebles's career.

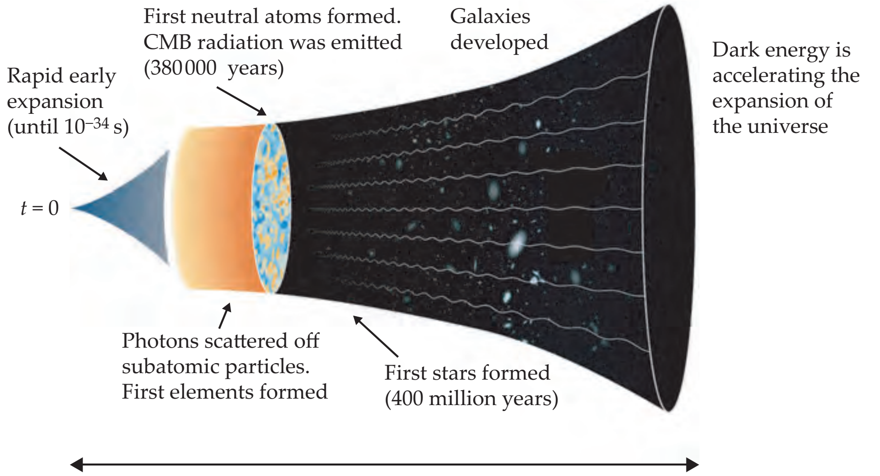


FIGURE 1. JAMES PEEBLES LAID OUT A FRAMEWORK for the evolution of the universe. Models and observations based on his work continue to refine the predictions about key stages of the universe's past, some of which are shown here. (Nobel Prize organization.)

Pigeon droppings or CMB?

In 1964 Peebles prepared a manuscript that described how a dense "primeval fireball" of subatomic particles and radiation expanded and cooled to create the universe. As the universe cooled, the particles lost some of their energy, and atomic nuclei began to combine with electrons to form stable atoms. Radiation no longer scattered off the highly ionized matter and was free to travel unimpeded as the universe expanded to its current density.

Peebles also predicted the radiation would have a thermal, blackbody spectrum. He calculated that the radiation would have cooled from an initial temperature greater than 1010 K down to just 10 K. Concurrently, colleagues Wilkinson and Peter Roll developed a radiometer to measure radiation at a wavelength of 3 cm, chosen to rule out emissions from other extraterrestrial sources, which should be orders of magnitude cooler at that wavelength. The team intended to measure the temperature of radiation emitted by the early universe.

Arno Penzias and Robert Wilson of Bell Labs beat them to that measurement. Still riding the post-war radio astronomy wave, Bell Labs had built an antenna to detect radio signals as part of an early satellite communication system. When the antenna became obsolete, it was made available for research, giving Penzias and Wilson the chance to use it to examine radio signals originating from the space between galaxies. Instead, their 1964 measurements revealed a persistent hum of microwave noise at a temperature of 3.5 K, coming from every direction. The researchers considered possible sources for the noise including pigeon droppings that had collected in the antenna. When a colleague told them about Peebles's work, a logical explanation for the persistent hum appeared. The thermal noise was a relic of the Big Bang in the form of blackbody radiation with a peak emission in the microwave region. "That measurement had a dramatic impact. It turned cosmology into a quantitative science," says Kaiser. For their work, Penzias and Wilson were awarded the 1978 Nobel Prize (see PHYSICS TODAY, December 1978, page 17).

In 1965 Peebles, Dicke, and their colleagues published a paper in *Astrophysical Journal* that linked the cosmic microwave background (CMB) radiation measurement with Peebles's calculations of a hot Big Bang afterglow.[1] That paper cemented the Big Bang as the prevailing cosmological model. It also stated that "more measurements are needed to determine a spectrum" to test that the CMB, at all wavelengths, matched a blackbody. Decades would pass before those measurements could be made.

Peebles went on to develop many of the concepts that underlie modern understanding of the universe's evolution (see figure 1). Shortly after his seminal 1965 paper, he showed how small variations in density, and hence gravity, in the early universe could result in formation of galaxies and galaxy clusters. Blackbody radiation would have created a drag on electrons that countered the gravitational force on protons and would have prevented density variations in the early universe from growing enough to form gravitationally bound systems until the universe had expanded to a critical size.[2]

In 1966 Peebles calculated that helium-4 would have emerged as the dominant nuclide from the hot plasma of the seconds-to-minutes-old universe. Working backward from the universe's present CMB temperature, mass density, and expansion rate, he determined that helium-4 would have made up 26–28% of the early universe's matter. That value has been confirmed in numerous observations. In 1968, he proposed that free protons and electrons combined 380 000 years after the Big Bang to form neutral hydrogen atoms that, along with helium, make up most of the early universe's matter.[3] Those and other calculations set the stage for understanding how matter is distributed on large scales throughout the universe.

The case for dark matter

Peebles sought to explain how different types of matter could have clustered and evolved into the uneven distribution that makes up the contemporary universe. Pressure waves oscillating in the hot plasma before neutral atoms began to form compressed some regions of plasma and stretched others, producing minute variations in density. Slightly denser regions in a near-uniform distribution of matter attracted more matter via gravitation, which led to clusters of gas and stars. In 1970 Peebles, with graduate student Jer Yu, determined that early density

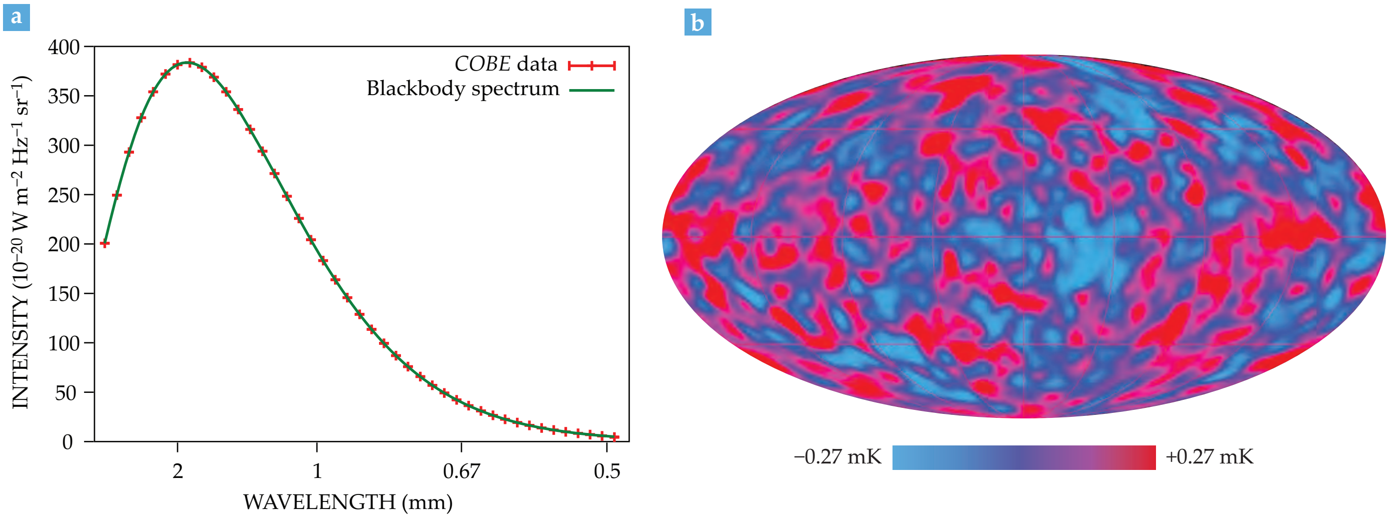


FIGURE 2. THERMAL RADIATION FROM THE EARLY UNIVERSE, as measured by NASA's *Cosmic Background Explorer* (*COBE*). **(a)** The Far Infrared Absolute Spectrophotometer measured the cosmic microwave background (CMB) at wavelengths from 0.1 to 10 mm. The solid curve shows a blackbody spectrum, at a temperature of 2.725 K, as predicted by the Big Bang theory. **(b)** The Differential Microwave Radiometer measured fluctuations in the CMB radiation at a level of 1 part in 100 000. This sky map, created from the first two years of *COBE* data, provided the first view of the anisotropies in the CMB. Those variations gave rise to the structures seen today. (Courtesy of NASA's Goddard Space Flight Center.)

variations should correlate with observable CMB temperature fluctuations.[4] Over long time scales, those anisotropies would have magnified and created today's distribution of galaxies. Similar calculations were carried out simultaneously in the Soviet Union by Yakov Zeldovich, but neither scientist knew about the other's work.

To investigate galactic evolution, Peebles and Princeton astronomer Jeremiah Ostriker conducted numerical simulations that tracked the motion of stars orbiting in a disk like that of our own galaxy. For an object the size of the Milky Way the stars rapidly rearranged themselves into an elongated bar-shaped object—nothing like the spiral shape of the Milky Way and numerous other galaxies. "Lo and behold, if a galaxy looks like astronomers said it should, that galaxy should be wildly unstable," says Ostriker.

To explain the apparent conflict, Peebles and Ostriker revived an idea presented by Fritz Zwicky in the 1930s. Zwicky had concluded that galaxies bound by gravity into a cluster must contain a large amount of "dark" matter that is not accounted for by the mass of stars in those galaxies. By adding a distribution of such dark matter to their simulations, Ostriker and Peebles found that a recognizable galactic structure emerged.[5] The extra dark matter existed as a spherical halo surrounding the main stellar disk and prevented it from turning into a bar. They estimated that the total mass density of dark matter in the universe was 0.2 of the "critical value" that would give the universe a flat geometry. That estimate is very close to today's current best estimate of 0.26.

"In the 1970s, people began to think about dark matter as more than just a puzzle," says Simon White, a director of the Max Planck Institute for Astrophysics. White and his colleague Martin Rees built on Peebles's work to formalize a hierarchical process in which dark matter first clustered into halos due to gravitational forces. The ordinary matter in those halos then cooled and condensed to form the more easily observed dense luminous component of galaxies. (For more on galaxy formation, see Jeremiah Ostriker and Thorsten Naab, PHYSICS TODAY, August 2012, page 43.)

Astronomical observations lent further support for Peebles's predictions of dark matter. Vera Rubin, Kent Ford, and others measured the orbital speeds of stars and gases at different distances from the center of the Andromeda Galaxy. (See the Reference Frame by Vera Rubin, PHYSICS TODAY, December 2006, page 8.) In the absence of dark matter, Newton's law of gravitation predicts that objects farther away from the galaxy's center should travel more slowly than those near the center. But Rubin found that the outermost stars travelled at nearly the same speed as the innermost ones. Her finding implied that the total mass increases linearly with distance. Similar measurements of 60 spiral galaxies led Rubin and Ford to conclude that "enormous amounts of nonluminous matter extend far beyond the optical galaxy."

The elusive lambda

David Spergel, theoretical astrophysicist at Princeton, says "Peebles and Ostriker showed that the stability of disk galaxies required the existence of dark matter." But although nobody knew what it really was, Peebles hypothesized in 1982 that the universe was dominated by "massive, weakly interacting particles" that do not interact with radiation and that travel at nonrelativistic speeds—in other words, cold dark matter.[6] He calculated that in such a universe, the CMB would have a temperature variation of 5 parts in 100 000, a value, he explains, that illustrates "the important observation that the distribution of galaxies is very clumpy, while the distribution of radiation is close to smooth."

At the time, "most people had glommed on to the idea that the Einstein–de Sitter model was the simplest model of the universe," says Peebles. That model posits an expanding universe of critical mass density and zero curvature. But by 1984 Peebles was skeptical that the universe's mass could be as large as the model suggested.

In his original theory of general relativity, Einstein had introduced a scaling parameter Λ, called the cosmological constant, to achieve a static universe. He later abandoned the idea because it contradicted observations of an expanding universe. (See the article by Tom Banks, PHYSICS TODAY, March 2004, page 46.) Peebles reintroduced the cosmological constant to balance the apparent conflict between the measured matter density of the universe and the constraint that an expanding universe remain flat on large scales. Peebles's model became known as the Lambda–Cold Dark Matter model, or ΛCDM.[7] But, he says, "I was uneasy about the popularity of ΛCDM. What makes us think that the universe should look like the simplest model?"

Things unknown

Measurement by NASA's *Cosmic Background Explorer* (*COBE*), proposed in 1974 by Nobel laureates George Smoot and John Mather and launched in 1989, provided the measurements that showed that ΛCDM was on the right track. (See PHYSICS TODAY, December 2006, page 18.) *COBE* proved that the CMB had the expected thermal spectrum, corresponding to a temperature of 2.725 K, as shown in figure 2a. "I still remember the moment I first saw the spectrum measurement," says Peebles. The mission also provided the first map of anisotropies of CMB temperature, shown in figure 2b, which Peebles had predicted. "I was truly impressed," he says.

ΛCDM is also consistent with the 1998 discovery that the universe's expansion rate is accelerating (see PHYSICS TODAY, June 1998, page 17), and Λ is now synonymous with dark energy. Experiments since *COBE* have provided increasingly detailed maps of the CMB and have further constrained the content, age, and geometry of the universe, all consistent with predictions of ΛCDM. Understanding dark matter and dark energy has been a major focus of cosmology experiments since the turn of the 21st century. "Peebles brought a mathematical foundation to everything we do in cosmology," says Wendy Freedman of the University of Chicago, whose work focuses on measuring both the current and past expansion rates of the universe and on probing the nature of dark energy.

Peebles pins high expectations on explicit observations of dark matter, and he anticipates that measurements in the dark sector are a "Nobel Prize waiting." The *Wide-Field Infrared Survey Telescope*, for example, slated to launch in the mid 2020s, will measure how the distribution of galaxies has changed over time and provide another measure of how dark energy and dark matter have affected the cosmos. "They're looking for deviations from the simple picture. We give dark energy a label but it doesn't act like a physical force. It's just a number as far as we know," says Ostriker. And understanding why some galaxies deviate from the ΛCDM model is, according to Peebles, a rich field for future work. "I don't believe that a theory is ever final. We're still fishing around for something," he says.

Rachel Berkowitz

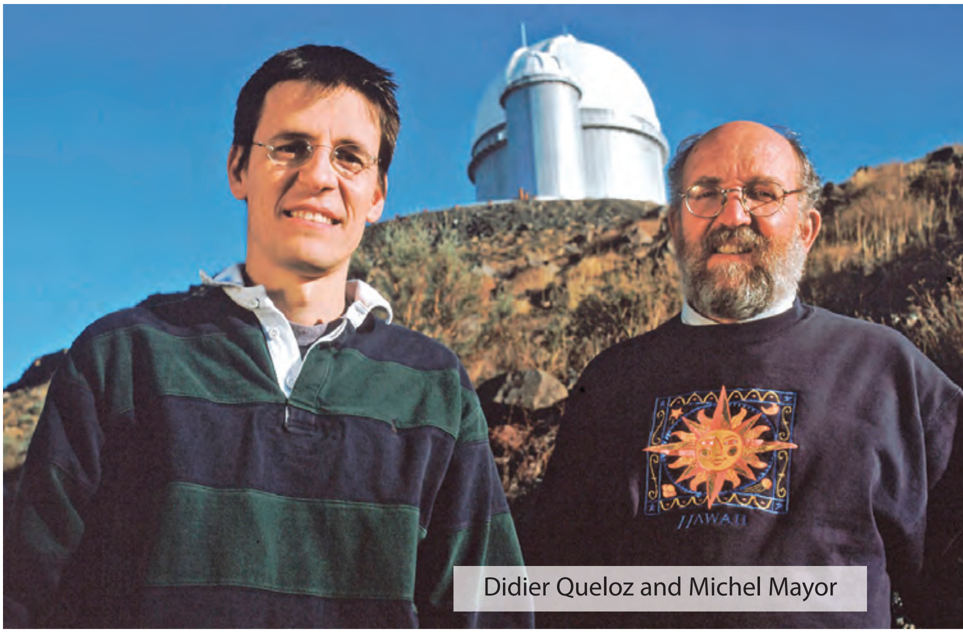
References

1. R. H. Dicke, P. J. Peebles, P. G. Roll, D. T. Wilkinson, *Astrophys. J.* **142**, 414 (1965).
2. P. J. E. Peebles, *Astrophys. J.* **142**, 1317 (1965).
3. P. J. E. Peebles, *Astrophys. J.* **153**, 1 (1968).
4. P. J. E. Peebles, J. T. Yu, *Astrophys. J.* **162**, 815 (1970).
5. J. P. Ostriker, P. J. E. Peebles, *Astrophys. J.* **186**, 467 (1973).
6. P. J. E. Peebles, *Astrophys. J.* **263**, L1 (1982).
7. P. J. E. Peebles, *Astrophys. J.* **284**, 439 (1984).

Half of Nobel Prize in Physics honors exoplanet trailblazers

By discovering an extrasolar planet orbiting a sunlike star, the laureates helped launch a field that explores a diverse set of worlds and their potential to host life.

EUROPEAN SOUTHERN OBSERVATORY



Didier Queloz and Michel Mayor

Today the number of known planets in the galaxy exceeds 4000. Extrapolating from that figure reveals that the Milky Way harbors more planets than it does stars.

Yet just a quarter century ago, the prospect of conducting such a galactic planet census seemed dim. Although planet-sized bodies had been detected around a neutron star,[1] those objects probably didn't form the way most planets do, and their dead host star is unlikely to foster an environment conducive to life. The only sunlike star known to host planets was the Sun.

It wasn't that astronomers didn't know how to go about looking for extrasolar worlds. By the 1980s a handful of researchers were trying to apply a 19th-century star-velocity measurement technique, known as the radial-velocity (RV) method or Doppler spectroscopy, to search for planet-sized companions.

Focusing on nearby bright stars, the astronomers inspected spectral lines for periodic redshifts and blueshifts stemming from an orbiting planet slightly tugging its host star about their mutual center of gravity. The magnitude of the back-and-forth wobble would depend on the masses of the planet and star, the planet–star distance, and the orientation of the orbital plane as viewed from Earth. Jupiter served as a template: An astute alien observer with a view of our solar system parallel to the ecliptic would notice shifts in the solar spectrum corresponding to a swing in velocity of up to 13 m/s. Although such a shift is detectable, traditionally RV had been used to measure velocities several orders of magnitude higher, such as in the study of binary-star orbits.

After multiple exoplanet discovery claims that proved unconvincing or flat-out wrong, everything changed on 6 October 1995. That's when Michel Mayor of the University of Geneva joined a panel at a conference in Florence, Italy, and announced that he and graduate student Didier Queloz had discovered 51 Pegasi b, a roughly Jupiter-mass object orbiting the nearby star 51 Pegasi.

Mayor and Queloz had found a Jupiter, but it wasn't the one anyone expected. Whereas Jupiter's orbital period is 12 years, 51 Pegasi b completes a revolution around its star every four days; the researchers pegged the planet's temperature at a sizzling 1300 K. It took several years for the astronomy community to fully embrace the discovery and the challenges it presents to theories of planetary formation. Yet the fact that such hot Jupiters exist, and that they were among the first extrasolar worlds discovered, has had a profound effect on the trajectory of exoplanet science.

Almost 24 years to the day of Mayor's announcement, the Royal Swedish Academy of Sciences awarded Mayor and Queloz a half share of the 2019 Nobel Prize in Physics. "An entire discipline has been built upon this discovery," says astrophysicist Natalie Batalha of the University of California, Santa Cruz.

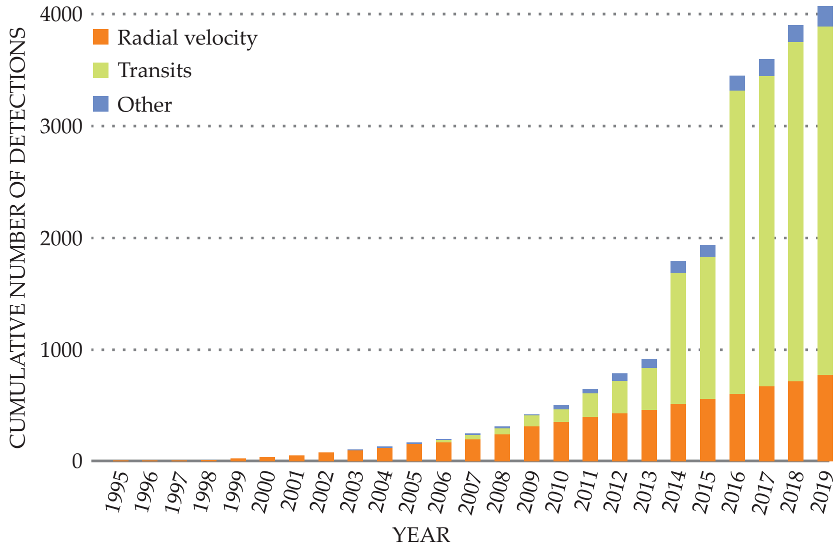


FIGURE 1. THE CUMULATIVE NUMBER OF EXOPLANET DISCOVERIES since 1995 has grown dramatically, particularly after the launch of the *Kepler* space telescope in 2009. (Adapted from the NASA Exoplanet Archive.)

Precision spectroscopy

Like many veteran exoplanet hunters, Mayor began as a stellar astrophysicist. In the 1970s he helped build CORAVEL, a spectrograph used for measuring the orbits of binary stars, tracking the motion of globular clusters, and various other studies. It also proved adept at spotting objects that were considerably less massive than the stars they orbited. In 1989 Mayor was part of a team that presented preliminary evidence[2] for an 11-Jupiter-mass body orbiting the nearby solar-type star HD 114762. The amplitude of the RV signal was about 600 m/s.

The following year Mayor tasked his new student Queloz with designing a spectrograph that could achieve an order of magnitude better precision than CORAVEL. Queloz started by revamping the optics. At the time, the best spectrographs were calibrated by shining light through a cell of hydrogen fluoride or iodine, which would superimpose a set of reference absorption lines onto the stellar spectrum. The approach worked well, but the intensity of the reference source often washed out the spectral features of all but the brightest stars.

Instead, Queloz installed a pair of optical fibers in the spectrograph. One was fed by the reference light of a thorium–argon lamp, the other by starlight. The spectrograph's separation from the lamp prevented the reference light from flooding the stellar signal, and its separation from the telescope allowed it to be housed in a carefully controlled environment. With that upgrade, plus the use of charge-coupled devices to precisely record the positions of dispersed photons, Mayor and Queloz were able to build a spectrograph with a precision of 13 m/s, right in the ballpark for detecting the RV signals from a Jupiter twin.

In 1994 Mayor and Queloz paired their spectrograph, called ELODIE, with a 1.93 m telescope at the Haute-Provence Observatory in southeast France and began a survey of 142 stars. One target was 51 Pegasi, located about 50 light-years away and in the same spectral class as the Sun. After making observations in September 1994 and January 1995, Queloz noticed an unmistakable periodic signal with an amplitude of nearly 60 m/s and a period of 4.2 days. Mayor was on sabbatical at the time, and the stars in the Pegasus constellation had dipped below the horizon, so Queloz obsessively analyzed the data he had, looking for any explanation aside from a planet. He couldn't find one.

Queloz presented his case on Mayor's return, and in July 1995 the two headed to the observatory to see if the tantalizing RV signal persisted. It did. "That's when we became convinced," Queloz says. They had strong evidence for a planet at least half the mass of Jupiter with an orbital radius of 0.05 astronomical units—an eighth of Mercury's average distance from the Sun.

Mayor and Queloz rushed to prepare a paper, which they submitted to *Nature* in August.[3] Soon after Mayor's announcement at the October conference, 51 Pegasi b was confirmed by San Francisco State University's Geoffrey Marcy and Paul Butler, Mayor and Queloz's main rivals.

Beyond stamp collecting

At first, theorists didn't think such a massive planet could form so close to a star or migrate inward without getting incinerated. In fact, astronomers still aren't sure how Jupiter-mass planets end up so near their host stars.[4] Despite the unresolved puzzle, the discovery of 51 Pegasi b opened the door to hundreds more exoplanet detections via the RV method. It also led to a crucial proof-of-principle for another planet-hunting approach.

In 1999 Harvard's David Charbonneau and his colleagues took photometric measurements of HD 209458, a star that Mayor and others had already flagged as harboring a hot Jupiter. Given the planet's large size and small period, there was a decent chance that its orbit would take it in front of its star as viewed from Earth. Sure enough, the geometry of the orbital plane was perfect: Every 3.5 days, HD 209458 b eclipsed its star, causing a brief dip in the measured stellar brightness. It was the first exoplanet identified via transit.[5]

The Charbonneau team's discovery, along with additional planet identifications via RV that had followed the detection of 51 Pegasi b, was a boon to a small group of NASA astronomers who had long proposed the construction of a space telescope that would detect planets via transit photometry. Despite having rejected the mission four previous times, NASA in 2001 approved *Kepler*, whose primary goal was to determine the abundance of Earth-sized planets in roughly yearlong orbits around sunlike stars. Launched eight years later, the telescope proceeded to transform our understanding of the galaxy's planetary population.

As expected, *Kepler*'s first discoveries were hot Jupiters like 51 Pegasi b. But smaller worlds soon emerged in the data. Some of those planets circled average-sized, middle-aged stars like the Sun; many others orbited red dwarfs, the universe's most common and long-lived stellar occupants (see the article by John Johnson, PHYSICS TODAY, March 2014, page 31). Using the fiber-fed HARPS spectrograph at La Silla Observatory in Chile, a team led by Mayor discovered a diverse set of worlds as well. Astronomers were able to pair some of the transit observations, which yield planets' diameters, with RV measurements, which yield their masses, to provide a glimpse at those worlds' bulk compositions.

After an initial phase in which researchers and the public fawned over each new discovery—Batalha, who worked on the *Kepler* team, calls it the era of stamp collecting—*Kepler* soon delivered enough detections to support robust statistical surveys (see PHYSICS TODAY, January 2014, page 10). As shown in figure 1, astronomers had identified a few hundred planets by the time *Kepler* launched; some 90% of those worlds were larger than Neptune. One decade and 3700 exoplanets later, about 90% of known planets are smaller than Neptune. The most common varieties spotted so far—rocky bodies larger than Earth and sub-Neptune-sized gas worlds—don't exist in our solar system.

FIGURE 2. THE *JAMES WEBB SPACE TELESCOPE*, shown fully assembled in August 2019, will analyze exoplanet atmospheres once it reaches orbit in 2021. (Photo by NASA/Chris Gunn.)

Just getting started

Now that astronomers have surveyed the exoplanet landscape, they want to zoom in on individual targets. Launched last year, the *Transiting Exoplanet Survey Satellite* is looking for planets around nearby bright stars that can be measured with enough precision to enable analysis of their atmospheres. Using large-aperture ground-based telescopes and next-generation observatories in space, astronomers can pick out starlight that has been absorbed or reflected by molecules in a transiting planet's atmosphere (see the Quick Study by Heather Knutson, PHYSICS TODAY, July 2013, page 64). The *James Webb Space Telescope*, shown in figure 2 and due for launch in 2021, will excel at separating out the spectral fingerprints of a planet's makeup.

For those pursuing exoplanet research, such studies are critical for entering the tantalizing era of searching for life (see PHYSICS TODAY, March 2019, page 24). Analyses of *Kepler* data suggest that the Milky Way hosts about 10 billion terrestrial planets potentially capable of supporting life as we know it, and astronomers want to closely examine as many as they can. Queloz hopes to take a step toward that goal with his Terra Hunting Experiment, a systematic search for Earth twins orbiting nearby stars. He plans to find those worlds via RV with a new spectrograph he helped design.

Andrew Grant

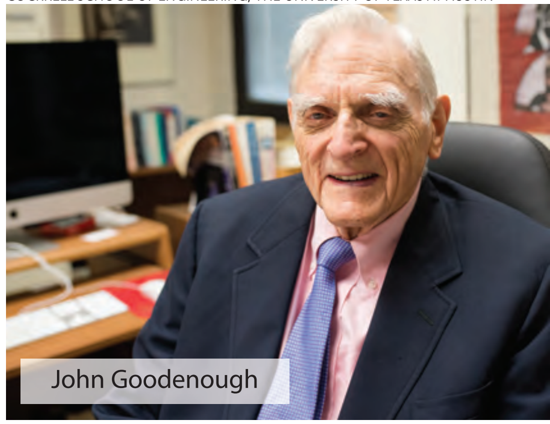
References

1. A. Wolszczan, D. A. Frail, *Nature* **355**, 145 (1992).
2. D. W. Latham et al., *Nature* **339**, 38 (1989).
3. M. Mayor, D. Queloz, *Nature* **378**, 355 (1995).
4. R. I. Dawson, J. A. Johnson, *Annu. Rev. Astron. Astroph.* **56**, 175 (2018).
5. D. Charbonneau et al., *Astrophys. J.* **529**, L45 (2000).

Lithium-ion battery pioneers awarded chemistry Nobel

The batteries have already powered one revolution in wireless consumer electronics. Now they're launching a new one in transportation.

COCKRELL SCHOOL OF ENGINEERING, THE UNIVERSITY OF TEXAS AT AUSTIN



John Goodenough

BINGHAMTON UNIVERSITY/JONATHAN COHEN

Stanley Whittingham

ASAHI KASEI

Akira Yoshino

Electric cars, at long last, are having their day. Cumulative global sales of all-electric and plug-in hybrid vehicles reached 1 million in September 2015, hit 5 million in December 2018, and could near 8 million by the end of this year. Essentially all such vehicles are powered by lithium-ion batteries—as are innumerable laptops and phones, medical devices, power tools, electric bikes, scooters, and more.

