PHYSICS TODAY

May 2025 • volume 78, number 5

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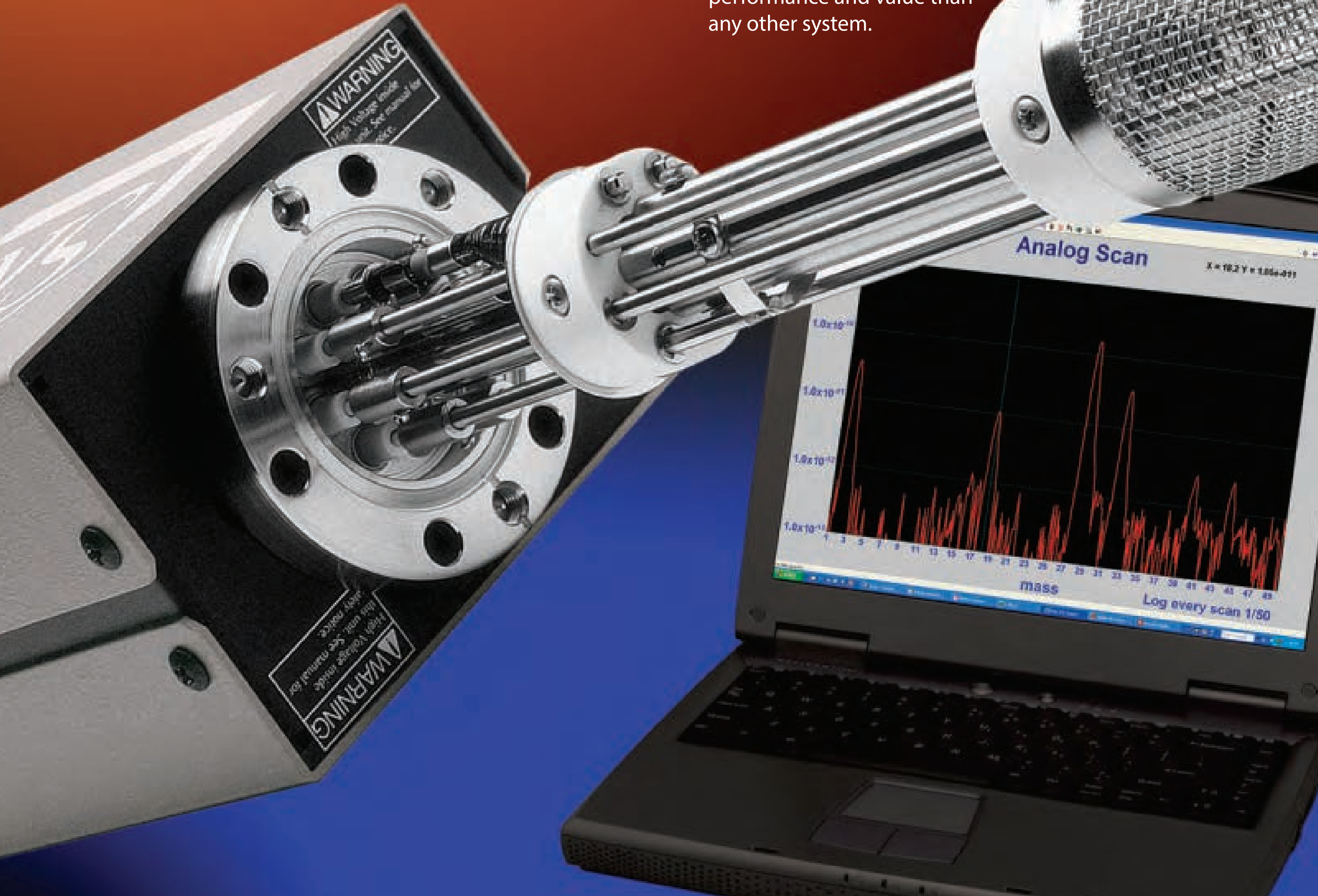

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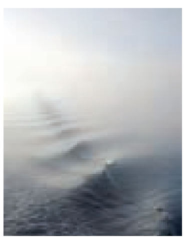
FEATURES



ON THE COVER: US leadership in ocean sciences is waning, warns the National Academies of Sciences, Engineering, and Medicine in a new report. But the report's authors suggest that scientists can reinvigorate the discipline over the next decade by uniting behind shared goals in basic research, ocean forecasting, and infrastructure investments. Doing so, they say, would safeguard national security, economic prosperity, and natural resources. To learn more, turn to the story on **page 16**. (Image by Pexels/Pixabay.)

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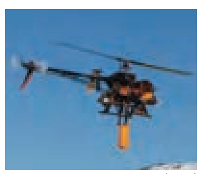

HANSEN ET AL., *NAT. GEOSCI.* (2025)

Greenland glaciers

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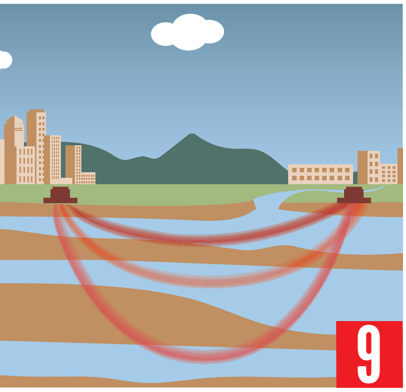

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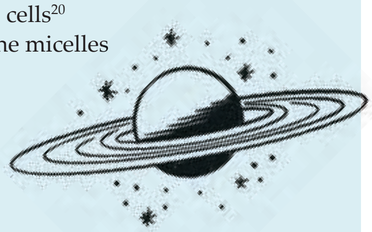

Bad reviewers!
Grant renewals!
When I'm feeling had
I simply remember my favorite things
And then I don't feel so mad

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Randall Kamien
(kamien@upenn.edu)
University of Pennsylvania
Philadelphia

On CERN and Russia

The December 2024 article "With no end in sight for the war in Ukraine, CERN ceases cooperation with Russia" (page 20) describes the CERN Council's decision not to renew an expiring cooperation agreement in light of Russia's ongoing invasion of Ukraine. That decision is an affront to all the dedicated Russian scientists who have contributed to its projects. Collaborations among scientists have been a positive vehicle and a way of engaging peaceful relations in the past, even in times of tension and war. Yet I must ask: Why did CERN not stop collaborations with the US in the wake of the hot wars in Vietnam in 1964–75 and in Iraq in 2003–11? Why was the Soviet intervention in Afghanistan in 1979–89 not a problem? Or the French intervention in Libya in 2011? Do we Europeans not care about invasions or wars so long as they do not happen on the European continent? Or do we dare not boycott certain nations involved in wars?

It would be naive to think that a boycott such as this one is the result of morality rather than geopolitics. As members of institutions, we may all have constraints imposed by political decisions; as individuals, however, we can strive to act in fairer and more nuanced ways.

Tanja Rindler-Daller
(tanja.rindler-daller@univie.ac.at)
University of Vienna
Vienna, Austria

Seismic data provide a deep dive into groundwater health

During times of sparse rainfall, many communities rely on pumping from wells to meet their water needs. But do the water reserves recover when the rains return?

Is California too dry, too wet, or both? Just weeks after greater Los Angeles was hit by January's devastating wildfires, which were exacerbated by several months with almost no rain, a wetter-than-usual February brought flooding and mudslides to the region. The variability is just as pronounced on a year-to-year scale: The average annual rainfall at Los Angeles International Airport is around 360 mm, but several recent years, including 2023, have brought more than twice that amount, whereas others have had less than half. That weather whiplash, which isn't confined to California, seems to be connected to anthropogenic climate change, so it's expected to continue, intensify, and spread.[1]

Rainfall and surface water don't tell the whole story. Groundwater is an important part of California's water supply, not just in the agricultural Central Valley but also in urban areas, such as greater Los Angeles. Stored in the cracks of rock and the pores of layers of sand and gravel, groundwater comprises more than 90% of California's water reserves, and it's especially important during times of drought, when surface lakes and rivers are quickly lost to evaporation. If

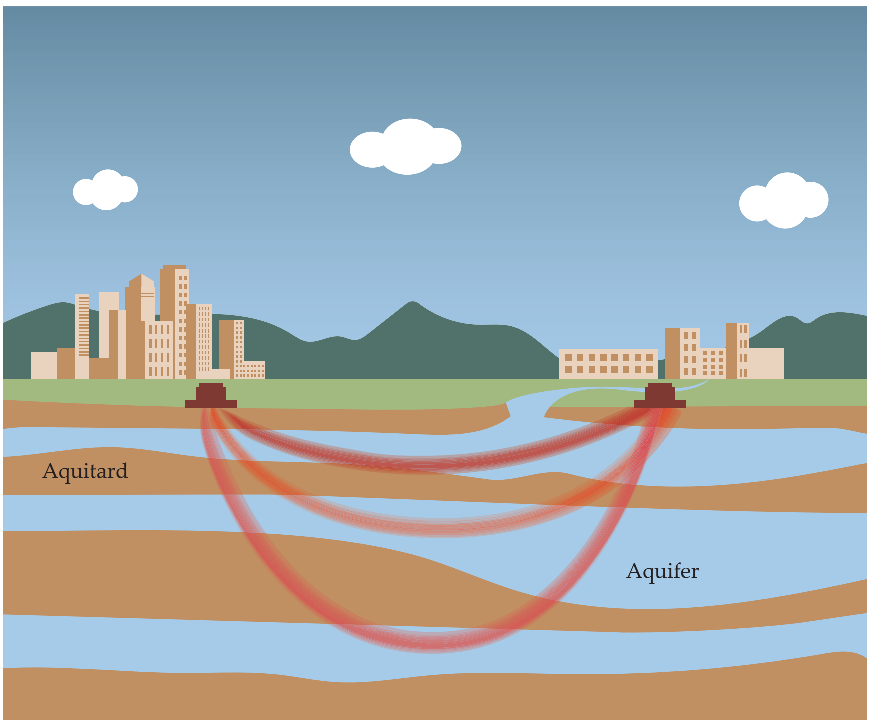

FIGURE 1. THE WATER BENEATH OUR FEET occupies a vast and complex network of porous aquifers separated by low-permeability aquitards. Because the connections and flow rates between the layers are largely unknown, it's difficult to keep track of how much water remains. Seismic sensing offers a solution: When aquifers are drained or refilled, the speed at which they conduct seismic waves changes. Through careful analysis of the never-ending ambient seismic noise, researchers can monitor the status of aquifers at different depths. (Image by Jason Keisling.)

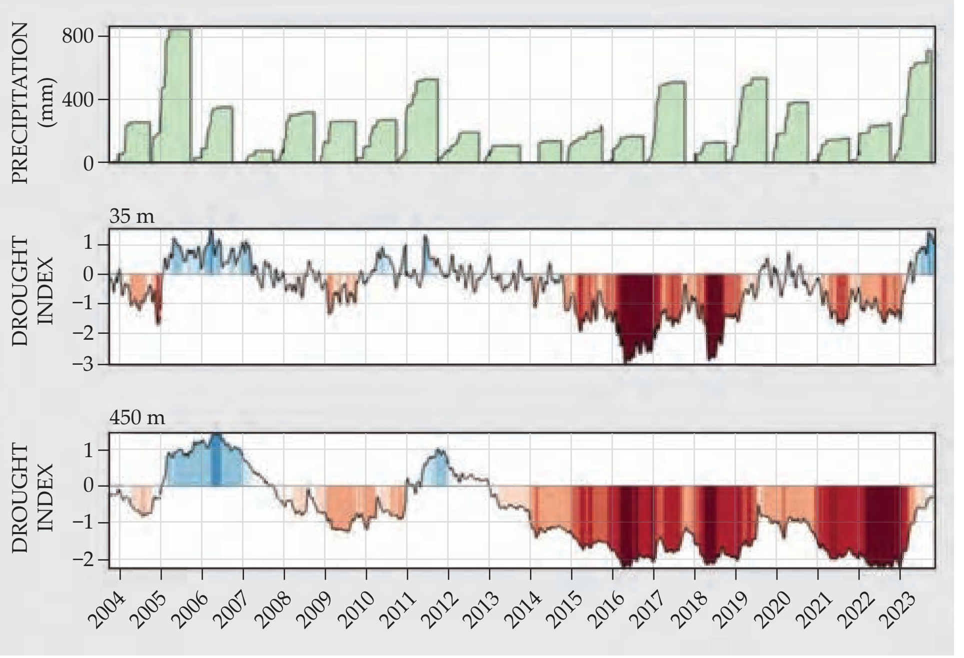

FIGURE 2. THE PAST 20 YEARS have seen greater Los Angeles go from wet to dry and back again, as shown by the plot of annual cumulative precipitation in the top panel. During dry periods, such as the one from 2012 through 2016, the metropolitan area relies on its groundwater supply even more than usual, but wet years, such as 2023, are not necessarily enough to refill the reserves. The bottom two panels show seismically derived drought indices for both shallow (35 m below ground level) and deep (450 m) groundwater. Shallow aquifers recovered well from the period of depletion, but deeper ones did not. (Figure adapted from ref. 2.)

surface water is like a region's checking account—easily accessible but rapidly fluctuating—then groundwater is the corresponding savings account: hidden, larger, and more reliable.

But California's savings account is at risk of being overdrawn, even in times when new deposits should be plentiful, according to new research led by Shujuan Mao (now a faculty member at the University of Texas at Austin, but a postdoc at Stanford University at the time she did the work).[2] Mao and colleagues used seismic data—collected in abundance in Southern California—to track groundwater levels in greater Los Angeles. Their method is unusual among groundwater-monitoring techniques because it offers resolution in all four dimensions: latitude, longitude, depth, and time.

The researchers found that after several years of drought, the exceptionally rainy year of 2023 did a good job of replenishing near-surface groundwater, but deeper water reserves remained significantly depleted. In a future of increasingly unsteady rainfall, their method may be a useful tool to guide water management decisions.

Seeing underground

The conventional approach to groundwater monitoring—drilling wells and observing the water level in them—provides only incomplete information. Unlike a surface lake, whose water level everywhere can be gauged from a measurement at a single point, groundwater inhabits a complex, unknown network of layers and channels. As shown in figure 1, the sandy, gravelly aquifers are separated by low-permeability layers of rock, clay, or silt called aquitards. And even in an aquifer, water doesn't flow as freely as it does on the surface (see the article by Mary Anderson, Physics Today, May 2007, page 42). A sparse set of observation wells is not enough to see what water is where.

Alternatively, one can look at changes in surface contours: Removing enough water from underground causes the ground level to sink. The effect is especially pronounced in the Central Valley, where so much groundwater has been pumped over the past century that the ground has subsided by several meters. Those large changes are irreversible, but smaller ones might not be: Satellites and GPS transponders can track the subtle fall and rise of the surface as aquifers are drained and refilled. They cannot, however, distinguish between deep and shallow groundwater.

Enter seismic hydrography, the technique used by Mao and colleagues. The speed of a seismic wave depends on what it's traveling through, so an aquifer full of water can be distinguished from a depleted one. The difference in speed is slight—on the order of a tenth of a percent—but it's measurable.

It's a decades-old idea to use seismic waves to probe beneath Earth's surface—to look not just for groundwater but for oil and gas, magma conduits beneath volcanoes, and more. But the method has not always been capable of the detail that Mao and colleagues acquired. Its capabilities have been pushed forward by two advances.

The first is that earthquakes are not the only useful generators of seismic waves. Ambient seismic noise—from sources such as ocean waves, car traffic, and Taylor Swift fans (see Physics Today, February 2025, page 21)—is constantly rumbling through Earth's crust. By calculating the interference of ambient vibrations recorded by pairs of seismometers, researchers can mathematically deduce the speed of waves through the intervening medium at all times, not just in the wake of an earthquake. (See the article by Roel Snieder and Kees Wapenaar, Physics Today, September 2010, page 44.)

The second realization is that special information is contained in part of the signal called the coda wave, the last piece of a seismic wave to reach its destination. The reason coda waves are delayed is that they take a longer path: Rather than traveling in a direct route, they bounce around several to hundreds of times. The multiple reflections amplify small changes in propagation speed—the very thing Mao and colleagues seek to assess.

In contrast to signals from discrete earthquakes, which make it easy to identify the last part of a wave to arrive at a detector, ambient seismic noise is a never-ending superposition of waves from many different sources. So it's a mathematically thorny task merely to find the coda waves, let alone figure out what they're saying about localized changes in propagation speed. But over the past decade, seismologists have developed theoretical tools[3] that are up to the task, and Mao and colleagues have refined the work into a 4D groundwater-imaging technique.

Wet and dry

Mao has been interested in seismic imaging of Californian groundwater ever since her graduate school days at MIT. But when she started her postdoctoral work at Stanford in 2022, the subject took on a new meaning. "In 2023, I was experiencing the storms for myself," she says. "And I saw posts on social media with the sentiment that 'the water shortage is a hoax,' with pictures of floods and surface water." She wondered how the groundwater reserves, hidden from view, were responding to the change in the weather.

For the new work, she and her colleagues used 20 years' worth of data from 68 seismometers across greater Los Angeles. Looking back much further in time would have been a challenge: Back in the days when data were stored on reels of magnetic tape, the standard practice was to retain data only from the time of an earthquake; everything else was deleted. "The Southern California Earthquake Data Center started recording continuous seismic data in the 1990s, before anyone appreciated the importance of it," explains William Ellsworth, one of Mao's postdoctoral advisers and coauthors. "It was a wise choice."

Figure 2 shows some of the results. The quantity plotted as "drought index" on the bottom two graphs is directly related to the researchers' calculations of seismic speed; it's just had the seasonal variations subtracted out, and it's been normalized to a scale that's already used to quantify droughts from surface-moisture conditions. The plots are representative of the whole greater Los Angeles area, but they're resolved by depth, which the researchers can do by filtering signals by frequency: Low-frequency waves probe deeper beneath the surface than higher-frequency ones.

As the plots show, both shallow and deep groundwater were steadily depleted during the extremely dry period between 2012 and 2016. In the intermittent wet years that followed, only the shallow aquifers recovered: By 2023, shallow groundwater stores were back to where they had been in 2006, while the deeper ones were still considerably short.

