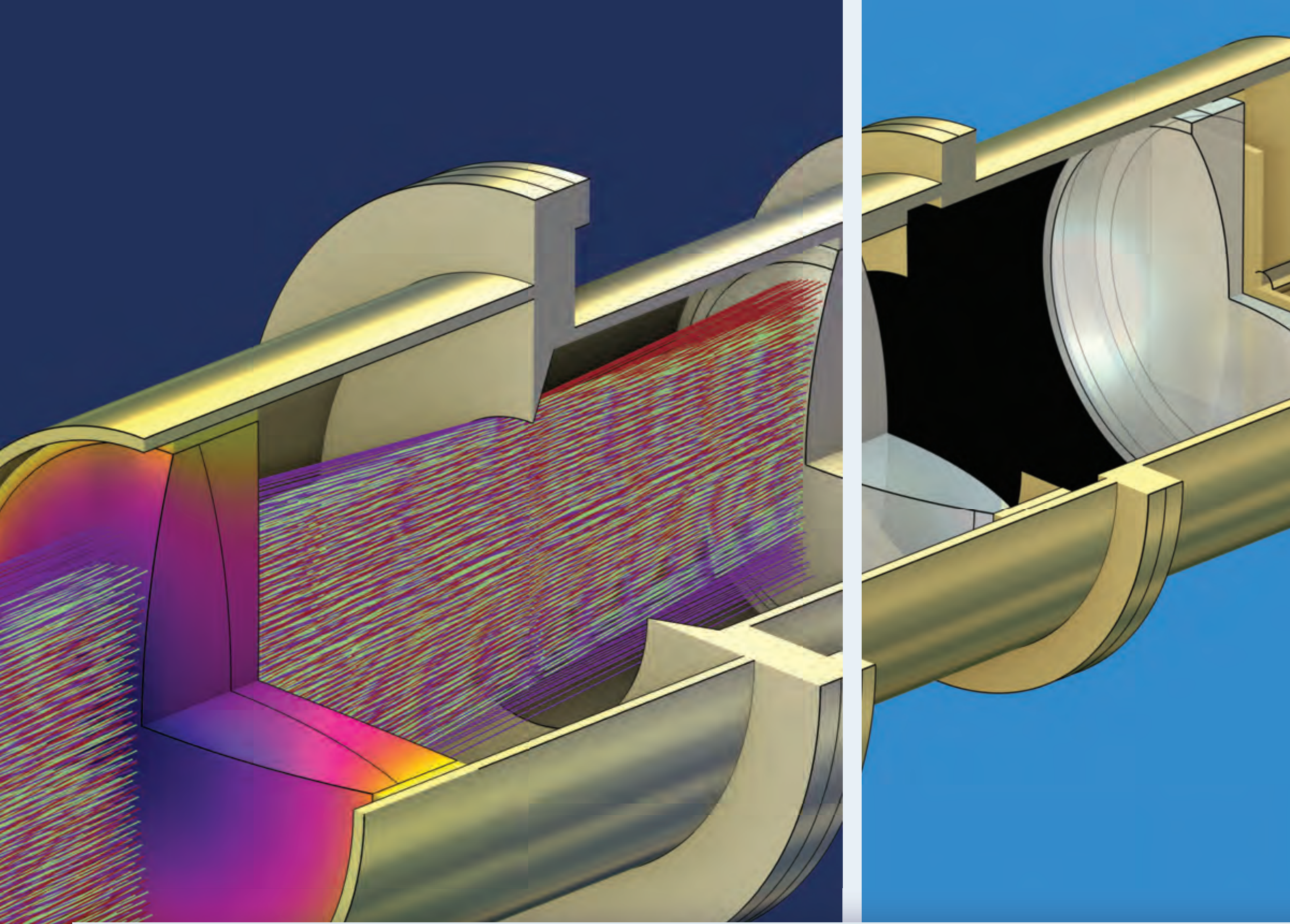

PHYSICS TODAY

March 2023 • volume 76, number 3

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QUBIT CHEMISTRY

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An early European nuclear reactor

Teaching with heart


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PHYSICS TODAY

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FEATURES

ON THE COVER: Molecules and molecular systems can host entangled pairs of spins, which are promising for applications in quantum information science. Such chemical platforms offer qubits with tailorable properties at precise locations. On **page 28**, Michael Wasielewski explains how molecular spin pairs can be formed, used to perform quantum gate operations, and scaled up to three and four qubits. (Image by Kiyoshi Takahase Segundo/Alamy Stock Photo; colorization by Physics Today.)

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HyperPhysics turns 25

In 1998 Georgia State University physicist Rod Nave launched a website called HyperPhysics to help education graduates teach physics. Since then, Nave has stuck with the original design but has continued to update the content, which has proved valuable for students, lecturers, and casual learners.

physicstoday.org/Mar2023a

USGS

Hawaii magma map

Although Hawaii's volcanoes are intensely studied, geologists still have a lot to learn about the magma transport in the underlying crust. By analyzing half a million earthquake events, researchers have now found evidence for a deep, widespread magma plumbing system beneath the Big Island.

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Math center in Ukraine

As the war in Ukraine enters its second year, a new mathematics center is being started in the country. A group of Ukrainian mathematicians from around the world launched the International Centre for Mathematics in Ukraine at a hybrid ceremony on 12 January. They are planning their first event for August.

physicstoday.org/Mar2023c

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DEPARTMENTS

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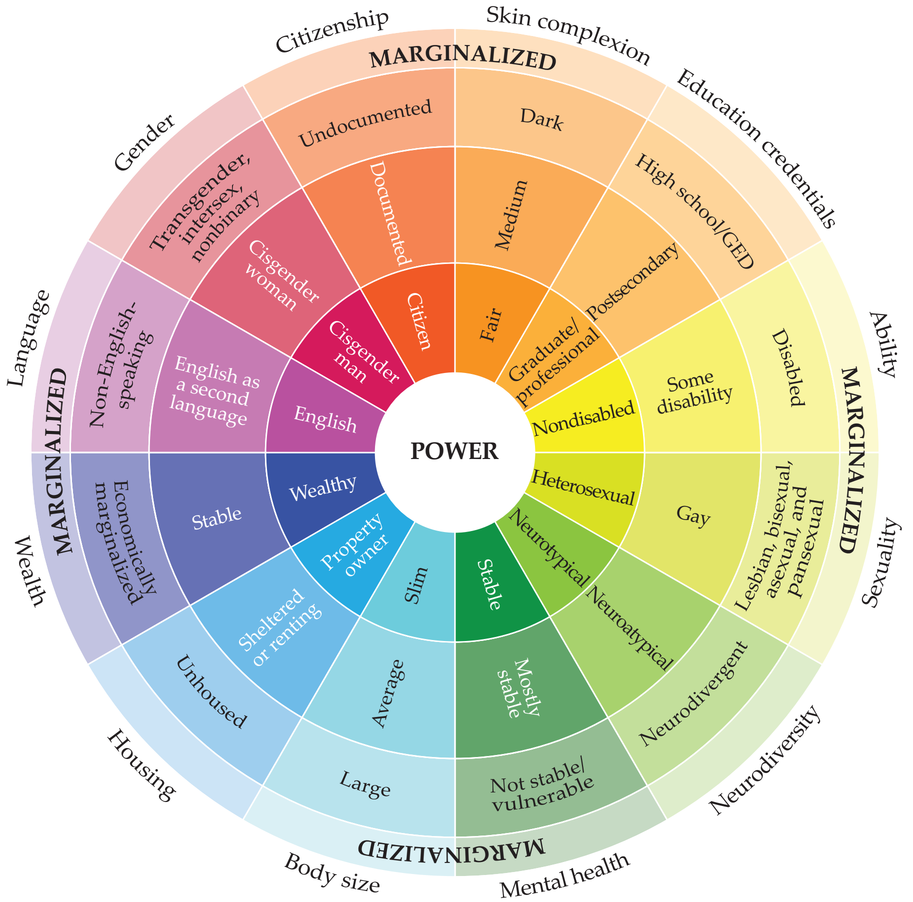
Commentary

Teach with heart!



THE WHEEL OF POWER indicates different aspects of identity or background as differently colored sectors. The closer one's identity or background is to the center of the wheel, the more likely that person will be recognized or empowered. (Adapted from a figure by Timmo Dugdale/University of Wisconsin–Madison/CC BY-NC 4.0.)

Are you concerned about the well-being of your students? Are you under so much pressure that you aren't fully present in the classroom the way you want to be? Do you feel that you rush through material without really connecting with your students? Do you want to offer more to your students than the technical aspects of your discipline?

Research shows that about 40% of postsecondary students faced a significant mental health challenge even before the pandemic.[1] In the rush to deliver the curriculum and deal with the pressures of academic life, many faculty members are overwhelmed, on the verge of or experiencing burnout.[2] After three years of adjusting education approaches in response to the COVID-19 pandemic, students and teachers, having had little time to reassess and recharge, are feeling the ripple effects of that disruption.

In the face of those challenges, how do we create a caring classroom environment in higher education that supports both faculty and student well-being? Can educators serve as role models of caring practices in the delivery of discipline-specific content to allow for development of the whole student and to give attention to student well-being? The Teaching with Heart project (https://twh.mines.edu) aims to support educators as they develop the mindset and teaching habits to create a caring class environment in science, technology, engineering, and mathematics fields in higher education. The project, which is supported by the John Templeton Foundation, offers workshops, creates an online community of faculty participants, and studies the impact those practices have on students and teachers.

In this commentary, we describe 12 Teaching with Heart practices that educators can incorporate into the higher-education classroom. Each practice takes little classroom time and doesn't disrupt the delivery of learning activities and content.

1. Use name tents and ask for preferred pronouns. We all have a deep desire to be heard and seen, and our students yearn to be known as individuals. Hence it is important for teachers to use students' names. Handing out name tents is an easy way to start using names immediately and learn them more quickly. Going over the name tents during a lull in class activities is an easy way to memorize names. Asking students to indicate preferred pronouns on the name tent helps teachers recognize and honor the identity of students, but students should not be forced to share them.[3] Simply inviting students to identify as they want creates a supportive and inclusive learning environment.

2. Ask students how you can best support them. Many students have specific needs, challenges, or insecurities, and it helps us as teachers to be aware of them. An easy way to learn about those needs is to ask students through an optional questionnaire. Open-ended questions, such as "How can I best support you?" or "Is there anything I need to know about you?," give the most revealing answers. Students appreciate just being asked such questions.

3. Be available, arrive at the classroom early, and reach out to students. A spontaneous in-person conversation is one of the best ways to connect with students. As teachers, we can easily create moments for such conversation by arriving at class five minutes earlier, not to tinker with projection equipment but to strike up conversations with students. We can send a quick email to a student who has missed classes to remind them of support options. A walk from one building to the next after class is another opportunity to connect with students.

4. Be aware of privileges. The wheel of power and privilege[4] (see figure) offers a graphic way to review factors such as gender, skin color, and sexual orientation. It can help us be aware of characteristics that determine privileges and access or barriers to opportunities. Being aware that students may face challenges that we individually may not have experienced allows us to develop compassion for our students and empowers underprivileged students through visibility.

5. Show up as a whole person, and be willing to be vulnerable. As teachers, we cannot educate the "whole person" if we do not show up as a whole person in class. Students appreciate it when we share our passions, our insecurities, and other drivers of our behavior. When intellectual humility becomes part of our teaching, we come off our pedestal as educators, which helps students connect with us as humans who are also learning.

6. Encourage students to be fearless. Many students live in fear of being "wrong," because being "right" is important for passing tests and for being rewarded in many classes. Learning is, however, an activity of trial and error, and being wrong is part of the creative process. We can encourage our students to think boldly, to experiment with different ideas, to express themselves fearlessly, and, yes, to be wrong at times without being judged negatively.

7. Develop students' analytical and intuitive thinking. Technical fields, including science and engineering, lean heavily on analytical thinking. But progress in those fields often relies on creative sparks, courage, mistakes, play, and free-flowing conversations. Bringing intuitive thinking into the classroom not only helps progress in science and engineering but also fosters the development of balanced young professionals.

8. Promote students' well-being. In the rush to get through class material, we may forget to address the well-being of students. We can show that we value student well-being by spending some class time on a conversation about wellness and campus resources, by not giving assignments over breaks, and by embodying healthy wellness practices ourselves. But most importantly, we should avoid reinforcing the common perception that higher education is only about grit and competition. Being meaningful educators involves caring about our students' growth and fulfillment.

9. Prioritize important issues over the class schedule. Sometimes traumatic events occur that preoccupy students' minds. An example is a suicide on campus. Students appreciate having a class conversation when such events happen. By creating an opportunity for one, we not only provide a platform where students can discuss unsettling events, but we also emphasize the importance of coming together as a community in times of crisis. A 20-minute class conversation can make a huge difference.

10. Focus on the potential of students instead of on their current level. Some teachers get their satisfaction from teaching students who are performing at the highest level. It is natural to like teaching your star students, but, by definition, not all students are "the best." Our perspective and satisfaction as teachers can shift dramatically when we focus not on the current academic achievement of students but on their growth rate. When we make that mental shift, our teaching is driven by student growth, not by metrics and rankings.

11. See the inner person beyond the outer person. We all have outer lives, including our body and verbal expression, and inner lives, including our emotions and dreams. It is easy to exclusively focus on the outer lives of students. Through careful observations and compassionate listening, we can get glimpses of our students' inner lives. Those can help us to connect better with students and support them more meaningfully.

12. Always love your students, even if you don't feel like it. If only we could always be a loving presence! The reality is that we sometimes are stressed or irritated and find it difficult to teach with a loving mindset. Cultivating our own well-being and approaching student interactions compassionately helps us consistently create a classroom environment in which students feel safe and cared for.

The practices listed above take little time to incorporate and easily merge with the delivery of classroom material. Habits 1–3 require no new skills, just a change of behavior. Habits 4–10 require a reflection on teaching methods and intentionally adapting our thinking and behavior over time. Such changes need attention and take some practice at first, but they can eventually become second nature. Habits 11 and 12 represent a sustained practice of Teaching with Heart.

We encourage teachers to select practices that fit them best to begin to shift their pedagogy. In doing so, they can make a positive change to the classroom atmosphere in higher education, one habit at a time. We invite you to join our efforts to elevate classroom interaction through attention to student and faculty well-being.

If you have found habits that are effective but are not listed here, please send them to us at rsnieder@mines.edu.

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LETTERS

More on the demons of thermodynamics

In her November 2021 article (page 44), Katie Robertson presents an elegant synthesis of Maxwell's, Loschmidt's, and Laplace's demons. Implicit in the text—and explicit in the conclusion—is the thesis that the second law of thermodynamics remains above reproach. Although that might have appeared to be the case at the close of the 19th and 20th centuries, it is not in the 21st. Since the mid 1990s, at least three dozen potent second-law challenges have advanced into the literature, some with strong experimental support, more than the total proposed during the previous century and a half.[1] One example involves two opposing filaments, each formed from a different material, in a diatomic gas atmosphere at uniform temperature.[2] Due to the different dissociation rates for the diatomic gas at the two surfaces, permanent gradients in pressure and temperature are formed, in apparent conflict with the second law.

The most successful of the newer demons do not suffer the ailments of their ancestors: They are macroscopic in size rather than microscopic, they operate on molecules wholesale rather than individually, and they don't think too much. Typically, they involve thermodynamic spatial asymmetries by which macroscopic energy reservoirs, which are regenerable thermally[2,3] or by other means,[4] are created at one or more of the system boundaries, standard hallmarks of discontinuities in chemical potential. Evidence for such demons should not be overlooked here, especially considering that they undercut the primary thesis of the work.

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THE FLAMMARION ENGRAVING has often been used to symbolize humanity's quest for scientific knowledge. (Engraving from Camille Flammarion, *L'atmosphère: météorologie populaire*, 1888, p. 163/public domain.)

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In her article "The demons haunting thermodynamics" (Physics Today, November 2021, page 44), Katie Robertson concludes the introductory historical summary by saying that modern developments in quantum foundations have banished the demons "once and for all." Unfortunately, no explanation or reference is given for that optimistic but controversial conclusion.

Robertson presents Erwin Hahn's 1950 spin-echo experiments[1] as the realization of Josef Loschmidt's vision of reversing momentum. But Hahn clearly described his spin-echo experiments as the effect of traditional spin dynamics for noninteracting spins in a spatially inhomogeneous magnetic field. Although the detailed explanation involves many particular subtleties of NMR dynamics in liquids, Hahn's interpretation does not imply any violation of the "second law"; it uses only the mild assumption that the spin observables are at thermal equilibrium before each start signal. Robertson's misunderstanding clearly appears when she writes that "atomic spins that have dephased and become disordered are taken back to their earlier state by an RF pulse" and, a few lines later, "it turns out that the spin-echo experiment is a special case; most systems approach equilibrium instead of retracing their steps back to nonequilibrium states." The spins have not become disordered: The phase of each spin remains directly related to the magnetic field at the spin's location, and that relationship explains the echo.

Two illuminating articles by Won-Kyu Rhim, Alexander Pines, and John Waugh describe spin-echo experiments in which the irreversible time evolution of a coupled nuclear spin system in solids is apparently "reversed" for a limited duration.[2] As the authors explain, the results arise from uniform spin manipulation and are still consistent with the laws of thermodynamics.

Another aspect of Robertson's article that disturbed me is the lack of discussion of the relations between the actual experiments performed on large (macroscopic) systems and the microscopic-scale models used in attempts to make predictions about those results.

Consider a mixture of oxygen and hydrogen at atmospheric pressure and room temperature. Standard thermodynamics and statistical mechanics will lead to excellent predictions of the equation of state, specific heat, and the like. But the standard models ignore the possibility of the chemical reaction producing water. Improved models are needed if one is to allow for, say, a slow, isothermal catalytic reaction or—much more complicated—an explosion in an isolated system at constant volume. Spin systems offer a rich variety of experimental possibilities for external manipulation and observation, but the corresponding models are related to the real experimental situations by complicated transformations and approximations that must be chosen according to the situation under study.

Robertson invokes two models in the context of Maxwell's demon. One is a biological machine using a ratchet-style mechanism. But in the cited article, the abstract carefully indicates that the evolution does not violate the second law because the microscopic mechanism is coupled to the exterior of the system.[3] In the demon-style experiment of Robertson's figure 3, a complete realistic discussion of an actual implementation of the experiment leads to the similar conclusion that the second law is not violated.

My conclusion is that demons and the related controversies are features of models and that the interpretation of actual experiments should be subjected to critical examination, preferably by those who performed the experiment and have a complete knowledge of all details.

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Katie Robertson's article gives a delightful overview of the vanquishing of demons haunting thermodynamics (Physics Today, November 2021, page 44). We want to add that Maxwell's demon plays a special role in physics apart from concerns about vanquishing. Maxwell's demon reveals a subtle link between information acquisition and thermodynamics.

Over the past two or so decades, that link has provided inspiration for the development of a robust field, stochastic thermodynamics, which enables analysis of the energetics of nonmacroscopic systems with information feedback. Stochastic thermodynamics formalizes what the demon has taught us informally—namely, that information is a resource that can enhance the ability of a system to do work, and erasure of each bit of information in the demon's memory increases entropy by $k_B \ln 2$ (with k_B being Boltzmann's constant), assuring the sanctity of the second law. Without Maxwell's demon, it is questionable whether stochastic thermodynamics and a host of interesting nonmacroscopic experimental results would exist today.

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► **Robertson replies:** Daniel Sheehan, Garret Moddel, and James Lee draw attention to an interesting book, *Challenges to the Second Law of Thermodynamics: Theory and Experiment*, which provides a survey of recent work that throws doubt on the inviolability of the second law. Do those avenues resurrect Maxwell's demon? Do they conjure new ones?

Of course, no scientific law is immutably beyond reproach, no matter how many famous physicists have sworn by it. But in considering the avenues suggested in the book, it can be helpful to scrutinize what we mean by the "second law."[1] If the second law is that entropy—of which there are many forms—cannot decrease, then it can surely be violated; the Boltzmann entropy decreases in macroscopically indeterministic processes. But if the second law is taken to be that no engine is more efficient than a Carnot engine, then at least the previous example is not necessarily a violation.

As David Wallace said in a talk at the University of Cambridge in November 2015, the distinction is between whether we can find ingenious and cunning devices or whether we can solve the energy crisis! The faith in the implausibility of the latter—that we will not find a perpetual motion machine of the second kind—is what those aggrandizing thermodynamics attest to. I meant to have captured that distinction between different kinds of "violations" of the second law in my discussion of "deft illusionists" versus "true magicians." But that may have sounded dismissive; to be clear, important insights are revealed by studying the cases that Sheehan, Moddel, and Lee highlight, especially with respect to how the macroscopic domain may differ from the mesoscopic and microscopic ones. And if there were a true magician, then that would be welcome news in the current energy crisis.

Similarly, whether the spin-echo experiment counts as a violation depends on precisely what we mean by the second law—no one is expecting to create a greater-than-Carnot efficiency engine out of that scenario. The point is merely that a system "retracing its steps" may have seemed nigh on impossible to Josef Loschmidt, but the spin-echo case provides a nice illustration of its feasibility. I am sympathetic to Jean Jeener's view that the spin echo is not a case of increasing and then decreasing entropy, but then again, if we just look at the unitary dynamics, then entropy is neither increasing nor decreasing.

One feature absent from my original article—as rightly emphasized by Harvey Leff and Andrew Rex—is the connection between thermal physics and information forged by Maxwell's demon. That is often the lynchpin or starting place for those interested in quantum thermodynamics (referenced as "quantum steampunk" in my article) and, as Leff and Rex emphasize, stochastic thermodynamics. That brings up a question though: If information is central to thermodynamics, does that raise the specter of anthropocentrism?

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Faculty interviews—traps and tips

The year was 1995, and I was a postdoc working to develop a low-temperature near-field scanning optical microscope to study exciton charge and spin transport in nanostructures. It was my third year of the appointment, and I had some nice results that got me an invited talk at the APS March Meeting and a half dozen faculty interviews.

Like nearly all faculty candidates, I was forced to think about what I wanted to do with my career in the longer term as an independent researcher. The optical techniques I had developed were still new to me and significantly different from my PhD research, which was on sliding charge-density waves and their nonlinear dynamics, so it felt natural to consider what other systems I could investigate using similar approaches. I decided to focus on spatiotemporal behavior of ferroelectric materials. But beyond that, I had only a vague idea of what I was going to do. I had never done any actual research with such materials, although I had read many papers on them, which at the time involved trekking to the library at night to read journal articles printed on real paper.

Unfortunately, I had the deeply mistaken notion that I could get by in a faculty appointment interview with a cursory plan of attack and assuring the recruiters that I would "figure it out" along the way. Not surprisingly, I bombed interview after interview. The talks usually went OK, but when it came to a discussion of my research plan, I struggled to provide details. By the time the 1995 APS March Meeting came around, I had already botched five interviews. I attended the meeting with dread, knowing that my remaining interview, and possibly my last chance to become a professor, was scheduled for the following week.

Like most of the others, my interview at the University of Pittsburgh was a two-day affair, with the first day reserved for my seminar and a few meetings and the second day filled with one-on-one discussions, where I would inevitably be questioned about my research plan. The seminar went well, but I went to sleep with a slight irritation in my throat. The next morning, my voice was gone. I had a full-on case of laryngitis.

My future colleagues at Pitt were exceedingly kind and understanding. Instead of being peppered with questions, I was served soothing herbal tea with honey. I distinctly remember gazing helplessly at two of the faculty search committee members as they discussed my fate, right in front of me. Maybe they thought that since I couldn't speak, I also couldn't hear what they were saying. One of them really wanted to ask me about the details of my proposed research program. The other was defending me, saying sympathetically, "Oh, I'm sure he has a good plan."

And that's how I got my faculty offer at the University of Pittsburgh.

I have participated in many faculty searches over the past 25 years, and I am confident that my 1995 self would not have been selected by any of those committees. The two-talk format is commonplace nowadays. Faculty give one talk based on prior research and the other focusing on their "five-year plan." I do understand why the hiring process is structured that way: Faculty hires constitute a huge investment, and search committees need to be convinced that the successful candidate can build an independent research program with clearly articulated themes and initial projects.

Here's my advice to faculty who populate search committees: Remember that a successful research career can span 30–40 years. When you are evaluating the research plans of your candidates, consider rewarding those whose ideas border on the adventurous. A balanced portfolio, mixing high-certainty paths with those that have less certain outcomes, is likely an indicator of your future colleague's long-term success. And when you hire that person, make sure that they get the support they need to be successful.

My advice to postdocs interviewing for faculty positions is to not follow the path I did. Formulate your research plan, and be ready to articulate and defend it. At the same time, be aware that it is easy to get trapped in your own expertise "polaron." The early stage of your career will be when patterns are set in motion. By the time you receive tenure, it may be hard to maneuver away from what is "expected" by your colleagues, the broader community, and yourself. I have tried to avoid that trap: Since joining Pitt, I have ventured into several new areas of research in which I initially had no prior exposure. Did I make rookie mistakes in the beginning of those adventures? Every time. But as an outsider, I eventually brought new insight and perspective into those fields.

So once you get the job, look up and look around. You might be inspired by a paper you read or a talk you heard at the March Meeting, and you might come up with an idea or research direction that seems much more interesting and compelling than your initial plan. Don't be afraid to embrace those ideas, change course, expand your horizons, and work in areas in which you are not an expert. Both you and that field will be better off because of it.

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No uncertain terms

Three words—forecast, projection, and prediction—in scientific terms are similar, but they have distinct implications in specific contexts. I find it concerning when I read research papers, announcements by government agencies and modelers, or popular science coverage that use the terms incorrectly. Such misuse may cause misinterpretations. And in the worst-case scenario, the correct meanings may be dismissed and the incorrect meanings enforced. It is the responsibility of scientists to correctly and appropriately use scientific terms and to interpret and communicate them with caution.

"Forecasts" of the COVID-19 pandemic have been offered by agencies, institutions, and teams around the world. As this issue of Physics Today goes to press, the COVID-19 Forecasting and Mathematical Modeling webpage, via the US Centers for Disease Control and Prevention (CDC), each week provides four-week "forecasts" for COVID-19 hospitalizations and deaths.[1] (Case forecasts have not been posted since December 2021.) The results presented include both the ensemble forecasts and the independent ones that the ensemble numbers are based on.

Obviously, huge uncertainties are associated with those forecasts. The CDC's hospitalization and death forecast pages state that "models make various assumptions about the levels of social distancing and other interventions, which may not reflect recent changes in behavior." Thus the possible scenarios may not necessarily be probable because of unpredictable factors such as national policies and human behaviors.[2] The CDC case forecast page states, "While they have been among the most reliable forecasts in performance over time, even the ensemble forecasts have not reliably predicted rapid changes in the trends of reported cases, hospitalizations, and deaths. They should not be relied upon for making decisions about the possibility or timing of rapid changes in trends."