The lithium-ion battery's extraordinary rise is a result of a half century of research in solid-state physics, electrochemistry, materials science, and engineering.[1] (Political, economic, and social forces were also involved; for more on that side of the story, see the article by Matthew Eisler, PHYSICS TODAY, September 2016, page 30.) Of all the researchers who worked on battery development over the years, the Royal Swedish Academy of Sciences has chosen three for this year's Nobel Prize in Chemistry: John Goodenough of the University of Texas at Austin, Stanley Whittingham of Binghamton University in New York, and Akira Yoshino of the Asahi Kasei Corp in Tokyo.

During the 1970s and 1980s, the three laureates contributed landmark developments that led to the first commercial lithium-ion battery in 1991. And now the fruits of their labor are changing the world.

Ions at work

The basic structure of all batteries, depicted in figure 1, hasn't changed since 1799, when Alessandro Volta introduced his voltaic pile. (See the article by Héctor Abruña, Yasuyuki Kiya, and Jay Henderson, PHYSICS TODAY, December 2008, page 43.) Electrons flow through an external circuit from a high-energy state in the anode to a lower-energy state in the cathode. To maintain charge neutrality, a so-called working ion flows between the electrodes through an electrolyte inside the battery.

Traditionally, no matter what materials were used for the anode and cathode, the electrolyte was always a watery solution, and the working ion was always hydrogen. A water-based battery, however, can't have more than a 2.0 V potential difference between its anode and cathode without the water molecules being ripped apart. Higher-voltage, more-energy-dense batteries would require a sturdier electrolyte—and, because water is the only known liquid that conducts protons, a new working ion.

Lithium has some advantages that make it an appealing alternative, but its supremacy was not inevitable. (See the article by William Walsh, PHYSICS TODAY, June 1980, page 34.) It's the third lightest of all the elements, but a battery's weight doesn't necessarily depend much on the mass of its working ion. As an alkali metal—a member of the first column of the periodic table—it readily gives up its outermost electron, so a lithium-based anode is a good source of high-energy electrons. But other alkali metals, such as sodium and potassium, are almost as good.

In the 1950s William Harris and his PhD supervisor Charles Tobias showed that several organic solvents could dissolve alkali-metal salts and conduct their constituent ions. The final basic ingredient, then, was a cathode material. An ideal cathode would store both the alkali-metal ion and its electron—but without putting them back together, which would necessitate placing the electron back in its high-energy state.

Transition-metal compounds fit the bill. Unlike elements from the periodic table's outer edges, which strongly prefer to shed or pick up electrons until their outermost electron shells are full, transition metals, from the middle swath of the table, gain and lose electrons from their *d* orbitals, which don't so much mind being partially filled, so they can pick up an extra electron with little energy penalty.

Furthermore, some transition-metal compounds were known to accommodate, or intercalate, alkali metals or other ions in varying amounts without changing their structure. In some cases, the compounds are composed of layers held together by van der Waals forces (see the article by Pulickel Ajayan, Philip Kim, and Kaustav Banerjee, PHYSICS TODAY, September 2016, page 38) and store the guest ions between the layers; in others the guests are accommodated in voids in a three-dimensional lattice.

At first, intercalation compounds were of interest primarily for their electronic and magnetic properties.[2] For example, if a transition-metal compound superconducts at low temperature, intercalating a guest ion could raise its critical temperature. But in the early 1970s, Whittingham, then a postdoc at Stanford University, and colleagues noticed that when they intercalated potassium into tantalum disulfide, energy was released. Says Whittingham, "And we thought, hey, we can make a battery out of this."

Putting the pieces together

Whittingham continued his work at Exxon, where he and several of his Stanford colleagues moved to in 1972. A TaS_2-based battery, he reasoned, was never going to be practical—tantalum was too heavy and too expensive—so he switched to titanium disulfide. Not only was TiS_2 the lightest and cheapest of all the layered transition-metal compounds, it was electrically conductive, and it maintained the same structure for the full range of lithium intercalation compositions, all the way up to $LiTiS_2$. "We started with a test tube experiment, then invested in some more serious equipment," recalls Whittingham, and within a year he had a patent filed.

But there was a problem. Although the TiS_2 cathode could take up and release lithium ions reversibly, the anode—made of pure lithium metal—was another matter. As the battery was recharged and lithium ions rejoined the anode, they didn't form smooth layers, but rather pointed, whisker-like dendrites. If the dendrites bridged the electrolyte and reached the cathode, the battery would short-circuit.

One potential solution was to replace the lithium metal with a different anode material—Whittingham considered a lithium–aluminum alloy—that would make it energetically favorable for the lithium ions to seep back into the electrode bulk instead of forming dendrites on the surface. Any such material, however, would store lithium atoms at a lower energy than lithium metal itself, so it would reduce the battery voltage. The TiS_2 battery voltage, at 2.2 V, was modest to begin with.[3] Any reduction would wipe out most of its advantage over water-based batteries.

That voltage was a function of the energies of titanium's 3*d* orbitals and sulfur's 3*p* orbitals, which hybridize to create the bands that receive electrons from the circuit. Goodenough's contribution was to identify a cathode material that could receive electrons at a lower energy, so the battery could operate at a higher voltage and thus accommodate a safer anode. He switched from sulfides to oxides—oxygen's 2*p* orbitals are more tightly bound than sulfur's 3*p* orbitals—and from titanium to transition metals with slightly higher nuclear charge and thus lower-energy 3*d* orbitals.

At Oxford University in 1980, he and his group landed on lithium cobalt oxide, whose structure is depicted in figure 2a. Notably, it's not cobalt oxide; that doesn't exist, at least not in the layered structure Goodenough was seeking. The material could be synthesized only in its lithiated form, $LiCoO_2$. The battery, therefore, had to be assembled in its discharged state, and it could never be fully charged: Extracting too much of the cathode's lithium would make the structure unstable, liberate oxygen gas, and risk igniting the flammable organic electrolyte. But its voltage—nearly 4 V with a lithium metal anode—was a milestone.[4]

Goodenough and colleagues were still using lithium metal for their anode, which still formed dangerous dendrites when recharged. But by the early 1980s, several groups were exploring the possibility of a graphite anode. Like the layered transition-metal materials, graphite

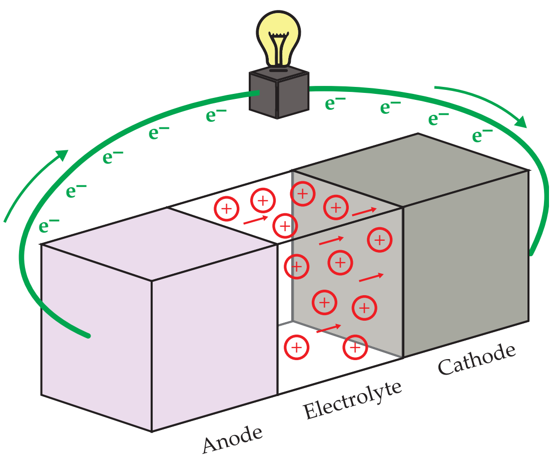


FIGURE 1. THE STRUCTURE OF A BATTERY, shown here being discharged. When the battery is recharged, the electron and working-ion flows are both reversed.

was known to form intercalation compounds with a variety of guest species (see the articles by John Fischer and Thomas Thompson, PHYSICS TODAY, July 1978, page 36, and by Hiroshi Kamimura, PHYSICS TODAY, December 1987, page 64), including lithium, as shown in figure 2b. A graphite anode has an electrochemical potential of just 0.2 V less than a lithium-metal one. But the intercalation worked a little too well: Graphite took not just lithium ions into its interlayer spaces, but also electrolyte molecules, which seemed to unavoidably damage the electrode and the electrolyte.

At the same time, Yoshino was experimenting with polyacetylene, an electrically conductive polymer that would secure its inventors the Chemistry Nobel in 2000 (see PHYSICS TODAY, December 2000, page 19). "I thought it could be a good anode material," he says, "but my biggest problem was finding a cathode material to pair with it." Most cathode materials, such as TiS_2, contained no lithium, and neither did polyacetylene. But a lithium-based battery needed to get its lithium from somewhere. "At the end of 1982, I was cleaning up my lab when I found Dr. Goodenough's paper on $LiCoO_2$," Yoshino recalls, "and immediately, I knew it was just the kind of cathode material I had been searching for."

Polyacetylene turned out to have poor chemical stability, so Yoshino eventually switched to an anode of petroleum coke, a partially disordered form of carbon. Petroleum coke stores only half as much lithium per unit weight as graphite, but it solved the problem of electrolyte intercalation. After testing the safety of his prototype battery, he transferred the technology to Sony, which introduced the name "lithium-ion battery" to highlight the fact that it contained no dangerous metallic lithium.

To market

The new batteries hit the shelves in 1991. At first, Sony used them only in handheld video cameras. "That market still exists, but it is only 0.2% of the total market for lithium-ion batteries today," says Yoshino.

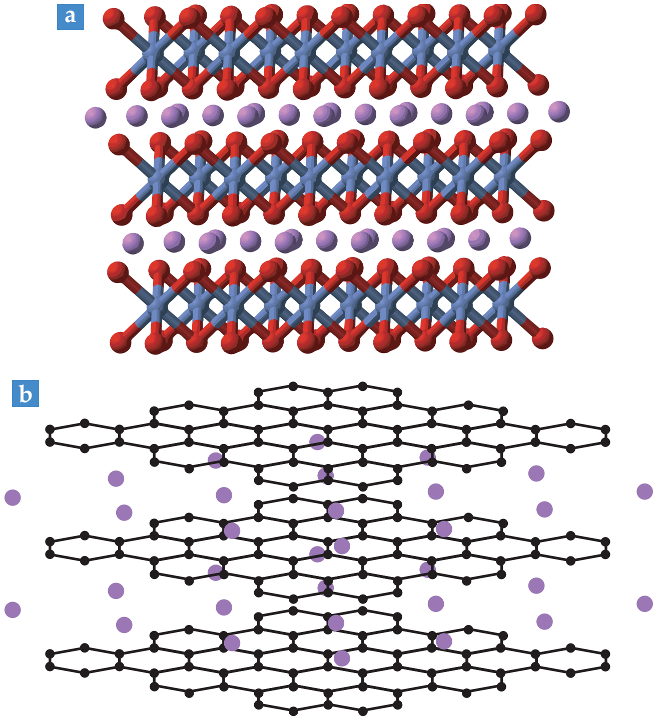


FIGURE 2. LAYERED INTERCALATION COMPOUNDS for storing lithium ions (purple). **(a)** Lithium cobalt oxide, often used as a cathode material, stores lithium between layers made of cobalt (blue) and oxygen (red). **(b)** Lithiated graphite, LiC_6, is a common anode material. (Panel a by Ben Mills, PD-US; panel b adapted from V. Petkov et al., *J. Phys: Condens. Matter* **23**, 435003, 2011.)

"That means that the market is 500 times larger than I thought it would be."

With a few exceptions, lithium-ion batteries today still use something like Yoshino's recipe with ingredients inspired by Whittingham and Goodenough: a carbonaceous anode, a transition-metal-oxide cathode, and an organic liquid or polymer electrolyte. Nowadays, most anodes are made from graphite—the electrolyte intercalation problem, it turns out, could be solved by using a different electrolyte—rather than petroleum coke, and manufacturers can choose from a range of transition-metal cathode compounds. But most importantly, the industry now has the benefit of 28 years' worth of manufacturing know-how. And that counts for a lot.

There's more to making a battery, after all, than simply choosing the right materials. For example, a manufacturer must consider how to arrange the components to maximize their surface area, what size the particles of electrode material should be to enable the lithium ions to get in and out, and how to optimize manufacturing processes to reduce waste. Thanks to steady improvements in all those areas and more, batteries today store almost three times as much energy per unit weight as they did in the 1990s. And the price has come down even more dramatically. According to an analysis by Bloomberg New Energy Finance,[5] the average cost of a one-kilowatt-hour lithium-ion battery pack has dropped by 85%, from \$1160 to \$176, just since 2010.

In consumer electronics, those improvements may be easy to overlook. "The first mobile phones had small monochrome screens," says M. Rosa Palacín of the Institute of Materials Science of Barcelona, "and now we have large screens and are always connected, so even if batteries are performing much better, we don't realize it." And the batteries are small enough—7 to 10 watt-hours for a phone, 40–70 Wh for a laptop—that they're not a major driver of the device cost.

Electric vehicles are another story. To achieve a driving range in the hundreds of kilometers, an electric car needs a battery capacity of 10s to 100 kWh. Until just a few years ago, the battery cost alone was enough to confine electric vehicles to a luxury niche market. But as prices fall, the situation is rapidly changing, and electric cars are growing in mass appeal.

There's still a long way to go. Worldwide, electric vehicles make up just half a percent of passenger cars on the road and a modest 2% of vehicle sales. (The numbers for the US are similar to the global average.) But with some help, they can claim a much larger market share. In Norway, far and away the world's electric-vehicle leader, more than 10% of all cars and half of all car sales are electric, due in large part to substantial taxes on conventional vehicles and perks for electric ones, including free parking and access to bus lanes.

Perhaps surprisingly, lithium-ion batteries are also gaining appeal for grid-scale storage of electric power. Even though they've been optimized for their small size and light weight—factors that matter little for a stationary power-storage facility—they're still the cheapest of all batteries for that purpose.[6] "The technology has gotten so good, and so inexpensive," explains Gerbrand Ceder of the University of California, Berkeley, "that it's the best option even though on paper it might not look that way."

The electrical grid needs storage capacity for many reasons, and smoothing the fluctuations of renewable energy—delivering power even when the wind isn't blowing or the Sun isn't shining—is only one of them. The US currently gets less than 10% of its electricity from wind and solar power, and their variability, for now, is easily absorbed by the rest of the grid. But grid storage is still important for balancing supply and demand from instant to instant, or for satisfying times of peak consumption without building more power plants.

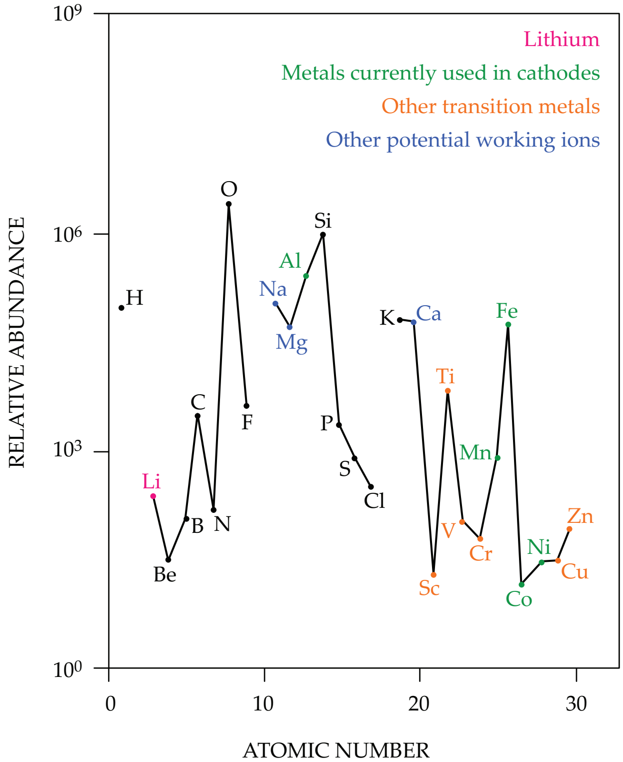


FIGURE 3. ELEMENTAL ABUNDANCES in Earth's crust; highlighted in color are elements relevant to lithium-ion battery technology and post-lithium battery research. None of the elements shown here are terribly rare—for comparison, gold and platinum have abundances of less than 10^{-3} in these units. (Adapted from USGS Fact Sheet 087-02.)

The vast majority of grid storage in the US is currently pumped-storage hydroelectricity: pumping water uphill and letting it flow back down. But lithium-ion-battery storage is already cheaper for applications requiring a quick burst of power over a short time. "I recently visited a grid storage facility near Saratoga Springs," says Whittingham, "and there were lithium ions going back and forth on a scale we couldn't have dreamed of even 10 or 15 years ago."

Limitations

Lithium-ion batteries are still getting smaller and cheaper, but those trends can't continue forever without some dramatic technological change. To store one electron's worth of charge—or about 4 eV of energy—a battery with today's technology needs one lithium atom, one transition-metal atom, two oxygen atoms, and six carbon atoms. That adds up to almost 2 kg of material per kWh of energy, even discounting the mass of the electrolyte, any unusable electrode capacity, and other material components. For comparison, the best lithium-ion batteries today weigh about 4 kg per kWh.

Materials availability is also a concern. More than a billion cars travel the world's roads; converting all of them to electric vehicles with 50 kWh batteries and $LiCoO_2$ cathodes would take 60 million tons of cobalt. Current world cobalt reserves amount to only 7 million tons. "And by the way, you can't have all of it," notes Ceder; in addition to batteries, cobalt is used in many other applications, including pigments, high-performance alloys, and industrial catalysts.

Cobalt's scarcity equates to a relatively high price. And because cobalt is usually mined as a by-product of other metals such as copper and nickel, that price is vulnerable to rapid fluctuations as industry struggles to match the supply to the demand. Between 2016 and 2019, the price of a kilogram of cobalt shot from \$30 to \$90 and back to \$30—a swing that can make a difference of thousands of dollars in the price of a vehicle-sized battery.

Furthermore, half of all cobalt reserves are in the Democratic Republic of the Congo, one of the poorest countries in Africa and in the world. Most of the cobalt mining is overseen by foreign corporations, but a significant minority is "artisanal," meaning that individuals—sometimes children—are digging with hand tools and no safety equipment for very little money.

For all those reasons, the electric-vehicle industry (but not the consumer electronics industry) has largely switched to cathode materials with less or no cobalt.[7] Some of the best performing alternatives are mixed metal oxides that combine nickel, cobalt, and either manganese or aluminum. Nickel is only a little less scarce than cobalt, as shown in figure 3, but at least its reserves are geographically less concentrated. Lithium manganese oxide and lithium iron phosphate are serviceable options made from cheap and abundant materials, but their energy densities pale in comparison with their costlier cousins.

Lithium itself is widespread in Earth's crust, but it can be economically extracted from only a few locations, such as the salt flats in and around the Atacama Desert in South America. The world's lithium reserves can meet the battery industry's needs for the foreseeable future—but to continue to meet them for generations to come, battery recycling will become increasingly important.

The future

In their pursuit of a smaller, cheaper, safer, and more sustainable battery, researchers are exploring several ideas. (See PHYSICS TODAY, June 2013, page 26.) One possibility is to replace the liquid or polymer electrolyte with an inorganic solid to create an all-solid-state battery. Removing the flammable organic material would all but eliminate the risk of fire. And it would offer a path to safely bringing back the lithium metal anode—dendrites can't pierce so substantial a solid barrier—and thereby give a huge boost to the battery energy density.

Ceramic materials that can conduct ions have been known for decades (see the article by John Bates, Jia-Chao Wang, and Nancy Dudney, PHYSICS TODAY, July 1982, page 46). But only recently have their conductivities begun to rival those of liquids, and it's still a challenge to stabilize the interfaces between a solid electrolyte and solid electrodes that are constantly growing and shrinking.[8] "This is the new kid on the block trying to beat the existing electrolyte," says Yang Shao-Horn of MIT, "and we need to discover the design principles" to explore the possible materials more efficiently than by trial and error. "There is a very small solid-state battery on the market now," notes Yoshino, "but can it be made into a large format suitable for electric vehicles? That still requires a breakthrough in production technology. I think it should be possible, but it will take time."

Another research direction has explored replacing lithium with a cheaper, more abundant working ion, such as sodium, magnesium, or calcium.[9] Sodium is chemically similar to lithium, so many (but not all) of the materials and processes developed for lithium-ion batteries can be adapted for sodium-ion batteries. Calcium and magnesium, on the other hand, would require a whole new set of materials. They're appealing, though, because their ions are doubly charged, so a battery could supply twice as much current for a given number of working ions.

Lithium-ion batteries aren't going away anytime soon. "Even if I came up with a great new battery tomorrow," says Marca Doeff of Lawrence Berkeley National Laboratory, "it would take 10 or 15 years of work to get to where lithium-ion batteries are now. And the goalposts keep moving." But as Shirley Meng of the University of California, San Diego, notes, that's all the more reason for urgency. "Now is the time to worry about resource availability," she says. "If we want to use batteries to store clean energy and combat climate change, we don't have a lot of time."

Johanna Miller

References

1. M. S. Whittingham, *Chem. Rev.* **104**, 4271 (2004); J. B. Goodenough, *Acc. Chem. Res.* **46**, 1053 (2013); A. Yoshino, *Angew. Chem. Int. Ed.* **51**, 5798 (2012); M. Winter, B. Barnett, K. Xu, *Chem. Rev.* **118**, 11433 (2018).
2. See, for example, J. B. Goodenough et al., *J. Appl. Phys.* **29**, 382 (1958).
3. M. S. Whittingham, *Science* **192**, 1126 (1976).
4. K. Mizushima et al., *Mater. Res. Bull.* **15**, 783 (1980).
5. BloombergNEF, *Electric Vehicle Outlook 2019* (2019), figure: "Volume weighted average lithium-ion pack price."
6. K. Mongird et al., *Energy Storage Technology and Cost Characterization Report*, PNNL-28866, Pacific Northwest National Laboratory (July 2019).
7. R. Schmuch et al., *Nat. Ener.* **3**, 267 (2018).
8. T. Famprikis et al., *Nat. Mater.* (2019), doi:10.1038/s41563-019-0431-3.
9. A. Ponrouch, M. R. Palacín, *Phil. Trans. R. Soc. A* **377**, 20180297 (2019).

Magnetic semimetals host massless quasiparticles

Two materials have an unusual electronic band structure that can support fast, low-dissipation electronic transport.

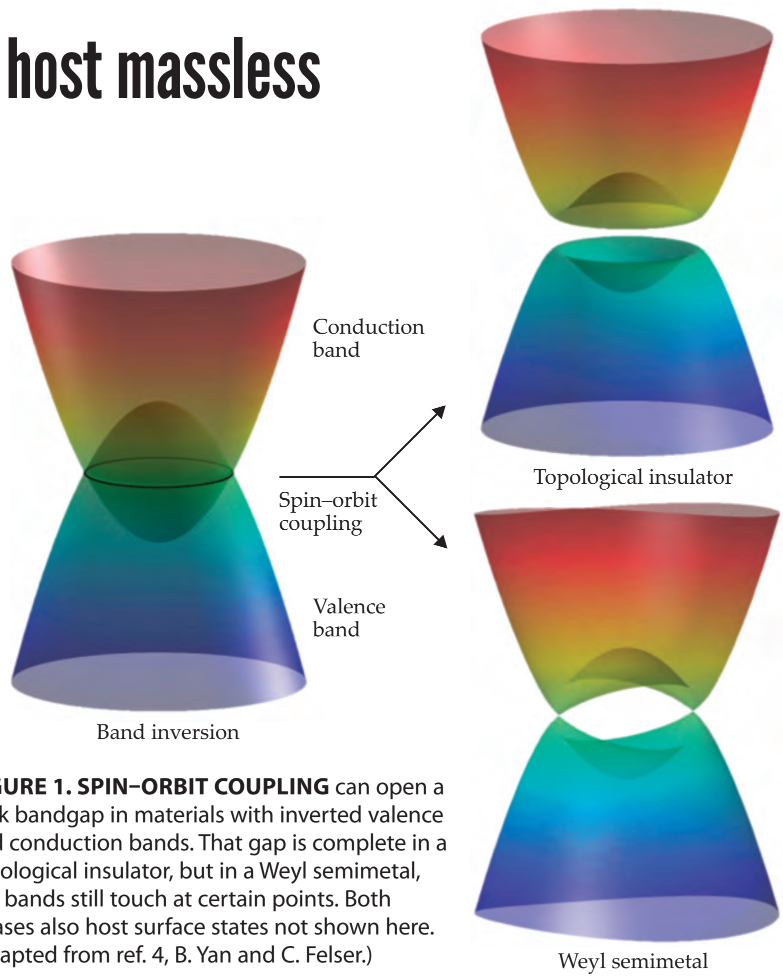


FIGURE 1. SPIN–ORBIT COUPLING can open a bulk bandgap in materials with inverted valence and conduction bands. That gap is complete in a topological insulator, but in a Weyl semimetal, the bands still touch at certain points. Both phases also host surface states not shown here. (Adapted from ref. 4, B. Yan and C. Felser.)

When Paul Dirac introduced his famous equation for relativistic fermions in 1928, he aimed to describe one well-known particle: the electron. Shortly thereafter, Hermann Weyl observed that the equation has a special solution when the mass is set to zero. The so-called Weyl fermions embodied by that solution would be charged, like electrons, but being massless, they would travel faster and with less energy dissipation. The particles would also be chiral, like neutrinos, with each one's handedness depending on whether its spin is aligned or antialigned with its momentum. Those features make Weyl fermions appealing candidates for use in electronic and spintronic devices.

No such elementary particle has yet been found. However, in 2015 three groups of researchers identified the first Weyl semimetal (WSM), tantalum arsenide, which hosts quasiparticles—collective excitations of electrons—with the properties of Weyl fermions.[1] A WSM must have a broken symmetry, and in TaAs, it's inversion symmetry. Researchers, however, have continued searching for materials, particularly ferromagnetic materials, that instead rely

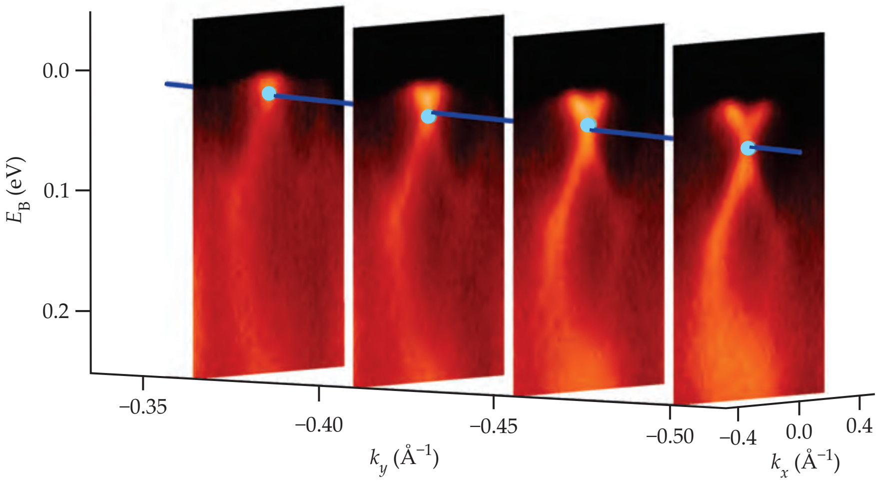


FIGURE 2. A NODE LINE APPEARS in angle-resolved photoemission spectroscopy measurements of Co_2MnGa. Slices of data showing binding energy E_B as a function of the momentum component k_x display linear bands and their points of intersection (light blue), key components of a Weyl semimetal's band structure. The features persist for a range of momenta k_y, so the points form a nodal line (blue). (Adapted from ref. 3.)

on broken time-reversal symmetry. Tying a WSM crystal's properties to magnetism, which can be adjusted using temperature changes or external fields, makes them potentially tunable.

Three new papers provide experimental evidence for magnetic WSMs. Yulin Chen's team at Oxford University and Haim Beidenkopf's team at the Weizmann Institute of Science, together with collaborators,[2] presented studies of $Co_3Sn_2S_2$, and Zahid Hasan's group at Princeton University[3] looked at Co_2MnGa. The works identify important features in the electronic structures of both materials' bulk and surface states.

Electronic underpinnings

The secret to a WSM's behavior is in its band structure, which has similar origins to that of a topological insulator.[4] In both cases, interactions cause the conduction and valence bands to invert near the Fermi surface. Spin–orbit coupling then opens a gap between them, as illustrated in figure 1. In topological insulators, it opens a bandgap throughout the bulk. (See PHYSICS TODAY, April 2009, page 12.) But in a WSM, the valence and conduction bands still touch at a set of points.

A WSM's band structure is similar to a three-dimensional version of graphene. In both materials the dispersion relation is linear around the bands' contact points, so low-energy electron excitations travel at a constant speed set by the dispersion relation's slope. Having a constant speed that doesn't depend on energy makes the excitations effectively massless. But that doesn't mean they travel at the speed of light—they are still about two orders of magnitude slower than photons.

In graphene, the points at which the valence and conductance bands meet are degenerate because the system is invariant under both inversion and time-reversal symmetry (see the article by Andre Geim and Allan MacDonald, PHYSICS TODAY, August 2007, page 35). Known as Dirac points, they describe excitations of both chiralities, so the momentum and spin can be either parallel or antiparallel. But in a WSM, the presence of a broken symmetry lifts that degeneracy and splits the Dirac points into pairs of Weyl nodes with opposite chirality.

