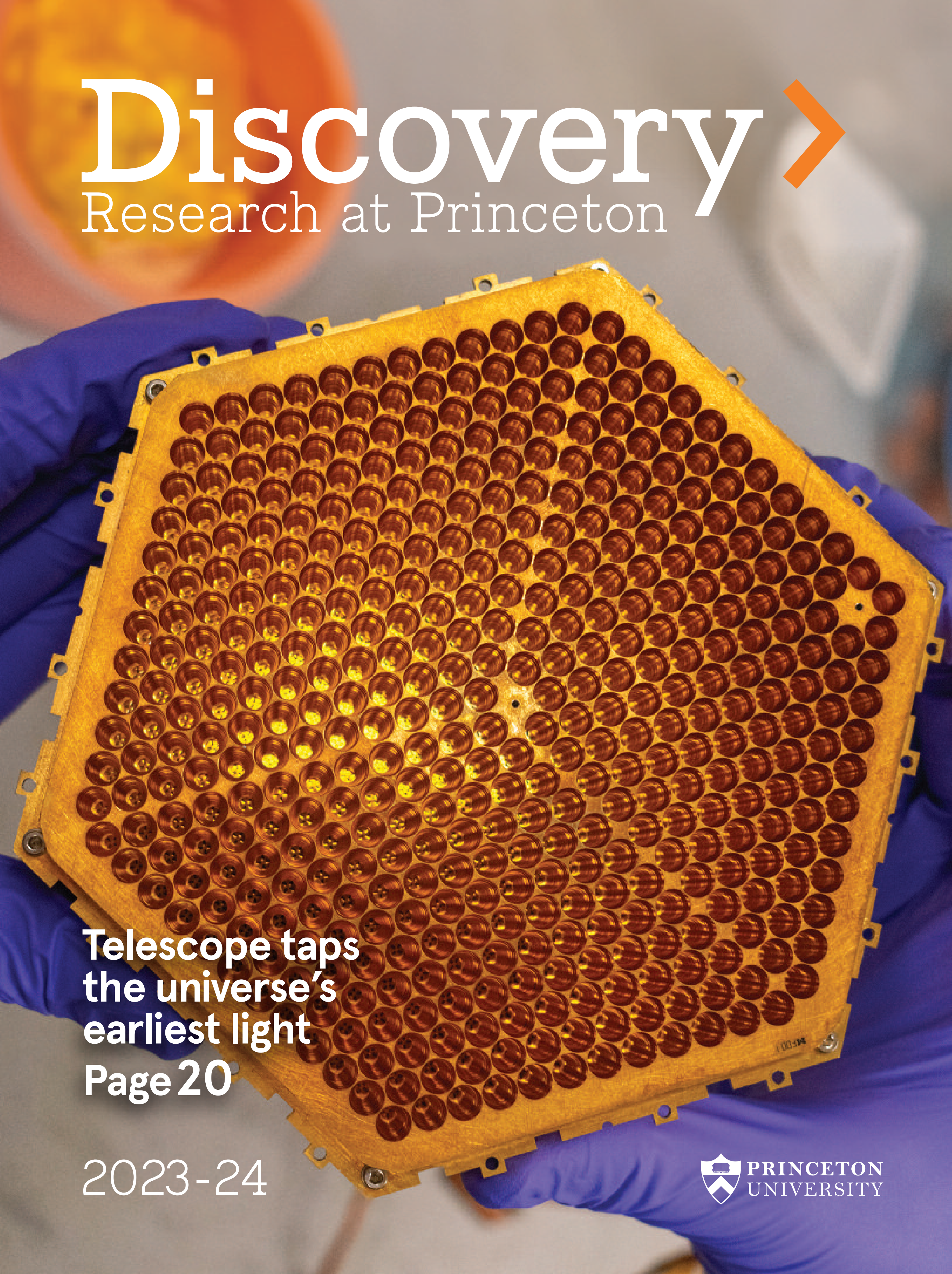
Discovery
Research at Princeton

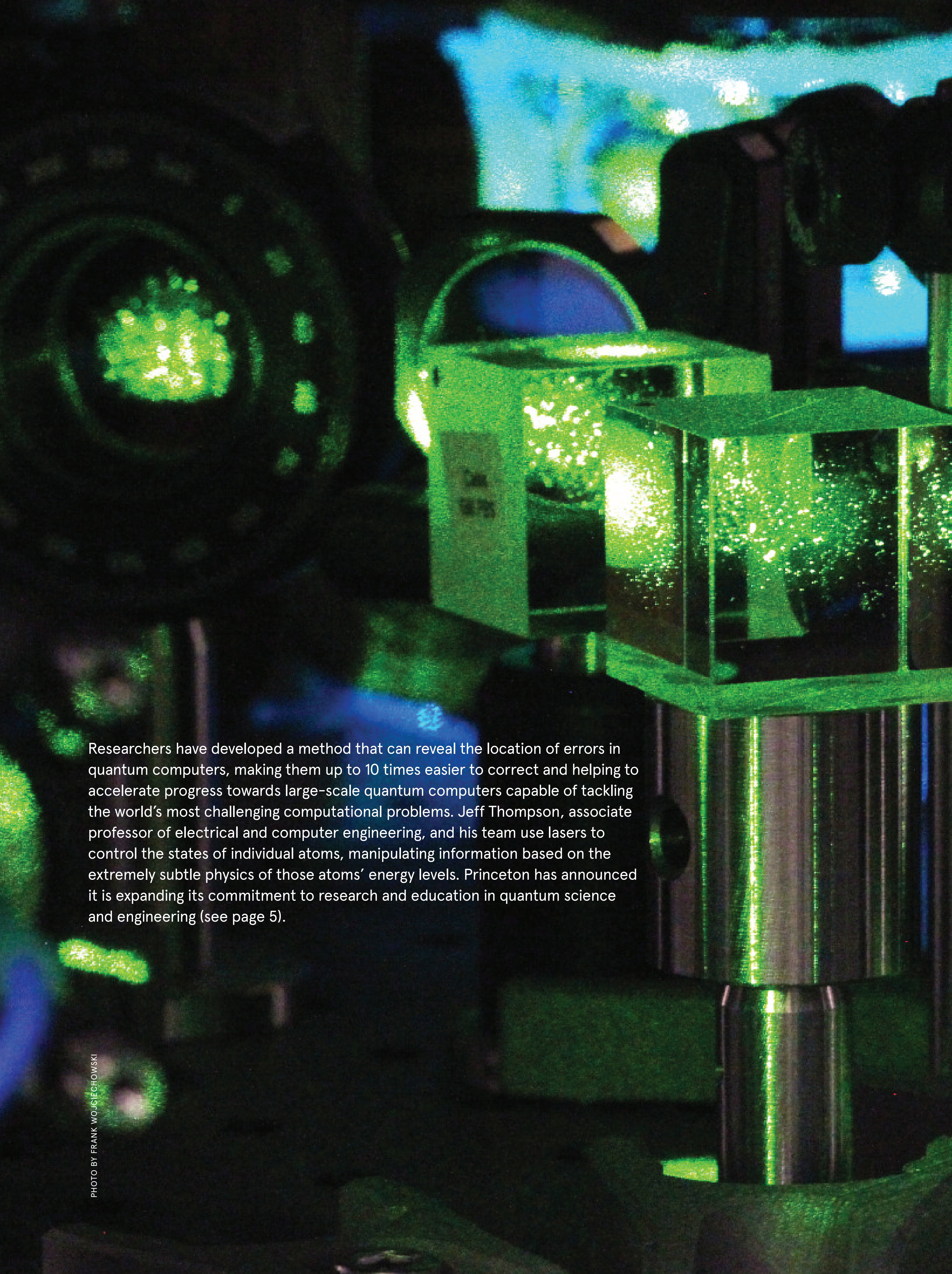


Telescope taps the universe's earliest light

Page 20

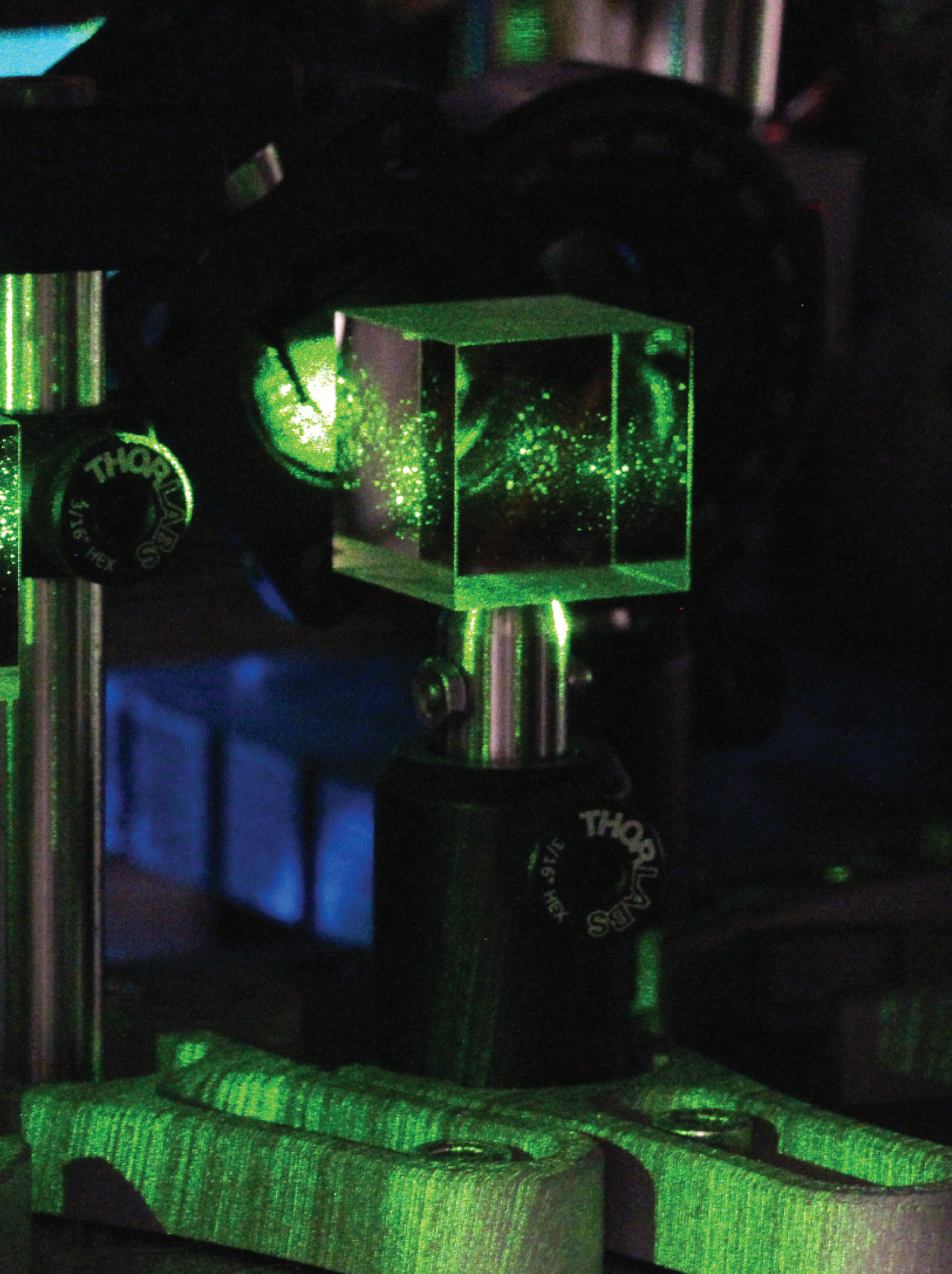
2023-24

PRINCETON UNIVERSITY



Researchers have developed a method that can reveal the location of errors in quantum computers, making them up to 10 times easier to correct and helping to accelerate progress towards large-scale quantum computers capable of tackling the world's most challenging computational problems. Jeff Thompson, associate professor of electrical and computer engineering, and his team use lasers to control the states of individual atoms, manipulating information based on the extremely subtle physics of those atoms' energy levels. Princeton has announced it is expanding its commitment to research and education in quantum science and engineering (see page 5).

PHOTO BY FRANK WOJCIECHOWSKI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Welcome to *Research at Princeton*

If there is a theme that unites the stories in this issue, it is exploration. Research inherently involves travel to new places, whether metaphorically to gain a deeper understanding of the natural world, experimentally through technologies that penetrate realms not previously accessible to humans, or physically to a location on the globe suitable for answering the biggest questions.

The theme of journeys also applies to my own path as Princeton's new Dean for Research. As a recently arrived faculty member at this storied institution, I am attuned to the ways that the University travels a unique trajectory as one of the nation's oldest research institutions and one that is at the forefront of excursions into the unknown. It is an honor to serve Princeton's research community, which is dedicated to working collaboratively across disciplines, developing the next generation of scholars and leaders, and sharing its findings with new audiences, all in the spirit of benefiting humanity.

Our investigations into the big questions — how our universe formed, who we are as humans, what we've learned from our history — are some of the broad issues covered in this year's *Discovery: Research at Princeton* magazine. This issue is perfect for armchair travelers. Join Princeton researchers as they travel to a remote mountain telescope in Chile to look back in time at the origins of the universe (page 20), a Greek island to overturn centuries of accepted dogma about ancient architecture (page 36), and a 17th-century-era Philippine convent to reconstruct a Spanish-Empire library plundered by treasure hunters (page 14). Or join our researchers' journeys of the mind, here on the Princeton campus, to unravel the universality of music as a common human experience (page 26) and to decipher the delicate structures of lungs across species, yielding insights that can inform future human therapeutics (page 30).

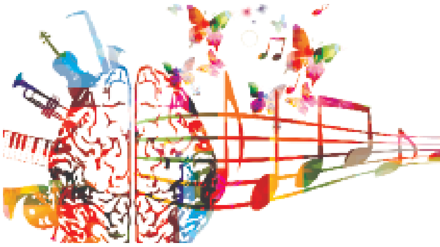
These research journeys are a sampling of the diversity of questions that our faculty and their teams address across the sciences, engineering, social sciences and humanities. We invite you to join us on these excursions through the pages of *Discovery: Research at Princeton*.

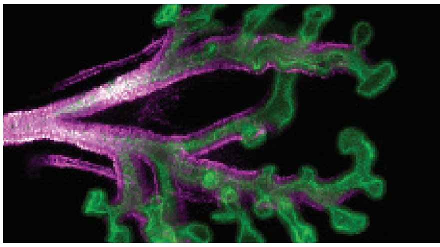
Peter Schiffer
Dean for Research
Professor of Physics

PHOTO BY SAMEER A. KHAN/FOTOBUDDY

Inside

Discovery › Research at Princeton annual research magazine 2023-24





ON THE COVER:
Hexagon-shaped arrays of detectors will line a new telescope being built in Chile to explore the origins of the universe. Page 20.
Photo by Yaakov Zinberg

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In the Nation's Service and the Service of Humanity

PHOTO BY SAMEER A. KHAN/FOTOBUDDY

ARTIFICIAL INTELLIGENCE

Princeton Language and Intelligence initiative pushes the boundaries of large AI models

A new initiative aims to enhance our fundamental understanding of AI, enable its use in academic disciplines, and examine AI's safety, policy and ethical implications. The Princeton Language and Intelligence (PLI) initiative, announced in October 2023, will enable the purchase of a state-of-the-art computer cluster and also fund human intelligence, in the form of a group of postdoctoral research fellows and research scientists and engineers at all levels. Sanjeev Arora, Princeton's Charles C. Fitzmorris Professor in Computer Science, who has conducted research at the intersection of language and AI for many years, will be the PLI director. The computer cluster will be one of the biggest in academia, giving Princeton researchers access to the hardware needed to innovate with large language models, which are at the heart of technologies such as ChatGPT.

"Over the past year or so, the pace of progress in artificial intelligence has surprised even the experts in the field, leading to exciting applications, unprecedented commercial investment — and understandable societal concerns," said Princeton Provost Jennifer Rexford at the kickoff symposium for the initiative on Sept. 26, 2023. ***—Liz Fuller-Wright***

ENVIRONMENT

Climate research collaboration grows with renewed support

A highly successful 50-year collaboration between Princeton's Atmospheric and Oceanic Sciences (AOS) Program and the nearby Geophysical Fluid Dynamics Laboratory (GFDL) has been renewed for another five years by the National Oceanic and Atmospheric Administration. Over its history, the Cooperative Institute for Modeling the Earth System (CIMES) has contributed to the development of oceanic and atmospheric models, produced research on climate and biogeochemical cycling, and educated several generations of postdoctoral researchers and graduate students, in addition to other scientific efforts. The 2021 Nobel Prize in physics was awarded to Princeton AOS Senior Meteorologist Syukuro (Suki) Manabe for his work on "modeling of Earth's climate, quantifying variability and reliably predicting global warming." CIMES was renewed for its highest dollar amount yet, totaling up to $85 million to support Earth system science research, education and outreach.

"The massive increase in funding for CIMES — roughly a fourfold increase in just one decade — reflects the significance and excellence of the fundamental climate and Earth system research of CIMES," said CIMES Director Stephan Fueglistaler, professor of geosciences and the director of AOS. "I look forward to another five years of collaborations and progress with our colleagues at GFDL."
—Samantha Schuh

CIMES

ENERGY

Public-private partnership grants to speed the arrival of fusion energy

An unprecedented six new public-private partnership grants have been awarded to the U.S. Department of Energy's Princeton Plasma Physics Laboratory, which is managed by Princeton University, for research on the science and engineering of fusion. The partnerships — representing one-third of the 18 the DOE's Innovation Network for Fusion Energy (INFUSE) selected for 2023 — aim to accelerate the production of fusion energy, the same power that drives the sun and stars.