To forecast is to calculate some future events or conditions, usually as a result of study and analysis of available pertinent data. A forecasted event is a probable occurrence. The term is frequently used in reference to the weather—which is forecasted on the basis of correlated meteorological observations. If a weather forecast shows that it is going to snow tomorrow, that means snow is a rather probable weather condition for the next day. And whether it will snow tomorrow does not in the least depend on how humans behave or politicians debate.

The way the CDC and many groups use the term "forecast" may cause confusion among the public, policymakers, and decision makers, leaving the wrong impression that a COVID-19 forecast is comparable to a weather forecast. In fact, "projection" is a more appropriate term to use with COVID-19 data. A projection offers only a conditional possible response that depends on the validity of the assumed future scenarios.

To help explain the distinction between projection, forecast, and prediction, consider three sample sentences:

1. The weather forecast by the Bureau of Meteorology shows that it is going to snow tomorrow. (The forecast is a probable occurrence.)

2. The team's projection shows that the world population will rise to over 11 billion by 2100. (The projection tells conditional possibilities.)

3. Astronomers can make accurate predictions about when an eclipse is going to occur. (The prediction is an inference with certainty.)

I have seen the term "projection" used correctly by COVID-19 modelers. A good example is modeling work from October 2021 reporting projections of how population contacts during the end-of-year holiday in Mexico City would potentially affect future pandemic outcomes, including infections, deaths, and hospitalizations.[3] Some may argue that the term "prediction" should be used for COVID-19 modeling. But that would not be appropriate because a prediction implies an inference with certainty and does not convey the conditional possibilities implied by projection.

Confusion between those two terms is by no means rare among scientists working in climate science, as revealed in a survey.[4] Unfortunately, in a recent paper reporting the relationship between coastal carbon sequestration and climate change, the authors state that they "go beyond recent soil C stock estimates to reveal global tidal wetland C accumulation and predict changes under relative sea level rise, temperature and precipitation."[5] But there are large uncertainties regarding the assumptions underlying the scenarios, such as unforeseen socioeconomic and technological conditions and uncertain global population growth in the coming decades. So the term "project" would be more appropriate here because the authors are talking about a conditional possible response that depends on the validity of the assumed future scenarios.

I strongly recommend careful use of forecast, prediction, and projection in the reporting of science, particularly with regard to climate change and COVID-19. The public, decision makers, and policymakers will gradually get used to the uncertainties associated with projections.

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Ionocaloric refrigeration makes its debut

Adding salt to a material lowers its melting point and removes heat. New work describes how to make that process reversible and cyclic.

For the past century, vapor-compression technology has run most of our refrigerators and air conditioners. It's inexpensive, reliable, and simple. When a gas is sufficiently compressed, it heats up; it then condenses into a liquid, dumping heat to the outside. After the pressure is released, the liquid evaporates and cools the inside surroundings. The changes in entropy produced during those phase transitions are large enough to make the cycle an extremely useful refrigerator.

Unfortunately, its primary coolants, hydrofluorocarbons, pose an environmental hazard. They are powerful greenhouse gases, with a global warming potential thousands of times that of carbon dioxide. (Their ozone-destroying predecessors, chlorofluorocarbons, were even worse—see the article by Anne Douglass, Paul Newman, and Susan Solomon, Physics Today, July 2014, page 42.) And with growing populations in parts of the world, the demand for refrigeration, and in turn hydrofluorocarbons, is expected to triple by 2050.[1]

To counter that trend, engineers have looked to certain solid-state materials that offer a more eco-friendly alternative. Known as calorics, they undergo a phase transition in response to an external field and cool the surroundings without involving any greenhouse gases. The temperature changes are induced by an electric field, magnetic field, or mechanical stress, for instance—levers that induce what are known as electrocaloric, magnetocaloric, and elastocaloric effects, respectively. (See the article by Ichiro Takeuchi and Karl Sandeman, Physics Today, December 2015, page 48.)

But those alternative methods come with their own problems. In electrocaloric devices, electric fields of 200 MV/m are common. That's more than 50 times the dielectric strength of air and can be safely produced only across micrometer-sized films. Some magnetocaloric devices similarly require incredibly strong fields, up to 5 T, which are difficult to produce using permanent magnets alone. And elastocaloric devices with a high temperature span operate at stresses of 800 MPa—four times as large as the stress that steel can endure before deforming. What's more, the payoff of caloric materials is weak: They produce much smaller cooling power than does a hydrofluorocarbon.

Doctoral student Drew Lilley and his adviser, Ravi Prasher, both at California's Lawrence Berkeley National Laboratory, now propose a new caloric process they call the ionocaloric effect. The work arose from a question that Prasher posed to his group a decade ago: How can we most

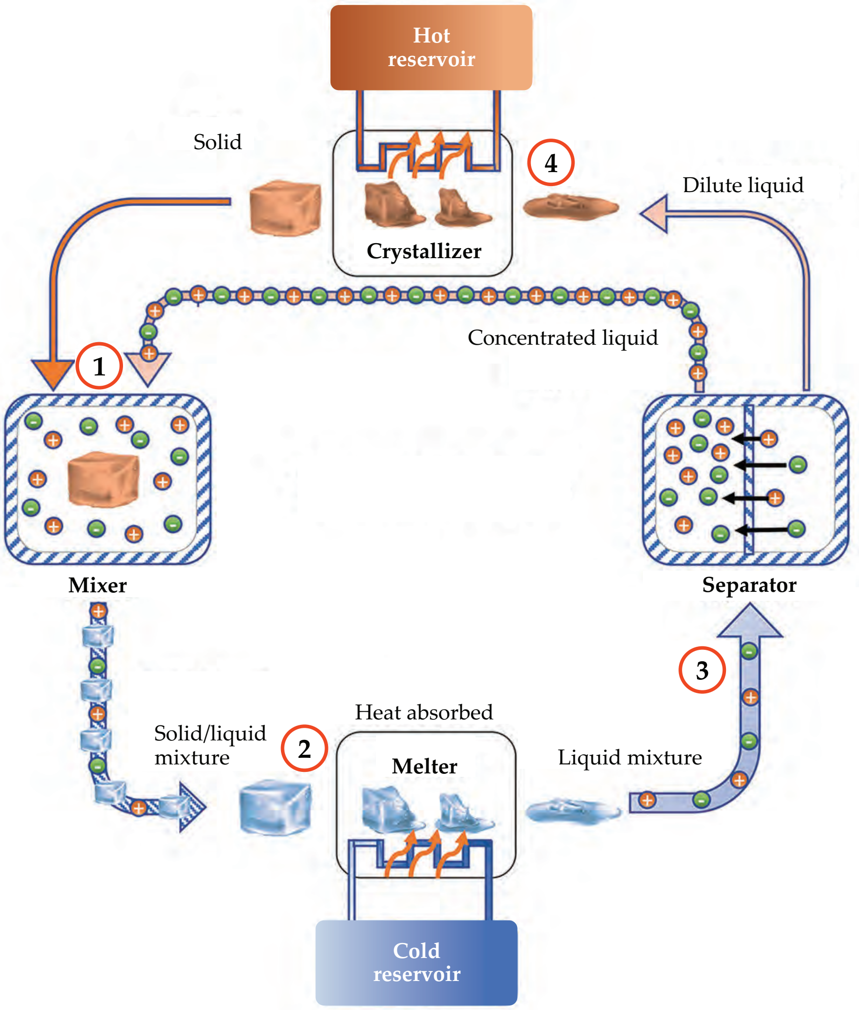

FIGURE 1. THE IONOCALORIC CYCLE spans four stages: **(1)** A salt is mixed into a solid solvent, which cools the mixture to its now-lower melting point. **(2)** The slurry is then pumped into a second chamber, where it melts while absorbing heat from its surroundings. **(3)** It's then pumped through a desalination circuit that applies a small voltage to separate the salt from the solvent, a process that raises the solvent's melting temperature. **(4)** Finally, the diluted liquid recrystallizes on contact with a hot reservoir at the now-higher melting point. It and the concentrated salt can then restart the cycle. (Adapted from ref. 2.)

efficiently change the melting temperature of a solid? "I realized that none of the existing caloric materials would provide a high-enough temperature lift between the hot and cold side of a refrigeration cycle without the expense of such high fields," he says. "And it struck me that the most efficient approach would be to diffuse ions into a solvent."

The ionocaloric effect works on the same principle as an old-fashioned ice-cream maker: Adding salt to a material lowers its melting temperature and can trigger a phase change. The researchers chose sodium iodide as the salt and ethylene carbonate as the solvent material. Unlike other calorics, whose phase transitions take place entirely in the solid state and involve changes only in crystal orientation, ionocalorics manifest a solid–liquid phase change.

In the new work, Lilley and Prasher did more than reproduce an effect that's evident every time you churn out ice cream at a summer picnic. They described how to make it reversible and, in a proof-of-concept device, demonstrated its feasibility in a closed system.[2]

Entropy generator

Because the whole medium participates in the phase change, the entropy change produced in the carbonate–salt system is 500 J/K·kg. That's more than 10 times the entropy change found in state-of-the-art magneto-, electro-, and elastocaloric materials and comparable to that of R134a (today's most common hydrofluorocarbon, whose entropy change is 650 J/K·kg). The ionocaloric system's temperature change was large as well, 29 °C.

The large entropy change wasn't accidental. The researchers had established specific criteria for the ideal properties of the refrigerant. The solvent should have a melting point above room temperature and a eutectic point—the binary salt mixture's melting point—well below room temperature. It should also have a high latent heat of fusion to maximize the heat absorbed per cycle and a high cryoscopic constant (the depression in a solvent's melting point on dissolving one mole of a substance in 1000 g of it) to ensure that the large temperature change can be achieved using small amounts of electrolyte.

With those criteria in mind, they identified the ethylene carbonate–sodium iodide (EC–NaI) system as the most

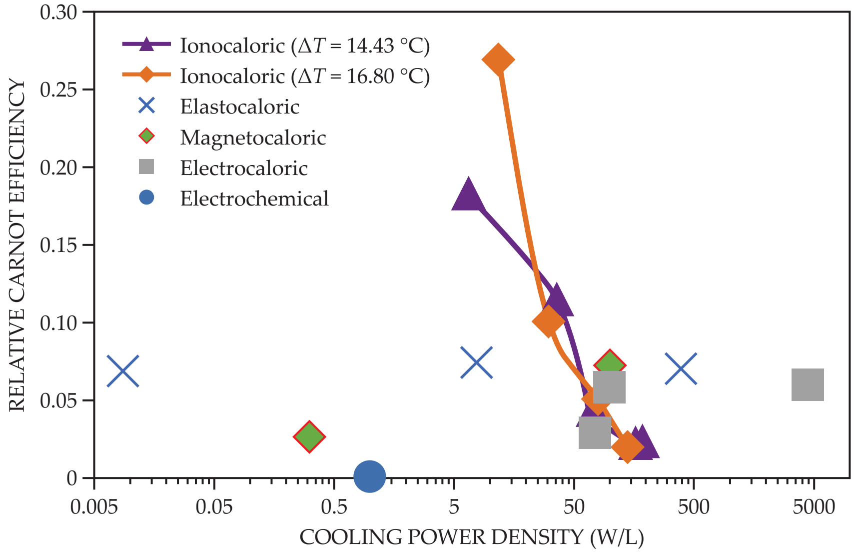

FIGURE 2. THE EFFICIENCY of the ionocaloric system compares well with that of other caloric prototypes. Two different ionocaloric curves (orange and purple) are presented because the performance depends on the temperature difference maintained between the hot and cold sides. Taken at different operating conditions of the cycle, the data reveal different efficiencies and cooling powers depending on whether the system was run quickly (higher power but lower efficiency) or slowly (lower power but higher efficiency). (Adapted from ref. 2.)

promising. At 205 J/mL, the carbonate's latent heat of fusion is not much less than that of water, whose value (330 J/mL) is among the highest of known molecules near room temperature. Ethylene carbonate is a common additive to lithium-ion battery electrolytes.

The cooling cycle, shown in figure 1, starts with the addition of solid NaI to solid EC close to the solvent's melting temperature of 36 °C. The temperature of the mixture quickly drops to 6 °C and it partially melts. The liquid-solid slurry is then pumped into a second chamber, where the remaining solids melt by absorbing heat from their surroundings.

To desalinate the mixture and restore the ingredients to their original forms, the researchers pump the liquid to a separator stage, where a voltage is applied across two ion-exchange membranes. The technique they use, electrodialysis, takes as little as 0.22 V to manipulate and separate ions from the solution. Through a clever arrangement of the membranes, the electrodialysis purifies—and therefore reheats—the carbonate: A concentrate of sodium cations and iodide anions flows into one compartment while a dilute liquid of EC collects in another.

The EC next flows to a fourth chamber, where it releases its heat and crystallizes. It is then ready to recombine with the NaI, shuttled through a separate tube, to restart the cycle.

Relative Carnot efficiency

In principle, the larger the entropy change, the larger the cooling energy. But the Achilles' heel of the system is its slow desalination step, which limits the cycling frequency and therefore the cooling power. The commercial membrane (Nafion) has a flow resistance for the electrolytes in EC–NaI that is about 100 times as large as it is for the water-based systems the membrane was designed for.

Even so, the experimental prototype performs nearly 30% as well as a Carnot refrigerator—the theoretically ideal case. "That efficiency puts us on the map commercially," says Lilley. In a plot of its relative Carnot efficiency versus cooling power density (figure 2), the ionocaloric prototype exhibits a higher efficiency than most other caloric methods.

Conventional hydrofluorocarbon refrigerants are not plotted. Vapor–compression technology would have a far greater cooling power density—on the order of 600 W/L, says Lilley, where the reference volume is that of the compressor—compared with about 10 W/L measured for the ionocaloric prototype at a similar efficiency. Nonetheless, he and Prasher hope to address the difference by reducing the membranes' resistance. The improvement in ion conductivity would increase the power density of their ionocaloric device.

They have yet to test the system's durability, but it appears to show little fatigue. "You can repeat the freeze–thaw cycle as many times as you'd like," Lilley says. The ion-exchange membranes themselves were standard, commercial models, and the researchers have yet to develop others better suited for the electrolytes.

Still, Lilley and Prasher remain optimistic that a practical version of the new refrigerator technology is within reach. They have filed a US patent application.

R. Mark Wilson

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The subtle math of a heartbeat gone wrong

For one type of cardiac arrhythmia, trouble comes in threes.

A healthy heart leads from the top. In the upper right chamber is an oval-shaped strip of tissue, called the sinoatrial node, that serves as the heart's natural pacemaker. The periodic electrical impulses it emits are what keep the organ beating at its steady cadence.

Sometimes, though, the bottom of the heart gets its own ideas. An ectopic (out-of-place) pacemaker can form in one of the lower chambers and send out a separate set of competing signals to try to control the heart's rhythm. The result is a type of cardiac arrhythmia called parasystole. As heart conditions go, parasystole is more annoying than it is dangerous, although if left untreated in the long term it can be linked to complications.

In 1986 Leon Glass (a physicist turned physiologist at McGill University in Montreal) and colleagues showed that the beat patterns of parasystole should be uncannily regular.[1] For any given values of the two pacemaker periods, the number of intervening normal beats between two successive ectopic beats could take only three possible values. What those values are depends on the beat periods and the refractory period. But there are always just three.

Glass and colleagues' paper was theoretical, and it invoked a simplified model of parasystole. The authors neglected the spatial separation of the two pacemaker sites, the time it takes a signal to travel from one to the other, and all the irregularities and complexities of the physical heart.

Now McGill's Gil Bub and colleagues (including Glass) have returned to the problem to fill in the gaps.[2] Through lab experiments and a more detailed mathematical analysis, they've found that the central result of the 1986 paper—the trios of numbers of intervening beats—is applicable in the real world. In addition to highlighting a surprising connection between math, physics, and biology, the

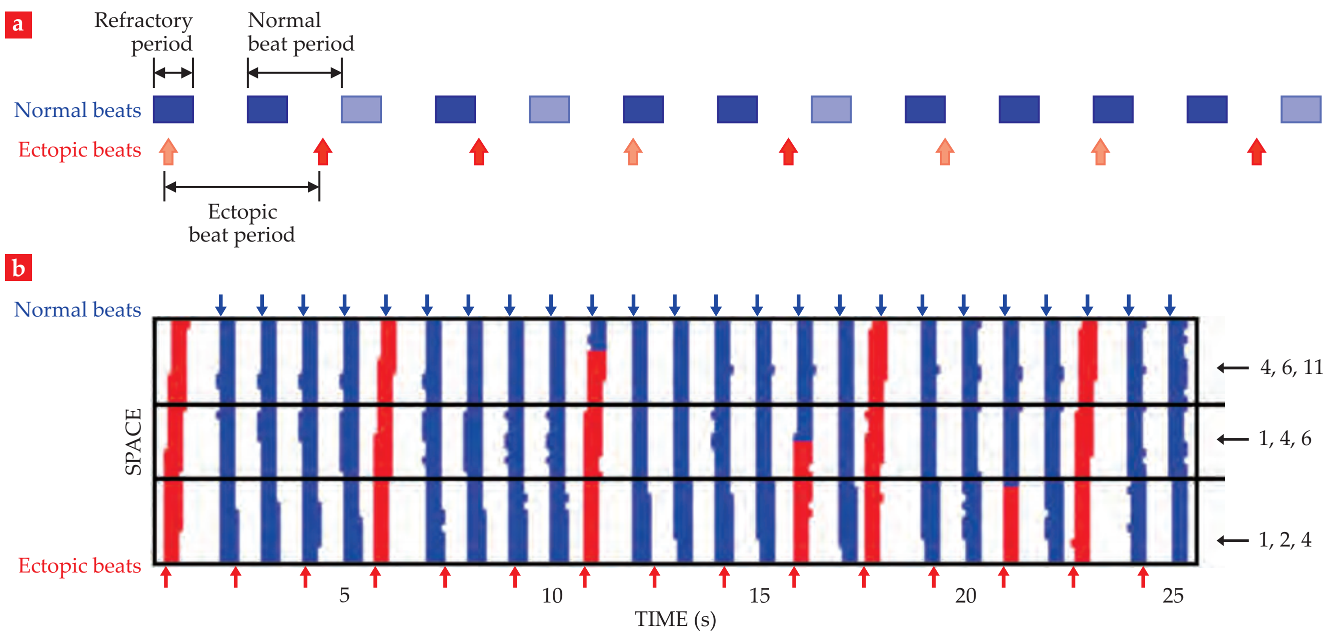

FIGURE 1. COMPETING PACEMAKERS. (a) In a simple model of a cardiac arrhythmia called parasystole, the heart's normal pacemaker and an ectopic, out-of-place pacemaker each generate periodic beat signals. If a signal falls within the previous beat's refractory period, it's blocked (light shaded symbols); otherwise, it goes through (dark solid symbols). No matter the ratio of beat periods, the number of normal beats between two successive ectopic beats can have only three possible values. Here, those values are 1, 2, and 4. (Adapted from ref. 1.) **(b)** Optogenetic *in vitro* experiments explore the role of the pacemakers' spatial separation. The same intervening-beat trios still shine through, but which trio is observed is now a function of position. (Adapted from ref. 2.)

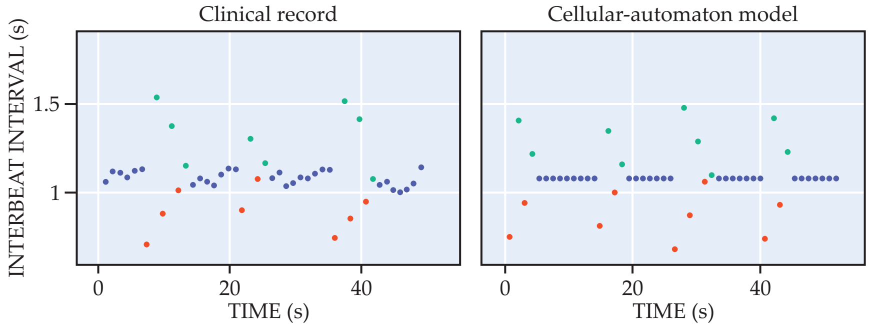

FIGURE 2. PARASYSTOLE IN PRACTICE. On the left is a plot of electrocardiogram data from a 71-year-old patient; the corresponding model simulation is shown on the right. Plotted on the vertical axis is the interbeat interval: the time from one heartbeat to the next. Shorter-than-usual intervals, shown in red, arise from normal beats followed by ectopic beats; longer-than-usual intervals, shown in green, are from ectopic beats followed by normal beats. Blue data points are the intervals between two normal beats. Between any pair of successive red points, the number of blue and green points is always 1, 8, or 10—one of the allowed trios the model predicts. (Adapted from ref. 2.)

work is a step toward diagnosing parasystole in patients and guiding them to the most important treatment.

Feel the beat

Parasystole is one of a class of heart-rhythm disorders that are characterized by premature ventricular contractions (PVCs): The ventricles, or lower heart chambers, contract before the signal from the upper chamber tells them to. If PVCs are happening to you, it can feel like your heart is skipping beats.

Why would the heart be skipping beats, if the problem is that it's getting too many signals to beat? Heart tissue is a nonlinear medium: Unlike linear waves such as sound and light, which can pass right through each other, electromechanical waves in the heart don't act independently of one another. Rather, after each excitation, the tissue has a refractory period of a few hundred milliseconds, during which it can't be excited again. If a PVC prompts the heart to beat before an expected normal beat, the normal beat is blocked—and its absence can sometimes be felt.

PVCs can arise in several ways. They can be caused by an ectopic pacemaker, as in parasystole. Or they can result from cardiac reentry—in which a wave that started out as a normal beat propagates around in a circle and excites the heart again—or other causes.

The treatment for PVCs depends on what's causing them. Most don't need intervention at all, and those that do can often be remedied with medication or lifestyle changes. But sometimes it's necessary to use RF radiation to remove the ectopic pacemaker. A question of clinical interest, therefore, is whether the cause of PVCs can be diagnosed on the basis of the sequence of normal and ectopic beats alone: What patterns of heartbeats could signal that an arrhythmia is parasystole, rather than something else?

Three of hearts

In their 1986 attempt to answer that question, Glass and colleagues developed a model that's schematically shown in figure 1a. The normal and ectopic pacemakers each produce signals with a regular period. If an ectopic beat signal falls inside the normal pacemaker's refractory period (dark-blue rectangles), it's blocked (light-red arrows); otherwise, it goes through (dark-red arrows). Because of the asymmetry of how the heart conducts signals, an ectopic beat that goes through always blocks the next normal beat (light-blue rectangles), regardless of the refractory time. The question becomes, What possible sequences of dark rectangles and dark arrows can the model generate?

Put that way, the problem is hardly limited to cardiac medicine. The same or similar dynamics can show up in many diverse contexts. (It's reminiscent, for example, of the question of how many steps you can take on a sidewalk before you step on a crack.) In fact, while Glass and colleagues were putting together their paper, they discovered that the problem had already been discussed in the mathematics literature.[3]

The main result—that there are only three possible values of the number of intervening normal beats between two successive ectopic beats—comes from looking closely at where each ectopic beat falls in the window between one refractory period and the next. If t is the position of one ectopic beat within the window and $f(t)$ is the position of the next, then f is a piecewise linear function that maps the window onto itself. As Glass and colleagues explained, there can be only two possible points of discontinuity: $f^{-1}(t_i)$, where t_i is the beginning of the window, and $f^{-1}(t_f)$, where t_f is the end of it. The function f therefore divides the window into three continuous segments, each with its own value for the number of intervening beats.

The space between

Glass and colleagues' model treated the normal and ectopic pacemakers as if they were right on top of each other. It gave no consideration to the time waves would take to travel from one pacemaker to the other, let alone the inhomogeneity of the tissue they would pass through along the way. "The behavior of the model with space has been an open problem since then," explains Bub. "But when Thomas Bury, who has a math background, joined my group as a postdoc, Leon saw the opportunity to revisit the question."

Bury and Glass turned back to the old proofs and extended them to the case of spatially separated pacemakers. They found a similar result: There are always three possible values for the number of intervening beats, except that now, which three values are allowed also depends on where in space the beats are measured.

Bury's augmented model took into account some of the effects of tissue heterogeneity. For example, the model still works if the wave speed is not uniform in space, or even if waves propagate at different speeds in each direction. But it's fundamentally one-dimensional and deterministic: It considers only one path that waves can take between the pacemakers, and the propagation is always perfectly predictable. Real hearts are more complicated than that, and cardiac waves can propagate in all kinds of messy ways. Would the tidy theoretical predictions survive the noise of a living system?

To find out, Khady Diagne—a PhD student in Bub's group—performed experiments on patches of heart tissue derived from mice. She used optogenetic technology to genetically engineer the tissue to be responsive to light, then created two artificial pacemakers by shining two spatially separated light pulses on the tissue patch. Figure 1b shows the results of one of her experiments; it agrees well with the theory, down to the different intervening-beat trios observed at different points in space.

Even in real hearts, the model has had some success. The left panel of figure 2 shows clinical data from a 71-year-old man with probable parasystole. The corresponding model simulation is shown at right.

Rhythm gone wrong, gone wrong

Looking for intervening-beat trios could be an appealing way for clinicians to distinguish parasystole from other conditions that cause PVCs so they can more confidently make decisions about treatment. But many complicating factors remain to be accounted for.

In Bury's model and Diagne's experiments, both pacemakers are perfectly steady over time. But real heart rates fluctuate in response to stress, activity, and other factors, and the normal and ectopic pacemakers don't have to move in tandem, so a patient might not exhibit any one intervening-beat trio for very long. To tease out the intervening-beat trios and diagnose parasystole, doctors may have to record a patient's heart rhythm for hours or days. Luckily, with today's wearable medical devices, such long records are easy to come by.

Moreover, and more importantly, the McGill group's research so far is limited to so-called pure parasystole, in which each pacemaker is unaffected by the other and the heart is healthy in every other respect. Clinically, pure parasystole is the exception, not the rule: Only one out of the 47 patients with frequent PVCs whose records the McGill group looked at seemed to have it. More commonly, patients might have modulated parasystole, in which signals from the normal pacemaker periodically reset the ectopic pacemaker's phase. Or their PVCs might arise from a combination of causes, such as an ectopic pacemaker and cardiac reentry working together in the same heart.