A WSM that breaks inversion symmetry but preserves time-reversal symmetry must have at least four Weyl nodes because time reversal flips the signs for both momentum **k** and spin **s**. If (**k**,**s**) describes a Weyl node, then under time reversal, so does (−**k**,−**s**). But those have the same chirality, so (**k**,−**s**) and (−**k**,**s**) with opposite chirality must also be included to maintain zero net chirality. If, instead, inversion symmetry is preserved and time-reversal symmetry is broken, there can be just two Weyl nodes. Inversion symmetry changes only the sign of the momentum, so the inversion-symmetric points (**k**,**s**) and (−**k**,**s**) already have opposite chirality. Therefore, to produce

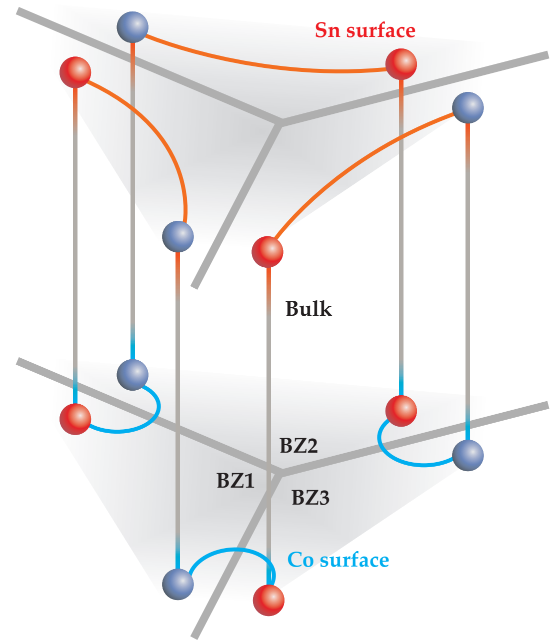


FIGURE 3. THE SURFACE TERMINATION of the Weyl semimetal $Co_3Sn_2S_2$ determines the connectivity of the Weyl points (blue and red dots) by surface Fermi arcs (blue and red lines). A crystal cleaved to reveal a tin surface (top) has pairs of Weyl points that are connected within the same Brillouin zone (BZ), whereas if it has a cobalt surface (bottom), the Weyl points are connected between adjacent Brillouin zones. (Adapted from ref. 2, N. Morali et al.)

the simplest WSM with only two Weyl nodes—which would be ideal for studying the underlying physics—the material must break time-reversal symmetry.

Weyl nodes in crystal momentum space behave like magnetic monopoles in real space. If an electron made a closed loop around a magnetic monopole, its wavefunction would acquire a nonzero phase. A Weyl node does the same thing. Like a vector sliding along the surface of a mobius strip, the wavefunction's failure to regain its initial state reflects the nontrivial curvature and topology of the underlying space. (See the article by Joseph Avron, Daniel Osadchy, and Ruedi Seiler, PHYSICS TODAY, August 2003, page 38.) Weyl nodes serve as sources and sinks of so-called Berry curvature, and they are associated with nonzero values of a topological invariant known as the Chern number. The topological nature of the Weyl points makes them appealing for electronic applications because it protects the surface states. Perturbations don't change the underlying topology, so the states aren't destroyed by moderate deformations or impurities.

Another hallmark of a WSM is the appearance of spin-polarized surface states. In momentum space, the states appear as lines, known as surface Fermi arcs (SFAs), that connect surface projections of pairs of Weyl points with opposite chirality. The SFAs are confined to the surface of the material by the topology of the band structure.

Hunting for quasiparticles

The researchers suspected that the materials they were investigating could be WSMs because they belong to a long list of candidates suggested by previous numerical and experimental studies. Clinching the case entailed looking for telltale features in the materials' band structures—Weyl nodes with linear dispersions and SFAs. To find bulk Weyl points, the groups led by Hasan and Chen turned to angle-resolved photoemission spectroscopy (ARPES). The technique, which both groups used to identify the WSM TaAs in 2015, involves bombarding the materials with x rays of various energies and measuring the energies and momenta of the ejected photoelectrons at different escape angles. The end product is a map of the distribution of electron binding energies in reciprocal, or momentum, space. In both materials, the ARPES data uncovered linear bands meeting near the Fermi energy. In $Co_3Sn_2S_2$, they meet at six individual points; because of a degeneracy in Co_2MnGa, they instead form a nodal line, as shown in figure 2.

Although ARPES is a surface technique, the photons penetrate deeply enough that bulk electron states predominate. Nevertheless, both groups clearly saw surface states connecting the Weyl points. In $Co_3Sn_2S_2$, the states appeared as lines connecting Weyl nodes, and in Co_2MnGa, as a drumhead-like plane bounded by a nodal line. Because surface states are restricted to a two-dimensional boundary in real space, they should also manifest as 2D features in momentum space. Indeed, both groups confirmed that the states remained unchanged when the momentum varied in the normal direction.

A large Berry curvature has been linked to a particularly large anomalous Hall effect,[5] so Hasan's team turned to that behavior to confirm the topological nature of the surface states in Co_2MnGa. After measuring a conductivity of 1530 ohm^{-1} cm^{-1}, similar to what had previously been seen in $Co_3Sn_2S_2$, the researchers compared their data with a known scaling relation to pin down the source of the effect. The data's functional form and a model's quantitative fit parameters pointed to a large Berry curvature, rather than electron-scattering processes, as the source of the enhanced anomalous Hall effect.

Instead of looking for the Weyl points, Beidenkopf and coworkers focused solely on the surface states. They used scanning tunneling spectroscopy, in which a voltage is applied between a metal tip and the surface of interest to map the electron density across the surface. Although the technique can't look beyond the surface at the bulk Weyl nodes, its high resolution helped the researchers uncover how the nodes' connectivity depends on which atoms are at the surface.

A $Co_3Sn_2S_2$ crystal can be cleaved to reveal three chemically distinct faces, and each face led to different surface states. With the tin termination, SFAs connected Weyl points within the same Brillouin zone (see figure 3). However, with cobalt termination, the SFAs connected pairs of points in adjacent Brillouin zones. For the sulfer-terminated surface, the researchers could not infer the SFA connectivity because the surface potential caused the states to overlap with other metallic bands. The unique band structure of each of the surfaces provides a knob for tuning the material's electronic properties.

There's still more to learn about WSMs that break time-reversal symmetry. "Their topological classification is directly affected by their magnetic ground state," says Beidenkopf. "Therefore, their magnetic phase diagram gives rise to a rich topological phase diagram that can now be explored." For practical applications, Co_2MnGa may have an edge: It's ferromagnetic at room temperature, with a Curie temperature of 690 K, whereas $Co_3Sn_2S_2$ is ferromagnetic only below 175 K. If WSMs find applications in future electronic and spintronic technologies, that difference will likely make Co_2MnGa the more desirable candidate.

Christine Middleton

References

1. S.-Y. Xu et al., *Science* **349**, 613 (2015); B. Q. Lv et al., *Nat. Phys.* **11**, 724 (2015); L. X. Yang et al., *Nat. Phys.* **11**, 728 (2015).
2. D. F. Liu et al., *Science* **365**, 1282 (2019); N. Morali et al., *Science* **365**, 1286 (2019).
3. I. Belopolski et al., *Science* **365**, 1278 (2019).
4. M. Z. Hasan et al., *Annu. Rev. Condens. Matter Phys.* **8**, 289 (2017); B. Yan, C. Felser, *Annu. Rev. Condens. Matter Phys.* **8**, 337 (2017).
5. Q. Xu et al., *Phys. Rev. B* **97**, 235416 (2018); E. Liu et al., *Nat. Phys.* **14**, 1125 (2018). PT

Should carbon emissions be taxed or capped and traded?

In the fight against climate change, many nations and states have put systems in place to price carbon dioxide emissions. There is no consensus on which of two mechanisms is better.

In October, media outlets trumpeted the headline conclusion of an analysis from the International Monetary Fund (IMF): A global tax of $75 per ton of carbon dioxide emissions from fossil fuels could put the world on track to limit future temperature increases to 2 °C above preindustrial levels. Unfortunately, experts say, it's not that simple.

The IMF report said that the production of oil, gas, and coal should each be assessed a fee based on the CO_2 content. The tax should be imposed immediately and rise to $75 per ton by 2030. It estimated that the tax would cause gasoline prices to rise by an average of 15% and electricity charges by 45%. The revenues generated could be rebated to consumers or used for other purposes, such as providing assistance to low-income households or reducing budget deficits.

Economists of all stripes agree that imposing a price on CO_2 emissions is the single most efficient way to prod the world into the urgent decarbonization required to prevent the worst effects of climate change. But even if a globally observed and uniform tax on CO_2 was feasible, it would not be enough to ensure that the technologies needed to supplant fossil fuels would be developed and implemented in the time frame required to prevent the worst effects of climate change.

"The view of economists is that carbon pricing is necessary but not sufficient," says Robert Stavins, professor of energy and economics at Harvard University's Belfer Center for Science and International Affairs. "There are other market failures that affect technological change. Even the right price signals won't bring about what economists would consider to be the efficient amount of R&D activity."

Companies that perform early stage R&D don't get all the benefits from the technologies they develop. Competitors reap some of the spillover benefits from those investments, Stavins says; he points to how Apple's research for the iPhone was copied by others. Companies don't typically have incentives to carry out the right amount of R&D because of the spillover. "That's an important factor in the climate change context because of the huge amount of the technology, invention, and innovation that will be required," he says.

Some additional policies targeting technological change will be required to go along with a carbon price, but "unfortunately, it's easier to say that than to say what those policies would be," says Stavins. "It might be government funding of private-sector research, or funding of research at Department of Energy labs." Clean-energy standards alone won't incentivize R&D, but will stimulate diffusion of existing clean-energy technologies, he adds.

Erica Morehouse, senior attorney with the Environmental Defense Fund, agrees that market barriers prevent the level of investment in R&D and innovation that would achieve a zero-carbon economy. That's a problem for mitigation technologies still in their infancy, such as direct air capture of CO_2 and long-term energy storage. "There is an important role for government to play in directly investing in those innovation-spurring technologies," she says.

As for what the required carbon price should be, those interviewed for this article demurred. "The IMF is correct that what's in place now is definitely insufficient, but in terms of how much is being covered by a price and what the prices are, I wouldn't hang my hat on $50, $75, or $100 as being right," says Kevin Kennedy of the World Resources Institute.

Questions of international equity would complicate adoption of a uniform international carbon price, given the wide disparity of wealth and development among nations. "You're not going to be able to wave a wand and say there is a global carbon price," says Nathan Hultman, director of the Center for Global Sustainability at the University of Maryland. "If you suggest to people from different countries that everyone gets the same carbon price, you will get a lot of conversation about that, to put it diplomatically." In other words, there would have to be some degree of differentiated responsibility in any global carbon-pricing arrangement.

A single world price would be most efficient to incentivize polluters to cut emissions where it is cheapest, the IMF says. But equity might be achieved by charging a higher tax to developed

TENS OF THOUSANDS OF DEMONSTRATORS marched through central Paris in October 2018 to demand stronger actions to address climate change. The government's proposed increase in France's fuel tax, including a hike to the carbon tax, touched off the yellow vest protests the following month.

economies or by providing financial or technological assistance to less developed countries in exchange for their adherence to the global price.

Taxes and trading

Carbon pricing isn't new; the World Bank counts 46 nations and subnational entities that have implemented carbon taxes or emissions trading systems (ETSs), covering 20% of global emissions. Better known as cap and trade, an ETS allows the market to set a carbon price after a set amount of CO_2 allowances are auctioned or distributed to major emitters. The cap on allowances is gradually lowered over time to bring emissions down. Emitters are free to buy or sell their allowances to other sources depending on how rapidly they curtail their own emissions.

ETSs vary in the proportion of the total emissions they cover. The oldest and largest, the European Union's, covers 11 000 power plants and manufacturing facilities and applies to aviation within the EU, but it still excludes 55% of total EU greenhouse-gas emissions. Much of the remainder is subject to carbon taxes that have been enacted by many EU member states. Those levies vary widely from more than \$120 per ton in Sweden to \$2.20 per ton in Estonia.

Once allowances are auctioned off or issued by the government, their value in ETSs fluctuates according to market conditions and the effects of other climate change mitigation policies, such as renewable and energy efficiency standards, on reducing CO_2 emissions. Soon after the ETS was initiated in 2005, values fell to zero as the cap was set higher than actual emissions. EU allowances traded this fall for about \$32.50 per ton, according to the International Carbon Action Partnership. As recently as 2017, credits traded for around \$5 a ton.

The EU ETS is on track to meet its goal of cutting emissions 21% from their 2005 levels by next year. Since inception, it has generated more than \$42 billion in revenues.

China, the world's largest CO_2 emitter, has pilot ETSs underway in seven cities and plans to implement a nationwide system next year. But the country, which has said it anticipates continued increases in emissions until 2030, is expected to employ a tradeable performance standard, aimed at lowering the CO_2 emissions per unit output of individual sources, says Stavins. In that way, it will resemble the inaugural ETS used to phase out leaded gasoline in the 1980s.

The US lacks a national carbon-pricing regime, but California initiated a cap-and-trade system in 2012 that now covers 80% of its CO_2 emissions. Nine states in New England and the Mid-Atlantic region formed the Regional Greenhouse Gas Initiative (RGGI) in 2009. Three other states in the region are planning or considering joining the RGGI. Their initiative covers only the power-generation sector, though most of the RGGI members now plan to add a cap-and-trade system to emissions from transportation.

California's ETS program had less to do with the state achieving its 2020 emissions reduction target four years ahead of time than it did with the effects of energy and mileage standards, says Kennedy. Formerly employed by the state, Kennedy helped design the ETS. "We understood that the heavy lifting out to 2020 was going to be done by the complementary policies," he says. Following implementation of the ETS in 2012, the value of allowances fell to the floor price built into the ETS, but prices recovered once the realization set in that the program would continue through 2030.

In retrospect, California set its emissions caps too high. "Perhaps we could have been more ambitious," Kennedy admits. Still, the ETS provides a policy backstop, says Morehouse. "If one of the other policies wasn't achieving reduc-

SELECTED CARBON PRICING ARRANGEMENTS, 2019

Country or region	Year introduced	2019 price ($/ton CO_2)	Coverage of GHGs,* 2018: Million tons	Coverage of GHGs,* 2018: Percent
Carbon taxes				
Chile	2017	5	47	39
Colombia	2017	5	42	40
Denmark	1992	26	22	40
Finland	1990	65	25	38
France	2014	50	176	37
Ireland	2010	22	31	48
Japan	2012	3	999	68
Mexico	2014	1–3	307	47
Norway	1991	59	40	63
Portugal	2015	14	21	29
South Africa	2019	10	360	10
Sweden	1991	127	26	40
Switzerland	2008	96	18	35
Emissions trading systems				
California, US	2012	16	378	85
China	2020	na	3232	
European Union	2005	25	2132	45
Korea	2015	22	453	68
New Zealand	2008	17	40	52
Regional Greenhouse Gas Initiative**	2009	5	94	21
Carbon price floors				
Canada	2016	15	na	70
United Kingdom	2013	24	136	24

* GHGs—greenhouse gases
** The Regional Greenhouse Gas Initiative is an emissions trading system formed by nine New England and Mid-Atlantic states.

INTERNATIONAL MONETARY FUND, ROBERT STAVINS, AND WORLD BANK

tions at the rate expected, the cap-and-trade program would pick up the slack."

As for the likelihood of a global carbon price such as envisioned by the IMF report, Morehouse says efforts involving two or more nations linking their carbon-pricing arrangements are more likely than a top-down, universal approach. She notes California's recent linkage to Quebec's ETS, an arrangement that the Trump administration sued to block in October.

What's ahead

In the past year, there have been several instances of pushback against carbon-pricing regimes. An increase in France's fuel tax that was based in part on the country's carbon tax helped spark the ongoing yellow vest protests, leading the government to rescind the hike. In the US, voters in Washington State rejected for the second time a carbon tax in 2018. Oregon was on track earlier this year to enact an ETS that would link with California's, but Republican members in Oregon's state Senate maneuvered to block passage this summer. The likelihood that Virginia will enter the RGGI has risen after Democrats gained control of the legislature in last month's elections.

Resistance to carbon taxes shows the importance of designing pricing schemes that ensure costs and benefits are shared fairly across a nation or state, says Morehouse. In California, the increase in electricity rates caused by the ETS is rebated to consumers by utilities twice a year in a lump sum that isn't connected to the amount of electricity used. "For most households, that more than makes up for the rate increases, but it still provides incentives to do energy efficiency improvements and other measures to cut energy costs," she says.

Economists disagree on the relative merits of a tax or ETS. In principle, an ETS could raise the same revenue as a carbon tax through the auctioning of emissions allowances, the IMF report says. In practice, though, some governments have given the initial permits away. The administrative burden of an ETS could be prohibitive for some governments, whereas a carbon fee could easily be added to existing taxes on fossil fuels, notes the IMF report, which prefers a tax. Stavins's own research has found little difference in terms of an ETS's emissions reductions, costs, and other measurements. "You could design one to be just like the other. There's a continuous spectrum from a pure carbon tax to a pure cap and trade." What's more important is the specific designs of the two systems.

Some ETS regimes, for example, have evolved to include attributes of a tax system. California's features price "collars"—caps and floors—that build in a degree of price certainty. And proposals for carbon taxes being discussed by some Democrats in Congress include an emissions insurance mechanism, says Kennedy, which looks a lot like a cap. "You set an initial rate and an escalation rate [for price], but also an emissions target. If you are falling off the target, the tax goes higher."

Given today's polarized US political climate, analysts agree that Democrats winning the presidency and gaining control of the Senate in 2020 is a necessary condition for any hope of a national carbon-pricing scheme. But even if that happens, opposition will likely abound. "There's a lot of tendency for politicians to try and hide costs. And carbon-pricing systems are not good at hiding the costs," says Stavins.

David Kramer

Self-driving cars face a cloudy future

Better weather predictions and more data on driving could accelerate the widespread deployment of automated and connected vehicles.

A SELF-DRIVING SHUTTLE identical to the one shown here by EasyMile, a company headquartered in Toulouse, France, was tested earlier this year by the Regional Transportation District in Denver, Colorado. Snow and heavy rain confused the onboard sensors, disrupting the shuttle service.

Although they are already on the road, automated vehicles (AVs) don't perform well in bad weather. From January through August, the Regional Transportation District, the public transit agency for metropolitan Denver, Colorado, tested a driverless shuttle that looped between four local commuter rail stations on a predetermined route. The vehicle's sensors malfunctioned during snow and heavy rain, which led to service disruptions, according to a blog post by Dave Genova, CEO and general manager of the agency.

The performance of AVs in challenging weather conditions is improving, however. Atmospheric scientists and engineers from academia, the automobile industry, and technology companies are upgrading onboard hardware—cameras, lidar sensors, and radar units, for example—so AVs can better monitor weather conditions. At the same time, computer scientists are using artificial intelligence (AI) to safely navigate the roads.

AVs will need weather and pavement-condition forecasts more frequently than the 15-minute updates currently available from governments and companies. Some of that data could come from fixed roadside sensors that collect temperature, pressure, humidity, and other meteorological data. Additional information from onboard instruments, including windshield wipers and headlights, could be collected by and shared among the vehicles themselves.

To act like a human

Many vehicles on sale to the public have semiautonomous or driver-assist features. The most familiar is likely cruise control, which for decades has been used to maintain speed. Some vehicles, including models from Tesla, Volvo, and Audi, already have more advanced capabilities that automate such tasks as parking and lane centering. Fully autonomous, or self-driving, vehicles are still in the R&D phase and would ideally operate with no human driver, or a human would only intervene during poor conditions.

AVs sport an array of onboard sensors that mimic and aim to surpass a human driver's eyes. Cameras detect potential obstacles and environmental features near and far. Lidar units emit near-IR light pulses that bounce off nearby objects, and the light's travel time is used to calculate a three-dimensional map of the surrounding area. Radar sensors measure the Doppler shift of pulses to monitor mobile features, such as pedestrians, cyclists, and other vehicles. (For more information about AV hardware, see the Quick Study by Colin McCormick, PHYSICS TODAY, July 2019, page 66.)

To gather and exploit even more data, researchers are considering vehicle-to-infrastructure communication in which AVs wirelessly connect to weather sensors. For example, employees of the US Department of Transportation's Smart Roadside program have been examining how to provide AVs with information about pavement and traffic conditions from weather sensors deployed along roads.

Vehicles with no drivers could be monitored by a person at a centralized location. Earlier this year in Florida, a driverless truck made by Starsky Robotics of San Francisco navigated along a highway for 15 kilometers. The truck maintained its speed and changed lanes. The driving decisions were monitored by someone in a control center who could take over if necessary.

Computer scientists are using AI to develop improved decision-making systems for AVs. Machine-learning and neural-network methods apply algorithms to data sets, and the results are used to inform probabilistic decisions. Such algorithms are based on AI that is used in image processing and in weather forecasting (see PHYSICS TODAY, February 2019, page 17, and May 2019, page 32).

Some companies such as Vaisala, based in Helsinki, Finland, use environmental, industrial, and weather data coupled with AI to provide road-prediction and road-condition services to clients. Every 5–15 minutes they update information about moisture, snow, and ice for 2-kilometer road segments. In 2015 Vaisala started RoadAI, which uses vehicle-mounted cameras to spot upcoming cracks, potholes, and other road features that may affect AV performance.

One difficulty for AI methods is that they require large amounts of quality-controlled data to make statistically significant decisions. To meet that demand, companies are having their AVs drive millions of miles each year. "Techniques certainly exist to cull the data and get a sense of what's good, what's bad, and maybe what's questionable," says Curtis Walker, a meteorologist and AV scientist at the National Center for Atmospheric Research in Boulder, Colorado. But, he adds, "When it comes to quality control, there's always room for improvement."

Mobile weather stations

Automated vehicles can benefit from vehicle-to-vehicle communication via onboard sensors. Such buddy checks also provide a means to test whether an AV's own sensors are functioning properly. If a sensor detects rain and the AV "starts checking with the vehicles around [it]," says Walker, but "none of them are using their wipers or have their headlights on or have their antilock braking systems activated, then that vehicle might question its sensors."

In wintry conditions, snow and ice can quickly accumulate on the cameras or the lidar and radar units and blind the vehicle to environmental conditions it's supposed to monitor. "If the vehicle next to me has its headlights and wipers on, maybe I should too," says Walker. Vehicles could communicate to each other about other critical information, including friction and stability control, speed, direction of travel, and whether hard braking is necessary.

Vehicle-to-vehicle communication was demonstrated in Germany earlier this year by logistics company DB Schenker, vehicle manufacturer MAN Truck & Bus, and researchers from the New York campus of Fresenius University of Applied Sciences. A pair of trucks—electronically linked and driving in the same lane 20 meters apart—traveled some 35 000 kilometers back and forth between Nuremberg and Munich. The human drivers intervened an average of once every 2000 kilometers, mainly when other vehicles cut into their lane. The two trucks drove closer together compared with trucks without the technology, and fuel consumption was consequently reduced by 3–4%.

Vehicle-to-vehicle communication does have limitations. "An AV needs to have equipment and sensor systems so it is always safe and can operate without any connectivity," says Petri Marjava, a senior business development manager at Vaisala. He says that car companies are often protective of their data. "There needs to be a business case for the vehicle [manufacturers] to fetch that data from the fleet because everything has its costs," he says. Nondisclosure agreements with AV manufacturers often prevent researchers from sharing their safety and performance analyses.

AV research, says Walker, "is largely for the benefit of advancing the technology and certainly the product and ultimately profit, not so much to get peer-reviewed papers out there for the community to assess performance. Though there is room for that as well." Waymo, the self-driving R&D subsidiary of Alphabet Inc, in August released on its website AV sensor data that may be useful to researchers studying topics such as predicting vehicle behavior and sensing environmental conditions. The open data set contains 1000 road segments that each

THESE TWO AUTOMATED TRUCKS drove some 35 000 kilometers in Germany between Nuremberg and Munich earlier this year with minimal human intervention.

MAN TRUCK & BUS

span 20 seconds of driving in urban and suburban environments under various weather conditions.

Some car manufacturers are sharing with each other. BMW, Daimler, Ford, and Volvo announced in June that they were partnering with data service providers and national transportation authorities in six European countries to supply a common server that will receive, combine, and disseminate safety data to connected AVs. The pilot project comes after the European Parliament in April approved a revised general safety regulation that governs European Union motor vehicles. Among its new requirements are minimum mandatory safety technologies that must be installed in vehicles starting in 2022.

On every block

Walker says that weather is only one issue AVs face; ethical considerations and political regulations need to be addressed too. "If the vehicle has the choice to hit a deer or to steer off the road and hit a tree, possibly injuring the driver, will the vehicle always decide to take out the deer?" he says. "But then what if instead of a deer it's a kid who runs out chasing a ball or a toy or something?"

One solution could be AI software akin to MIT's Moral Machine platform. Researchers designed thought experiments of the moral dilemmas AVs could face and compiled 40 million decisions from millions of people in 233 countries on how a vehicle should act in those cases. Respondents showed a strong preference for an AV to hit a nonhuman animal if doing so was the only way to spare a child that darted into the road. The researchers say their results, which also included preferences for sparing more lives than fewer and young people over older people, could contribute toward a global, socially acceptable set of principles that the vehicles would abide by.

AVs also need frequent weather forecasts that predict conditions on a scale of a few kilometers or better. Better forecasts could come from the US National Weather Service, which currently provides predictions at a scale of about 30 kilometers, or IBM's forthcoming Global High-Resolution Atmospheric Forecasting System, a tool designed to provide hourly updates at 3-kilometer resolution. The constraints for providing weather predictions to people can be relaxed for AVs, which can take probabilities and use their AI algorithms to determine the most likely environmental conditions.

Besides better predictions and more data, AVs likely need improvements in pavement-condition characterization. To determine the road-friction threshold needed for safe driving, prediction models must account for local subsurface moisture, the road's material properties, how it was constructed, and how the materials respond to different weather.

Such models are currently used during winter weather in maintenance-decision support systems, says William Mahoney, a research director at the National Center for Atmospheric Research. Transportation departments use them to identify the best approaches for keeping pavement clear of ice and snow during storms. As federal and state highways are repaired and renovated, new road properties should be incorporated in pavement models, Mahoney says. He adds that designs and materials that improve the ability to collect weather and material data should be prioritized.

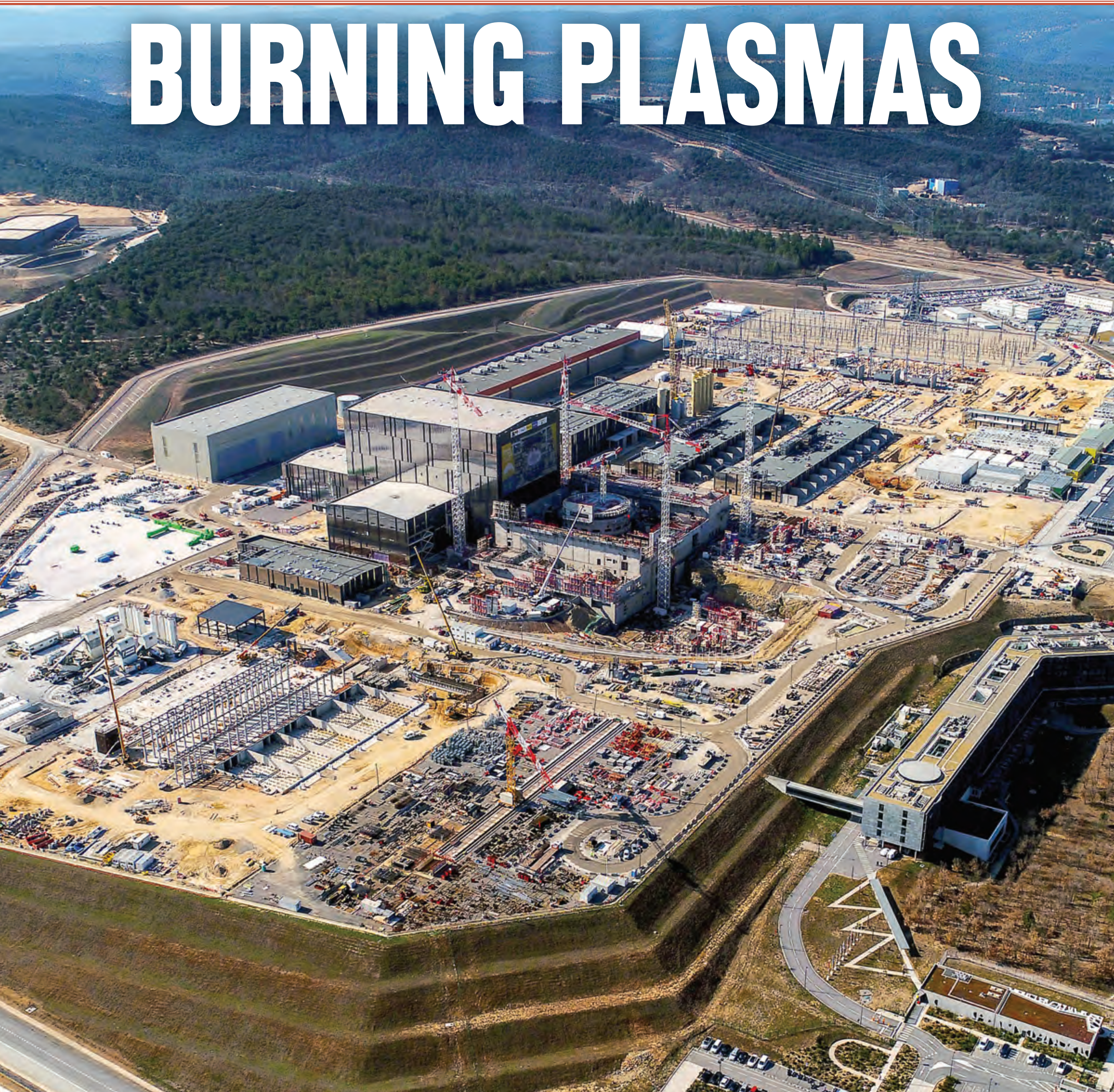
Mahoney expects a gradual transition to AVs. "We're seeing a build-a-little, test-a-little, and implement-a-little process." Once an AV can travel through short segments on predetermined routes or through restricted-lane areas, longer and more complicated routes may be possible. He says the automobile industry can learn from airline companies: Atmospheric scientists have helped improve airplane safety and reliability in adverse weather for decades. A similar team effort between the meteorology community and automobile industry is necessary to hasten AV development and adoption, he says.