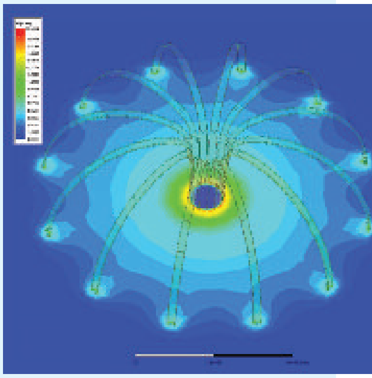


IMAGE BY YUHU ZHAI

In one such partnership, PPPL scientists will team with Germany's Gauss Fusion to explore a type of high-temperature superconductor designed to work with future fusion reactors, including spherical tokamaks that have high magnetic fields. Engineer **Yuhu Zhai** will use PPPL's modeling capabilities to lead the exploration. The project also will compare low-temperature superconductors, which must operate in liquid helium at near-zero temperature, with high-temperature superconductors that can run at higher current density, temperature and magnetic fields. ***—John Greenwald***

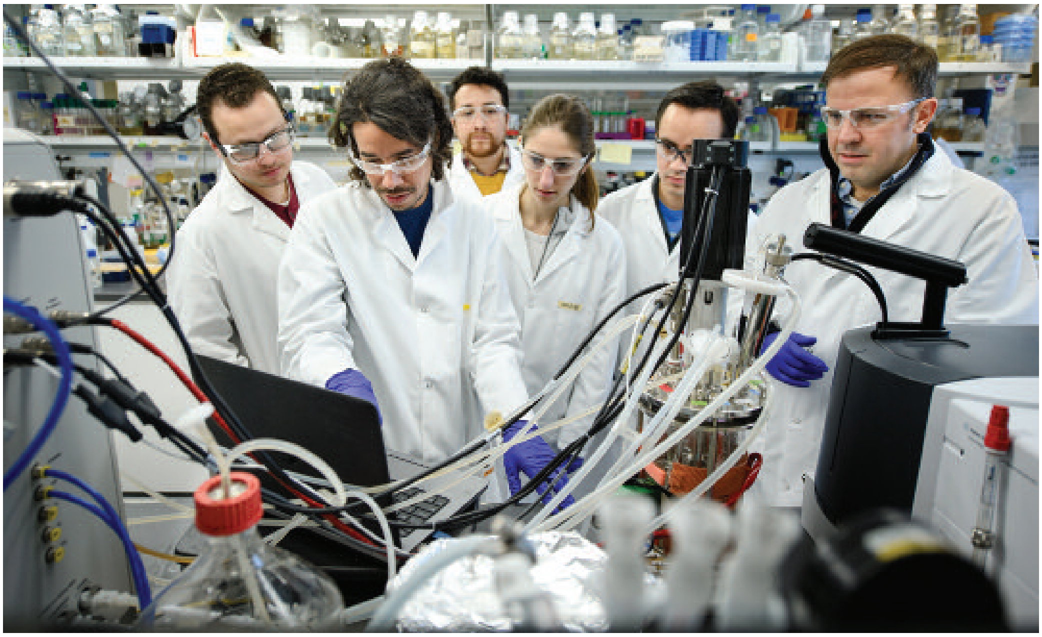


PHOTO BY SAMEER A. KHAN/FOTOBUDDY

BIOENGINEERING

At Omenn-Darling Bioengineering Institute, quest for better lives starts with curiosity

Princeton's new Omenn-Darling Bioengineering Institute will promote new directions in research, education and innovation at the intersection of engineering and the life sciences while serving as the home for new interdisciplinary bioengineering postdoctoral, graduate and undergraduate programs. The new institute, announced July 18, 2023, builds on many areas of work that were already developing under the Princeton Bioengineering Initiative created in 2020, with 35 core and affiliated faculty from across the University, a new Ph.D. program, and growing ties to the region's life sciences industry.

The institute, which will be led by Clifford Brangwynne, the June K. Wu '92 Professor of Chemical and Biological Engineering and a Howard Hughes Medical Institute investigator, will be housed in its own building currently under construction as part of a broad new campus neighborhood for engineering and environmental studies. The institute is named to honor a gift from Gilbert Omenn, Princeton Class of 1961 and a notable physician, biomedical and public health researcher, and academic leader, and Martha Darling, who earned her master of public affairs degree in 1970 at Princeton and served in numerous national and state policy roles. ***—Jeffrey Labrecque and Steven Schultz***

QUANTUM RESEARCH

University strengthens commitment to quantum science and engineering research and education

Princeton University is expanding its commitment in quantum science and engineering research and education with a new graduate program, a broader leadership structure for its initiative, and plans for a new building. These expanded programs, along with ongoing recruitment of top faculty, graduate students and postdoctoral researchers, reflect the University's recognition of the transformative potential of quantum science and technology to benefit society in the decades ahead.

This endowment-enabled initiative will be led by co-directors Andrew Houck, professor of electrical and computer engineering, who earned his undergraduate degree in electrical engineering at Princeton in 2000, and Ali Yazdani, the Class of 1909 Professor of Physics. The vision for the new institute is to bring together and support faculty and students across science and engineering who are pushing the boundaries of discovery around quantum information, particularly in the areas of quantum computing, communication and sensing. ***—Steven Schultz***

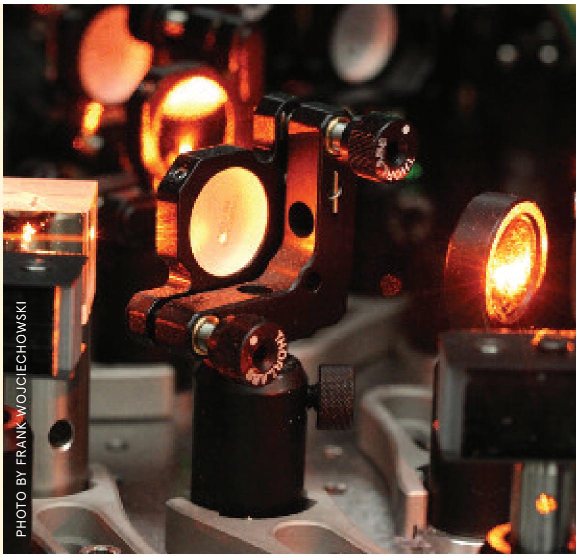


PHOTO BY FRANK WOJCIECHOWSKI

AI hope versus hype:

Arvind Narayanan dispels myths around artificial intelligence

By Alaina O'Regan

If you're starting to deploy artificial intelligence in your everyday life, how can you be sure that the tools you're using are trustworthy? As the reach of AI extends deeper into our daily routines, Princeton's in-house AI expert Arvind Narayanan aims to help the public disentangle fact from fiction.

"There is a lot of public confusion about what artificial intelligence is, and what it is and isn't capable of," said Narayanan, professor of computer science and director of Princeton's Center for Information Technology Policy.

In an upcoming book called *AI Snake Oil*, co-authors Narayanan and graduate student Sayash Kapoor — both named among TIME magazine's 100 most influential people in AI in 2023 — pull back the technical curtain on AI. While certain AI technologies are progressing at a rapid rate — specifically, "generative AI" tools that conjure up text, images and videos — many other AI tools are not up to speed with the hype, attest Narayanan and Kapoor.

> "There are a lot of people who want to know what kinds of jobs can be automated by AI. But the relevant question is, who has power in the labor market?"
>
> — **Arvind Narayanan**

For example, AI is not keeping up with the claim that it can predict the future. A set of tools called "predictive AI" is already being used to make consequential decisions about who might commit crimes and which job candidate is best suited for a position. "The fact is that it is hard to predict the future using AI, and its ability to do that is not improving," Narayanan said. "There are really fundamental limitations to using these kinds of predictive decision-making tools that can really foreclose people's life chances. This is the kind of AI we largely refer to as 'AI snake oil.'"

In this interview, Narayanan answers some questions about the possibilities and pitfalls of AI today.

How is predictive AI different from other kinds of AI?

A key difference is the task you're asking the tool to do. Generating text or images is something that a person can do, but that generative AI can do faster.

But with predicting the future, the laws of nature and social aspects of people's behavior make it hard to predict if someone is going to be a good employee, or if someone is going to be arrested for a crime. These are not things that become easier to predict with AI, even when you have lots of data. In some cases, predictive AI is no better than a random number generator.

One of the big dangers with predictive AI is that the tools just reflect what's in the data, which is often historical data that reflects people's prejudices, stereotypes and biases.

What should people be aware of when it comes to AI in the media?

When it comes to generative AI, although we believe that technology is progressing very quickly, I think the hype around those technologies is progressing even faster than that.

A lot of people who hype these technologies are talking about how ChatGPT is going to allow you to be 10 times more productive, but is that true? Should you be dropping everything to try to use this tool?

Why is ChatGPT such a big deal?

When you ask a question to ChatGPT, it's doing this really crude thing — someone on the internet described it as freestyle rapping because at any moment, it's thinking about the word or character that should come next. Just by doing that over and over again, it's actually able to produce some really interesting output.

These technologies have now finally gotten to a point where they're useful to everyday people. So it looks like it's everywhere, but this has actually been quite gradual.

Should I be worried that AI will take my job?

Generative AI in particular is having a lot of impact on the labor market, but I think that has to be viewed through the lens of capitalism. It's a question of economic factors and power asymmetries between workers and people who control the means of production.

There are a lot of people who want to know what kinds of jobs can be automated by AI. But the relevant question is, who has power in the labor market? And how might the people who have a lot of power be able to abuse it, while using AI as an excuse?

Some of these big tech companies have a lot of unaccountable power. There is a lot of policymaking activity around AI, and to prevent companies from exercising outsized power, I think part of what is needed is for the public to be well educated.

What impact do you hope to see from your book?

I hope it can serve as a resource for policymakers and journalists as they encounter claims about these technologies.

I also hope that it will have some small effects on companies avoiding overhyping their products too much, and people feeling comfortable to call out hype when they see it.

Narayanan and Kapoor write about AI on Substack at aisnakeoil.com.

Arvind Narayanan, professor of computer science and one of TIME magazine's 100 most influential people in AI, sheds light on the capabilities and pitfalls of artificial intelligence.

PHOTO BY DENISE APPLEWHITE

Bright mind:

Wolf Cukier discovers planets, demystifies a meteor shower, and marvels at the universe

By Alaina O'Regan

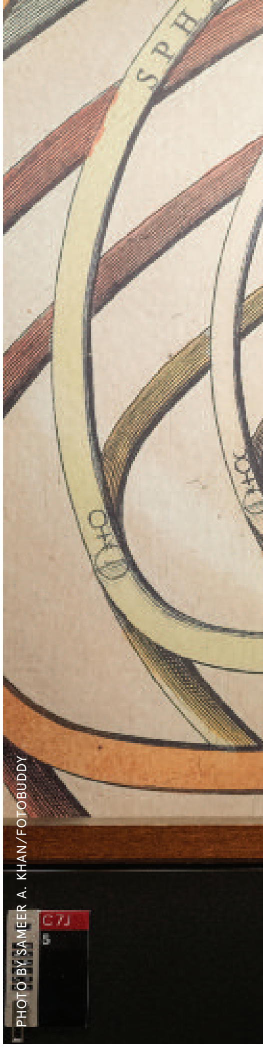


PHOTO BY SAMEER A. KHAN/FOTOBUDDY

If a planet orbits two stars, how close can it get to one of them before all of its oceans boil off? Could a giant explosion have launched living organisms from Venus all the way to Earth 3.5 billion years ago? What caused the violent birth of one of Earth's brightest annual meteor showers?

These are all questions that Princeton undergraduate Wolf Cukier has explored, and he hasn't even earned his bachelor's degree yet.

The Princeton senior is no stranger to making discoveries. In high school, Cukier stumbled upon a planet that orbits two stars during a summer internship at NASA. He was helping to search for planets outside our solar system by looking at dips in starlight that happen when a planet passes in front of a star. Cukier was tediously poring through data from a telescope when he came upon something unusual.

Cukier and Szalay found that the Geminid meteor shower was likely born from a sudden, catastrophic event.

"I think it was on my third day looking through this data, and I found an interesting signal," he said. "I sent a list to my supervisor of about 100 interesting targets, emphasizing one that I thought was the most interesting. That one was actually a planet."

The discovery landed the high school student a flood of media attention, including feature articles in national news outlets. "The experience was a bit surreal," Cukier said. "One day I'm on my way to a Science Olympiad competition, and I get a call from a reporter at *The Washington Post*."

Unearthing mysteries

Earlier this year, Cukier examined the origin of the Geminids meteoroids, a stream of tiny dust grains that appear to us as shooting stars each December. The Geminids meteoroids have fascinated scientists for decades because, while most meteoroids trail behind a comet, which is a chunk of ice and dust, the Geminids are emitted from an asteroid, a rocky object that normally doesn't produce a tail.

Cukier teamed up with Jamey Szalay, a research scholar in the NASA-funded Princeton Space Physics Lab, to explore how the Geminids meteoroids could have formed from an asteroid. By running computer simulations of different possible scenarios, they found the Geminids were likely born from a sudden, catastrophic event such as a violent collision or explosion. Cukier became the first author on the resulting publication in the June 2023 issue of *Planetary Science Journal* — not a small feat for an undergraduate — and was invited for an interview on CNN.

An earlier research experience for Cukier came in 2021, on a project that explored the origin of life on Earth. Cukier read a study in an astrobiology class that asked if a meteorite strike on Mars could have caused enough destruction to launch microbe-carrying particles through space and all the way to planet Earth. Cukier worked with the course instructor, Christopher Chyba, Princeton's

Wolf Cukier garnered national media attention for finding a new planet during a high school internship at NASA. He has continued his streak of discoveries as a Princeton undergraduate.

Dwight D. Eisenhower Professor in International Affairs and professor of astrophysical sciences, to explore whether this scenario could have been possible for Venus, and found that to be less likely than for Mars.

Cukier pursued this project to fulfill one of his "junior paper" research requirements, of which each third-year undergraduate majoring in astrophysical sciences at Princeton must complete two. Cukier, however, did his first junior paper as a sophomore.

Chyba said he knew Cukier was prepared to take on independent research when he read his final class paper. "I think I proposed the topic to him with two sentences," Chyba said. "And Wolf ran with it, and explored the literature in many different directions to get the pieces he needed to write a serious research paper. With more work, it probably could have been submitted for publication."

This summer, Cukier teamed up with Adam Burrows, professor of astrophysical sciences, to explore what exoplanets are made of by looking at how light bounces off their atmospheres. "Knowing how exoplanets are structured gives us more information about the environment in which they were formed, and can give us interesting insights into atmospheric physics in general," Cukier said. "And of course, whether or not these planets can support life is always an interesting question."

The stars are the limit

For as long as Cukier can remember, his mother, a geologist, provided scientific explanations for questions about dinosaurs, outer space and any other query that his inquisitive mind could conjure up. "The fact that my curiosity was always encouraged meant that my interests in these questions continued to grow," Cukier said.

Cukier aims to continue to pursue planetary research as a career and is currently applying to graduate programs. "I like looking at our solar system because it's observable and tangible, but it's still heavily unknown because we're all here on our little planet," he said. "We're looking out at Saturn, Titan, the Geminids meteor shower… all of this is really cool to think about. If you think about the universe at scale, it almost breaks your mind."

Like clockwork:

How circadian rhythms govern the body's defenses against disease

By Yaakov Zinberg

We like to think that our immune system protects us 24/7, but it turns out that the likelihood of contracting some infections varies based on the time of day. Like sleep, appetite, and body temperature, immunity operates on a circadian rhythm — an innate, 24-hour cycle that relies on light signals from the environment to regulate the body's internal clock. John F. Brooks II, assistant professor of molecular biology, is trying to understand how our immune abilities fluctuate throughout the day — and how that knowledge can be used to protect people's health.

"I'm really taken by this idea that contrary to what we thought previously, our immune systems do not function all the time at capacity, and that there are these daily rhythms in their functioning," said Brooks, who joined Princeton in 2022. "A better understanding of how this circadian regulation of immune functions is occurring might allow us to optimize therapeutics."

One link between circadian rhythms and immune system strength, Brooks and other researchers have found, is the gut microbiome, the community of beneficial bacteria that live within the digestive tract. These microorganisms promote the production of antimicrobial proteins in the animal host that kill invading bacteria, but the rate of production oscillates dramatically between day and night. As a postdoctoral researcher at the University of Texas-Southwestern Medical Center, Brooks led a study that showed how some of the antimicrobial proteins produced in mice are more abundant at night. Mice are nocturnal and their circadian rhythm prompts them to eat when it's dark in their environment. These eating patterns in turn trigger the expression of proteins that confer resistance against pathogens.

The triangular relationship between the circadian rhythm, the microbiome, and immunity likely evolved to protect mice against foodborne pathogens, Brooks said. The antimicrobial proteins they produce are effective against several of these pathogens, and the mice save energy by producing them exclusively at night, when encountering these foodborne pathogens is most likely. When mice eat, the circadian rhythm essentially anticipates that they might be exposed to harmful bacteria and starts preparing the defenses.