It's too early to tell just how valuable the intervening-beat math will be in understanding those more complicated arrhythmias, but it looks like Diagne's optogenetic experiments could be a useful platform for studying them. While some of the genetically engineered tissue patches showed the clean interactions of two light-induced pacemakers, as shown in figure 1a, others exhibited messier dynamics, including spontaneously formed natural pacemakers and forms of cardiac reentry. The researchers focused on the clean systems at first, but now they're keen to explore the messy ones. "I think the key is to have experiments that rival the clinical data in complexity and duration," says Bub. "That should allow us to tease out the mechanisms and provide a bridge between theoretical models and the clinical data."

Johanna Miller

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Community heightens attention to accessibility for physicists with disabilities

Fostering participation benefits the whole field, note proponents.

"My disability affects my work every day, in every conversation," says Michele Cooke, a geosciences professor who studies fault mechanics at the University of Massachusetts Amherst. Cooke has been part deaf since before she could speak. For her, a pivotal moment was when she realized that her peers in college were learning more than she was. "I didn't know what I didn't know," she says. She began using assisted-listening devices and advocating for herself.

Brandon G. Villalta Lopez, a double major in physics and neuroscience at Bates College, realized late in high school that he was autistic. Ever since, he has disclosed that information to his professors and arranged his time and the way he interacts with people to optimize his performance and well-being. He's also become an advocate for diversity, equity, inclusion, and accessibility in STEM (science, technology, engineering, and mathematics): At the January meeting of the American Astronomical Society, he was a panelist on a community-initiated session on neurodiversity.

Although the STEM community has for years talked about and tried to increase representation of women and other marginalized groups (see, for example, Physics Today, February 2020, page 20, and July 2021, page 20), disabilities have largely been absent from the discussion. Data are sparse on people with disabilities in STEM, but surveys by NSF, the Statistical Research Center of the American Institute of Physics (AIP is the publisher of Physics Today), research groups, and other sources suggest that from 10% to 30% of STEM researchers and students identify as having a disability. That includes deafness, blindness and low vision, and mobility conditions; chronic illnesses; some forms of neurodivergence; and mental health illnesses.

JASON E. YBARRA

NEURODIVERSITY IN ASTRONOMY was explored at a well-attended session at the January meeting of the American Astronomical Society in Seattle, Washington. The panel members—(from left) Hannah Fritze, Jessica Schonhut-Stasik, Brandon G. Villalta Lopez, and Samantha Johnson—aim to continue to work for acceptance and accommodations in science.

Scientists with disabilities have always had to craft their own solutions to barriers they've faced working in environments structured to favor nondisabled people. They have had to self-advocate by asking for devices such as high-brightness computer screens, specific meeting or teaching times, and other accommodations. And they have received inconsistent access to accommodations from host institutions. To a great extent, physicists with disabilities still have to overcome workplace barriers individually, but efforts to improve accessibility on wider scales are beginning to gain traction. The STEM enterprise, including individuals, educational institutions, professional societies, and national agencies, is taking a closer look at what it can do to be more inclusive.

Work-arounds

Jochen Guck is a director at the Max Planck Institute for the Science of Light in Erlangen, Germany. A car accident left him paraplegic when he was 17. The main barriers he's had to face in his professional life, he says, have been maneuvering around labs and protecting his eyes: In his wheelchair, his eyes are level with lasers on optical tables. When he arrived for graduate studies at the University of Texas at Austin in 1996, the physics building didn't have a wheelchair-accessible bathroom; workers crafted a makeshift solution for him.

Conserving energy is important for scientists living with many types of disabilities. Amy Robertson, who has had juvenile arthritis since she was two, earned her physics PhD at the University of Washington in 2011. She is now a research professor of physics at Seattle Pacific University, where her primary research topic is structural oppression in physics. She never wanted a tenure-track position, she says, because of the "grueling pace" and consequent inaccessibility for her as a chronically ill physicist. Instead, she supports herself and her students through grant money. "I chose this because a full-time job is not sustainable for me," she says. On soft money, she adds, she can set her own schedule, and the university benefits from the overhead her grants bring in.

A few years ago, Cooke started tracking how much time she spent listening to people and rating how tired she was. She has since limited how many hours a day she teaches or participates in meetings, and she has become more patient with herself. "Collecting data gave me some peace and helps me combat internalized ableism," she says. Still, the listening fatigue causes tension for Cooke. For example, she is giving extra consideration to whether to step into broader leadership roles, something she has been encouraged to do and is interested in.

Ian Shipsey, a particle physicist who chairs the physics department at the University of Oxford, became deaf because of treatment he underwent for leukemia while a postdoc working on the CLEO particle detector at Cornell University in 1989. He had already accepted a position as an assistant professor at Purdue University, or he doesn't think he "would have been offered a job in academia," he says. Because of his department's assumptions that his deafness would hinder his ability to communicate with students, he was not assigned to teach—until he had to in order to go up for tenure. He took a personal approach: He told his students he was deaf and that he didn't know them well enough to lip-read. He devoted the first class to questions about the course material, introductory astrophysics. The students posed them in writing. "That broke the ice," Shipsey says. "The students gained confidence to ask questions, and we got along well."

Shipsey also "avoided going to coffee hours because it was too difficult to understand people. And it was extremely embarrassing for hearing people—they often gave up trying to be understood." He eventually got a cochlear implant. Suddenly, he says, colleagues sought him out. But the pressure to use cochlear implants—and other devices that assist disabled people—can be controversial:

JOCHEN GUCK, a biophysicist, explains concepts to group members from his wheelchair. He is a director at the Max Planck Institute for the Science of Light in Erlangen, Germany.

Some people object to the implication that a disability is a deficit to be cured.

Noninclusive settings

Scientists with other disabilities are also deterred from participating in informal networking events. Villalta Lopez, like many autistic people, doesn't feel comfortable with unstructured conversation. And the typical arrangement of people standing around during social times at conferences and seminars is inaccessible for people who cannot stand at all or for long periods.

Conferences can be thorny for many people with disabilities for other reasons too. Travel and lodging can be tricky, and on-site setups can pose difficulties. Often institutes insist employees make purchasing decisions solely on the basis of cost, without consideration of other needs. Guck notes that conferences in remote locations and historic buildings are often not equipped for wheelchair access. Robertson says that despite the extra cost she always books a single room so she can set up accommodations to manage her pain.

Keivan Stassun is a professor of physics and astronomy at Vanderbilt University. He had noticed students in his group becoming agitated because of sensory overstimulation when people were interrupting each other. "Traditionally, I would have thought such interactions were a sign of a vibrant, healthy interaction," he says, "but for some members of my team it caused physical shutdown." He asked his group members what they needed to participate and in response "made it possible for any group member to participate remotely in the weekly two-hour meeting," he says. "That way, they could turn off the lights, sit in comfy chairs, or do whatever they needed to feel comfortable participating. This was before COVID." About a quarter of his students are autistic, he adds.

Jessica Schonhut-Stasik is studying galactic archaeology for her PhD in astronomy with Stassun. Since realizing as an adult that she is autistic, she says, "I've learned a lot about myself, and my productivity and self-esteem have skyrocketed."

"There are some incredible strengths" of autism, Schonhut-Stasik continues. Many autistic people have a heightened ability to focus. "If we are stimulated but not hyperstimulated, we can work for hours and hours." Some autistic people are exceptionally good at pattern recognition, outlier detection, and classification, notes Stassun. Those skills are extremely valuable "in this era of data-intensive science."

Structural change is slow

The Americans with Disabilities Act of 1990 addresses some barriers to participation in the scientific enterprise, but many remain. (See "ADA at 30: Scientists urge efforts beyond compliance," Physics Today online, 3 August 2020.) To a large extent, individuals with disabilities still have to advocate for themselves. The

Selected resources

- *The Mind Hears: A Blog by and for Deaf and Hard of Hearing Academics*, https://themindhears.org
- American Chemical Society Inclusivity Style Guide, https://www.acs.org/about/diversity/inclusivity-style-guide.html
- The American Society for Cell Biology, "How to make scientific figures accessible to readers with color-blindness" (2019), https://www.ascb.org/science-news/how-to-make-scientific-figures-accessible-to-readers-with-color-blindness
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physics community needs "to change our culture such that the default is for everyone to understand that accommodations are available and to habitually provide them as an integrated part of our professional lives," says Elise Novitski, a neutrino physicist at the University of Washington.

Campuses, professional societies, and funding agencies are paying increasing attention to disability accommodations. A growing number of students have official accommodation plans that allow them extra time on tests, quiet locations for test taking, or other measures intended to remediate inequities. A few colleges extend such accommodations to any student who requests them, even if they don't have an official diagnosis—which can be expensive to obtain. Some faculty members report being more flexible with such accommodations. Bethany Wilcox, a physics education researcher at the University of Colorado Boulder, says the pandemic shifted her perspective: "Suddenly nobody felt fully functional. I am now much more willing to accommodate students' needs. I have made changes that I previously resisted."

In 2018 Vanderbilt University opened the Frist Center for Autism and Innovation. Based in the school of engineering, the center focuses on bringing the strengths and talents of neurodivergent scientists and engineers to the workforce. It offers coaching in social communication, develops virtual-reality environments for neurodivergent individuals to practice interviewing for jobs, and works with potential employers. It has helped dozens of individuals get "really good, highly technical, good-paying jobs," says Stassun, the center's director.

It's often unclear who should pay for remedies—a faculty member's grant, some campus entity, or the state or federal government, says Paul Goldbart, a condensed-matter physicist at Stony Brook University who gained insight into campus accessibility issues during his leadership roles at several universities. Some accommodations would be straightforward, such as setting up chairs for people to talk with speakers after presentations, installing soap and towel dispensers lower on bathroom walls, or making sure door-opening switches work. But things like infrastructure adjustments, sign-language interpretation, and captioning of talks or lectures are costly. "Campuses ought to have a well-advertised budget for providing accommodations," Goldbart says.

Researchers can request accessibility funding when they apply for grants from some foundations and federal agencies. "If that became more common, it would improve the situation for people with disabilities," says Novitski. "And it's a way for applicants to demonstrate effort on diversity, equity, and inclusion, which many funding agencies require."

Novitski served as accessibility coordinator for Snowmass, the community planning exercise for particle physics, which was held last summer in Seattle, Washington (see Physics Today, October 2022, page 22). "Accessibility for disabled people is entirely sufficient to justify the effort of providing accommodations," she says, adding that people who don't consider themselves disabled also often appreciate the accommodations. Many people benefit from captioning and from the use of color or pattern schemes designed to assist color-blind viewers. Setting up multiple coffee and snack stations at a conference makes the lines shorter for everyone, not just for those who can't stand for long times. Offering QR codes to download presentations is helpful to anyone who may miss a talk or have difficulty following for hearing, attention, language, or other reasons.

Beyond such general measures, it's important to give people the chance to request specific accommodations, says Novitski. "It's not one-size-fits-all."

Beth Cunningham notes that the American Association of Physics Teachers, of which she is CEO, has codified many accessibility measures for conferences and events and is creating a road map for improving accessibility. The association's activities are part of a broader movement among professional societies, she says.

In early June, the National Academies of Sciences, Engineering, and Medicine is hosting a workshop, Beyond Compliance: Promoting the Success of People with Disabilities in the STEM Workforce. Maria Lund Dahlberg, acting director for the National Academies' Board on Higher Education and Workforce, is co-organizing the workshop. She says, "Nothing inherently prevents people with disabilities who want to do science from doing it."

Toni Feder

NIF success gives laser fusion energy a shot in the arm

Startup companies are betting on different approaches and laser technologies for fusion to become a commercially viable energy source.

The attainment of fusion ignition and energy gain on the world's most energetic laser late last year was indisputably a major scientific accomplishment. But the road to fusion as a viable source of energy will be a long one, if not a dead end. And if it does ultimately become a reality, most experts say that it is unlikely that a laser-driven fusion power plant will be based on the approach taken by the National Ignition Facility (NIF), where the fusion milestone occurred.

The December shot, which produced 1.5 times the 2 MJ of energy that was fired on the fusion fuel, has silenced skeptics who said that ignition could never be created by bombarding tiny capsules of deuterium–tritium fuel with lasers. (See "National Ignition Facility surpasses long-awaited fusion milestone," Physics Today online, 13 December 2022.) "They have done something very important: demonstrating ignition and burn," says Stephen Bodner, a retired head of the laser fusion branch at the US Naval Research Laboratory who once was a persistent critic of NIF's approach.

And the milestone is likely to open the floodgates to new investments in the handful of startups that are pursuing inertial fusion energy (IFE). "I think you will see a proliferation of companies devoted to IFE or aspects of IFE because of this and because of investor interest," says Todd Ditmire, a University of Texas at Austin physicist who is chief technology officer of Focused Energy, an IFE startup.

Yet despite the fanfare greeting the announcement, the fact is that the fusion energy yield from the successful shot amounted to less than 1% of the 300 MJ taken from the electricity grid to power NIF's 192 beams. And the energy released was enough to boil about 10 tea kettles. Many experts say that economically viable fusion will require fusion reactions yielding energy gains of at least 100 times the energy deposited on the fuel capsule—two orders of magnitude greater than the NIF shot.

LONGVIEW FUSION ENERGY SYSTEMS

A LASER FUSION power plant proposed by Longview Fusion Energy Systems would generate 1000 MWh or more of electricity. The plant would compress fusion fuel by using indirect drive, the same approach used at the National Ignition Facility, which in December announced that it had produced ignition and gain, the first time that fusion researchers have attained those milestones.

Bedros Afeyan, a consultant who has worked in fusion R&D at three national laboratories, estimates that the NIF accomplishment places IFE at 10% of the way to commercialization. "IFE is so difficult that the solution will be a black swan," he says. "Whatever the idea ends up being, it will be unique."

An IFE power plant will need to fire a laser shot at least every few seconds, compared with the several-hours interval between NIF shots. The machine will also need to breed its own fuel and to load it into tiny capsules that somehow must be kept at cryogenic temperatures for a split second after they are injected into a hellishly hot reactor chamber. And the plant must cost-competitively produce either electricity, industrial process heat, or an energy storage medium such as hydrogen.

Direct or indirect?

At least three fundamental questions need to be resolved as IFE developers move on from NIF, which was designed not for energy production but to simulate processes that occur in nuclear weapons. First, will the laser's light implode fuel capsules directly, or should NIF's indirect-drive approach, where the light is first converted to x rays to squeeze the pellets, be emulated? Second, what type of laser can best do the job? And finally, what is a viable path to designing and mass-producing the targets containing the D–T fuel at minimal cost? The answers to those questions will be key to whether laser fusion can be made economical.

Two US startups—Focused Energy and LaserFusionX—are pursuing direct drive, using different laser types. Longview Fusion Energy Systems, based in Orinda, California, is developing a NIF-style, purely indirect-drive approach. Xcimer Energy, in Redwood City, California, has proposed a hybrid indirect–direct scheme.

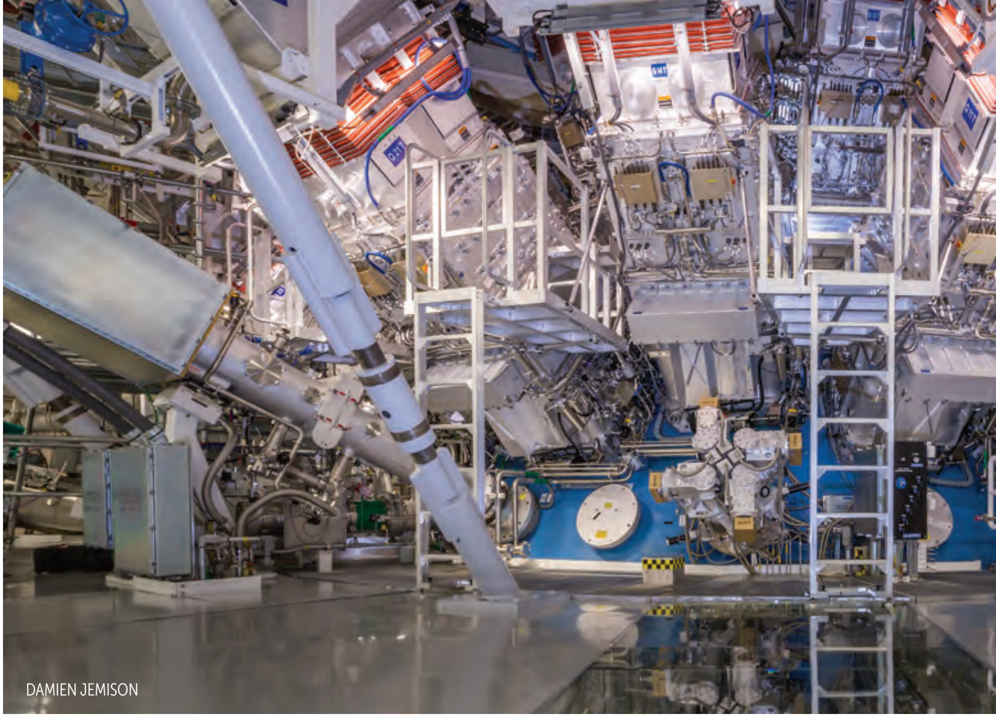
Many laser experts say indirect drive can't be made efficient enough to achieve the level of gain necessary to produce electricity at an acceptable cost. Michael Campbell, retired director of the Laboratory for Laser Energetics at the University of Rochester, says too much laser energy is lost during the absorption of UV rays and emission of x rays that occur inside the hollow cylinder, or hohlraum, that surrounds the capsule of fusion fuel.

The more complex targets required for indirect drive are likely to be more expensive than the simple spherical fuel capsules that are being proposed for direct drive. The NIF targets, which are not mass-produced, cost \$10 000 or more apiece. To be viable, each of the hundreds of thousands of individual targets that will be imploded each day will have to cost less than \$1. Target design must be kept as simple as possible, says Afeyan. "Forget about indirect drive. It's out of the question," he says.

The hohlraums of indirect drive could provide a modicum of protection for capsules containing cryogenic D–T fuel as they are injected in rapid-fire fashion into the target chamber. But debris from exploded hohlraums could rapidly pile up, potentially presenting a cleanup problem.

Direct drive has been pursued mostly at the Laboratory for Laser Energetics, which is supported by the Department of Energy and houses the Omega laser. Direct-drive researchers have so far been unable to produce implosions with the precise symmetry required for ignition. The more energetic the laser, the less precision will be required for direct-drive implosions that would produce ignition and gain, Campbell says.

Omega is too small in any case, Campbell says, producing just 25 KJ of light. "There needs to another research facility built with enough energy to get plasmas to ignite in a direct-drive configuration."



THE TARGET BAY of the National Ignition Facility (NIF), where the world's first laboratory-scale fusion ignition and energy-gain experiment occurred in December. NIF's 192 beams converge at the center of a spherical target chamber covered with beamlines and diagnostic instruments and deposit just over 2 MJ of UV light onto a target containing a tiny sphere of deuterium–tritium fuel. The bay served as the set for the engine room in the 2013 movie *Star Trek: Into Darkness*.

Glass versus gas

The two primary laser candidates today are the NIF-like solid-state glass system and the excimer, which uses krypton fluoride or argon fluoride gas. Excimer lasers, which pump and excite a gas with electron beams instead of photons, are more efficient, but for IFE use, they will require innovations in pulsed power and nonlinear optical elements that can amplify without glass or mirrors, Afeyan says.

LaserFusionX, based in Springfield, Virginia, and Xcimer are pursuing different types of excimer lasers. Focused Energy and Longview are using glass lasers.

Afeyan says the feasibility of IFE will hinge on whether lasers can be made sufficiently large—providing 20–30 MJ to the target. Simple, cheap targets can't be driven using simple lasers, he says. "If the targets are cheap, the laser has to be huge." That, he says, eliminates glass lasers from consideration. "Making a glass laser 100 or 50 times bigger [than NIF] is out of the question. Glass lasers are inherently inefficient." Heat buildup will keep them from ever becoming efficient enough to operate a million or more times each day, no matter how well they are cooled, he adds.

Ditmire insists that glass's thermal problems can be managed. He notes that Lawrence Livermore National Laboratory (LLNL) has built 100 J, 10 Hz glass lasers that use helium cooling. And the Pentagon has done considerable work on thermal management in glass-laser directed-energy weapons, he says.

"From a physics standpoint, excimers have a problem in that they don't store energy," says Ditmire. Glass stores energy in the upper laser state for hundreds of microseconds, thus allowing for the extraction of the nanoseconds-long pulses needed for implosions, he says. "The amount of energy per square centimeter that I can get out of a glass laser is much higher than in an excimer laser."

Glass lasers will need to fire multiple times each second. An LLNL program known as Laser Inertial Fusion Energy (LIFE; see PHYSICS TODAY, April 2014, page 26) explored what an IFE power plant with indirect drive might look like. Discontinued in 2014, LIFE estimated a rate of 16 Hz—using 1.3 million targets per day.

Focused Energy's approach calls for two solid-state lasers producing pulses for each shot: a nanoseconds-long pulse to implode the target and a picoseconds-long pulse to then ignite the fuel. Known as fast ignition, the technique differs from the "hot spot" implosion of NIF, which, like a diesel engine, relies on compression alone. Focused Energy aims to use 180 beams—80 to implode the capsule and 100 for the fast-ignition spark plug, Ditmire says.

The NIF results have stimulated interest from investors, Ditmire says. "The timing couldn't have been better. We are seeing investors coming out of the woodwork." Focused Energy is currently closing a \$60 million funding round, and it plans to raise another \$200 million to build a single-beam prototype laser in Austin by 2027. That would be followed by a second laser in Texas that the company hopes will achieve ignition and gain by the early 2030s. A third demonstration laser also is planned that would fire at 10 Hz.

Marvel Fusion in Germany and Australia's HB11 Energy also propose fast ignition, but they seek to combine boron and protons rather than D–T. The p–^{11}B reaction, although offering the environmental benefit of producing virtually no neutrons, requires temperatures of 3 bil-

lion kelvin, about 10 times what is needed to burn D–T. (See "The commercial drive for laser fusion power," Physics Today online, 20 October 2021.)

Xcimer's indirect–direct hybrid approach offers the thermal shield provided by a hohlraum, which also confers "significant smoothing of the laser imprint" on the fuel capsule, says CEO Conner Galloway. Only a small fraction of the laser's energy will be directed at the hohlraum; most of the energy will be used for pulses from the same laser that are deposited directly on the fuel. Xcimer's scheme borrows from the 1980s-era Strategic Defense Initiative, which used high-power KrF lasers and stimulated Brillouin scattering, a nonlinear optical method for compressing the laser's microseconds-long pulses to the nanoseconds needed for implosions. Because of anticipated energy gains of up to 150, Galloway says, a 10 MJ KrF laser driver would need to fire only once per second, or even every few seconds, to produce grid-scale energy.

Excimer lasers can be much less costly than glass, Galloway says. He explains that NIF's \$3.5 billion cost included 120 tons of expensive glass-laser amplifier slabs and a total optical area of $30\ m^2$. Xcimer's use of a gas-amplifying medium and a beam that's manipulated with "gas mirrors" instead of glass makes the approach cheaper.

In the future, Xcimer may be able to dispense with the hohlraum, which would moderately increase the fusion gain of the target, Galloway says. As with other fusion startups, the company plans to pursue additional revenue opportunities for the laser technologies it develops on the way to its IFE goal.

Xcimer has raised \$12 million to date from several venture capital firms, including Lowercarbon Capital, Prima Ventures, Starlight Ventures, and Wireframe Ventures. Another funding round, expected to be completed this spring, will finance a multi-kilojoule laser to be completed in two years. That device will prove out the fundamental concept and scalability of using the pulse compression technique, Galloway says. That is slated to be followed by a 4 MJ prototype in 2028 that could achieve target gains of 30–50. He anticipates a working fusion energy pilot plant with a 10 MJ laser that produces grid-scale power in 10 years.

With the incorporation of LaserFusionX last year, Stephen Obenschain is hoping to commercialize ArF excimer laser technology developed at the Naval Research Laboratory, from which he retired last year. He says that ArF produces shorter-wavelength light with a broader bandwidth than KrF and should therefore better suppress instabilities in the fusion plasma. A commercial-scale pilot plant could be built in 16 years, he says.

Obenschain has been financing his effort from his personal investments. He's talking to venture capitalists, and he hopes to get some help in those discussions from DOE's Advanced Research Projects Agency–Energy. "The challenge you run into is if you ask for too much, the billion-dollar VCs won't do it, and if you ask for too little, it's not exciting. I'm trying to find the middle ground," he says.

Longview CEO Ed Moses, a former NIF director, points out that indirect drive is the only approach that has demonstrated ignition and gain. Borrowing from the LIFE program, Longview plans to achieve gains of 50–60 from targets imploded at a rate of 15 Hz. The concept would require producing more than a million targets per day, or 500 million a year. That's not only feasible, Moses says, but it is also less difficult than manufacturing bullets for the military. Each target, costing 50¢ or less, would consist of a fuel capsule surrounded by a hohlraum made of lead. Several utilities have shown interest in his proposal to build gigawatt-scale power plants costing about \$4.5 billion, which he says is typical for other types of baseload generating stations. The plants could be sited at retiring fossil-fuel-fired facilities to make use of their existing turbine and transmission infrastructure, he says.

Longview plans on using diodes to pump its 384 laser beams. Unlike NIF's flashlamps, which produce white light, just 3% of which is absorbed by the laser optics, diodes can be tuned to the laser's absorption frequency. That makes the transfer of light to the laser close to 100% efficient, Moses says. Plans call for five years of design work and reducing technology risks, to be followed by the five-year-long construction of the first laser prototype. To minimize thermal problems, Longview will use optical elements that are one-fifth as thick as NIF's glass. The tons of lead per month that would accumulate from the exploding hohlraums can be recycled into new targets, which would be fabricated on-site, Moses says. He declined to discuss the company's financing, investors, or the size of its workforce.

Other technology needs

To be sure, many other challenges need to be dealt with before IFE becomes a reality. Some are common to both IFE and tokamak and other magnetic fusion schemes. Those include how to breed required amounts of tritium, purify it, and load it into targets. Another is finding materials that can protect reactor walls from damage caused by the high-energy neutrons and x rays that will be constantly bombarding them. Many developers are counting on FLiBe, a molten salt made from a mixture of lithium fluoride and beryllium fluoride. Some propose using it as a blanket to line the chamber. Others would locate the material behind a solid wall made of tungsten or other radiation-resistant metal. In either case, high-energy neutrons would initiate a nuclear reaction that transmutes the lithium in the salt to tritium.

A report from a DOE Fusion Energy Sciences workshop held last year on basic research needs for IFE says that a suite of facilities will be needed "to increase the rate of learning and test new technologies." Those facilities range from "'at scale' physics facilit(ies) for testing concepts to a wide range of component and sub-system development facilities." Responding to congressional urging, DOE's fusion program established a \$3 million IFE effort in the current fiscal year.