But because of fierce competition for venture capital funding, vehicle companies often stay quiet about the development challenges they face. To address that problem, in 2018 Mahoney organized an American Meteorological Society summit that brought together the AV and meteorology communities at the National Transportation Safety Board in Washington, DC. "One of the things I've noticed over the last several years is that the [auto] companies and weather community are not working together as closely as they should," says Mahoney. "We're having mixed results so far, but we are working steadily to bring these communities together."

Alex Lopatka PT

The challenge and promise of studying

BURNING PLASMAS



Richard Hawryluk is the associate director for fusion at the Princeton Plasma Physics Laboratory in New Jersey. **Hartmut Zohm** is a director at the Max Planck Institute for Plasma Physics in Garching, Germany, and an honorary professor of physics at Ludwig-Maximilians University Munich.

Richard J. Hawryluk and Hartmut Zohm

Answers to open questions that will be addressed by the ITER experiment should enable the production of fusion energy.

In burning plasmas, the energy from charged particles created by fusion reactions compensates for heat loss. Burning plasmas power the Sun and other stars, and they could provide abundant energy for humankind. In the Sun, proton fuel is used in fusion reactions. But on Earth, the highest performance fuel is composed of deuterium and tritium ions. Scientists have several ways of producing fusion energy in the laboratory, most notably through magnetic and inertial confinement.

The progress made on magnetic fusion has led to the planning and construction of ITER, the international fusion research facility. Significant fusion power has been achieved for a little less than a second in magnetically confined plasmas—up to 10 MW in the Tokamak Fusion Test Reactor in the US[1] and up to 16 MW in the Joint European Torus in the UK.[2] In those experiments, the deuterium–tritium fuel is self-heated by fusion products—alpha particles—which provide a modest fraction (less than 13%) of the total heat supplied to the plasma. Whereas the original ITER design was based extensively on empirical results, designs for tokamak power plants such as those run by EUROfusion increasingly use theoretical and computational research coupled with empirical results from current experiments.

The construction of ITER in Provence, France, is already underway as shown in the opening photo. The facility will provide the opportunity to study burning plasmas in which at least two-thirds of the total heating will come from fusion reactions that could produce 500 MW of power for more than 300 seconds. The facility will also enable the first in-depth study of burning plasmas in a magnetic confinement configuration.[3] ITER will be one of the largest scientific experiments ever undertaken, with participation by China, the European Union, India, Japan, Russia, South Korea, and the US. Despite the high cost of the project, the worldwide community's sharing of scientific and technical knowledge has contributed to the breadth of the international collaboration. Although project costs increased and the construction schedule was delayed early on, ITER has been successfully adhering to the current schedule in recent years after a major reorganization in 2015 (see PHYSICS TODAY, May 2015, page 21). It aims to begin experiments with hydrogen in the mid 2020s and to perform burning plasma experiments in the mid 2030s.

ITER will create an axisymmetric toroidal plasma inside a chamber, whose cross-sectional view is shown in figure 1. For deuterium–tritium plasmas with ion temperatures in the range of 10–20 keV (116–232 million K), the fusion power density is approximately proportional to the ion pressure squared. The plasma core has the highest pressure and reactivity. Its temperature there is determined by the balance of plasma heating and heat loss from the core to the edge of the plasma. The heating balance is mostly affected by small turbulent density fluctuations on the order of a few percent or less in amplitude. During the initial phase before the switch to deuterium–tritium fuel, the plasma will be mostly heated by an external source.

Once the plasma pressure is sufficiently high, the self-heated phase begins. During that burning phase, fusion reactions generate suprathermal alpha particles, which are confined by the magnetic field and heat the plasma as collisions with the background plasma slow them down. The alpha particles self-heat the plasma about twice as much as any external heating source, and 80% of the fusion power is released as energetic neutrons, which do not interact with the plasma.

Their energy is transferred as heat to the surrounding blanket; in power plants, the blanket converts the heat to electricity. Twisting magnetic fields that lie on nested toroidal magnetic flux surfaces confine the plasma in the core. But outside of the last closed-flux surface, called the separatrix, the magnetic field lines are no longer closed and thus intersect the first wall, ideally in the so-called divertor region beyond the scrape-off layer, seen in figure 1. The separatrix is formed by the plasma field current interacting with the current that's carried by the large superconducting divertor coil below the plasma chamber. The large heat flux from the plasma core impinges on the divertor surface and needs to be carefully controlled.

Producing a burning plasma requires plasma parameters that are different from those in current, nonburning experiments. Similar to fluid dynamics, dimensionless parameters for the core plasma can be determined theoretically and then the plasma's behavior can be scaled from one set of experiments to another.[4] ITER will have to simultaneously achieve several conditions. Large values of system size, which are related to how many ion Larmor radii r_L fit along the plasma minor radius a, $(1/\rho^* = a/r_L)$, will be required. The frequency of plasma collisions will need to be low, such that the mean free path between Coulomb collisions is much longer than the characteristic distance around the plasma along magnetic field lines. ITER will also need to produce modest values of the plasma pressure p that is normalized by the magnetic field pressure B, where the ratio β is proportional to p/B^2.

Another parameter has been found to describe various limitations to the plasma density n_e achieved in experiments. The so-called Greenwald density n_e^{GW} is proportional to the plasma current and inversely proportional to the square of the plasma minor radius. Although n_e^{GW} does not come from idealized equations often used for plasma dynamics, it successfully describes the upper-density limits in the edge region where closed magnetic lines exist, the beginning of confinement degradation at high separatrix density, and the onset of magnetohydrodynamic instabilities. The instabilities may arise from atomic-physics effects in the edge region and from electromagnetic radiation emitted by impurities, such as tungsten and beryllium, from the first-wall material.

Present-day experiments, individually but not simultaneously, can achieve ITER's typical parameter values. Therefore, scientists will use ITER to study burning plasmas and the unique regime of dimensionless parameters, important for facilities that will produce electricity from burning magnetically confined deuterium–tritium plasmas.[5]

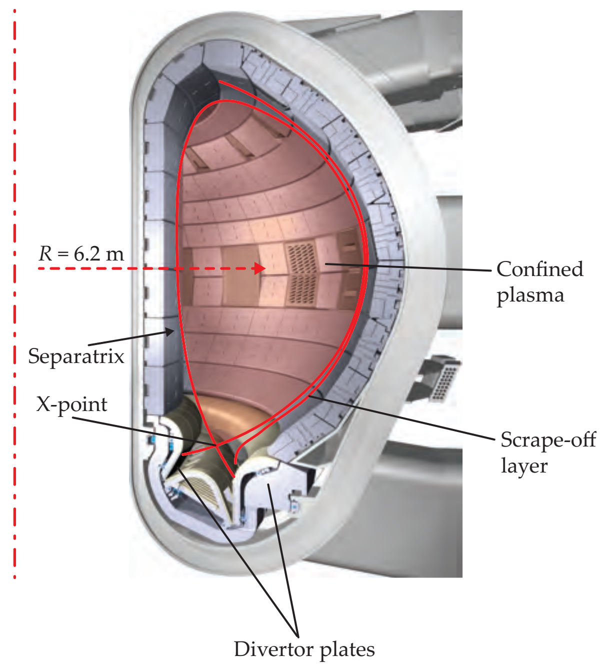


FIGURE 1. THE POLOIDAL CROSS SECTION OF ITER shows a magnetic separatrix that encircles closed magnetic flux surfaces. The separatrix is introduced by creating a so-called X-point, in which the plasma field current interacts with the current that's transported by a large superconducting divertor coil. Closed magnetic surfaces exist inside the separatrix, and the plasma outside it flows in the narrow, few-mm-wide scrape-off layer toward the divertor. The dashed, red line indicates the size of the major radius *R* measured from the torus's dash-dotted symmetry line to the plasma center. (Credit © ITER Organization.)

Transporting heat and particles in the plasma core

ITER was designed mainly using empirical projections of the confinement of heat in the plasma based on experimental results from around the world. The results come from a mode of operation in which there is reduced turbulent transport in the edge region.[5] The so-called H-mode, or high-confinement mode, is a consequence of sheared plasma flow that breaks up turbulent eddies.[6] The eddies generate a narrow zone of steep radial gradients in the edge that corresponds to the pedestal region shown in figure 2.

Since the ITER facility design began, scientists have made substantial progress in understanding the turbulent processes in the core and comparing detailed experimental results with sophisticated theoretical models. One such model indicates that heat flux is not simply proportional to the temperature gradient but can be highly nonlinear. The heat flux strongly increases above a threshold value for the normalized temperature gradient R/L_T, where R is the major radius of the torus and the gradient scale $1/L_T = |\nabla T|/T$. The value of R determines the curvature of the magnetic field lines, which is responsible for the microinstabilities that give rise to strong turbulent transport once the threshold value of R/L_T is exceeded.[7] Strong turbulent transport implies that R/L_T is relatively constant for parameters of interest. It also means that the shape of the radial temperature profiles $T(r) \sim C\exp(-r/L_T)$ is approximately self-similar to the plasma edge at the top of the pedestal. Those expectations are supported by theoretical calculations that predict the critical normalized temperature gradient for the increase in heat flux and the dependence of the heat flux on the gradient. That dependence is also affected by additional plasma parameters, including the gyroradius.

ITER is predicted to operate in a range in which those turbulent processes are important, so the temperature in the plasma core is approximately proportional to the temperature at the top of the pedestal. The sensitivity of the predicted fusion power to the pedestal temperature is illustrated in figure 3. Whereas the transport model predictions of power amplification Q versus pedestal temperature T_{ped} were based on sophis-

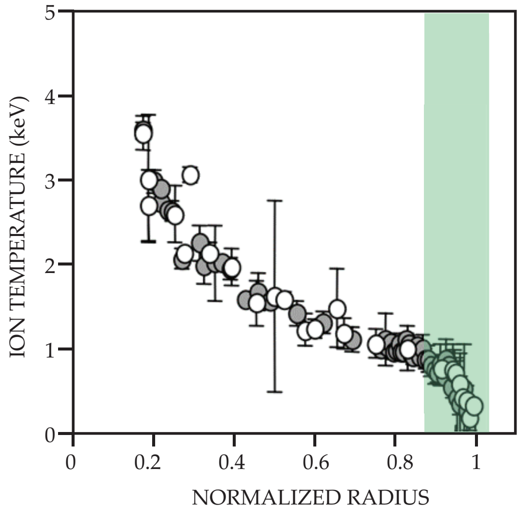


FIGURE 2. A TYPICAL ION TEMPERATURE PROFILE, plotted versus the normalized minor radius of the confined plasma, features a pedestal region (green) of steep gradients at the plasma edge. In ITER, the expected temperature values will be about five times as high. (Adapted from ref. 14.)

ticated turbulence simulations using some of the largest supercomputers a decade ago, some simplifications were assumed. Higher performance is expected based on estimates that include various stabilizing effects—density peaking, magnetic components of turbulence, and beam-driven rotation—that were neglected in figure 3.

The modeling of the nonlinear, turbulent plasma state has become increasingly more sophisticated. Some have described how the rotation in the plasma arises from a combination of externally applied torque from the injection of neutral beams and from turbulence-induced processes, a phenomenon known as Reynold's stress in fluid dynamics. So the same turbulence that mainly determines the loss of heat can enhance the plasma rotation and help in determining the saturation level of turbulent transport. Even for plasmas with no applied torque, significant rotation is observed. Although the applied torque for ITER is smaller than in current experiments, it may still drive enough rotation to improve performance, and additional rotation may be driven by turbulent processes. Modeling now simultaneously considers turbulence at both ion- and electron-scale lengths, the role of shear in the profile of plasma rotation, and the effect of fast ions in the relationship between the heat flux and the normalized temperature gradient.[8] Experiments have shown regimes of operation in which the heat flux may decrease because of an increase in the plasma rotation or the presence of fast ions.

Experiments and theory predict that turbulence results in particle transport and produces a peaking of the electron density profile in low-collisionality plasmas, in which the mean free path between Coulomb collisions is much longer than the characteristic distance around the plasma along magnetic field lines.[9] That is advantageous for fusion reactivity because the fuel concentrates in the high-temperature part of the plasma. In present-day experiments, low collisionality is only achieved at low normalized density. ITER and future power-producing experiments, however, will operate at high normalized density. Such experiments will therefore be important in validating the theoretical models in new regimes where the fast ion effects are due to alpha particles operating at very low collisionality and in large systems. In addition to transporting the main fuel species, it's important to transport the alpha-particle ash from the deuterium–tritium reactions to the edge and subsequently pump the ash to avoid accumulating impurities and diluting the fuel. Turbulent processes are expected to dominate collisional processes and will help determine the fuel dilution and the presence of impurities in the core from plasma material interaction at the edge.

Pedestal performance

The reduced transport in the edge region associated with H-mode plasma results in steep temperature and pressure gradients, as shown in figure 2, and has many ramifications in addition to the confinement in the core. The steep pressure gradient in the edge region generates parallel currents through a mechanism similar to that in thermoelectric-driven currents. Large pressure and current gradients affect the magnetohydrodynamic (MHD) stability of the edge region and can trigger edge instabilities, or edge-localized modes[10] (ELMs) that can be seen in figure 4. The resulting operating boundaries due to ELMs are relatively well understood by MHD models that simulate the stability of the edge.

Whereas the global pedestal stability is described well by linear, ideal MHD modeling, the parameters at the top of the pedestal are determined by a combination of MHD stability and the transport mechanisms between the edge of the plasma and the top of the pedestal. The edge pedestal (EPED) model successfully predicts the width and height of the pedestal pressure by combining linear MHD stability analysis of the pedestal with a simplified assumption about the transport in the region.[11]

However, recent experiments using tungsten as a wall ma-

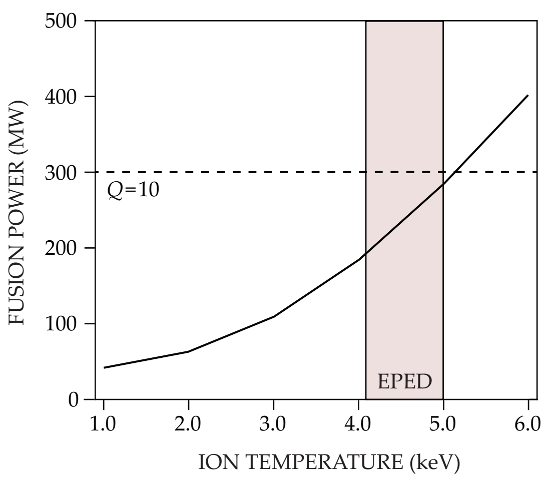


FIGURE 3. THE FUSION POWER P_{fus} AND POWER AMPLIFICATION Q FOR ITER depend strongly on the ion temperature at the top of the edge pedestal shown in figure 2. The box labeled EPED shows the range of pedestal temperature T_{ped} predictions from a leading model.[11] (Adapted from ref. 15.)

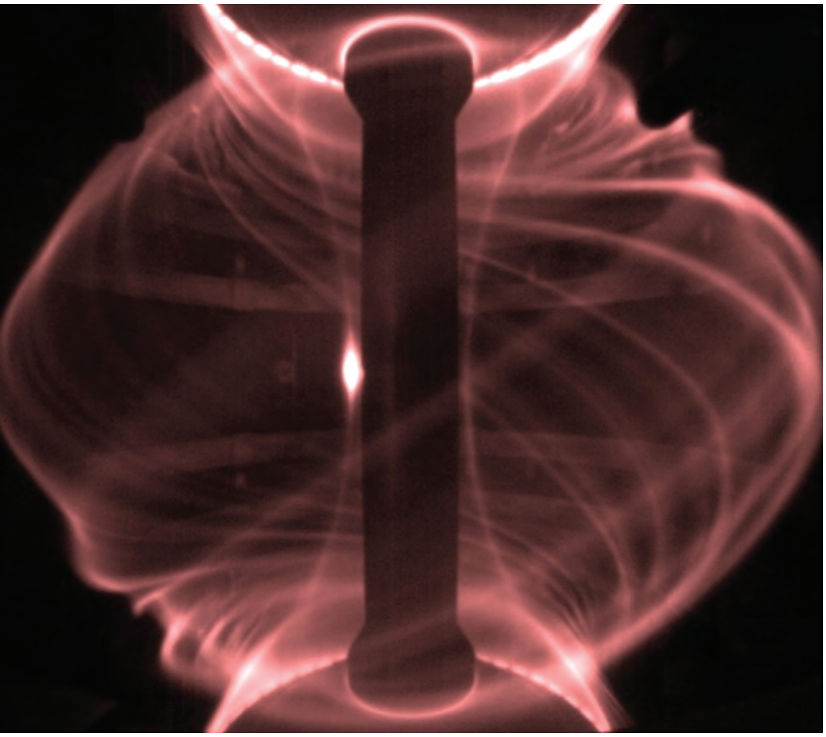


FIGURE 4. AN EDGE-LOCALIZED MODE (ELM) INSTABILITY appears on this fast camera image from the Mega Amp Spherical Tokamak. The wide-angle view shows the whole plasma, and the enhanced hydrogenic line emission clearly delineates plasma filaments, which are ejected from the edge by the ELM instability.[16] (Courtesy of Andrew Kirk.)

terial in the Axially Symmetric Divertor Experiment (ASDEX) Upgrade and the Joint European Torus tokamaks have shown a degradation that could not be explained by the MHD model. The temperature and density profiles can respond differently, partly because of an influx of recycled neutral particles from the wall into the region between the plasma edge and the pedestal top. Consequently, additional transport physics will have to be incorporated into the EPED model to improve predictions.

ITER will be operating in a different system-size regime from its predecessors, so the role of neutrals may change. ITER's combination of low collisionality and large system size may alter the turbulence characteristics in the pedestal region and affect the height of the pedestal. As the first device to combine a pedestal with low-collisionality parameters and operate at high densities relative to the Greenwald density, ITER provides a unique opportunity to validate the understanding of the edge pedestal.

For ITER, the large ELM instabilities could damage divertor components. Techniques have been developed to suppress those instabilities, such as by operating within the stability boundary with additional coils that give rise to small three-dimensional perturbations of the tokamak axisymmetry, $\tilde{B}$/B, on the order of 10^{-4}, where B is the magnetic field.

Plasma-boundary interactions

A major challenge for ITER will be controlling the heat and particle exhaust. The sharp pressure gradients in the edge region extend to just beyond the last closed-flux surface from which heat and particles are rapidly transported along the open magnetic field lines to the divertor plates. Recent experiments on various devices have shown that the heat flux width at the plane where the plasma has its largest radial extension is narrow and would extrapolate to as low as 1–2 mm in ITER. Advances in transport modeling across the magnetic field on the open field lines describe the heat flux width in current experiments reasonably well. When the same model is applied to ITER, it indicates that turbulence changes in the edge may increase the heat flux width up to 5 mm. That prediction requires stringent experimental tests that may only be possible using ITER.

To illustrate the magnitude of the heat-exhaust challenge, consider that the heat flux into the ITER boundary will be 150 MW if the power lost by radiation is ignored. Taking into account the extrapolated experimental heat-flux-width range, that heat exhaust would far exceed the approximately 10 MW/m^2 power-handling capability of steady-state, high-heat-flux components with tungsten armor that will be used in the ITER divertor.

Two approaches are used to reduce the heat flux on the divertor plates. In the first, the incident angle of the magnetic field lines carrying the heat flux is reduced by expanding the magnetic flux surfaces in the vicinity of the divertor plates and tailoring the angle of the plates so that they are nearly tangential to the magnetic field. That approach demands accurate alignment of individual target plates to ensure that the leading edges do not overheat. The heat flux on the target would be substantially reduced to about 40 MW/m^2 in the ITER geometry.[12] The decrease depends on the heat-flux-width assumptions, but the value is comparable to the heat flux on the surface of the Sun, which is roughly 60 MW/m^2.

In the second approach, part of the heat flux is dissipated by intentionally injecting seed impurities, such as nitrogen, into the divertor plasma. The impurities will emit line radiation to distribute the heat load homogeneously in all directions. At constant-impurity concentration, the radiation losses increase with the square of the electron density. A high density at the separatrix is also required for effective power dissipation. Both techniques have been successfully demonstrated for various experiments. Figure 5 shows how the radiation losses from the divertor and X-point regions can be enhanced by adding nitrogen.

One role of ITER is to test ideas to stably exhaust power and particles in a future fusion power plant at relatively high separatrix densities while simultaneously optimizing the fusion power. Among the questions to be addressed are Will confinement be degraded because of the high density in the scrape-off plasma as seen in present-day experiments? And will the fuel concentration in the core be decreased by impurity ions penetrating the core from the divertor plasma, which reduces the plasma reactivity?

Control of burning plasmas

Perhaps the most important question is whether the high-energy alpha particles that sustainably heat the burning plasma deposit their energy to the ions and electrons via Coulomb colli-

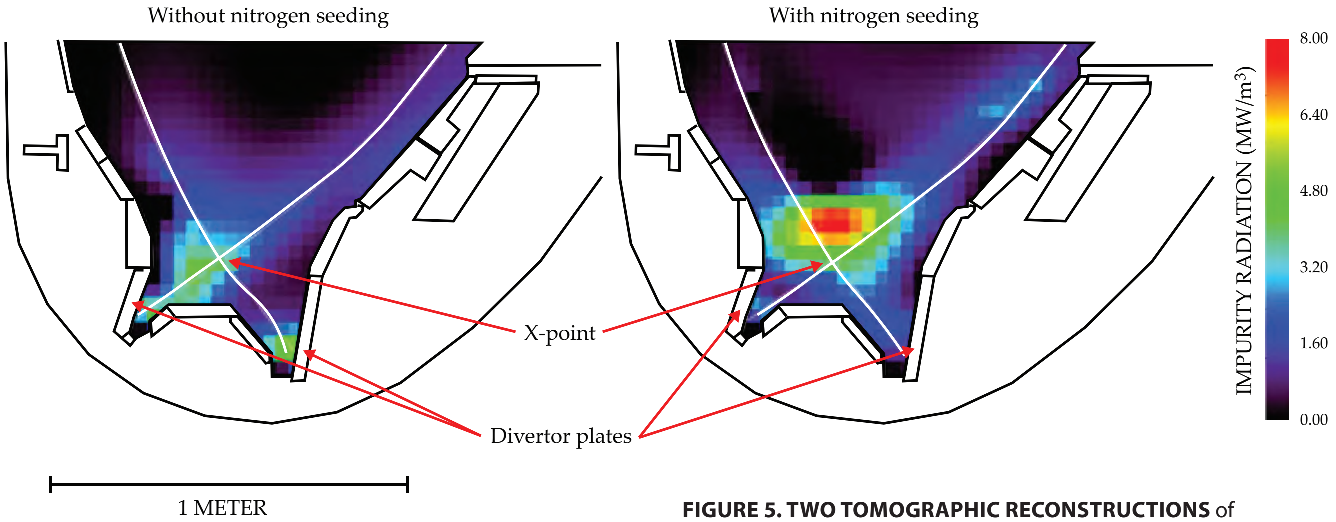


FIGURE 5. TWO TOMOGRAPHIC RECONSTRUCTIONS of impurity radiation from the divertor and X-point regions show clear differences in their enhanced radiation losses. For an experiment of the ASDEX Upgrade tokamak without additional impurities (left), about 50% of the heating power is dissipated by electromagnetic radiation. But when nitrogen seeding is added (right), a zone of high radiation occurs at the X-point, and the radiated power fraction rises to values in excess of 80%. (Adapted from ref. 17.)

sions or whether their interaction with electromagnetic waves results in a spatial redistribution or loss of alpha particles. (See the article by David Pace, Bill Heidbrink, and Michael Van Zeeland, PHYSICS TODAY, October 2015, page 34.) Deuterium–tritium experiments on both the Joint European Torus and the Tokamak Fusion Test Reactor found initial indications of alpha-particle heating. The slowing of the 3.5 MeV alpha particles to energies comparable to the core ion temperature is in good agreement with calculations tested in plasma conditions that are most similar to what's planned for ITER's first set of high fusion power experiments.

However, in those experiments, the ratio of intrinsic alpha-heating to external heating was small, about 10% or less. ITER will be the first device to conduct experiments that have the alpha-heating dominating the heating power, that address the nonlinear wave–particle interaction, and that decrease the uncertainty associated with low-power alpha-heating experiments. ITER will be able to test whether electromagnetic waves generated by the energetic alpha particles are less stable than in current experiments due to the large system size. Those results will enable researchers to determine optimal operating conditions and minimize or even avoid such instabilities.

Controlling fusion power in a burning plasma would appear to be straightforward. The fusion reactivity in ITER decreases with increasing temperature, and the confinement time of the plasma energy decreases with heating power, which enables a stable operating point. The problem becomes more interesting when the consequences of changes in confinement are considered. In future power plants, a 10% increase in confinement could roughly double the fusion power. The power increase could provide feedback control because it occurs over the time scale of several energy confinement times. Large concentrations of fast ions can reduce the plasma confinement and decrease the efficiency of the alpha-particle heating by interacting with electromagnetic waves. Hence there is significant uncertainty about how the fast ions will affect the burn-control dynamics and whether the system will respond nonlinearly. Only ITER, with its dominant self-heating by alpha particles, will enable a comprehensive exploration of burn control.

Researchers do know that burn control is affected by additional operational constraints related to the maximum density; the MHD stability of the plasma, which is strongly related to the plasma pressure; and the heat flux to the plasma-facing components. Consider the effect of increasing the plasma density. In principle, it's advantageous because it increases plasma reactivity and the power radiated. However, as the density approaches its maximum, observations show that the confinement time degrades. Experimental physicists are using theoretical models to help fine-tune the experimental conditions to optimize the performance and prevent the plasma from touching the operational boundaries. Sophisticated plasma control systems manage various actuators, such as fueling by gas valves, frozen deuterium pellets, and the auxiliary heating power.

The simulations used to predict the discharge performance for ITER will need to take into account the alpha-heating dynamics and the plasma control systems to avoid breaching an operational boundary. The challenge is that the control actuators, such as for auxiliary heating, have a smaller effect on burning plasmas than in present experiments because alpha heating will play a larger role in the power balance.[13]

Demonstrating control of a burning plasma in ITER for both inductive and noninductive regimes is essential before extrapolating to a power plant. During the flat-top phase of the discharge, the current for an inductive regime is driven by a flux change from a central solenoid, whereas the flux change is essentially zero in a noninductive regime. The required power amplification in a plant is expected to be higher, $Q \sim 20$–50, than ITER's $Q = 10$ and $Q = 5$ in a fully noninductive, steady-state operation. For a noninductive, steady-state tokamak power plant, a large fraction of the current would be self-driven by temperature and density gradients. As alpha heating will be the dominant heating mechanism that determines the temperature gradient, controlling the heat becomes more challenging.

Touching an operational boundary can lead to the occurrence of MHD instabilities that can terminate the plasma discharge. In present experiments, the worst plasma confinement disruption occurs when a substantial plasma current of the order of 1 MA is lost rapidly on a time scale of several milliseconds. In ITER, 15 MA of plasma current could be rapidly terminated over a somewhat longer time. A sudden termination of the plasma discharge generates large toroidal electric fields that can drive energetic runaway electron currents, transmit heat fluxes to the plasma-facing components, and apply large forces to the vacuum vessel and its components. Mitigation systems are being implemented to ameliorate the disruptions if the operating boundaries are exceeded, and active control systems will be used to ensure that the plasma operates within safe boundaries. Furthermore, active control of MHD instabilities—including by driving an additional current in the plasma by injecting RF waves or by applying 3D magnetic field perturbations—has made a lot of progress. Research has demonstrated that a localized current of a few percent of the total plasma current created through the injection of RF waves can be sufficient to remove magnetic islands that are responsible for some disruptions and will likely be used in ITER.

Experiments with the forthcoming ITER will be a unique opportunity to study burning plasmas, develop the tools needed to better understand them, and validate outstanding predictions. The experiments will provide seminal answers to questions that are central to the prospects for fusion. ITER will be a major step in bridging the gap between current understanding and the knowledge needed to design and operate fusion power plants as safe, sustainable energy sources.

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REFERENCES

1. R. J. Hawryluk, *Rev. Mod. Phys.* **70**, 537 (1998).
2. M. Keilhacker et al., *Nucl. Fusion* **39**, 209 (1999).
3. National Academies of Sciences, Engineering, and Medicine, *Final Report of the Committee on a Strategic Plan for U.S. Burning Plasma Research*, National Academies Press (2019).
4. T. C. Luce, C. C. Petty, J. G. Cordey, *Plasma Phys. Control. Fusion* **50**, 043001 (2008).
5. M. Shimada et al., *Nucl. Fusion* **47**, S1 (2007).
6. F. Wagner, *Plasma Phys. Control. Fusion* **49**, B1 (2007).
7. M. Kotschenreuther et al., *Phys. Plasmas* **2**, 2381 (1995).
8. X. Garbet et al., *Nucl. Fusion* **50**, 043002 (2010).
9. C. Angioni et al., *Plasma Phys. Control. Fusion* **51**, 124017 (2009).
10. H. Zohm, *Plasma Phys. Control. Fusion* **38**, 105 (1996).
11. P. B. Snyder et al., *Nucl. Fusion* **51**, 103016 (2011).
12. R. A. Pitts et al., *J. Nucl. Mater. Suppl.* **415**, S957 (2011).
13. M. D. Boyer, E. Schuster, *Plasma Phys. Control. Fusion* **56**, 104004 (2014).
14. H. Urano et al., *Nucl. Fusion* **48**, 045008 (2008).
15. J. E. Kinsey et al., *Nucl. Fusion* **51**, 083001 (2011).
16. A. Kirk et al., *Phys. Rev. Lett.* **96**, 185001 (2006).
17. F. Reimold et al., *Nucl. Fusion* **55**, 033004 (2015).