While it's still unclear if this exact mechanism is present in humans, it's certainly the case that disrupted circadian rhythms increase the risk of infection. Night-shift workers, whose internal clocks become disconnected from their environmental light cycles, are more likely than night-sleepers to contract a number of infectious diseases, including COVID-19. These workers also develop obesity and diabetes at elevated rates, likely due to dramatic changes in the composition of their microbiomes.

To investigate how the circadian rhythm-microbiome relationship might function in people, Brooks and his research team are approaching the research question from multiple directions. They use small and large intestine organoids — lab-grown versions of living tissue — to identify human-specific attributes of these interactions, while simultaneously delving into bacterial genetics and pinpointing when harmful bacteria are most potent.

"We still don't really understand how the microbiome influences our health and fitness," said Brooks. "And we definitely don't understand how we can tailor the microbiome to benefit health and fitness." Figuring out how the human microbiome is affected by circadian rhythms, however, could pave the way for new microbiome-based therapeutic approaches. People could one day take a probiotic at a specific time of the day if, say, researchers determine it's the most opportune moment to introduce a beneficial microbe into the crowded microbiome. Likewise, antibiotics could be tailored against a single bacterial strain and administered exactly when it's most vulnerable.

Though he's in the process of getting his own lab off the ground, Brooks is already making numerous contributions to the broader Princeton biology community. In 2023, he was one of 22 scientists worldwide named a Pew Scholar in Biomedical Sciences and one of 15 scientists named a Searle Scholar, distinctions which provide funding that will help support his lab's research. Brooks and his group are establishing a germ-free mouse facility, where mice are born without a microbiome. This allows scientists to study what might go wrong in the absence of a microbiome as well as the functions of individual microorganisms they can selectively introduce into the mice.

In the coming years, researchers will likely develop many microbiome-based therapeutics. For now, Brooks is focused on laying the groundwork in this new area of study. "Right now, I'm much more interested in the basic biology of how the circadian clock drives immunity," he said.

"Our immune systems do not function all the time at capacity. There are daily rhythms."

— John Brooks II

John Brooks II, assistant professor of molecular biology, is exploring the link between circadian rhythms, the immune system, and the community of beneficial bacteria that live within the digestive tract.

PHOTO BY C. TODD REICHART

Making the Supreme Court:

New book explores the rising influence of political forces on presidential nominations

By Siya Arora

President Richard Nixon had a golden opportunity in 1971 to fill a double vacancy on the Supreme Court when two justices resigned within the span of six days.

"Is there a woman yet? That would be a hell of a thing if we could do it," Nixon said in a conversation with Attorney General John Mitchell about the selection.

By nominating the nation's first female justice, Nixon calculated that his choice would be an easy sell for the Senate, which must confirm each appointment. Nixon also prioritized conservative ideology, credentials and experience — but not too much experience. Supreme Court justices serve for life, so in Nixon's calculation the individual ideally would be young enough to make conservative judicial decisions for many years to come.

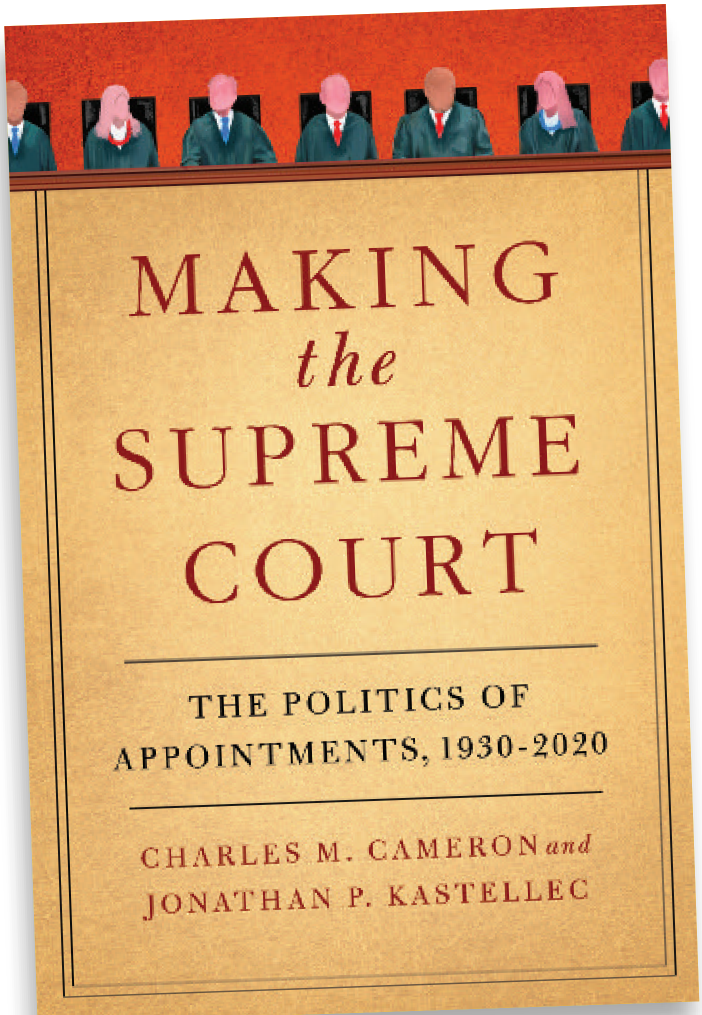
The selection process has gone from presidents who reward friends and allies to political parties and interest groups who influence presidents.

Nixon ultimately chose a man for the position (the first female justice, Sandra Day O'Connor, would join the Court in 1981), but the conversation provides a glimpse into the selection process for the nation's highest court, which is charged with interpreting the Constitution and settling some of the most significant legal disputes in the United States. In their new book, *Making the Supreme Court: The Politics of Appointments*, 1930-2020 (Oxford University Press, August 2023), Princeton professors Charles Cameron and Jonathan Kastellec analyze the evolution of nominations from a process based largely on friendships and patronage to one highly influenced by organized interest groups and political parties. They trace the roots of today's ideological split consisting of six conservative and three liberal justices, and discuss how reforms such as expanding the number of justices and imposing term limits could lead to a Court that is more representative of the nation.

Their analysis comes at a time when the Court has come under scrutiny for decisions on issues many argue do not reflect popular sentiment. In June 2022, the national right to abortion was returned to the states when Roe v. Wade was reversed. A year later, the Supreme Court made the decision to end affirmative action, barring colleges and universities from factoring race into admissions.

Cameron and Kastellec's exploration of how nominee selection has changed over the past 90 years was a massive undertaking, involving collaborators and students, including undergraduates, who collected and analyzed data from numerous sources. "In the beginning, we thought, Oh, this is going to be a pretty simple story about bargaining between presidents and Congress," said Cameron, professor of politics and public affairs. "But the data just kept saying, 'that's not the way it is.' Our ideas underwent pretty much a complete transformation from the beginning to the end."

The process by which presidents choose nominees has evolved substantially, the team found. In the Great Depression of the 1930s, President Herbert Hoover spent just a few hours selecting candidates for each of three Court vacancies. His successor Franklin D. Roosevelt chose nine justices using the requirement that candidates support his New



Deal economic and social programs. President Harry Truman in 1949 replaced a vacancy with Sherman Minton, a trusted friend and colleague, who walked into the White House and said, "Harry, I want that job on the Supreme Court," and Truman replied, "Okay, I'll give it to you." Ronald Reagan in the 1980s delegated selection to the Department of Justice and the White House legal counsel.

Over the past 40 or so years, however, political parties and special interest groups have strengthened their ability to influence the president to choose candidates with specific values, such as being pro-life or tough on crime. "What surprised us is that you can look at the changes in the nomination process as kind of part and parcel or even an outgrowth of the broader changes in American politics," said Kastellec, professor of politics.

The rise of external influences on presidential decisions has also led to demographic changes in the makeup of the Court. While more representative of gender and race than past Courts, today's justices are less representative of the U.S. population in other ways. For example, eight of today's nine justices graduated from either Harvard or Yale law schools, and most are from the East Coast.

The researchers used data to demonstrate that the past four decades of activism by parties and interest groups has indeed created a Court that reliably produces conservative decisions. What is more, computer simulations conducted by the authors predict that, barring highly unlikely events, the conservative bent of the Court will persist for several decades.

To examine ways to restore the Court's ideological parity, the authors considered two potential reforms: implementing term limits and expanding the number of justices. Via simulations, the team found that imposing term limits of either nine or 18 years would at first cause a swing to the left, but by 2060 would result in a Court that is roughly balanced between conservative and liberal justices.

The researchers also considered what would happen if the number of justices is increased. The strategy has been tried before. Between 1789 and 1869, the number of seats on the Court varied between six and 10. The authors found that adding just two Democrat-appointed seats would create a more ideologically balanced Court, but warn that a tit-for-tat process could ensue, resulting in a roster of 30 justices by 2100.

Presidents, agendas, and even the law changes. There was a time when a president blatantly said he wanted a young, conservative woman to be the next justice. Now, nominees are chosen via agendas regarding how they would vote in certain decisions. The selection process has gone from presidents who reward friends and allies to political parties and interest groups who influence presidents. With an ever-evolving political environment, it is only natural to wonder how much more change is to come and whether it will strengthen or weaken American democracy.

Based on rich data and exhaustively researched evidence, *Making the Supreme Court: The Politics of Appointments, 1930–2020* tracks the personal and political pressures behind presidential Supreme Court nominations and the creation of our modern ideologically driven and polarized Court.

Bringing history home

Scholars digitally repatriate manuscripts raided from a 17th-century Spanish-Empire convent

By Yaakov Zinberg

AN ENGLISH TWO-DECKER LYING HOVE TO, WITH OTHER SHIPS AND VESSELS IN A FRESH BREEZE, PAINTING BY DOMINIC SERRES

The battle for Manila had already been won, but the British were after the spoils.

Britain's incursion into the Philippines in 1762 was not the archipelago's first colonial experience. By then, the Spanish crown had controlled the Philippines — named in honor of Spain's King Philip II — for nearly two centuries, seeking greater access to the spice trade and to convert Filipinos to Roman Catholicism. Conquering the Philippines would enable Britain to strike a blow against its European rival and seize some of its resources. A 13-ship fleet landed at Manila Bay and disgorged more than 6,000 men, who easily breached the city's poorly fortified walls and secured a Spanish surrender. With Manila theirs, treasure-hungry soldiers then turned their attention to its churches.

Among the many churches Spanish missionaries had built throughout Manila, none were as old or magnificent as the Church of San Pablo, an Augustinian edifice first built in 1571 whose present structure was completed in 1607. It's known today as San Agustin Church and is a designated UNESCO World Heritage site. Within its towering stone walls and underneath its vaulted ceilings, San Pablo housed a trove of jewels, paintings, furniture and church organs. The British pillaged as many treasures as they could get their hands on.

But they also seized a far more valuable, albeit unassuming, prize. Tucked away in a quiet corner on the church's upper level was a library containing some 1,500 rare manuscripts, maps and printed materials relating to the Philippines and other regions of Asia that interested the Spanish.

The 1762 British sacking of Manila scattered valuable books and manuscripts across the continents. Now an international collaboration is reuniting these treasures in an online repository.

Alexander Dalrymple, who served as governor general of the Philippines for just two weeks, claimed the collection for himself and brought it to his private library in London. The items eventually went to auction, and today the books and manuscripts are scattered across several continents. Most of the items are now in the possession of the Lilly Library at the University of Indiana, while SOAS University of London, King's College, and the British Library also hold collections. Few of the original materials are in the Philippines.

Princeton scholar Christina Lee is part of a team that is digitally reuniting these stolen materials. Lee, professor of Spanish and Portuguese and the acting chair of the department, has partnered with Princeton University Library as well as colleagues at other leading universities including in the Philippines to construct an online archive that will represent what the San Pablo library might have looked like before the British sacking. The completed archive will feature images, transcriptions, English translations, and analyses of the documents, which have never before been systematically organized or studied.

The project will enable Filipinos to engage with sources from their own history that were taken from the library.

"By looking at the materials in the archive, you can get a very good sense of what's going on in the Philippines from the 1600s through the first part of the 18th century," Lee said.

Lee and her collaborators are building the online repository not only for use by academics, but for students in the Philippines and the general Filipino public as well. She describes the project as a "digital repatriation," because while the original materials will remain in their current locations, their virtual counterparts, made accessible by Lee and her colleagues, will enable Filipinos to engage with sources from their own history that were once taken from them. These previously unexplored sources may challenge some of the prevailing narratives in Philippine history.

A forgotten chapter

The idea for the digital archive was conceived by Cristina Martinez-Juan, a research fellow at SOAS and founder of its Philippine Studies program. While studying Philippine sources in the UK, she began noticing that some of the documents she came across contained a label with an elaborate emblem and the name "Dalrymple." Intrigued, she consulted other archives and found more of the Dalrymple insignia, soon realizing that the contents of the plundered library of San Pablo, dispersed and neglected among various library and museum collections, were ripe for scholarly analysis. Simultaneously, she had heard about a new grant for digital scholarship initiatives, offered jointly through the U.S. National Endowment for the Humanities (NEH) and the UK's Arts and Humanities Research Council. The grant required an American partner, and Martinez-Juan was confident Lee would make for an excellent teammate in digitally restoring the lost archive.

"I knew she was very good with transcriptions," said Martinez-Juan of Lee, "and has a really good grasp of the spelling conventions and abbreviations that are necessary to be able to decipher the materials."

These are crucial skills in paleography, the process of studying historical manuscripts. Even if a manuscript is legible — not guaranteed given sloppy handwriting and the wear to documents over time — the spelling, punctuation and grammar conventions from an earlier era can make it difficult to render the source into readable English. The materials in the San Pablo collection are also linguistically diverse: the majority are written in Spanish, but Chinese, Japanese, Latin, and Philippine indigenous languages are represented as well.

Lee meticulously studies these challenging sources alongside a team of scholars she's assembled. A core component of this team, which will transcribe and


PHOTO COURTESY OF CHRISTINA LEE

summarize about 300 of the 1,500 San Pablo materials, consists of students from the University of the Philippines, who've been implementing paleography training from Lee to decipher documents on their own. Lee also works closely with assistant professors Nicholas Sy and Ros Costelo, who meet with the students to provide feedback and guidance on their work.

"They're learning from me, I'm learning from them," Lee said. "There's no way I'd be able to do this without them."

Carlos Joaquin (CJ) Tabalon, a 23-year-old student from Manila who is pursuing a Master of Arts in Philippine history, joined the project to help publicize a forgotten chapter of his country's past, in addition to gaining experience working with original sources. "It was a great opportunity to be exposed to actual colonial documents from the 18th century, an understudied part of our history," he said of the project.

Scholars have traditionally believed that Filipino natives submitted to the forced conversions and land seizures of Spanish colonization without much resistance. Together with Lee, Tabalon and other Filipino research assistants have transcribed a document, written partially in Tagalog — which forms the basis of Filipino, the national language of the Philippines — and partially in Old Spanish, that says otherwise.

The source tells of a near-fatal altercation in May 1717 between the native residents of Dongalo, a small village administered by the Parañaque parish to the south of Manila, and Fray Juan Serrano, the Augustinian priest responsible for evangelizing

At the San Agustin Museum and Library in Manila, Christina Lee, professor of Spanish and Portuguese at Princeton (center), reviews historical documents with Louella Revilla-Baysic, San Agustin's Museum and Library collections manager and conservationist (left) and Regalado Trota José, a retired archivist at the University of Santo Tomas in Manila.

PHOTO BY CRISTINA JUAN

An elaborate bookplate, or label affixed to the inside cover of a book to show ownership, alerted modern-day scholars to rare manuscripts once in the possession of Alexander Dalrymple, who was governor general of the Philippines during the Battle of Manila in 1762. Dalrymple transported the contents of the plundered library of San Pablo to London, where they were later auctioned and dispersed to various library and museum collections.

them. According to the documentary account, the dispute centered on the location of a fence that separated indigenous and Augustinian land. Serrano and his servants traveled to the site to investigate what they perceived as an encroachment onto their territory. The Filipinos wouldn't budge, insisting the contested land was rightfully theirs. Insults traded between the two parties soon gave way to blows, and the brief skirmish ended when Serrano, heavily outnumbered, fled on horseback to safety.

Like any historical document, the Dongalo account bears the bias of its author, which, in this case, is Serrano himself. The official title of Serrano's first-person narrative, "Account and other materials about the disrespect that the natives of Dongalo, a pueblo of Parañaque, showed against their prior and minister," betrays his slant. He describes Filipinos as ruthless "sayónes," an Old Spanish word meaning "executioners," implying, according to Lee, that the Dongalo natives would commit the supposedly un-Christian act of taking a life. If Serrano's account is to be believed, he was patiently trying to argue for the Augustinian (and therefore divine) point of view, while his colonial subjects were out for blood.

By portraying Filipinos as the aggressors, Serrano inadvertently highlights their courage and implicitly recognizes their strength. He also quotes native voices, preserving the defiant rejoinder of a Dongalo leader named Captain Pablo: "I know very well what I do, and I know which are our lands and you don't...you are trying to take away what is ours."

Tabalon and his colleagues believe this one-sided narrative is evidence for the resistance of native Filipinos to Spanish rule. "As evidenced excellently in the Dongalo document, there were times when the agency of the Filipino natives showed and they asserted their place," Tabalon said.

For the Filipino research assistants, these newfound historical discoveries are not just about setting the scholarly record straight, but are intimately tied with their sense of Filipino identity. "We Filipinos, we were at the receiving end of colonialism," Tabalon said. "When the voices and experiences of the colonized are displayed and discussed," he added, "it's a really good way to forge a more relevant national history."