David Kramer PT

Light-driven Spin Chemistry for Quantum Information Science

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Michael Wasielewski is the Clare Hamilton Hall Professor of Chemistry, director of the Center for Molecular Quantum Transduction, and executive director of the Institute for Sustainability and Energy at Northwestern University in Evanston, Illinois.

Michael R. Wasielewski

Molecular systems can host multiple electron spin qubits that have promising properties for quantum applications.

Quantum information science (QIS) has many types of qubits to choose from, including superconducting and trapped-ion qubits, all with their advantages and disadvantages. Although less developed than some of the other qubit platforms, molecules and molecular systems can serve as spin-qubit arrays with distinct benefits. For example, molecular synthesis can create qubits at atomically precise locations; tailor the qubits' magnetic, optical, and electronic properties; and construct large ordered qubit arrays through self-assembly and other strategies.[1]

Experiments from the mid 1970s showed that when light triggers electron transfer between molecules, the electrons and the electron vacancies they leave behind—known as holes—can form entangled spin states. The presence of those spin pairs is clear from time-resolved electron paramagnetic resonance (TREPR) spectroscopy, which measures the absorption or emission of gigahertz radiation as a function of an applied magnetic field—in effect, the method probes the magnetic interactions between the electron spins. Important early experiments focused on the photosynthetic-reaction-center proteins, which are responsible for the primary transduction of solar photon energy into electron–hole pairs. After photoexcitation, those proteins showed strong absorptive and emissive resonances.[2] Since then, various chemical electron donor–acceptor systems have been investigated.[3]

About 10 years ago, researchers realized that photoinitiated electron–hole spin pairs can serve as spin-qubit pairs (SQPs), whose spin dynamics are of practical and fundamental interest in QIS. As with many quantum platforms, a primary challenge is generating well-defined initial states that maintain their

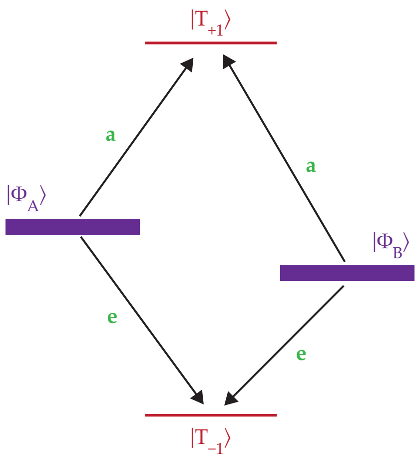


FIGURE 1. THE ENERGY LEVELS for an entangled pair of spins change in a high magnetic field. For a molecular system, the result is the mixing of the singlet $|S\rangle$ and one of the triplet $|T_0\rangle$ spin states to form the states $|\Phi_A\rangle$ and $|\Phi_B\rangle$, which are overpopulated. As a result, the system has strong absorptive and emissive microwave transitions—labeled **a** and **e**, respectively—to the $|T_{+1}\rangle$ and $|T_{-1}\rangle$ triplet states.

spin coherence long enough to undergo spin manipulations and carry out quantum gate operations.[4] Those criteria are difficult to fulfill in most other materials used to create electron spin qubits because the energy gap between the spin states is so small. For example, Boltzmann statistics require millikelvin temperatures to achieve greater than 95% spin polarization. Even if one applies a 10 T magnetic field to increase the energy gap between electron spin states through the Zeeman interaction, adequate spin polarization still requires temperatures on the order of 4 K. By contrast, when electrons in molecules are excited by light, the spins resulting from electron transfer are highly polarized even at room temperature. Those molecular spin pairs can be expanded from two-spin systems to three- and four-spin systems that demonstrate desirable properties for QIS applications.

Spin-qubit pairs

Electron spins are good qubits because their two spin states constitute a prototypical two-level quantum system, in which the two states can exist in a superposition. Two or more spins can also couple through distance-dependent magnetic spin–spin exchange (with coupling constant J) and magnetic dipole–dipole interactions (with coupling constant D). Those interactions can create quantum entanglement between spins and allow for two-qubit gates essential for executing quantum algorithms. Such spin coupling occurs in many chemical systems. When a donor molecule (D) absorbs a photon, its excited electron can transfer to an acceptor molecule (A) that's covalently linked to D by a bridge molecule (B). The resulting two spatially separated, entangled spins at D and A can function as an SQP in a well-defined pure initial quantum state.[5]

Femtosecond and nanosecond transient absorption spectroscopies are typically used to characterize the ultrafast electron-transfer dynamics of D-B-A molecules. Following selective photoexcitation of D, B, or A, researchers monitor the electronic spectra of each intermediate state as a single electron transfers between subsequent component pairs. For example, if D is selectively photoexcited, an electron transfers from D to B and then from B to A, which gives intermediate states of $D^{\bullet+}$-$B^{\bullet-}$-A and $D^{\bullet+}$-B-$A^{\bullet-}$, respectively, where the superscript dot and + or − sign denote the presence of an unpaired electron spin and the net charge on D, B, and A. The spin dynamics of the SQP are then probed with TREPR spectroscopy using either continuous or pulsed microwave irradiation. The advantage of using pulsed microwaves is that one can perform specific manipulations of the spin states as a function of time that are useful for executing quantum logic gates.

The entanglement in SQPs results from spin exchange (J) and dipolar (D) couplings. The two electron spins also experience different magnetic environments because of differing electron–nuclear hyperfine couplings (a-tensors) in $D^{\bullet+}$ and $A^{\bullet-}$ and differing spin–orbit interactions that lead to distinct electronic g-tensors. When the SQP is generated in a magnetic field that is much larger than all the magnetic interactions between the two spins, the SQP wavefunctions consist of a singlet state $|S\rangle$ and three triplet states $|T_0\rangle$, $|T_{+1}\rangle$, and $|T_{-1}\rangle$, where $|S\rangle = 1/\sqrt{2}(|\uparrow\downarrow\rangle - |\downarrow\uparrow\rangle)$ and $|T_0\rangle = 1/\sqrt{2}(|\uparrow\downarrow\rangle + |\downarrow\uparrow\rangle)$ constitute two of the system's four possible entangled states, known as Bell states.[6] The other two Bell states, $1/\sqrt{2}(|\uparrow\uparrow\rangle + |\downarrow\downarrow\rangle)$ and $1/\sqrt{2}(|\uparrow\uparrow\rangle - |\downarrow\downarrow\rangle)$, arise from linear combinations of $|T_{+1}\rangle = |\uparrow\uparrow\rangle$ and $|T_{-1}\rangle = |\downarrow\downarrow\rangle$.

Only the $|S\rangle$ and $|T_0\rangle$ states are close in energy and mix to give $|\Phi_A\rangle$ and $|\Phi_B\rangle$, as shown in figure 1. Those mixed states are described by $|\Phi_A\rangle = \cos\phi|S\rangle + \sin\phi|T_0\rangle$ and $|\Phi_B\rangle = \cos\phi|T_0\rangle - \sin\phi|S\rangle$, where the angle ϕ describes the degree of mixing and is related to J, D, and the differences in the a- and g-tensors of the two radical ions.[5] The $|T_{+1}\rangle$ and $|T_{-1}\rangle$ states are energetically far removed from $|T_0\rangle$ and do not mix with $|S\rangle$.

Because the SQP starts in a pure $|S\rangle$ state, $|\Phi_A\rangle$ and $|\Phi_B\rangle$ are overpopulated, which produces strong absorptive and emissive transitions from $|\Phi_A\rangle$ and $|\Phi_B\rangle$ to $|T_{+1}\rangle$ and $|T_{-1}\rangle$ that can be observed readily using TREPR spectroscopy. Transitions between $|S\rangle$ and $|T_0\rangle$ are forbidden, but the coherence between $|S\rangle$ and $|T_0\rangle$ can create so-called quantum beats—a quantum analogue of interference beats in classical waves—in high time-resolution TREPR experiments.

Many of the interactions quantified by the variables g, a, and D are anisotropic. But they are averaged out in room-temperature TREPR measurements of SQPs in solution. That information can be regained by performing the experiments on solid-state samples. Two methods can transform SQP solutions into solids. Many experiments freeze dilute solutions into a low-temperature glass state. Researchers also employ nematic liquid crystals (LCs) to order D-B-A molecules containing SQPs.[3] The long axis of the LC typically aligns in the direction of an applied magnetic field. The LC in turn aligns the long axis of the surrounding D-B-A molecules parallel to it. Freezing the LC locks in the orientation of the molecule, which can then be rotated relative to the magnetic field direction to explore the anisotropies of g, a, and D.

The distance between the two spins strongly influences the SQP lifetime and $|S\rangle - |T_0\rangle$ mixing because both J and D are distance dependent. To test those dependencies, my colleagues and I and other groups first needed to design appropriate molecular systems. Figure 2 shows a molecular triad comprising a tetrathiafulvalene electron donor, an aminonaphthalimide bridge molecule, and a pyromellitimide acceptor, which are all covalently linked to form a rigid, rodlike D-B-A system.[3] The molecule is aligned parallel to an applied magnetic field when dissolved in the nematic LC 4-cyano-4′-(n-pentyl)biphenyl, or 5CB. At 85 K, a nanosecond pulse from a violet laser excites B and causes rapid two-step electron transfer to yield a $D^{\bullet+}$-B-$A^{\bullet-}$ SQP with a coherence time of 1.8 μs.

Decoherence of SQPs is driven largely by hyperfine interactions between the electrons and nearby nuclei. Reducing the magnetic moments of those nuclei can thus significantly lengthen the coherence time. Although values of a few microseconds are typical for SQPs, recent work in my lab indicates that coherence times approaching 10 μs are readily achievable by swapping the hydrogen atoms in D and A for deuterium, which has a magnetic moment smaller than that of hydrogen by a factor of roughly 6.5.

Molecular SQPs can execute quantum gate operations. Quantum computing requires, for example, the two-qubit controlled-NOT (CNOT) gate, which uses a control bit to set the state of a target bit. If the control bit is off, then the application of a CNOT gate preserves the target bit's initial on or off state. If the control bit is on, then application of the CNOT gate will flip the target bit from on to off or from off to on. Using the D-B-A molecule in figure 2, my colleagues and I showed that a photogenerated $D^{\bullet+}$-B-$A^{\bullet-}$ SQP can successfully implement a CNOT gate.[3] The 1.8 μs coherence lifetime is long enough for a sequence of five microwave pulses roughly 10–60 ns long to execute the CNOT gate followed by two pulses that read out the result. Extending the coherence lifetimes of such systems to more than 10 μs will enable the sequential gate operations needed for simple quantum algorithms.

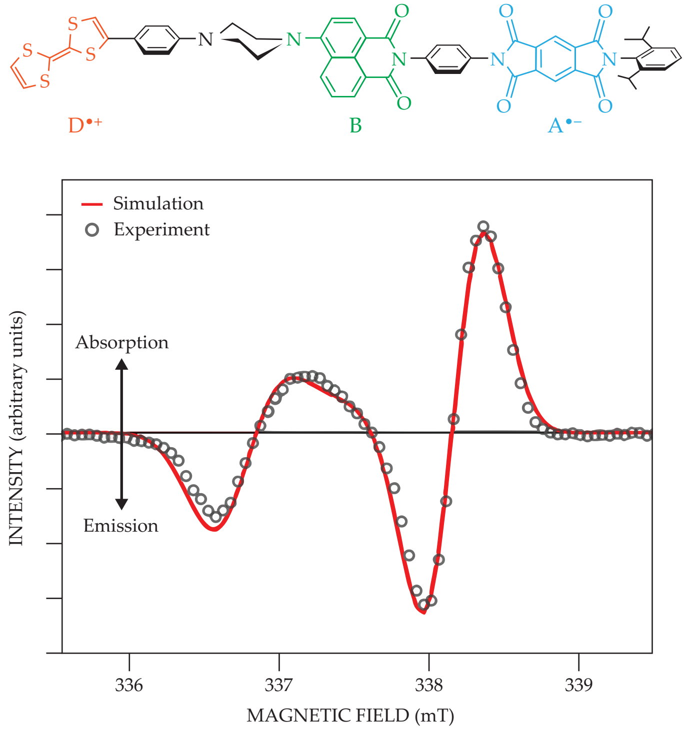


FIGURE 2. A MOLECULAR TRIAD comprises a linked-together tetrathiafulvalene electron donor (D), aminonaphthalimide bridge molecule (B), and pyromellitimide acceptor (A). After being aligned by nematic liquid crystals and frozen into place at 85 K, it has a time-resolved electron paramagnetic resonance (TREPR) spectrum that's typical for a molecular system hosting a spin-qubit pair. A photoexcited electron moves from D—leaving behind a hole—across B, and to A. The spectrum shown here occurs 100 ns after a laser pulse and has a pattern of emission, absorption, emission, and absorption from low field to high. (Adapted from J. N. Nelson et al., *J. Chem. Phys.* **152**, 014503, 2020.)

Chirality in molecular spin qubits

Molecules offer a wide variety of properties that can be exploited to control spin states. One such property of growing interest is molecular chirality—that is, handedness. Chirality is a key property of molecules and important in many physical and nearly all biological processes. Ron Naaman, David Waldeck, and their colleagues presented the first evidence of the relationship between chirality and electron motion[7] in 1999. In a thin film of chiral molecules, they observed that far more electrons with one spin polarization passed through the layer than those with the other polarization. Their work was an example of a phenomenon known as chirality-induced spin selectivity (CISS).

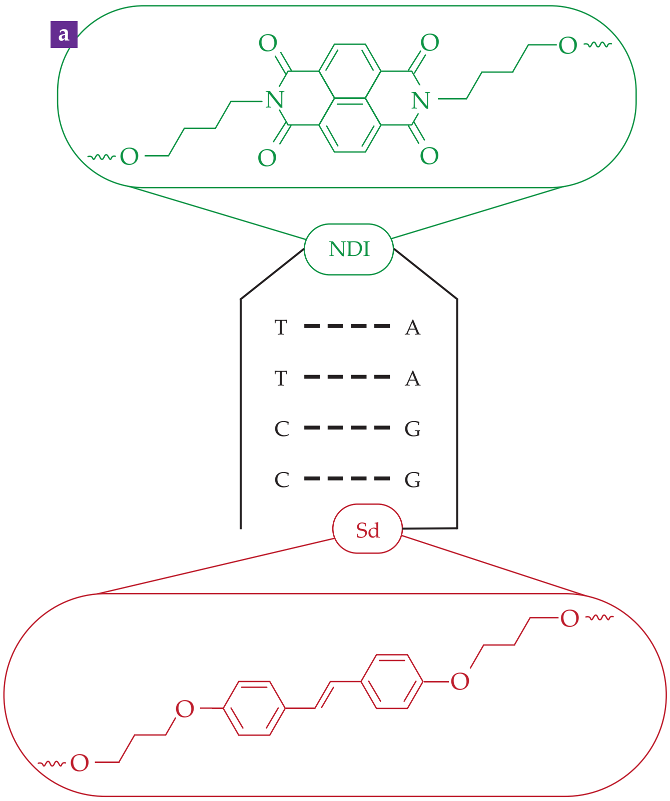
When an electron travels along the helical potential generated by a chiral molecule, it experiences a polarizing force from the induced magnetic field. So the transmitted electron mostly ends up with a spin parallel or antiparallel to its motion, depending on the handedness of the chiral molecule. The spin selectivity of the effect can be very high, even at room temperature, and cannot be explained solely by spin–orbit coupling effects, which are relatively weak in molecular structures that are primarily composed of light atoms.

The theoretical foundation of CISS is still being explored, and its potential for spin manipulation relevant to QIS has only recently been recognized. Some fundamental questions that remain are the following: Does CISS affect intramolecular electron transfer for molecules not on a substrate? Can magnetic resonance techniques directly measure the spin polarization created by the CISS effect? Can an electron's resulting spin polarization be transferred to other quantum spin systems? Can optical methods read out the results of the CISS effect on electron spin states?

If charge transfer occurs through a chiral spacer, denoted as B_χ in D-B_χ-A, the bridge molecule induces a spin polarization that depends on its chirality and the direction of the electron transfer. As a result, electron–hole pairs end up primarily in the $|\Phi_B\rangle$ spin state with diminished entanglement between the hole and electron spins.[8] The CISS effect can thus impart initial strong electron spin polarization as well as change the spin polarization of an SQP.

DNA helices, which provided the first observation of the CISS effect on spin dynamics, can also be used as bridge molecules to study the CISS effect on SQP. My colleagues and I recently studied DNA hairpins, so-called to evoke the molecule's shape.[3] In one example, a naphthalenediimide (NDI) chromophore acceptor molecule links two short single strands of DNA, as depicted in figure 3a. An SQP is prepared by selective photoexcitation of NDI, followed by hole transfer to the DNA strand in less than 1 ps, first to an adjacent adenine nucleobase and then through the adenine and guanine bases. The hole is finally trapped at the terminal stilbene diether (Sd) donor molecule to yield an $NDI^{\bullet-}$-$Sd^{\bullet+}$ SQP.

TREPR techniques using pulsed microwaves reveal detailed information about *J*, *D*, and spin coherence for photogenerated SQPs in DNA hairpins. For example, say photogeneration of an SQP is followed by a microwave pulse that rotates the spin ensemble away from the direction of the magnetic field (*z*-direction) into the *xy*-plane. Local magnetic field variations resulting from the spins' interactions then cause the spins to



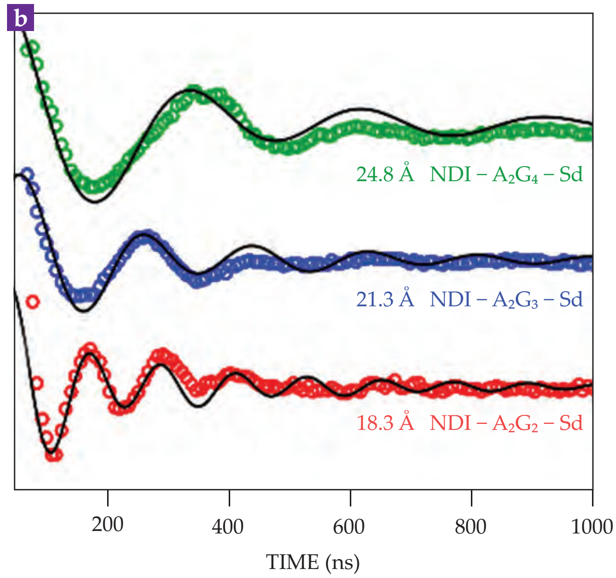


FIGURE 3. DNA HELICES can bridge a variable gap between electron spins. **(a)** A DNA hairpin composed of adenine (A), thymine (T), cytosine (C), and guanine (G) bases connects a naphthalenediimide (NDI) acceptor chromophore to a stilbene diether (Sd) donor molecule to form a single structure such as NDI-A_2G_2-Sd, shown here. **(b)** After the formation of a spin-qubit pair at 85 K, what's known as the out-of-phase electron spin-echo envelope modulation can reveal the distance between the NDI and Sd spins, shown here for three separations (colors) with corresponding simulations (black). (Adapted from J. H. Olshansky et al., *J. Am. Chem. Soc.* **141**, 2152, 2019.)

fan out in the *xy*-plane. A second microwave pulse can refocus the spins, resulting in a so-called spin echo. The measured echo amplitude as a function of the interpulse delay oscillates with a frequency related to both *J* and *D*.[9]

When the experiment is performed on spin-coherent SQPs, the echo experiences a characteristic phase shift relative to the microwave pulses and is therefore termed an out-of-phase electron spin-echo envelope modulation (OOP-ESEEM).[9] If *J* is small (as it usually is), the OOP-ESEEM oscillation frequency is approximately $2D/3$. Because $D \propto 1/r_{DA}^3$, where r_{DA} is the distance between the SQP spins, OOP-ESEEM can indicate the distances between the spins. Most importantly, strong OOP-ESEEM shows that spin coherence is maintained in the SQP.

Recent theoretical work has shown that based on the phase relationships of spin-echo oscillations, OOP-ESEEM and TREPR in general can detect the CISS effect on the spin dynamics of SQPs.[10] Figure 3b, for example, shows coherent OOP-ESEEM oscillations in three DNA hairpins with differing SQP distances; the differences in oscillation frequency result primarily from changes in *D*. Performing pulsed TREPR measurements on related DNA hairpins has also demonstrated SQP coherence times[3] of 4 μs, which according to theory is enough time for the spin manipulations needed to determine the CISS effect.[10] Such tests of the effects of CISS on the coherent spin dynamics of SQPs will require hairpins of left-handed chirality, which can be prepared using L-nucleosides.

Adding a third spin

Quantum communications is often depicted as long-range transmission of information, such as establishing secure links to orbiting satellites. But coherent information transfer over length scales ranging from 1 nm to 100 nm is critical for the connections between quantum processors, so-called quantum interconnects. It is in that regime that molecular systems are particularly promising. Those interconnects necessarily involve more than two electron spins, so strategies are needed to deal with multiple spins—for example, quantum teleportation in a three-spin system.

Quantum teleportation is the transfer of a quantum state over an arbitrary distance through quantum entanglement. Copying a quantum state is impossible because measurement destroys the information encoded in a quantum superposition—a phenomenon known as the no-cloning theorem. In 1993 Charles Bennett and colleagues proposed a workaround that uses quantum entanglement to transfer the information without destroying it:[11] Given a particle (particle 1) and a pair of entangled particles (particles 2 and 3), the state of particle 1 can be transferred to particle 3 through a joint so-called Bell-state measurement on particles 1 and 2. Experiments since have demonstrated quantum teleportation in photonic qubits, trapped ions, atomic ensembles, superconducting circuits, nuclear spins, electron spins in quantum dots, and a combination of the electron and nuclear spins of nitrogen–vacancy centers in diamond.

In 2007 Kev Salikhov and his colleagues proposed a method to perform quantum teleportation with an SQP. One electron in the entangled SQP spontaneously transfers to an adjacent stable organic radical that has an unpaired electron prepared in a specific initial spin state. The electron transfer would reduce the third radical to a diamagnetic anion and serve as the

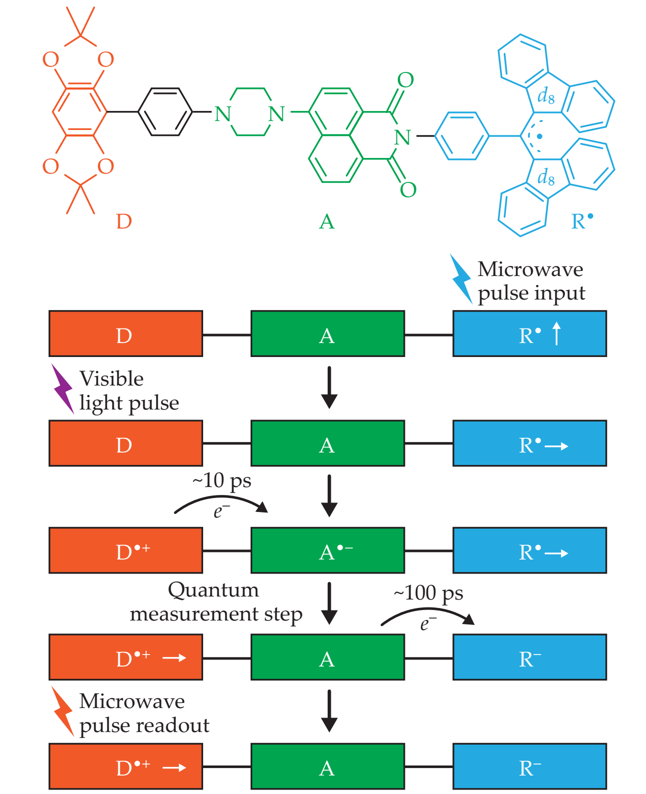


FIGURE 4. QUANTUM TELEPORTATION is possible in the donor-acceptor-stable radical (D-B-R•) molecule, shown at top, composed of tetramethylbenzodioxole (D), aminonaphthalimide (A), and *α*,*γ*-bisdiphenylene-*β*-phenylallyl (R•). (The label d_8 indicates that the fluorenyl rings are deuterated.) In the teleportation scheme at bottom, a microwave pulse puts R• in a selected spin state. A visible laser pulse then excites an electron e^-, which in about 10 ps transfers from D to A and forms an entangled pair with the hole it left behind. When the electron transfers to R•, the process is equivalent to a measurement. As a result, the initial spin state at R• is teleported to the hole at $D^{\bullet+}$, where its state can be read out by microwave pulses.

Bell-state measurement step. As a result, the third radical's initial spin state teleports to the remaining member of the original SQP.[12]

Using that strategy, my colleagues and I implemented quantum teleportation in a donor-acceptor-stable radical (D-A-R•) molecule, shown in figure 4, in which D was tetramethylbenzodioxole, A was aminonaphthalimide, and R• was *α*,*γ*-bisdiphenylene-*β*-phenylallyl, or BPDA.[13] First, we prepared R• in a specific spin state using a microwave pulse that rotated the ensemble of spins 90° with respect to an external applied magnetic field. Photoexcitation of A then formed a singlet SQP $D^{\bullet+}$-$A^{\bullet-}$. The spontaneous ultrafast chemical reaction $D^{\bullet+}\text{-}A^{\bullet-}\text{-}R^{\bullet} \rightarrow D^{\bullet+}\text{-}A\text{-}R^{-}$ constituted a Bell-state measurement. Finally, TREPR spectroscopy with pulsed microwaves showed that the initial spin state of R• teleported to $D^{\bullet+}$ with about 90% fidelity over a distance of 2 nm. Extensions of the strategy to distances of 10–1000 nm are important for future quantum interconnects.

Another promising approach to create and manipulate three-molecular-qubit systems employs an optically excited chromophore covalently linked to a stable radical. For example, recent work has focused on perylenediimide (PDI) chromophores, which are widely available, robust organic dyes used in some red paint formulations. My colleagues and I linked PDI to the stable BPDA radical, which following photoexcitation of PDI produces a spin-polarized quartet state that subsequently transfers its spin polarization to the doublet ground state of the BPDA radical.[14] Using optical pumping to spin polarize a stable radical is an important outcome because it can be used for QIS applications in a manner analogous to the way defect sites in diamond or silicon carbide are used. But molecular systems have the advantage of being easily modified and placed at spatially precise locations.

Four for the price of one

Singlet fission (SF) is a process in which a photoexcited molecule in its excited singlet state interacts with a neighboring molecule in its ground state[15] such that the molecules end up in a pair of coupled triplet states ^{1}(TT) with an overall singlet spin state ($S = 0$). Although SF has been known about for about 50 years, it has attracted considerable interest recently as a way to improve the performance of solar cells. In the past five years or so, researchers have also realized that SF is an efficient way to use one photon to prepare four entangled molecular spin qubits.[16,17] In an organic semiconductor, the rate of SF depends on how strong the interaction is between the neighboring molecules and the energies of the singlet and triplet excitons, E_S and E_T, respectively—rapid rates are achieved when $E_S \geq 2E_T$.