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The **DEPARTMENTS OF MATHEMATICS AND COMPUTER SCIENCE** in the College of Science at Purdue University invite applications for up to five positions in Quantum Information Science (QIS) to begin August 2020. These positions will be at the assistant/associate professor level based on scholarly record. When appropriate, successful candidates may be considered for joint and interdisciplinary appointments across the College.

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The College of Science is especially seeking to enhance our existing strengths in research at the interface within Computer Science and Math through strategic hiring of creative scientists to be part of the cutting-edge interdisciplinary environment provided by Purdue University. Successful candidates will have research interests that can build a comprehensive suite of capabilities in quantum algorithm research, information theoretic analysis, topological quantum computing, chemical physics, and quantum materials, experimental and/or theoretical quantum computing with superconducting qubits, spins in semiconductors and other condensed matter systems, cold atomic ions, Rydberg atoms, photonic systems, or quantum materials.

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and must include (1) a cover letter (including a discussion of diversity efforts as indicated below), (2) a complete curriculum vitae with publication list, (3) a brief statement of present and future research plans, and (4) a statement of teaching philosophy. In addition, candidates should arrange for at least 4 letters of reference, one of which discusses the candidate's teaching qualifications, to be sent to qissearch@purdue.edu. Questions regarding the position and search should be directed to chgreene@purdue.edu. Applications completed by December 15, 2019 will be given full consideration, although the search will continue until the position is filled.

Purdue University's Departments of Computer Science and Mathematics are committed to advancing diversity in all areas of faculty effort, including scholarship, instruction, and engagement. Candidates should address at least one of these areas in their cover letter, indicating their past experiences, current interests or activities, and/or future goals to promote a climate that values diversity and inclusion. A background check will be required for employment in this position.

TOP S

John Wheeler's

Alex Wellerstein

In 1953, as a political battle raged over the US's nuclear future, the eminent physicist lost a classified document, about the hydrogen bomb, on an overnight train from Philadelphia to Washington, DC.

There may never be a good time to lose a secret, but some secrets are worse than others to lose, and some times are worse than others to lose them. For US physicist John Archibald Wheeler (see figure 1), January 1953 may have been the absolute worst time to lose the particular secret he lost. The nation was in a fever pitch about Communists, atomic spies, McCarthyism, the House Un-American Activities Committee, Julius and Ethel Rosenberg, and the Korean War. And what Wheeler lost, under the most suspicious and improbable circumstances, was nothing less than the secret of the hydrogen bomb, a weapon of unimaginable power that had first been tested only a month before.

Wheeler is best remembered today for being an audaciously original thinker whose contributions span fields from the theory of nuclear fission through relativity and quantum theory and for coining several new pieces of physics vocabulary, including the now ubiquitous term "black hole." Wheeler's deep connections to the budding national security state, however, are less well known. He was a major scientist at the Hanford plutonium production site in Washington State during World War II, and from 1951 to 1953, he was the head of Project Matterhorn B, the H-bomb project centered at Princeton University.

It was his role at Matterhorn B that led Wheeler to take a fateful overnight train trip from his home in Princeton, New Jersey, to Washington, DC, in January 1953. He had with him a short but potent document that explained exactly how the US, at that time the only nation in the world with an H-bomb, had overcome the many obstacles to producing a multimegaton thermonuclear weapon. Somewhere on the train ride, that document went missing. Wheeler's Federal Bureau of Investigation file, re-

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H-bomb blues

KUNAL MEHTA/ALAMY STOCK PHOTO

cently released under the Freedom of Information Act, has shed new light on the incident, the secrets that lay at its heart, and the massive search for the missing document. A multitude of consequences came out of that single event—a testimony to the power of secrecy during the Cold War and to the ways in which a few pages, improperly situated in spacetime, can set off an unexpected chain of events.[1]

A split physics community, a secret design

To understand how Wheeler came to be in such a troubling situation, we must know what the document in question was and why Wheeler, of all people, had it with him on a train in the first place. The H-bomb document was no ordinary technical report: It was a bureaucratic weapon aimed directly at its creators' political enemies.

The detonation of the first Soviet atomic bomb in 1949 sent many US policymakers and scientists into a tailspin. Physicists Edward Teller and Ernest Lawrence argued that the only sane response was a vigorous effort to build the next generation of nuclear weapon: the "Super," or hydrogen, bomb. They found a receptive audience in Lewis Strauss, a member of the Atomic Energy Commission (AEC), who took up the cause with vigor.

Scientists had contemplated the idea of a bomb powered by nuclear fusion as early as 1942, and they had discussed it throughout World War II and even the postwar period. Any fusion reaction clearly would need to be powered by the energy from a fission bomb, and the technical difficulty of such a design, coupled with the US focus on building up an adequate supply of fission bombs, meant that little progress was made until 1949.

As the push by Teller, Lawrence, and Strauss gathered political converts, especially in Congress, it also caused a schism in the US physics community. For those who wanted the US to have an H-bomb, it was an inevitable next step. Opponents, however, questioned the H-bomb's military necessity, morality, and feasibility. J. Robert Oppenheimer, the former head of Los Alamos during the war, strongly opposed it, as did Enrico Fermi, I. I. Rabi, James Conant, and other members of the AEC's General Advisory Committee. Their argument rested on the fact that nobody had a good idea of how to make the "Super" in the first place, and it was not yet clear whether one could be built at all.

In January 1950 President Harry Truman concurred with the recommendations of his National Security Council and ordered the AEC "to continue with its work on all forms of atomic energy weapons, including the so-called hydrogen or superbomb."[2] The H-bomb lobby appeared to have won, for the moment. But the win came at a cost: an increasingly bitter disagreement within the physics community. The H-bomb's opponents saw its supporters as wanting weapons of genocide, whereas supporters saw their opponents as being dangerously naive about the safety of the nation and the world. And one of the most vigorous supporters of the H-bomb program was Wheeler.

B is for bomb

After his stint at Hanford during World War II, Wheeler returned to his academic post at Princeton, but after the Soviet detonation, he quickly volunteered to join the H-bomb work. He initially expected that he would move to the Los Alamos laboratory to work on the project, but difficulty in recruiting top scientific talent to New Mexico dictated a change of site. Wheeler would instead create an H-bomb project, which ultimately received the code name of Matterhorn B, at Princeton. The B stood for "Bomb."

There was one small problem: Neither Wheeler nor anyone else had a good idea of how to make a working H-bomb in early 1950. The main idea Teller and others had pursued at Los Alamos, nicknamed the "Runaway Super," increasingly seemed unworkable. But in March 1951, a collaboration between Teller and mathematician Stanislaw Ulam produced a new design that seemed like it might just work.

The key feature behind the so-called Teller–Ulam design was that it took the x-ray radiation from an exploding fission bomb and used it to compress a mass of fusionable material to a very high density before trying to heat it and begin thermonuclear fusion. In retrospect, that might seem straightforward, but at the time it was highly unintuitive to the weapons designers, who believed that the trick to making an H-bomb work was to discard the initial and seemingly useless burst of radiation.[3]

Considerably more details needed to be worked out, but scientists, including H-bomb skeptics like Oppenheimer, immediately recognized that the Teller–Ulam design's application of radiation implosion was likely a workable approach. Its success was demonstrated at the "Mike" test of Operation Ivy in November 1952 (see figure 2). Mike exploded with the force of more than 10 million tons of TNT. That event inaugurated the megaton age with 700 times more energy than the first atomic bomb.

The Mike device, however, could not be easily converted into a military weapon. It required some 80 tons of cryogenic equipment to keep its hydrogen (deuterium) fuel in a liquid state—not exactly something that could be carried on an airborne bomber. As of late 1952, the US knew how to build an H-bomb but had none that it could actually use.

So 1953 was a precarious time for advocates of the H-bomb. A fission–fusion bomb had been shown to be feasible in concept but was not yet a true weapon. It was also on the cusp of what many in the US national security establishment dubbed "the year of maximum danger," in which the Soviet Union for the first time would be in a position to deliver a surprise nuclear attack against the US homeland.

FIGURE 1. JOHN ARCHIBALD WHEELER in the early 1950s. This portrait was also Wheeler's FBI file photo. (Courtesy of the AIP Emilio Segrè Visual Archives, Wheeler Collection.)

A secret history, a dark vendetta

Even before the success of the Mike test, early supporters of the H-bomb program were feeling vindicated. Scientists such as Teller had argued that the H-bomb could be built in a relatively short amount of time, and they had turned out to be correct, though that did not bring them relief. They were still bitter about criticism from Oppenheimer and others, and they felt that US national security had been harmed by opposition to the H-bomb program. They began to wage a secret war against their opponents in the hope of removing them from power. The weapon they would use was history.

In early April 1952, the chairman of the AEC, Gordon Dean, attended a meeting with Secretary of State Dean Acheson to listen to a briefing led by Teller on the history of the Super. Teller's key argument was that Los Alamos scientists knew the Super was a sure thing as early as 1946—something he certainly believed, but most others did not. He claimed that in attendance at the conference where that conclusion was aired was none other than Klaus Fuchs, the physicist who had been arrested as a major Soviet spy in early 1950. In Teller's view, the effort to build the H-bomb had been, and still was, inadequate at Los Alamos, and it should be assumed that the Soviets knew nearly as much about building one as the Americans.[4]

Word of Teller's claims somehow reached the ears of physicist Hans Bethe, another Manhattan Project veteran who had opposed the building of the H-bomb but had gone to Los Alamos to work on it after Truman's 1950 order.[5] Bethe strongly opposed any suggestion that those who had cast doubts about the H-bomb's feasibility were technically wrong. He prepared his own historical counterattack. In several classified memos in May 1952, Bethe argued that the real history of the H-bomb told a very different story. The Teller–Ulam design was, Bethe wrote in a cover letter, "almost exactly the opposite" of the Runaway Super discussed at Los Alamos in 1946. Thus, if Fuchs had given that information to the Soviets and they had acted on it, "we can only be happy because they would have wasted a lot of effort on a project without military significance."[6]

News of Bethe's memos almost immediately reached the ears of the staffers at the Joint Committee on Atomic Energy, the congressional committee charged with oversight of the nation's atomic programs. The Joint Committee often operated as something of its own intelligence agency during that period of the Cold War; it looked into supposed scandals and rumors about the US nuclear program and used the information gained for political leverage. Most Joint Committee staffers had been staunch supporters of the H-bomb. Like Bethe and Teller, they saw the history of the H-bomb as a topic of utmost political relevance. One staffer even reported that the US Air Force had concluded that "the Bethe Chronology was solicited by Oppenheimer et al as a white-wash of their activities."[7] They began collecting primary source material to use in their own historical account.[8]

The Joint Committee's chief of staff, William Borden, led that historical program. Borden was a recent graduate of Yale Law School. He had secured political patronage from Senator Brien McMahon (D-CT) after writing *There Will Be No Time: The Revolution in Strategy* (1946), a book about preparing for a "nuclear Pearl Harbor," and by purchasing a newspaper ad challenging Joseph Stalin to either "atomic war or atomic peace." Borden's job, as he saw it, was to root out any forces in the AEC that might interfere with the "atomic abundance" he felt the US ought to have. He was particularly suspicious of Oppenheimer; he disliked the scientist's positions, had heard rumors about political skeletons in his closet, and interpreted what others saw as charm and charisma as the sinister signs of a hidden agenda.[9]

Borden wanted to compile a history that would appear authoritative and objective. It would be based almost entirely on documentary sources—records of meetings, memorandums, reports, and even secret patent applications. The documents would be arranged in chronological order to give the impression of maximum disinterestedness. However, Borden's approach heavily favored Teller; as an H-bomb enthusiast, Teller had deliberately salted the official record with his overly optimistic assessments of the Super's progress and potential.[10]

Throughout 1952 Borden and his assistants compiled their H-bomb history. Their goals were transparent: The group wanted to show that the AEC, and Oppenheimer in particular, had at least been negligent with regard to the H-bomb's development, and at worst may even have been trying to sabotage the program. The group received considerable help from pro-H-bomb scientists working for the air force and the AEC, whom they spoke with regularly.

Borden's team completed a draft of the history, a 91-page document titled *Policy and Progress in the H-Bomb Program*, in January 1953. Figure 3 shows the document's title page. It was classified as top secret because it contained the entire history of the development of the first successful H-bomb design. That kind of centralization of sensitive information was generally frowned on, as it went against the policy of compartmentalization ("need to know"), but it was crucial for the staffers' argument. The authors proudly acknowledged the unusual nature of the document in the introduction: "So far as known, no similar document is in existence."[11]

Wheeler's no good, very bad day

Wheeler met with one of Borden's top staffers, John Walker, for more than three hours in early June 1952. He quickly became one of the staffers' most important confidential sources in their quest to show that the H-bomb program had been mismanaged. Wheeler's knowledge of the H-bomb program and the physics involved was deep, and his anger at those who had, in his mind, slowed its development was intense. As he put it a year later, he felt that "the professional hand-wringers who kept us from getting [the H-bomb program] under way… have much to answer for."[12]

Walker met with Wheeler again in December 1952 to show him a draft copy of *Policy and Progress in the H-Bomb Program*. Wheeler thought it a "conscientious and extremely illuminating review of the U.S. effort and lack of effort in the thermonuclear field," as he later recorded in a deposition to the FBI.[13]

In early January 1953, a six-page extract from the final draft was sent to Wheeler at his office in Princeton. Covering a "key phase" in the bomb's development, the extract was arguably the most sensitive portion. Walker had learned that Fuchs and John von Neumann had worked on a version of radiation implosion as early as 1946. The Fuchs–von Neumann thermonuclear weapon had even resulted in a secret patent application.

The fact that radiation implosion, in any form, was being entertained in 1946 would have been interesting in itself. Having Fuchs, the spy, as a coauthor made the extract seem absolutely incendiary—even though the Fuchs–von Neumann design was ultimately somewhat confused and used radiation implosion in a minor way. Modern scholars agree that the Fuchs–von Neumann proposal did not contribute materially to the final development of an H-bomb in either the US or the Soviet Union.[13,14]

The complete contents of the six-page extract are still classified today, but Wheeler later summarized the pertinent facts in a helpfully numbered list:

> 1. U.S. is on the way to a successful thermonuclear weapon.
>
> 2. There are several varieties of the thermonuclear weapon considered to be practical.
>
> 3. Lithium-6 is useful. [i.e., as a solid fusion fuel]
>
> 4. Compression is useful.
>
> 5. Radiation heating provides a way to get compression.[13]

As of January 1953, those facts were the crown jewels of the US thermonuclear program. They drew a clear path from the fission bomb to multimegaton weapons and showed how the US had gotten out of the conceptual trap that was the Runaway Super.[13]

Because the topic required considerable technical sophistication, Walker reached out to Wheeler for his assistance in composing the final version. Wheeler agreed to read a draft, which arrived at Princeton on 5 January. Despite being perhaps the most important technical section of the entire top-secret history, it was only classified as secret; a higher classification would have made it much harder to transmit to Wheeler. By virtue of running Project Matterhorn B, Wheeler had a high-grade Q security clearance, but top-secret documents could be sent only by armed guard, whereas secret documents could be sent by registered mail.

The document went into Wheeler's office safe at Princeton. He had plans to be in Washington, DC, on 7 January to consult with representatives from the US Naval Research Laboratory on an unrelated project. A plan formed in his mind: He would take an overnight train from Princeton to Washington on 6 January, review the H-bomb history extract on the train, and meet with the Joint Committee staff to deliver his comments and corrections by hand.

A train ride between Princeton and Washington does not take all night—in 1953 it was a little over three hours. But if Wheeler spent the night in a Pullman car (see figure 4 for a schematic), he could avoid the extra inconvenience of checking into a hotel. He would take the train and sleep in a bunk. The train would begin its journey in the middle of the night and arrive at Washington's Union Station early the next morning. The porter would wake Wheeler at a reasonable hour, and he could dress and tidy up before leaving the train. From there, he would head directly for his meeting near the Capitol, do his part to combat the enemies of the H-bomb, and return to Princeton by train that evening.

Like many well-made plans, this one would not come to pass.

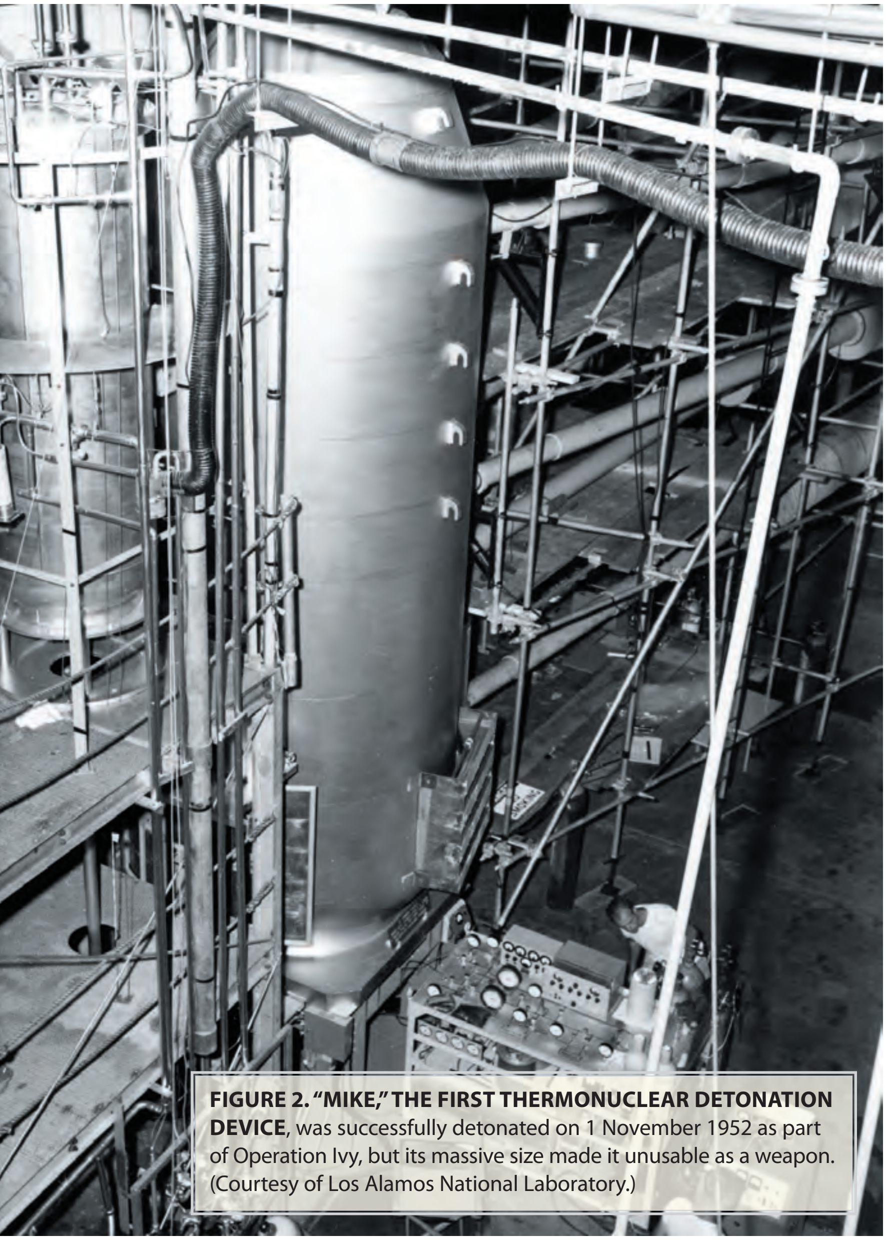


FIGURE 2. "MIKE," THE FIRST THERMONUCLEAR DETONATION DEVICE, was successfully detonated on 1 November 1952 as part of Operation Ivy, but its massive size made it unusable as a weapon. (Courtesy of Los Alamos National Laboratory.)

The fateful trip

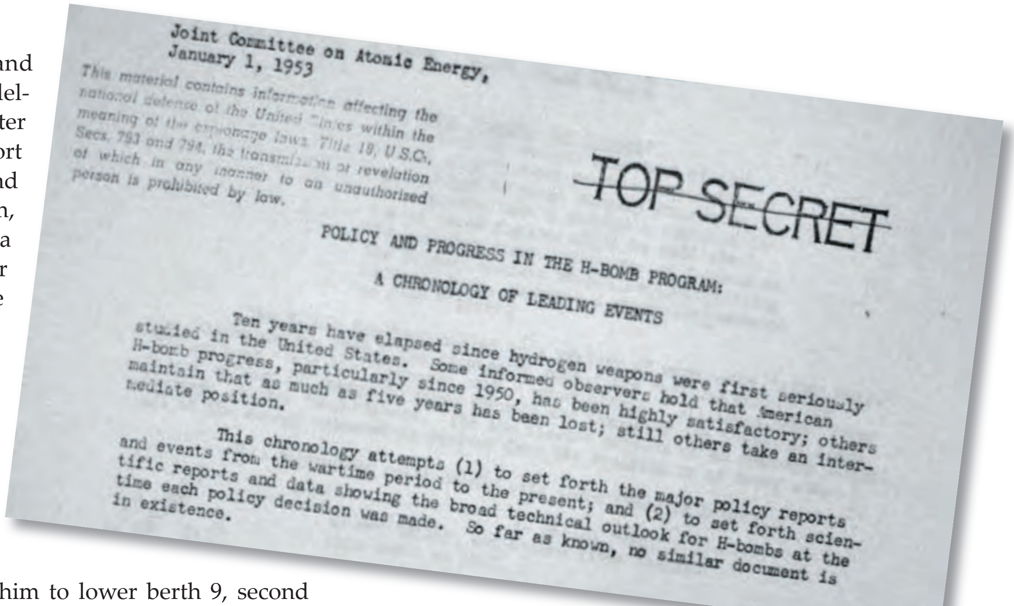
The chronological account that follows comes from recently released files, created as part of the FBI's intensive investigation into what happened to Wheeler and his secret document on that trip.[15]

Tuesday, 6 January 1953, around 1:00pm, Wheeler's secretary called to make a reservation for two people on a Washington-bound Pullman sleeper train leaving from Philadelphia. An example of the train car is shown in figure 5. Around the same time, Wheeler telephoned Jay Berger, a colleague at Princeton, to tell him they would both have business with the Naval Research Laboratory in Washington the following day and would be taking the train that night.

At 4:50pm Wheeler signed out two documents from his safe in his secretary's presence. One was the extract of the secret H-bomb history, the other was unrelated classified work. He put the secret history into a white envelope and put both classified documents inside a manila envelope, which he put in his suitcase. He then went home and had dinner.

Wheeler was picked up by a taxicab from his house in Princeton at 8:45pm and was taken, along with another passenger, to the Princeton train station. He boarded a train to Princeton Junction.

Wheeler arrived at Princeton Junction at 9:01pm and made his way to board a train to Trenton. Berger was on the same train, but he and Wheeler did not see each other. Wheeler later admitted that he was avoiding Berger because he did not want to talk to him. Their train arrived at Trenton by 9:17pm. Wheeler sat in the Trenton station waiting room. He took both documents out of the suitcase, but he did not read the H-bomb history. By 9:29pm, both he and Berger were on a train to Philadelphia, although once again they did not have contact with one another.


Joint Committee on Atomic Energy,
January 1, 1953

This material contains information affecting the national defense of the United States within the meaning of the espionage laws, Title 18, U.S.C., Secs. 793 and 794, the transmission or revelation of which in any manner to an unauthorized person is prohibited by law.

~~TOP SECRET~~

POLICY AND PROGRESS IN THE H-BOMB PROGRAM:

A CHRONOLOGY OF LEADING EVENTS

Ten years have elapsed since hydrogen weapons were first seriously studied in the United States. Some informed observers hold that American H-bomb progress, particularly since 1950, has been highly satisfactory; others maintain that as much as five years has been lost; still others take an intermediate position.

This chronology attempts (1) to set forth the major policy reports and events from the wartime period to the present; and (2) to set forth scientific reports and data showing the broad technical outlook for H-bombs at the time each policy decision was made. So far as known, no similar document is in existence.

FIGURE 3. THE TITLE PAGE OF *POLICY AND PROGRESS IN THE H-BOMB PROGRAM*, the top-secret history of the hydrogen bomb that William Borden hoped would discredit his opponents.[11]

At 10:06pm Wheeler and Berger's train arrived in Philadelphia. Berger, according to later interrogation, went for a short walk around the station to find shaving supplies. At 10:10pm, Wheeler boarded car #101 of a Pennsylvania Railroad sleeper car heading to Washington. The car was a Pullman 3410 model featuring 12 double berths, one private drawing room, and two lavatories (see figure 4). The berths were convertible from seats into upper and lower beds. Privacy for the berths was provided by a set of curtains.

Wheeler's ticket assigned him to lower berth 9, second from the end on the right-hand side of the train. Wheeler immediately went to his berth, which was already converted to its sleeping mode. He buttoned the privacy curtains and undressed. In his testimony to the FBI, he said that at that point he sat in bed, removed the H-bomb history from the two envelopes, and read it. His memory of reading it was vivid, for he made notes in the margins in pencil and was later able to reconstruct those notes.

Wheeler later said that when he finished a little after 11:00pm, he believed that he replaced the history into its white envelope, put that back inside the manila envelope, put the envelope back in the suitcase, and then wedged the suitcase between himself and the wall. That was, even for a secret document, inadequate security protocol, as Wheeler later admitted. He then slept.

Other passengers joined the train over time. Some had bought their tickets ahead of time, like Wheeler. Some bought them just before boarding, paid in cash, and left little in terms of documentation—at most, a signed name. The car was only about half full, and no one had been assigned the bunk above Wheeler's.

At 11:30pm, according to the porter on duty, Berger returned. He asked the porter for the passenger list, hoping to connect with Wheeler. He was denied the list per standard Pullman policy. Berger gave up on seeing Wheeler and went to his own assigned bunk, berth 10, not knowing he was directly across from Wheeler. Berger then slept.

On Wednesday, 7 January, at 2:43am, the train left Philadelphia. At 5:15am, it arrived at Washington's Union Station. Wheeler reported waking twice in the night, each time rechecking that his suitcase was undisturbed.

At 6:45am the porter, Robert Jones, woke Wheeler at the time Wheeler had earlier specified. Wheeler took his suitcase and walked to the men's lavatory at the other end of the train. At 6:50am he put his shaving gear and his suitcase, with the manila envelope inside it, on the washstand. An unknown man entered and used the wash basin beside Wheeler. Wheeler left his suitcase on the counter, took the manila envelope with him into the men's "saloon" (toilet stall), and closed the door. Finding nowhere to put the envelope, he wedged it between some pipes and the wall, just under the window on his right. He used the toilet. He exited the stall, continued washing up—and then realized he had left the envelope wedged against the saloon wall.

At that point two other men were using the wash basins and another man was occupying the toilet stall. Not letting decorum get in the way of security, Wheeler climbed on the washstand and attempted to peer through the metal grate on the toilet door. He could not see the envelope, but he could see the other man on the toilet and could see that he was not reading anything. Wheeler watched him until he finished his business and opened the door, at which point Wheeler ran in behind him and grabbed the manila envelope from behind the pipes. It did not seem tampered with.

No doubt breathing a sigh of relief—and no doubt seeming odd to his fellow riders—Wheeler continued washing up, shaved, put the envelope and his shaving gear back in his suitcase, and went back to his berth. There he finished dressing. Jones directed him to sit in berth 6, which had been converted into its daytime sitting mode. While waiting for Berger to appear, Wheeler thought to check on the document. At 7:20am, he opened his suitcase and took out the manila envelope. The white envelope, which had contained the secret of the H-bomb, was not inside.

Berger left berth 10 at 7:45am and, for the first time on the trip, saw Wheeler, who was in a panic. He had found the porter and was securing his help in searching the train. Berger was assigned the role of watching Wheeler's bags while Wheeler and Jones went through the dirty linens from Wheeler's berth and searched the lavatory and the trash. No white envelope. Going through his suitcase again, a deeply distraught Wheeler began tearing up anything that was no longer of value (magazine articles, unclassified correspondence) and strewed them as confetti on the train's floor.

At 7:55am, per railroad regulations, car #101 had to be vacated for the day. Wheeler and Berger left and immediately searched Union Station for the other men who had been in the

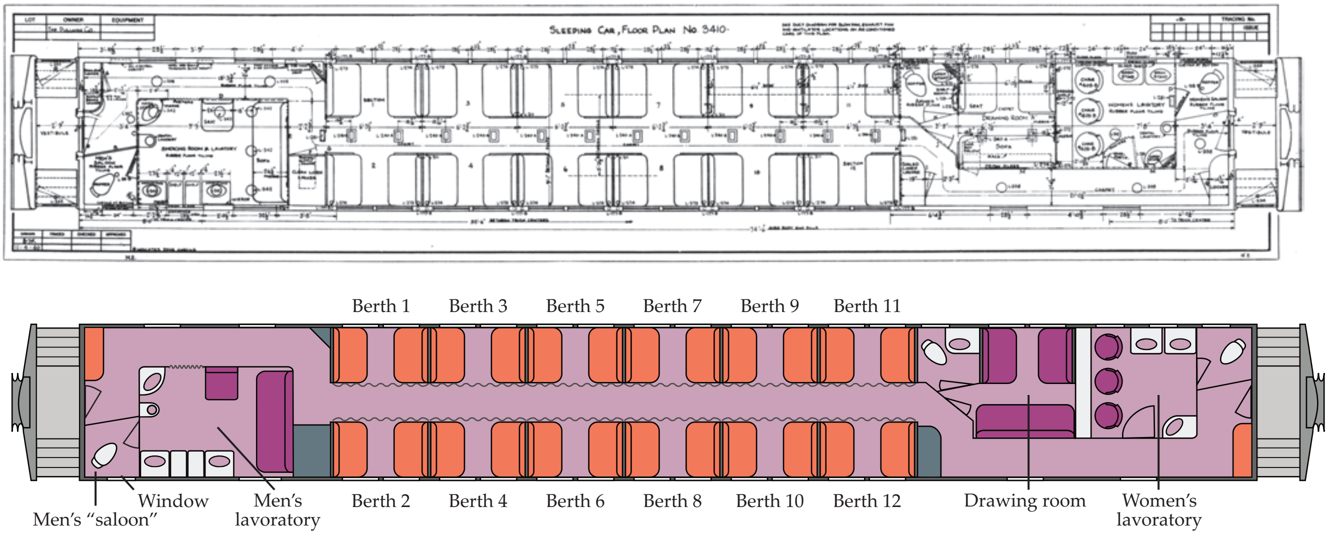


FIGURE 4. SCHEMATIC DRAWING OF THE PULLMAN CAR where John Wheeler spent the night on 6 January 1953. On top is the Pullman Company's original diagram. (Image courtesy of Newberry Library, Chicago.) On bottom is the author's rendering of the car.

lavatory. The search was futile. In a depressingly desperate act, they went to the station's lost-and-found office. Nobody had turned in any documents containing the secret of the H-bomb. Likely contemplating their futures, they ate breakfast at the station, then headed over to the nearby congressional Office Building where the Joint Committee staff were waiting.