Jan Cherome Sison, a University of the Philippines student who also helped transcribe the Dongalo document, agreed. "It is in our history to resist against abuse no matter where it came from," she said.

Finding buried treasures

Any archive, physical or digital, is only as good as the infrastructures that allow researchers to find the materials they seek. Esmé Cowles, assistant director for library software engineering, and other staff at the Princeton University Library will work with Lee in tagging each item from the San Pablo collection with metadata — information about the origin, authorship and content of a source — to facilitate comparisons between multiple items. Metadata for the Dongalo document, for instance, will include keywords like "Parañaque," "Indios" and "Tagalog," which will link to other sources with the same metadata.

"What got me excited about the idea of digital repatriation is that it is an area where a well-resourced library like ours can contribute in a respectful way," said Anu

Vedantham, assistant university librarian for research services, teaching and social sciences at Princeton University Library.

Shortly after the digital repository project was launched, Lee and Martinez-Juan traveled to San Agustin Church to hunt for pre-1762 documents that the British may have left behind. They joined forces with Regalado Trota José, a recently retired archivist at the University of Santo Tomas in Manila. José has been keeping busy in retirement lending his expertise in the artwork and history of Philippine churches to Lee and Martinez-Juan.

Inside the church's storeroom, the trio dug through dusty crates overflowing with contemporary newspaper clippings and theological journals. Towards the bottom they found leather- and vellum-bound volumes wrapped in plastic, and after browsing through about a dozen, Lee let out a scream. She spotted a stamp on the reverse side of a volume cover bearing the words "Ex. Bibliotecha Conv. S. Pavli" — "from the library of the convent of San Pablo."

"We were all practically jumping with joy," said José, who's now helping the staff at San Agustin scan and catalog the 67 volumes they possess.

Father Ricky Villar, the director of the San Agustin Museum, had initially been hesitant to grant access to the materials but was delighted by the find. "He wants us to help him restore as much as possible of the library with the items they have," Lee said. Technicians at San Agustin are beginning to create scans of these newly unearthed books. Father Villar has been appointed director of the San Agustin Center for Historical and Archival Research, where researchers can handle the church's San Pablo materials in person. And as they continue scrutinizing the materials one by one, Lee and Martinez-Juan are planning a series of workshops across the Philippines to engage communities with the archive.

Another eureka moment came at the Lopez Museum and Library in Manila, which held some mysterious bound manuscripts in storage. In January of this year, José and Martinez-Juan found the vellum-bound volumes with the help of the Lopez Head Librarian Mercy Servida. They discovered that minuscule numbers on the spines of the volumes matched those in an auction lot and a catalog of San Pablo items written in the 1960s. This past July, Christina Lee went to the Lopez Library with Princeton graduate students David Rivera and You-Jin Kim to inspect the discovered volumes. They also found rare local documents produced in the indigenous languages of Bicolano (along with Tagalog) and an entire bundle of royal orders found hidden at the home of Governor of the Philippines Manuel de León after his death in 1676. Researchers at the University of Santo Tomas, the University of the Philippines, and Princeton are working together on transcribing the most significant documents found at the Lopez Library.

Another eureka moment came at the Lopez Museum and Library in Manila, which held some mysterious bound manuscripts in storage.

For Lee and her colleagues, this is what it means to repatriate the stolen archive to the Philippines. "We have very carefully thought about how to bring this back to Filipinos," said Lee. "For me, it's an intellectual pursuit. I don't necessarily have a personal attachment to Philippine history," she added. "But for them, this is really important: this is about their national history."

After the British looted the San Pablo library, the treasure-seekers scattered its contents across several countries, where they resided in obscurity for over two centuries. It is fitting that an international collaboration of scholars, librarians and students is piecing together this lost archive and reuniting it with the nation whose full history remains to be told. ●

The Simons Observatory's three small aperture telescopes (SATs), now under construction in Chile, are designed to detect gravitational waves from the first moments of the universe. Pictured, the sun shines through one of the platforms awaiting the installation of its telescope.

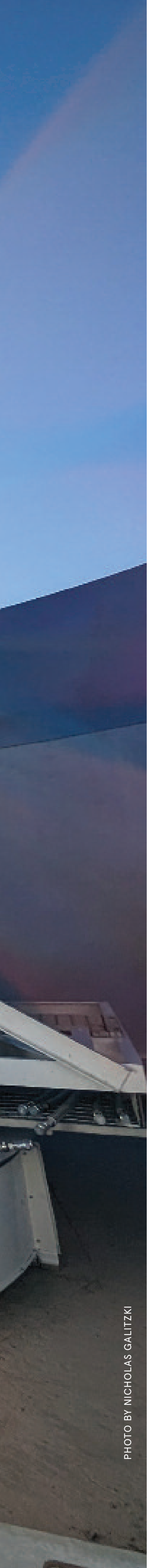


PHOTO BY NICHOLAS GALITZKI

Early light

A major new telescope project brings physicist Suzanne Staggs's research on the origins of the universe into sharp focus

By Yaakov Zinberg

It's a familiar experience for air travelers: your suitcase is pulled aside for inspection by an airport security officer after the X-ray machine flags something inside. The culprit is often something simple, like a forgotten water bottle or a tube of toothpaste slightly over the size limit, and you continue on your way without needing to explain much about the contents of your bags.

But when Daniel Dutcher, associate research scholar in Princeton's physics department, recently traveled through the airport on business, his luggage raised more eyebrows than usual. Dutcher is advised by Princeton cosmologist Suzanne Staggs, whose specialty is the early universe and who is designing telescope components that allow scientists to study it. On a trip to Chile, where the Staggs research team is involved in building a new observatory, Dutcher was tasked with transporting the group's delicate handiwork: hexagonal stacks of silicon and copper, each housing about 2,000 ultra-sensitive detectors, worth about $100,000 apiece, that sit within telescopes and can detect faint light signals from deep space.

After briefly explaining all this to slightly confused TSA officers, Dutcher was allowed to proceed with his precious cargo in hand, which he carefully stowed under the seat in front of him once onboard.

This was one of the more minor challenges of the Simons Observatory, an ambitious project that consists of four next-generation telescopes situated on a barren plateau 17,000 feet above sea level in northern Chile's Atacama Desert. The area's skies are free of the moisture that can interfere with observations of outer space, making it one of the only places on Earth suitable for

PHOTO BY MICHAEL RANDALL

Suzanne Staggs, second from left, is co-director of the Simons Observatory in Chile, where the research team poses in front of one of the small aperture telescopes, its detector modules visible as gold-colored hexagons. Pictured from left to right: Nicholas Galitzki, assistant professor, University of Texas-Austin; Suzanne Staggs; Tomoki Terasaki, graduate student, University of Tokyo; Erin Healy, postdoctoral researcher, University of Chicago, and Princeton Ph.D. 2022; Tran Tsan, graduate student, University of California-San Diego; Jenna Moore, graduate student, Arizona State University; and Michael Randall, graduate student, University of California-San Diego.

imaging the oldest observable light in the universe, the cosmic microwave background, or CMB. The Simons Observatory aims to detect this primordial light with unprecedented sensitivity to arrive at fundamental insights about how the universe was formed and has evolved.

"A huge amount of information about our universe, and our standard cosmological model that we have now, has come from doing studies of the CMB radiation," said Staggs, Princeton's Henry DeWolf Smyth Professor of Physics and a member of the Simons Observatory Executive Board. "We'll be able to do even better with the Simons Observatory."

Staggs juggles several leadership roles within the observatory, which is primarily supported by the Simons Foundation — a private organization that supports scientific research — and is a collaboration among the University of Pennsylvania, Princeton University, University of California campuses at San Diego and Berkeley, University of Chicago, Lawrence Berkeley National Laboratory, and institutions around the world. As one of the two co-directors of the Simons Observatory (the other is Mark Devlin, a former Princeton postdoctoral fellow who is now a professor at the University of Pennsylvania), Staggs is charged with overseeing the research efforts of the project's more than 300 collaborators working from labs across the globe. And over the past 25 years, Staggs has mentored the next generation of cosmologists — some who themselves have assumed leadership roles within the Simons Observatory.

"The thing about it that's incredibly interesting," said Staggs of her research, "is we're just asking a ridiculously bold type of question, which is: what are the large scale structure, dynamics and contents of the universe?" Staggs is optimistic that the Simons Observatory's detection of light signals from the birth of the universe will provide answers. "The goal is to explain the evolution of the universe over 14 billion years into the thing it is today by making measurements of this primordial signal," said Staggs. When asked if this research is worthwhile despite its challenges, Staggs was unequivocal: "Heck yeah, how could we stop now?"

Strange background

Though light travels a speedy 186,000 miles per second through space, the stars and galaxies we can see in the night sky are distant enough from Earth that the light they emit takes time to reach us. Whenever we look at a faraway light source, we're therefore, in a sense, looking backwards in time. Light from our sun, for example, travels through space for eight minutes before reaching Earth, so the sun always appears to us as it was eight minutes ago. And because the speed of light is constant throughout the universe, the same idea applies to the cosmic microwave background — on a vastly larger scale.

Unlike sunlight, the CMB is invisible to the human eye; the "microwave" in its name refers to its wavelength, which is outside the narrow range of visible light (microwave ovens use a similar wavelength). And rather than originate from our solar system, the CMB comes from the deepest part of space: it travels for 13.8 billion years, since nearly the beginning of the universe, before reaching Earth.

Some cosmologists refer to the CMB as the "baby picture" of the universe because it's like a snapshot of what the universe looked like in its earliest days. According to the prevailing theory, all matter, light and space sprang into existence in an event known as the Big Bang, in which a single point of infinite density began spreading and cooling into the universe we know today. By about 380,000 years into its existence, the universe cooled enough to allow light to propagate freely into the expanding void. This light is the cosmic microwave background, and it is considered "background" because it now fills all the empty space between galaxies in the universe.

Staggs and her colleagues wouldn't need to build state-of-the-art telescopes in the Chilean desert if they were just trying to view the CMB. In fact, it was discovered accidentally in 1964 in Holmdel, New Jersey — roughly 40 miles from Princeton — by two researchers, Robert Wilson and Arno Penzias, both at Bell Laboratories, who kept receiving a strange background signal from their antenna. The two later received the Nobel Prize for their discovery.

The Simons Observatory, however, will capture the cosmic microwave background radiation in incredible detail, tracking minute temperature fluctuations of a few millionths of a degree Celsius across different parts of the sky. The intensity and location of these ever-so-slightly hot and cold spots encode information about the age of the universe and how the hot, dense conditions present after the Big Bang evolved into today's galaxies, a relationship pioneered by another Princeton physicist, James Peebles, the Albert Einstein Professor of Science, Emeritus, who won the 2019 Nobel Prize in Physics. Peebles was also one of four Princeton astrophysicists who in 1964 published a companion paper to the work of Wilson and Penzias to explain the origins of the mysterious signal.

PHOTO BY MARK DEVLIN

The Simons Observatory is a collection of four next-generation telescopes situated on a barren plateau 17,000 feet above sea level in northern Chile's Atacama Desert.

As light travels through spacetime, the gravitational pull of galaxies and other massive objects causes light to bend as if it were traveling through a lens. This gravitational lensing, predicted by Einstein's theory of general relativity, can reveal the locations of dark matter — a substance that makes up about 85% of all matter in the universe but is invisible because it does not interact with light. As the CMB light travels, its path is bent by the gravitational pull of dark matter as well as visible galaxies and galaxy clusters. Tracking this path can reveal how the universe evolved over time, where it was "lumpy" with clusters of galaxies and dark matter, and how fast the universe expanded.

Mapping the CMB at this resolution is the job of the Large Aperture Telescope (LAT), one of the four telescopes in construction at the Simons Observatory. The LAT boasts two 20-foot-in-diameter mirrors that reflect light from space into the telescope's camera, hitting the detector modules assembled by the Staggs group. Each module contains nearly 2,000 detectors that transmit the signal from CMB light. By taking advantage of a technique called multiplexing, thousands of detectors can be read out using only a handful of wires.

The efforts and expertise of many different groups were required to design and test the LAT. A company from Germany built the LAT's outer structure and mirrors, while a team from the University of Pennsylvania designed the camera and the cryogenic chamber that keeps the detectors close to absolute zero, the only temperature at which they can operate. Detector components were fabricated at sites including the National Institute of Standards and Technology in Boulder, Colorado, and were tested at the University of Chicago or Cornell University before Dutcher escorted them to Chile.

The LAT builds on the discoveries of the Atacama Cosmology Telescope (ACT), which is located on the same Chilean mountaintop and recently finished collecting data. The two telescopes operate similarly, but the LAT will contain 10 times as many detectors as ACT did, guaranteeing that it will produce a higher-fidelity CMB image. "More detectors means you can just see the detail in the microwave background light better, which then leads to science we couldn't do with ACT," said Jo Dunkley, professor of physics and astrophysical sciences and — along with Lyman Page, Princeton's James S. McDonnell Distinguished University Professor in Physics and a long-time CMB researcher — a member of the Simons Observatory Executive Board.

Professor Suzanne Staggs prepares a detector module for installation into one of the Simons Observatory small aperture telescopes. On the right is Erin Healy, Suzanne's former graduate student and a current postdoctoral fellow at the Kavli Institute of Cosmological Physics at the University of Chicago, who is installing the modules into the telescope receiver.


PHOTO BY MICHAEL RANDALL

Finding inflation

Dunkley and Staggs are part of a multi-generational Princeton tradition of pushing CMB research to new frontiers. Staggs, who earned her Ph.D. at Princeton, owes her involvement in the field to one of the early pioneers, the late David Wilkinson. She initially wanted to work in nuclear physics, but the faculty member with whom she hoped to work soon left for another research institution. Staggs thought about following him, but Wilkinson personally appealed to her to stay.

The chance to explore the CMB with one of its foremost experts was too good to pass up. "Wilkinson just sold me on it," Staggs recalled. "He was an extremely charismatic person with a great understanding of physics and cosmology." A NASA mission that launched in 2001 and created a full-sky map of the CMB is called the Wilkinson Microwave Anisotropy Probe (WMAP) in his honor.

Princeton has also been closely associated with an important cosmology theory called inflation that stands to be validated by the Simons Observatory. To solve cosmological observations that can't be explained by the Big Bang, scientists have proposed that in the first trillion-trillion-trillionth of a second after the Big Bang, the universe expanded exponentially — it inflated — before settling into a much slower expansion rate. Although the theory has many supporters, no hard evidence for inflation exists.

The small aperture telescopes (SATs) at the Simons Observatory may change this. These three telescopes, whose lenses measure only 20 inches in diameter, pale in size to the LAT, but their design could allow them to detect gravitational waves from the first moments of the universe: these primordial

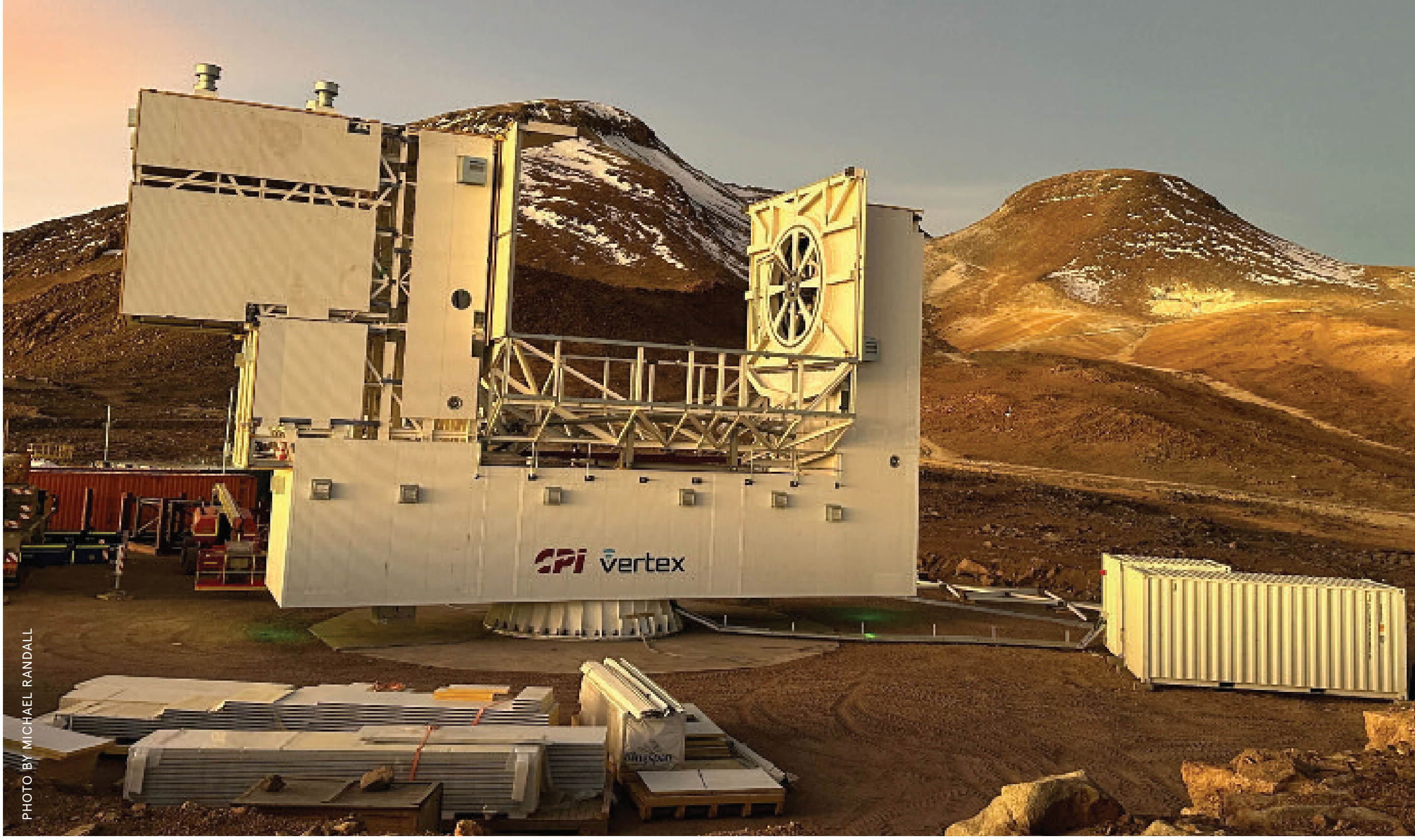


PHOTO BY MICHAEL RANDALL

Mapping the light from the earliest stages of the universe at high resolution and over a large fraction of the sky is the job of the Large Aperture Telescope (LAT), now under construction at the Simons Observatory.

gravitational waves should exist if inflation truly happened. Light is an electromagnetic wave, and as it travels it creates an electric field in a defined direction, or polarization. The CMB light carries a distinctive pattern of polarization that can be measured by the SATs. Gravitational waves twist the patterns in certain ways, and finding evidence of the gravitational wave signature pattern would be really exciting, Staggs said.