If the ^{1}(TT) lifetime is sufficiently long, spin evolution can produce the quintet ($S = 2$) state ^{5}(TT), which has four unpaired electrons, before the spins eventually decohere,[16] as depicted in figure 5. The ^{5}(TT) state's four entangled spins can be put into a pure, well-defined quantum state through optical pumping. With the right combination of microwave pulses, the spins can execute quantum gate operations, the results of which can be read out with TREPR spectroscopy using pulsed microwaves. Optical detection can also monitor the spin-state changes because ^{5}(TT) decay by triplet–triplet annihilation often produces delayed fluorescence. Using SF to produce the ^{5}(TT) state may enable transduction between photons and spins, which can serve as propagating and stationary qubits, respectively.

Several other qualities of the ^{5}(TT) state also make it attractive for QIS applications. Because of its many possible spin orientations, the ^{5}(TT) state can be utilized as a five-level qudit—the multilevel analog of the two-level qubit. Qudits could facilitate greater storage and processing power than qubits and may provide built-in error correction. The ^{5}(TT) state can also be photogenerated on demand at arbitrary locations. Despite the ^{5}(TT) state's intriguing properties, investigations of it for QIS applications have been limited thus far. The mechanisms of its decoherence are not yet well understood, and strategies for extending coherence lifetimes have not been fully realized.

Although SF occurs in molecular dimers and higher aggregates of chromophores[15] in both solution and the solid state, the ^{5}(TT) state has been relatively elusive in solid-state materials. To realize a long-lived ^{5}(TT) state, the intermolecular electronic interaction must be sufficiently strong to allow efficient SF and prevent dissociation of the triplet-pair state but sufficiently

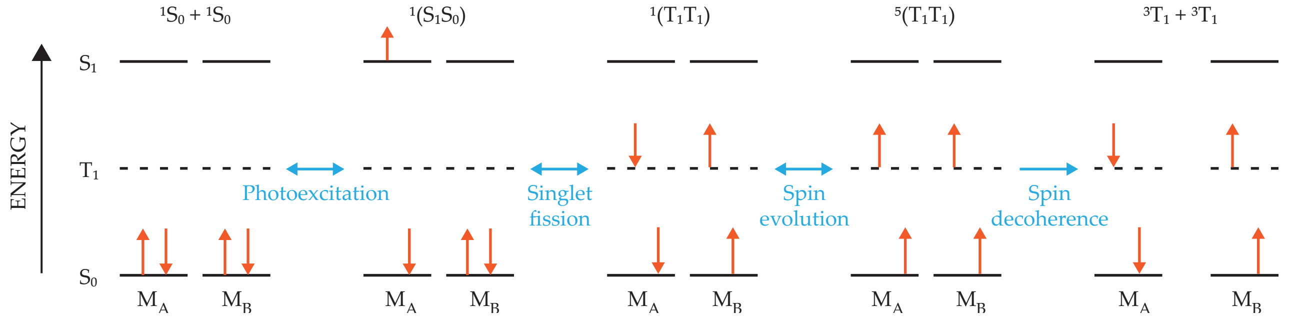


FIGURE 5. **SINGLET FISSION** uses a single photon to generate four spin qubits. A pair of molecules (M_A and M_B) start in their ground states S_0. After photoexcitation, M_A enters its singlet state S_1. The two molecules then interact such that they both end up in excited triplet states T_1. After enough time, the spins can evolve to form a five-level state $^5(T_1T_1)$ that has four unpaired electrons. Eventually the spins decohere altogether.

weak to minimize triplet–triplet annihilation and triplet diffusion. Striking that delicate balance is a major challenge. In solid-state materials, electronic coupling is dictated by the crystal structure, which is difficult to predict or control because of the various weak intermolecular forces that govern molecular packing.[16]

Recently some colleagues and I have managed to engineer the crystal morphology of the chromophore tetracene.[17] By attaching bulky tris(cyclohexyl)silylethynyl groups to it, adjacent pairs of tetracene molecules are placed far enough apart in the crystal to be effectively isolated. Photoexcitation of tetracene results in formation of the ^{5}(TT) state, which is confirmed by its TREPR spectrum and observable even at room temperature. The lifetime of the ^{5}(TT) state is 130 μs, and its spin-coherence lifetime is 3 μs at 5 K. The crystals spatially align and organize the interchromophore spacing to optimize the electronic interaction needed for favorable ^{5}(TT) properties. With that optimization taken care of, future work can focus on identifying decoherence sources.

Scaling up and outlook

Light-driven processes in molecules are increasingly revealing themselves as promising spin qubits. The coherence lifetimes of those systems are constantly improving through, for example, deuteration of the organic molecules. Molecular spin qubits have already demonstrated basic operations essential to QIS, such as transferring coherence and polarization to neighboring spins and essential quantum gate operations, including the CNOT gate. Further work on spin teleportation in molecular arrays will extend the distance over which quantum information can be transferred from the nanoscale to the microscale.

Now that some of the basic concepts intrinsic to quantum information have been demonstrated, further development of photogenerated molecular spin qubits will likely take many directions. For example, multispin systems comprising even a few qubits can execute simple algorithms and serve as intelligent nanoscale sensors. A key challenge to those and other applications is finding ways to photogenerate larger numbers of SQPs and control individual spins. Toward that goal, two colleagues and I have already shown that it is possible to generate two SQPs in a single molecular system by using laser pulses at two wavelengths.[18]

Exploiting the CISS effect in molecular systems may make it possible for molecular building blocks to execute well-defined spin manipulations similar to what is achieved today using microwave pulses. Different molecular building blocks that execute different spin manipulations could combine to create functional molecular quantum circuits on the nanoscale. Lastly, DNA hairpins and other systems that mimic nature provide a readily accessible platform to scale up molecular quantum components. Exploiting chemistry to create new multispin systems provides a broad range of new molecules and materials whose properties can be tailored to specific QIS applications.

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PT

Scientists working at the Dutch–Norwegian nuclear reactor, the Joint Establishment Experimental Pile, sometime in the 1950s. (Photo from NTB/Alamy Stock Photo.)

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Splitting atoms together

Machiel Kleemans and Hans Wilschut

Despite the US's strict postwar limitations on sharing nuclear knowledge, Norway and the Netherlands together were able to build a nuclear reactor several years after World War II ended.

Between the end of World War II and the start of the US Atoms for Peace program in late 1953, nuclear physics was largely a classified field. Fissile materials were tightly controlled by the US government. Eager to catch up on the new science of nuclear fission, European countries emerging from German occupation were stonewalled by their wartime ally. Despite those restrictions on knowledge and materials, Norway and the Netherlands managed to jointly construct a nuclear reactor by 1951. Called the Joint Establishment Experimental Pile (JEEP), the Dutch–Norwegian reactor was the first to be constructed by nonmajor powers. Why were the Dutch and Norwegians the first smaller countries to build a reactor, and how did they succeed so quickly?

One major reason was because of the scientists who led the joint reactor project, Dutch physicist Hans Kramers (see box 1) and Norwegian astrophysicist Gunnar Randers (see box 2). After the war it was clear that the frontier of physics had shifted from Europe to the US. So for European countries looking to rebuild science, researchers with strong transatlantic networks were invaluable. Kramers and Randers fit the bill: Kramers had been an assistant to Niels Bohr in the early 1920s and was well acquainted with J. Robert Oppenheimer, while Randers had worked in the US before and during the war and built an extensive personal network that included Albert Einstein and Enrico Fermi.

Another reason for the Dutch and Norwegians' success was their access to two critical nuclear ingredients: uranium and heavy water. The Netherlands had acquired 10 tons of uranium just before the war, and Norway had its own heavy-water production facility. As was characteristic for the early postwar era in Europe, the Dutch and Norwegian governments left their scientists a relatively free hand with those materials. Kramers and Randers were able to take advantage of narrow but crucial windows of opportunity to make the technical and political advances necessary to realize the reactor project.

Dutch uranium

The discovery of nuclear fission by Otto Hahn, Lise Meitner, and Fritz Straßmann in December 1938 sparked feverish research efforts around the world. In Paris, for instance, Frédéric Joliot-Curie led an advanced research group on nuclear physics. Following closely behind was a team led by Enrico Fermi and Leo Szilard in New York (see the article by Spencer Weart, Physics Today, February 1976, page 23). Early in 1939, the researchers in Paris and New York both discovered that nuclear fission could be used in uranium to initiate a chain reaction, which in turn could power an explosive device or be exploited to generate power.

News of the discovery reached the Netherlands that March, when Joliot-Curie informed the Dutch physicist Wander de Haas about his preliminary results. De Haas, one of the directors of the Kamerlingh Onnes Laboratory at Leiden University, quickly realized the strategic value of uranium and sprang into action. He used his close government contacts to persuade the Dutch prime minister, Hendrik Colijn, to immediately order a large amount of uranium from the Belgian firm Union Minière du Haut-Katanga, which mined deposits in the Belgian Congo.

The Dutch placed their uranium order just a few weeks before Joliot-Curie made Union Minière aware of uranium's new potential. When 200 50-kilogram barrels of yellowcake—a form of uranium oxide—arrived at his laboratory in Leiden, De Haas initially had them stored in his laboratory. But the uranium increased radiation levels and interfered with measurements, so the barrels were moved to a locked room in a basement at the Delft University of Technology. Remarkably, they remained undisturbed in the basement during the war, undiscovered by the German occupiers.

Across the Atlantic Ocean, the US, with assistance from the UK and Canada, initiated the Manhattan Project in 1942, which culminated in the successful development of an atomic bomb three years later. The wartime allies simultaneously began attempting to gain control of strategic nuclear materials across the world. Starting in summer 1944, a team of UK and US scientists and diplomats set out to negotiate control over uranium and thorium ores. They were concerned about the latter because it could be used to breed fissile uranium-233, a potential bomb material.

On behalf of the Dutch government, Kramers and Dutch foreign minister Eelco van Kleffens negotiated a secret agreement with US and UK officials in late summer 1945 stating that export of thorium from the thorium-rich monazite sands in the Dutch East Indies (present-day Indonesia) would be subject to UK–US control. The agreement was signed in London on

Box 1. Hans Kramers

Hendrik Anthony "Hans" Kramers (1894–1952) began studying physics with Paul Ehrenfest at the Netherlands' Leiden University, where he received his doctorate in 1919. Most of his doctoral work, however, was done with Niels Bohr in Copenhagen, and Kramers remained there after finishing his studies. During that time, he became one of the early pioneers of quantum mechanics. He returned to the Netherlands in 1926, when he was named professor of theoretical physics at the University of Utrecht. After Ehrenfest's death in 1933, Kramers succeeded him as a professor of theoretical physics in Leiden.

After World War II, Kramers became the Dutch government's main adviser on rebuilding physics and nuclear issues. In 1946 he served as chairman of the technical subcommittee to the United Nations Atomic Energy Commission. He then spent spring 1947 at the Institute for Advanced Study in Princeton, New Jersey. During that visit to the US, he also attended the Shelter Island Conference on the Foundations of Quantum Mechanics, where his discussion of mass renormalization probably inspired Hans Bethe to determine how to calculate the Lamb shift (see the article by Freeman Dyson, Physics Today, October 2005, page 48). That was a crucial step toward renormalizable quantum field theory. From 1950 on, Kramers focused on realizing the nuclear reactor project with Norway. An influential figure in the founding of CERN, Kramers died in April 1952, just before CERN's first council meeting.

HANS KRAMERS pictured in 1946 in his capacity as chair of the technical subcommittee to the United Nations Atomic Energy Commission. (Courtesy of the Kramers family.)

FIGURE 1. J. ROBERT OPPENHEIMER (left) and Hans Kramers (right) in the US, around 1930. (Courtesy of the Kramers family.)

4 August, two days before the bombing of the Japanese city of Hiroshima. On signing, the US ambassador in London, John Winant, confided to Van Kleffens that the UK wartime nuclear project "would receive considerable publicity within a few days."[1]

The bombings of Hiroshima and Nagasaki made European physicists realize how far behind they were. Kramers was named chair of a Dutch committee that began an extensive program of nuclear research. Even though he and the committee members rejected developing nuclear weapons, they decided to keep secret the knowledge of Dutch uranium stores. In 1946–47 Kramers spent considerable time in the US, where he was called on to assist Van Kleffens—now the Dutch ambassador to the US—with United Nations Security Council discussions concerning nuclear weapons and energy. Kramers was chair of the UN technical subcommittee that came to the unanimous conclusion that international control of nuclear weapons was possible.[2] But rising tensions between the USSR and the US forestalled such an agreement.

Kramers's stay in the US also gave him the opportunity to reestablish contacts with friends in the physics community. He spent spring 1947 in Princeton, New Jersey, where he met regularly with Oppenheimer, who had just assumed the directorship of the Institute for Advanced Study. Kramers and Oppenheimer, who had known each other since the 1920s (see figure 1), also served as

Box 2. Gunnar Randers

Gunnar Randers (1914–92) studied astrophysics at the University of Oslo until 1937, when he became an assistant to the theoretical astrophysicist Svein Rosseland. He then traveled to the US, where he worked at the Mount Wilson Observatory from 1939 to 1940 and then at the University of Chicago's Yerkes Observatory until 1942. His main contribution to physics dates from that period, when he introduced what is now known as Randers geometry in general relativity.

In Chicago, Randers became acquainted with Enrico Fermi and his team, who were building the world's first nuclear reactor. A few months before the Chicago reactor went critical, Randers moved to the UK, where he joined Rosseland and other Norwegian scientists in assisting with the war effort. During that time, he worked under the UK nuclear physicist John Cockcroft, who was closely involved in constructing the UK's first reactors and would be an important postwar contact.

In summer 1946 Randers traveled to the US with a gifted engineer, Odd Dahl, and collected valuable classified nuclear information that would eventually lead to the construction of a Dutch–Norwegian heavy-water reactor in 1951. Randers dominated Norwegian nuclear policy for several decades. He was instrumental, for example, in pushing through a sale of heavy water to Israel for its Dimona reactor in 1959 without public scrutiny.[12] He served as the personal adviser on nuclear affairs to United Nations secretary general Dag Hammerskjøld, and from 1968 to 1973, he was NATO's assistant secretary general of scientific affairs. He died in February 1992.

GUNNAR RANDERS (right) with Queen Juliana of the Netherlands (left) during a visit to the Dutch–Norwegian reactor in May 1953. (Courtesy of the Norwegian Museum of Science and Technology, CC BY-NC-SA 4.0.)

discussion leaders at the famous Shelter Island Conference on the Foundations of Quantum Mechanics. Although there's no evidence that Kramers shared knowledge of the Dutch uranium trove with Oppenheimer, his renewed acquaintance with the Manhattan Project leader would help Kramers a few years later when he asked Oppenheimer for advice. Nevertheless, as the 1940s came to a close, Dutch scientists still lacked a reactor design for their uranium.

The Norwegian reactor

The genesis of Norway's civilian nuclear program lay in its heavy water supply. Shortly after the discovery of deuterium in 1931, Norway began to produce heavy water on an industrial scale at a fertilizer plant operated by the company Norsk Hydro in the town of Rjukan. During World War II, the Allies and the Norwegian resistance famously sabotaged the plant to prevent the Germans from acquiring nuclear weapons. The Norwegians, however, quickly got it up and running again after the war ended. At the same time, Randers began perusing the Smyth Report—the semitechnical survey of the Manhattan Project, released by the US government in August 1945, that marked the limits of declassified nuclear knowledge. He realized the importance of Norway's heavy water.

Randers had gone to the US in 1939 and worked in Chicago from 1940 to summer 1942. His office was in the same building as Fermi's group, which finished constructing the world's first nuclear reactor by the end of 1942. Informal exchanges with Fermi and his staff gave Randers a decent idea of what they were working on. Randers then moved to the UK to assist in the war effort. There he worked with John Cockcroft, the UK nuclear physicist and future Nobel Prize recipient.

While in the UK, Randers was shown the French patent for a heavy-water reactor, which helped inspire him to build a reactor in Norway. Frustrated yet stimulated by the incomplete information available in the Smyth Report, Randers set out to gather the materials and knowledge necessary to design a reactor. He felt it was crucial for the country to be involved in such a modern science project to "secure its existence in the long run."[3]

Together with the gifted engineer Odd Dahl, Randers traveled to the US in summer 1946, where he collected valuable information. During that time, most physicists who had been involved in the Manhattan Project generously provided information under the assumption that nuclear secrets would soon be declassified. In that spirit of budding transparency, Randers talked with old friends, including Fermi and Walter Zinn, with whom he discussed the construction of the world's first heavy-water reactor, Chicago Pile-3. But the biggest coup from the trip was when Randers learned the average number of secondary neutrons, a piece of information that was only officially declassified in 1950.

The short window for open scientific exchange on nuclear physics soon closed when President Harry S. Truman signed the Atomic Energy Act on 1 August 1946. Also known as the McMahon Act, the law specified that US citizens could not share nuclear knowledge with foreign nationals. Violators could face the death penalty. But Randers and Dahl had already obtained the information they needed, which was that a Norwegian reactor would be feasible with only modest amounts of heavy water and uranium.[4]

Back in Europe, Randers started cooperating with Joliot-Curie's group in France, which was being supplied with heavy water by Norsk Hydro. During the war, most of the French scientists in the group had worked on a small heavy-water reactor in Canada, the Zero Energy Experimental Pile (ZEEP), which they now aimed to copy in France. Even though the French scientists had been required to pledge secrecy when they left Canada, Randers got easy access to the French nuclear program by playing the heavy-water card.

In exchange for heavy water, the French scientists also provided Randers and Dahl with reactor-design information and 50 tons of pure graphite for the neutron reflector. (In early heavy-water reactors, a layer of graphite was positioned on the outside of the reactor to reflect escaping neutrons back into the core and minimize the required quantities of uranium and heavy water.) Dahl started building the reactor at a site in the town of Kjeller, outside Oslo, while Randers desperately looked for a supply of uranium.

Randers first approached Cockcroft, who had headed the wartime ZEEP project in Canada and was now head of the UK nuclear effort, with an offer to trade Norwegian heavy water for uranium. Although Cockcroft wanted to help, he was stymied by the US's uranium monopoly. Randers then considered continuing the collaboration with France. But that was unattractive because Joliot-Curie, who during the war had joined the Communist Party, wanted to serve in a leading capacity, and the Norwegian government did not want to offend the US at a time of early Cold War tensions.[5] Randers then looked into the uranium ore available in Norway, but it was too low grade to use.

By early 1950 the reactor was almost finished, although the prospects for a quick start looked bleak without the required uranium. But unexpected help was on the way. In the Netherlands, a group of small countries had just gathered to discuss possible nuclear initiatives. Norway, however, had been unable to attend. So Kramers then went to Norway looking for a partner to build a reactor. He brought with him a dowry of uranium, which was a godsend to the Norwegians. Kramers and Randers were struck by the sudden opportunity. On the spot, they decided to start a collaboration that would be formalized shortly thereafter.[6]

Openness versus secrecy

To protect its nuclear monopoly, the US implemented strong secrecy measures to prevent nuclear information from spreading. In Europe, secrecy as a policy tool emerged more slowly, and scientists were generally trusted to deal with nuclear matters as they saw fit. Nevertheless, many European policymakers and physicists first sought to emulate the US. Kramers, for example, began working on a draft of a Dutch atomic energy act with Van Kleffens in 1948 that initially contained a secrecy clause.

But Kramers changed his mind after speaking with "a prominent American, 'O.'"—almost certainly Oppenheimer—at the 1948 Solvay Conference on Physics in Brussels. Based on those discussions, Kramers reported to the Dutch government that the US secrecy policy had been a disaster. The restrictions on sharing nuclear knowledge, he wrote in a report, had led to "the direst consequences" and threatened to "end in Russia-like terror situations." A "great struggle" was occurring behind closed doors, and Kramers suggested that US allies could aid proponents of atomic openness by opposing "extreme" US secrecy policies.[7]

That argument successfully forestalled the inclusion of a formal secrecy arrangement in the Dutch law. The government's willingness to forego secrecy policies may have also been because of the situation in the thorium-rich Dutch East Indies. After Indonesia gained its independence in 1949, the Netherlands lost access to the thorium ore, which meant it no longer needed legal secrecy measures. But the Dutch government also seemed to have had little desire to control its physicists. They were given a free hand—at least until tangible results were in sight.

But the Dutch and Norwegians still required UK and US consent. Earlier Norwegian requests for reactor assistance had been denied. Views on the control of nuclear knowledge and technology, however, started to shift after the Soviet nuclear test in 1949 and the revelation in early 1950 of Klaus Fuchs's wartime nuclear espionage. The question for the Dutch and Norwegians was how to approach their more powerful allies: through trusted scientific contacts or at the government level?

Although the Dutch government preferred using scientific contacts, Oppenheimer dissuaded Kramers from sounding things out on a technical level. Knowing that the US government was beginning to exert more control over scientists than its European counterparts, Oppenheimer told Kramers to talk to US officials at the State Department and the Atomic Energy Commission (AEC). The Dutch ambassador to the US gave Kramers the same advice, which turned out to be valuable because the State Department saw itself as the first point of contact on nuclear matters. Moreover, it did not oppose the Dutch–Norwegian reactor plan.

Subsequent discussions with AEC scientists in June 1950 went smoothly. Although the AEC wasn't willing to assist the Dutch and Norwegians, it did not oppose what it termed their "modest developments" in nuclear energy.[8] In a letter to Cockcroft, Kramers informed the UK about their plans. After some discussion, the Dutch and Norwegians agreed to keep the UK government informed, with Cockcroft serving as the intermediary. The political obstacles were cleared, which meant that only the technical hurdles remained. Foremost among them was purifying uranium yellowcake and using the resulting ore to produce nuclear fuel.

That was not a trivial matter. The US State Department had discouraged the Dutch and Norwegians from seeking further assistance from France, which left the UK as the best option for help. So Kramers began discussing fuel elements with Cockcroft. Randers's initial idea had been to copy the French reactor design and use sintered uranium oxide as fuel, but he didn't have access to US data on its heat conductivity, which was classified. Efforts to extract that information from US colleagues also failed.

So Cockcroft and Kramers had to calculate the value themselves. But they made an error regarding the conductivity of uranium oxide, which resulted in their projected value for the heat conductivity being far too low. The value implied that at the reactor's intended power output of more than 100 kilowatts, the heat buildup in the center of the sintered blocks would destroy them. So Cockcroft and Kramers incorrectly concluded that oxide would not work. It was precisely the kind of mistake Oppenheimer had warned against in a March 1950 lecture: "We know that in secrecy error, undetected, will flourish and subvert."[9]

FIGURE 2. RODS OF URANIUM FUEL for the Joint Establishment Experimental Pile reactor, pictured in 1951. (Courtesy of the Norwegian Museum of Science and Technology, CC BY-SA 4.0.)

The Dutch and UK governments eventually decided to exchange the Dutch yellowcake for UK uranium metal. Cockcroft offered Kramers and Randers uranium rods that wouldn't work in the UK's larger plutonium production installations but were good enough for the small Dutch–Norwegian reactor. The rods were modified slightly so that they could be placed together in pairs, and they fit in the existing design (see figure 2). Having successfully avoided the problems of uranium purification and fuel production, the Kjeller reactor became operational[10] in July 1951.

Internationalism and legacy

Analogous to its Canadian predecessor ZEEP, the Dutch–Norwegian reactor was called the Joint Establishment Experimental Pile (JEEP). It was the first open, international research reactor. A US physicist, A. W. McReynolds, was among the early visitors, and he reported on his experience at Kjeller in an April 1955 PHYSICS TODAY article (page 13). As he wrote, the "roster of nationalities" of visitors at Kjeller read "like a roll call of the UN." Left unsaid was the paradoxical fact that during his year at Kjeller, McReynolds had worked in a more open research environment than at his home institution of Brookhaven National Laboratory—or, for that matter, any nuclear research facility in the US.

That same internationalism was displayed at the Kjeller Conference on Heavy Water Reactors in August 1953, one of the first international meetings on nuclear physics. It was attended by representatives from 18 countries, including Argentina, India, Israel, and what was then Yugoslavia. Many of those representatives would go on to play central roles in their countries' nuclear programs.

One of the Yugoslav scientists at the conference, Dragoslav Popović (see figure 3), was in the midst of a multiyear stay in Norway. During his time at Kjeller, he succeeded in measuring the fission cross sections of uranium-235 as a function of neutron energy.[11] At that point those detailed cross sections were still classified in the US and their publication caused a minor uproar. Moreover, the enriched uranium targets he used were produced by a small calutron in Amsterdam, the first source of enriched uranium in the West outside of the US and UK. Popović's research and the Dutch calutron confirmed the increasing ineffectiveness of the existing US nuclear secrecy regime. In December 1953 President Dwight Eisenhower announced the Atoms for Peace program, which was meant both to dispel the militaristic image associated with atomic energy and to provide breathing room for a commercial nuclear industry to develop. It allowed the US to share nuclear technology and materials with foreign countries.

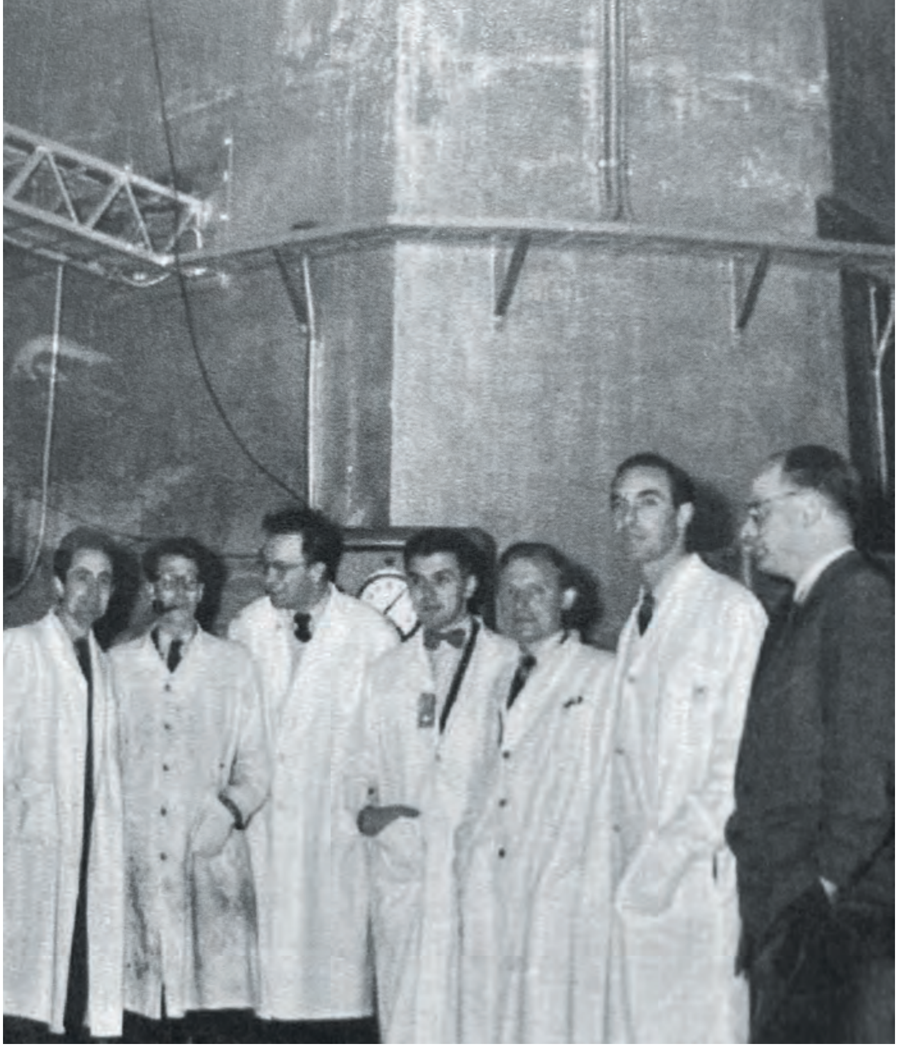

FIGURE 3. FOREIGN SCIENTISTS in front of the Dutch–Norwegian Joint Establishment Experimental Pile reactor. In the middle, with bowtie, is the Yugoslav physicist Dragoslav Popović. The US physicist A. W. McReynolds is second from right. (Courtesy of BetaText.)