Search and investigation

By 9:30am Wheeler had told the staffers, including Borden, what had happened. They all headed back to car #101, which had since been moved to the railroad yards, to search it again. They found nothing. They secured an official hold on the car so it would not be sent out again and put a lock on the door. Borden was beginning to panic—he had just participated in the loss of the secret of the H-bomb, and had done so while waging a private conspiracy against the AEC. Much more than merely his career was on the line. Mishandling nuclear secrets was legally punishable by jail time, fines, and even, in extreme cases, the death penalty. Around noon, giving into his desperation, Borden did the only other thing he could think of: He called the FBI, told them they had lost a document, and begged for help.

The agent that Borden spoke to was initially unimpressed. Finding the lost documents of congressional staffers is not, Borden was informed, within the FBI's mandate. Borden then told him that it involved thermonuclear weapons secrets. That got the agent's attention. The FBI sent over agents to interview Borden and Wheeler near the Capitol. Wheeler, by the FBI's account, was almost totally incoherent with panic.

The FBI agents found the situation incredibly odd. Shouldn't the AEC be involved in a case of lost nuclear secrets? Did Borden intend to alert them? No, Borden said, he did not. The FBI could tell them, he explained, but *he* was not going to. The agents quickly realized that this was a situation of some delicacy and intragovernmental intrigue.

FBI agents explained the situation to AEC officials two days later and found them livid, both about the loss of the document and about Borden's silence. How, the officials wondered, did Joint Committee staffers decide it would be a good idea to concentrate the secrets of the H-bomb in a single document and then handle that document with such lax security measures? There was a delicious irony to the whole thing—the Joint Committee staffers had hoped their secret history would show that the AEC officials had been negligent toward the development of the H-bomb. Instead, AEC officials were now in a position to argue that it was the staffers who had damaged national security by being reckless with secrets.

J. Edgar Hoover, the notorious head of the FBI, became directly involved with the investigation. He personally wrote letters informing the attorney general and the AEC's director of security about the investigation, and Hoover's handwriting is at the bottom of many major FBI documents about the search: "EXPEDITE. Get after all phases of this. Leave no stone unturned." The FBI special agents assigned to the investigation were given almost unlimited resources to uncover the fate of the Wheeler document.

The investigation focused on tracking down every person who might have been near the document that day and reconstructing its last known whereabouts. They scrutinized bit players like the person who shared Wheeler's cab to the train station and embarked on a largely fruitless effort to track down the other people on the train. The handwriting for the registry of passengers was so bad that the FBI's forensic handwriting laboratory, supposedly the best in the nation, simply had to give up. The FBI even showed Wheeler photographs of people who had been at rallies to protest the imprisonment of the Rosenbergs in the hope that he might recognize one of them from the washroom. He did not.

Three people received special focus. One, of course, was Wheeler himself, who was interviewed multiple times and gave a formal deposition to the FBI. As one agent put it, they wanted to know "every step he had taken, persons with whom he had talked, whether he had gone home after receiving the document, how he had gone to the train, whether he had called anyone, how long he had been at each place, what he did with the document at every step and, in fact, his actions should be traced minute by minute."[16] The FBI files don't seem to suggest

FIGURE 5. AN ADVERTISEMENT FOR THE UNION PACIFIC RAILROAD circa 1950, depicting a Pullman sleeper car. The car in the image is configured for daytime seating. (Union Pacific Railroad, PD-US.)

reading it that night on the train and that it was somehow swept up into the trash and destroyed. But if that were true, it would be impossible to verify. The FBI could not discount the possibility that foreign agents, through one route or another, might have acquired it—they simply lacked any evidence for it. They had, unsatisfyingly, no closure either way.

The fallout

AEC officials were furious to learn about the loss of the document. They had a long list of reasons for their anger. For one, the secret of the H-bomb might have been compromised. For another, the entire affair had revealed the Joint Committee staff's conspiracy against them. To add insult to injury, one of their own scientists, Wheeler, had been at the center of both of those problems.

On paper, the AEC looked like a powerful organization. It made the country's atomic bombs, after all. But in the political ecosystem of Washington, it was actually quite weak. What the AEC's relationship with the military was meant to be was never entirely clear. The AEC also lacked natural allies; even the scientists were ambivalent toward commission personnel, and scientists were never a powerful lobby in the US. The AEC's only real political autonomy derived from the president—if he supported it, it was strong; if he abandoned it, it was weak.

So it is understandable what AEC officials did after they got the news of Wheeler's loss: They went to newly elected President Dwight Eisenhower and told him that Congress had lost the secret of the H-bomb. Eisenhower had received the full copy of Borden and Walker's H-bomb history a few days before he received that call, and he may have misunderstood the news; at times, he appears to have believed that the *entirety* was lost, not just Wheeler's six pages.[18]

Note that the efforts of Borden, Walker, and the other Joint Committee staff were not well known among the congressmen who served on the Joint Committee. Borden's patron McMahon had apparently approved the plan before his early death from cancer, though no documentary evidence of that approval has survived. McMahon's successor on the committee, Representative Carl Durham (D-NC), gave his approval to continuing the work. But none of the other 16 members of the committee appear to have been informed that such a document had been created, let alone lost.

So Sen. William Knowland (R-CA) was more than a little surprised when Eisenhower called him aside to berate him about Wheeler's mishap during an event at the Congressional Club; Knowland told other members of the committee that he had never seen the president so agitated. Eisenhower then summoned the chairman and vice chairman of the committee to the White House to give them a dressing down. The president also asked Hoover to give him a daily report of the investigation—hence Hoover's own sense of urgency.

that anyone thought Wheeler was some kind of spy—for one thing, it would be a dumb way to go about spywork, and nobody thought Wheeler was dumb. But the FBI did seem to have considered him something of a klutz.

Another suspicious character was Berger, Wheeler's colleague. Where, exactly, did he go in Philadelphia before boarding the train? Why did Berger work so hard to locate Wheeler? Berger's interviews also contained inconsistencies. Perhaps those inconsistencies were due to slips of memory, but the FBI speculated that maybe he really had something to hide.

The other character who received multiple interviews was Jones, the porter for car #101. He was the only one awake in the car all night long, and his records for when people entered and left were crucial. Like all Pullman porters, Jones was African American at a time of segregation and overt racism, when civil rights leaders and unions alike were targeted by the FBI as potential Communist sympathizers. On the basis of his job and race, and on his relative proximity to the lost six pages, Jones was instantaneously rendered suspect.

The FBI also got deeply involved in the minutiae of Pullman trains. How exactly did walk-on tickets work? What happened to paper trash found on the trains? (It was disposed of in a vat of lye.) If trash fell between the floorboards somehow, where would it end up? Diagrams of the specific train car circulated among various FBI offices in the vain hope that somewhere in that top-down view of berths and bathrooms, an answer would materialize. The car itself was "completely dismantled," according to the chairman of the AEC. There were even discussions about having agents walk the entirety of the line between Philadelphia and Washington to look for the missing paper, but instead the agents sought the help of the regular track walkers who were in charge of inspection.[17]

Ultimately, the FBI's efforts were in vain. They had only so many places to look and people to interview. No truly promising leads ever arose. They concluded that the most likely scenario was that Wheeler didn't put it back in the envelope after

An emergency session of the Joint Committee was convened two days later. The congressmen were furious at their staffers run amok. Borden was summoned to a closed session and asked to account for his role in the creation and loss of the document.

Borden argued that the staffers should not be blamed if Wheeler, their brilliant scientific consultant, had not followed regulations correctly. Furthermore, he insinuated that a bit of counterconspiracy might be at work. AEC personnel, he explained, would be "less than human" if they were not "somewhat fearful" of his damning H-bomb history. Perhaps, Borden argued, they should not take the AEC's indignation at face value—at the very least, the AEC was likely making a big deal out of the Wheeler incident to deflect attention from its own failures.[19]

The politicians understood, though, that what mattered here was not whether the study was intellectually valid, not whether the regulations had been followed precisely, and not whether it was Wheeler's or Borden's fault that the document was lost. What mattered was that Borden had put the committee in a bad position with respect to the president and the AEC. The now-declassified transcript of the meeting records reveal Sen. Eugene Millikin (R-CO) unleashing scathing criticism at Borden.

Millikin: "What was the idea? What crossed your mind to think that this is the thing that should be done?"

Borden: "I set it in motion, Senator, and if that is wrong, then I am wrong, and you can hold me for it."

Millikin: "What can I do, shoot you?"

Borden: "Shoot me or fire me."[19]

The committee chose the less violent option. Someone had to take the fall, so Borden was quickly dismissed from his job. Wheeler got off with a personal reprimand from AEC chairman Gordon Dean, who in a memo expressed the organization's "extreme displeasure and concern" with him and his actions. As Dean told the Joint Committee later, Wheeler was just too important to punish. "We do not see anything we can do above that at the moment. We still want him in the program. He is a very valuable man, and we do not know anything else we can do without cutting off our nose to spite our faces." The committee concluded that if you give a man numerous secret documents, over the course of time he is bound to lose a few.[20]

For Wheeler, the consequences probably hurt his pride more than anything else. Whenever he needed his security clearance renewed, the FBI would dig up the entire sorry episode again, but that was it. The loss of the H-bomb secret does not seem to have affected his career trajectory.

But the story does not end there. After being fired, Borden went back into private law practice. His initial suspicions of the AEC blossomed into an obsession with a conspiracy theory. What if the AEC had been behind the loss of the document? He began to believe that Oppenheimer himself, long an object of his suspicions, had somehow induced Wheeler to lose the document. For the rest of 1953, Borden would conspire—with help from other enemies of Oppenheimer—to bring Oppenheimer down, one way or another.

The culmination of that activity was a letter that Borden wrote to Hoover in November 1953, alleging that after years of considered study he believed "that more probably than not J. Robert Oppenheimer is an agent of the Soviet Union." It was a letter he never could have written as chief of staff for the Joint Committee on Atomic Energy because it would have engendered too much political turmoil. But as a former chief of staff, not only could he write it, but it could carry some extra weight. Being fired, in a practical sense, freed Borden of having to be political about expressing his fears.[21]

Borden's letter to Hoover contained no new evidence against Oppenheimer, but Oppenheimer's enemies—most notably Strauss, who in July 1953 had been appointed the new chairman of the Atomic Energy Commission—seized on it as an excuse. Strauss went to Eisenhower, who decreed that a "blank wall" needed to be erected between Oppenheimer and US nuclear secrets.[21] Oppenheimer was given the chance to accept that in silence or to contest it. He chose the latter.

Thus the infamous Oppenheimer affair, with its tortuous security hearing and humiliating termination of Oppenheimer's security clearance, was set in motion. The Oppenheimer affair is regularly cited as a pivotal moment of the Cold War, a direct blow to scientists' autonomy as government advisers and a reassertion of bureaucrats' control over nuclear weapons policy. And it was set in motion by six pieces of paper occupying the wrong place in spacetime, as Wheeler might have put it.

The unsolved mystery

People lose papers every day. But losing six pages of *secrets* is something unusual. The Cold War weapons state required vast infrastructure for the generation and policing of secrets and for the control of those who dealt in them. That a six-page text could lead to such a momentous realignment of power is a testimony to the almost totemic quality such secrets acquired.

The Wheeler affair was the locus around which forces that had been building for years—the H-bomb debate, the classification system of the security state, rivalries between government agencies, the state of atomic politics in the high Cold War—suddenly crystallized, with wide-ranging consequences. The incident derailed at least two careers—Borden's and Oppenheimer's—and put the livelihoods of many others in jeopardy, including Wheeler, the Pullman porter, anyone else on that train, and even the FBI agents tasked with getting results at any cost.

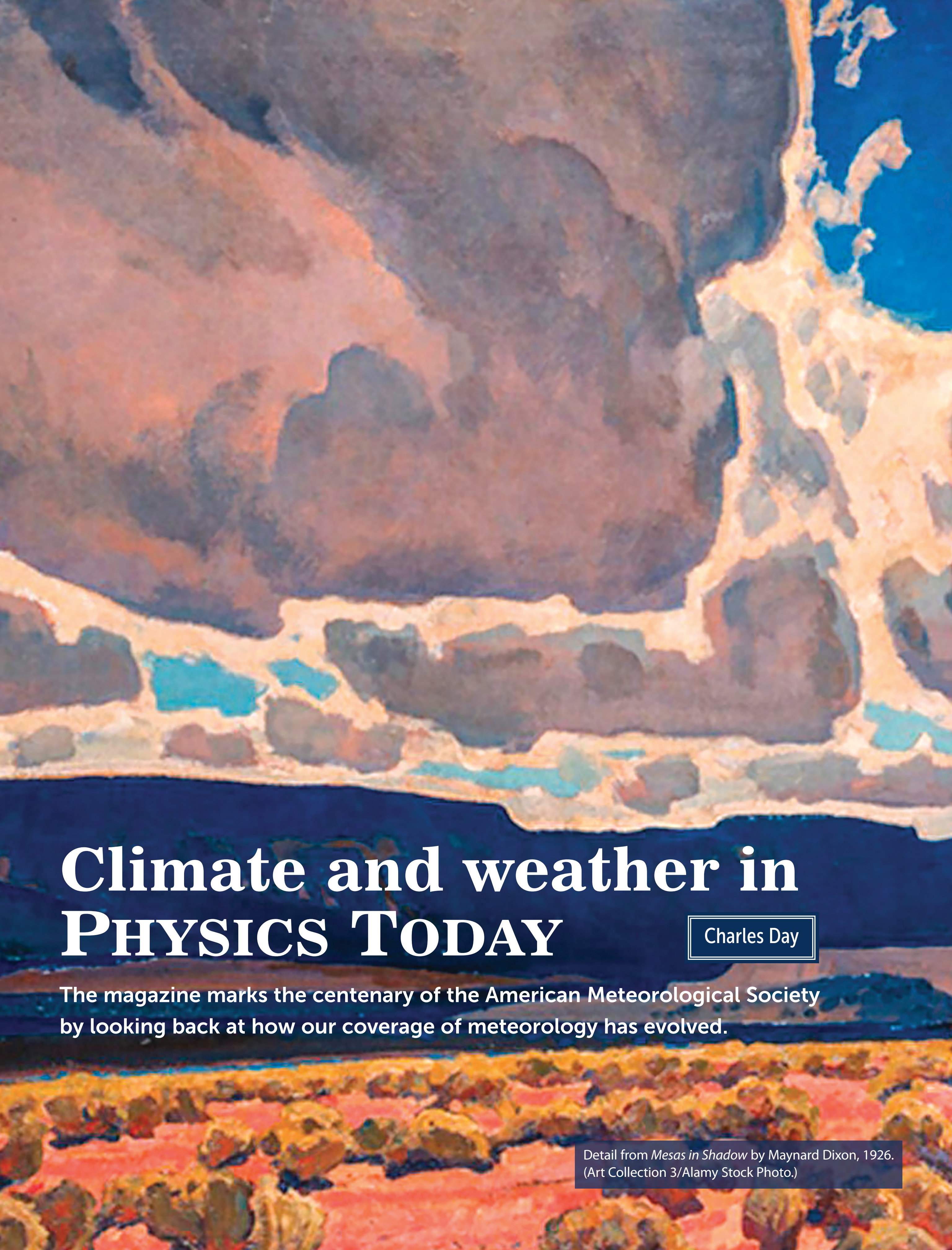
So what happened to the document? If anybody truly knows, they have not said. Did Wheeler just lose it harmlessly? As the FBI continued to reinterview Wheeler, his confidence in his memory got more uncertain. Did he really put the document back into the white envelope, and the white envelope back into the manila envelope, after he had read it? In later interviews, Wheeler backed off from his certainty: Maybe he didn't. Maybe it somehow got lost in the sheets of the bed. Perhaps it was simply lost and thrown away, seen by no eyes except Wheeler's, but that would be impossible to verify.

Did a foreign agent somehow acquire it? The document has not shown up in a foreign archive, but that doesn't necessarily mean it wasn't taken. On the other hand, it would have been odd for a foreign agent to have stolen only one of the two secret documents in Wheeler's manila envelope. And since the end of the Cold War, Soviet intelligence agencies have proudly revealed and bragged about their other atomic spying successes. If the intelligence agencies could steal credit for the Soviet H-bomb away from dissident physicists like Andrei Sakharov, they probably would have done so by now[22] (see the article by Alex Wellerstein and Edward Geist, PHYSICS TODAY, April 2017, page 40).

I like to imagine that the porter found it at some point after the hunt for it was well under way and, realizing that it was nothing that an African American working man in the early 1950s wanted to be involved with, immediately disposed of it. Did that happen? Probably not—but in the vacuum created by a lack of information, the imagination soars.

REFERENCES

1. J. A. Wheeler, K. Ford, *Geons, Black Holes, and Quantum Foam: A Life in Physics*, W. W. Norton (1998), p. 284; G. Herken, *Brotherhood of the Bomb: The Tangled Lives and Loyalties of Robert Oppenheimer, Ernest Lawrence, and Edward Teller*, Henry Holt (2002), p. 257; R. G. Hewlett, J. M. Holl, *Atoms for Peace and War, 1953–1961: Eisenhower and the Atomic Energy Commission*, U. California Press (1989), p. 34.
2. C. Hansen, *The Swords of Armageddon: U.S. Nuclear Weapons Development Since 1945*, vol. 2, 2nd ed., Chukelea (2007), p. II-112.
3. K. W. Ford, *Building the H Bomb: A Personal History*, World Scientific (2015), p. 7; see also ref. 2, vol. 1, p. I–97.
4. G. Dean, diary entry (1 April 1952), document NV074390, and J. Walker to B. Borden, memorandum (3 May 1952), document NV0311527, Nuclear Testing Archive, Las Vegas, NV.
5. S. S. Schweber, *In the Shadow of the Bomb: Oppenheimer, Bethe, and the Moral Responsibility of the Scientist*, Princeton U. Press (2000).
6. H. Bethe to G. Dean, cover letter to memorandum (28 May 1952), quoted in D. Hirsch, W. G. Mathews, *Bull. At. Sci.* **46**, 22 (1990), pp. 26, 28.
7. J. S. Walker, "Thermonuclear Matters and the Department of Defense," memorandum (3 October 1952), box 58, Records of the Joint Committee on Atomic Energy, record group 128, series 2, National Archives, Washington, DC.
8. J. Kenneth Mansfield, memorandum (28 May 1952), and J. S. Walker, memorandum (28 May 1952), box 58, in ref. 7.
9. Ref. 1, G. Herken, p. 194.
10. R. Serber, interview by A. Fitzpatrick (26 November 1996), Niels Bohr Library and Archives, American Institute of Physics, College Park, MD.
11. Joint Committee on Atomic Energy, *Policy and Progress in the H-Bomb Program: A Chronology of Leading Events* (1 January 1953), box 60, in ref. 7.
12. J. A. Wheeler to S. Cole (1 December 1953), box 60, in ref. 7.
13. J. A. Wheeler, FBI deposition (3 March 1953), National Nuclear Security Administration, Washington, DC. Obtained through the Freedom of Information Act.
14. J. Bernstein, *Phys. Perspect.* **12**, 36 (2010).
15. F. J. Liddy Jr, "Loss of highly secret atomic energy document by Professor John Archibald Wheeler, Princeton University, January 7, 1953," memorandum (4 February 1954), John Wheeler file, Federal Bureau of Investigation, Washington, DC. Obtained through the Freedom of Information Act.
16. A. H. Belmont to D. M. Ladd (14 February 1953), in ref. 15.
17. G. Dean, testimony before an executive session of the Joint Committee on Atomic Energy (24 March 1953), box 14, in ref. 7; C. E. Hennrich to A. H. Belmont (18 February 1953), in ref. 15.
18. Ref. 1, Hewlett, Holl, p. 41; L. B. Nichols to Mr. Tolson (19 February 1953), in ref. 15.
19. Joint Committee on Atomic Energy, executive session (18 February 1953), box 12, Records of the US Senate, record group 46, app. 4, National Archives, Washington, DC.
20. G. Dean to J. A. Wheeler (1 April 1953), Office Files of Gordon Dean, record group 326, National Archives at College Park, MD; G. Dean, testimony, in ref. 17.
21. Ref. 1, Herken, p. 267.
22. G. Gorelik, A. W. Bouis, *The World of Andrei Sakharov: A Russian Physicist's Path to Freedom*, Oxford U. Press (2005), p. 180. PT



Climate and weather in PHYSICS TODAY

Charles Day

The magazine marks the centenary of the American Meteorological Society by looking back at how our coverage of meteorology has evolved.

Detail from *Mesas in Shadow* by Maynard Dixon, 1926. (Art Collection 3/Alamy Stock Photo.)

Charles Day is the editor-in-chief of Physics Today.

The American Meteorological Society was 29 years old when the first issue of Physics Today was published in May 1948. Then, as now, the magazine's mission was to ensure that readers were kept informed about what was going on across the spectrum of physics and its related sciences regardless of their own specialties. At the turn of the past century, meteorology was largely a qualitative, observational science. But by 1919, when the AMS was founded, it was increasingly a quantitative, physical science. By 1948 the transformation was well underway.

Did Physics Today's coverage of weather and climate recognize and reflect that transformation? As I discovered when I went through the magazine's back issues, the answer is yes—but only partially and with some odd biases. What those biases were and what they might mean form the impetus of this article. But before I begin my exploration, I should say my use of "meteorology" embraces all the fields represented in the current portfolio of AMS journals. Physical oceanography qualifies, as do the economic effects of weather and climate on society.

Meteorology made a propitious debut in Physics Today with the publication in the fourth issue of "Down to the sea," a feature article by the director of the Woods Hole Oceanographic Institution, Columbus O'Donnell Iselin. His opening lines were doubtless intended to grab attention.

> Physical oceanography has been, until recently, the most unsuccessful of the geophysical sciences in enlisting the aid of physicists. Laboratory-trained, they have preferred to remain in their laboratories rather than set up their instruments in as unfavorable an environment as a small vessel. This has been exasperating to that small group of scientists having a burning desire to understand the physical aspects of the earth and its surrounding atmosphere.

In retrospect, Iselin's feature represents a style of meteorological article that continues to appear in Physics Today. An author introduces a natural phenomenon, confidently presumes readers are interested in it, and then goes on to explain the underlying physics. Hans Panofsky's feature article from December 1970, "Analyzing atmospheric behavior," fits that successful pattern, as do "Climate models" by Kenneth Bergman, Alan Hecht, and Stephen Schneider (October 1981); "Modeling oceanic and atmospheric vortices" by David Dritschel and Bernard Legras (March 1993); "Sprites, elves, and glow discharge tubes" by Earle Williams (November 2001); and "Unraveling the mysteries of megadrought" by Toby Ault and Scott St. George (August 2018).

That consistency in features, however, was not matched by abundance of coverage for most of Physics Today's history. No meteorological articles appeared in 1950–52, and just 13 did in 1953–69. The paucity of meteorology lasted until the 2000s, when articles and news stories about climate change began to frequent the magazine's pages.

In December 2013 AMS joined the American Institute of Physics, and its members began to receive Physics Today as a result. In the 12 months before, and without regard to AMS joining the institute, the magazine published the feature articles "Water in the atmosphere" by Bjorn Stevens and Sandrine Bony and "The Arctic shifts to a new normal" by Martin Jeffries, James Overland, and Don Perovich. News stories appearing in that year covered stream networks, global warming, and carbon capture.

The upswing in meteorological coverage began in the mid 1990s and arose, in part, from the determination of my predecessor as editor-in-chief, Stephen Benka, to broaden the magazine's editorial scope beyond condensed matter, particles, and other so-called mainstream physics. Accounting for the decades-long dearth is more challenging, because it entails figuring out why people *didn't* do things.

Thirty years of fluid dynamics

The September 1978 issue of Physics Today included a feature article by Raymond Emrich and four coauthors to celebrate the 30th anniversary of the American Physical Society's division of fluid dynamics (DFD). The article began with following lines:

> Interest in fluid dynamics as a separate field of physics with its own set of problems came about largely as a result of experiences during World War II. Until that time, the various events occurring in fluids were usually thought of as problems in mathematics or engineering.

The opening would have puzzled readers in Britain and France, where physicists have been doing research in fluid dynamics for more than a century. Joseph Boussinesq, Maurice

MEMBERS OF THE METEOROLOGY PROJECT at the Institute for Advanced Study (IAS) in Princeton, New Jersey, in 1952. Left to right: Jule Charney, Norman Phillips, Glenn Lewis, Norma Gilbarg, and George Platzman. One of the earliest electronic computers, the IAS machine, is in the background. Project member Joseph Smagorinsky took the photo. (Courtesy of the AIP Emilio Segrè Visual Archives, gift of John M. Lewis.)

Couette, Lewis Richardson, George Stokes, G. I. Taylor . . . (I could go on) were all born in the 19th century.

Despite the DFD's efforts, the status of fluid dynamics in the US as a field of physics has been equivocal. Given that much of meteorology is applied fluid dynamics, it's conceivable that meteorological coverage in PHYSICS TODAY might have suffered from that uncertain status—not directly, perhaps, but as a consequence of the magazine's stable of advisers not regarding fluid dynamics as physics.

Evidence of that bias is manifested in the pages of PHYSICS TODAY in three ways. First, fluid dynamics has been covered even less frequently than meteorology. Second, the field itself has been underfunded in the US, presumably because of priorities set by physicists who advise and work for funding agencies. In 1986 a committee of the National Research Council published the 168-page report *Physics through the 1990s: An Overview*. The report was the focus of an April 1986 special issue of PHYSICS TODAY. Fluid dynamics appeared in the article on plasmas and fluids, whose author, Bruce Schechter, observed, "Many areas of fluid physics are neglected by the university research community simply because of a complete absence of support."

The third and most recent manifestation of bias was a column by the late Jerry Gollub in the October 2008 issue. Gollub decried the absence of fluid dynamics in undergraduate physics curricula in the US. Fluid phenomena, he argued, are ubiquitous, relevant, and, if taught well, accessible.

Earth is the oddball

The Search and Discovery department made its debut in PHYSICS TODAY's January 1967 issue. From then on, meteorological research papers were candidates for news coverage. The department's first meteorological story reported observations of the atmosphere of Venus by two space probes, the Russian *Venera 4* and the US *Mariner 5*. "Earth is the oddball" was the subtitle of that January 1968 story.

The story did not cite any publications or presentations, but subsequent meteorological stories did. Many of them covered research published in *Science*. If *Science* had an outsized influence on PHYSICS TODAY, what sort of meteorology did the august journal publish?

Readers of *Science* from the late 1940s to the early 1960s received an oddly limited view of meteorology. In August 1948, for example, geologist William Herbert Hobbs contributed an article entitled "The climate of the Arctic as viewed by the explorer and the meteorologist." Biologist Frits Went wrote in October 1950 about the effects of climate on plants. Veterinarian Glenn Van Ness wrote in November 1953 about the effect of climate on blue comb, a disease that afflicts young hens in summer.

In the late 1950s and early 1960s, a new concern appeared in *Science*: modifying climate. Meteorologist Morris Neiburger contributed a long research article in October 1957 about the effects of smog on climate, notably in Los Angeles. Meteorologist Harry Wexler wrote in October 1958 about large-scale weather modification. When I encountered the two articles, I recalled that Walter Orr Roberts had written on climate modification for PHYSICS TODAY's August 1967 issue.

In the 1970s and 1980s, *Science*'s meteorological coverage increased. Most of it was about pollution, aerosols, planetary atmospheres, paleoclimate, and the effects on agriculture. Then, in the late 1980s, ozone depletion and climate change became more prominent in *Science* and its rival, *Nature*. Ozone, planetary atmospheres, and paleoclimate duly appeared in PHYSICS TODAY's news pages.

My own meteorological reporting followed that blinkered tendency to look only to *Nature* and *Science*. My first story reported on the tracking of 110 kg of a tracer, sulfur hexafluoride, that had been released in the South Atlantic Ocean at a depth of 4000 m (PHYSICS TODAY, March 2000, page 18). The experiment's goal was to determine how water from different depths mixed vertically. The paper, by James Ledwell, appeared in *Nature*.

What did we miss?

In her book *Weather and Climate* (2007), historian of science Kristine Harper provides a decade-by-decade survey of advances in meteorology. From the chapter on the 1940s, I learned of the University of Chicago's Thunderstorm Project, the largest field campaign of its time. Five radar-equipped P-61 aircraft flew into thunderstorms over Ohio and Florida in 1946–47. Ground-based radar tracked balloons that had been released as tracers. From that data trove, the project's scientists identified for the first time the three stages of thunderstorm formation.