Brighter future

The situation is not all doom and gloom. Groundwater resources can be managed with sophisticated and efficient strategies. Municipal water providers can implement dynamic pricing schemes based on a sustainable rate of withdrawal. And engineers can channel stormwater and treated wastewater so that they filter back into the aquifers instead of flowing out to sea.

The effectiveness of those strategies is highlighted by some of Mao's previous work.[4] One paper, which pre-dates the 2023 storms, reported seismic measurements of the general variability of groundwater levels in response to weather changes. For their analysis, Mao and colleagues divided the greater Los Angeles region into basins—among them, the Los Angeles Central Basin and the Santa Ana Basin—and they found that the latter was much more resilient to weather shocks than the former.

The boundary between those basins is geographical, not geological: The Santa Ana Basin lies in Orange County, and the Los Angeles Central Basin lies in Los Angeles County. No natural hydrological barrier separates the regions; the biggest salient difference is that their water supplies are managed by different jurisdictions.

But the researchers caution against concluding that one municipality is better at groundwater management than another. Water management strategies are not free, and different water districts have different resource bases to draw on. Policymakers and engineers need to manage competing priorities to meet the present and future needs of their populations, and so far, they've been working with an incomplete picture of the health of their aquifers over time. Seismic hydrography could fill those information gaps.

It's not just earthquake-prone coastal California, with its existing network of seismometers, that needs information for groundwater management. Groundwater is critical to supporting agriculture and human communities in the Central Valley, the southwestern US, and the Great Plains above the Ogallala Aquifer, among other regions. Seismic hydrography can work in those regions, too, thanks to a technique called distributed acoustic sensing, which uses optical fibers, instead of dedicated seismometers, to measure seismic waves. (See the Quick Study by Ethan Williams, PHYSICS TODAY, October 2022, page 70.)

The details of the analysis will need to be adjusted because seismometers measure ground movement, whereas optical fibers measure ground strain. "But fibers are everywhere, even where there are no seismometers," says Ellsworth. "With seismometers, you might get one measurement every ten miles. Fibers give thousands of measurements over the same distance. So the information content just explodes."

Johanna Miller

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To make atomically thin metals, just squeeze

Metals aren't naturally stable in 2D form. But when forced into thin sheets, they exhibit new and unusual properties that researchers are eager to explore.

Since sticky tape was used just over two decades ago to isolate a single layer of graphene, an entire field of research has emerged to find more 2D materials, which have the thickness of just one or a few atoms. (See the article by Andrey Geim and Allan MacDonald, PHYSICS TODAY, August 2007, page 35.) Materials with atomic-scale dimensions exhibit distinct and exotic properties because of quantum confinement effects. Graphene, for example, has exceptionally high electrical conductivity because its structure hosts mobile electrons that behave like massless particles. (See PHYSICS TODAY, December 2010, page 14.)

Graphene provided a natural route into the realm of 2D materials because its one-atom-thick sheets have strong internal bonds but connect to other graphene sheets through weaker van der Waals forces. Those features make graphene relatively easy to peel off from its bulk form, graphite. Development of other 2D van der Waals materials, such as the insulating boron nitride and the semiconducting molybdenum disulfide (MoS_2), has followed. (See the article by Pulickel Ajayan, Philip Kim, and Kaustav Banerjee, PHYSICS TODAY, September 2016, page 38.) Theory is used to predict some of the exotic properties of new 2D material phases. Under certain conditions, for example, 2D bismuth is expected to be a topological insulator—a material that conducts charge along its surfaces or edges while its interior acts as an insulator.

But bismuth, like other ordinary metals, is not thermodynamically stable as atomically thin sheets, so finding a way to make 2D materials out of it and other metals has not been straightforward. One approach to creating 2D metals has been to mix transition metals with carbon, nitrogen, or both—such mixtures make up a class of materials known as MXenes (pronounced Maxines, like the name; see PHYSICS TODAY, June 2023, page 12). Very small pieces of pure metal films, ranging from nanometers up to about 10 μm across, have been synthesized using various other approaches, such as chemical vapor deposition, molecular-beam epitaxy, hot pressing, and growth confined between other 2D materials.

Researchers have probed the material properties of those small pieces, but the samples are not large or uniform enough to be useful in engineered applications like microchips or qubits. Now, doctoral student Jiaojiao Zhao, his coadviser Luojun Du, lab director Guangyu Zhang, and their colleagues at the University of Chinese Academy of Sciences in Beijing and Songshan Lake Materials Laboratory in

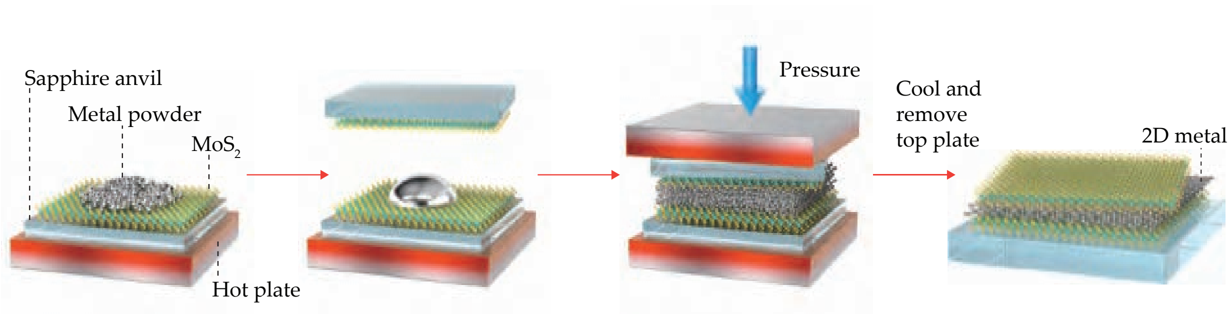

FIGURE 1. SQUEEZING A MOLTEN METAL between two sheets of molybdenum disulfide (MoS_2) produces sheets of metal just two atoms thick. The MoS_2, a van der Waals material that is stable as atomically thin sheets, provides a near-perfectly flat surface on which a 2D metal can be formed. Being encapsulated by MoS_2 prevents the 2D metal from oxidizing but still allows access to the unique material properties that emerge because of quantum confinement effects that occur in atomic-scale materials. (Schematic adapted from ref. 1.)

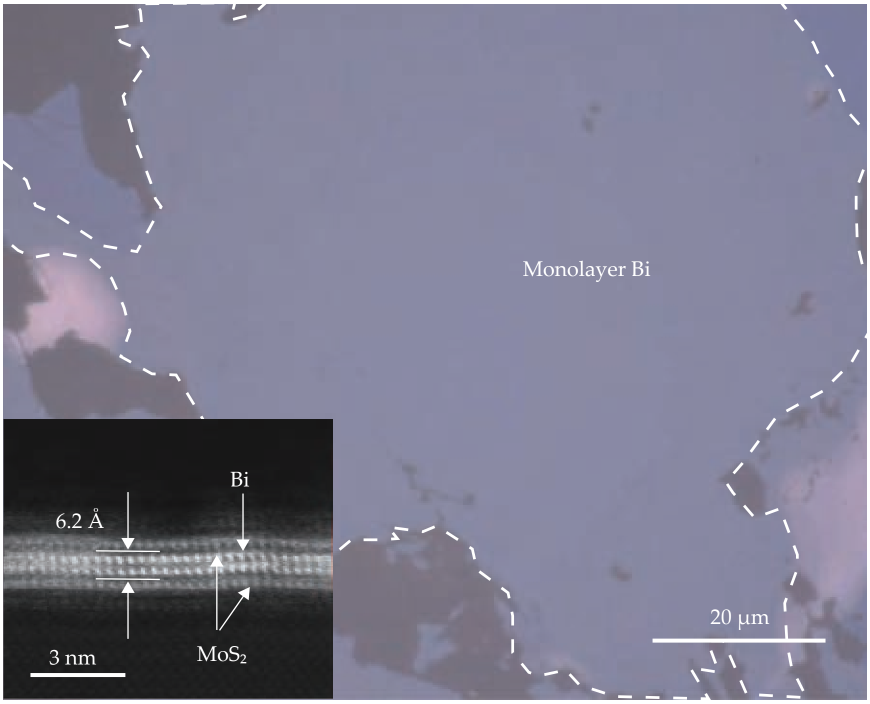

FIGURE 2. AN ATOMICALLY THIN SHEET OF BISMUTH is more than 100 µm across, an order of magnitude larger than 2D metals that have been created by other approaches. Imaging of the edge of one such sheet (bottom left inset) reveals a two-atom-thick monolayer of bismuth sandwiched between sheets of molybdenum disulfide (MoS_2). (Images adapted from ref. 1.)

Dongguan, China, have created atomically thin metal sheets that are orders of magnitude larger by squeezing them with a hydraulic press.[1] "We have developed a very simple technique to prepare 2D metal, using an atomically flat surface to squeeze elements, and it works well," says Zhang, who led the research.

A form of flattery

The atomically flat surfaces used to squeeze the metals are sapphire anvils fully coated with single layers of MoS_2 and trimmed into 1 cm^2 squares (see figure 1). In recent years, Zhang's lab had fabricated exceptionally large (circles more than 20 cm across) and uniform monolayer MoS_2 on sapphire crystals using chemical vapor deposition. Those MoS_2 sheets are useful in their own right, but they also provided the researchers with the tool needed to create atomically thin metals, something the lab had been working toward since 2015.

As shown in figure 1, the MoS_2-coated sapphire anvils are heated to melt a metal powder, which is then gradually squeezed to up to 200 MPa, roughly double the pressure at the bottom of the Mariana Trench. While maintaining high pressure, the researchers let the system slowly cool to room temperature. The MoS_2-encapsulated metal, shown in figure 2, can then be easily peeled from the sapphire blocks with tweezers. "In some sense, what they have achieved is the flattest substrate ever realized," says Javier Sanchez-Yamagishi of the University of California, Irvine. "Sapphire is already very flat, but you put this layer of MoS_2 on it, and it makes it even flatter."

In addition to providing a flat surface to guide the pressed metals into a 2D form, the sheets of MoS_2 also protect the metal from air. If one sheet of MoS_2 is removed via reactive-ion etching, the metal quickly oxidizes and balls up. With the protection of the van der Waals material, though, the metal sheets are stable for at least a year.

Because the metals are not chemically bonded to the MoS_2, their intrinsic electronic, optical, and magnetic properties can be probed—similar to the way that you can read what is written on a laminated a piece of paper. But at room temperature, MoS_2 is a semiconductor. So to isolate the electronic properties of the confined metal, the researchers took measurements at cryogenic temperatures. At those low temperatures, MoS_2 acts as an insulator and doesn't contribute to the system's conductivity.

Zhao and colleagues used the squeezing technique to produce 2D sheets of bismuth, indium, tin, lead, and gallium. They focused their material characterization on 2D bismuth, which has been shown in previous studies (on smaller samples) to exhibit attractive properties, such as photoluminescence[2] and exceptional electronic transport.[3] By connecting the 2D bismuth to electrodes, the researchers observed electronic properties that aren't seen in bulk metals. For example, the bismuth's conductivity could be altered by an applied electric field in a phenomenon known as the field effect—a useful quality for building transistors.

Just a phase

The bismuth film produced in Zhao and colleagues' study is, at its thinnest, two atoms thick. Those two atoms constitute a unit cell of the material's rectangular crystal phase, the phase produced in the study. But many other phases can exist. A hexagonal phase of bismuth is predicted to have topological insulating properties at room temperature. Tweaking the fabrication technique's conditions, such as the temperature or the angle between MoS_2 sheets, could allow the creation of more material phases in the future.

Sheets of bismuth with four or six layers of atoms were produced when the researchers adjusted the pressure applied to the anvils. The researchers have had success with every single-element material they have tried the technique on, and their future work will investigate mixtures. "The first thing to do is study. We have almost no knowledge of these structures, 2D metals. We should first look at their fundamental properties," says Zhang.

"It's a great technological advance that can be applied to more materials," says Princeton University's Sanfeng Wu, who also works on the engineering of novel 2D metals. "I see a bright path forward for 2D metals and for techniques based on them to engineer quantum devices."

By further refining the technique to produce extremely uniform surfaces to work with, the researchers may be able to create even larger metal sheets. The immense squeezing pressures inevitably scratch the steel plates used to compress the sapphire anvils, for example, so they must be polished back to a perfectly flat surface after each experiment. Any blemish in the surface can lead to the anvils fracturing at high pressures. But those are straightforward technological challenges Zhang is confident his lab can overcome.

"It's not how people usually think about growing crystals—it's a creative approach," says Sanchez-Yamagishi. "It's very cheap and simple compared to the million-dollar ultrahigh-vacuum systems which are typically used for growing thin crystals. Now that they've shown that it works, I expect other people to try."

Laura Fattaruso

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Precision tabletop neutrino science starts with rare isotopes

To learn about the aloof particles' quantum states, researchers are watching radioactive beryllium, not water.

Pitching neutrinos can be easier than catching them. Because the lightweight particles stream mostly unencumbered through any matter they encounter, neutrino detectors must monitor gargantuan volumes of water or other material, ever vigilant for the signs of a rare neutrino interaction, wherever it may occur. On the other hand, the processes that create neutrinos, including certain nuclear decays and particle reactions, can be readily localized and precisely studied even in a tabletop experiment.

That's the idea behind the BeEST (Beryllium Electron capture in Superconducting Tunnel junctions), an experiment headed by Kyle Leach of Colorado School of Mines in Golden and Stephan Friedrich at Lawrence Livermore National Laboratory. As illustrated in figure 1, a thin film of tantalum is sprinkled with beryllium-7, a radioactive isotope that decays via electron capture into lithium-7. The decay's only products are the ^{7}Li nucleus and an 862 keV electron neutrino. So from the ^{7}Li recoil energy, which is converted into a measurable current by a superconducting tunnel junction, the researchers can learn about previously unknown properties of the neutrino. To start, they've probed the spatial extent of the neutrino's quantum state.

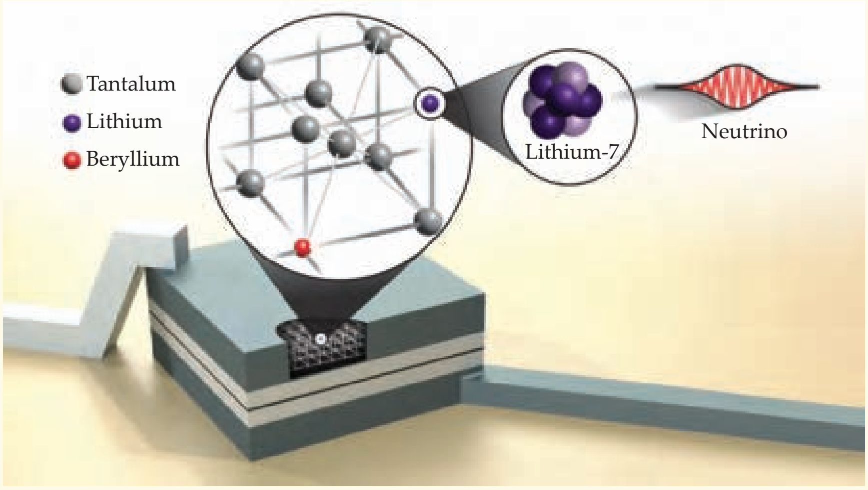


FIGURE 1. BERYLLIUM-7 decays into lithium-7 via electron capture, a process whose only byproduct is an electron neutrino. By embedding ^{7}Be atoms in the tantalum film of a superconducting-tunnel-junction sensor, researchers can precisely measure the recoil energy imparted to the ^{7}Li by the decay. (Image adapted from J. Smolsky et al., *Nature* **638**, 640, 2025.)

The experiment wouldn't have been possible more than a handful of years ago, because ^{7}Be occurs in only trace amounts in nature, and there was no way of making it in bulk with the required purity. The situation changed with the advent of rare isotope factories, including the Advanced Rare Isotope Laboratory (ARIEL) at the TRIUMF accelerator center in Canada and the Facility for Rare Isotope Beams (FRIB) at Michigan State University in the US (see Physics Today, June 2023, page 21). Leach and colleagues got their ^{7}Be from TRIUMF; the isotope's half-life of 53 days provides ample time for shipment to the experiment site in Livermore, California.

Figure 2 shows the BeEST's measurement of the recoil energy spectrum: The most common decay channel, shown by the large blue peak, has a standard deviation in energy of 2.9 eV, which corresponds to a ^{7}Li momentum uncertainty of 16 keV/c. Because the nucleus and neutrino have equal and opposite momenta, their momentum uncertainties must be equal. So by the Heisenberg uncertainty principle, the neutrino's position uncertainty—the size of its wavepacket at the moment of its creation—is at least 6.2 pm. That's a conservative lower bound, because not all of the energy spread is due to quantum fluctuations.

Why does it matter how big a neutrino's wavepacket is? Although the implications aren't fully clear, the researchers note that 6.2 pm is several thousand times the size of the ^{7}Be nucleus. Theorists have debated how quantum mechanics treats nuclear decays: Are the interactions localized on the scale of the nucleus or the whole atom? An electron-capture decay, which necessarily involves an electron from outside the nucleus, is perhaps not the best platform for answering that question. Repeating the experiment with a beta decay, whose starting state is an isolated nucleus, is on Leach and colleagues' to-do list. (J. Smolsky et al., *Nature* **638**, 640, 2025.)

Johanna Miller

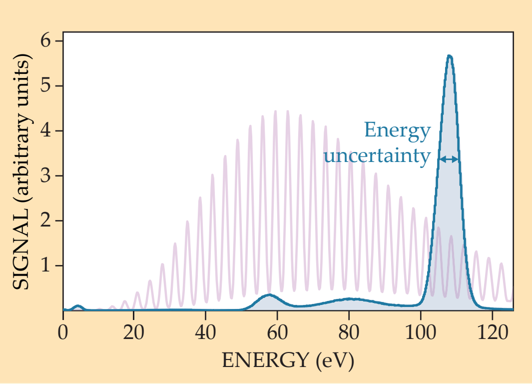


FIGURE 2. IN THE RECOIL ENERGY SPECTRUM of lithium-7, shown in blue, the largest peak has an energy uncertainty of 2.9 eV. From conservation of momentum and the Heisenberg uncertainty principle, it follows that the neutrino produced in the nuclear decay has a position uncertainty of at least 6.2 pm. The frequency comb in faint purple is the spectrum of the calibration laser that researchers used to convert the currents they measured into energy. (Figure adapted from J. Smolsky et al., *Nature* **638**, 640, 2025.)