In the decades since Wilkinson offered to advise Staggs, she in turn has advised dozens of students at all levels. Claire Lessler completed her undergraduate senior thesis with Staggs at Princeton in 2022 and is now a graduate student at the University of Chicago, where she works with Professor Jeffrey McMahon (who himself earned his Ph.D. from Princeton in 2006, under Staggs's mentorship). Lessler, who fabricated a component of the detector module for her thesis, said that even with Staggs's responsibilities leading the Simons Observatory, she was a diligent undergraduate thesis adviser and a supportive mentor.

"Suzanne went and checked every single one of my citations," recalled Lessler, who was also encouraged by Staggs to pursue graduate studies. "I went to Suzanne and asked, 'Do you think I could go to grad school?' and she was very, very supportive. She was also excited that I was a woman and going to grad school — that was a big deal to her," said Lessler.

Widening the pipeline

It'll be a number of years before the Simons Observatory yields answers to the cosmological mysteries it was built to address. Though it is set to make its first scientific observations in May 2024, data collection and analysis will together take several years, and the team expects to have published substantial results by the end of the decade.

Before that happens, the Simons Observatory will go through a major upgrade, thanks to a recent $53 million grant, led by Mark Devlin, from the National Science Foundation.

It will allow the Princeton team to assemble more detector modules for the LAT, rapidly accelerate the data pipeline, and fund an array of solar panels to generate 70% of the observatory's power, which previously relied exclusively on diesel generators.

A lot of scientists are motivated by the potential societal benefits of their research, Staggs said. "In different areas of science, you might become interested because it's going to lead to various inventions that in the future will change things. That's not really true, to my mind, with our area," she said. Instead, she builds telescopes to achieve something more profound: to answer fundamental questions about the nature of the universe. "It just still seems crazy to me that we can even pursue them," Staggs said of these questions, "and so very exciting to keep doing so." ●

They're playing our song

Elizabeth Margulis builds bridges between music, imagination and memory

By Alaina O'Regan

What do you think about when you hear your favorite song? Maybe it stirs up vivid memories of an old romance, or you imagine the flames and scent of a bonfire on a humid summer evening.

It turns out that the images that we see in our minds while listening to music are not as individualistic as we might think. People from similar cultural backgrounds tend to visualize similar stories while listening to music, according to a study published in January 2022 in the *Proceedings of the National Academy of Sciences* by Elizabeth Margulis, professor of music at Princeton, and international colleagues.

"There's one track we play where people tell us, again and again, that it sounds like there's a man in a city in the 1920s at night who spots a woman down the street and romantically pursues her," Margulis said. "There's another track where most people imagine little animals waking up and starting to frolic."

Margulis and her group in Princeton's Music Cognition Lab use music as a tool to study human creativity and memory, and their findings are helping to explain the similarities and differences in what we daydream about while we listen to music. Their studies of how music connects us to our past could also be key to understanding how memories can be preserved into late stages of dementia.

"Getting people to talk about their subjective, internal experiences as they listen to music can help us scientifically understand the relationship between what's happening with the sound and what's happening in their brains," Margulis said.

A natural connection

Combining research from the humanities and sciences, Margulis teamed up with Uri Hasson, professor of psychology and neuroscience at Princeton, to investigate which neural mechanisms we rely on to imagine vivid scenes while listening to instrumental music.

By exploring the neuroscience of human communication, Hasson has pioneered new methods of computing that make it possible

Professor of Music Elizabeth Margulis combines research in neuroscience, psychology and music to explore the science behind imagination and creativity.

PHOTO BY SAMEER A. KHAN/FOTOBUDDY

to analyze people's responses to complicated scenarios, like a detailed story or movie. His new methods make it possible to move beyond the typical "beeps" and "boops" played during traditional brain scan studies.

"You can think of music as a modality of human communication," Hasson said. "For this new project, we want to ask, does the same mechanism by which we communicate using language also govern the ways we communicate using music?"

To find out, Margulis and Hasson played excerpts of music that they already knew would make people imagine certain stories — like the one that inspired thoughts of animals frolicking — to a group of volunteers undergoing brain scanning with functional magnetic resonance imaging (fMRI) machines, which detect blood flow to various parts of the brain, indicating increased activity. The team then asked the volunteers to tell them what they imagined as the music was played.

Next, the researchers brought in a new group of volunteers and played for them an audio narration drawn from the same words that the people in the previous group had used when describing what they had imagined. By comparing what parts of the brain light up for people daydreaming under different circumstances, the team aims to find out exactly which brain mechanisms are used to imagine stories while listening to music and while listening to narration.

Understanding how music cues imagination and memory could open paths to treatment for Alzheimer's disease and other forms of dementia.

The science of creativity

Although most people from similar cultural backgrounds imagine similar stories, some people consistently come up with something different. Why do some people imagine more conventional stories, while others come up with more outlandish, unusual stories?

To better understand human creativity, Margulis is exploring the root of cultural and individual differences in imagination.

"People often think of imagination as scientifically intractable, like it's this unbounded creative capacity," Margulis said. "But because we've seen that music guides imagination in a particular way, we see that imagination is constructed out of past experience, memory and perception, and has these very predictable components that we can study and understand."

To disentangle cultural familiarity from individual imagination, Margulis and her collaborators played music for people in two geographic locations in a musical scale that would be unfamiliar to each, the Bohlen-Pierce scale. It uses an alternative tuning pattern and has different rules about how notes are played together.

The researchers looked at how people's individual differences, like musical training or sensitivity to a key change, would affect the stories people imagined. They analyzed people's word choices using natural language processing, a branch of artificial intelligence where computers learn to understand text and speech.

The researchers determined the most commonly associated words and phrases for each listener, and mapped the stories onto a spatial representation of language, where words and sentences are placed closer together or farther apart based on how similar they are to one another.

Margulis and her team will use this data along with further studies to find out more about the factors that give rise to human creativity.

Music inspires memory

Understanding how music cues imagination and memory could open paths to treatment for Alzheimer's disease and other forms of dementia, as well as inform other currently used applications of music therapy.

"There is a serious clinical potential to this kind of work," Margulis said. "There are existing, well-supported clinical practices that ask people to recall memories while listening to music, but there hasn't been a lot of research about the science around how these memories come up."

Gabrielle Hooper, a graduate student in the Music Cognition Lab who studies the role of music in medicine, is conducting an analysis of the existing research on these topics. "By understanding how music impacts people with neurological diseases, we have the opportunity to introduce them to a new way to remediate their symptoms that may not have otherwise been available," Hooper said. "For many dementia patients who experience a state of confusion at specific times of day, for instance, clinicians implement a personalized playlist to help ease their negative emotions."

Margulis and a group of students in her lab are conducting studies that aim to link people's autobiographical memories with the fictional stories that they imagine while listening to music. "We know from previous research that remembering something that happened to you relies on very similar mechanisms as imagining something totally fictional," Margulis said. "We're taking advantage of that relationship to bring together two lines of work about music that previously had not spoken to each other: narrative imagination and evoked memories."

The team has conducted several studies aiming to understand which kinds of music are more likely to evoke memories, and which are more likely to cause someone to imagine a fictional story.

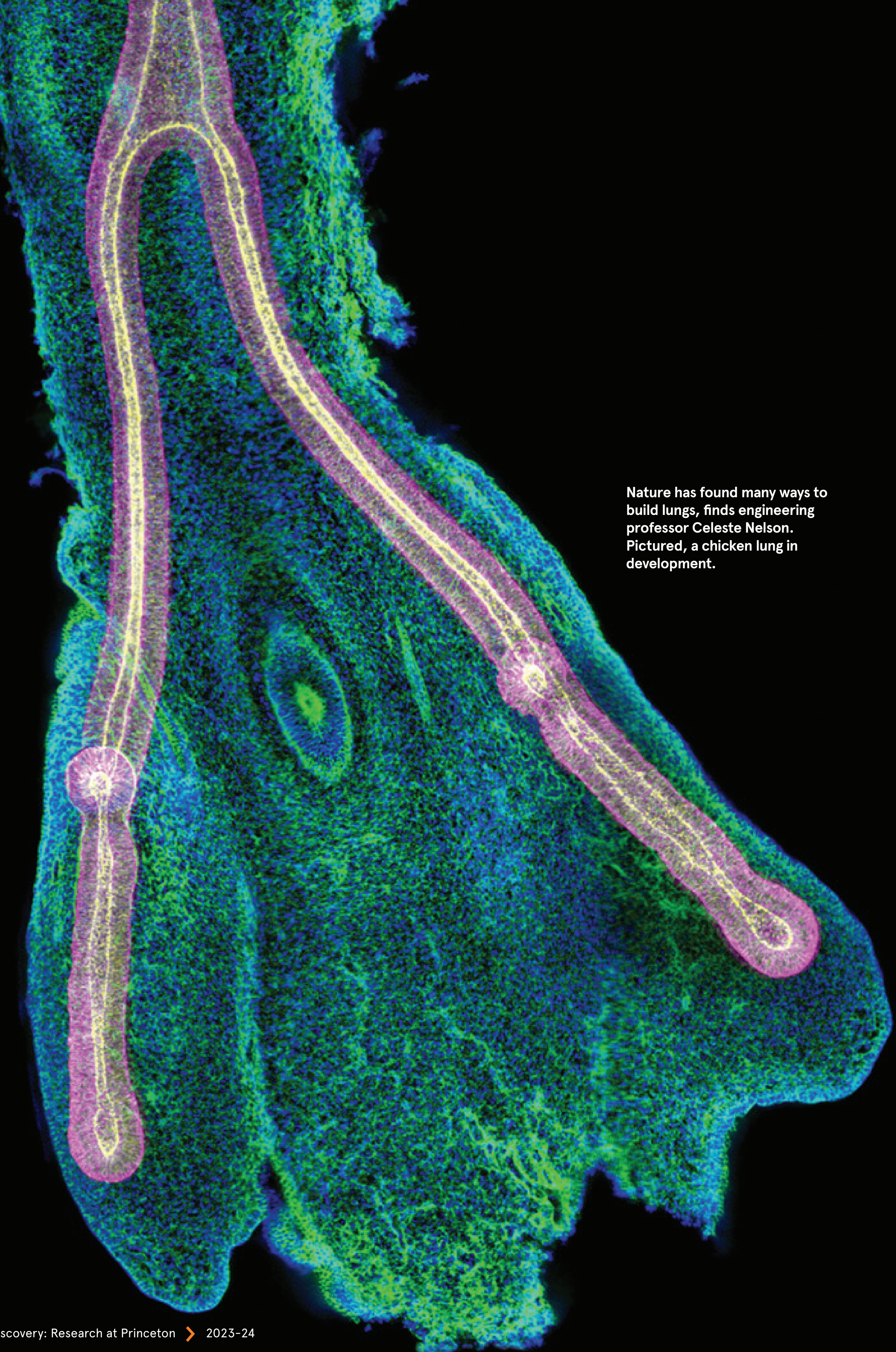
So far, they've found that in the same way people raised in similar cultures imagine similar stories, they also tend to recall similar memories when listening to music. "There are certain songs where people often tell us that they remember getting ready for prom with their friends," Margulis said. "If you're in a similar age demographic, there are specific ways that you were likely to hear music, which you'll remember when it's replayed." Understanding these neural connections may lead to better understanding of how to implement music-based interventions in medicine.

Via her exploration of music through the lenses of music theory, psychology and cognition, Margulis has constructed new pathways for understanding music's impact on our lives.

Her 2013 book, *On Repeat, How Music Plays the Mind*, digs into what features of music "hook" listeners, and how our craving for repetition is satisfied through music. In 2023, MIT Press published a book Margulis co-edited called *The Science-Music Borderlands*, which is a collection of interdisciplinary essays on topics in music psychology.

"Why is it that every known human culture has music?" Margulis said. "The answer that continually comes up is related to social bonding. If we're listening to music, and we're able to picture something similar, or remember something similar, then there is something there that connects us in an important way."

Margulis is currently writing a new book that she hopes will inspire others to look at music through the intersection of science and art, and to harness the power of music to build bridges between disciplines and cultures.



Nature has found many ways to build lungs, finds engineering professor Celeste Nelson. Pictured, a chicken lung in development.

PHOTO BY BEZIA LEMMA, POSTDOCTORAL RESEARCH FELLOW

Patterns of life

Celeste Nelson and her team find we have much to learn from the lungs of other species

By Yaakov Zinberg

Celeste Nelson has been upending assumptions about developmental biology since she opened her lab at Princeton some 16 years ago.

As part of her research into how lungs develop before birth, she and an undergraduate mentee found they could measure the effect of a particular chemical on the patterns of lung growth in chicken embryos. They excitedly submitted their work for peer review but were met with a lukewarm response.

"One of the reviewers said that this is fine," recalled Nelson, "but this had already been known, because folks had observed similar phenomena in mice, and mice are the same as chickens." Because the conventional wisdom at the time said that chicken lungs form and behave like mouse and human lungs, Nelson's findings in chickens were considered unremarkable.

Instead of accepting this status quo, Nelson became motivated to further investigate how lung development, also known as lung morphogenesis, differs across species. "It was in part because of that comment that we decided to dive deeply into these possible differences between birds, mammals, and reptiles," said Nelson, who today is the Wilke Family Professor in Bioengineering at Princeton. She and her research team have since identified unique mechanisms that govern how lungs are built in mice, chickens, and, most recently, a lizard called the brown anole. Rather than focus on the molecules that are involved in these processes, they use physics and materials science to understand how lung tissue bends and folds into lungs that can support breathing immediately after birth.

She and her research team have found that members of the animal kingdom have efficient designs for building lungs that can change the way we approach human tissue engineering. Evolutionary diversity in the development of lungs could inspire new ways of constructing human lung tissue outside the body, which could be used to treat people suffering from chronic lung diseases.

"Conventional tissue engineering would be to say, 'How does the mouse do it? How does the human do it? Let's do it that way,'" said Nelson. But nature, says Nelson, has found many ways to build lungs, and we can learn something from each of those ways. "There's beauty in diversity," she added, "and we can construct an engineering toolbox from the diversity of mechanisms we uncover."

Variations in lung development across species may inspire new ways of constructing human lung tissue outside the body, which could be used to treat people suffering from chronic lung diseases.

Balloon animals

No synthetic material can perfectly match the properties and function of lungs, but Nelson compares lungs to balloons: both balloons and lungs take in and expel air and are insulated from the outside environment by a thin layer of material, be it plastic or lung cells. To shape a simple balloon into a more complex structure — think balloon animals — you'd need to know the balloon's material properties, like how elastic and compressible it is, as well as the amount and kinds of forces to apply to the material. The same factors dictate how lungs are formed.

Nelson found that a type of stiff tissue called smooth muscle, which was previously assumed to lack a role in lung development, is critical for the formation of branches in mouse lungs. Mammalian lungs contain millions of microscopic tubes called bronchioles that sprout like tree limbs from larger airways.

Using mouse cells that express fluorescent proteins, Nelson's team created a time-lapse video that showed smooth muscle wrapping around the elongating bronchiole like a telephone cord, forcing the softer bronchiole to fork into two daughter branches that, fittingly, together resemble Mickey Mouse ears. This process occurs at the terminus of each growing branch, resulting in millions of such branching events over the course of lung development. The researchers found that this mechanism results from the elasticity of the different tissues and the physical forces within the budding lung.

Nelson's lab's latest model organism, the brown anole, has provided surprising insights into how simple lung development can be. This lizard is about the length of a pencil as an adult and is recognizable by its dewlap, a vibrant orange flap of scaly skin hanging from the throat. Because these anoles are highly invasive in Florida, two graduate students from the lab traveled there to capture some and road-tripped through the night back to Princeton with their new companions. (It turns out you can't bring a dozen anoles aboard a plane or check into a hotel with them.)