The first stage, cumulus, occurs when daytime solar heating of the ground drives the formation of clouds in moist air. The storm enters the second, mature, stage when the cloud grows so large and heavy with water that rain falls while air continues to rise through the cloud. The two opposing flows, up and down, cause lightning to accompany what becomes heavy rain. In the third stage, dissipation, the updraft peters out, the rain becomes lighter, and the cloud disappears, starting from the bottom.

That momentous finding[1] did not make it into the pages of

PHYSICS TODAY. Others the magazine missed include Edwin Fisher's 1956 finding that warm ocean water provides most of a hurricane's energy,[2] Edward Lorenz's 1963 discovery that weather depends so sensitively on initial conditions that forecasting beyond 10 days is impossible,[3] and Jacob Bjerknes's proposal that the El Niño off the coast of Peru and the Southern Oscillation responsible for Asia's monsoons are manifestations of the same interannual phenomenon.[4]

PHYSICS TODAY might be excused for overlooking individual papers, but the magazine pretty much failed to cover the early advances in numerical weather prediction. Joseph Smagorinsky was the founding director of the US Weather Bureau's Geophysical Fluid Dynamics Laboratory. He was one of the originators of numerical weather prediction and its application to model Earth's climate. His 1963 paper[5] "General circulation experiments with the primitive equations: I. The basic experiment" has been cited almost 7000 times. Regrettably, Smagorinsky's name did not appear in PHYSICS TODAY until this article.

A hint of an explanation for the magazine's meteorological blind spots can be found in the career of another pioneering climate modeler, Jule Charney. He and Smagorinsky were among the meteorologists recruited by John von Neumann after World War II to work on numerical weather prediction at the Institute for Advanced Study in Princeton, New Jersey.

Von Neumann is best known to physicists for his work on quantum mechanics, game theory, and the theory of computation. He became and remained interested in numerical weather prediction because he had determined that it was feasible with the rudimentary computers of the time. Charney ran his computer model for the first time in 1950 and published his momentous conclusions a year later.[6]

Charney favored publishing his research in meteorological journals. Of his 44 major publications, only five appeared in a journal, *Proceedings of the National Academy of Sciences*, whose editorial ambit extended beyond meteorology. The same preference is manifest in the meteorological milestones that I cite above: All were published in AMS journals. Past editors of PHYSICS TODAY apparently did not seek research published in meteorological journals.

Climate change

How has PHYSICS TODAY covered climate change? The first article to address changes to Earth's climate was Roberts's 1967 feature, "Climate control." Among the influences on climate that he discussed were changes in solar luminosity, ash blasted into the atmosphere by volcanoes, and secular shifts in global circulation patterns. He did not mention the greenhouse effect caused by anthropogenic carbon dioxide.

Bergman, Hecht, and Schneider did not repeat that omission in their article "Climate models" in October 1981. Indeed, they wrote, "Of concern for the immediate future is increasing evidence that atmospheric concentrations of the trace gases ozone and carbon dioxide are being changed by human activities." They went on to cite predictions that a doubling of CO_2 would lead to an increase in temperature of 2–4 °C. They wrote that confidence in the predictions was premature, given their range and the oversimplifications needed in a model that could run at all.

Nine years later (February 1990) PHYSICS TODAY's Barbara Goss Levi reported on the status of climate change research. The title of her story, "Climate modelers struggle to understand global warming," captures the contestable confidence of modelers at the time, but it also reflects the fact that a rise in Earth's mean surface temperature had been measured and was increasingly uncontestable.

TOBY AULT AND SCOTT ST. GEORGE'S feature article about the decades-long droughts that afflicted the western US in past centuries was the cover story for the August 2018 issue.

In his November 1994 feature, Jeffrey Kiehl reviewed research in what remains one of the largest sources of uncertainty in climate models: the physics of clouds. A doubling of atmospheric CO_2 was one of the scenarios he considered.

One of the most significant articles that PHYSICS TODAY published on climate change was "The discovery of the risk of global warming" by historian of science Spencer Weart, which appeared in January 1997. Weart noted that Svante Arrhenius published in 1896 the first extensive discussion of the warming effect of adding CO_2 to the atmosphere. But making a strong case for the risk in the 1950s required, among other things, improvements in IR spectroscopy, better understanding of seawater chemistry, and accurate monitoring of atmospheric CO_2—all in the face of indifference and skepticism from the mainstream meteorological community.

By the 2000s PHYSICS TODAY's coverage of climate change implicitly acknowledged that it's real and that it's caused by anthropogenic carbon dioxide. In recent years, our news reporting and features have included more about the effects of climate change. For the magazine's May 2016 issue, PHYSICS TODAY's David Kramer reported on how rising sea levels threaten the city of Norfolk, Virginia, and its vast US naval station.

Climate change will continue to appear in our pages, as will weather and all the other aspects of meteorology that AMS members, past and present, have done so much to elucidate.

REFERENCES

1. H. R. Byers, R. R. Braham Jr, *J. Meteorol.* **5**, 71 (1948).
2. E. L. Fisher, *J. Meteorol.* **15**, 328 (1958).
3. E. N. Lorenz, *J. Atmos. Sci.* **20**, 130 (1963).
4. J. Bjerknes, *Mon. Weather Rev.* **97**, 163 (1969).
5. J. Smagorinsky, *Mon. Weather Rev.* **91**, 99 (1963).
6. J. G. Charney, in *Compendium of Meteorology*, T. F. Malone, ed., American Meteorological Society (1951), p. 470.

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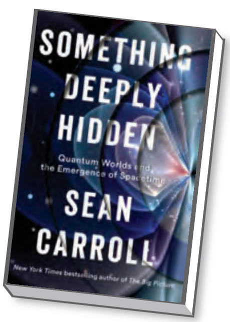
Does the many-worlds interpretation hold the key to spacetime?



Something Deeply Hidden
Quantum Worlds and the Emergence of Spacetime
Sean Carroll
Dutton, 2019. $29.00

I think I can safely say that nobody is as tired of a certain Richard Feynman quote about quantum mechanics as I am. We use it to say, "Look, this really smart person said that the theory cannot be understood, so we won't even try." The prologue of Sean Carroll's new book, *Something Deeply Hidden: Quantum Worlds and the Emergence of Spacetime*, is a polemic against that attitude, and I am thoroughly on board. Quotes like "Physicists tend to treat quantum mechanics like a mindless robot they rely on to perform certain tasks, not as a beloved friend" indicate that it is going to be an enjoyable read. To be clear, I disagree with almost every other opinion that Carroll states in the book, but the point of view he offers is one worth considering.

Carroll, a theoretical physicist at Caltech, sets himself the task of explaining the problems with quantum theory and how solving them may lead to progress in physics. He is an advocate of Hugh Everett's interpretation of quantum mechanics, the many-worlds theory. If you want to know why some people take that approach seriously and what you can do with it, then Carroll's latest is one of the best popular books on the market.

The first part of *Something Deeply Hidden* starts with a description of Everett's many-worlds view: There is only unitary evolution of a wavefunction of the universe, in terms of which everything else can be explained. It gives a concise treatment of topics such as wave–particle duality, quantum interference, Schrödinger's cat, and Einstein-Podolsky-Rosen (EPR) and Bell experiments, and it emphasizes the Everettian view on those concepts.

My only complaint about the section is its light treatment of Bell's theorem. The EPR paradox is easily resolved by imagining that quantum systems really do have definite values for each observable. Bell's theorem is needed to interpret why that solution would be problematic, but Carroll does not offer any explanation of how Bell's theorem works. Given that one of the major selling points of Everett's many-worlds interpretation is its ability to get around the limits of Bell's theorem, I would have liked to see a more detailed treatment.

The second part of the book is its real meat. Here Carroll explains how multiple worlds emerge from Everett's view, how to think about probability, and what it would be like to live in an Everettian universe. Carroll does a good job of defending Everett against common criticisms, such as that a plurality of unobserved worlds violates Occam's razor, and of explaining the role of decoherence in the emergence of worlds.

Carroll's attitude to the locality of world splitting, however, is a bit blasé for my liking. The issue is whether, when enough decoherence occurs, we should say that the entire universe splits or just the part of the universe described by the parts of the wavefunction that are entangled with the degrees of freedom causing the decoherence. To my mind, if we are to save a semblance of locality, it must be the latter. Carroll, on the other hand, says that since the concept of worlds is emergent, we should not be too bothered that there is more than one way of defining the worlds.

Physicists are used to the idea of an inherent ambiguity in defining emergent concepts—at least when that ambiguity makes no difference to the physics. But when I make a quantum measurement here on Earth, there are either immediately more moons than before or the same number. That seems like a real physical difference of macroscopic significance. More to the point, it seems like it should matter for the issue of whether Everett's many worlds really resolves the tension of Bell's theorem.

The middle section ends with a chapter on alternative interpretations, such as de Broglie–Bohm theory, spontaneous collapse theories, and quantum Bayesianism. Although Carroll charitably says he is glad others are studying those approaches, it comes off as disingenuous because he gives all of those theories bad reviews. For example, he makes a big deal of the alleged difficulties coming up with a Bohmian version of quantum field theory, but he later argues that QFT should emerge from a more fundamental discrete theory, whereas stochastic Bohm-like models for such discrete theories are known. Not that I want to advocate Bohmian theories myself, but the alternatives to Everett are not as hopeless as Carroll makes them out to be.

In the third part of the book, Carroll describes recent work by himself and others that aims to derive spacetime as emergent from quantum theory. If we look at the vacuum state of a QFT, it tends to have entanglement correlations between regions of space that decrease with the distance between those regions. The idea is to invert that relation and define space in terms of the entanglement entropy between systems in a substrate of finite-dimensional quantum systems. More ambitiously, Carroll envisages defining the areas of surfaces in spacetime in terms of entanglement and using those areas to construct a metric. That is one version of the "it from qubit" approach, which has become popular in recent years.

Noticing that two quantities are always the same and then trying to construct a theory in which they are identical has been a route to progress in the past. The fact that inertial and gravitational masses are always the same is just a coincidence in Newtonian mechanics, but their necessary identities played a part in constructing general relativity.

Correlation, however, does not always imply identity. Often, a numerical correlation between two quantities is explained by the laws of a theory rather than by a literal identity of concepts. In the case of entanglement and metric, it seems that we have a perfectly good explanation in terms of laws: The locality of the Hamiltonians of QFT, combined with the fact that the initial state is close to the vacuum state, means that entanglement will drop off with distance. If a credible quantum theory of gravity grew out of that approach, I would change my tune, but I do not see strong evidence of that.

Although I am skeptical of many of the ideas described in this book, I still think it is an excellent one. A great deal of uncertainty about the foundations of quantum theory remain—more than most physicists are willing to admit—so naturally we all disagree. This is a masterful popular account of one approach, but for true balance, you are going to have to read a lot of other books alongside it.

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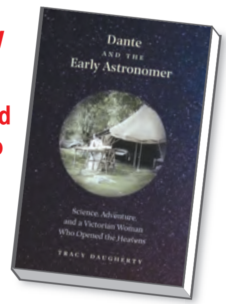
Astronomer's biography skimps on the science

Dante and the Early Astronomer
Science, Adventure, and a Victorian Woman Who Opened the Heavens
Tracy Daugherty
Yale U. Press, 2019. $26.00



Although the lives of select female astronomers, such as Caroline Herschel, have been well documented, books about women who conducted astronomical studies before the 20th century are generally few and far between. In *The Hidden Giants* (2006), Sethanne Howard reported on the lives and contributions of women scientists, including astronomers, throughout 4000 years of history. More recently, Dava Sobel told the story of Harvard computers in *The Glass Universe: How the Ladies of the Harvard Observatory Took the Measure of the Stars* (2016).

When I first heard about Tracy Daugherty's new book, *Dante and the Early Astronomer: Science, Adventure, and a Victorian Woman Who Opened the Heavens*, what most piqued my interest was the subtitle. I was expecting to read about the scientific contributions of yet another female astronomer whose story has been hidden or relegated to footnotes. I also expected to learn more about Dante and how Mary Acworth Evershed (née Orr), the Victorian woman in the title, interpreted his astronomy as written in his poetry.

The title, however, is misleading.

Although Daugherty includes some information about Mary Evershed and her work, how she "opened the heavens" is not the primary focus. The author, a distinguished professor of English and creative writing emeritus at Oregon State University, has penned an imaginative account that focuses instead on Mary's husband, John, and other male astronomers with whom the couple interacted, including E. Walter Maunder. I found this read to be less the story of a woman astronomer and more the story of John (mostly) and Mary (sometimes). The science is scarce, and the adventure consists of travelogues and descriptions of everyday life at an observatory in India at the start of the 20th century.

Mary made two major contributions to astronomy. Based on her own observations, she created the first thorough atlas of southern stars, which was published in 1897. She also documented the history of the named lunar craters in a 1938 publication. Both contributions indeed "opened the heavens," but the author spends just a few paragraphs describing them and glosses over the scientific details. In contrast, Daugherty uses a little over four pages to describe what we currently know about the Sun.

Dante and the Early Astronomer also spends a great deal of time describing John's struggles as director of the observatory in Kodaikanal, India. We read details about its less-than-modern infrastructure and its poor-quality and poorly maintained equipment. We also learn, multiple times, about John's own dissatisfaction with his place in history and his potential legacy as a solar astronomer.

The title of the book is borrowed from Mary herself, who published the original *Dante and the Early Astronomers* in 1913. But Daugherty provides us with few references to her interpretations of Dante's publications. The author tells us—often, and without citation—that Mary ruminated on the accuracy of Dante's cosmography in *The Divine Comedy* but does not clearly relay the importance of her contributions. The frequent mentions of Mary's doting attention to John's mental and physical health overshadow the science and adventure I was promised in the subtitle.

As stated on the jacket, the book is a "creative tale" written by an author who brings "keen skill as a fiction writer." But Daugherty takes too much artistic license when telling the story of Mary and John as a couple. He provides a great deal of speculation without much support. For example, based on a casually draped arm in one photo, Daugherty suggests that John had an adulterous affair with a family friend who cared for Mary while she was ill; he eventually married the woman after Mary's death. Furthermore, the author's description of astronomer Annie Maunder as "frumpy," Mary as "gaunt," and John as "handsome and distinguished" in a photo from one of their last excursions together reminded me of recent conversations about journalists' tendency to describe women in ways in which they do not describe men.

Even with those flaws, Daugherty's material on the operations of the observatory, including the focus on obtaining solar data and the lifestyle of its astronomers, is enlightening. Descendants of John's employees carry on the work at Kodaikanal today. I also appreciated the interwoven story of the Eversheds' reactions to astronomical observations that changed our views of the heavens and the challenges they faced chasing solar eclipses to prove the theory of general relativity. Mary's persistence and self-direction in teaching herself about astronomy was also well described.

If you can read *Dante and the Early Astronomer* as a work of creative history, then you may gain some insight into the life of Mary Orr Evershed. The bibliography is extensive, and I surmise that readers can learn more about Mary from the historical primary sources. However, as a stand-alone read, the title's promise of "science" from a "woman who opened the heavens" goes unfulfilled.

Nicolle Zellner
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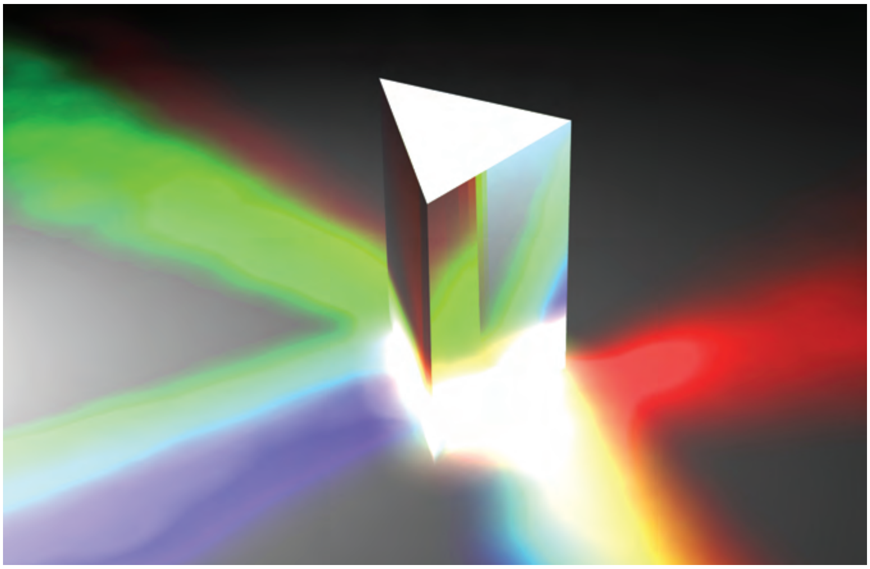

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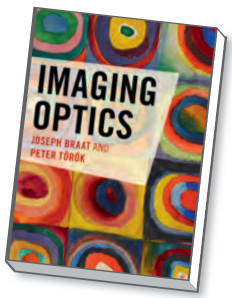
Connecting optical theory to practical applications



Imaging Optics
Joseph Braat and Peter Török
Cambridge U. Press, 2019. $99.99

My first reaction upon receiving a copy of *Imaging Optics* by Joseph Braat and Peter Török could have been, "Do we really need a new book on optical imaging?" But after reading their work, I am convinced that we do. *Imaging Optics* brilliantly complements an already well-supplied field that includes such classics as *Principles of Optics* by Max Born and Emil Wolf (7th edition, 1999).

Imaging Optics establishes a clear connection among the electrodynamic theory of optical propagation, the various approaches to diffraction theory, and the practical methods used in the design and optimization of imaging systems. The book's way of linking those topics is original, as is the way the text moves from the conceptual aspects of optics to immediately usable practical results. The ability to transition smoothly between theoretical foundations and practical methods is one of the book's best features. Examples include the transition from Maxwell's equations to geometrical optics and lens design and the combined use of vector diffraction and coherence theories to describe recent imaging approaches that utilize light polarization. The depth of the content and great coherence in the presentation reflect the extensive teaching experience of both authors. In addition, each of the book's three parts begins with a historical discussion that provides illuminating context for their topics.

Part 1, "Electromagnetic Theory in the Optical Domain," covers the propagation of electromagnetic waves in isotropic media. Readers will appreciate the comprehensive treatment of Gaussian beams. The section also covers multilayer and periodic geometries and a useful introduction to specific numerical methods. The authors devote a full chapter to propagation in anisotropic media, with a clear discussion of conical diffraction. My only concern is the treatment of material dispersion, a topic overlooked in the first two chapters. The issue of dispersion is only addressed in chapter 3 with the introduction of metamaterials. That chapter also offers an interesting introduction to the concept and limitations of a perfect lens.

In part 2, "Geometrical Theory of Optical Imaging," Braat and Török start with a derivation of the laws of geometrical optics from first principles and then move on to introduce the concept of a characteristic function and its use in practical situations. The next chapter presents an analysis of aberration in the framework of geometrical optics, including a clear classification of the different types of aberrations and a detailed calculation of the Seidel aberration coefficients. The section finishes with two chapters that describe imaging systems and examine their optimization. Those chapters will be very useful to readers concerned with learning the basic methods for designing components and imaging systems.

Part 3, "Diffraction Theory of Optical Imaging," reviews the theory of diffraction and its applications, from the complete vector to the scalar theory. The section's ultimate goal is to characterize imaging systems beyond geometrical optics. Here formal theories are smoothly connected to practical methods that are illustrated with real examples, such as scanning confocal microscopy and the imaging of fluorescent molecules embedded in a multilayer structure. I thought the in-depth treatment of the subtle problem of calculating the fields in the focal region was a strong point in this section, and I also appreciated the discussion of the relationships between the different theoretical approaches to diffraction.

The authors then cover diffraction in the presence of aberrations, including a detailed presentation of the Nijboer–Zernike theory, and give an analysis of imaging systems in terms of a transfer function. Part 3 ends with a chapter on vector imaging that uses polarization degrees of freedom. The beautiful explanation of the underlying theory merges concepts and methods from diffraction and partial coherence theories. The chapter gives readers a glimpse into an active field in optical imaging research. I suffered one little frustration: Scanning near-field optical imaging was omitted, which is unfortunate since it is an interesting technique both conceptually and because of its broad range of applications.

Imaging Optics contains a high level of technical detail, but its content can be approached at different levels, from conceptual to technical and applied. The authors' success at creating a complete, precise, and pedagogically effective text should make *Imaging Optics* not only a good choice for students, but also a useful reference book for physicists and engineers interested in the design, development, and optimization of optical imaging systems.

Rémi Carminati
ESPCI Paris
Paris, France

NEW BOOKS & MEDIA

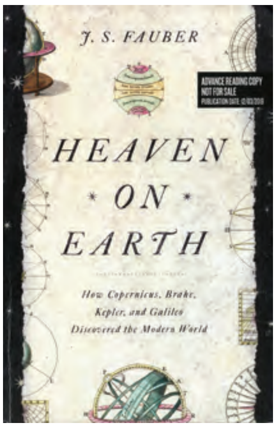
Science Vs

Wendy Zukerman

Gimlet, 2016–present

In this lively 30-minute podcast, host Wendy Zukerman explores the science on controversial topics from health fads to political issues. Recent shows investigated the scientific evidence around cannabis oil as a pain reliever, the use of emotional-support animals, and the neurological risks of playing American football. Episodes often incorporate historical arcs to put their science in context. For instance, a recent episode titled "Race: Can We See It in Our DNA?" tackled the ugly history of scientists' support for eugenics. New episodes are released Thursdays.

—MB



Heaven on Earth

How Copernicus, Brahe, Kepler, and Galileo Discovered the Modern World

L. S. Fauber

Pegasus Books, 2019. $29.95

The publication of Nicolaus Copernicus's heliocentric model of the solar system in 1543 kicked off a revolution in humans' understanding of the cosmos. In *Heaven on Earth*, computer scientist L. S. Fauber weaves together biographies of Copernicus and three of his successors—Tycho Brahe, Johannes Kepler, and Galileo Galilei—who strove to collaborate across great geographical distances to improve the Copernican system. Fauber's vivid narrative provides insight into his subjects' personal lives and their scientific work and highlights the obstacles posed by the social, political, and religious attitudes of the era.

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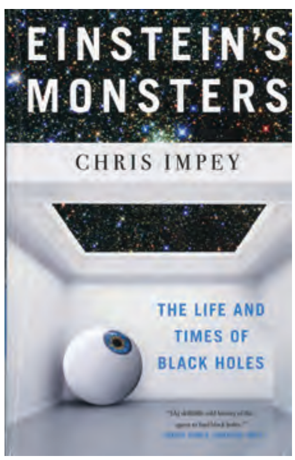


Einstein's Monsters

The Life and Times of Black Holes

Chris Impey

W. W. Norton, 2019. $16.95 (paper)

"Black holes are the best known and least understood objects in the universe," according to astronomer Chris Impey. He attempts to rectify that deficiency with his new book, *Einstein's Monsters: The Life and Times of Black Holes*, in which he combines a history of their discovery with a presentation of current knowledge regarding their birth and effects on the universe. Along the way, he discusses the many astronomers and physicists whose work contributed to our present understanding. The book's title, Impey says, was inspired by the work of Albert Einstein, whose theory of gravity jump-started the search for these invisible yet powerful phenomena that lie at the heart of all galaxies.

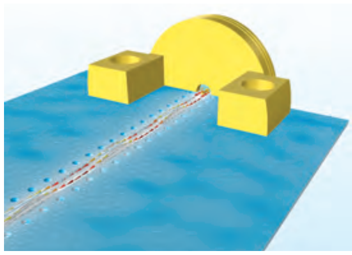
—CC PT

Focus on software, data acquisition, and instrumentation

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

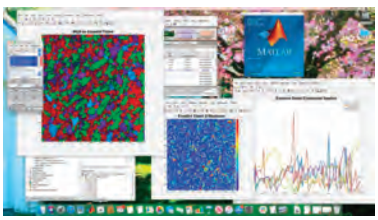
Andreas Mandelis

Multiphysics circuit simulation

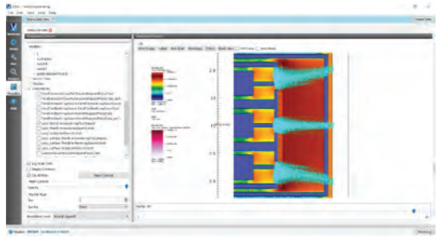


Comsol has announced advances in its Multiphysics software to support microwave and RF users working on 5G, internet of things, automotive radar systems, and satellite communications. Designers can model printed circuit-board materials and study how they affect the performance of microwave and millimeter-wave circuits. Connectors and low-loss materials are key components of electronic devices and systems, and they must work reliably in circuits that transmit and receive information. Comsol Multiphysics users can couple electromagnetic simulations with heat transfer, structural mechanics, fluid flow, and other physical phenomena to represent real-world physics effects. They can accurately investigate designs and benefit from the virtual prototyping capabilities that multiphysics simulation offers. ***Comsol Inc***, *100 District Ave, Burlington, MA 01803, www.comsol.com*

Mathematical programming software



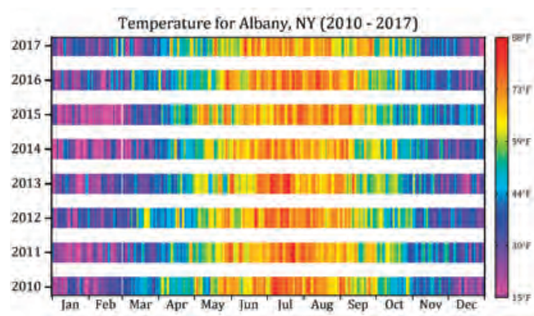
MathWorks has introduced version 2019b of its MATLAB and Simulink software. New features include training resources for event-based modeling and support for artificial intelligence and robotics. MATLAB's Live Editor Tasks allow users to interactively explore parameters, preprocess data, and generate MATLAB code that becomes part of the live script. A new Simulink Toolstrip helps them discover and access capabilities as needed. To help users train advanced network architectures, the Deep Learning Toolbox provides such features as custom training loops, automatic differentiation, shared weights, and custom loss functions. The Automated Driving Toolbox delivers support for 3D simulation in the automotive industry, including the ability to develop, test, and verify driving algorithms. ***The MathWorks Inc***, *1 Apple Hill Dr, Natick, MA 01760-2098, www.mathworks.com*



Multiphysics simulation software

Tech-X has released VSim 10, the latest version of its flexible multiphysics simulation software tool. VSim is designed to run computationally intensive electromagnetic, electrostatic, and plasma simulations for complex materials used on systems ranging from laptops to supercomputing clusters. To simulate complex geometries, it uses finite-difference time-domain methods with structured orthogonal meshes that feature cut-cell boundaries. Geometries can be imported from computer-aided-design models or constructed in the VSimComposer graphical user interface. Maxwell's equations are solved in the presence of charged particles using particle-in-cell and charged-fluid methods. VSim comes with prebuilt examples to help users get started in simulation. Among the enhancements in VSim 10 are improved electromagnetics example simulations, a new Drude–Lorentz MIM waveguide, and new example simulations of microwave devices and plasma discharges. ***Tech-X Corporation***, *5621 Arapahoe Ave, Ste A, Boulder, CO 80303, www.txcorp.com*

Data analysis and graphing software



Version 2019b of OriginLab's data analysis and graphing software, Origin and OriginPro, adds more than 75 new features, apps, and improvements. HTML Reports lets users choose either Markdown or HTML syntax to create custom reports that include graphs, analysis results, and metadata information. Reports can be embedded into a workbook for use as a template for batch analysis. Data Connector standardizes the process of developing tools for importing data into Origin from Web and local files. The file source and data selection details are saved in the worksheet; data can be cleared and reimported as needed. New graph types include split heat-map plots, rug plots, and heat-map plots from XY and XYZ data. Among the new apps are Speedy Fit, Quantile Regression, Hysteresis, and 2D Correlation. ***OriginLab Corporation***, *One Roundhouse Plaza, Ste 303, Northampton, MA 01060, www.originlab.com*

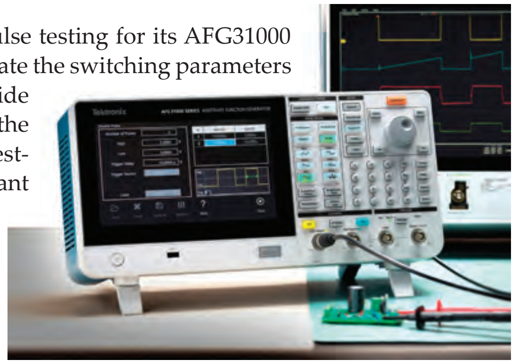
Micro gas chromatograph

Agilent designed its 990 Micro GC system to monitor the safe distribution, energy content, and odorant level of natural gas. According to the company, the micro gas chromatograph's plug-and-play architecture and smart-connected user-assist functions make it easy to install, use, and troubleshoot, and the transportable system delivers laboratory-quality data. The compact, rugged 990 Micro GC is housed in a new modular platform. Its battery life is double that of previous models and provides more than eight hours of remote operation. An optional mobile browser interface allows remote connectivity with mobile devices such as laptops and tablets and facilitates hands-free, unattended operation in places that are difficult or unsafe for humans to access. ***Agilent Technologies Inc***, *5301 Stevens Creek Blvd, Santa Clara, CA 95051, www.agilent.com*

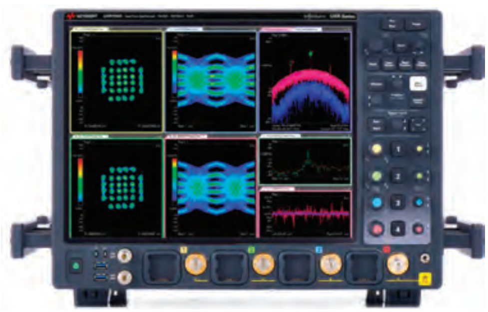
Multichannel arbitrary waveform generators

The DN6.65x series of generatorNETBOX instruments from Spectrum Instrumentation can produce multiple electronic test signals simultaneously. The arbitrary waveform generators (AWGs) offer 24 to 48 synchronous channels. According to the company, such a high channel count sets a new standard for AWGs—most conventional products only offer one, two, or four channels—and delivers a low cost per channel. Suitable for multichannel automated-testing applications, the eight variants in the series can be controlled remotely through a simple Ethernet connection to a PC or local area network. They are easy to integrate into almost any test system. The units feature 16-bit digital-to-analog converter technology and low-noise flexible outputs. They can generate almost any test signal in the DC to 60 MHz frequency range. ***Spectrum Instrumentation Corp***, *401 Hackensack Ave, 4th Floor, Hackensack, NJ 07601, https://spectrum-instrumentation.com*

Software for double-pulse testing



Tektronix has made available a software plugin that allows rapid double-pulse testing for its AFG31000 arbitrary function generator. The software enables users to measure and evaluate the switching parameters of power devices made from wide-bandgap silicon carbide and gallium nitride materials. Users can define pulse parameters from a single window on the AFG31000's large touch-screen display and generate the pulses needed for testing in less than a minute. According to the company, that represents a significant time savings compared with alternative methods. The application offers impedance adjustment of pulse width, which can range from 20 ns to 150 µs, and the time gap between each pulse, up to 30 pulses. Users can download the AFG31000 double-pulse-test software free of charge from the company website. ***Tektronix Inc****, 14150 SW Karl Braun Dr, PO Box 500, Beaverton, OR 97077, www.tek.com*



Wideband millimeter-wave measurement

Keysight has launched the first single-box, multichannel solution for wideband millimeter-wave measurements. Due to new functionality, the company's UXR oscilloscope series delivers fast, coherent analysis for wideband measurements up to 110 GHz, which could accelerate the development of next-generation millimeter-wave and satellite communications, and radar applications. The oscilloscopes offer unique bandwidth pricing: Rather than purchase the full frequency range supported by the oscilloscope hardware, users can buy just the analysis bandwidth needed. Limited only by the hardware's maximum-supported frequency range, users can also configure optional 5 GHz or 10 GHz analysis bandwidth windows within and above the UXR's natively licensed bandwidth. ***Keysight Technologies Inc****, 1400 Fountaingrove Pkwy, Santa Rosa, CA 95403-1738, www.keysight.com*

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ASSISTANT/ASSOCIATE PROFESSOR QUANTUM INFORMATION SCIENCE – PHYSICS & ASTRONOMY/CHEMISTRY

The **DEPARTMENTS OF CHEMISTRY AND PHYSICS & ASTRONOMY** in the College of Science at Purdue University invite applications for up to five positions in Quantum Information Science (QIS). These positions would be at the assistant/associate level appointments based on scholarly record. When appropriate, successful candidates may be considered for joint and interdisciplinary appointments across the College.

