Discovery

Research at Princeton

Bridging the divide
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2022-23

PRINCETON UNIVERSITY

Expanding spaces, expanding knowledge

Visiting Princeton today, you'll see a landscape of expansion. At construction sites across campus, we are adding four science and engineering buildings, a new home for the Princeton Art Museum, and new residences and facilities for graduate and undergraduate students.

Physical growth often mirrors other types of growth that are essential to what it means to be a university — a place that fosters the expansion of the boundaries of knowledge, as well as personal and professional growth through research, teaching and learning. Over the years, Princeton has balanced its comparatively small size with a remarkable level of research impact, as measured by journal citations and other metrics that indicate the degree to which its contributions to human knowledge influence the scholarly community and the world at large. Princeton is consistently ranked as one of the top 10 research universities in the world.

Research spending at Princeton on awards funded by the federal government, industry and foundations has increased steadily over the past decade, enabling new projects and research directions across the humanities, the social sciences, the natural sciences and engineering. Reflecting this exciting growth in the scope and intellectual diversity of our research programs, Princeton is now home to the Space Physics laboratory, which is developing NASA-funded instruments to study the sun and solar corona, with the goal of understanding the universe and helping to protect earthly communications against solar storms (page 4). Growth is also occurring in research areas such as the humanities (page 24); artificial intelligence, through the hiring of new faculty in the Department of Computer Science (page 28); and development economics, as reflected by the joint program between the Department of Economics and the School of Public and International Affairs (page 34).

Through these pages, we invite you to meet our faculty members and their teams who work to expand knowledge, and in so doing strengthen the vitality of Princeton's commitment to education, research and service. As the jackhammers and construction vehicles continue their work, we look forward to the new opportunities that our campus expansion will bring to reaffirming and strengthening Princeton's commitment to research in the service of humanity.

PHOTO BY FRANK WOJCIECHOWSKI

Pablo G. Debenedetti
Dean for Research
Class of 1950 Professor in Engineering and Applied Science
Professor of Chemical and Biological Engineering

Inside

Discovery › Research at Princeton annual research magazine 2022-23

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In the Nation's Service and the Service of Humanity

ON THE COVER:
A new joint program between the School of Public and International Affairs and the Department of Economics seeks solutions to the challenges facing lower income households. Page 34. Photo by Aude Guerrucci.

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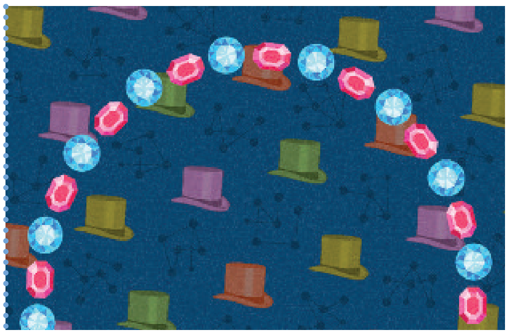


PHOTO BY BUMPER DEJESUS

ENGINEERING

Solar technology marks major milestone

Researchers have developed the first perovskite solar cell with a commercially viable lifetime, marking a major milestone for an emerging class of renewable energy technology. The research team projects their device can perform above industry standards for around 30 years, far more than the 20 years used as a threshold for viability for solar cells.

Perovskites are semiconductors with a special crystal structure that makes them well suited for solar cell technology. They can be manufactured at room temperature using much less energy than silicon, making them cheaper and more sustainable to produce.

The Princeton team, led by Lynn Loo, the Theodora D. '78 and William H. Walton III '74 Professor in Engineering, revealed their new device and their new method for testing in a paper published June 16, 2022, in *Science*.

Due to perovskites' well-known frailty, long-term testing hasn't been much of a concern until now. But as the devices get better and last longer, testing one design against another will become crucial in rolling out durable, consumer-friendly technologies.

"The really exciting thing is that we now have a way to test these devices and know how they will perform in the long term," Loo said. ***—Scott Lyon***

GEOSCIENCES

Shark Week was every week for Megalodon

New research shows that prehistoric megatooth sharks, the biggest sharks that ever lived, were at the very highest rung of the prehistoric food chain — what scientists call the highest "trophic level." Indeed, their trophic signature is so high that they must have eaten other predators and predators-of-predators in a complicated food web, say the researchers.

"We're used to thinking of the largest species — blue whales, whale sharks, even elephants and diplodocuses — as filter feeders or herbivores, not predators," said Emma Kast, a 2019 Ph.D. graduate in geosciences who is the first author on the study in the June 22, 2022, issue of *Science Advances*. "But Megalodon and the other megatooth sharks were genuinely enormous carnivores that ate other predators, and Meg went extinct only a few million years ago."