Rather than compare anole lungs to a balloon, Nelson and her lab found that they more closely resemble a different material: a stress ball — specifically, the kind with a mesh exterior that bulges into little orbs of goo when squeezed. Anole lungs do not contain the intricate branches found in mouse lungs. Instead, the lung precursor is a lobe of thin tissue known as epithelium that develops bumps across its surface. Smooth muscle forms a hexagonal lattice through which the bumps of epithelium protrude due to the force of fluid pressure from within the lung. Not more than two days after this process begins — dubbed by Nelson's group as "stress-ball morphogenesis" — the lungs are fully formed, ready to perform gas exchange through the bumps of epithelium.

Much more research is needed before scientists can construct lungs outside the body. Building the delicate blood vessels that keep tissue alive, for example, is an especially tricky puzzle bioengineers haven't yet cracked. Nelson's work of studying lung development in


PHOTO BY ADENA STEVENS

Celeste Nelson, the Wilke Family Professor in Bioengineering at Princeton, compares growth and branching of lungs across species to reveal new facets of human development.

different species helps identify models of biological design that can potentially inspire biotechnology applications; though anole and human biology have very little in common, the unexpected (and previously unknown) speed and elegance of stress ball morphogenesis could prove useful for engineers trying to simplify the design of artificial human lungs.

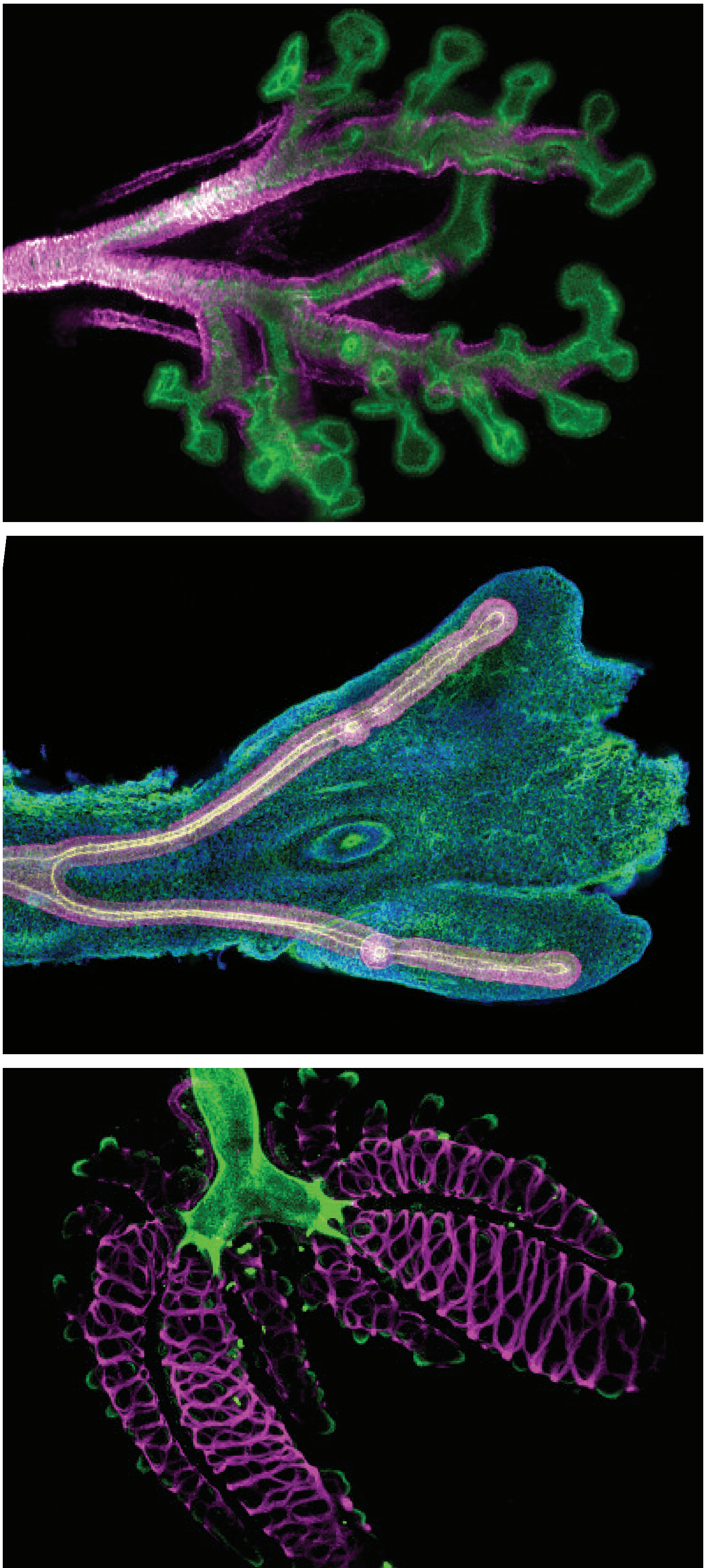
Seeing the system with fresh eyes

Most academic research groups are highly specialized: biologists are typically the only ones who'd work in a biology lab, and chemists and physicists will similarly stick to their own kind. Nelson's research group, however, is remarkably diverse, and includes biologists, physicists, mathematicians, bioengineers and herpetologists (reptile experts) who collaborate on a regular basis. For Nelson, creating an interdisciplinary environment is key to the research process.

"What I like about putting them all together in one lab is that they start to question each other's assumptions," Nelson said.

"Everyone comes in with a certain level of ignorance, and that ignorance is a massive superpower, because they don't know what the dogmas are," she added. "Just about all our major findings have come from being completely ignorant about how biology is supposed to work, and actually seeing the system with fresh eyes."

Within the biology community, for instance, it's traditionally been assumed that conserved traits — those shared by different species and selected by evolution on multiple occasions — are inherently important, while nature's outliers are less worthy of study. Because many in Nelson's group were trained outside the world of biology, they're not beholden to its assumptions and have no issue



IMAGES: BEZIA LEMMA, POSTDOCTORAL RESEARCH FELLOW, PRINCETON UNIVERSITY, AND KATHARINE GOODWIN, PRINCETON PH.D. 2022 AND POSTDOCTORAL FELLOW AT CAMBRIDGE UNIVERSITY

prioritizing the study of unconserved traits, like mechanisms of lung development.

Bezia Lemma, a postdoctoral research associate working with Nelson, exemplifies the team's versatility. With a Ph.D. in physics, Lemma wanted to apply his background to study developmental diseases in chickens. Everyone told him the two were incompatible, but he found a home in Nelson's group, where he is now investigating the thermodynamics of chicken lung development. He credits his new colleagues with catching him up to speed on techniques not in the arsenal of your average physicist, like dissecting chicken embryos.

"People were very forgiving of my lack of knowledge about developmental biology, and were very willing to both speak to me in my language of physics, and also try to bring me into the language of developmental biology," Lemma said of his labmates.

Lemma compared a typical lab meeting to an introductory foreign language class. "Everybody in the room is trying to learn French, but nobody in the room speaks the same language, and we all have to be okay stumbling over French together. And then there are a few French people in the room who somehow agree to walk us through it," said Lemma, where "French" could be materials science one day and molecular biology the next.

These communication skills enable the scientists to discuss their research with each other, and Nelson hopes the team will use these skills to communicate their future research to the general public once they leave Princeton. Skills like explaining jargon, breaking down difficult concepts into digestible parts, and distilling data into a story about a single research question never become obsolete for the scientist interested in sharing their research, even if the methods of conducting research do.

"These are skills that aren't typically taught to scientists and engineers," said Nelson, "and they really are, I think, some of the most

Images of lungs in development across various species — mouse, chicken, chameleon — provide researchers in the laboratory of Professor Celeste Nelson with information about the diverse architectures that provide life-giving oxygen, knowledge that could prove useful for engineers trying to simplify the design of artificial human lungs.

important training we can give. Whatever career path they choose, being able to communicate is essential."

Branching out

It was thanks to a generous graduate student that Nelson set her sights on a career in research. As an undergraduate at the Massachusetts Institute of Technology, she had a work-study job washing glassware in a biology lab. She always had an interest in biology, but thought of it as something you learned in a classroom, not a hands-on undertaking in which a person could make discoveries — and certainly not something out of which you could build a successful career. During the fall of her sophomore year, a grad student in the lab asked if she wanted to help with an experiment, a relatively simple one to measure how cells interact with different proteins. Nelson was hooked.

"I was just so excited," she said. "I flew home for winter break, and I was just jumping up and down, telling my mom that I was going to get to work with antibodies. There was just something intoxicating about going into the lab and setting up an experiment and then seeing a result for the first time. That drew me into science."

Nelson said this enthusiasm is shared by Princeton scientists. "It's the one place I've ever been where people are legitimately excited each and every time they talk about science and are eager to help," said Nelson. This makes collaborations between different labs commonplace on campus, and Nelson works closely with two Princeton colleagues. One is Andrej Košmrlj, associate professor in mechanical and aerospace engineering, who leads a group that specializes in building computational models to simulate the forces behind biological processes like lung morphogenesis. By incorporating data about the material properties of lung tissue, these models show how the tissue responds to forces within the embryo.

The other member of the trio is Jared Toettcher, associate professor of molecular biology, who uses optogenetics, a technique to control gene expression using light signals, to monitor and manipulate cell behaviors. As part of the anole study, Toettcher and his team engineered optogenetic components that successfully enabled control over when and where smooth muscle contracts, which could be the first step toward controlling how engineered human lungs grow.

The lungs aren't the only organ to grow via a branching pattern, and Nelson is investigating some of the others as well. She recently received the National Institutes of Health Director's Pioneer Award to investigate how the timing of lung, pancreas, and kidney development is coordinated such that all three organs have fully matured by birth. She calls this her "Thanksgiving dinner" project.

"If you think about Thanksgiving dinner, you want everything done at dinner time: you want the turkey done at the same time as the stuffing at the same time as the veggies at the same time as the gravy. If something's done too early, then it gets dry or cold. If something's done too late, then people are complaining because they're waiting."

> **"Just about all our major findings have come from being completely ignorant about how biology is supposed to work, and actually seeing the system with fresh eyes."**
>
> — **Celeste Nelson**

Flaws in the timing of organ development are associated with birth defects and chronic disease, yet it's still a mystery how organs develop at just the right pace. "The embryo manages to solve the Thanksgiving dinner problem each and every time, no matter what the species is," Nelson said.

The lungs, however, will always have Nelson's heart. And there are many more kinds of lungs to figure out. Her lab is now beginning to study lung development in tadpoles, which are born with gills but grow lungs as they metamorphose into frogs. Nelson and her lab are a diverse team of experts working out yet another mechanism of lung development to further reveal nature's endlessly diverse beauty. ●

TRADE SECRETS

Archaeologist Samuel Holzman discovers hidden architecture in ancient Greek ruins

By Kirstin Ohrt

W

With an L-square, paper and pencil, archaeologist Samuel Holzman uncovered a 2,000-year-old trade secret held by the ancient builders on the northern Greek island of Samothrace. The finding, that the "flat arch" building technique was used in the island's covered walkway, or stoa, alters the timeline of Greek and Roman architectural history.

Flat arches, Holzman discovered, appeared on Samothrace 150 years prior to what had previously been considered its debut in Rome. His discovery has architectural historians taking out their own L-squares and revisiting the drawing board on other ancient structures. "This new finding prompts the suspicion that more examples are also hiding in plain sight in other already excavated stoas, with the unexpected going overlooked," said Holzman, assistant professor of art and archaeology and the Stanley J. Seeger '52 Center for Hellenic Studies.

A wellspring of rivalry and innovation

Samothrace juts out of the northern Aegean Sea to a mile-high peak that scrapes moisture from the clouds and funnels it through waterfalls to crystalline pools around the island. Perhaps it's the dramatic and uniquely verdant landscape that creates the special aura, described in writings by the ancient Greeks, that still draws visitors from around the globe today.

Since at least the seventh century B.C.E., Samothrace was the home of the "Sanctuary of the Great Gods," a site for initiation into one of the ancient world's most renowned mystery cults. Plato and Aristophanes mention it, and the fifth-century B.C.E. historian Herodotus was himself an initiate. Philip II of Macedon and Olympias met during their initiations here, connecting the site to their son, Alexander the Great.

The most prominent excavated structures date to the third and fourth centuries B.C.E. and reflect a panoply of architectural paragons erected by Alexander's successors, each vying to outdo the other. This competitive spirit created an innovation incubator of sorts, brimming with architectural ingenuity: Samothrace boasts the largest rotunda of the Greek world, oldest known façade of freestanding Corinthian columns, first use of tapered beams, and Holzman's latest discovery, the first known use of the flat relieving arch. The island is also the original home of the sublime Winged Victory of Samothrace statue, representing the goddess Nike, now exhibited at the Louvre in Paris.


PHOTO BY KIRSTIN OHRT

On an off-the-beaten path Greek island, archaeologist Samuel Holzman uncovered a hidden architectural feature called the flat arch in Greek structures constructed 150 years earlier than the first known use by Romans.

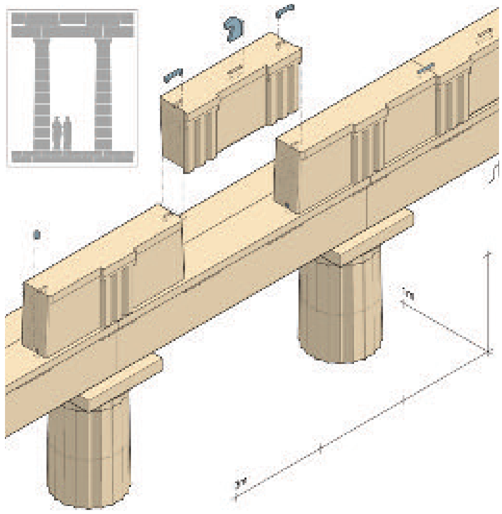
Of scholarly interest since 1444, Samothrace had been investigated by French, German, Austrian, Czech and Greek archaeologists before the American-led excavations began in 1938. The Institute of Fine Arts of New York University (NYU) and Emory University sponsor the American Excavations Samothrace project, which is funded by the National Endowment for the Humanities, National Geographic, and private donors. Since 2021, a grant from the Loeb Classical Library Foundation has supported work on the ancient city wall.

Holzman joined the Princeton University faculty in 2021 and began bringing students on the excavation. The team works under the auspices of the American School of Classical Studies at Athens and the supervision of the Greek Archaeological Service for the Evros region.

It's all about the gap

The site of Holzman's flat arch discovery is the Sanctuary's largest building, the 104-meter-long stoa; "it just goes on for days," Holzman said. Its rough outline was determined in 1866 by a French expedition, and NYU archaeologists revealed the building's full plan in 1967 after a five-year excavation. Despite investigations in the decades since, the method by which ancient Greek builders had managed to construct this massive Doric structure from sub-optimal local limestone remained elusive.

The answer had been hiding among the blocks, waiting for a captive audience to detect it. "It was during the summer of 2020, when the COVID pandemic kept us from going into the field, that I sat down at home and tried to get to the bottom of the problem," Holzman said. "Using our field measurements,


SOURCE: SAMUEL HOLZMAN

The Greeks hid reinforcing structures called flat arches atop the Sanctuary's largest building, a column-lined covered walkway, or stoa. The flat arches included trapezoidal blocks that distribute weight across the architrave, or main beam, spanning each bay.

I sketched each of the blocks schematically so that I could try fitting them together in different ways. It was only in looking at the blocks all at once like jigsaw puzzle pieces that the pattern emerged." Holzman had to contain his excitement at solving the problem until 2021 when he could return to the site and recheck all the measurements. "That's when everything clicked into place," he said.

Holzman had pieced together evidence that the stoa's classic Doric frieze — the decorative band above the building's columns — concealed flat arches as a fail-safe against cracks in the beams below. Trapezoidal blocks in the shape of the keystone of an arch distributed the weight of the roof onto the columns. This gave the builders greater confidence that the limestone would not crack and unlocked a trade secret later used by the Romans to build larger and lighter structures.

The wedge-shaped blocks making up the flat arch had such subtle inclinations, just approximately three degrees, that it was easy to overlook their shape, until now. Placing an L-square on a stoa block, however, shows the critical difference: "You have this gap here," Holzman said.

Holzman and his team meticulously re-measured many of the stoa's 1,700 surviving blocks and found that the keystone blocks had space for a gap below, and each bore a cutting on top for lifting it with pulleys. Holzman deduced that blocks were placed in consecutive order in a continuous direction with keystones lifted into place. This allowed builders to maintain precise vertical control over the keystone while manipulating other blocks. The team published their findings in the September 2023 issue of the *Journal of the Society of Architectural Historians*.

With size as its wow factor, the stoa's construction could not make use of the prohibitively expensive white marble imported


COURTESY: THE AMERICAN EXCAVATIONS SAMOTHRACE

from Athens and the islands of Thasos and Proconnesos (the latter is now called Marama Island) and employed in other Samothracian buildings. "To get such a big building, they had to use local limestone. And the local stone had limitations," Holzman explained, noting its copious cavities and geological irregularities. Builders stretched poor-quality building material to cover maximum ground and summoned the flat arch technique to make it possible. In Holzman's words, "They've innovated to do more with less."

Holzman's discovery is even more astounding given that the evidence was intentionally obscured by the ancient Greeks. "They liked the technology of the arch and they wanted to use it," explained Holzman, "but god forbid you see it!" They veiled the flat arch blocks with a traditional Doric triglyph and metope frieze pattern, allowing triglyphs to slightly overlap metopes to conceal the angled joints. Rather than showcase their innovation, builders prioritized impressing their patrons with a classic-looking structure pushed to awe-inspiring proportions.