Although Atoms for Peace was a blessing for many countries with nuclear aspirations, it augured the end of the Dutch–Norwegian collaboration. By selling reactors complete with fuel, the US regained some control over the burgeoning nuclear reactor programs of its allies. The Netherlands bought a research reactor with enriched fuel from the US, which served its own interests but not Norway's. As a result, Norway built its own new heavy-water reactor in Halden, on the Swedish border. It became operational in 1958.

Because Norway possessed a significant amount of hydroelectric power, it was initially interested in using nuclear power—namely, special heavy-water reactors—for naval propulsion. In the Netherlands, on the other hand, research into nuclear power and isotope production was high on the agenda. As a result, the joint research program slowly disintegrated during the late 1950s. But JEEP remained important as a training and teaching instrument. The Dutch–Norwegian reactor school was founded there in 1958. JEEP began to suffer from technical problems by 1960, so Norway built a successor, JEEP II, which became operational in 1967. The original JEEP was retired, and its reactor vessel was buried. It was dug up in 1993 amid concerns about nuclear waste originating from the early reactor program (see figure 4).

But the physical remnants of the reactor do not define JEEP's legacy. It was the first open research reactor in the world, and it successfully challenged the postwar US standard of secrecy and control. It helped both Norway and the Netherlands develop early nuclear programs and train a pool of young scientists. Furthermore, scientists from many other countries began their nuclear careers in Kjeller, which was often the first step in their own countries' nuclear programs, most of which were peaceful.

JEEP was a symbol of postwar progress, national pride, and scientific self-confidence. It fostered an early form of nuclear internationalism that foreshadowed global collaborations like Atoms for Peace. It also taught the international community an early lesson about the control of nuclear technology. Without early access to heavy water and uranium, Norway and the Netherlands never could have built JEEP as early as they did. The control of strategic materials remains the bedrock of international nonproliferation efforts today.

FIGURE 4. THE REACTOR VESSEL of the Joint Establishment Experimental Pile was dug up in 1993 amid fears of contamination at the Kjeller site. (Courtesy of IFE.)

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ENGDAO WICHITPUNYA / ALAMY STOCK PHOTO

Michael Edgeworth McIntyre is a professor emeritus at the University of Cambridge in the UK and a fellow of the Royal Society. This article is based on his book *Science, Music, and Mathematics: The Deepest Connections*, published by World Scientific, and on a paper he published in *Meteorology* in April 2022.

CLIMATE TIPPING POINTS: *A personal view*

Michael Edgeworth McIntyre

The worst uncertainties about climate change are outside the scope of climate models but can be thought about in other ways—especially by learning from past climates.

Earth's future climate might or might not have a domino-like succession of tipping points that turns the system into a hothouse after an uncertain number of centuries. Sea levels would rise by about 70 m, and new extremes of surface storminess would likely lie well outside of human experience. Such worst-case scenarios are highly speculative. But they cannot be ruled out with complete confidence in the present state of climate science and climate modeling. So there has never in human history been a stronger case for applying the precautionary principle. Today there is no room for doubt about the need to reduce net greenhouse gas emissions urgently and drastically, far more than what is possible through so-called offsetting by, for example, planting trees, which can compensate for the emissions but not quickly enough.

I come to such issues not as a mainstream climate scientist but as an expert on fluid dynamics—more specifically on problems such as understanding atmospheric jet streams and their oceanic cousins like the Gulf Stream. My research group was never funded for climate science. My work on the fluid dynamics of jet streams has, however, brought me close to mainstream climate science.

Arguably, the climate problem is by far the most complex of all the problems confronting humanity today. It involves not only the complexities of human behavior and the human brain but also a vast, multiscale jigsaw puzzle of other interacting pieces, from global-scale atmospheric and oceanic circulations, through cyclones and thunderstorms, and all the way down to the scales of forest canopies, soil ecologies and mycorrhizal networks, phytoplankton, bacteria, archaea, viruses, and molecules. Millimeter-scale ocean eddies shape global-scale deep-ocean structure and carbon storage.[1] Also crucial to carbon storage are deep overturning circulations and plankton ecologies.[2] Ice sheets flow and melt or shatter in dauntingly complex ways, which elude accurate modeling. Some scientists dismiss some pieces of the jigsaw puzzle as unimportant, but I think that there can be no such certainty about any of them.

Nearly all the climate system's real complexity is outside the scope of any model, whether it's a global climate model that aims to represent the climate system as a whole or a model that only simulates the carbon cycle, ice flow, or another subsystem. The same goes for purely data-based statistical or machine-learning models. A common misconception is that uncertainties about the real climate system can be estimated from the variability within and between climate models. Of course, the models can be valuable when used in ways that respect their limitations.[3]

I believe that to develop the best possible scientific understanding of any problem, one must keep looking at it from all possible viewpoints and lines of evidence. It's important to maintain a certain humility and to resist the urge to rely on a single viewpoint based, for example, on a particular kind of model.

This article steps aside from model predictions and instead explores other ways to think about the most troublesome uncertainties. They include the uncertainties about how climate and weather might or might not behave over the next few decades and centuries and whether human civilization will survive.

Information from the past

Paleoclimates are our main source of information about the workings of the real climate system. That information takes full account of its complexity. Researchers have the most detailed observations on the last several tens of millennia, when the system was fairly close to its present state.

During that time, there were abrupt climate changes called Dansgaard–Oeschger warmings, which occurred at irregular intervals of several millennia or so. In the North Atlantic area, the temperature rose by at least several degrees Celsius and perhaps even more than 10 °C. In some cases, warming events took only a few years and appear in paleoclimate records across most of the Northern Hemisphere.[4–8] Changes taking only a few years are almost instantaneous from a climate-system perspective. They're a warning to take seriously the possibility of tipping points in the dynamics of the real climate system.[9] The warning is needed because some modelers have argued that tipping points are less probable for the real climate system than for the simplified, low-order climate models studied by dynamic-systems researchers.[3]

Other researchers, however, have suggested that such a tipping point may be reached sometime in the next few decades or even sooner.[6,7] Some of its mechanisms resemble those of the Dansgaard–Oeschger warmings and would suddenly accelerate the rate of disappearance of Arctic sea ice. As far as I am aware, no such tipping points have shown up in the behavior of the biggest and most sophisticated climate models. The suggested tipping-point behavior depends on fine details that are not well resolved in the models, including details of the sea ice and the layering of the upper ocean.

Also of concern are increases in the frequency and intensity of destructive weather extremes. Such increases have already been observed in recent years. Climate scientists are asking how much further the increases will go and precisely how they will develop. That question is, of course, bound up with the question of tipping points. A failure to simulate many of the extremes themselves, especially extremes of surface storminess, must count as another limitation of the climate models. The reasons are related to the resolution constraints of climate models.

Warmings and sea ice

How do we know that the Dansgaard–Oeschger warmings were almost instantaneous? The answer comes from Greenland ice-core records, which have countable annual layers. As noted by ice-core expert Richard Alley, "these records provide annual resolution for some indicators through 110,000 years."[4] The indicators in the ice cores are measured variables such as chemical concentrations and isotope ratios in the ice, in trapped air bubbles, and in dust from various sources. Oxygen and hydrogen isotopes are known to be correlated with temperature

FIGURE 1. AN ICE CHUNK fell from Grey Glacier in Chile in 2009. Such collapses may happen for several complex, interrelated reasons, including friction patterns, hydrofracturing, and intruding seawater. To improve the scientific understanding of climate tipping points, all of those complexities and their uncertainties need to be observed and modeled as a whole. (Photo by iStock.com/gcoles.)

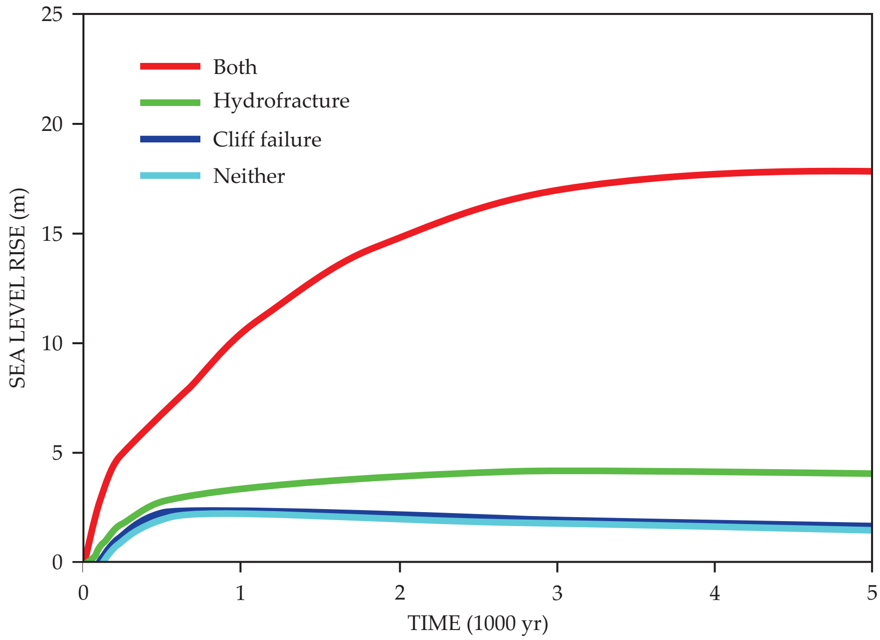

FIGURE 2. SEA LEVELS are predicted to rise with or without hydrofracturing and one of its consequences, ice-cliff failure, according to an improved ice-flow model. (Adapted from ref. 15.)

changes. The precisely dated ice-core records provide evidence not only for the extreme rapidity and the steplike nature of the North Atlantic temperature jumps but also for the consequences of those jumps, which were widespread and close to synchronous across the Northern Hemisphere.

When viewed in finer detail, the warming events often seem to have involved more than one sharp stepwise jump within a few decades, with each jump taking only a few years. The mechanisms in play are exceedingly complex. In particular, the warming events are related to global-scale oceanic and atmospheric circulations and sea-ice cover, especially in the Nordic Seas, between Scandinavia and Greenland.[5–8] With one exception, however, the mechanisms considered have time scales too long to produce the sharp jumps. The exceptional mechanism—the only mechanism suggested so far that is fast enough—involves the Nordic sea ice and the fine structure of upper-ocean layering underneath the ice.[6,7]

The exceptional mechanism depends on the northward inflow of warm, salty subsurface Atlantic water under the sea ice. During cold intervals, the uppermost layers of the Nordic Sea were stably stratified with a strong halocline—a boundary that separates the warm, salty subsurface Atlantic inflow from colder, fresher, more buoyant upper layers capped by sea ice. That stratification and the presence of sea ice is supported by evidence in ocean sediment cores from the Nordic Seas region that show planktonic and benthic species and isotope abundances.[6,7] But if the subsurface inflow warms enough, the water can become sufficiently buoyant to break through the halocline and up to the surface, where it quickly melts the sea ice. When such sudden sea-ice melting happens over a substantial area, or in steps over a succession of substantial areas, the atmosphere can respond quickly with major changes in its weather patterns on a hemispheric scale.

Today some areas in the Arctic Ocean may be approaching a similar state, albeit still short of buoyant breakthrough.[10] Recent underwater observations made in 2003–18 show a weakening halocline being eroded by turbulent mixing, which allows more subsurface heat to reach the surface, at rates that increased from 3–4 $W\,m^{-2}$ in 2007–08 to about 10 $W\,m^{-2}$ in 2016–18. As buoyant breakthrough conditions are approached, the current rate of sea-ice melting—already accelerating through the well-known ice-albedo feedback—may likely accelerate further and more drastically. As with the Dansgaard–Oeschger warmings, there could be several such episodes of increased acceleration as different areas of Arctic sea ice are melted in a stepwise fashion.

Exactly what will happen is extremely hard to predict since, in climate models, the fine structure of the upper ocean with its halocline and sea ice, the associated buoyancy-related and turbulent-mixing processes, and the subsurface ocean currents and eddies are not accurately represented in enough detail. But an educated guess would be to anticipate a drastic acceleration of Arctic sea-ice loss quite soon, perhaps over the next decade or two, with knock-on effects that could include accelerated melting of the Greenland ice sheet.

Ice-flow uncertainties

The stepwise sudden shattering of the Larsen A and Larsen B Ice Shelves off the Antarctic peninsula in 1995 and 2002, respectively, reminded scientists of the complexities of ice flow. The consequences of such shattering events are not confined to the marine side of the picture. As long as a marine ice shelf holds together across an embayment, it can have a buttressing effect that reduces the flow rate of ice coming off adjacent land surfaces. Those and other ice-flow complexities are under intense scrutiny by glaciologists (see the article by Sammie Buzzard, Physics Today, January 2022, page 28). Inevitably, though, the complexities are far from being accurately represented in any climate model.

Ice-flow modeling is peculiarly difficult because of its dependence on the fracture and stress patterns involved. Some of those include ice-cliff failure, as illustrated in figure 1, and the frictional properties and velocities of the glacier-like ice streams found in ice sheets. Ice streams flow faster than their surroundings because of fractures and weakened friction at their sides. In addition, there is a complex interplay with the meltwater flow networks beneath grounded ice, which can lubricate the bulk ice flow.[11,12]

An important process is so-called hydrofracturing that's caused by surface meltwater chiseling its way down through an ice sheet. The meltwater, being denser than the surrounding ice, can sometimes force a crevasse to open all the way to the bottom of the ice sheet. That is how the Larsen B Ice Shelf was shattered.[13] The phenomenon has also been observed on parts of the Greenland ice sheet,[11] whose melting rate has accelerated in recent years.[14] Hydrofracturing is also involved in ice-cliff failure.[15]

A major overall challenge to ice-flow modeling—a challenge as yet unmet as far as I am aware—again comes from looking further back in time. It is the challenge of understanding what are called Heinrich events. During the past 80 millennia, there were six such events. Their imprint is conspicuous in North Atlantic ocean sediment cores, which contain layers of ice-rafted rocky debris originating on the North American or European landmass. The debris must have been carried by huge ice flows that eroded the rocks and then spread out into the ocean as icebergs. While melting, the icebergs dropped the debris to the ocean floor. The ice flows that began the process might have been large-scale versions of the ice streams observed today in the Greenland and Antarctic ice sheets. Lubrication via geothermal heating at the base of the ice might have contributed, but the details remain obscure.

In today's conditions, the Pine Island and Thwaites areas in West Antarctica are of special concern. Observations at those locations point to many complexities, including those already mentioned. The complexities include ice streams and their fracture and friction patterns as well as a possible large-scale instability, which is associated with the fact that the West Antarctic Ice Sheet is grounded below sea level at depths that increase with distance into the ice sheet from its edge. The instability is characterized by seawater intruding farther and deeper under the ice, allowing the ice flow rate to accelerate over a large area. The instability is another example of tipping-point behavior. Some researchers believe that, in the Thwaites area, a tipping point of that kind has already occurred.[12]

About 3 m of sea-level rise over the coming century, shown in figure 2, has been predicted by using improved ice-flow models that allow for hydrofracturing and ice-cliff failure.[15] That prediction is far more than in any intergovernmental climate report so far.

Other possible tipping points have been discussed elsewhere.[9,16] They include runaway deforestation scenarios in the Amazon, for instance, and the melting of methane hydrates or clathrates from ocean sediments and from below melting ice sheets. Another mechanism less often discussed is the carbon-cycle instability studied by Daniel Rothman of MIT, which suddenly decreases the rate at which upper-ocean phytoplankton remove carbon dioxide from the atmosphere.[17]

Weather extremes, whales, and dolphins

Another limitation of climate models is that they underpredict many kinds of devastating weather extremes. Admittedly, a few extremes are represented well in the models. Examples include the heat waves and firestorms of summer 2021 across western parts of Canada and the US and large-scale outbreaks of freezing weather, such as those of February 2021 and December 2022 that reached as far south as Texas, from amplified jet-stream meandering. Most of the extreme behavior, however, depends on scales of fluid motion far smaller than the scales resolvable by climate models.

The simplest and clearest case is cumulonimbus rainstorms and thunderstorms, which can produce devastating flash floods and mudslides. The airflow into cumulonimbus clouds takes place on spatial scales so small that, even with today's computing power, they are barely resolved even in the most computationally expensive local operational forecasting models.

The airflow into a single cumulonimbus cloud, however, is accessible to the simplest of fluid-dynamic intuitions. The cloud is like a tall vacuum cleaner that pulls air from its low-level surroundings. The flow is powered by water vapor—think of it as a weather fuel. Water vapor can reasonably be called weather fuel because of the latent-heat energy released when it condenses. The Clausius–Clapeyron relation says that air can hold around 6–7% more weather fuel for each degree Celsius of temperature rise. So global warming is global fueling.

Other things being equal, a cumulonimbus cloud that happens to be surrounded by more weather fuel will pull the fuel in faster and reach a greater peak intensity sooner. That's a robust and powerful positive feedback mechanism that's capable of producing heavier and more sudden downpours and heavier flash flooding.

> **"Global warming is global fueling."**

As is now well recognized, such extremes of storminess are becoming more frequent and more intense today. Evidence of extremes can also be found in past climates. The most notable example comes from the hothouse climate of the early Eocene epoch. Peak temperatures were reached around 56 million years ago at the Paleocene–Eocene Thermal Maximum. With a far greater supply of weather fuel than today, the same robust feedback makes it likely that some of the storms were more violent and devastating than anything within human experience. Research has shown geological evidence of massive erosion by storm-flood events at that time, for example.

Furthermore, there's an independent line of evidence for storminess that comes from evolutionary biology. The whales, dolphins, and other aquatic mammals that exist today came from land-dwelling ancestors that, according to the fossil record, began taking to the seas around the same time, 56 million years ago.

What could have induced land-dwelling mammals to seek a new habitat and at that particular time? Why did some of them then become fully aquatic in a mere few million years? Selective pressures from extremes of surface storminess can begin to explain those extraordinary evolutionary events. Those events could have begun with hippo-like behavior in which the water was little more than a refuge from the storms. That of course is only a hypothesis. But in my judgment, it's strongly arguable. And today's whales and dolphins are related genetically to today's hippos.

The amplifier metaphor for climate

The uncertainties in climate science and climate-model limitations have long been used by the climate-disinformation industry to proclaim that there is no cause for concern, unless additional pending assessments say otherwise. The foregoing reminds us that those uncertainties and limitations were always reasons for being more concerned, not less. In my recently published book, I discuss the powerful psychological methods used by the disinformation industry that exploit, among other things, language as a conceptual minefield (reference 18, chapter 2). On climate, the book includes a discussion of extreme cyclonic storms and their meteorological complexities, including so-called conveyor belts that carry weather fuel across long distances. Climate-model limitations include an inability to represent the most extreme cyclones accurately, again because of resolution constraints.

Another theme in the book is the idea of an amplifier metaphor for climate. The metaphor emphasizes that some parts of the climate system are more sensitive than others, a point that the disinformation industry has always worked hard to conceal. Even in the scientific community, the point has been obscured sometimes by too much focus on gross energy budgets. What matters is that the system is far more sensitive to human inputs of noncondensing greenhouse gases, such as CO_2 and methane, than it is to human inputs of water vapor. Of course the climate amplifier is highly nonlinear and very noisy, quite unlike an ordinary audio amplifier in that respect.

In its role as weather fuel, water vapor can be seen within the metaphor as a part of the amplifier's power-supply circuitry. The rate at which latent energy in water vapor is exported from the tropics and subtropics, for example, is roughly of the order of one or two petawatts. That dwarfs any human input of water vapor.

By contrast, the noncondensing greenhouse gases can be seen as part of the amplifier's sensitive input circuitry. So when the disinformers say that atmospheric CO_2 is unimportant because there's much less of it than atmospheric water vapor, it's like saying that the input current to an amplifier is unimportant because it's much less than the power-supply current. Furthermore, the CO_2 input signal from fossil-fuel burning can hardly be considered small. Today that input has already pushed atmospheric CO_2 far outside its natural range of variation over the glacial–interglacial cycles of the past 400 millennia.

The natural range is about 100 ppmv (parts per million by volume). That is the parameter against which present and future atmospheric CO_2 changes should be compared. It is one of the most securely known properties of the real climate system, coming from a powerful line of research on Antarctic ice cores.[18] In round numbers, atmospheric CO_2 variations had a peak-to-peak amplitude of 100 ppmv across the huge range of climate conditions that were encountered during the glacial–interglacial cycles. Today's CO_2 value is well over 400 ppmv, which is more than 200 ppmv above the minimum values found in glacial times, when CO_2 was less than 200 ppmv. Atmospheric CO_2 has now increased by more than twice its natural range.

As with the earlier examples of the Antarctic ozone hole and tobacco and lung cancer, there is now reason to hope that the disinformation industry, although still powerful, may have ceased to be the overwhelming political influence that it was a decade ago. As noted in my book, "All three cases show the same pattern: disinformation winning at first, then defeated by a strengthening of the science along with a wave of public concern powered by real events" (reference 18, page 148). Another reason to be hopeful is the new economic reality around energy from renewables and battery storage. They're far cheaper and more reliable than fossil fuels, as demonstrated at scale in South Australia.

Economic forces and public concern may help to counter today's rearguard action by the disinformation industry, which includes the deception that fossil-fuel burning without carbon capture and storage can continue to be promoted and subsidized through so-called "offsets." Reference 16 discusses the scale of that deception. The word "offsets" well illustrates language as a conceptual minefield because it can embody an unconscious assumption that such activities fully compensate for the effects of fossil-fuel burning as they occur, when in reality they only partially compensate and not quickly enough. Younger generations, however, allow some optimism that more and more people will see through such deceptions as the weather extremes ramp up over the coming years.

Many expert colleagues have helped me on climate and paleoclimate research.[17,18] *A foundational influence to my development as a scientist came from my PhD supervisor Francis Patton Bretherton, whose obituary appeared in the March 2022 issue of* PHYSICS TODAY. *Francis was a brilliant lateral thinker and was one of the first scientists to think seriously about the real climate system in its full complexity, as summarized in the well-known "Bretherton diagram."*

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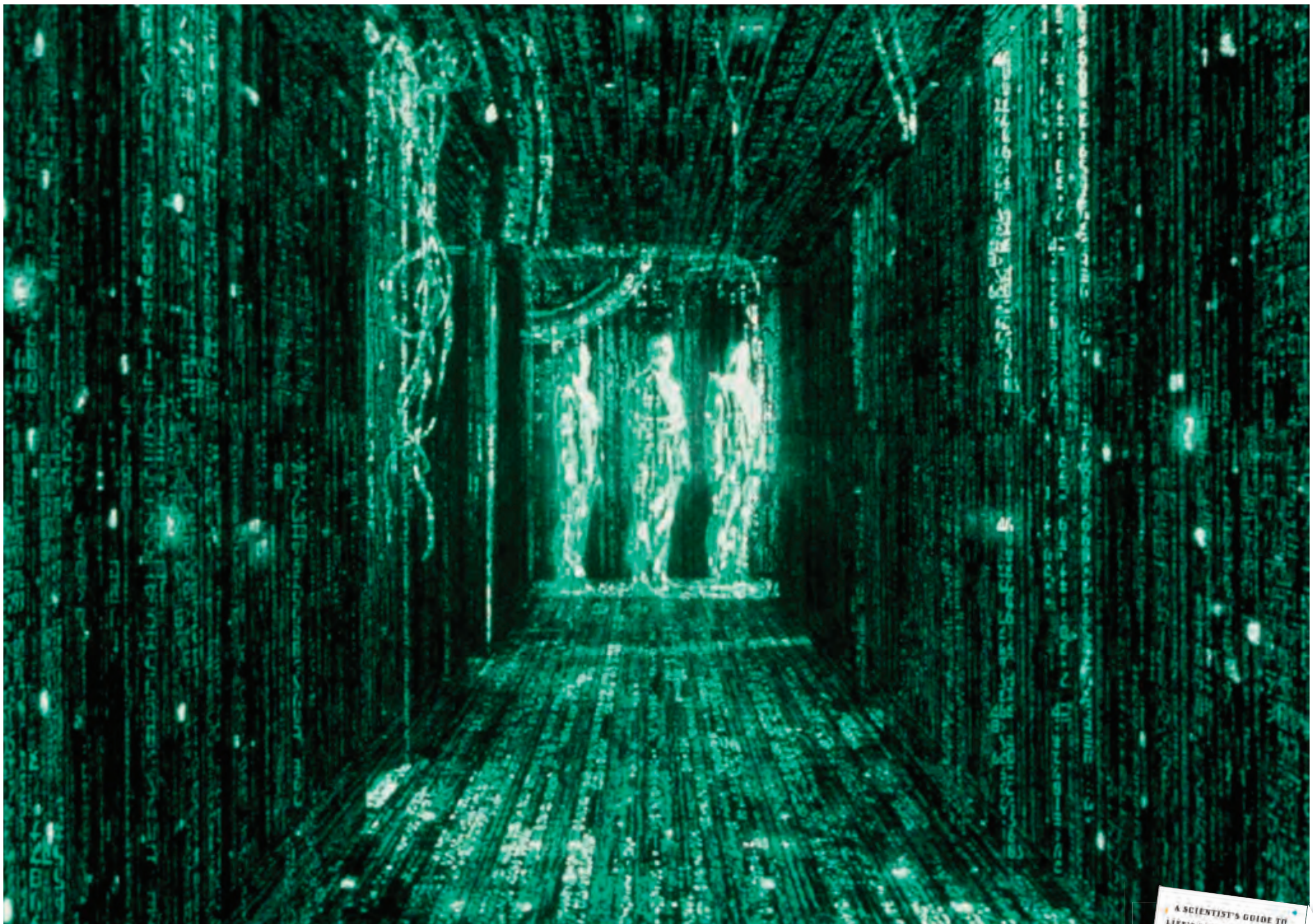

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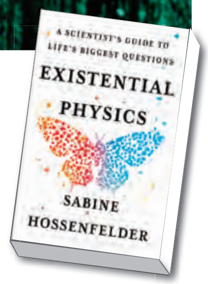
The 1999 film *The Matrix* famously made mainstream the hypothesis that our reality may actually be a simulation constructed by a superintelligence.