To reach these conclusions, Kast, along with her adviser Danny Sigman, Princeton's Dusenbury Professor of Geological and Geophysical Sciences, and their colleagues used a novel technique to measure the nitrogen isotopes in the sharks' teeth. Several lines of evidence point to cannibalism in both megatooth sharks and other prehistoric marine predators.

"If Megalodon existed in the modern ocean, it would thoroughly change humans' interaction with the marine environment," Sigman said. ***—Liz Fuller-Wright***

PHOTO BY HARRY MAISCH

Collaborator Harry Maisch of Florida Gulf Coast University holds a Megalodon tooth.

PHOTO COURTESY OF THE GALÁPAGOS CONSERVANCY

ECOLOGY AND EVOLUTIONARY BIOLOGY

'Fantastic giant tortoise,' believed extinct, confirmed alive in the Galápagos

A tortoise from a Galápagos species long believed extinct has been found alive and now confirmed to be a living member of the species. The tortoise, named Fernanda after her Fernandina Island home, is the first of her species identified in more than a century.

The Fernandina Island Galápagos giant tortoise (*Chelonoidis phantasticus*, or "fantastic giant tortoise") was known only from a single specimen, collected in 1906. The discovery in 2019 of a female tortoise living on Fernandina Island provided the opportunity to determine if the species lives on. By sequencing the genomes of both the living individual and the museum specimen, and comparing them to the other 13 species of Galápagos giant tortoises, Princeton postdoctoral researcher Stephen Gaughran showed that the two known Fernandina tortoises are members of the same species, genetically distinct from all others. The study was published in the June 9, 2022, issue of *Communications Biology*.

Scientists estimate that Fernanda is well over 50 years old, but she is small, possibly because the limited vegetation stunted her growth. Encouragingly, tracks and scat of at least two or three other tortoises were found during other recent expeditions on the island. ***—Liz Fuller-Wright***

COLLABORATIVE RESEARCH

New research partnerships with HBCUs

Ten research collaborations between Princeton University faculty and their peers at historically Black colleges and universities (HBCUs) have been selected to receive support through the Princeton Alliance for Collaborative Research and Innovation (PACRI). These are the first projects to be launched through the groundbreaking alliance announced in May 2022.

Each of the collaborations will be co-led by a team of researchers from Princeton and one of five HBCU partnering institutions: Howard University, Jackson State University, Prairie View A&M University, Spelman College and the University of Maryland Eastern Shore. UNCF (United Negro College Fund) partnered with Princeton to launch the program.

Spanning the natural sciences, social sciences, humanities and engineering, the projects take up some of the most difficult challenges of our day, from cybersecurity to climate change to public health and the social safety net. The projects also draw on the diverse expertise and perspectives of the research teams, pairing academics from different disciplines.

"We started the Princeton Alliance to generate trailblazing ideas from collaborators who otherwise might not have the opportunity to work together — and researchers from across Princeton and our HBCU partners responded," said Tod Hamilton, professor of sociology and a faculty co-founder of the PACRI program. ***—Tracy Meyer***

CHEMISTRY

DNA barcoding advances nanoparticle self-assembly

More than two decades ago, scientists demonstrated that the self-assembly of nanoparticles — for fabrication of miniaturized devices, for example — was possible if the nanoparticles could be labeled with a known number of DNA molecules.

For this to work, scientists would need a way to control the number of DNA molecules on the surface of nanoparticles, a challenge that went unmet for 25 years.

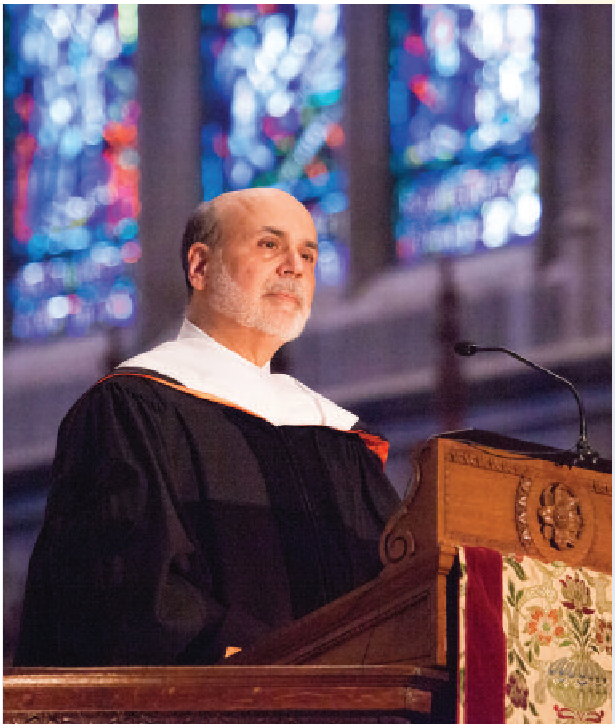
Now, researchers led by Haw Yang, professor of chemistry, have created a sorting technology that distinguishes nanoparticles by exploiting DNA's programming language, specifically its ability to selectively associate and recognize complementary sequences.