In their commitment to the illusion, Greeks used especially slight angles despite the increased risk of blocks slipping out of place. Later examples one can see around Rome diminish that risk and lay bare the technique, showing the zigzagging effect of angled blocks leaning against one another; to use Holzman's description, for the Romans, "there's no shyness about having cattywampus joints on the façade."

Though technology plays an important role in much of Holzman's research and teaching, it was decidedly absent from his investigative methods in this discovery. "I draw," said Holzman, "and drawing is an essential skill for this kind of research. It's hard to understand what a ruined building originally looked like unless you make a drawing of it. Our team includes architects, surveyors and digital modeling specialists, but I still draw many architectural finds by hand with pencil and paper. Drawing forces you to slow down, look very carefully, and think through what you are seeing."

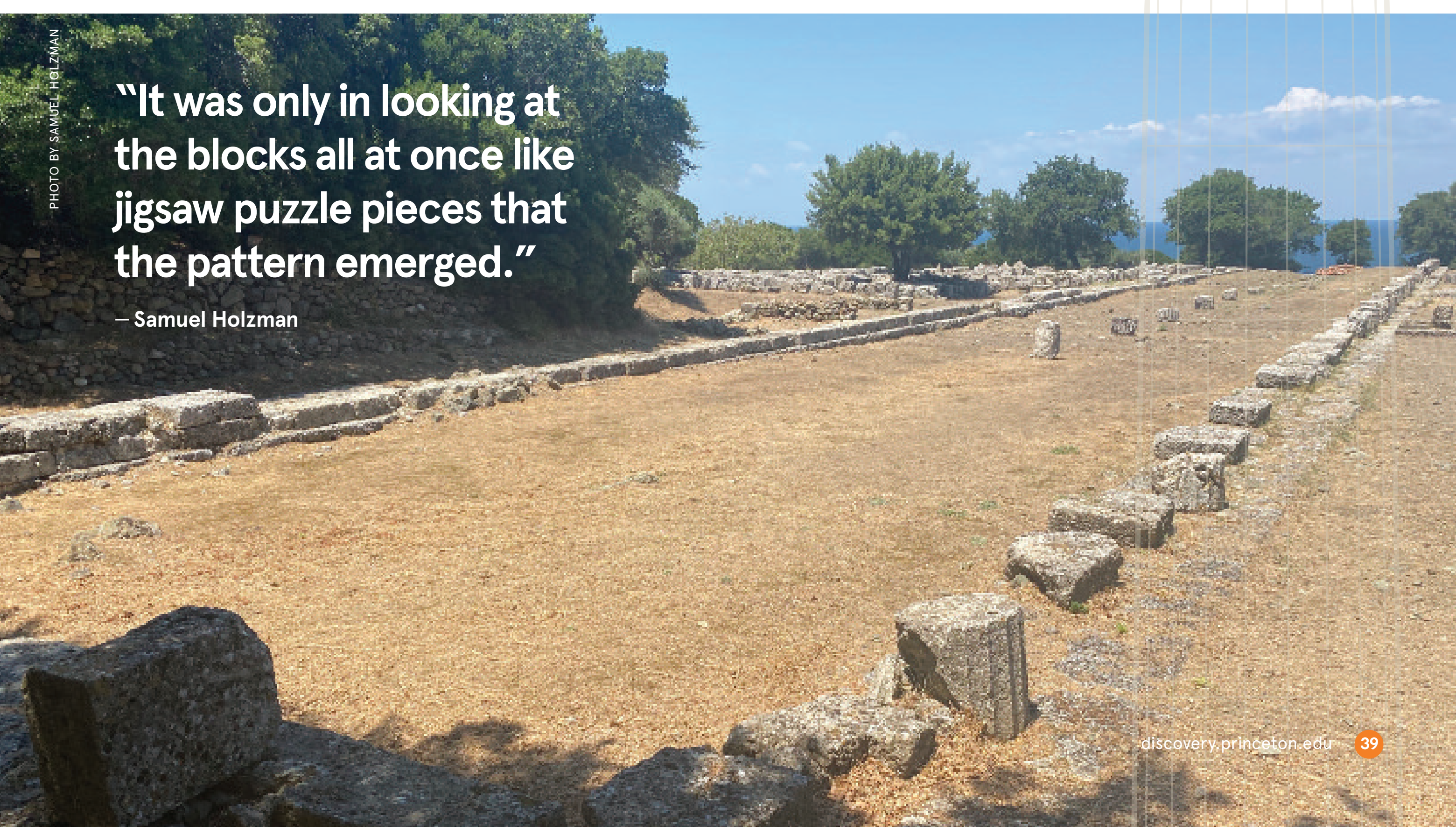
For Holzman, technology has an invaluable role to play in developing, confirming or illustrating an idea — post-epiphany.

Following breadcrumbs

The stoa's innovative construction applies a tenet of engineering demonstrated in two other Samothracian structures built in the previous century: that a beam undergoes maximum stress at its midpoint. A different solution was conceived in two other

The 104-meter long stoa, or column-lined walkway, was built in the third century B.C.E. (left) and fully excavated by 1967 (right), but the method of construction remained elusive.

PHOTO BY SAMUEL HOLZMAN

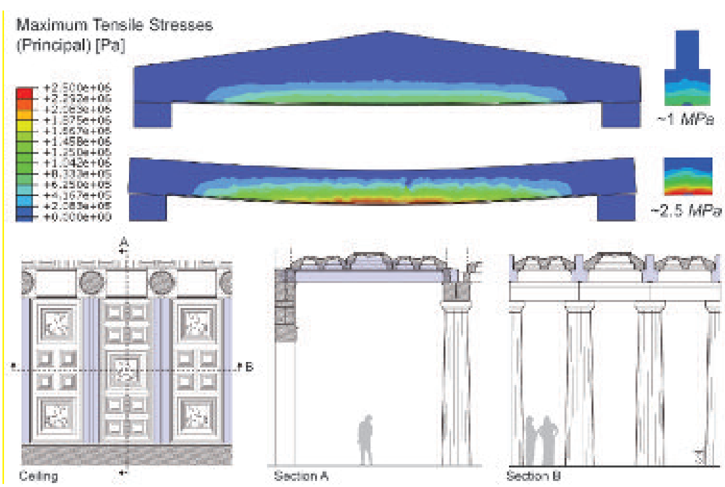


"It was only in looking at the blocks all at once like jigsaw puzzle pieces that the pattern emerged."

— Samuel Holzman

structures, the Hall of Choral Dancers and the Hieron, which both have the columnar façades common to Greek temples but housed gathering spaces for initiation.

Ceiling beams that cross significant spans require maximum strength and size for which Greek builders deciphered a strategy that offered both fortitude and grace. They carved marble beams with a central spine that came to its highest peak at the midpoint, tapering down at the ends.



SOURCE: ANTONIO MARIA D'ALTRI AND SAMUEL HOLZMAN

The researchers modeled the maximum tensile strength, or resistance of a material to breaking under tension, of a marble ceiling beam from the Hieron, obtained using numerical modeling. The additional height of the peaked structural spine hidden above the level of the ceiling doubled the strength of the beam.

In 2023, Holzman collaborated with Branko Glišić, professor and chair of civil and environmental engineering, to explore the beam design's efficiency. Using a static structures analysis, Glišić's team evaluated the stress distribution and structural performance of the beam, employing both analytical expressions and numerical modeling. Jonathan Gagnon, a Class of 2024 student majoring in civil and environmental engineering, worked on the analytical expressions as part of his junior-year research project, and Professor Antonio Maria D'Altri of the University of Bologna assisted with numerical model verification.

To Glišić's surprise, ancient builders had managed to optimize the shape of the beam based on the load. "Today's structures are designed using scientific concepts, such as solid mechanics and beam theory, which enables structurally sound, reliable and safe-optimized design," Glišić said, "whereas ancient Greeks optimized beams based on engineering intuition, experience and experimentation." Of the two approaches, Glišić said, "the latter is the one that sparks curiosity, creativity and exploration, and this mixture of playfulness and discipline showed excellent results some 2,000 years before the scientific concepts even started to be developed."

Glišić rates historical studies on structural engineering as extremely important. Though he had worked previously on heritage structures, his work with Holzman was Glišić's first collaboration with an archaeologist. Modern engineering has resolved the challenges Greek builders faced, Glišić said, but we continue to learn from their approach. "New technologies certainly help in solving complex problems related to structural analysis and design," he said, "but it is the understanding of the evolution of the engineering thoughts and experiences that helps build the intuition, creativity and confidence necessary to push the boundaries of the discipline."

Holzman looks forward to collaborating with Glišić on the new flat arch discovery. He is also reaching across disciplines on another aspect of his research, working with the Parsons Conservation Lab at Emory University and Princeton's newly formed interdisciplinary Art Conservation and Materials Science Working Group led by Craig Arnold, the Susan Dod Brown Professor of Mechanical and Aerospace Engineering and Vice Dean for Innovation, and Janna Israel, the Andrew W. Mellon Curator of Academic Engagement, Art Museum, to harness isotopic signatures to track the lead-sheathed iron staples that held the stone blocks of the stoa together.

PHOTO BY KIRSTIN OHRT

Other nuts to crack

As long as there is a question, the Samothrace excavation team will dig for its answer. In the summer of 2023, they sought the gate in the fortification wall that allowed passage between the Sanctuary and the ancient town. Investigating three possible locations simultaneously, the team has zeroed in on a passageway they have dubbed the West Gate: "We got it — and it's exciting!" Holzman declared.

Princeton alumna Hannah Smagh, who earned her Ph.D. in art and archaeology in 2023, along with Princeton graduate students Chiara Battisti, Eirini Spyropoulou and Robert Yancey, as well as undergraduate student

Holzman and Eirini Spyropoulou, graduate student in art and archaeology, measure a limestone block with L-squares near the Samothrace city wall.

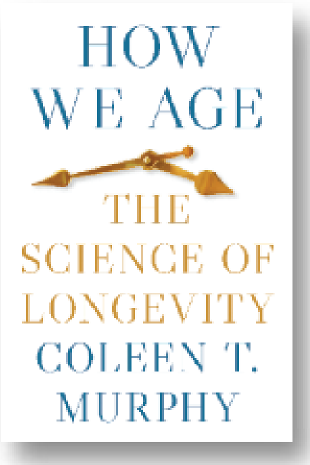
Elena Evnin, Class of 2024, all engaged in this endeavor in 2023. Their efforts were supported by summer fieldwork grants from the Seeger Center for Hellenic Studies. Spyropoulou worked on the location once mistaken for the gate, which is now understood to have been a tower. Paralleling the important work on the stoa, she measured and catalogued blocks associated with this structure. The next step will be to draw the stones and try to piece them together, one of her favorite challenges.

Spyropoulou values the first-hand experience and intellectual exchanges with her fellow students, but above all, she is grateful for the insight she has gained from Holzman, her adviser. "The way he reconstructs things, it's amazing!" she exclaimed. "He draws like Leonardo da Vinci."

Holzman credits his first mentor, Tasos Tanoulas, the architect who oversaw the restoration of the Propylaea, or ceremonial gateway, on the Acropolis, with shaping his approach to archaeology. "As a college student, Tasos opened my eyes to how much there still is to discover," said Holzman, "and he was one of the first people I told about our flat arch find. I had to get his read on it."

When asked whether he thinks more architectural secrets may lie hidden on Samothrace, he responded: "Of course! We cracked this nut, but there's a list of other tough ones that we're still chipping away at."

That said, next summer's tasks are well defined. "We're scratching the surface of something remarkable at the West Gate, and it will take several summers to uncover it completely," he said, "and Princeton students who join our excavation in summer 2024 will be instrumental in getting to the bottom of it." ●



How We Age: The Science of Longevity

Princeton University Press, November 2023

Coleen T. Murphy, James A. Elkins Jr. Professor in the Life Sciences; Professor of Molecular Biology and Director, Lewis-Sigler Institute for Integrative Genomics

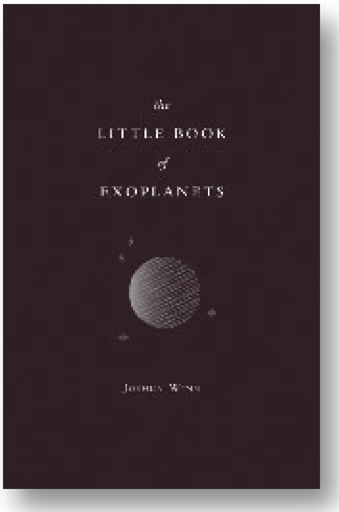
All of us would like to live longer, or to slow the debilitating effects of age. In *How We Age*, Coleen Murphy shows how recent research on longevity and aging may be bringing us closer to this goal. Murphy, a leading scholar of aging, explains that the study of model systems, particularly simple invertebrate animals, combined with breakthroughs in genomic methods, have allowed scientists to probe the molecular mechanisms of longevity and aging. Understanding the fundamental biological rules that govern aging in model systems provides clues about how we might slow human aging, which could lead in turn to new therapeutics and treatments for age-related disease.

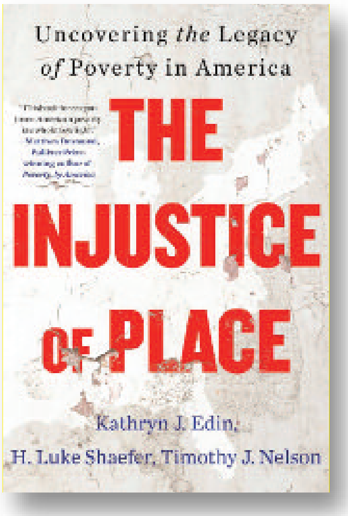
The Little Book of Exoplanets

Princeton University Press, July 2023

Joshua Winn, Professor of Astrophysical Sciences

For centuries, people have speculated about the possibility of planets orbiting distant stars, but only since the 1990s has technology allowed astronomers to detect them. At this point, more than 5,000 such exoplanets have been identified, with the pace of discovery accelerating after the launch of NASA's Transiting Exoplanet Survey Satellite and the Webb Space Telescope. In *The Little Book of Exoplanets*, Princeton astrophysicist Joshua Winn offers a brief and engaging introduction to the search for exoplanets and the cutting-edge science behind recent findings. In doing so, he chronicles the dawn of a new age of discovery — one that has rapidly transformed astronomy and our broader understanding of the universe.





The Injustice of Place: Uncovering the Legacy of Poverty in America

Harper Collins, August 2023

Kathryn Edin, William Church Osborn Professor of Sociology and Public Affairs, Princeton School of Public and International Affairs; Director, Bendheim-Thoman Center for Research on Child Wellbeing

Timothy Nelson, Lecturer in Sociology and Public Policy, Princeton School of Public and International Affairs

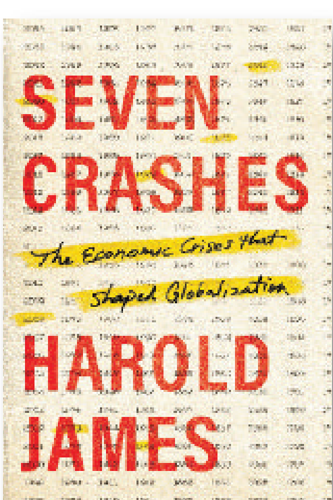
H. Luke Shaefer, University of Michigan

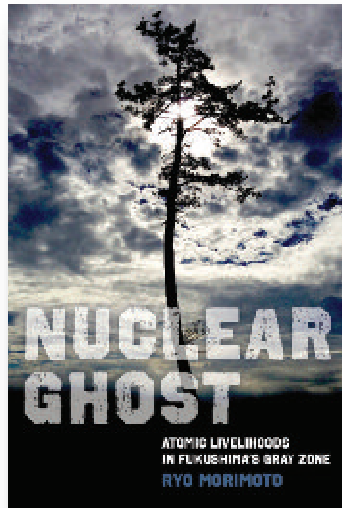
Three of the nation's top scholars — known for tackling key mysteries about poverty in America — turn their attention from the country's poorest people to its poorest places. Based on a fresh, data-driven approach, they discover that America's most disadvantaged communities are not the big cities that get the most notice. Instead, nearly all are rural. Little if any attention has been paid to these places or to the people who make their lives there. The unfolding revelation in *The Injustice of Place* is not about what sets these places apart, but about what they have in common — a history of raw, intensive resource extraction and human exploitation. This history and its reverberations demand a reckoning and a commitment to wage a new War on Poverty, with the unrelenting focus on our nation's places of deepest need.

Seven Crashes:
The Economic Crises That Shaped Globalization
Yale University Press, May 2023

Harold James, Claude and Lore Kelly Professor in European Studies, Professor of History and International Affairs

The eminent economic historian Harold James presents a new perspective on financial crises, dividing them into "good" crises, which ultimately expand markets and globalization, and "bad" crises, which result in a smaller, less prosperous world. Examining seven turning points in financial history — from the depression of the 1840s through the Great Depression of the 1930s to the Covid-19 crisis — James shows how crashes prompted by a lack of supply, like the oil shortages of the 1970s, lead to greater globalization as markets expand and producers innovate to increase supply. By contrast, crises triggered by a lack of demand — such as the Global Financial Crisis of 2007-08 — result in less globalization as markets contract, austerity measures are imposed, and skepticism of government grows. By considering not only the times but also the observers who shaped our understanding of each crisis — from Karl Marx to John Maynard Keynes to Larry Summers — James shows how the uneven course of globalization has led to new economic thinking, and how understanding this history can help us better prepare for the future.