A physicist gets philosophical

Existential Physics
A Scientist's Guide to Life's Biggest Questions
Sabine Hossenfelder
Viking, 2022. $28.00



Sabine Hossenfelder's provocative first book, *Lost in Math: How Beauty Leads Physics Astray* (2018), garnered a lot of well-deserved attention for its blunt and largely compelling argument: An overreliance on mathematical elegance and a nonchalance about the want of empirical evidence, she contended, had pointed fundamental physics down a yellow-brick road that led not to the Emerald City but to a fantasy land of speculative alternatives to the standard model, none of which have yet found a toehold on the firm ground of empirical reality.

Although it is aimed at a different audience and engages with a different set of questions, her delightfully provocative new book, *Existential Physics: A Scientist's Guide to Life's Biggest Questions*, is equally blunt. It speaks to a general audience of readers who want to know, for example, whether our best current science sheds any light on such deep and important questions as how the universe began, whether it was designed by God to be a comfy home for humans, whether we humans are part of a simulation constructed by a superintelligence, and whether human intelligence could reside equally well in a machine.

Hossenfelder works hard to be a fair arbiter and to respect the motivations behind those questions. Her most frequent response is that science is neutral, which means that the answers hoped for by some and sometimes boldly proclaimed by others, including eminent scientists like Richard Dawkins and Lawrence Krauss, are at best "ascientific." But when the evidence is clear, Hossenfelder doesn't shy away from declaring that some cherished beliefs are simply ruled out by science. Partly for reasons of style, my favorite example of that latter kind is in her chapter on the existence of free will. After considering the question from a variety of perspectives, she wraps up the discussion of each by repeating a simple mantra: "The future is fixed except for occasional quantum events that we cannot influence."

On only two points would I want to quibble. The first concerns Hossenfelder's discussion of wavefunction reduction, which she introduces in chapter 1, "Does the Past Still Exist?," as one of only two exceptions to the time-reversal invariance of our fundamental dynamical equations (the other is black hole evaporation). Although she acknowledges the long-standing puzzlement over whether measurement is a well-defined concept and whether measurements can therefore play a physically unique role in nature, Hossenfelder nonetheless at first asserts that the question of wavefunction reduction has "largely been answered," suggesting that it is a matter of established fact that the phenomenon really occurs, and defines a measurement as "any interaction that is sufficiently strong or frequent to destroy the quantum behavior of a system."

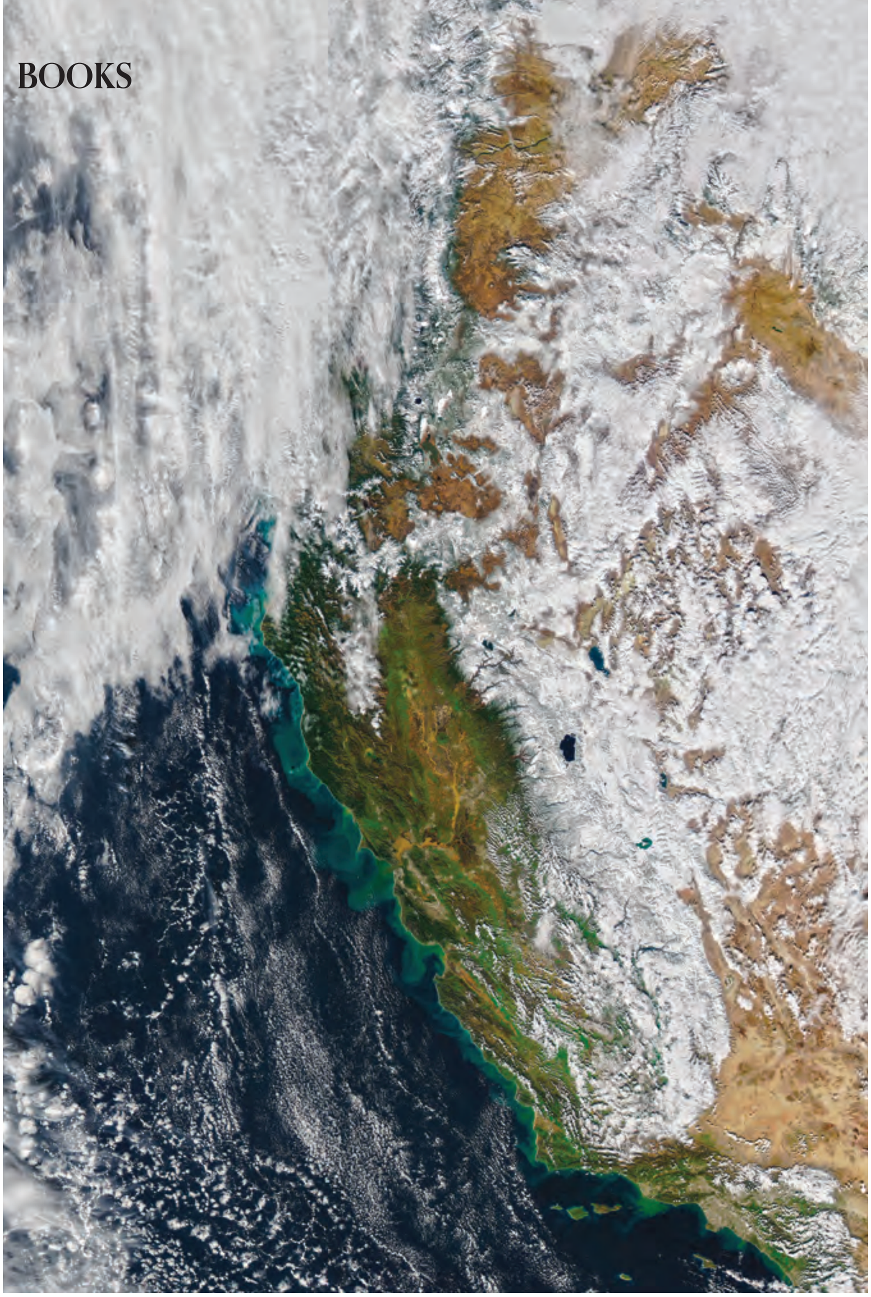
The first problem with that description is that most decoherence theorists would deny that the quantum behavior is destroyed, which it cannot be because the decoherence dynamics is linear, Schrödinger dynamics. Those theorists would argue that in all but a few cases, the quantum behavior is driven so deeply into hiding as not to reappear within the likely lifetime of the universe. The second problem is that two pages later, Hossenfelder writes, "If you don't believe the measurement update is fundamentally correct, that's currently a scientifically valid position to hold." She adds that she herself believes that wavefunction reduction will be replaced by a physical process in a future, underlying theory that will restore determinism and time-reversal symmetry. If so, the question of wavefunction reduction has not "largely been answered."

My second quibble concerns the discussion of reductionism and quantum entanglement in chapter 4, "Are You Just a Bag of Atoms?" On the whole, Hossenfelder's defense of a strong form of ontological reductionism is a good one, and one with which I largely agree. Her main point is that the evidence shows "that things are made of smaller things, and if you know what the small things do, then you can tell what the large things do."

But deep down at the quantum level, that is not so, because when two or more systems become entangled with one another through an interaction, the post-interaction state of the joint system cannot be written as a product of separate states for the subsystems. In other words, $\psi_{12} \neq \psi_1 \otimes \psi_2$. There is no more scientifically well-established example of holism—the idea that the whole is more than the sum of its parts—than that. So when Hossenfelder writes that entanglement "doesn't contradict reductionism," she's wrong. Does that make for a serious problem with the larger argument for reductionism? Does holism extend up the ladder of scale to the macroscopic level? That is a hard and open question. But I am still mainly on Hossenfelder's side.

I do not want to leave a misimpression. I really enjoyed *Existential Physics*, and you will too. It is engaging, informative, and accessible to the nonspecialist. The spirit of frank but open and sympathetic dialogue with people who might be discomfited by what science is teaching us should stand as a model for other scientists who sincerely want to make their science relevant to the concerns of a broader public.

Don Howard
University of Notre Dame
Notre Dame, Indiana



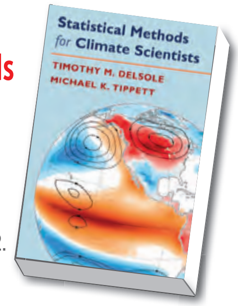
JOSHUA STEVENS/NASA EARTH OBSERVATORY

A satellite image of the western US taken 17 January 2023, after a month of atmospheric rivers battered the area. The swirls of sediment off the coast and extensive snowpack in the Sierra Nevada are evidence of the tremendous amount of precipitation.

A climatologist's introduction to data analysis tools

Statistical Methods for Climate Scientists

Timothy M. DelSole and Michael K. Tippett
Cambridge U. Press, 2022. $69.99



Asked to define climate, most people—including many physical scientists!—give confused answers. A typical reply would likely conflate climate with weather. A slightly more sophisticated response might mention how Earth's mean temperature is increasing. A better answer would be that climate is the statistics of weather, which echoes Robert Heinlein's quip, "Climate is what we expect, weather is what we get." In reality, there is no sharp distinction between climate and weather: The seasonal cycle is just one example of an oscillation that occurs at time scales between the two.

In addition to the behavior of the lower atmosphere, climate also deals with the oceans, the upper atmosphere, Earth's icy regions, and the biosphere. Statistics of interest to climate scientists include not only mean temperatures, variances, and extreme events but also spatiotemporal patterns, which are sometimes called teleconnections. The influence of the El Niño–Southern Oscillation on weather around the globe is the best known and most important teleconnection, but there are many others.

Students entering the field of climate science need to get up to speed quickly with the statistical tools commonly used in the discipline. They are typically familiar with some of the methods, but others, like extreme-value theory and data assimilation, are likely new, and budding climate scientists have typically needed to consult many different texts to learn about them. In *Statistical Methods for Climate Scientists*, Timothy DelSole and Michael Tippett aim to streamline students' mathematical training by collecting the most important methods into a single textbook. Taking all their examples from the climate system, the authors include intuitive explanations, helpful figures, and formal proofs, and they cover some advanced topics.

DelSole is a professor of atmospheric, oceanic, and Earth sciences at George Mason University; is well known for his work in geophysical fluid dynamics on such topics as wave instabilities and stochastic modeling; and is the former co-chief editor of the *Journal of Climate*. Tippett is an associate professor of applied physics and applied mathematics at Columbia University and focuses his research on the El Niño–Southern Oscillation and extreme weather phenomena. The book is based on climate-statistics courses they taught for many years, and it includes insights they gained from "flipping" the format of the class: Instead of lecturing, they had students read chapters and submit questions beforehand and devoted instructional time to answering the submissions.

DelSole and Tippett begin the book with an overview of basic concepts in statistics. Next comes hypothesis testing, which is also a topic most students will be familiar with. But by focusing on the climate system, the authors present the ideas from a fresh perspective. They then turn to time-series analysis, power spectra, and model selection.

The second half of the book is largely concerned with methods to effectively reduce the dimensionality of a system. It's an appropriate topic because the climate is a system with nearly an infinite number of degrees of freedom. One chapter is devoted to principle-component analysis, which is perhaps the mostly widely used approach to reducing dimensionality. Subsequent chapters explore related methods, such as canonical-correlation analysis. Chapters on extreme-value theory and data assimilation round out the book.

Statistical Methods for Climate Scientists does have some weaknesses. Power-spectra estimation is given a rather cursory treatment despite its importance to climate science and to many other fields. That means readers will need to look elsewhere for information about different choices for tapering windows. And it is rather surprising that machine learning receives no attention given its rapidly growing importance to climate science. The index also could be more comprehensive.

Perhaps more curiously, DelSole and Tippett chose not to supply code or pseudo-code in the book even though a computer is required to reproduce nearly every example they discuss. The authors argue in the preface that no code was included because it is essential for students to write their own code instead of using existing software packages so that they can more deeply understand what they are doing. I wholeheartedly agree with DelSole and Tippett, but readers could benefit from some guidance.

Those weaknesses are more than compensated for by the pedagogical value of bringing together disparate methods of statistics into one volume. As more climate scientists venture into such subtle problems as whether to attribute extreme events like prolonged heat waves to climate change, the critical statistical-thinking skills fostered in *Statistical Methods for Climate Scientists* will be of increasing importance.

Brad Marston
Brown University
Providence, Rhode Island

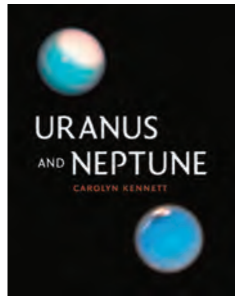
Severance

Dan Erickson, creator
Apple TV+, 2022

Can't stop thinking about work on the weekend? What if you could permanently bifurcate yourself so that your work life never impinged on your leisure self? The Apple TV+ series *Severance* envisions such a world. A mysterious corporation, Lumon Industries, requires certain employees to undergo the titular, irreversible procedure. Situated on Lumon's "severed floor," they have no idea what they work on—or what their outside selves are like. Mark Scout, known at work only as Mark S., originally took a job on the severed floor of Lumon to hide from grief after losing his wife in a tragic accident. But when a new employee, Helly R., starts asking questions and tries to quit her job, Mark begins to question his decision. *Severance*'s strict devotion to the rules of its universe add gravitas to this taut thriller. —RD

Uranus and Neptune

Carolyn Kennett
Reaktion Books, 2022. $40.00



Until some three decades ago, not much was known about the two outermost planets in our solar system. That changed with the *Voyager 2* mission, which conducted flybys of Uranus in 1986 and Neptune in 1989. In her recent book, the astronomer Carolyn Kennett provides a comprehensive introduction to both of those distant worlds. She discusses their discovery and origins, *Voyager 2*'s flybys, and observations made from space- and ground-based telescopes. Written for a general audience, the text is nontechnical and illustrated with more than 100 images. —CC

The One

How an Ancient Idea Holds the Future of Physics

Heinrich Päs
Basic Books, 2023. $32.00

The key to understanding the universe is to consider it as one unified whole rather than decompose it into increasingly smaller particles, according to Heinrich Päs, a professor of theoretical physics. The philosophy of monism is not new; it dates back some 3000 years. In *The One*, Päs presents the history and science of monism and explores how it can be applied to quantum mechanics and the quest for a theory of everything. Tackling difficult philosophical ideas and scientific concepts, such as quantum entanglement and decoherence, *The One* is a dense and challenging read. —CC

Astronomy Minute

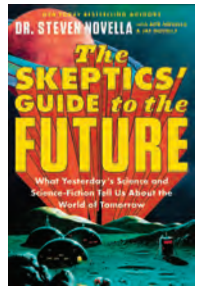
Ata Sarajedini, host
2020–

In this ongoing podcast, Ata Sarajedini, a professor at Florida Atlantic University, provides bite-sized introductions to various topics in astronomy. Episodes focus on celestial bodies, such as neutron stars, spiral nebulae, and the local group of galaxies; astronomical theories like relativity and the hypothetical Big Crunch; and observatories, including the *James Webb Space Telescope*. Although Sarajedini sometimes exceeds the titular minute—some episodes clock in at two and a half minutes!—*Astronomy Minute* is refreshing in its brevity in an era when the podcast sector has become dominated by longer-form content. —RD

The Skeptics' Guide to the Future

What Yesterday's Science and Science-Fiction Tell Us About the World of Tomorrow

Steven Novella
Grand Central, 2022. $30.00



Where are the flying cars, Moon settlements, and robot servants that have been described in so many science-fiction books and movies? In *The Skeptics' Guide to the Future*, the author and clinical neurologist Steven Novella tackles the question of why we're so bad at predicting the future and offers advice on how to do better. Novella, host of the popular podcast *The Skeptics' Guide to the Universe*, applies the critical thinking, logic, and scientific expertise that he is known for to examine current technologies—such as genetic manipulation, robotics, and virtual reality—and make his own predictions on what the future holds. —CC PT

NEW PRODUCTS

Focus on photonics, spectroscopy, and spectrometry

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

Andreas Mandelis

High-power CW laser

Hübner Photonics has released a higher-power model of the Cobolt Twist 457 nm laser from the 05-01 Series platform. Because it delivers up to 300 mW of single-frequency CW output power, the Cobolt Twist is suitable for demanding applications in holography. The 05-01 Series diode-pumped lasers operate at a fixed wavelength between 320 nm and 1064 nm. Single-frequency operation provides an ultranarrow spectral linewidth of less than 1 MHz, a long coherence length of greater than 100 m, and excellent spectral purity. The lasers offer a high-quality TEM_{00} beam, low noise of less than 0.1% rms, and wavelength stability of less than 1 pm over a temperature range of ±2 °C and duration of 8 h. Because all the control electronics are contained in the laser head, the lasers are compact and do not need an external controller. Besides holography, they can be used for interferometry, Raman spectroscopy, optical tweezers, superresolution microscopy, and laser Doppler velocimetry. ***Hübner Photonics Inc**, 2635 N 1st St, Ste 202, San Jose, CA 95134, https://hubner-photonics.com*

Optical photothermal IR spectroscopy

The mIRage-LS IR multimodal microscope and spectroscopy system from Photothermal Spectroscopy combines simultaneous Raman and colocated fluorescence microscopy with submicron IR in a single platform. In addition, the company says new developments in its optical photothermal IR (O-PTIR) spectroscopy technique have pushed the IR spatial resolution to less than 500 nm for life-sciences applications. According to the company, the integrated platform uniquely combines the benefits of fluorescence microscopy to support fast, easy targeting of molecular features of interest with submicron-IR spectroscopy to characterize the molecular structure of biomolecular features, including subcellular and tissue applications. Besides life-sciences applications, the mIRage-LS system and O-PTIR technique are suitable for research in microplastics and polymers. ***Photothermal Spectroscopy Corp**, 325 Chapala St, Santa Barbara, CA 93101, www.photothermal.com*

Rotary vane pump for mass spectrometry

Pfeiffer Vacuum has introduced what it says is the first rotary vane pump for mass spectrometry (MS) that has a hermetically sealed pump housing. The SmartVane serves as a backing pump for inductively coupled plasma MS and liquid chromatography–MS for applications in environmental, food, pharmaceutical, and clinical analytics. The vacuum pump is designed to prevent contamination by ensuring that no oil leaks occur. The integrated motor does not require a conventional seal, which means it needs less maintenance. With its typical operating pressure of less than 10 hPa, the SmartVane is quieter than other pumps used for this type of application, according to the company. Its compact design makes it easy to incorporate in existing systems. The energy-efficient interior-permanent-magnet motor with standby function reduces the pump's operating costs and carbon dioxide footprint. ***Pfeiffer Vacuum Inc**, 24 Trafalgar Sq, Nashua, NH 03063, www.pfeiffer-vacuum.com*

Pulsed, broadly tunable fiber laser

The SuperK Chromatune pulsed fiber laser from NKT Photonics offers gap-free tuning from 400 nm to 1000 nm and a constant output power of 1 mW. The reliable fiber laser is suitable for applications such as spectroscopy, microscopy, optical characterization, fluorescence and lifetime imaging, and plasmonics and metamaterials research. It is designed to be easy to use, but in advanced mode, users can change the linewidth, increase the power in different wavelength ranges, and automate wavelength sweeps and other functionalities. The laser runs at quasi-CW MHz repetition rates as standard, but that can be changed by users studying lifetime phenomena. Everything is controlled by an intuitive software interface, but a free software development kit allows for additional control or integration. ***NKT Photonics Inc**, 23 Drydock Ave, Boston, MA 02210, www.nktphotonics.com*

Rugged UV CMOS camera

The Hawk Indigo camera from Raptor Photonics uses a next-generation ⅔-inch CMOS sensor that enables high UV sensitivity and high quantum efficiency of 36% at 250 nm. With a pixel size of 2.74 μm, the camera achieves a resolution of 8.1 MP. It offers global-shutter, progressive-scan technology to deliver real-time, lag-free images at 15 Hz full frame through a CameraLink interface. The rugged Hawk Indigo can be used in harsh environments; it works from −20 °C to 55 °C but can be equipped to handle more extreme temperatures. Suitable for integration into industrial applications, it offers high precision in the hyperspectral imaging of transparent materials, such as plastic and PET, and semiconductors; wafer and mask inspection; combustion imaging; and high-voltage diagnostics. ***Raptor Photonics Ltd***, *Willowbank Business Park, Larne, Co Antrim BT40 2SF, Northern Ireland, UK, www.raptorphotonics.com*

SWIR camera

The pco.pixelfly 1.3 shortwave-IR (SWIR) camera from Excelitas offers high performance in machine vision due to its indium gallium arsenide image sensor. The Sony model IMX990 sensor is highly sensitive in the shortwave-IR, near-IR, and visible ranges, with sensitivity up to 90% in the shortwave-IR region. The 5 μm × 5 μm pixels enable the use of small-magnification optics in microscopy. A low dark current facilitates long exposure times with excellent quantum efficiency of greater than 90%. The pco.pixelfly 1.3 SWIR camera is suitable for various applications, including life-sciences research; medical use such as in surgical microscopes, *in vivo* imaging, and *in vivo* and intravital microscopy; smart farming and food-processing quality control; pharmaceutical and other product-packaging industries; and waste sorting. ***Excelitas Technologies Corp***, *200 West St, 4th Fl E, Waltham, MA 02451, www.excelitas.com*

Compact near-IR hyperspectral imagers

Resonon has unveiled two hyperspectral imagers that operate in the near-IR range (925–1700 nm): the Pika IR-L and Pika IR-L+. Compared with the current generation of near-IR imagers, they are smaller, are nearly three times as light, and offer improved spectral resolution, according to Resonon. Their near-IR spectral range is particularly suitable for delineating land and water boundaries, imaging through low clouds and smoke, classifying various minerals and vegetation covers, and contrasting dry and wet soils. Applications for the hyperspectral imagers include scientific research, survey work, and precision agriculture. Airborne systems can be acquired as a kit that includes a data acquisition unit; a GPS receiver and inertial measurement unit; georectification, postprocessing, and analytical software; a system mount for unmanned or piloted aircraft; radiometric calibration, including a target; and a rugged travel case. ***Resonon Inc***, *123 Commercial Dr, Bozeman, MT 59715, https://resonon.com*

Fast, thermally stable spectrometer

A new high-resolution, configurable spectrometer from Ocean Insight provides rapid acquisition speed and high thermal stability for applications ranging from plasma monitoring to pharmaceuticals analysis. The Ocean HR2 spectrometers are compact and robust, with integration times as fast as 1 μs. Thermal wavelength drift of just 0.06 pixels/°C helps ensure reliable spectral performance as temperatures change. Ocean HR2 models cover various wavelength ranges within about 190–1150 nm, with a choice of slit widths to help users manage throughput and optical resolution. The new spectrometers come with the OceanDirect cross-platform software-developers kit, which includes an application programming interface. It lets users optimize spectrometer performance, access critical data for analysis, and enable the High Speed Averaging Mode. That function, available with newer-model Ocean Insight spectrometers, can significantly improve the signal-to-noise ratio. ***Ocean Insight***, *3500 Quadrangle Blvd, Orlando, FL 32817, www.oceaninsight.com*

Microplastics analysis system

Agilent has enhanced its 8700 LDIR (laser direct IR) chemical-imaging system for the analysis of microplastics in environmental samples. The improved package includes Clarity 1.5 software—an upgrade that advances the speed of analysis; enhances spectral acquisition, transformation, and library matching; and provides automated workflows for direct analysis of microplastics on a filter substrate. A redesigned sample holder allows the on-filter sample to be presented to the instrument more easily and consistently. According to Agilent, since the 8700 LDIR brought high-speed analysis and ease of use to IR spectroscopy, it has emerged as the benchmark technique for the analysis of microplastics particles; the development of on-filter analysis for the platform further increases speed and throughput. Increased testing volumes will help facilitate a greater understanding of the extent of microplastics contamination and the development of appropriate environmental standards and regulations. ***Agilent Technologies Inc***, *5301 Stevens Creek Blvd, Santa Clara, CA 95051, www.agilent.com*

IR–AFM spectrometer for nanometrology

The Park NX-IR R300 system integrates advanced IR spectroscopy of photo-induced force microscopy (PIFM) and the Park NX20 300 mm atomic force microscopy (AFM) platform to deliver accurate analysis of the chemical composition of materials. It provides chemical property information and mechanical and topographical data for semiconductor research, failure analysis, and defect characterization on semiconductor wafers up to 300 mm in diameter. According to Park Systems, it does so at an unprecedentedly high nanoresolution. The PIFM spectroscopy provides chemical identification with a spatial resolution of less than 10 nm. It uses a noncontact technique that offers damage-free spectroscopy probing and high resolution and accuracy throughout scans. By providing spectroscopy information at varying depths, the Park NX-IR R300 can offer valuable insight into sample composition. ***Park Systems Inc***, *3040 Olcott St, Santa Clara, CA 95054, https://parksystems.com*

Mass spectrometers for high-mass analysis

Hiden now offers its Cluster series of quadrupole mass spectrometry (MS) systems and components for monitoring high-mass species in gas, residual gas, plasma, and surface analysis. The series was developed particularly to perform the high-mass analysis required to study nanoparticles. Multiple sampling configurations are offered to suit research requirements: Systems include the 9 mm EPIC and the 20 mm DLS-20 for the analysis of species up to 20 000 amu. Components include quadrupole assemblies with pole diameters of 9 mm and 20 mm and high-power RF; they operate at optimum frequency to accommodate the high-mass transmission required in cluster analysis. The series features precision Tri-Filter quadrupole assemblies and an optional 90° ion-beam deflector. For pulsed-deposition processes, time-resolved measurements are offered to a resolution of 50 ns. Applications include nanoparticle, molecular-beam, and precursor and contaminant analysis for high-mass species. ***Hiden Analytical Inc****, 37699 Schoolcraft Rd, Livonia, MI 48150, www.hidenanalytical.com*

Scientific CMOS cameras for life-sciences research

Andor Technology, an Oxford Instruments company, has upgraded its Zyla sCMOS camera series for life-sciences research with its ZL41 Cell 4.2 and ZL41 Cell 5.5. Superseding the Zyla 4.2 Plus, the Zyla ZL41 Cell 4.2 offers a maximum quantum efficiency (QE) of 82% and subelectron read noise. It is suitable for applications that benefit from optimal sensitivity and speed, such as calcium imaging and light-sheet and single-molecule-localization microscopy. The broad QE profile, highly optimized to a wide range of common fluorophores, provides excellent coverage of the visible and near-IR wavelength range. The high sensitivity allows for shorter exposure times, faster frame rates, and reduced phototoxicity. With the company's SRRF-Stream+ technology, the ZL41 Cell 4.2 can cost-efficiently transform a normal fluorescence microscope into a super-resolution microscope. Replacing the Zyla 5.5, the ZL41 Cell 5.5 offers a sensor with a 22 mm format and a QE of 64%. It also features a global-shutter mode suitable for snapshot imaging of fast-moving objects without temporal distortion. ***Andor Technology Ltd****, 7 Millennium Way, Springvale Business Park, Belfast BT12 7AL, UK, https://andor.oxinst.com*

IR Raman microscope

According to Shimadzu, its AIRsight IR Raman microscope is the world's only instrument that lets users perform both IR spectroscopy and Raman spectroscopy; combining the two analytical techniques provides complementary information. When connected with a Fourier-transform IR spectrophotometer, the AIRsight can acquire IR and Raman spectra from the same position in a very small section. Compared with a setup in which both an IR and a Raman microscope are installed, the AIRsight requires less space, and operability is enhanced since the same software can be used to control both techniques. The AIRsight is effective for analyzing aqueous solutions, inorganic substances, and microscopic samples, which are difficult to analyze using just an IR microscope. Applications include the analysis of trace contaminants; research into microplastics; and quality control in the chemical, electrical, electronic, and transportation-equipment fields. ***Shimadzu Scientific Instruments Inc****, 7102 Riverwood Dr, Columbia, MD 21046, www.shimadzu.com* PT

Lev Petrovich Pitaevskii

The extraordinary theoretical physicist Lev Petrovich Pitaevskii died on 23 August 2022 in Rovereto, Italy, from the consequences of a fall, compounded by age-related health issues. He was known across the physics community for his encyclopedic scientific knowledge; important discoveries in low-temperature physics; contributions to the understanding of superfluidity in helium-3 and helium-4; and the theories of Bose–Einstein condensates, van der Waals forces, and low-density ionospheric plasma. Pitaevskii will also be remembered as a coauthor, with Lev Landau and Evgeny Lifshitz, of the world-famous 10-volume series *Course of Theoretical Physics*.