US ocean sciences decadal report calls for regaining leadership

Worried about brain drain and national security, US ocean scientists say that the antidote is reinvigorating basic research and the country's research vessels.

The top priorities of the US ocean sciences community through 2035 are a continued investment in basic, curiosity-driven research and a unified effort to improve ocean forecasts to meet national and global environmental challenges. Those and other recommendations are detailed in *Forecasting the Ocean: The 2025–2035 Decade of Ocean Science*, a survey of the field that was conducted over 18 months by a committee of US researchers.

The US "is at a critical juncture," the committee writes in its report, which was released in February. The NSF research budget in ocean sciences has not kept pace with inflation, according to data provided to Physics Today by the committee. Additionally, the country's ocean research fleet is shrinking, and the country has lost its only deep-sea scientific drilling vessel, says the report. Investment decisions could either revitalize the discipline or drive US ocean scientists to labs overseas, says report co-chair Tuba Özkan-Haller, dean of Oregon State University's College of Earth, Ocean, and Atmospheric Sciences. The report states that the outcome also has national security implications: Sea-level rise is threatening defense infrastructure, and melting ice is rapidly changing access to the Arctic.

The decadal survey is the second ever issued for US ocean sciences, making it a relatively new practice compared with the long history of decadal surveys in astronomy, which go back to the 1960s. Scientists use decadal reports to present a unified voice when appealing for federal funding.

Recommendations from the decadal survey are aimed at NSF's division of ocean sciences, the US's primary funder of basic ocean sciences research. The division had a total research and infrastructure expenditure of around $420 million in 2023, the most recent year with data available. NSF received roughly $9.9 billion in appropriations that same year.

Proposed cuts to NSF's budget and workforce by the Trump administration have been reported in the time since the decadal survey's release. "The committee didn't know that [ocean sciences] would be facing the potential of significant cuts to NSF funding, but I think that we are very fortunate that [the committee] decided to focus the priorities so clearly," says Scripps Institution of Oceanography director Margaret Leinen, who did not participate in the report.

Basic research to strengthen forecasts

The roughly 150-page study was written by a committee of 23 scientists convened by the National Academies of Sciences, Engineering, and Medicine. They used a wide pool of published sources and received community input. The committee organized in-person and virtual town halls and heard presentations by more than 100 experts.

The report emphasizes the importance of ocean forecasts, which includes predictions of wave heights for ports, water temperature for fishing boats, and flooding levels for city planners. Linking basic research findings to forecasts is "sorely needed," writes the committee. Recent advancements in modeling and scientific understanding of ocean phenomena led to the early identification of Hurricane Helene when the storm was still very weak, according to a recent analysis.

But more research is needed to link ocean processes to forecasts, the committee writes. For example, the eastern Bering Sea's snow crab fisheries collapsed following heat waves between 2018 and 2021. If scientists had better understood the scientific links between heat and mass starvation, forecasts could have aided in mitigating the heat waves' effects on the fishing economy. To help fill the gaps, the committee recommends that NSF prioritize research in three key areas: ocean and climate, ecosystem resilience, and extreme events. Continuing strong US leadership in ocean sciences research in those areas will enhance economic prosperity and decision-making about coastal and ocean resources, states the report.

The committee says that NSF can better prepare the ocean sciences workforce by incentivizing transdisciplinary research through skills-sharing among US industry, academia, and mission-based government agencies like NOAA. NSF could fund academic scientists to embed themselves in industry or in federal research agencies for short periods, says Özkan-Haller.

The report's dual emphasis on basic research and a transdisciplinary approach is important, says Hilairy Hartnett, director of the University of Washington's School of Oceanography (she did not participate in the report). "There is some tension in that recommendation, but the problems of modern and future ocean sciences require both," she says.

A RESEARCHER prepares to release an anchor and chain for an ocean buoy in 2020. Collecting ocean observations for basic research is one of the main priorities of the latest US ocean sciences decadal survey. (Photo by Mitch Lemon/USGS.)

Ships need a refresh

The report says that 90% of US scientific ocean drilling objectives will not be met going forward because of the decommissioning in 2024 of the *JOIDES Resolution* (see Physics Today, September 2023, page 21), a scientific drillship that had operated since 1985. NSF had been supporting the drillship with $48 million annually since 2014, but rising costs, stagnating US investment, and large cuts from international funding led to its retirement.

No future drillship has been planned, and "it is unlikely that such U.S. leadership can be regained without a U.S.-based drillship," according to the report. Deep-sea cores collected from around the world since the 1960s have been key in providing supporting evidence for plate tectonics and geologic climate change (see the article by Rebecca S. Robinson, Sonia Tikoo, and Patrick Fulton, Physics Today, February 2024, page 28). Maximizing the scientific value of existing deep-sea cores is vital for continuing research, writes the committee. The report praises the International Ocean Discovery Program's Legacy Asset Projects, a pilot program that supports large-scale studies on previously collected cores.

Collaboration with international scientific drilling partners is "one of the most important recommendations" of the report, says Binghamton University paleontologist Adriane Lam, who participated in three *JOIDES Resolution* expeditions and presented to the committee during the report's preparation. Future international connections will be crucial for training the next generation of the US scientific workforce and for obtaining new deep-sea sediment records, she says.

The US Academic Research Fleet is top of mind for Deborah Bronk. She is president and CEO of the nonprofit Bigelow Laboratory for Ocean Sciences in Maine and did not participate in the making of the report. The fleet is a group of ships operated by universities and laboratories through the University-National Oceanographic Laboratory System (UNOLS) for conducting research on the ocean, atmosphere, and seafloor. "We've lost half of our fleet in the last 50 years," she says, from 34 to 17 vessels. In contrast, China has 64 research ships, according to an analysis by the Center for Strategic and International Studies, a bipartisan think tank in Washington, DC.

Although three new regional-class ships are joining the US research fleet this decade, four other existing ships will reach the end of their life by 2030. If they are not replaced, the ocean sciences community could lose approximately 20% of the fleet's annual maximum available ship time, according to UNOLS executive secretary Doug Russell, who presented to the committee during the preparation of the report. Three additional ships will reach the end of their already-extended service lives by the early 2040s. Those US Navy–owned global-class research ships make up the most robust ship class in the fleet that can travel in ice-free waters. "Without them, our ability to address the most important issues and questions of ocean science is severely compromised," says the University of Washington's Hartnett.

Balancing the portfolio

The first US ocean sciences decadal survey, published in 2015, arose from concern about the rising infrastructure costs of NSF's ocean sciences division. Scientists worried that without intervention, infrastructure costs would continue to grow and pull money away from research grants. The first report advised that NSF rebalance its portfolio to evenly support infrastructure and research.

Following the 2015 report, NSF pulled back its ocean sciences infrastructure investments to be on par with research funding levels. It decreased funding for the US scientific drilling program, the real-time ocean data network Ocean Observatories Initiative, and one of its academic research ships. But that balance has recently tilted again, with the division spending roughly $24 million more on infrastructure than on research and education in 2022 and $35 million more in 2023. The new report says that infrastructure costs are the cause, "particularly due to operating an aging Academic Research Fleet" and the NSF division's flat budget.

"The US is losing, or maybe has already lost, leadership in the ocean sciences world," Özkan-Haller says. "We might have a brain drain to other places that are investing heavily in the ocean sciences right now." The new survey aims to urgently unite the ocean sciences community around specific scientific efforts that the committee believes can safeguard US leadership for decades to come. "Now is not the time to be caught up in the details," Özkan-Haller says. It's the time to "come together around a few important priorities."

Jenessa Duncombe

Portraits of dismissed scientists personalize US government cuts to science

A hurricane researcher. An invasive-insect entomologist. An e-cigarette toxicologist. A biomedical librarian. Those are some of the people included in Silenced Science Stories, a visual storytelling project dedicated to featuring the US scientists who have been laid off from government jobs or had their research grants halted by the Trump administration. Thousands of positions at federal science agencies have been eliminated; grants in health, environmental science, and other research areas have been canceled; and funding for diversity, equity, and inclusion initiatives has been rescinded.

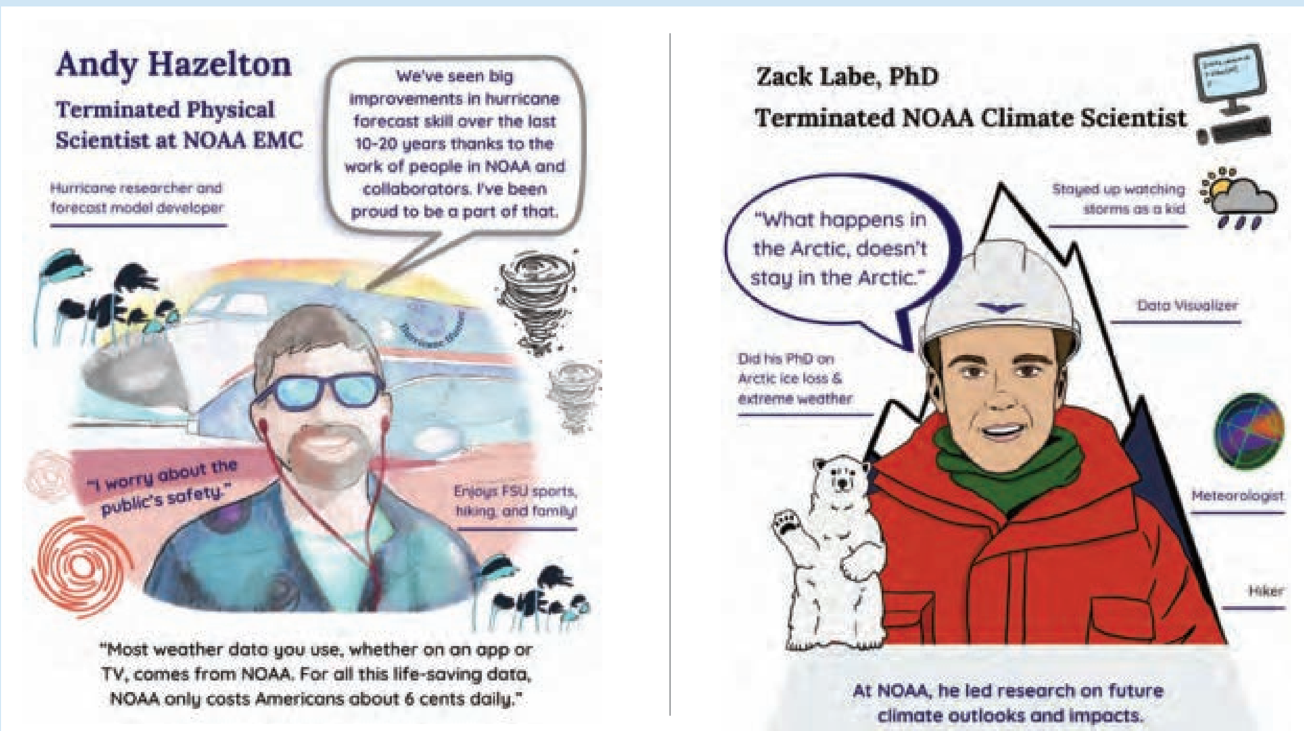
Project cocreator Paige Brown Jarreau came up with the idea for Silenced Science Stories in February as she watched her National Institutes of Health colleagues receive dismissal notices. A science communications contractor with NIH's Center for Alzheimer's and Related Dementias, Jarreau began messaging terminated federal scientists on LinkedIn about whether they wanted to share their experiences. Some scientists responded enthusiastically, she says, whereas others were hesitant to get involved because of ongoing court challenges to federal layoffs. Separately, Jarreau put out an open call for illustrators and received more than 50 volunteers, who were then paired with the participating scientists to create portraits highlighting the researchers' work. Chinmaya Sadangi, a digital marketer with a PhD in neuroscience, offered to colead the initiative with Jarreau and helped build the project's digital presence.

By mid-March, the first illustration was ready for LinkedIn and Instagram, and Silenced Science Stories was born. Within two weeks, the project posted about a dozen portraits on its website and social media; at press time, a dozen more were in production. Some of the featured scientists have told Jarreau that they have since been reinstated and put on professional leave, and at least one has returned to work after a court order.

Efforts by scientific societies, lawmakers, historians, and others to collect stories of affected scientists are proliferating. The various initiatives post testimonials from scientists on social media, share them with lawmakers, or collate them into archives or maps. Scientists who are interested in being profiled by Silenced Science Stories can reach out on the project's website, https://silencedsciencestories.com.

Silenced Science Stories leverages the power of art to help people "talk about very serious and maybe even controversial things" with less defensiveness, says Jarreau. She thinks the portraits could help to promote the scientists while they search for new jobs and to publicize the types of research being shut down. "We're not making political statements in the portraits," Jarreau says. "We're showing [the scientists'] work and their lives."

Jenessa Duncombe



TWO FORMER NOAA SCIENTISTS are among those featured in Silenced Science Stories. The portrait of former Environmental Modeling Center (EMC) researcher Andy Hazelton **(left)** was illustrated by Laura Fitzgibbons, and the portrait of climate scientist Zack Labe **(right)** was illustrated by Melanie Ortiz-Alvarez de la Campa. (Images courtesy of Silenced Science Stories.)

Q&A: Marty Baylor enhances students' skills and their sense of belonging as physicists

The teaching framework she has developed makes students feel at home in physics and prepares them for the workforce.

Before Martha-Elizabeth Baylor went to Kenyon College in Ohio, she was planning to study paleontology. When she got there, though, that major wasn't an option. "I identify as first generation, and I didn't know anything about college," she says. During high school, she had done an internship at NASA's Goddard Space Flight Center—not, she says, because she was interested in the program but because "my mom was like, 'It's a paid summer opportunity, you are going to do this.'" When Baylor had to pick a new major, she turned to physics.

After she graduated in 1998, Baylor spent a few years teaching middle and high school physics and working at NASA Goddard. She then went on to earn a physics PhD in 2007 from the University of Colorado Boulder.

Now a physics professor at Carleton College in Minnesota, Baylor teaches and does research on optical signal processing and photopolymers. Over the past few years, she has developed what she calls the Practicing Professionalism Framework, through which she weaves skills and confidence-building into her courses to benefit students in their working lives. One aim is to change students' perceptions so that they see physics as a cooperative, communal space where people have multiple interests. The approach, she says, can be adapted to different curricula and teaching styles.

PT: How did you choose to pursue optics?

BAYLOR: I was taking microeconomics, and I really hated the professor. He was mean. I wanted to do an independent study where physics destroys microeconomics. A physics professor mentioned having seen a nitrogen laser in the basement and said, "Why don't we see if we can get it working and then burn a hole through your economics book?"

It was a pulsed laser that had been built by a student in the 1980s and was gathering dust. I got it working, but it caught fire. I ended up throwing my economics book into the fire before putting the fire out.

I didn't know this would stimulate my career in optics.

PT: You taught school and worked at NASA before going to graduate school. Tell me about that.

BAYLOR: Toward the end of my time at Kenyon, I had a mental health breakdown. I dropped all courses except those that I needed to graduate, so I had some gaps. After I graduated, I needed time and space to recover. I got a job teaching middle and high school at a private school in Washington, DC. During the two years I taught there, I put my life back together and decided to apply to graduate school.

First, I went to NASA for two years. I did some really cool stuff. I worked on LISA [the Laser Interferometer Space Antenna, a planned mission to detect gravitational waves in space], and I was involved in designing star trackers for attitude orientation of spacecraft. I worked on *JMEX*, the *Jupiter Magnetospheric Explorer*, a telescope to study auroras on Jupiter, and I built an optical test bed to select between programmable slit technologies for the near-IR spectrometer on the *James Webb Space Telescope*.

While at NASA, I spent my evenings and weekends teaching myself what I needed in order to do well enough on the physics GRE to be able to apply for grad school.

PT: You've lived in China. How did that come about?

BAYLOR: The engineers I worked with at NASA when I was in high school were doing a joint project with Japan, so I thought I'd study Japanese for my language requirement. But when I got to Kenyon, the music presentation at orientation conflicted with [the presentation for] Japanese, so I went to the presentation by the Chinese department. I really liked the professor, so I stayed in Chinese. I studied at Nanjing University for a semester.

At the time, my department chair told me I shouldn't go, that it was more important for me to prepare for graduate school. But I thought I might never have the opportunity again. I declared Chinese as a minor so that my academic adviser—a different professor in the physics department—could sign the form. She was supportive.

Later, as a graduate student at an NSF IGERT [Integrative Graduate Education and Research Traineeship] program in optical sciences and engineering, I had to do four rotations—three in labs plus an

MARTY BAYLOR (Photo courtesy of Carleton College.)

internship. I arranged for my internship to be at a laser company in Shenzhen, China.

My experiences in China are a connecting point between me and my students. Not only can I speak to my Chinese students, but I also show students that it is OK to study abroad in a non-English-speaking country and do something other than physics. My experiences in China still very much shape who I am today.

PT: What attracted you to academia, and what was your path to Carleton?

BAYLOR: My passion is teaching. I will do it in a grocery store checkout line. After I got my PhD, I was a visiting professor at Carleton for part of a year. Then I went back to Boulder and did a two-year postdoc. In 2010, I started a permanent position at Carleton, and I've been here ever since.

PT: Tell me about your research program.

BAYLOR: I typically have about eight undergraduates working in my group. We published research in which my students used interfacial surface tension between water and photopolymers to fabricate lenses. We also make integrated optofluidic devices. The students measure the difference in refractive index that you can get from different formulations of the photopolymer, which determines whether you can make a multi- or single-mode waveguide within the slab. But the pace of research is slow with undergrads.

PT: What led you to develop the Practicing Professionalism Framework?

BAYLOR: I was teaching a sophomore-level atomic and nuclear physics course, and I was frustrated by the way students were approaching their assignments. In their drive for efficiency, they were letting bias influence how they made choices, and it also meant they were not developing the skills I was trying to teach them.

PT: What's an example of those biases?

BAYLOR: In the lab, I heard students say things like, "You are the woman, why don't you take notes?" "You are Asian, you are good at math. Why don't you propagate the uncertainty?" And the white male would say, "I tinker in the garage with my dad, so I will work with the apparatus." It wasn't these exact words, and it wasn't every group, but the net effect was that, on average, women were taking notes, Asian students were doing the math, and white men were working with the apparatus. After several years of that, in 2016, I started intervening to interrupt that pattern.