Nuclear Ghost:
Atomic Livelihoods in Fukushima's Gray Zone
University of California Press, April 2023

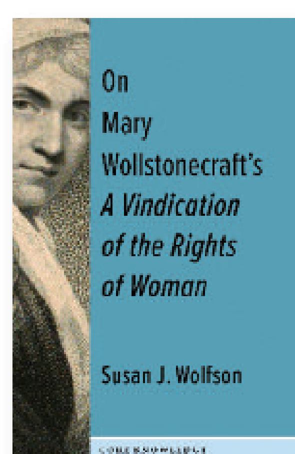
Ryo Morimoto, Assistant Professor of Anthropology, Richard Stockton Bicentennial Preceptor

"There is a nuclear ghost in Minamisōma." This is how one resident describes a mysterious experience following the 2011 nuclear fallout in coastal Fukushima. Investigating the nuclear ghost among the graying population, Ryo Morimoto encounters radiation's shapeshifting effects. What happens if state authorities, scientific experts, and the public disagree about the extent and nature of the harm caused by the accident? In one of the first in-depth ethnographic accounts of coastal Fukushima written in English, *Nuclear Ghost* tells the stories of a diverse group of residents who aspire to live and die well in their now irradiated homes. Their determination to recover their land, cultures and histories for future generations provides a compelling case study for reimagining relationality and accountability in the ever-atomizing world.

On Mary Wollstonecraft's *A Vindication of the Rights of Woman*
Columbia University Press, April 2023

Susan Wolfson, Professor of English

Mary Wollstonecraft's *A Vindication of the Rights of Woman* (1792) made a pioneering and durably influential argument for women's equality. Emerging from the turbulent decade of the French Revolution, her vindication delivered a systematic critique of the treatment of women across time and place. Drawing on extensive experience teaching and writing about Wollstonecraft, Susan J. Wolfson offers new insight into how Wollstonecraft's particular methods, style and energy make this case for her readers. Wolfson reveals her as a pioneer in decoupling sex from gender and shows how she provided an enduring model of how to be a female intellectual. Sharing the excitement of reading Wollstonecraft's work with care for her literary as well as political genius, this book provides fresh perspectives both for first-time readers and those seeking a nuanced appreciation of her achievements.



Viviana Zelizer receives highest award from American Sociological Association

PHOTO BY DENISE APPLEWHITE

The American Sociological Association (ASA) recognized Viviana Zelizer, the Lloyd Cotsen '50 Professor of Sociology, for her pioneering contributions with its highest honor, the W.E.B. Du Bois Career of Distinguished Scholarship Award. Zelizer also received the ASA's Distinguished Career Award for the Practice of Sociology. In the W.E.B. Du Bois award citation, the committee wrote: "Considered by many one of the greatest and internationally impactful living sociologists, Professor Zelizer has, over a career spanning more than four decades, made field-defining and generative contributions to various areas, including economic sociology, the sociology of childhood, the sociology of intimacy, and perhaps most fundamentally, the sociology of money." ***–Daniel Day***

Alsdorf, Leving and Mendelberg receive 2023 Guggenheim Fellowships

Three Princeton faculty members have received 2023 Guggenheim Fellowships.

Bridget Alsdorf, professor of art and archaeology, was awarded the Guggenheim in the field of fine arts research. Her research specializes in European art of the 19th and early 20th centuries, especially art's intersections with literature, philosophy and social theory.

Yuri Leving, professor of Slavic languages and literatures, was awarded the Guggenheim in the field of intellectual and cultural history. His research specializes in contemporary Russian literature and film, Eastern European cinema, the visual arts, and digital humanities.

Tali Mendelberg, the John Work Garrett Professor in Politics, director of the Program on Inequality at the Mamdouha S. Bobst Center for Peace and Justice, and co-director of the Center for the Study of Democratic Politics, was awarded the Guggenheim in the field of political science. Her areas of specialization are political communication, gender, race, class, public opinion, political psychology and experimental methods. ***–Jamie Saxon***

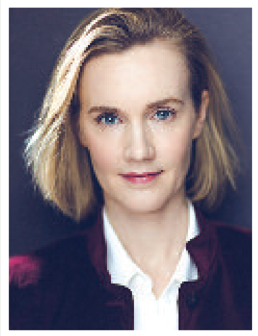


PHOTO BY DAVID NOLES

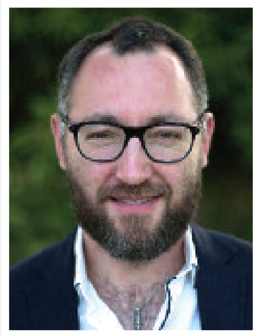


PHOTO BY ANNE GONSCHOREK

PHOTO BY CHRIS FASCENELLI

Ecologist Jeanne Altmann and ethicist Peter Singer honored with Frontiers of Knowledge Awards

Two Princeton professors, Jeanne Altmann and Peter Singer, have been awarded 2023 Frontiers of Knowledge Awards by the BBVA Foundation. The awards recognize basic research and creative work worldwide that significantly enlarges the stock of knowledge in a discipline, opens up new fields, or builds bridges between disciplinary areas.

PHOTO BY BRIAN WILSON

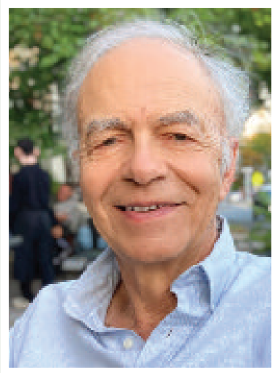


PHOTO BY KATARZYNA DE LAZARI-RADEK

Altmann, Princeton's Eugene Higgins Professor of Ecology and Evolutionary Biology, Emeritus, is one of three recipients of the 2023 Ecology and Conservation Biology award, recognized "for their outstanding contributions to the behavioral and evolutionary ecology of animals."

Singer, the Ira W. DeCamp Professor of Bioethics in the University Center for Human Values, is one of two recipients of the 2023 Award in Humanities and Social Sciences for his work focusing on the ethical consideration of animal rights. ***–Liz Fuller-Wright and Daniel Day***


PHOTO BY DENISE APPLEWHITE


PHOTO BY MICHAEL FRANKEN


PHOTO BY TORI REPP/FOTOBUDDY


PHOTO BY FRANK WOJCIECHOWSKI

Four engineering professors receive Moore Foundation experimental physics awards

Four Princeton University researchers — Nathalie de Leon, Julia Mikhailova, Barry Rand and Jeff Thompson — have won a Gordon and Betty Moore Foundation Experimental Physics Investigators Initiative award. The grants will support research into quantum computing, advanced solar cells and laser-based sensing technologies, as well as efforts to foster inclusive research communities.

The Moore Foundation announced 21 such awards for 2023. Each investigator will receive $1,250,000 over the next five years to advance scientific frontiers in experimental physics. ***–Office of Engineering Communications***

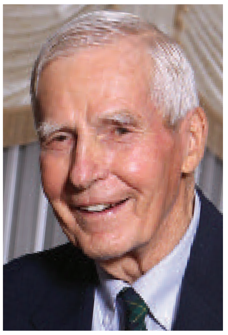


PHOTO BY FRANK WOJCIECHOWSKI


PHOTO BY DENISE APPLEWHITE

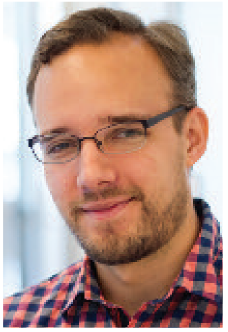


PHOTO BY SAMEER A. KHAN/FOTOBUDDY

Bryan, McComas and Buschman receive prestigious honors from the National Academy of Sciences

Three Princetonians are among the 16 scientists receiving the highest honors given by the National Academy of Sciences (NAS). These major awards recognize extraordinary scientific achievements in a wide range of fields spanning the physical, biological, social and medical sciences.

Kirk Bryan Jr., senior oceanographer, emeritus, received the Alexander Agassiz Medal (awarded every five years) for pioneering and visionary work in oceanography and climate science.

David McComas, Princeton's vice president for the Princeton Plasma Physics Lab and professor of astrophysical sciences, received the Arctowski Medal (awarded every two years) for pioneering contributions to experimental space plasma physics.

Timothy Buschman, associate professor of psychology and neuroscience, received a Troland Research Award (won by two scientists each year) for his groundbreaking contributions and insights into the neural mechanisms of cognitive control. ***–Liz Fuller-Wright***

Patricia Smith and Ilya Kaminsky named Academy of American Poets Chancellors

Patricia Smith, professor of creative writing in the Lewis Center for the Arts, and Ilya Kaminsky, professor of creative writing, have been named Academy of American Poets Chancellors. Chancellors serve six-year terms during which they consult with the organization on artistic matters, judge the organization's largest legacy prizes for American poets, and act as ambassadors of poetry in the world at large. Kaminsky, raised in Odessa, Ukraine, is author of numerous poems that have been translated into over 20 languages. Smith is the author of eight books of poetry. She joined the Princeton faculty in 2023 after holding a visiting professorship. Previously, she was a distinguished professor at the City University of New York. ***–Jamie Saxon***


PHOTO BY JONATHAN M. SWEENEY


PHOTO BY ILYA KAMINSKY

Research at Princeton aims to advance the frontiers of human knowledge and improve societal well-being. Funding for research comes from both external and internal sources. External sources include federal agencies, foundations, industry and other funders. Internal sources of research funding include donors and the Princeton University endowment. The University allocates internal funds to research projects and infrastructure across the sciences, engineering, social sciences and humanities.

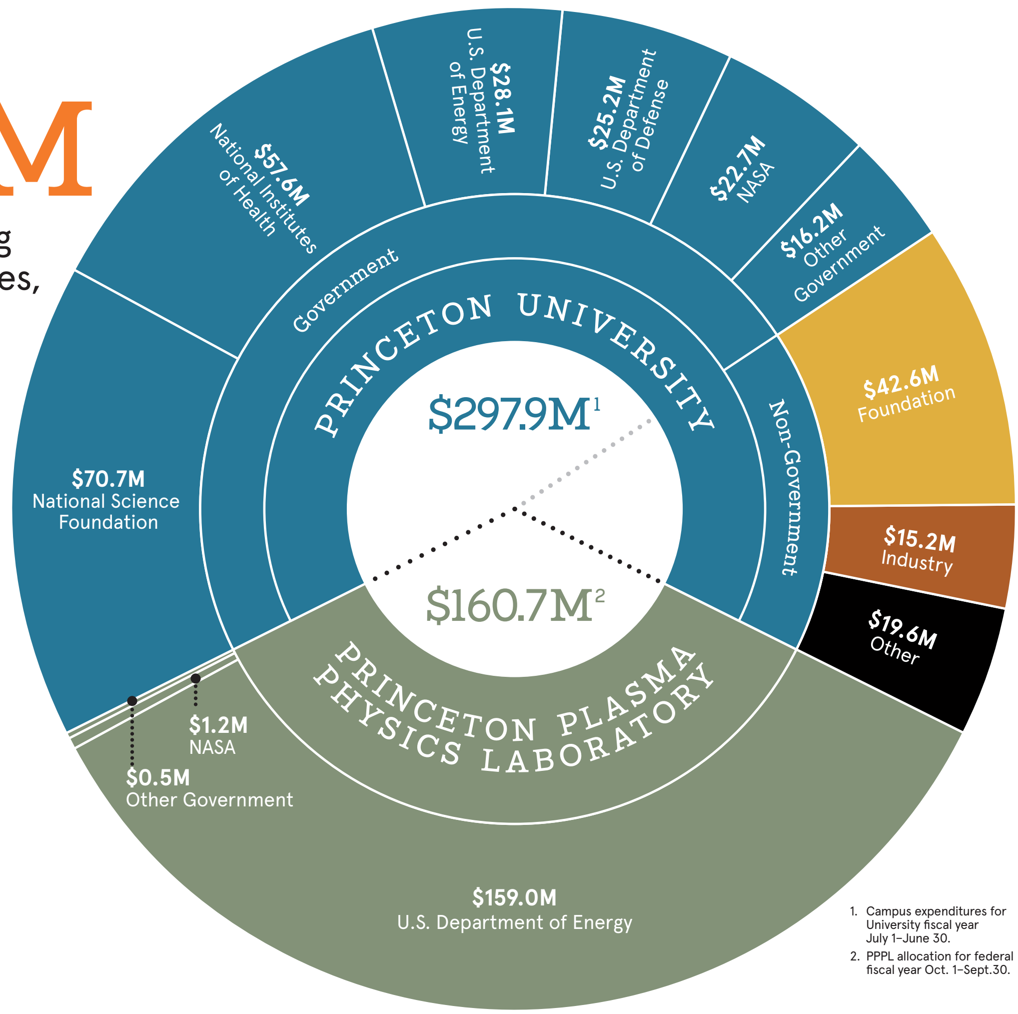
This page provides information about external sources of research funding, as measured by research expenditures, for the Princeton University campus and the University-managed Princeton Plasma Physics Laboratory.

TOTAL $459M

in research spending from external sources, fiscal year 2023

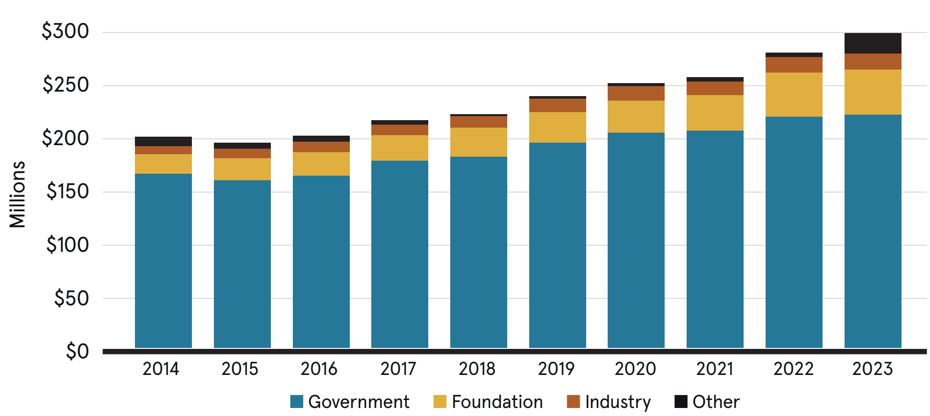
This chart shows research expenditures by funding source, excluding gifts and internal sources.

Source: Office of Research and Project Administration Annual Report; Princeton Plasma Physics Laboratory (PPPL).



1. Campus expenditures for University fiscal year July 1–June 30.
2. PPPL allocation for federal fiscal year Oct. 1–Sept.30.

CAMPUS RESEARCH SPENDING



Office of Research and Project Administration Annual Report, fiscal years 2014–23. Excludes gifts and internal funding.

EXPANDING OPPORTUNITIES FOR RESEARCH AND INNOVATION

Over the past 10 years, the University's research activities have expanded dramatically, as measured by spending on research. The growth in research expenditures reflects increases in government, foundation, industry and other support, excluding gifts and internal funding.

Source: Office of Research and Project Administration, FY14-FY23

49% ↑	TOTAL RESEARCH SPENDING
34% ↑	GOVERNMENT SOURCES
99% ↑	INDUSTRY SOURCES
131% ↑	FOUNDATION SOURCES
119% ↑	OTHER SOURCES

INNOVATION

Faculty-led discoveries inspire new products and technologies that can benefit humanity. Fiscal year 2023 activities include:

113
INVENTION DISCLOSURES

183
PATENT APPLICATIONS

27
U.S. PATENTS ISSUED

18
LICENSE AND OPTIONS AGREEMENTS

Source: Office of Technology Licensing

STARTUPS AND ENTREPRENEURSHIP

Startup activity based on Princeton research grew significantly since 2020, when the Princeton Innovation initiative launched.

25
STARTUPS FORMED

OVER **50%**
OF NEW LICENSES WENT TO STARTUPS

MORE THAN **$550M**
IN FUNDING RAISED BY STARTUPS

Source: Office of Technology Licensing

Princeton Research › Office of the Dean for Research

We support Princeton researchers as they create knowledge, make discoveries, and address scientific and technical challenges. Our offices enable research, innovation and entrepreneurship to transition discoveries into benefits for society.

research.princeton.edu

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NHP Research Program
Mario Rodriguez, Director

Special Projects
Stuart Leland, Director

PHOTO BY JARED FLESHER

Lauren Pincus studies the interaction of microplastics and heavy metals in the natural environment of New Jersey's Barnegat Bay (pictured) and at Lake Carnegie on Princeton University's campus. Pincus, a National Science Foundation Earth Sciences Postdoctoral Fellow, is an environmental chemist working to understand the risks that microplastics pose to ecosystems.

Princeton Research › Office of the Dean for Research

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When the British attacked Manila in 1762, they pillaged many Spanish-Empire treasures, including roughly 1,500 rare manuscripts, maps and printed materials relating to the Philippines and other regions. An international collaboration is reuniting these materials through a new digital archive. **Page 14.**

AN ENGLISH TWO-DECKER LYING HOVE TO, WITH OTHER SHIPS AND VESSELS IN A FRESH BREEZE, PAINTING BY DOMINIC SERRES