Pitaevskii was born on 18 January 1933 in the ancient Russian town of Saratov on the Volga River. He possessed an inquisitive mind from a young age and went to study physics at Saratov State University, where his father was a professor of economics. While a student there, he passed the entire set of nine "theoretical minimum" exams designed by Landau—only 43 theoretical physicists in the Soviet Union succeeded in passing them. Landau was duly impressed and, after Pitaevskii received his degree in 1955, offered him a highly coveted place as a graduate student in his research group at the Institute for Physical Problems in Moscow. He earned his PhD in 1958, supervised by Lifshitz, for his work on the theory of superfluid ^{4}He.

Upon Pitaevskii's graduation, both Landau and Pyotr Kapitsa wanted to hire him. But he lacked a Moscow residence permit and instead took a position at the Institute of Terrestrial Magnetism, Ionosphere, and Radio Wave Propagation in Troitsk, some 30 miles south of Moscow. Eventually, in 1960, Kapitsa solved Pitaevskii's registration problem in a most inventive way. At a banquet at the Kremlin for Soviet elites held by Nikita Khrushchev, Kapitsa remarked that a brilliant young scientist, akin to the legendary polymath Mikhail Lomonosov, could not serve science for lack of a Moscow registration permit. Khrushchev immediately gave orders to grant one, and Kapitsa was able to hire Pitaevskii at the Institute for Physical Problems. Pitaevskii was head of its theoretical department from 1988 to 1992, taking the post once held by Landau, Ilya Lifshitz, and Yakov Zel'dovich.

In 1958 Pitaevskii and Vitaly Ginzburg constructed a semiphenomenological theory of superfluidity in the vicinity of the phase transition. A year later Pitaevskii predicted the transition of ^{3}He into a superfluid state at very low temperatures due to a Cooper-coupling mechanism arising from the van der Waals interaction. He also investigated threshold phenomena in the excitation spectrum of superfluid ^{4}He.

Pitaevskii's best-known scientific contribution is the Gross–Pitaevskii equation, which governs the motion of the superfluid component of a weakly interacting Bose–Einstein gas. It was obtained independently by Eugene Gross and by Pitaevskii in 1961. Pitaevskii also collaborated with Evgeny Lifshitz and Igor Dzyaloshinskii on the theory of van der Waals forces in dispersive media. In a widely recognized series of publications, he and Alexander Gurevich developed a theory of collisionless low-density ionospheric plasma to better understand a satellite's orbit and stability.

After Landau's death in 1968, Evgeny Lifshitz and Pitaevskii wrote the last two volumes and completed the unique *Course of Theoretical Physics*. After Lifshitz died in 1985, Pitaevskii guided the project by keeping new editions of the volumes up to date. The series is a pride of Russian science and widely recognized as a unique synthesis of classical, relativistic, and quantum physics.

Pitaevskii first visited the University of Trento in Italy in 1989 and started a collaboration on superfluidity in helium clusters. After the first experimental realization of Bose–Einstein condensation in ultracold atoms in 1995, Pitaevskii and the Trento team focused their attention on the emerging field of ultracold atomic gases, where the Gross–Pitaevskii equation turned out to be a fundamental and successful tool.

After spending a few years at the Technion–Israel Institute of Technology, in 1998 Pitaevskii accepted a permanent position in Trento. He and his wife settled in a small apartment near the physics department, with a beautiful view of the Dolomites. He experienced a burst of productivity in those years in Italy. In 1999 Pitaevskii and the Trento team published the *Review of Modern Physics* article "Theory of Bose–Einstein condensation in trapped gases," one of the most cited papers in the field. The scientific collaborations of Pitaevskii and the Trento team continued to flourish, resulting in the publication of around 100 papers.

Lev Petrovich Pitaevskii

Among Pitaevskii's awards were the 1980 Landau Prize from the Soviet Academy of Sciences, the 2008 Landau Gold Medal from the Russian Academy of Sciences, the 2018 Enrico Fermi Prize from the Italian Physical Society, and the 2021 Lars Onsager Prize from the American Physical Society. After his death, the Trento Center on Bose–Einstein Condensation was renamed the Pitaevskii Center on Bose–Einstein Condensation.

Despite his busy academic schedule, Pitaevskii always had time for literature and music. Having had the good fortune to know him, we will miss his kindness, charisma, and readiness to help young scientists.

We thank Marina Sakharov-Liberman for her contributions to this obituary.

Michael A. Liberman
Nordic Institute for Theoretical Physics
Stockholm, Sweden
Valery L. Pokrovsky
Texas A&M University
College Station
Sandro Stringari
Pitaevskii Center on Bose–Einstein Condensation
Trento, Italy PT

Aled Roberts is a materials engineer and founder of DeakinBio, a UK startup that develops sustainable alternatives to concrete and ceramic materials.

Building on Mars with human blood and urine

Aled D. Roberts

Researchers look to the human body as a feasible resource for construction materials beyond Earth.

Mars has no significant geomagnetic field to deflect harmful solar flares or cosmic rays. For NASA to have any sustained human presence there, it will need to protect inhabitants from deadly radiation exposure. The most sought after real estate is likely to be subterranean caves, which provide a natural buffer against the harsh conditions. But if Mars's explorers land in spots far from such rocky hollows, their protection will need to come from habitats with meter-thick walls and ceilings that reduce radiation exposure to tolerable levels. (See the Quick Study by Larry Townsend, Physics Today, March 2020, page 66.)

Obtaining bulk material for that purpose is a challenge. With no infrastructure or economy on the red planet, it won't be as simple as popping down to a local builders' supply store for a few bags of cement or pile of bricks. Everything used on Mars will have to be either shipped from Earth or produced locally.

It currently costs about $5000 to ship a single brick's worth of material (2.27 kg) into low Earth orbit and significantly more to transport and land it safely on Mars's surface. Given that many tons of material will be needed to build even a minimal habitat to protect humans from deadly radiation, the only feasible option is to use resources available on-site—a concept known as *in situ* resource utilization.

Living off the land

The geological and atmospheric conditions on Mars have eroded much of its surface into an extremely fine dust known as regolith. To resist erosion from Martian dust storms, regolith will need to be consolidated into a sturdy material for use in construction and radiation shielding. Researchers have proposed several technologies to stabilize the regolith into monolithic materials, but most have serious limitations.

One proposed method is to melt the regolith and cast it into blocks or deposit it through a 3D-printer nozzle. Although the method would produce a strong and stable material, it would also require tremendous quantities of energy. That in turn would necessitate bringing substantially more energy-generation equipment, such as solar panels, on a mission to Mars. And the additional mass would largely offset the benefit of *in situ* resource utilization in the first place.

Another option is to produce a Martian equivalent of terrestrial concrete. Rovers have identified deposits of gypsum, basanite, and carbonate minerals, which could be mined, purified, and processed into cement and combined with regolith to produce concrete. (See "Martian concrete could be tough stuff," Physics Today online, 10 November 2022.) That method would constrain the placement of habitats in regions with such mineral deposits, and the need for heavy mining equipment would add to the mission's cost and complexity.

Synthetic polymers produced from constituents of the Martian atmosphere—carbon dioxide, mainly—could serve as binders and turn loose regolith into a solid composite. But that technology is still in its infancy and would likely consume large quantities of energy and another scarce Martian resource—water. Even so, if successfully developed, the production of plastics from thin air would be a useful technology and worth pursuing for benefits on Earth as well as in space.

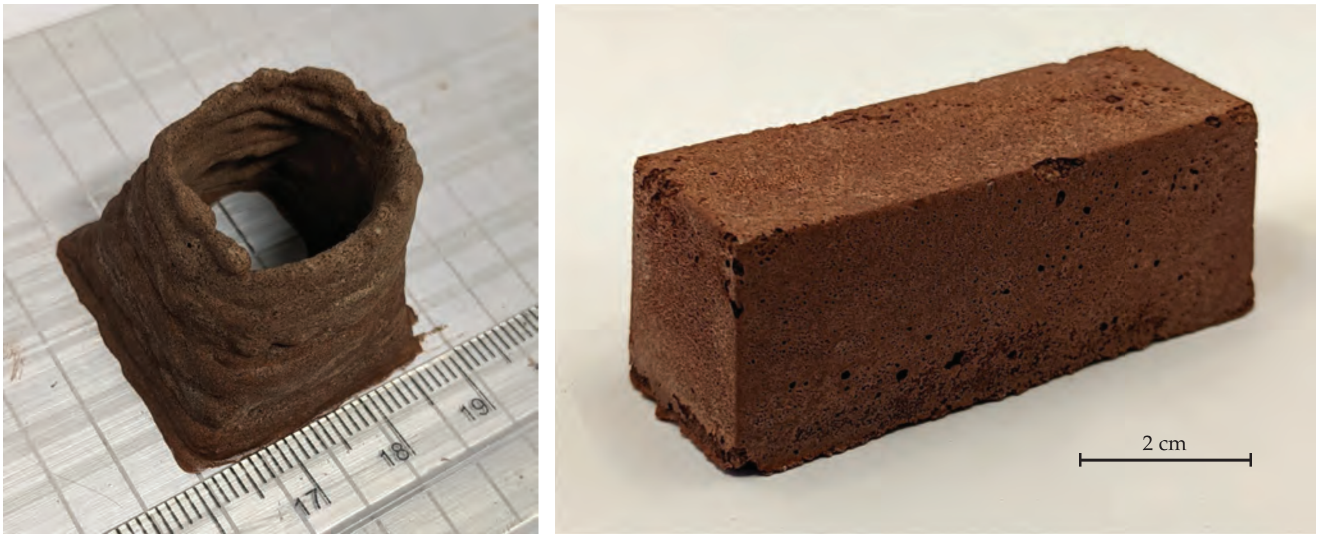
Polymeric binders can also be produced through biotechnological routes. Historically, proteins and carbohydrates served as adhesives and binders before the development of synthetic alternatives—an improvement that saved many horses a one-way trip to the glue factory. In recent times engineers have not only elucidated the structure–function relationships of proteins and other biopolymers but also developed toolkits to produce tailored proteins synthetically. Some have even suggested that bioreactors could be taken to Mars to produce biopolymers from engineered microorganisms, such as photosynthetic algae, that could be sustained by CO_2, nitrogen, water, sunlight, and trace minerals on Mars.

Although such biotechnological methods could significantly reduce launch mass, and thus mission cost, downsides abound: a low yield of bioreactors—typically less than 10 grams per liter per day—along with a lot of waste and water usage. The mass and volume of the bioreactors and the need for spare parts and backup systems for redundancy would also be a significant contribution to a launch's mass and cost, despite the prospect of long-term benefits.

Is the answer inside us?

Aside from regolith, atmospheric gases, and an extremely limited amount of water, one resource that we know will be available on a crewed mission to Mars is the crew themselves. Surprisingly, the concept of humans as an *in situ* resource has gone largely unnoticed by the scientific community. To redress the oversight, my colleagues and I at the University of Manchester decided to investigate.

We were developing new glues based on synthetic spider silk that adheres to glass. As a control experiment to establish a baseline stickiness, we decided to test a protein known as bovine serum albumin (BSA). The main protein in cow blood plasma, BSA is commonly used by biologists and biochemists in control experiments. To our surprise, BSA was able to stick



HUMAN BEINGS naturally produce serum albumin and urea. The first can be extracted from their blood plasma, and the second from their urine, sweat, and tears. Combined with Martian regolith, those ingredients can make a biocomposite material termed AstroCrete—pictured as a 3D-printed structure **(left)** and a brick **(right)**—that's stronger than terrestrial concrete.

glasses together extremely well—much better than our carefully engineered spider silk proteins and comparable to commercially made adhesives.

That finding got us digging around in the scientific literature. Recent research studies had little to say. The sticky properties of BSA appeared to have been overlooked despite the protein's common use. A deeper search, however, revealed that animal blood had been used historically as an adhesive and binder and could even produce some remarkably beautiful materials, such as Bois Durci—a substitute for wood, leather, bone, metal, and hard plastic.

If BSA can bond glass together so well, we reasoned, shouldn't it also be able to adhere particles of sand, since glass and sand are both made of silicon dioxide? A quick experiment with some waste sand from the lab confirmed the suspicion. And if regolith on the Moon and Mars is also mainly silicon dioxide, shouldn't its powdery particles be able to stick together too? Transporting cows to Mars would hardly be practical. But humans will necessarily be aboard any crewed mission, so why not instead use the human equivalent, human serum albumin? The protein is abundant in human blood plasma at a concentration of up to 50 g/L in healthy adults. And it can be extracted safely without removing the precious red and white blood cells from the body.

A few tests confirmed the proof of principle: The protein from human blood can transform lunar or Martian regolith into a concrete-like biocomposite material. We then set out to find out how and why it does so. After probing the bonding mechanism with some spectroscopy, we determined that the protein unfolds from a tightly bound globular state into an extended state where it interacts strongly with adjacent proteins and surfaces. Curiously, that's also how spider silk behaves.

To test our hypothesized mechanism, we added a substance known as urea to the formulation. Because urea is commonly used in biochemistry labs to unfold and destabilize proteins, we expected that the strength of our materials would drop with its inclusion. To our surprise, however, adding the urea actually makes the materials up to three times as strong. Conveniently, urea is the second main component of human urine, after water. We already know that astronauts will have to extract and recycle water from their urine on any space habitat—indeed, it's a common practice on the International Space Station—so they would have a ready supply of urea on any mission.

Tests done on the resulting biocomposite material, which we named AstroCrete and made from simulated Mars dust, yielded compressive strengths as high as 11.9 MPa. And when the experiments were performed on AstroCrete made from simulated Moon dust, the materials were even stronger—up to 39.7 MPa. By comparison, ordinary concrete typically has a compressive strength of 20–41 MPa. Considering that gravity on Mars and the Moon is low—just 38% and 16.6%, respectively, of that on Earth's surface—the AstroCrete is strong enough for most practical applications. It's certainly strong enough to serve as a radiation-shielding material.

According to our calculations, for a mission to Mars, a total of 550 kg of high-strength AstroCrete could be produced over 72 weeks with a six-person crew. That's too little to make the required quantity of radiation-shielding material to construct a Martian habitat. But if it's used as a mortar for sandbags or heat-fused regolith bricks like the one shown in the figure, calculations suggest that it's plausible for each crew member to produce enough additional habitat construction materials to support an additional future crew member. That would allow potentially rapid growth of an early Martian colony.

Additional resources

▶ M. Z. Naser, "Extraterrestrial construction materials," *Prog. Mater. Sci.* **105,** 100577 (2019).

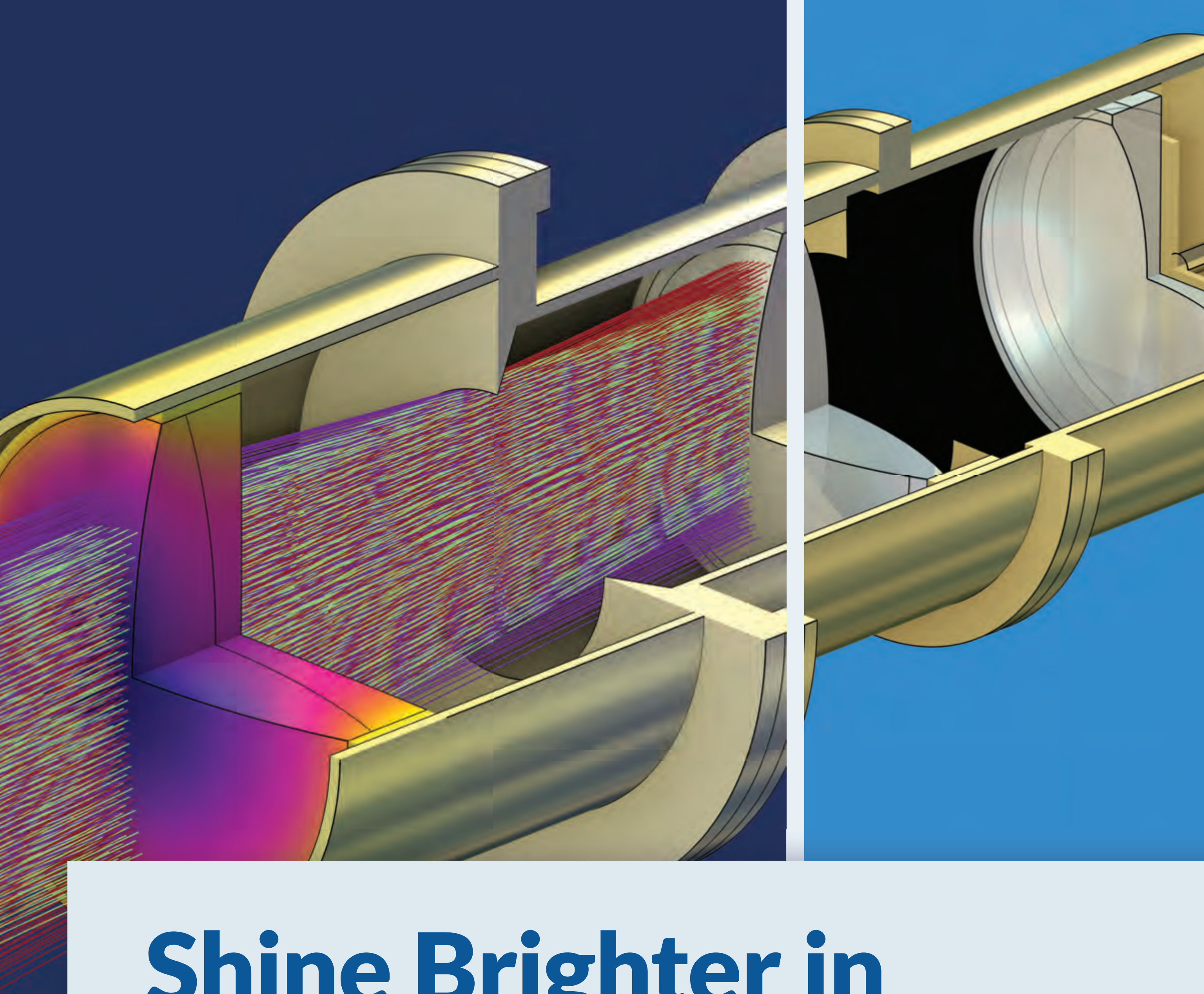
▶ S. N. Nangle et al., "The case for biotech on Mars," *Nat. Biotechnol.* **38**, 401 (2020).

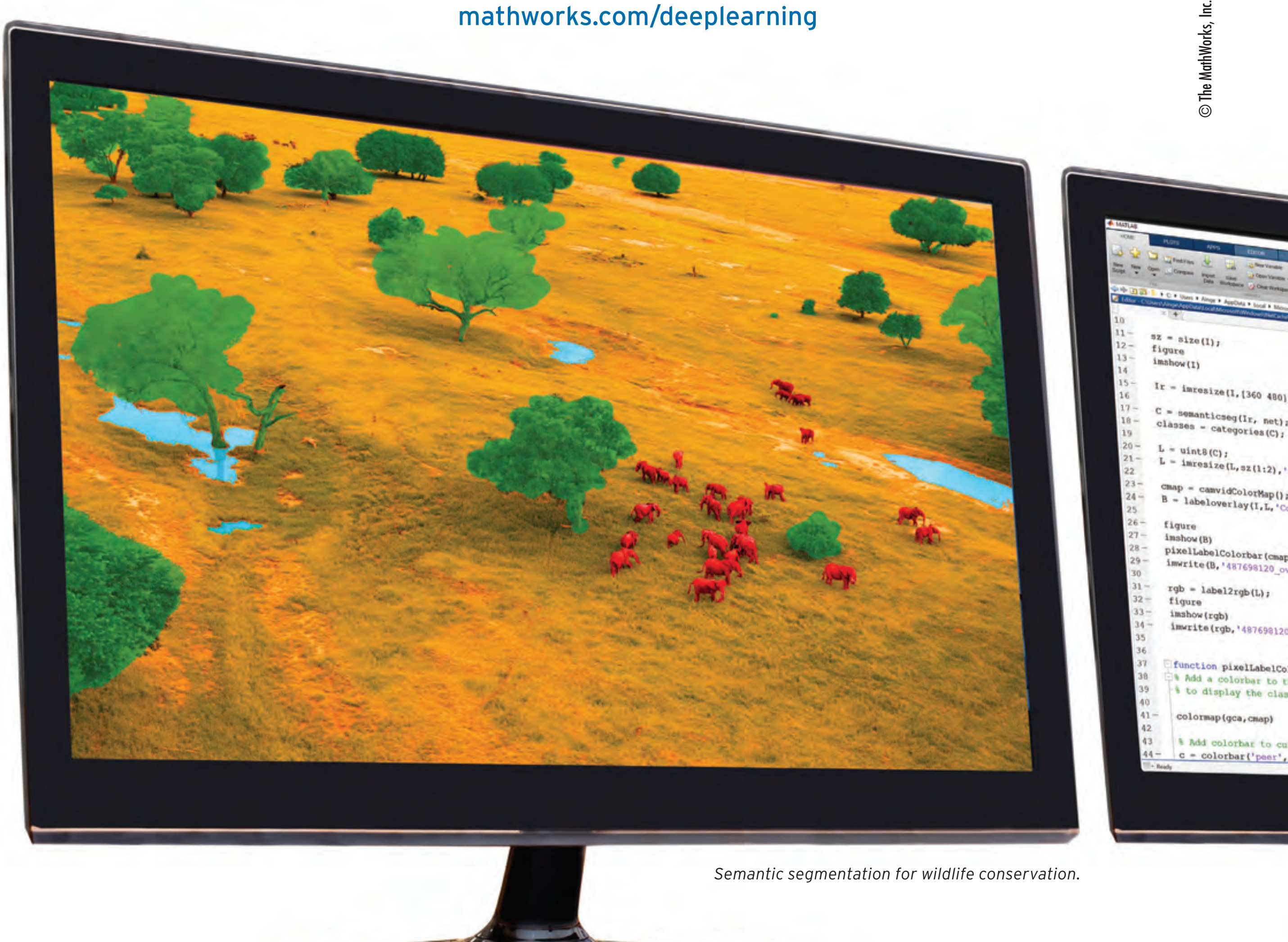
▶ A. D. Roberts et al., "Blood, sweat, and tears: Extraterrestrial regolith biocomposites with *in vivo* binders," *Mater. Today Bio* **12**, 100136 (2021); for a video commentary on the paper, see https://www.youtube.com/watch?v = 8X1aTdYM2oM. PT

Galactic immigration history

Because of Earth's position in one of the Milky Way's minor spiral arms, it is difficult to see other portions of the galaxy. We can't easily observe immigration events of groups of stars, for example, which would provide a record of galactic mergers and other cosmic history. The Milky Way's nearest neighbor is the Andromeda galaxy. Its proximity to Earth provides telescopes with a relatively unobscured view. To learn more about the immigration history of stars in the Andromeda galaxy, Arjun Dey of NSF's NOIRLab in Tucson, Arizona, and colleagues analyzed the spectra of some 11 400 stars collected by the Dark Energy Spectroscopic Instrument on the Nicholas U. Mayall 4-Meter Telescope at Kitt Peak National Observatory.

Superposed on this optical image of the sky are the motions of the individual stars in Andromeda. The color coding ranges from red, which indicates those moving away from us, to blue, for those moving toward us, relative to the galaxy. A detailed analysis of the stellar motions outside Andromeda's bright central disk reveals dynamical evidence for an immigration event 1 billion to 2 billion years ago. The new data triple the number of stars with measured spectra outside of Andromeda's central disk. They suggest that most of the galaxy's inner halo, which stretches around the disk and across most of the roughly 5.5° by 6.7° field of view, formed from a single merger event. Given the similarity between Andromeda and the Milky Way, the results may reveal what the Milky Way looked like several billion years ago. (A. Dey et al., *Astrophys. J.* **944**, 1, 2023; image courtesy of KPNO/NOIRLab/AURA/NSF/E. Slawik/D. de Martin/M. Zamani.) —AL





Semantic segmentation for wildlife conservation.