PT: So that was the first step toward developing the framework?

BAYLOR: Yes. Another observation also played a role: Graduating seniors would come into my office and say, "Marty, I don't know what I am going to do with a physics degree. I don't know how to do anything."

I asked myself, How do I frame a course so that students understand what they are doing, why they are doing it, and how it connects to professional practice? How do I get students to develop the habits of mind that they need to understand what it means to be a physicist?

This shifted my thinking. I added a new dimension to how I teach. This practicing professionalism dimension is, I think, critical to broadening students' perceptions of who a physicist is and what a physicist does.

PT: Describe the framework.

BAYLOR: It has three parts. What a physicist knows, which is content. What a physicist does, the skills—experimental, theoretical, computational, analytical—that we develop in our students. And then there is what physicists care about. This third area is what motivates my career.

PT: What are examples of the third category, and how do you bring that aspect into teaching?

BAYLOR: Physicists can care about many things—history of science, outreach, public policy, inclusion and justice. When instructors try to bring these topics into the classroom, more often than not students push against it and say it's not physics.

What I started doing was, on the first day of class, after I introduce myself, I tell my students to take five minutes to look through *APS News*. While I take attendance, I ask them to share the topic or title of an article that caught their eye that was not about physics theories or apparatus.

By using *APS News*, I am showing them that, independent of me, the physics community is having conversations about other topics. When I started motivating topics with this approach, all the pushback stopped.

PT: How does the Practicing Professionalism Framework change how you teach?

BAYLOR: I lay out in a transparent way what students need to know and how they need to approach their work. I grade them on whether they are approaching their work like a professional would. This is for journal articles, homework, and exams. They are intentionally developing that "professional approach" muscle.

Most students fail their first assignments. But early attempts don't affect their grade. They need to be able to practice and fail without fear. This approach changes my relationship with the students, from being a gatekeeper trying to keep them out to someone who is doing an assessment to figure out where they are and coaching and mentoring them to get where they want to be. It's more satisfying as a teacher.

Another aspect of the framework is that I assign students roles in the lab: notebook-meister, apparatus-meister, and analysis-meister. The students rotate through those roles multiple times. By the time they are in a senior-level lab, they can work in a group more organically.

PT: What differences do you see?

BAYLOR: I have reflection essays from the students that show an increased sense of belonging. That helps the overall atmosphere: I have observed that students who feel they don't belong may withdraw with anxiety and impostor feelings. Or they lash out by aggressively challenging the teacher to show that they belong and are brilliant. Or they step on a fellow student to show how smart they are.

When they realize that a physicist doesn't have to be a lone genius who wins the Nobel Prize—it can just be someone who is interested in physics and wants to spend time learning about the world—they don't feel pushed out. They feel welcomed and can welcome others.

PT: Is that approach likely to get caught up in the Trump administration's actions targeting diversity, equity, and inclusion [DEI] efforts?

BAYLOR: When I was creating the Practicing Professionalism Framework and named it, I never viewed it as a DEI intervention. It's a way of broadening the audience, focusing on skills, and maintaining rigor. But it's not framed from a space of identity. For me, this has always been about making physics accessible to everybody. So I am not worried about it.

PT: Is there anything you'd like to add?

BAYLOR: At Carleton, my largest class is 48. I am working with colleagues at the University of Washington to explore how one might implement the Practicing Professionalism Framework in large introductory courses across STEM. If we can get over that hurdle, then we can spread the framework more broadly.

Toni Feder

Graduate assistantship pay often falls short of a living wage

The graduate student stipends offered by many US physics departments are insufficient to live on, even for students who split housing costs. That's according to *Physics Graduate Student Compensation: Academic Year 2023–24*, a recent report by the statistical research team of the American Institute of Physics (publisher of Physics Today). The report includes the analysis of compensation data collected from more than 100 public and private PhD-granting physics departments.

For first-year teaching assistants, stipends ranged from about $18 000 to $47 000; the average was $30 000. For fifth-year research assistants, stipends were from around $20 000 to nearly $50 000; the average was $32 700. In addition to a stipend, students often receive benefits such as health insurance and free tuition.

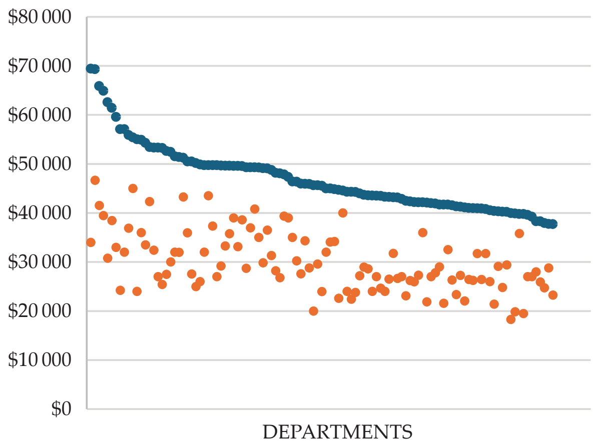
In the 2020–21 academic year, a teaching assistantship was the main source of financial support for 56% of first-year physics PhD students. In the same period, 60% of fifth-year students were employed as research assistants, which served as their primary source of income. Service hours varied, but most departments required student assistants to work roughly 20 hours a week, according to the report. Private schools typically paid more than public ones, and schools with larger graduate programs tended to pay more than those with smaller programs.

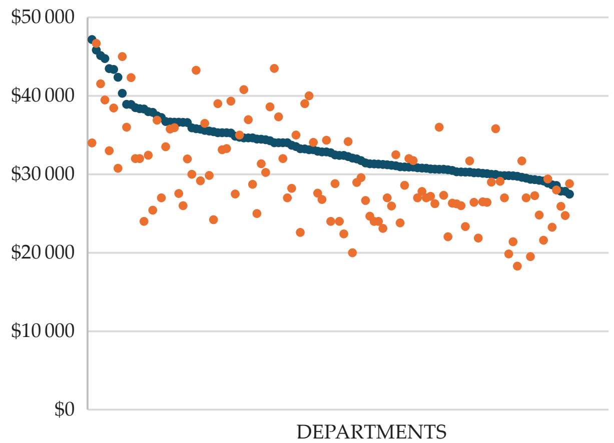
Do teaching and research assistantships provide a livable wage? The researchers tackle that question with a calculator developed at MIT. The calculator accounts for such factors as the prices of rent, food, transportation, and other basic needs for a given location. For someone living alone in Boston or New York City, for example, the living wage is around $69 000—well above the stipend amount a physics student would receive from an assistantship. For those who live in a shared apartment, around $46 000 would do. For comparison, in St Louis, Missouri, or Toledo, Ohio, the living wage would be about $39 000 for someone living alone and $29 000 for someone sharing an apartment.

The accompanying figures plot the living wage in blue, from high to low, for a student living alone (left) or splitting costs with a roommate (right) in the locations of the institutions. The typical first-year teaching assistant stipend offered by each institution is plotted in orange. All the schools' stipends shown in the left graph and three-quarters of the schools' stipends shown in the right graph fall below the blue line.

For more information on compensation for physics graduate student assistantships, see https://ww2.aip.org/statistics/physics-graduate-student-compensation-academic-year-2023-24. The Living Wage Calculator is available at https://livingwage.mit.edu.

Tonya Gary





TEACHING ASSISTANT STIPENDS for first-year physics graduate students (orange dots) fall below the living wage (blue dots) for living alone in a studio apartment in cities across the US **(left)**. Those stipends, which range from around $18 000 to $47 000, go further for students who share a two-bedroom apartment **(right)** but, in most cases, still fall short of a living wage. (Figure adapted from P. Mulvey, *Physics Graduate Student Compensation: Academic Year 2023–24*, AIP Research, 2025.)

Trump defunds NSF construction budget

Senate appropriators object to the president's assertion that he can dispute individual "emergency" appropriations made by Congress.

CREWS AT MCMURDO STATION in Antarctica work in 2015 to repair cracks in a pier. NSF had planned to allot some of the $60 million it requested for Antarctic infrastructure upgrades in fiscal year 2025 to replacing the pier, which is used to receive shipments of supplies. (Photo by Bill Henriksen/USAP/NSF/CC BY-NC-ND 4.0.)

The NSF budget for major construction projects is set to be eliminated for fiscal year 2025 after President Trump canceled some of the emergency funds that were appropriated by Congress in March. Top Senate appropriators argue that the action is illegal and puts at risk all $12.4 billion of the funding, which is allocated to NASA and other agencies.

If Trump's decision stands, it is unclear whether NSF could transfer money from other accounts to cover the $234 million shortfall in its Major Research Equipment and Facilities Construction (MREFC) account. That hole represents 2.6% of the agency's FY 2024 top-line budget of $9 billion.

Congress funded the MREFC account using emergency funding that was agreed to in a 2023 bipartisan side deal that allowed legislators to exceed spending caps set in law. Appropriators used the same funding method for MREFC in the final FY 2025 spending legislation that was enacted in March. The legislation largely carries forward spending levels from the prior year.

Trump wrote to Congress on 24 March declaring that the MREFC account and 10 others were "improperly designated by the Congress as emergency" in the 2023 deal.

Appropriators on both sides of the aisle objected to Trump's move as an encroachment on their spending power. Senators Susan Collins (R-ME) and Patty Murray (D-WA), who lead the Senate Appropriations Committee, sent a letter to the Office of Management and Budget stating that the language of the appropriations legislation "has always been interpreted to give the President a binary choice: He must concur with all or none of Congress's emergency designations."

Murray highlighted in a press release how the decision jeopardizes the MREFC funding and a $100 million appropriation for procurement and construction projects at NOAA. Both Collins and Murray said that the availability of all the emergency funding could now be at risk, including the $9 billion in spending that Trump has approved. Those expenditures include $250 million for NASA's construction and environmental compliance budget and $450 million for its human exploration budget.

NSF's MREFC account funds major projects, which cost more than $100 million to construct, and mid-scale research infrastructure, which costs $20 million–$100 million to build. The $234 million appropriated by Congress for FY 2025 falls short of the $300 million that NSF had requested.

The agency had requested $60 million for Antarctic infrastructure upgrades, such as building a new ice pier for offloading resupply vessels at the McMurdo research station. The current pier has failed three times in the past 12 years. "If the infrastructure that enables Antarctic science is not kept robust and efficient, [the US Antarctic Program] is at risk of losing science capabilities year over year as facilities, utilities, equipment, and the vehicle fleet degrade," the agency wrote in its budget request.

NSF had also requested $154 million for the Leadership-Class Computing Facility in Texas, which will host an academic research supercomputer that the agency had said would begin operations next year.

The agency had asked for another $85 million to fund mid-scale infrastructure projects. Recently funded projects include a new weather radar system, instruments for observing the cosmic microwave background, and a compact x-ray free-electron laser facility.

Many other major projects have been waiting in the wings for MREFC funding. Among the projects are the Giant Magellan Telescope and the Thirty Meter Telescope, either of which would require a significant and sustained MREFC budget increase to move forward with NSF support.

NSF declined to comment on how Trump's decision might affect its infrastructure projects.

Clare Zhang

FYI SCIENCE POLICY BRIEFS

Agencies start closing down science advisory committees

Following an executive order issued by President Trump in February, multiple government agencies began eliminating science advisory committees. The order, titled "Commencing the Reduction of the Federal Bureaucracy," calls for shutting down specific advisory committees and directs the heads of some agencies and departments to identify additional committees for termination. Whereas some federal advisory committees are created by Congress, many are nonstatutory and can be shuttered by senior agency leadership.

NOAA and the US Geological Survey are among the science agencies that have eliminated some nonstatutory advisory committees. Taking a different approach, NASA acting administrator Janet Petro directed the agency to consolidate its astrophysics, biological and physical sciences, Earth sciences, heliophysics, and planetary sciences advisory committees into a single committee, a NASA spokesperson told *FYI*.

During his first term, Trump called for the elimination of a third of all committees not required by law and attempted to cap the total number at 350. Then and now, science advocates criticized the president's actions, noting the importance of those committees in sharing scientific expertise with government leaders. Kristie Ellickson, a senior scientist at the Union of Concerned Scientists' Center for Science and Democracy, told *FYI* that she and her colleagues are tracking not only the elimination of advisory committees but also work delays and restrictions on who gets to participate: "All of these tactics aim to silence independent scientific advice to federal agencies." —LM

Climate change absent in new intel assessment

No mention is made of climate change in the US government's 2025 Annual Threat Assessment, which was released in March by the Office of the Director of National Intelligence (ODNI). Prior editions frequently identified climate change as a contributor to several worrying trends. The 2024 report listed it as a major challenge for US security and predicted that worsening droughts, flooding, and extreme storms would increase state instability worldwide and exacerbate economic problems that fuel terrorism and the illicit drug trade. The latest report also does not reference water resources or air quality, topics that past editions routinely flagged as security concerns.

Asked by Senator Angus King (I-ME) about the new report's lack of mention of climate change, ODNI director Tulsi Gabbard said, "Obviously, we're aware of occurrences within the environment and how they may impact operations, but we're focused on the direct threats to Americans' safety, well-being, and security." —JT

Kratsios confirmed as OSTP director

In a 74–25 vote on 25 March, the Senate confirmed Michael Kratsios as director of the White House Office of Science and Technology Policy (OSTP). Kratsios will also co-chair the President's Council of Advisors on Science and Technology.

Shortly after Kratsios's confirmation, President Trump wrote a letter tasking him with revitalizing the American scientific enterprise. Evoking a letter that President Franklin D. Roosevelt wrote to his science and technology adviser, Vannevar Bush, during World War II, Trump outlined three challenges for Kratsios, including securing the country's position as the "unrivaled world leader in critical and emerging technologies—such as artificial intelligence, quantum information science, and nuclear technology."

President Joe Biden wrote a similar letter to his OSTP director at the beginning of his administration that invoked Bush and the successes of the postwar scientific enterprise. —LM PT

FYI (https://aip.org/fyi), the science policy news service of the American Institute of Physics, focuses on the intersection of policy and the physical sciences.

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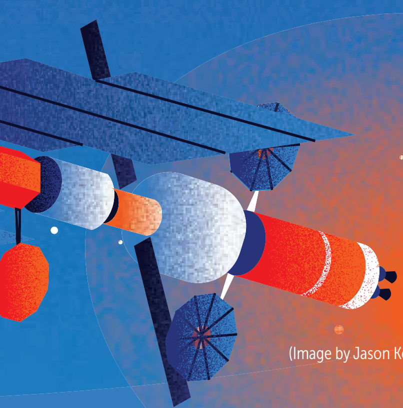
Anthony M. Calomino is the space nuclear technology portfolio manager for NASA's Space Technology Mission Directorate. **Kurt Polzin** is the chief engineer for NASA's Space Nuclear Propulsion project. **Venkateswara Rao Dasari** is with the Idaho National Laboratory and is a technical adviser for NASA's space nuclear activities. **Lindsey Holmes** is the vice president of advanced projects at Analytical Mechanics Associates and provides technological support for NASA's nuclear power and propulsion activities.

NUCLEAR FISSION TECHNOLOGIES FOR SPACE EXPLORATION

Anthony M. Calomino, Kurt Polzin, Venkateswara Rao Dasari, and Lindsey Holmes

NASA is developing multiple technologies for space nuclear power and propulsion to enable a sustained lunar presence and to propel a crewed mission to Mars.



(Image by Jason Keisling.)

Humans have been captivated by Mars for centuries. People dream of one day having a colony on our neighboring planet, but that future is fraught with many challenges. Although we have sent rockets carrying rovers to the surface, carrying humans will place additional demands: a larger spacecraft with different propulsion systems, more power during the stay, and resources to make a return journey.

Additionally, human health is of the utmost concern. Exposure to cosmic radiation and microgravity during a long flight to Mars poses many biological challenges, including decreased muscle mass and bone density, visual impairment, and an increased risk for degenerative diseases and cancers. Not to mention the potential for psychological stress because being in isolation with only the other crew members affects mental health.

Space nuclear technology isn't new. As early as the 1950s, propulsion systems based on the fission of uranium atoms were being designed for rockets. Nuclear fission propulsion systems harness the heat released when uranium atoms split. The energy then is used either to produce electricity or to directly heat a propellant such as hydrogen. To date, only one US-built nuclear reactor for space has successfully reached orbit; the country's other rockets remain reliant on chemical reactions for propulsion.

The technological limits of what chemical propulsion can provide have been reached. Human exploration cannot go much beyond the Moon without a new type of engine. Although chemical propulsion will still be used to escape Earth's gravity well, nuclear propulsion can expel propellant faster and allow a rocket to travel farther using less fuel. On the surface of another planet, nuclear systems may be the best way to power any permanent space bases, especially when greater power is needed and when solar power won't suffice. New nuclear efforts are currently being funded to facilitate missions to the Moon, Mars, and beyond.

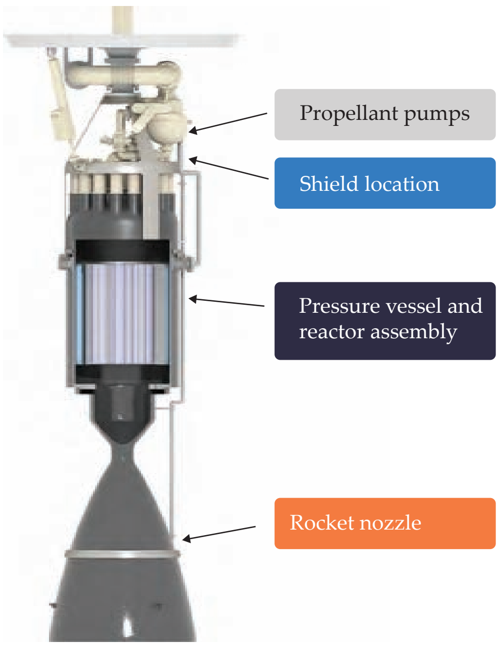


FIGURE 1. IN A NUCLEAR THERMAL PROPULSION SYSTEM, the combustion chamber of a conventional rocket is replaced by a nuclear reactor. Fission heat is directly transferred to a propellant that flows through the reactor. The hot propellant is then expanded through a nozzle to generate thrust. (Image adapted from Analytical Mechanics Associates.)