QIS is at the frontier of several traditional research disciplines including condensed matter physics, atomic, molecular, and optical physics, information theory, applied math and computer science, and chemistry. QIS strives to harness the unusual quantum mechanical properties of superposition and entanglement to provide breakthrough advances for computing, secure communications, and novel device functionalities. As such, QIS is part of a large-scale interdisciplinary hiring effort across key strategic areas in the College of Science—Purdue's second-largest college, comprising the physical, computing, and life sciences—these positions come at a time when the College is under new leadership and with multiple commitments of significant investment.

The College of Science is especially seeking to enhance our existing strengths in research at the interface of Chemistry and Physics and growth within Computer Science and Math through strategic hiring of creative scientists to be part of the cutting-edge interdisciplinary environment provided by Purdue University. Successful candidates will have research interests that can build a comprehensive suite of capabilities in experimental and/or theoretical quantum computing with superconducting qubits, spins in semiconductors and other condensed matter systems, cold atomic ions, Rydberg, photonic systems chemical physics, or quantum materials. Also of inherent interest for progress in this field are quantum algorithm research and information theoretic analysis.

Qualifications: Candidates must have a PhD in physics, chemistry, math, and computer science, or other fields related to QIS, with outstanding credentials in research, an excellent track record of publications and potential for developing a vibrant research program, as well as a strong commitment to excellence in teaching. Successful candidates are expected to develop a vibrant research program supported by extramural funding and teach courses at the undergraduate and/or graduate level. Applicants should submit a letter of application electronically, including their curriculum vita, summary of planned research, and a statement on teaching philosophy, to: **https://hiring.science.purdue.edu/**. Applicants should also arrange for three letters of recommendation to be uploaded. Applications will be reviewed beginning December 15, 2019, and will remain in consideration until the position is filled.

The Departments and College: The two Departments have over 100 tenured and tenure-track faculty, more than 300 graduate students, and over 500 undergraduate students between them. Over the last 5 years the two departments, Chemistry and Physics and Astronomy, have added more than 20 faculty and significant investment has been made in key areas of discovery. The College and the Departments have launched initiatives in new emerging areas, such as Data Science and Quantum Information Science, and committed the resources necessary to make the new growth impactful. For more information, see **http://www.physics.purdue.edu/** and **https://www.chem.purdue.edu/**.

Physics and Astronomy and Chemistry are part of the College of Science, which comprises the computing, physical, and life sciences at Purdue. It is the second-largest college at Purdue, with over 350 faculty and more than 6,000 students. Purdue itself is one of the nation's leading land-grant universities, with an enrollment of over 41,000 students primarily focused on STEM subjects. For more information, see **https://www.purdue.edu/purduemoves/initiatives/stem/index.php**.

Application Procedure: Applications need to be submitted to **https://career8.successfactors.com/sfcareer/jobreqcareer?jobId=8338&company=purdueuniv&username=** and must include (1) a complete curriculum vitae, (2) a publication list, (3) a brief statement of present and future research plans, and (4) a statement of teaching philosophy. In addition, candidates should arrange for at least 3 letters of reference to be sent to qissearch@purdue.edu. Questions regarding the position and search should be directed to chgreene@purdue.edu. Applications completed by December 15, 2019 will be given full consideration, although the search will continue until the position is filled.

Purdue University's Department of Physics and Astronomy is committed to advancing diversity in all areas of faculty effort, including scholarship, instruction, and engagement. Candidates should address at least one of these areas in their cover letter, indicating their past experiences, current interests or activities, and/or future goals to promote a climate that values diversity and inclusion. A background check will be required for employment in this position.

Ann Elizabeth Nelson

On 4 August 2019, the theoretical-physics community lost a giant: our supervisor, collaborator, mentor, and role model, Ann Elizabeth Nelson. We remember Ann as a remarkable physicist who pioneered models for the physical phenomena that cannot be explained by the standard model of particle physics. She was also an unequivocal advocate for diversity and inclusivity in the theoretical-physics community.

Ann was born in Baton Rouge, Louisiana, on 29 April 1958. With an undergraduate physics degree from Stanford University, she started her prolific career under the supervision of Howard Georgi at Harvard University in 1980. There Ann became fascinated with questions she would study throughout her career: What is the difference between matter and antimatter, and why is there more of the first? Since matter and antimatter mutually destruct, their respective abundances in our observable universe must be unequal.

To explain the origin of that inequality, physical theories of the early universe cannot treat matter and antimatter on the same basis: As physicists say, they need to violate *CP* symmetry, which asserts that a system is unchanged under the combined transformations of charge conjugation (*C*) and parity inversion (*P*). Experimentally, *CP* violation has been observed in interactions mediated by the fundamental weak force but not by the strong force; that theoretical conundrum has occupied physicists for decades. It speaks to Ann's brilliance that before she finished her PhD, she single-authored a 1984 paper proposing one of only two popular mechanisms that explains the apparent *CP* symmetry of the strong force. That mechanism now bears her name and that of another independent proposer, Stephen Barr.

In addition to her academic prowess, Ann cared about all aspects of the academic experiences of her junior colleagues. With classmates, she started the Harvard Puppet Show tradition, an entertaining way to prepare incoming PhD students for the peculiarities of the prestigious department. Ann enjoyed her work as a physicist and ensured that those around her did too, as is evident from the numerous online tributes ("Ann Nelson, 1958–2019," Physics Today online, 8 August 2019).

In 1987 Ann became the first tenure-track woman in physics at Stanford. A year later she moved to the University of California, San Diego. A story Ann liked to tell was that at a conference she attended as a junior faculty member, an older male colleague exclaimed, "I wasn't told there would be ladies here!" Unyielding, Ann understood that sexism and implicit bias keeps minorities and women away from academic physics, and she worked hard to dismantle those. The wake-up call she penned in 2017—"Diversity in physics: Are you part of the problem?" (Physics Today, May 2017, page 10)—is an essential read for the theoretical-physics community and beyond.

Ann and her husband-collaborator David Kaplan made their final academic move to the University of Washington (UW) in 1994. Over the course of her successful career, Ann published more than a hundred academic papers. Besides proposing innovative explanations of matter–antimatter asymmetry, she wrote seminal works on supersymmetry, the theory that extends the standard model by relating bosons and fermions, the two types of fundamental particles. She also probed electroweak symmetry breaking, a process that describes both the unification of the electromagnetic and weak forces at high energies and the origin of mass of fundamental particles. Many of her works clarified issues for the entire scientific community and are used as references for a wide array of applications. Ann never lost enthusiasm for innovative explanations of observed phenomena that she grounded in experimental verification.

At UW, Ann is remembered for her support for and engagement in social justice issues as much as for her mentorship and teaching. She wore a Black Lives Matter button in her office and signed her emails with her preferred pronouns. As


Ann Elizabeth Nelson

DAVID B. KAPLAN

an adviser, she cared deeply about the mental well-being of her students and postdocs, and she encouraged them to take email-free vacations. She gave lectures at a summer school in Palestine and voiced her opposition to a conference on cosmology and particle physics held in the occupied West Bank in 2018. UW is creating an honorary professorship in her name (see "Honoring a life of mentorship & advocacy: In memory of Dr. Ann Nelson," https://tinyurl.com/yyywr3ot).

Ann and David, both tenured professors, had two children. Their successful example of combining prolific academic careers with a rich family life serves as a model for many aspiring physicists. When one of us asked about the decision to have children, Ann replied that she simply could not imagine a life without them.

Ann and David spent their weekends and holidays trekking the mountain ranges of the Pacific Northwest together, with friends, and with their children. It was on one of those trips that she tragically had a fatal fall. Her loss to the theoretical-physics community leaves a hole that we can only fill by adopting a little more of both her curiosity and her compassion.

Djuna Lize Croon
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Vancouver, British Columbia, Canada
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TO NOTIFY THE COMMUNITY about a colleague's death, send us a note at http://contact.physicstoday.org
Recently posted notices and select online obituaries will appear in print.

George Veronis

A principal architect of geophysical fluid dynamics, George Veronis died on 30 June 2019 of natural causes. From fundamental advances in nonlinear stability theory to theoretical oceanography, his work provided frameworks for laboratory experiments and in-field observations alike.

George was born in New Brunswick, New Jersey, on 3 June 1926 to Greek immigrants. During World War II, he enlisted in the US Navy and served as a submariner in the Pacific Ocean. He attended Lafayette College on the GI Bill and obtained his BS in mathematics in 1950. He went on to Brown University for his PhD in applied mathematics, which he received in 1954 under George Morgan. Because of his navy experience and the importance of physical and mathematical sciences to the Allied war effort, he focused his thesis work on oceanographic flows.

Before Earth-observing satellites became available, researchers relied on sparse observations to understand atmospheric and oceanic dynamics. Much of the theoretical and observational focus in the 1950s centered around the behavior of currents, such as the Gulf Stream, and the general oceanic circulation, as described in the theories of George Carrier, Walter Munk, and Henry Stommel. Wind-driven circulation introduces Coriolis terms in the Navier–Stokes equations, and understanding their impact is complicated by the role of boundary geometry, among other things. So researchers turned to studies of large-scale flows in various simplified basin shapes as model problems.

A particular challenge for theorists was to incorporate the essential transient effects of wind forcing on the circulation. From the outset, George was at the cutting edge, pushing the boundaries of mathematical modeling. Hence, when John von Neumann and Jule Charney started the numerical forecasting group at the Institute for Advanced Study in Princeton, New Jersey, George was a natural candidate to hire; he moved to Princeton in 1953, before his thesis was complete.

In 1945 von Neumann proposed a high-speed digital computing system that could, in principle, solve the nonlinear partial differential equations of fluid flow. In 1953, multiple scientific computing efforts were underway. In Charney's meteorology group, George's focus was to numerically test the so-called quasi-geostrophic equations, which predict slow, large-scale motions and are insensitive to high-frequency processes such as gravity waves. He thus became intimate with both numerical analysis of differential equations and their geophysical implications.

At the institute, George met Stommel, who had a singular influence on his personal and professional trajectories. Stommel recruited him in 1956 to the Woods Hole Oceanographic Institution as a research mathematician. Fractious relations with the director led George and several others to leave in 1963 for MIT. George moved to Yale University in 1966 and was Henry Barnard Davis Professor of Geophysics and Applied Science when he retired in 2009.

Henri Bénard's observations that a layer of fluid heated from below begins to flow in a well-defined pattern beyond a critical heating motivated Lord Rayleigh in 1916 to analyze the linear stability of the heated fluid layer. In 1958 George and Willem Malkus defined the nonlinear, so-called finite-amplitude instability in the problem, and in so doing, laid down the mathematical framework for all nonlinear instabilities. One cannot overstate the impact in applied mathematics of that long and serious calculation, which provided the language and a demonstration of such nonlinear instabilities.

Perhaps motivated by that success and a like-minded milieu of colleagues, George, Stommel, Malkus, Louis Howard, Joseph Keller, Edward Spiegel, and Melvin Stern launched a summer program on geophysical fluid dynamics (GFD) at Woods Hole in 1959. Their view was that GFD, then in its early stages of development, should be treated as a subfield of theoretical physics that can provide a tapestry for the systematic education of graduate students in physical and mathematical sciences. With a modest grant, the 10-week program continues to bring together an international cadre of 10 graduate students and staff and to attract mathematically minded interdisciplinary scientists. For six decades, hundreds of graduate students have experienced its focused period of immersion in GFD. It was so influential to

George Veronis

TOM KLEINDINST © WOODS HOLE OCEANOGRAPHIC INSTITUTION

George that he viewed his career as having two intellectual homes—Yale and the GFD program.

At Yale, George taught the GFD lecture course to legions of students, and because of his central role in the evolving field, they received a cutting-edge view of it. As the director of undergraduate studies for the applied mathematics program, George exposed students to the connections between mathematics and the natural environment. His patience in research translated into his guidance of both colleagues and students. He was generous with his time and prudent with his advice.

George's memory was as legendary as his seriousness and good sense of humor. During the GFD program, he tried to teach fellows how to play softball to compete in the local league. His competitiveness was worn on both sleeves. If George felt an injustice had been dealt to a colleague or friend, he was a relentless advocate. That loyalty and support were most evident when it came to his wife and children, who were a constant source of pride and discussion. Their lakeside cottage on Crooked Pond was the last meeting place of GFD participants for nearly 60 years, and it is certainly his spiritual resting place.

Katepalli Sreenivasan
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Henry Pollack is an emeritus professor of geophysics at the University of Michigan in Ann Arbor.

Tip of the iceberg

Henry Pollack

The conditions required for an object to float in a stable orientation sometimes lead to surprising results.

The phrase "tip of the iceberg" suggests that what you see is much less than what is hidden from view. The concept of a tip above seawater and a much larger root below more or less conforms to Archimedes's principle of buoyancy: The force exerted on a body partially or completely immersed in a fluid of higher density is directed upward and is equal to the weight of the fluid that the body displaces.

When a totally submerged lower-density body is released, the buoyancy force causes it to rise until it reaches a floating equilibrium. The tip then rests above the surface and the root below it, with the mass of each determined by the density contrast between the floating solid and the surrounding fluid. Figure 1 depicts a common representation of such an equilibrium. But the configuration is pure artistic license—it does not display a stable orientation and does not exist in nature.

Sphere, cube, and cylinder

What's wrong with the image? A floating elongated iceberg can satisfy the buoyancy requirements of Archimedes's principle in many orientations, but most, including that depicted in figure 1, turn out to be unstable. To see an example of such an instability, take a wine cork and immerse it in water in any orientation. Upon release, the cork will rise to the surface and float only with its long axis horizontal—that is, parallel to the surface of the water.

An equilibrium orientation of a floating body occurs when the center of gravity (the center of mass of the whole object) and the center of buoyancy (the center of mass of just the submerged part) are vertically aligned. If perturbations from wind, waves, or melting lead to a small departure of that alignment, a torque is created that reorients the body. If the torque amplifies the misalignment, the orientation is unstable; if the torque reduces the misalignment, the orientation is stable.

What are the parameters that define a stable equilibrium orientation? A floating object must satisfy Archimedes's principle by displacing a mass of fluid equal to its own. Because the object is less dense than the underlying fluid, it projects some volume above the surface and some volume below. Thus the first parameter that determines the stable equilibrium is the density contrast between the floating body and the surrounding fluid, here defined as a ratio ρ of the two densities, with $0 < \rho < 1$.

The density of ocean water depends on both temperature and salinity; the density of ice depends on ambient temperature and the concentration of bubbles and structural voids. But an ice–water density ratio of 0.90 is accurate enough to characterize the stability of ice objects afloat in the ocean. It is behind the tip-of-the-iceberg concept because at typical densities of the two phases, about 90% of an iceberg's volume is submerged, leaving only the tip above water.

The second important parameter is the shape of the floating body. Consider a floating sphere. Once its fractional volumes

FIGURE 1. AN ARTISTIC RENDITION OF A FLOATING ICEBERG in apparent equilibrium. This orientation could never stably exist because an elongated piece of ice would float on its side, not on its head. (Image by iStock.com/the-lightwriter.)

above and below the fluid surface have been established by the density contrast, it will float stably in any orientation. But a cubic body has well-defined stable orientations relative to the fluid surface that over a wide range of densities do not include the intuitive orientations—floating with a face or edge parallel to the fluid surface or with a corner pointing upward, perpendicular to the surface. To test that assertion experimentally, just place a cube of wood in water and let it stabilize.

How will an iceberg shaped like the one shown in figure 1 establish a stable equilibrium orientation? A geometry useful for examining stability quantitatively is the circular cylinder of length H and diameter D, as shown in figure 2. When $H < D$, the cylinder is a disk, and when $H > D$, the cylinder is elongated, like a wine cork or pencil. The question raised by figure 1 is whether cylindrical bodies of ice whose lengths exceed their diameters float with their long axes perpendicular to the water surface? The answer is generally no, particularly for elongated cylinders with $H > 2D$.

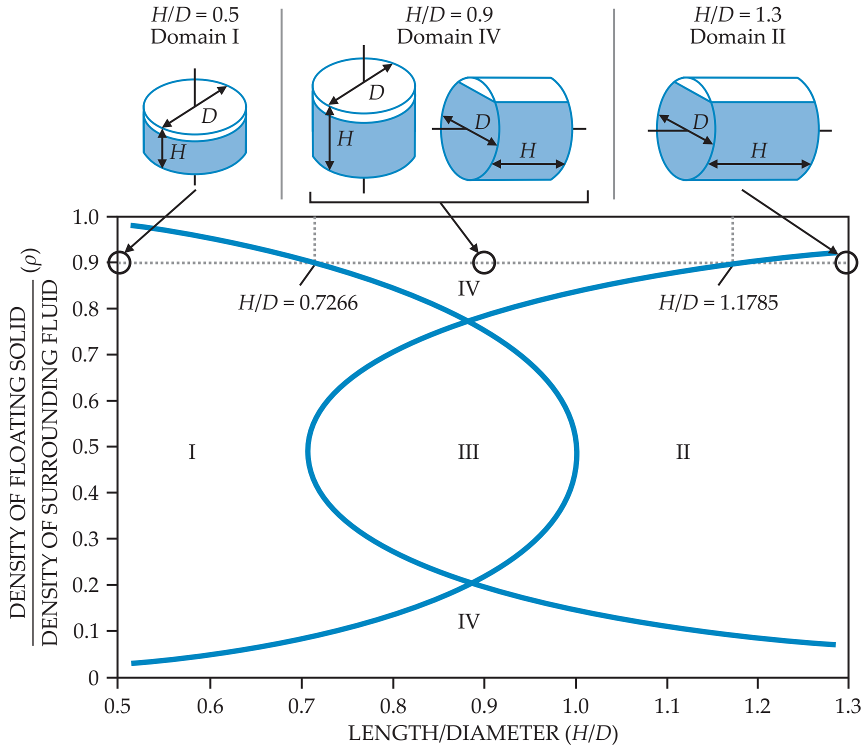


FIGURE 2. DOMAINS OF STABILITY FOR FLOATING CYLINDERS. A plot of four stability domains is shown as a function of a cylinder's shape H/D and the solid-to-liquid density ratio ρ. Each domain is characterized by the equilibrium orientation in which a cylinder will float. The dotted line at the density ratio $\rho = 0.9$ corresponds to ice floating in water. Illustrations of stable cylinder orientations in domains I, II, and IV at loci intersected by $\rho = 0.9$ are shown above the graph; their submerged roots are shaded and their above-water tips unshaded. An ice cylinder will float with its rotational axis perpendicular to the water surface when $H/D < 0.7266$, and with its rotational axis parallel to the surface when $H/D > 1.1785$. In the range $0.7266 < H/D < 1.1785$, both equilibrium orientations can coexist. (Adapted from D. S. Dugdale, *Int. J. Eng. Sci.* **42**, 691, 2004.)

The shape of stability

In 2004 D. S. Dugdale presented a useful discussion of the floating-cylinder problem. He defined four domains of stable equilibrium in density–shape space: (I) The cylinder floats with its rotational axis perpendicular to the water surface and its circular faces parallel to the water surface. (II) The cylinder floats with its rotational axis parallel to the water surface and its circular faces partially submerged to a depth dependent on the density of the cylinder. (III) The rotational axis of the cylinder is tilted at an angle neither parallel nor perpendicular to the surface. (IV) The orientations described in I and II are both stable.

Figure 2 illustrates the complexity of those domains of stable equilibrium as a function of density contrast and cylinder shape. For ice floating in water ($\rho = 0.9$), stable equilibria exist only under the conditions of domains I, II and IV; the density conditions that yield stable equilibria within domain III (that is, in the range $0.2 < \rho < 0.8$) exclude the ice–water density contrast. Therefore, ice cylinders floating in water will stabilize in only two orientations—with the cylindrical axis either perpendicular or parallel to the water surface.

In 1991 Edgar Gilbert showed that for a stable equilibrium with the cylindrical axis perpendicular to the water surface, the following condition must hold: $\rho(1 - \rho)(2H/D)^2 < 0.5$. For $\rho = 0.9$, the equation requires that $H/D < 1.1785$. A glance at the iceberg in figure 1 leaves little doubt that its H/D ratio is greater than that. So the iceberg violates the stability condition required for the cylinder to float with its rotational axis perpendicular to the water surface. It would therefore spontaneously reposition itself to an orientation with its rotational axis horizontal. In that equilibrium orientation, the waterline on the cylinder is a rectangle of length H and width w.

The width is determined by the density difference between the floating body and the fluid—that is, by how much of the cylinder is submerged. Gilbert showed that the equilibrium is stable if $w < H$. For $\rho > 0.5$, $w < D$, and all cylinders where $H/D > 1$, the condition for stability is met because $w < D < H$. The actual stability field, as determined from the condition $w < H$, is $H/D > 0.7266$, as shown in figure 2. Therefore, along the dashed line $\rho = 0.9$ and in the range $0.7266 < H/D < 1.1785$, both cylinder orientations are stable and can coexist. For $H/D > 1.1785$, certainly the case for the iceberg in figure 1, the equilibrium orientation is intrinsically unstable and does not occur in nature.

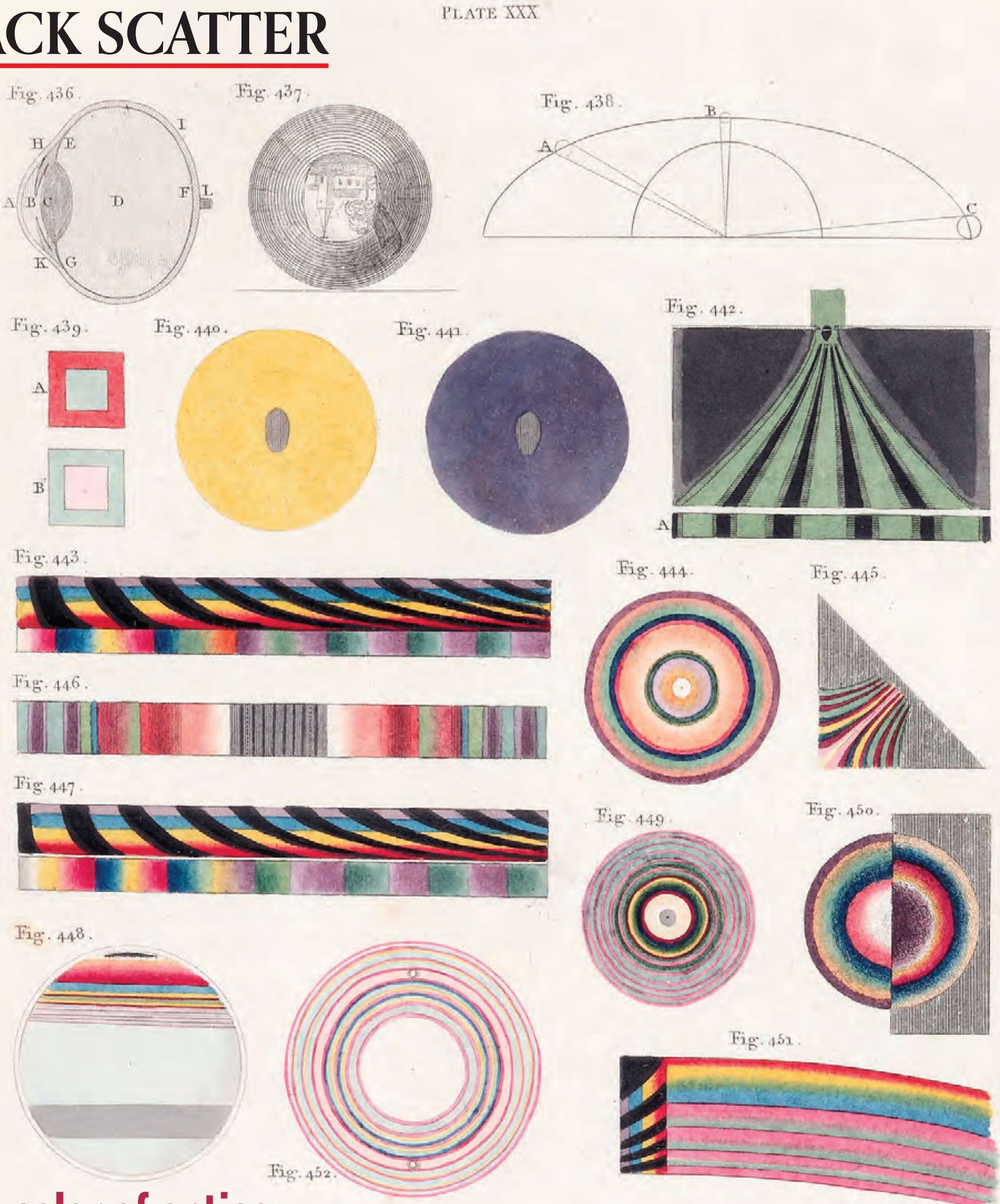
Additional resources

▶ D. S. Dugdale, "Stability of a floating cylinder," *Int. J. Eng. Sci.* **42**, 691 (2004).

▶ E. N. Gilbert, "How things float," *Amer. Math. Monthly* **98**, 201 (1991).

▶ J. F. Nye, J. R. Potter, "The use of catastrophe theory to analyse the stability and toppling of icebergs," *Ann. Glaciol.* **1**, 49 (1980).

▶ J. C. Burton et al., "Laboratory investigations of iceberg capsize dynamics, energy dissipations and tsunamigenesis," *J. Geophys. Res. Earth Surf.* **117**, F01007 (2012). PT



The color of optics

Thomas Young, a physician and physicist who studied optics and the anatomy of the eye, published *A Course of Lectures on Natural Philosophy and the Mechanical Arts* in 1807. The two-volume work covers a range of topics in the physical sciences, including astronomy and music. Pictured here are some of his observations from anatomy and optics experiments, including his famous double-slit experiment, shown in green and black in figure 442. In the caption, Young wrote that the experiment shows "the manner in which two portions of coloured light, admitted through two small apertures, produce light and dark stripes or fringes by their interference."

The volumes by Young, who also had a great interest in Egyptology and later helped translate the Rosetta Stone, were purchased in 2018 by the Niels Bohr Library and Archives as part of the Wenner Collection on the history of physics. The collection contains nearly 4000 rare books and serials from 1528 to 2016 (see "The history of physics, in 4000 manuscripts," PHYSICS TODAY online, 21 February 2018). To read more about the Wenner Collection and other library activities, visit the library's blog *Ex Libris Universum* at https://www.aip.org/ex-libris. (The library and archives are part of the American Institute of Physics, which publishes PHYSICS TODAY.)

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