Fission propulsion

Nuclear fission systems possess a high energy density: They deliver significant total impulse in a compact package. Applications for in-space propulsion include nuclear thermal propulsion (NTP) and nuclear electric propulsion (NEP). An NTP system, like that illustrated in figure 1, uses the heat generated in a fission reactor core to convert a liquid propellant into a gas, which is then expanded through a nozzle to provide thrust. Much like a terrestrial nuclear power plant, an NEP system, like that shown in figure 2, uses fission to generate electricity, which then ionizes and accelerates a gaseous propellant.

Compared with chemical propulsion systems, both NTP and NEP provide significantly higher specific impulse I_{sp}, defined as the momentum transferred to the rocket per unit weight of propellant flow and expressed in seconds. The greater I_{sp} means that less propellant is needed for a given mission. Nuclear propulsion systems could reduce trip times to Mars by 25% or more and deliver payloads of considerably greater mass, thereby supporting a human presence while still accommodating enough propellant for the return trip to Earth. The systems also provide significantly extended capabilities for aborting missions and flexibility in mission planning, including broader departure windows.

For a human Mars mission, the target I_{sp} is approximately 900 seconds, roughly twice as much as is achievable with conventional chemical systems. For hydrogen propellant—the leading option for a Mars mission because of its low molecular weight—that I_{sp} corresponds to a temperature of approximately 2700 K when the propellant exits the reactor.

The largest technological challenge involved in NTP is the development of robust fuel and reactor components that can withstand the extreme thermal, chemical, and mechanical environments associated with the process of rapidly heating cryogenic liquid hydrogen to 2700 K. The reactor increases to maximum power and temperature in as little as a minute. The engine then operates at maximum power for roughly 30 minutes per maneuver, of which there will likely be six to eight for a human Mars mission. The engine is needed to leave the Earth–Moon system and make midflight course adjustments.

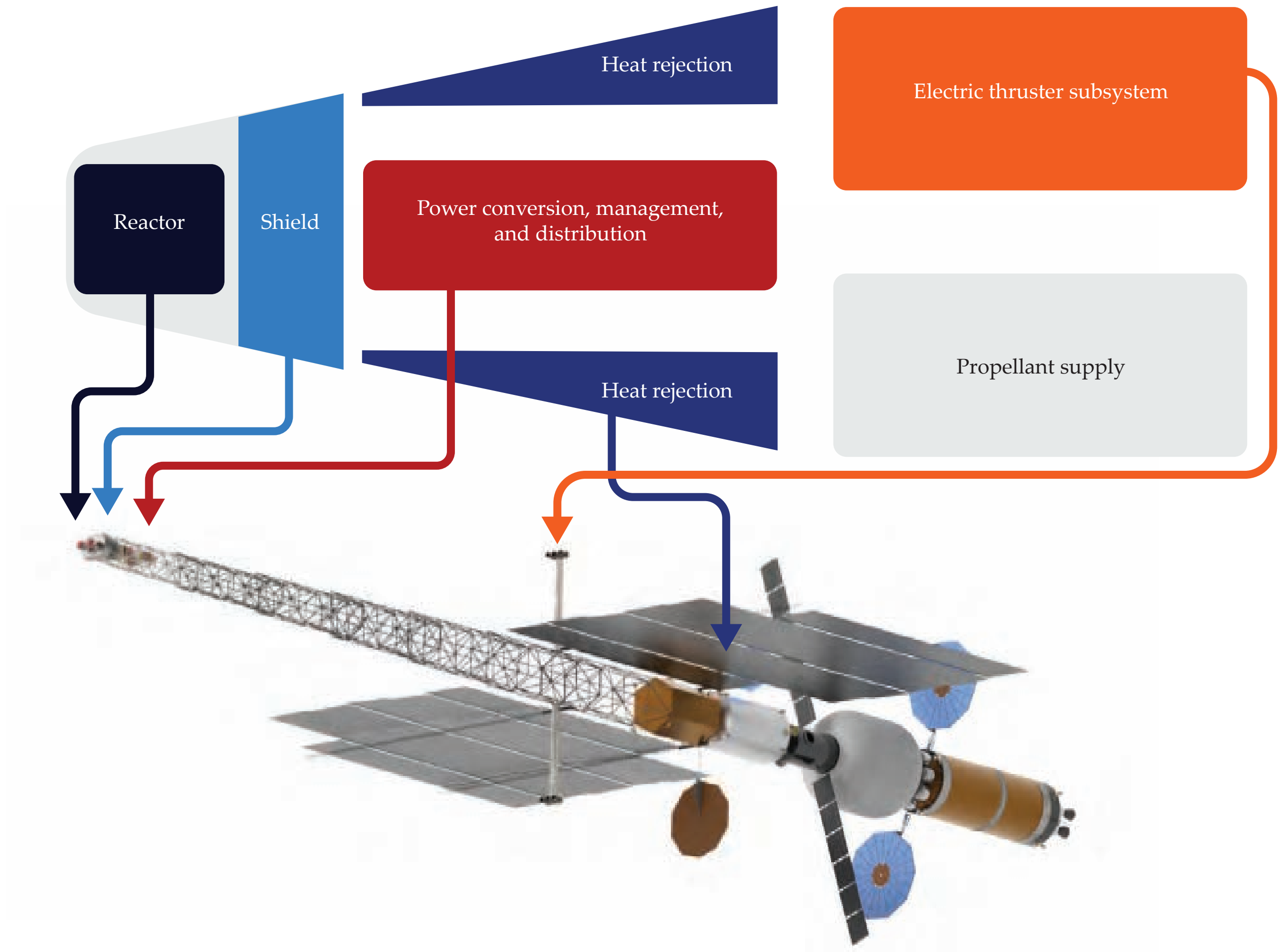


FIGURE 2. A NUCLEAR ELECTRIC PROPULSION SPACECRAFT is still conceptual, but work is being performed to develop the technology. An engineering rendering of one such design is shown alongside a simplified schematic of the components required to generate and distribute electrical power. The electricity accelerates an ionized gas to provide thrust. (Image adapted from Analytical Mechanics Associates.)

Another challenge is the long-duration storage of cryogenic hydrogen. A large quantity of hydrogen is needed for both the trip to Mars and the return, and an advanced cryogenic fluid management system is required to prevent boiloff. NASA is developing those systems alongside other technologies needed for a human Mars mission.

In NEP, the heat from the reactor core is converted through a closed thermodynamic cycle into mechanical energy, which drives a generator to produce electricity. An NEP system achieves and sustains considerably higher I_{sp} (2000–8000 seconds) compared with an NTP system but at much lower thrust, although thrust does increase with additional reactor power.

Although not as hot as NTP, NEP still requires a high-temperature reactor (above 1200 K) to reduce the power system specific mass—the mass per unit power produced—to the level at which a nuclear power source is a value-added design choice. For high-power missions, the radiators used for heat rejection will be large and will likely require in-space servicing, assembly, and manufacturing technologies. Those technologies, however, need to be developed. Ground testing a full-scale, fully integrated NEP system for a Mars mission is challenging because of its size and because it will need to operate for several years. Alternative ground-testing strategies may include independent subsystem tests combined with robust system modeling, testing for durations shorter than the full operational duration, and scaling to extend subscale test results to the full-scale system.

Some missions will likely use a spacecraft with a dual propulsion system. An NEP system's low-thrust, high-I_{sp} electric thrusters can pair well with a high-thrust system, such as chemical propulsion or NTP. The high-thrust system allows for fast escapes from and insertions into planetary gravity wells, while the high-I_{sp} NEP system can continuously accelerate the vehicle and significantly change its

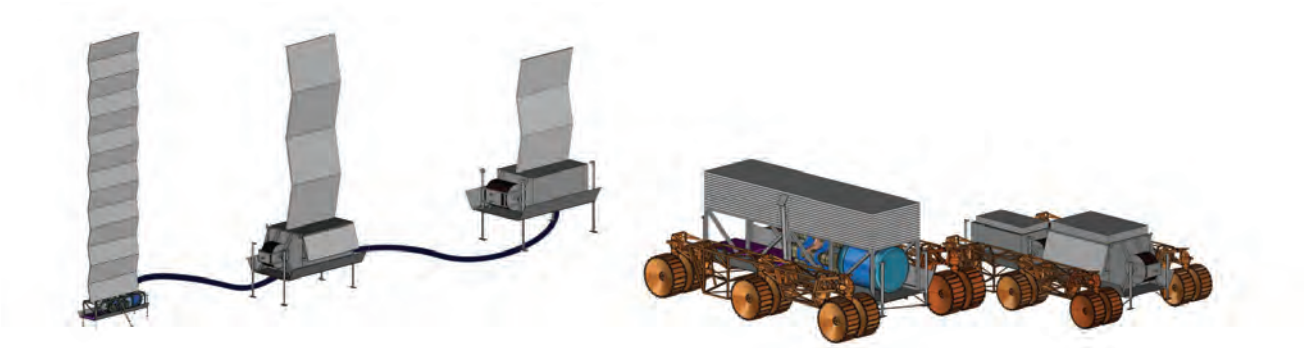


FIGURE 3. A FISSION SURFACE POWER CONCEPT developed by NASA. The design has three connected components that generate electricity, convert it to a usable voltage, and serve as a control unit. The system would supply 40 kW of electrical power on the lunar surface. Each of the components could be compactly stowed for transportation. (Illustration adapted from NASA.)

momentum as the thrust is integrated over the entire deep-space flight path.

Fission power

Rovers on the Moon and Mars currently rely on solar or radioisotope power to keep their systems running, but a human space base will need much more power. The power-rich environment provided by nuclear fission systems may enable the development of a robust lunar economy and permit human exploration on the surface of Mars and beyond. Conceptually, a fission surface power (FSP) system is modular and extensible to a wide range of electric power levels, from tens to thousands of kilowatts. When humans reach a new planet, they could unload FSP modules that could generate electricity for a variety of applications. Figure 3 shows one concept for a three-pallet system that can be stowed on rovers for easy transport.

The power-system mass is more of a constraint for FSP systems than for propulsion reactor systems because FSP systems must fit on a vehicle that lands on the surface of another planetary body rather than one that remains in space. Once on the surface, they can operate continuously in harsh environments for long durations without the need to refuel or rely on outside energy sources, such as the Sun. And unlike solar arrays, FSP systems don't have their output diminished by factors like dust accumulation.

NTP, NEP, and FSP reactors share some commonalities. Their core contains nuclear fuel, into which fissioning atoms deposit immense quantities of heat. An intricate network of channels incorporated into the reactor core is used to cool the fuel and extract heat. At peak operation, an NTP engine, for example, would deposit 500 MW of thermal power or more into the fuel. Failure to adequately remove that heat could cause the fuel to melt within seconds.

NEP and FSP power densities are two orders of magnitude lower than the power density of NTP, so the peak stress on the fuel elements is less. But power reactors operate for a long time, often many years, and the fuel elements in NEP and FSP systems receive a lifetime neutron dose that is at least an order of magnitude higher than what NTP elements receive. Although NEP and FSP power reactors operate at lower temperatures than NTP systems, the large total neutron dose, additional nuclear fuel burnup, and fission product buildup are likely to result in significant swelling and deformation of both nuclear fuels and structural materials. In some ways, that makes developing an NEP or FSP reactor just as challenging as an NTP reactor.

Historical efforts

Multiple NTP programs have been initiated over the past seven decades, including programs in the Soviet Union, the US, and, more recently, China. The only US programs to date to build and test NTP reactors and engines were Project Rover, active from 1955 to 1973, and the Nuclear Engine for Rocket Vehicle Applications (NERVA) program, which ran from 1961 to 1973. Rover and NERVA tested numerous reactors and engines, all using hydrogen propellant, in open air at the Nevada Test Site (now the Nevada National Security Site); one such test is shown in figure 4. Among the programs' achievements were an NTP-produced thrust of 250 000 pounds of force (lb_f), or approximately 1100 meganewtons; continuous operation of a reactor for 62 minutes; and a peak reactor temperature of 2750 K.[1]

There have been several NTP programs since Rover and NERVA, but none have successfully reached the point of producing integrated nuclear rocket systems that could be assembled, tested, and launched. That is partially because of challenges in testing an NTP engine on the ground. Increased regulatory and safety constraints now require performing extensive analysis, processing and scrubbing of the nozzle flow before exhausting byproducts into the environment, and building robust reactor-containment shielding, all of which increase test costs.

Numerous NEP and FSP programs have also been initiated over the years, with the most notable being the Systems for

Nuclear Auxiliary Power (SNAP) program, which ran from 1955 to 1973. It aimed to develop lightweight, compact nuclear electric systems for space, sea, and land use. Several reactors were developed and tested at the Santa Susana Field Laboratory, including the SNAP 10A system shown in figure 5.

On 3 April 1965, SNAP 10A became the first and so far only nuclear reactor launched by the US. Following launch, it produced more than 600 W of electrical power and operated for 43 days before an electrical system failure on the host spacecraft ended the mission. SNAP 10A remains safely in a high orbit to this day.[2]

Current US space nuclear activities

Several of today's efforts are aimed at developing the technologies that will enable NTP, NEP, and FSP for fast-transit missions to the Moon, Mars, and the outer planets and for power production to support permanent outposts on their surfaces. Current efforts are focused on utilizing high-assay low-enriched uranium (HALEU) nuclear fuels, which have ^{235}U enrichment below 20%. (For more on NASA's uranium fuel–based developments, see Physics Today, December 2017, page 26.) Using HALEU fuel reduces proliferation concerns, enables university and commercial-sector participation in the development of space nuclear systems, and is in line with President Trump's Space Policy Directive-6. Issued on 16 December 2020, the presidential memorandum states that "the use of highly enriched uranium in SNPP [space nuclear power and propulsion] systems should be limited to applications for which the mission would not be viable with other nuclear fuels or non-nuclear power sources."

Because space nuclear system designs and enrichment levels differ from the designs and fuels used in the past, it is harder to extrapolate from historical test data. The scope of the current projects covers the spectrum from technology advancement and maturation to preliminary design and analysis that support flight demonstration missions.

NASA's space nuclear propulsion project is responsible for all the agency's work related to NTP and NEP. Those efforts have focused on design and operational testing of components and subsystems at prototypical conditions. The test results are used to develop predictive modeling and simulation tools to guide additional R&D for the design and execution of future flight missions.

A program initiated under the space nuclear propulsion project is the investigation of multiple fuel and moderator types and various composite structures for containment and insulation. In 2021, the US Department of Energy, on behalf of NASA, selected three companies to design a HALEU-fueled NTP reactor that could operate at temperatures commensurate with a 900-second specific impulse, an engine thrust of 12 500 lb_f, and a reactor mass under 3500 kg. Two companies received additional funding in 2023 to focus on manufacturing demonstrations and the evaluation of hardware under various engine conditions, including high temperatures while exposed to hydrogen gas.

The space nuclear propulsion project is also partnering with the US Department of Defense, US Department of Energy, and commercial entities to develop and fly one or more NTP demonstration engines. That work will be a valuable operational, regulatory, and safety pathfinder and will establish precedent for mission planners contemplating the use of nuclear technologies.

NEP work is currently focused on maturing technologies that can be used both for lower-power science and robotic

FIGURE 4. ONE EARLY TEST of a nuclear thermal propulsion reactor as part of Project Rover, which ran from the mid 1950s to the early 1970s. Here, fission-heated hydrogen propellant is exhausted into the open air of the Nevada Test Site. (Photo courtesy of the National Security Research Center at Los Alamos National Laboratory.)

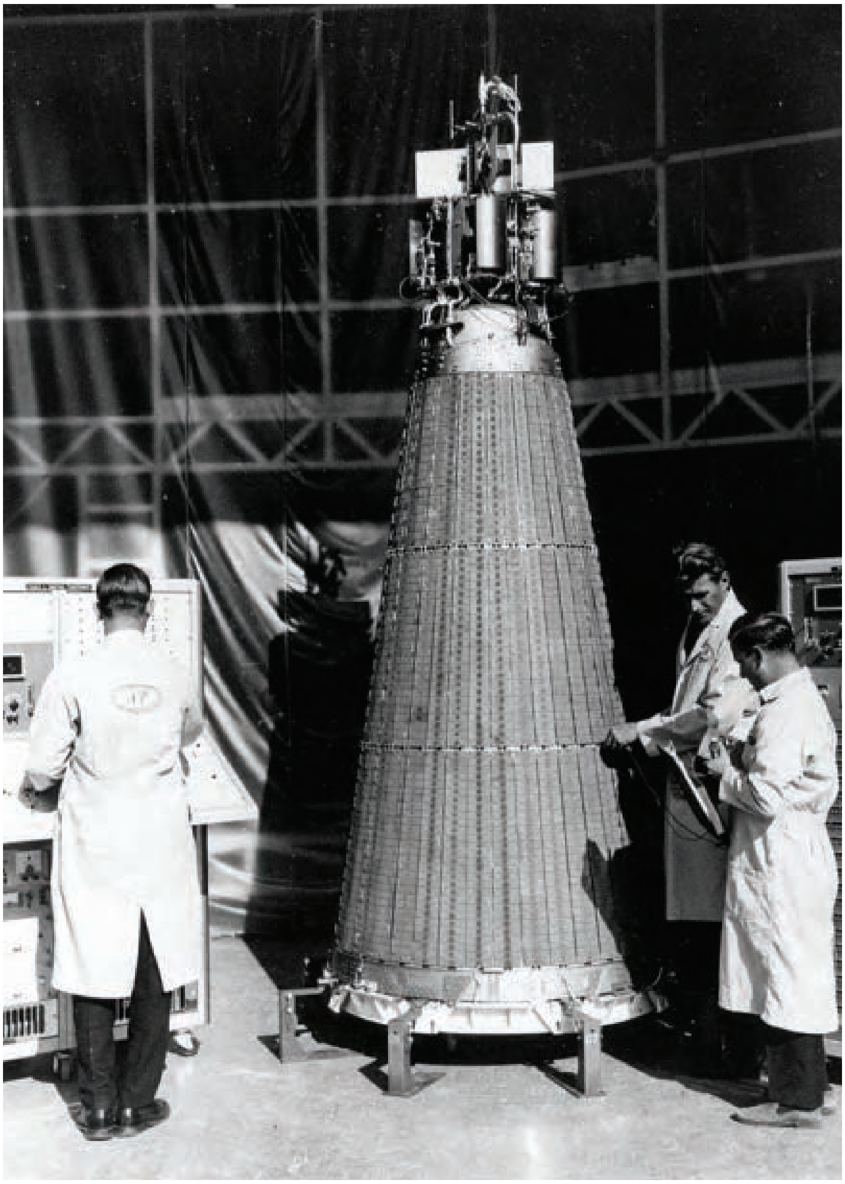


FIGURE 5. THE SNAP 10A OPERATIONAL SPACE POWER REACTOR SYSTEM is the only US nuclear reactor to reach orbit. Launched in 1965, it operated for 43 days before its nonnuclear components failed. (Photo from the US Department of Energy.)

missions requiring on the order of tens to hundreds of kilowatts of electric power (kW_e) and for megawatt-power missions that could support human exploration. The effort, formulated in response to a consensus report by the National Academies of Sciences, Engineering, and Medicine,[3] aims to fabricate and extensively test NEP subsystem hardware at scale. That requires assembling a database of measured hardware performance, mass, and wear mechanisms to quantify component and subsystem lifetimes. Through the effort, NASA will gain experience to support the assembly, launch, and operation of NEP systems.

The fission surface power (FSP) project is responsible for all NASA work related to the development and operation of a space nuclear power system that can be landed on the surface of a moon or other planetary body. The requirements for the recently completed phase-1 effort were a HALEU-fueled 40 kW_e reactor that had a mass of less than 6000 kg and could operate continuously for 10 years.

Outside of NASA, the US Space Force Joint Emergent Technology Supplying On-Orbit Nuclear Power (JETSON) program is funding space fission-reactor development to power conventional—and presently existing—xenon-fed Hall or ion thrusters at 6–15 kW_e. The JETSON phase-1 effort is scheduled for completion at the end of 2025.

Like many NASA programs of the past, nuclear technology designed for space has synergies with terrestrial applications and developments. Numerous companies are creating microreactors capable of producing tens of megawatts of electric power for commercial, residential, and military applications. Because mass is always a key consideration for space technologies, the push to reduce space-reactor sizes also supports terrestrial microreactor-sized activities. In addition, as space reactors overcome various design challenges, the solutions may result in improved terrestrial reactors. Developing space and terrestrial nuclear technologies in concert with each other will drive the refinement of nuclear policies, improvement of the regulatory process, and growth in the number of skilled technicians and engineers, all of which result in a safer and more reliable nuclear field.

NASA is investing in NTP, NEP, and FSP technologies to establish a sustained lunar presence, send the first humans to Mars, and enable a new era of interplanetary science missions. Nuclear power has the potential to usher in a new space age that will make our ancestors' dreams of living on the red planet a reality and pave the way for new and even bigger dreams.

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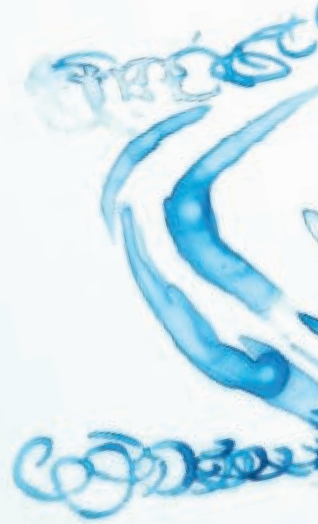
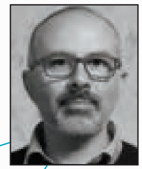
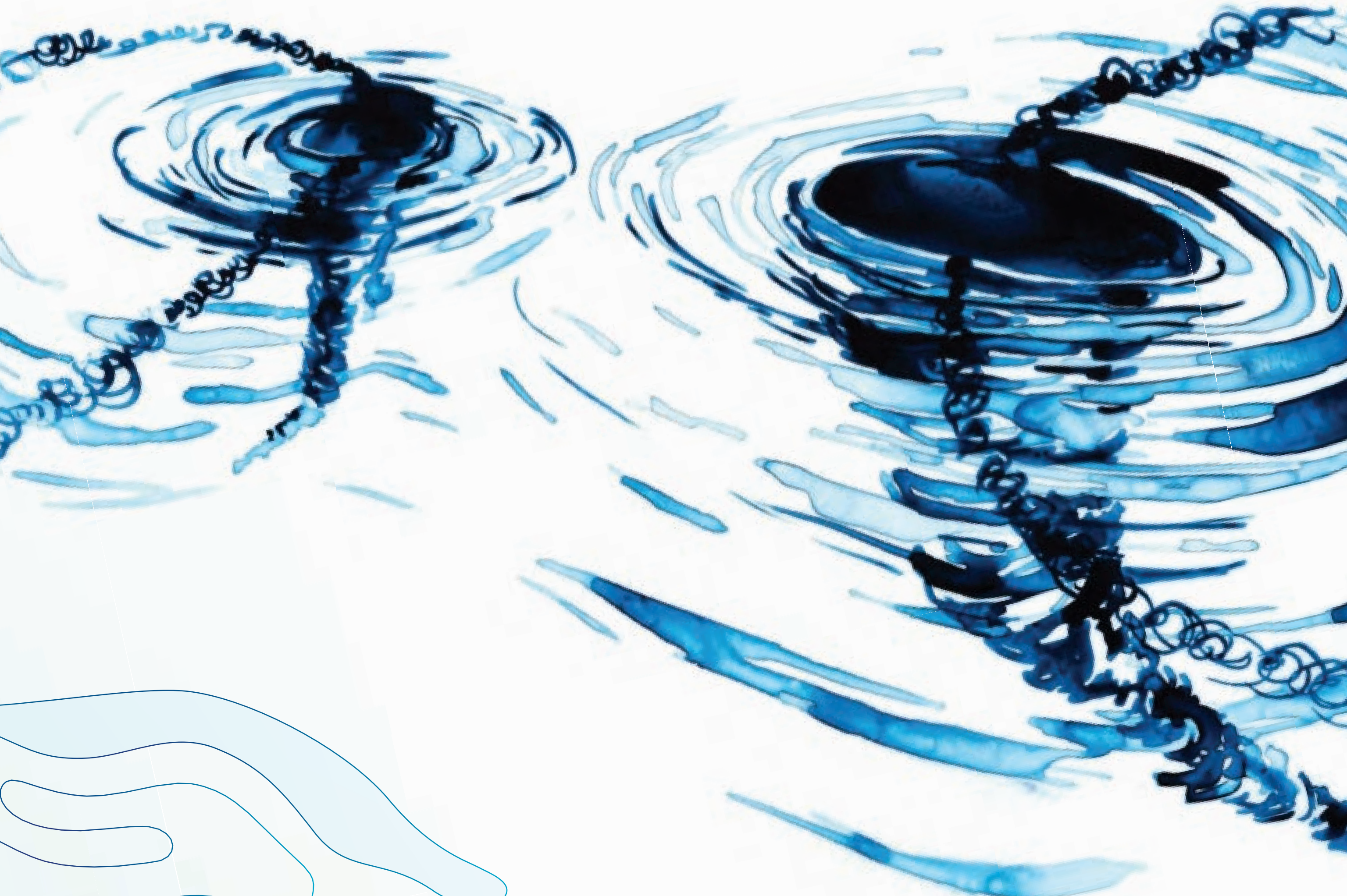
HOW BLACK HOLE SPECTROSCOPY CAN PUT GENERAL RELATIVITY TO THE TEST



Colliding Black Holes, by Lia Halloran, ink on Dura-Lar, 2016. (Image excerpted from *The Warped Side of Our Universe: An Odyssey through Black Holes, Wormholes, Time Travel, and Gravitational Waves*.

Emanuele Berti is a professor in the William H. Miller III Department of Physics and Astronomy at Johns Hopkins University in Baltimore, Maryland. **Mark Ho-Yeuk Cheung** and **Sophia Yi** are PhD students working with Berti.





Emanuele Berti,
Mark Ho-Yeuk Cheung,
and Sophia Yi

Einstein's theory makes specific predictions about the nonlinear spacetime oscillations that propagate from merging black holes. Next-generation gravitational-wave detectors should enable researchers to evaluate those predictions.

General relativity has passed every test that multiple generations of researchers have thrown at it. Those tests include the three that Albert Einstein proposed when he introduced the theory in 1915 as well as repeated precision experiments performed in the lab and through astronomical observations.

The 2015 direct detection of gravitational waves from the merger of two black holes[1] marked the opening of a new avenue for testing general relativity. The discovery occurred four decades after Russell Hulse and Joseph Taylor Jr confirmed the existence of gravitational waves indirectly by observing their effect on the orbit of a binary pulsar,[2] and it offered the promise of unprecedented access to the strong-field regime of gravity. The now hundreds of mergers that have been spotted by the Laser Interferometer Gravitational-Wave Observatory (LIGO) in the US, Virgo in Italy, and KAGRA in Japan involve black holes and neutron stars that are colliding at extremely high velocities and are subjected to some of the universe's strongest gravitational fields. If there are cracks in general relativity, then tests involving strong gravity present the ideal means of finding them.

And there is good reason to look for those cracks. Einstein's theory does not seem to meld with quantum mechanics, and it does not explain the mysterious phenomena of dark matter and dark energy. To solve such lingering questions, various modified theories of gravity have been proposed.

In the strong-field regime, researchers may find deviations from general relativity by studying the nonlinear nature of gravity: how tiny spacetime perturbations, in the form of gravitational waves, interact with themselves to produce more perturbations. The observable effects of that nonlinearity are too small to have been detected in previous tests. By using a technique called black hole spectroscopy to analyze how nonlinear effects are manifested in gravitational-wave observations of black hole mergers, researchers can devise powerful tests of general relativity—and perhaps find hints of how to modify the theory to answer some of the biggest open questions in physics.

Black hole ringdown

As two black holes begin to merge, they whip up linear perturbations in spacetime that interact to form nonlinear perturbations. The nonlinear effects are so complex that they can be faithfully modeled only by solving the Einstein equations on a supercomputer[3] (see the article by Thomas Baumgarte and Stuart Shapiro, Physics Today, October 2011, page 32). Eventually, when the black holes have merged, the object that forms is expected to be reasonably well described by an exact solution of Einstein's field equations. Found in 1963 by Roy Kerr, who is shown in figure 1, the solution

FIGURE 1. ROY KERR, pictured here in 2004, found in 1963 an exact solution to Einstein's field equations that describes a rotating black hole in isolation. The frequencies of the gravitational waves that are emitted as a newly merged black hole settles into a Kerr black hole are tied to the mass and spin of the final black hole. (Photo courtesy of the University of Canterbury.)

describes a rotating black hole in isolation, and it depends only on the black hole's mass and its angular momentum, or spin[4] (see the article by Remo Ruffini and John Wheeler, Physics Today, January 1971, page 30).

A sweet spot for studying nonlinearities occurs just after the merger, when the newly formed object is settling down into a Kerr black hole. The signal emitted during that phase, which lasts for about a millisecond for the events detected by LIGO, Virgo, and KAGRA, is similar to the sound waves emitted by a bell struck by a hammer, and thus it is called the ringdown.[5] The ringdown portion of the gravitational-wave signal from a prototypical black hole merger is shown in figure 2.

Ringdown waves can be modeled using black hole perturbation theory. Assuming that the remnant object is described almost exactly by the Kerr solution, then the perturbation consists of small deviations with respect to the Kerr spacetime. Researchers keep track of the size of the deviations with a bookkeeping parameter, ε.

Most perturbation-theory work on black hole ringdown over the past half century has been done at linear order, with all terms of order ε^2 and higher omitted. Derived using a formalism developed in 1973 by Saul Teukolsky, the solution of the Einstein equations at linear order in ε yields a ringdown waveform that consists of a superposition of quasi-normal modes: decaying oscillations of spacetime that give way to the stationary final black hole solution.[6–8]

The beauty of general relativity is that the frequencies at which quasi-normal modes oscillate and the rates at which they die out are determined exclusively by the mass and spin of the final black hole. As a result, measuring one quasi-normal mode frequency—which combines a real component (the oscillation frequency) and an imaginary one (the damping rate)—allows researchers to determine the black hole mass and spin. Then general relativity dictates what the rest of the oscillation spectrum for that black hole must be.

As a result, researchers can test general relativity by obtaining measurements of at least two quasi-normal mode frequencies: If general relativity holds, then the two frequencies must be consistent with the same black hole properties. Suppose that after inferring the mass and spin of the final black hole, researchers observe one or more additional frequencies that are not in the spectrum predicted by general relativity. The most likely explanation is some combination of instrumental, modeling, and astrophysical effects. But if significant deviations consistently appear that cannot be explained by any such effects, then they could be evidence for an alternative theory of gravity.

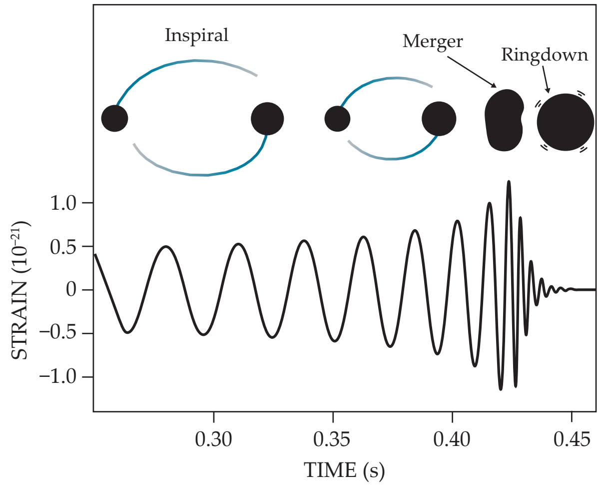


FIGURE 2. A RECONSTRUCTED GRAVITATIONAL-WAVE SIGNAL (bottom) from the black hole merger detected by the Laser Interferometer Gravitational-Wave Observatory in September 2015. At top, the two black holes spiral toward each other, coalesce, and then settle into a single rotating black hole. The settling phase, known as the ringdown, is a sweet spot for analyzing nonlinear perturbations that are encoded in the signal and for testing the predictions of general relativity. (Image adapted by Freddie Pagani from ref. 1.)

Experimental black hole spectroscopy

The observational program in which we use quasi-normal mode frequencies to identify the parameters of black holes is called black hole spectroscopy. It became an experimental science with the historic LIGO detection of September 2015 (see Physics Today, April 2016, page 14). At least a dozen signals from the black hole mergers detected via some combination of LIGO, Virgo, and KAGRA observations through 2020 have ringdown waves that are loud enough for researchers to confidently identify at least one complex quasi-normal mode frequency and thereby infer the mass and spin of the final black hole.[9]

But we still have a ways to go before we can use black hole spectroscopy to conduct robust tests of general relativity. Even the loudest gravitational-wave events observed to date have small signal-to-noise ratios in the ringdown, so it can be difficult to confidently measure the two or more quasi-normal modes that are required to test general relativity.

Next-generation gravitational-wave detectors should ameliorate some difficulties of ringdown analysis. Planned upgrades to LIGO, Virgo, and KAGRA should reduce noise in the signals that the observatories pick up, and a new detector

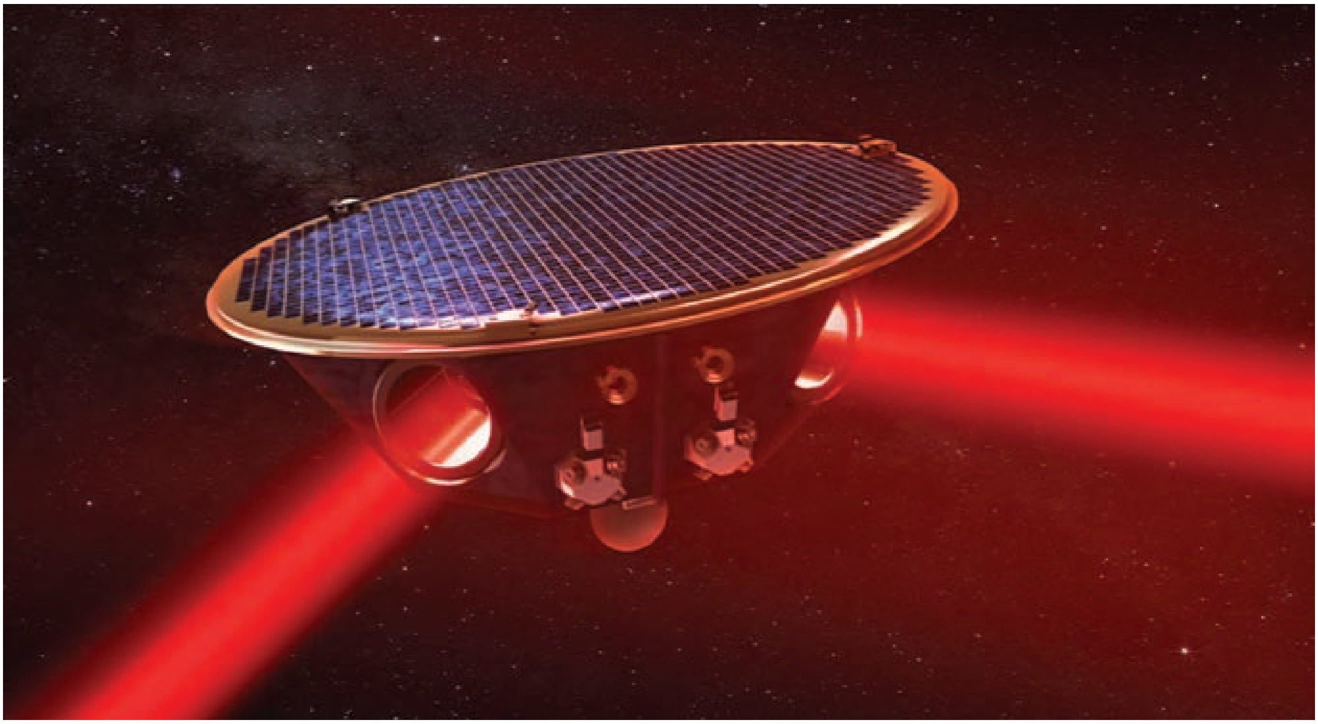


FIGURE 3. THE LASER INTERFEROMETER SPACE ANTENNA is slated to consist of a triangular network of three spacecraft, like the one illustrated here, separated by about 2.5 million kilometers. When gravitational radiation passes the satellites, the distances between them will change subtly. Researchers will be able to measure those distances using laser beams that are relayed between the spacecraft. The mission should be able to measure gravitational waves with a sufficiently high signal-to-noise ratio for researchers to perform stringent tests of general relativity. (Image from AEI/MM/Exozet.)

is slated to be built in India. Future ground-based detectors, such as the Einstein Telescope in Europe and Cosmic Explorer in the US, should have even higher sensitivity.[10,11]

There are also plans for a space-based gravitational-wave observatory, which is illustrated in figure 3. Whereas current observatories detect signals emitted by merging black holes with tens or hundreds of solar masses, the Laser Interferometer Space Antenna (LISA) would observe lower-frequency spacetime ripples that are generated by coalescing black holes that are millions of times as massive as the Sun. The signal-to-noise ratio for ringdown signals from those supermassive black holes is expected to be orders of magnitude larger than that for current signals. Several quasi-normal mode frequencies could be measured in a single merger event observed by LISA.

Although the anticipated dramatic enhancements in detection sensitivity would aid black hole spectroscopy research, they would not eliminate the theoretical challenges. Observing a louder signal makes smaller effects—including but not limited to nonlinearities—more visible. A crucial next step is to develop the ability to characterize those small effects accurately. Part of the current theoretical effort is understanding how and when the nonlinear quasi-normal modes at order ε^2 or higher in black hole perturbation theory will become significant in gravitational-wave observations.

Powerful tests with an improved ringdown model

Recent simulations of black hole mergers have shown conclusively that nonlinear quasi-normal modes are present in the waveforms and that their amplitudes can be similar to those from linear quasi-normal modes.[12–14] The results imply that accurately characterizing the gravitational-wave signal—and therefore the black hole source—requires more than the linear-based analyses we have relied on to date. It necessitates furthering our understanding of how both linear and nonlinear quasi-normal modes depend on the intrinsic parameters, such as mass ratio, spins, and eccentricity, of the binary progenitor. Researchers are exploring those connections using a range of analytical and numerical techniques.

Another challenge with detecting quasi-normal modes is that they decay exponentially as a function of time. A promising way to move forward is to try pushing the validity of perturbation theory to earlier in the merger by including more nonlinear effects. For example, although the mass and spin of the black hole is still evolving at early stages of the

The beauty of general relativity is that the frequencies at which quasi-normal modes oscillate and the rates at which they die out are determined exclusively by the mass and spin of the final black hole.

merger because of the effects of gravitational radiation, we could potentially model those effects by including third-order contributions in perturbation theory. An additional priority is identifying which quasi-normal modes are present in gravitational-wave signals and which are not.[15,16]

Once researchers get a handle on some of those outstanding questions, they can start planning even more stringent tests of general relativity. Because the frequencies of the nonlinear quasi-normal modes during the ringdown are the sum or difference of the frequencies of the linear modes, we can calculate the frequencies of the nonlinear modes from those of the linear ones. The nonlinear quasi-normal mode frequencies that are excited are restricted by selection rules that are similar to those that apply to atomic transitions in quantum mechanics. We can thus test whether the measured nonlinear quasi-normal mode frequencies in detected gravitational waves match the predictions of general relativity.

We do not have to stop there. From general relativity, we can compute the relative amplitudes of the linear and nonlinear quasi-normal modes.[17,18] The modes' relative amplitudes depend mainly on the spin of the remnant black hole, and they seem to be only mildly dependent on the initial conditions of the perturbation. We therefore can also predict the nonlinear mode amplitudes and phases from the linear modes that are sourcing them and compare the results with observations. Significant theoretical work is focused on understanding how the amplitudes of the nonlinear modes depend on the initial conditions of the merger. The effort is somewhat analogous to computing transition probabilities in quantum mechanics.

The future of black hole spectroscopy

Much of the current work in black hole spectroscopy involves developing a picture of how nonlinearities are excited in general relativity. But to test alternative theories of gravity, we will also have to understand nonlinear ringdown in each of those theories. Do we still expect the nonlinear frequencies to be the sum of the linear mode frequencies? How will the relative amplitudes of the nonlinear modes change because of deviations from general relativity? Those questions have yet to be answered.

Yet more theoretical work remains to be done to address other important questions. For example, will the presence of nonlinearities in general relativity inhibit our ability to see deviations from the theory in the quasi-normal mode spectrum?

Our best bet is to shore up the theoretical research of black hole spectroscopy so that when, in the 2030s, LISA is slated to start observing supermassive black hole mergers, we will be ready to use the measured nonlinear quasi-normal modes to perform tests of general relativity. The payoff will be a striking experimental confirmation of Einstein's general relativity in the strong gravity regime or, perhaps, the observation of deviations that could point to new directions in quantum gravity and cosmology.

We thank Lia Halloran for allowing us to use her painting for the opening spread. She is represented by the gallery Luis De Jesus Los Angeles and is a professor and the art department chair at Chapman University.

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NSF and POSTWAR US SCIENCE

Emily G. Blevins

FROM THE ARCHIVES
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Emily G. Blevins is a historian of science and technology. She currently works in science and technology policy in Washington, DC.

In the early days of NSF, its leaders dreamed of large-scale federal investment in basic science but had to carve out a place for the new foundation in the complicated landscape of US science funding.

Editor's note: To mark the 75th anniversary of the creation of NSF, Physics Today is reprinting this 2020 article about its early history.

A crowd began to form at the train station in Pocatello, Idaho, around 5:15am on Wednesday, 10 May 1950. Some 700 bleary-eyed townspeople had come to see the president and neither the day's cold weather nor the hour would deter them. When the train chugged into town, President Harry Truman was standing on the rear platform, ready to greet the crowd. The trip to Pocatello was part of a whistle-stop tour of the northern US that took the president to numerous small towns dotting the railway.

Although Truman spent most of his time in Idaho addressing local agricultural and economic issues, in Pocatello, he talked to the crowd about science. Earlier that morning, as his train sped along the tracks, Truman had signed the National Science Foundation Act of 1950. It created the first federal agency devoted to supporting fundamental research and education across all scientific disciplines. Standing before a group of chilly Idahoans, Truman made a case for the importance of large-scale federal support for scientific research.

The story of NSF's creation and early years of operation serves as an important window into the growth of postwar federal science policy. Science's role in World War II had convinced many in the government that public support was needed for scientific research. Once open, NSF became an important site where debates over science policy, federal support for civilian research facilities, and federal support for education in STEM (science, technology, engineering, and mathematics) played out in postwar America.

NSF's World War II roots

In June 1940, anticipating that the US might decide to enter World War II, the US government created the National Defense Research Committee (NDRC). Its role was to supplement the military's ongoing R&D activities by enlisting civilian scientists and industrial research laboratories. Vannevar Bush (see figure 1), president of the Carnegie Institution of Washington and a member of the National Academy of Sciences, became the head of the NDRC and worked to bring US scientific research to bear on the war effort. By June 1941 the NDRC was expanded into the Office of Scientific Research and Development (OSRD). The NDRC had been created through an executive order and funded through the president's emergency funds; the OSRD, in contrast, was established under the Office of Emergency Management and had its own budget and a more secure organizational home in the White House. The OSRD also expanded the NDRC's work to include medical research and new capabilities for weapons development and testing.

Bush funneled unprecedented levels of funding through the OSRD into the hands of civilian scientists working in universities and industrial laboratories and helped expand and deepen federal connections to those institutions. Primarily through the mechanism of the research contract, Bush ensured that scientists played a greater role than they'd had during previous military engagements, when they served largely as consultants who directed federal dollars to scientific and technological projects they deemed most likely to yield strategic advantages.

By the end of the war, the OSRD had spent nearly half a billion dollars and made 2300 R&D contracts with 321 different industrial companies and 142 academic and nonprofit organizations. The contracts greatly favored the industrialized Northeast and well-established centers of academic excellence. The top four contractors by funding—MIT, Caltech, and Harvard and Columbia Universities—revealed the patterns of patronage the OSRD followed and helped entrench in the postwar period.[1]

The OSRD coordinated research that led to the tactical use of radar, the production of penicillin, and the development of the atomic bomb. In short, it revolutionized the relationship between US science and the state. By demonstrating the importance of federal support for scientific research, the OSRD cemented important financial relationships between academia, industry, and the government. Pleased with the OSRD's success, scientists and administrators began to advocate for continued federal support after the war.

Competing visions for postwar science policy

Bush and the other leading scientists at the OSRD were not the only ones with a vision for federally supported scientific research. In 1942 and 1943, Harley Kilgore, a Democratic senator from West Virginia who served on the Military Affairs Committee, introduced two bills calling for the creation of an office of science and technological mobilization. Although Kilgore himself was not a scientist, he had become persuaded that the nation should strengthen its scientific resources in the name of national defense. His bills outlined plans for a new federal office that would fund and conduct science and technological research, coordinate all federal and private scientific research, engage in international activities, and promote the training and education of future scientists.

Neither of Kilgore's initial bills made it out of committee, but his vision for postwar science policy was enough to arouse Bush's ire. In a 12-page letter to the senator, Bush outlined his objections to the 1943 bill. His chief criticism was that Kilgore's legislation conceived of science and technology's benefits to society too narrowly. He charged that Kilgore's bill advanced science in the name of military preparedness at the expense of science's primary aim of "increas[ing] the knowledge and the understanding of man … [and] extending his grasp of the environment in which he lives and his appreciation of the vast and intricate system of nature by which he is surrounded."[2]

His critique of Kilgore's proposal helped Bush frame his own vision for postwar science policy. He laid out his ideas in a July 1945 report titled *Science—The Endless Frontier*, which he prepared in response to President Franklin Roosevelt's request for a plan that would continue the successes of the OSRD into peacetime. His most crucial suggestion was for the creation of a national research foundation.

In the report, Bush made a strong case for why the federal government needed to support basic scientific research in the postwar period. The war had devastated the European centers of learning that had been crucial to the education of Bush's generation of scientists. "We can no longer count on ravaged Europe as a source of fundamental knowledge," he wrote. "In the past we have devoted much of our best efforts to the application of such knowledge which has been discovered abroad. In the future we must pay increased attention to discovering this knowledge for ourselves particularly since the scientific applications of the future will be more than ever dependent upon such basic knowledge."[3] To fulfill that goal, Bush argued that US universities and researchers would need more resources—and those resources could come only from the federal government. "New impetus must be given to research in our country. Such new impetus can come promptly only from the Government. Expenditures for research in the colleges, universities, and research institutes will otherwise not be able to meet the additional demands of increased public need for research."[4]

FIGURE 1. VANNEVAR BUSH, head of the Office of Scientific Research and Development during World War II and one of the architects of NSF. The photograph is inscribed to Hugh Dryden, director of the National Advisory Committee for Aeronautics. (Photograph from the National Archives and Records Administration, courtesy of the AIP Emilio Segrè Visual Archives.)

Without consulting Kilgore, Bush arranged for Democratic senator Warren Magnuson of Washington state to introduce a bill based on the ideas put forward in *Science—The Endless Frontier*. On Thursday, 19 July 1945, Magnuson introduced S. 1285, which had been drafted by OSRD staff with Bush's guidance. Kilgore reportedly considered himself "double-crossed" by Bush's move to undercut his efforts and decided to submit a new bill, S. 1297, the following Monday.[5] The stage was set for a protracted legislative debate that would last nearly five years. The main disagreements surrounded patent rights for government-funded research, support for the social sciences, geographic diversity of funding distribution, and political control of foundation operations.[6]

The NSF Act Truman signed into law in 1950 represented a compromise between the two camps. It called for the creation of a new organization that would develop a national policy for promoting basic research and education in the

natural sciences. The agency would have three main categories of functions: support for basic scientific research, support for science education, and the evaluation and exchange of scientific research and information. NSF would be led by a presidentially appointed director who would share planning and decision making with the National Science Board, a new advisory body comprising 24 representatives from the scientific community.

Should there be a national policy for science?

NSF was born into a complex federal R&D landscape that skewed heavily toward research focused on national security. At the time of NSF's creation, the newly organized Department of Defense and the Atomic Energy Commission accounted for 90% of the $1 billion federal R&D budget[7] in 1949–50. Although Bush had hoped NSF would become the centralized place in the federal government for medical and military research, other agencies remained involved. The military services continued their individual basic research programs; the AEC and the Office of Naval Research maintained their support of fundamental science related to nuclear research and the operational needs of the US Navy; the National Institutes of Health became the primary patron of medical research. Such competition, along with the outbreak of the Korean War, led to meager initial budgets for the fledgling NSF. Congress voted to appropriate just $225 000 (around $2.4 million in current dollars) for NSF[8] in fiscal year 1951 (see figure 2).

The man charged with staffing NSF and building operational capacity with that shoestring budget was Alan Waterman (see figure 3), a seasoned science administrator who had worked for Bush's NDRC and served as the Office of Naval Research's first chief scientist after the end of World War II. A short, silver-haired man with square features and a stocky,

FIGURE 2. THE US CAPITOL BUILDING in Washington, DC, where Congress votes on legislation and budgets. (Photo by Martin Falbisoner, CC BY-SA 3.0.)

athletic build, Waterman was 58 years old when Truman appointed him as NSF's first director. During his 12-year term—the longest tenure of any NSF director to date—Waterman carefully paced the agency's growth, making decisions that would shape both its development and the landscape of federal civilian research funding.

The NSF Act laid out science policy and evaluation duties for the new foundation. Waterman was careful not to take on too much, too quickly. In the first few years of NSF's existence, Waterman worked closely with the Bureau of the Budget to work out the agency's scope and organization. The bureau, a predecessor to the Office of Management and Budget, had been tasked with implementing the president's strategies by issuing organizational directives to government agencies and setting budget priorities. Influential members of the bureau had become concerned about the proliferation of basic research programs across various agencies and in the DOD. They viewed NSF as an opportunity to rein in federal R&D programs and eliminate any potential duplication of efforts by centralizing control and evaluation in one agency.

Waterman and the National Science Board, however, recognized that the fledgling agency would face great operational difficulty if the bureau successfully saddled it with the herculean task of coordinating and evaluating all federal R&D programs. That would have required NSF to request detailed information about funding priorities and research performance from all existing federal science programs. They argued that the agency didn't have the necessary legal authority to evaluate and give direction to sister agencies and that such duties fell under the direct purview of the bureau. Waterman also disagreed with the bureau about how much control NSF should attempt to exercise over the direction of US science policy. "Those who insist that policy must be handed down 'ready-made' in the form of a proclamation or edict do not understand the nature of policy in the realm of science," he later wrote in a retrospective for *Science*. "To be workable, policy must evolve on the basis of experience; further, it must take fully into account the fundamental principles essential to the effective performance of research in science."[9]

Under Waterman's leadership, the foundation organized its operational activities and policymaking around the central belief that scientists, not government agencies or administrators, knew best how to organize and conduct scientific research. Therefore, the agency's process of evaluating proposals and awarding grants relied on the expertise and advice of scientists, which they solicited through in-person panels and mail-in proposal reviews. NSF's approach to policymaking also relied on information from the scientific community and careful policy studies and statistical surveys to produce general recommendations. A significant early example of that approach was the foundation's decision to support the development and operation of national research facilities.

FIGURE 3. ALAN WATERMAN, first director of NSF. (Photograph by Harris and Ewing, courtesy of the AIP Emilio Segrè Visual Archives, Physics Today Collection.)

New centers for research

Although NSF's budgets remained modest during its early years, the agency's policy decisions played a crucial role in establishing civilian-led, basic research in the military-dominated federal R&D landscape. The rising cost of conducting cutting-edge scientific research limited many researchers' access to essential equipment. After World War II, defense agencies and industry made large capital investments in research facilities, but those laboratories were largely occupied by military and industry-sponsored researchers working toward mission-oriented goals. When proposals requesting funds for research facilities in nuclear physics, astronomy, and computing began arriving at NSF offices, the leadership saw an opportunity not only to support individual research projects but also to encourage the construction and operation of entire facilities for civilian-led, basic scientific research.

Although the agency's original mandate did not mention research facilities specifically, the National Science Board at its May 1955 meeting adopted an official policy regarding facilities investment. It directed NSF to support large, basic scientific facilities "when the need is clear and it is in the national interest, when the merit is endorsed by panels of experts, and when funds are not readily available from other sources."[10] The facilities policy created a new budget category, "special budgets," to ensure that the funds for large projects were kept separate from research funds for individual investigators and small-scale projects. In presenting the new policy to the White House, Waterman justified the expansion of NSF support for civilian-led basic research facilities by pointing out that various defense agencies had also funded facility construction to support mission-related research.

NSF hoped that the facilities it funded would both improve the quality of basic research in fields that depended on specialized and costly equipment and redress geographical imbalances in equipment location. The US's leading research facilities and best equipment tended to cluster around elite universities on the East and West Coasts, and NSF recognized that researchers in other areas of the country encountered more difficulty gaining access to equipment such as large telescopes and particle accelerators.

NSF submitted its first request for construction funds to Congress for FY 1956. During that year the agency awarded $125 000 for grants to support research facilities in biological and medical sciences and $397 500 for facilities to support mathematical, physical, and engineering sciences.[11] The facilities grants represented only 3% of the agency's total financial obligations for FY 1956, but they supported a wide range of projects: the beginning phases of construction of a national optical observatory on Kitt Peak in Arizona and the National Radio Astronomy Observatory in Greenbank, West Virginia; a nuclear reactor at MIT; several biological research field stations; and computing centers at Caltech, MIT, Oregon State College, the University of Washington, and the University of Wisconsin.[12]

NSF's early investment in astronomy, in particular, demonstrated the importance of the agency's support for fundamental, scientific research as a balance to military and private funding sources. In contrast to mission-related research, which guided the direction of scientific inquiry toward specific aims, NSF support offered astronomers access to observatories regardless of institutional affiliation and the chance to pursue curiosity-driven research. (See Patrick McCray, "The contentious role of a national observatory," Physics Today, October 2003, page 55.) NSF's early support of astronomy facilities also illustrates how the needs of the scientific community shaped agency priorities, and it served as an early example of the type of "bottom-up" science policy formation that Waterman championed.

Influencing federal STEM education policy

Support for US STEM education also became a fast-growing area of investment for NSF during its first decade. Before 1958 the federal government primarily left education funding and support to individual states. Wide variation in public schools' funding led to large discrepancies in education quality and access between towns, cities, and states.

Although the US government had passed various measures to provide funding for agricultural and vocational schools during the early 19th and 20th centuries, federal investment in education remained a politically contentious issue. The political landscape began to change, however, when concerns about scientific manpower started to chip away at long-held resistance to the idea of federal education funding. After World War II, scientists began to directly connect the state of US education with national security concerns. In *Science—The Endless Frontier*, Bush had warned that the US would emerge from the war with a grave shortage of scientists. He had also expressed great concern over the state of US math and science education, saying that schools were failing to produce enough high-quality scientists and that the US needed them to secure the national defense. The growing specter of Soviet competition during the 1950s added increasing urgency to his warnings.

The NSF Act gave the foundation a broad mandate to support science education. Immediately after its creation, the agency initiated a program of support for a range of science education activities, beginning with the Graduate Research Fellowship Program in 1952. Although the majority of NSF's initial education programs focused on the university level, it became increasingly clear that major improvements needed to be made at the secondary level. NSF officials were initially hesitant to venture into the comparatively more politically contentious realm of precollege education, but they recognized the need to assist science, math, and engineering teachers whose training had become outdated after the rapid scientific developments during World War II. One NSF-supported study from the period found that the average public high school math teacher had some college coursework in math but had not majored in the subject.[13]

Strengthening high school STEM courses through improved teacher training became a focus for the agency. In 1954, scientists, mathematicians, and NSF staff members began organizing training programs for high school and college teachers at university campuses across the country. The Institutes Programs sought to update teachers' subject knowledge to include the latest scientific advancements, upgrade teachers' basic training in their subject areas, and increase teacher familiarity with the latest STEM curricula—some of which had been developed with NSF support.[14]

FIGURE 4. A REPLICA OF *SPUTNIK 1* (right) and a 1957 Soviet stamp **(left)** commemorating the successful launch of the satellite. (*Sputnik 1* image courtesy of the Smithsonian National Air and Space Museum; stamp is PD-RU-exempt, via Wikimedia Commons.)

The postwar fears about Soviet competition that had largely fueled congressional support for NSF's secondary education programs reached a fever pitch on 4 October 1957. The Soviet launch of *Sputnik 1*, the first artificial, Earth-orbiting satellite, sent shock waves throughout the US (see figure 4). The subsequent launch on 3 November of *Sputnik 2*, which carried a dog named Laika, prompted an alarmed Congress to summon scientists, including Bush, to testify in public hearings later that month. Legislators wanted to know why Soviet developments had seemingly eclipsed US capabilities and what could be done to regain the US's position as the global leader. In response to those questions, Bush reiterated one of his key points from *Science—The Endless Frontier*: that US scientific and technological competitiveness depended on a strong system of scientific education and training.

The Sputnik program became a potent symbol of the damage that US underinvestment in science education and research might cause to national security and prestige. Congress responded with across-the-board increases for federal science support. For FY 1959, NSF received a total budget of $132 940 000, nearly triple the FY 1958 budget. NSF's education programming received the largest boost from the post-Sputnik influx of funds, taking in a total of $62 070 000 for FY 1959—over $12 million more than NSF's entire budget from the previous year.[15]

Although the Sputnik program spurred Congress to provide much-needed financial support for the agency's ongoing education programs, it also increased political pressure on President Dwight Eisenhower's administration to formulate a strong, far-reaching education policy. To help craft it, the White House turned to NSF, which, as a federal innovator in the field, could boast a well-established record in science education programming. On 27 January 1958, the White House released its plan for strengthening US education. Eisenhower's accompanying statement explained that his administration had developed the proposed program in consultation with the directors of NSF and the Office of Education. He included high praise for NSF's science education improvement efforts, calling them "among the most significant contributions currently being made to the improvement of science education in the United States."[16]

NSF STEM education activities served as a model for the STEM-focused parts of the 1958 National Defense Education Act (NDEA), which Eisenhower signed into law on 2 September 1958. It transferred $1 billion to the Department of Health, Education, and Welfare for the administration of a need-based loan and college fellowship program, the expansion of school science labs and foreign language instruction, and the creation of state programs to improve science and mathematics education. The first example of comprehensive federal education legislation, the NDEA formed a cornerstone of a postwar federal strategy focused on strengthening the US scientific and technological workforce that continues today.

Foundations for future science and education policy

Even though the agency did not immediately become the counterbalance to military and applied research that many had hoped it would be, the strategic investments made during NSF's early years in fields such as science education and research infrastructure support made it possible for the foundation's limited budget to have an outsized impact. The early budget restrictions also revealed to agency leadership that the link between basic research and national security was not a firm one. NSF's place in the federal funding landscape would need to be perennially justified and reasserted through the lens of an ever-changing geopolitical and fiscal landscape.

During the first 12 years of the agency's existence, Waterman charted a course of steady, considered growth. In the face of attempts to saddle NSF with burdensome duties, Waterman kept the foundation true to its core mission: the support of fundamental science research and education. Although he often drew criticism from government officials and fellow scientists for his cautious approach, many observers attributed NSF's survival during lean budgetary years to his prudence and planning. His work positioned NSF for the rapid expansion it experienced at the end of the decade.

Waterman's guidance of the agency won the respect of Eisenhower as well. In a letter dated 6 January 1961, just two weeks before his departure from the Oval Office, Eisenhower wrote to Waterman to praise the foundation's work during his administration. Professing his wish to "pay tribute" to Waterman and NSF's staff for their work promoting the progress of science, Eisenhower reflected with pride on the fact that NSF appropriations had risen drastically during his administration, from $4.7 million in 1953 to $154.7 million in 1960. He noted that NSF served as an "excellent barometer" of the nation's response to the urgent need for "increasing the scientific effort."[17]

In the 60 years since Eisenhower stepped down, NSF has also served as a barometer of the nation's attitudes toward and concerns about government support of basic science. Many of the debates that existed at the time of NSF's creation—the extent to which the agency should fund applied research, the appropriate level of support for social-science research, the geographic distribution of research funding, and more—have continued to shape agency policy throughout its 70 years. Changing political, economic, and social forces, however, have given rise to new concerns. In recent years, attention to access and equity has driven a range of different agency initiatives focused on increasing the participation of women and minorities in STEM research and careers. New geopolitical tensions have given renewed urgency to the challenges of balancing national security with scientific openness and collaboration. Like science itself, NSF's programs and ambitions have never been static; they have evolved and changed in response to policy debates, public opinion, and the needs of civilian researchers in the US.

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QUICK STUDY

John Barentine is an astronomer and principal at Dark Sky Consulting in Tucson, Arizona. He coleads the Community Engagement Hub of the International Astronomical Union's Centre for the Protection of the Dark and Quiet Sky from Satellite Constellation Interference.

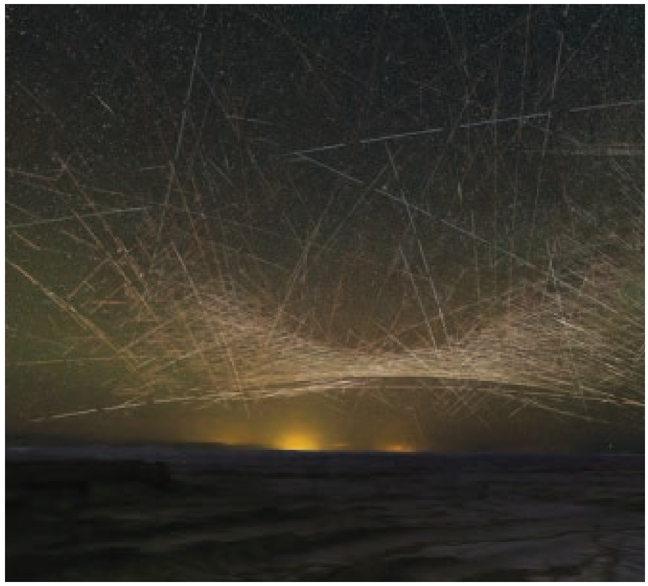
Threats to the dark and quiet sky

John Barentine

Night-sky contamination is a problem not just in the visible spectrum, and it's getting worse.

Dutch postimpressionist painter Vincent van Gogh wrote to his brother Theo in 1888, "For myself, I declare I don't know anything about [death]. But the sight of the stars always makes me dream." Indeed, understanding the cosmos and our place in it has been the dream of many humans over countless generations. But the mere sight of stars at night is now impossible for many people because of light pollution. Exquisitely sensitive detectors of light, especially at both radio and optical wavelengths, are threatened by anthropogenic pollution of the electromagnetic spectrum. And as humanity establishes a more extensive presence in space, those threats now come from both above and below.

Confronting the problem requires a more systemic approach than has historically been taken. The present and future of astronomical discovery depends on preserving what has come to be called the dark and quiet sky, where "dark" refers to an absence of visible light pollution and "quiet" refers to a lack of radio interference. The preservation movement pursues reduction of pollution sources both on the ground and in space and across the electromagnetic spectrum.



A NIGHTTIME LANDSCAPE IMAGE captured near Hanksville, Utah, during a five-and-a-half-hour exposure. The night sky is crisscrossed with light streaks mainly from sunlight reflected from satellites in two orbital shells. Sky glow from distant cities appears on the horizon at bottom center. (Photo © Jeff Warner–CatchingTime.com)

Light pollution

Light from outdoor sources on Earth's surface travels upward either directly from the source or indirectly after reflecting off the ground. Although most of that light escapes the atmosphere, what's left scatters and is redirected back toward the ground. The scattered light creates sky glow, which lowers the contrast between celestial objects and the background sky and reduces the number of stars visible to the unaided eye.

For observations made with telescopes, sky glow competes with the light of astrophysical sources, especially faint ones. It lowers the signal-to-noise (S/N) ratio of observations of a given exposure time. For observations limited by photon noise and the sky background, the exposure time required to reach a given S/N is proportional to the square of the S/N ratio. Sky glow therefore imposes a steep exposure-time cost on science performed with ground-based telescopes.

Sky glow can be reduced through effective legislation. For example, Chile has nationwide lighting standards that regulate the allowed average level of outdoor lighting. The standards impose strict limits on the use of fixtures, such as LEDs, that emit bluer light, which is more susceptible to Rayleigh scattering and thus creates more sky glow, and also promote the use of redder, longer-wavelength light. Smaller-scale legislation is also in force in the US, including around many US observatories.

Unfortunately, sky glow respects no political boundaries and often drifts hundreds of kilometers from its sources. The problem is accelerated by a lack of coordination between jurisdictions and the order-of-magnitude increase in the typical brightness of light fixtures brought about by the advent of white LED technology in the global lighting market. In a 2023 paper in *Science*, researchers reported that the brightness of the night sky increased at a global average rate of 7–10% per year from 2011 to 2022.

To evade the influence of sky glow, astronomers have for decades built observatories in locations far from cities. The proliferation of LED lighting now threatens observatories everywhere, and nowhere is safe from it—not even places with legislation to reduce light pollution. The spread of blue-rich LED lighting is a potentially existential threat for major facilities, both existing and planned for the future. And those facilities represent billions of dollars of public investment. They include the Very Large Telescope, the Vera C. Rubin Observatory, the Giant Magellan Telescope, and the Extremely Large Telescope, all of which are in Chile.

Radio interference

The radio spectrum is subject to international allocation and regulation between frequencies of about 8 kHz and 3000 GHz.

Certain frequency ranges are set aside specifically as protected bands for radio astronomy. Those frequencies are adjacent to ones used for either terrestrial or space-based communications. Sometimes, radio transmitters leak radiation into protected frequencies. Noise-limited observations are particularly susceptible to interference, which is becoming more common given the development of ultrasensitive radio receivers, such as those used in studies of the cosmic microwave background.

Spectrum management and regulation committees attempt to find a balance between the competing interests of radio astronomers and others, such as users working in commercial enterprises and militaries. The conventional solution is to build radio observatories in designated radio quiet zones (RQZs), inside which the emission of energy at radio frequencies is substantially prohibited. In the US, the National Radio Quiet Zone spans 34 000 km^2 around the Green Bank Observatory and the US Navy's radio receiving facilities in West Virginia.

But as commercial uses of the radio spectrum continue to ramp up, the radio skies grow louder. An increasing number of orbiting satellites with passive emission in protected bands and ones designed to communicate directly with mobile phones anywhere in the world threaten to undermine the efficacy of RQZs.

Space objects

Satellites and space debris—collectively, space objects—have affected astronomical observations since the launch of the first artificial satellite in 1957. Disruptions from satellites come in more forms than just radio transmission from communications satellites interfering with sensitive radio astronomy observations.

Orbiting high above Earth, satellites and disused pieces of launch hardware, such as rocket bodies, remain illuminated by sunlight. They can be seen from the ground, even by the naked eye, after local sunset or before sunrise as points of light moving across the night sky. In addition, space objects can obscure astronomical objects and lead to data loss by leaving streaks or trails of light in images from ground- and space-based telescopes.

Small pieces of debris, whether shed by intact satellites or generated from collisions of space objects, threaten to create even more junk by damaging, disabling, or destroying other satellites. Even such small particles, if reflective enough, are able to scatter and reflect so much light to the ground that they significantly elevate the brightness of the sky background—a new variety of sky glow.

For decades, the number of large, artificial objects orbiting Earth increased at a slow rate. But the rate skyrocketed in 2019, when private commercial enterprises began launching what are sometimes known as megaconstellations: collections of hundreds to tens of thousands of satellites to relay telecommunications signals with near-global coverage. Simulations of large satellite constellations predict serious problems for ground-based astronomy without adequate mitigation of their optical, IR, and radio brightnesses, both reflected and emitted. Voluntary efforts by major commercial space operators have begun to reduce the harm posed by their satellites to astronomy through techniques such as changing the exterior material to be less reflective and adjusting the satellites' orbits, but the problem is far from solved.

The steps to a solution

Although the effects of terrestrial light pollution on astronomical observations were reported as early as the 18th century, astronomers didn't begin organizing to combat terrestrial light pollution until the 1980s (see PHYSICS TODAY, December 1984, page 63.) Their efforts focused both on increasing the availability of astronomy-friendly outdoor lighting products, such as low-pressure sodium lamps, and enacting appropriate local regulations, such as switching off billboard illumination after midnight. And they successfully lobbied for the creation of RQZs to protect radio astronomy.

When the large satellite constellation issue dawned a few years ago, astronomers again organized to advocate for their field in the face of a novel threat. Taking a page from the terrestrial dark-sky movement, astronomers coordinated with people outside their field—in this case, commercial satellite manufacturers and operators. Astronomers encouraged them to innovate in satellite design and operation to reduce impacts on astronomy.

A 2021 conference resulted in publication of a landmark report, *Dark and Quiet Skies for Science and Society*, which examines potential harms of light pollution to both astronomy and human and animal well-being and makes a series of recommendations to address them. Among the recommendations are limitations on where artificial light is used, the wavelengths of such light, and shielding of the light source to direct light downward. The conference and report were organized at the request of the United Nations Committee on the Peaceful Uses of Outer Space, an international governing body established by the UN General Assembly in 1959 to consider legal issues arising from the exploration and use of outer space. The committee establishes the rules-based international order, to which UN member states generally adhere in enacting their own national space policies.

The ideal of a dark and quiet sky—with brilliant stars that inspire dreams—is one many astronomers fight to protect. Steps need to be taken to reduce the influence of electromagnetic pollution on the planet that is our shared home. Preservation of the night sky across the electromagnetic spectrum is an extension of the stewardship of a human environment that now goes beyond our planet and reaches toward the cosmic ocean. It is also key to the future of astronomical discoveries.

Additional resources

- ▶ A. C. Boley, M. Byers, "Satellite mega-constellations create risks in low Earth orbit, the atmosphere and on Earth," *Sci. Rep*. **11**, 10642 (2021).
- ▶ J. Barentine, *Artificial Light at Night: State of the Science 2024*, DarkSky International (2024).
- ▶ W. van Driel, "Radio quiet, please!—Protecting radio astronomy from interference," *Proc. Int. Astron. Union* **5**(S260), 457 (2009).
- ▶ Dark Sky Oases, Optical Astronomy, Bioenvironment, Satellite Constellation, and Radio Astronomy Working Groups, *Dark and Quiet Skies for Science and Society: Report and Recommendations*, Zenodo (2022).
- ▶ F. Falchi, S. Bará, "Light pollution is skyrocketing," *Science* **379**, 234 (2023).

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BACK SCATTER

Modeling hand clapping

Hand clapping is among the oldest and most fundamental human behaviors. The basic acoustics have long been known: Clapping cupped palms together, for example, produces a deeper pitch than clapping the fingers of one hand to the palm of the other. And the faster you clap, the louder the sound you produce.

But researchers have not devoted much study to understanding the physics of a round of applause. To investigate clapping acoustics, a team led by Yicong Fu and Sunghwan Jung of Cornell University used a microphone and a high-speed camera to capture footage of three common hand-clapping configurations—cupped, palm to palm, and finger to palm. The photo shown here is a still from one of the videos. To reproduce hand clapping in a controlled manner, the researchers digitally modeled the hand configurations and used a 3D printer to make replicas out of a silicone that resembles human skin. To help visualize the fluid motion of the air expelled from the palm cavity when the two hands collide, they dusted the replicas with baby powder.

Fu, Jung, and their team found that when hands clap together, the cavity they create operates like the one inside a Helmholtz resonator—a simple acoustic instrument essentially composed of a vessel with an outlet at the end of a neck. When pressurized air is forced out of the vessel, it resonates at a specific frequency. (Think of how blowing across the top of a soda bottle produces a distinct pitch.) The baby powder helped the team locate the resonator's neck and outlet, which were both determined to be at the opening between the thumb and the forefinger. The researchers also found that the soft tissue of human hands contributes to the short length of a clap because the tissue absorbs energy as it is deformed. They express the hope that architects and engineers will be able to use an accurate model of hand clapping to help in acoustic design. (Y. Fu et al., *Phys. Rev. Res.* 7, 013259, 2025; photo courtesy of Yicong Fu.) —RD