Yang and postdoctoral research associate Nyssa Emerson published the work July 11, 2022, in the *Journal of the American Chemical Society*.

The researchers used a process called DNA barcoding, which functions much like the codes used by supermarket scanners to identify a product. Each nanoparticle is assigned a unique barcode. The barcode itself consists of a short strand of DNA affixed to the nanoparticle.

"We can change the letters of that code, and that tells us what DNA molecule will react with what other DNA molecule," Emerson said. "There's really not anything else that is this programmable and easily made." ***—Wendy Plump***

PHOTO BY DENISE APPLEWHITE



ECONOMICS

Ben Bernanke, former Princeton professor and economics department chair, receives Nobel Prize in economic sciences

Ben Bernanke, a Princeton professor of economics and public affairs from 1985 to 2002, chairman of the economics department from 1996 to 2002, and founder of the Bendheim Center for Finance, is among three winners sharing this year's Nobel Prize in economic sciences.

The Royal Swedish Academy of Sciences awarded the Sveriges Riksbank Prize in Economic Sciences in Memory of Alfred Nobel 2022 to Bernanke, Douglas Diamond and Philip Dybvig for significantly improving "our understanding of the role of banks in the economy, particularly during financial crises." The prize amount is 10 million Swedish kroner, about $900,000, divided among the recipients.

The three laid the foundation of modern banking research in the 1980s. Their work clarifies why we have banks, how to make them less vulnerable in crises, and how bank collapses exacerbate financial crises. An important finding in their research is why avoiding bank collapses is vital. ***—Denise Valenti***

Soaking up the sun

NASA-funded lab sets its sights on the heliosphere

By Alaina O'Regan

Across our solar system, supersonic winds of charged particles from the sun blow at a million miles per hour. These winds form a protective bubble around our entire solar system that shields us from galactic radiation. However, this space weather can disrupt satellite communication and navigation systems, and can cause power outages here on Earth.

At the Princeton Space Physics laboratory, the lead institute for several NASA missions and instruments, researchers study the heliosphere — the extension of the sun's atmosphere into space. Their goal is to help protect the people and technology we send into space, and give insights into how the universe works on broader scales.

"Most universities don't have the ability to build a flight instrument for NASA," said David McComas, who heads the Space Physics group and is a professor of astrophysical sciences and vice president of the Princeton Plasma Physics Laboratory. "It's a really special thing for Princeton."

The lab is building one of the instruments that will travel on NASA's Interstellar Mapping and Acceleration Probe (IMAP), set to launch in 2025, for which McComas is the principal investigator and Princeton its lead institution. The spacecraft is being built at the Johns Hopkins Applied Physics Laboratory in Maryland, while the other instruments are being built at various locations throughout the United States and Europe.

The IMAP mission will investigate two of the most important issues in space physics — how particles from the sun accelerate and travel through space, and the effects of these particles on our solar system. The device being developed at Princeton, called the Solar Wind and Pickup Ion (SWAPI) instrument, will measure the solar wind and interstellar pickup ions, produced from cold neutral atoms drifting in from the surrounding interstellar medium.

PHOTO BY SAMEER A. KHAN/FOTOBUDDY

As part of its mission, the lab provides opportunities for undergraduate and graduate students to solve real-world problems in an active space instrument laboratory. The emphasis on education, McComas said, sets this lab apart from most others in the country.

"Providing that opportunity for the students who are interested in more experimental work is very high on my list," McComas said. "I have responsibilities to NASA to build instruments, and I am always striving to find the educational synergy there."

One student contribution involved ultrathin carbon foils, an essential piece of many space instruments, including the IMAP mission's SWAPI instrument. To install a foil in an instrument, researchers must first float the foil onto a metallic flight grid in a process known as foil floating. Variations in foil floating influence the quality of foils, thereby altering the performance of space instruments.

Last year, two students designed a standardized foil floating process to improve space mission outcomes for their joint undergraduate-master's thesis project. The procedure, developed by Grace Gong, undergraduate Class of 2022, and Nina Arcot, who earned her master's in mechanical and aerospace engineering in 2022, is now used at the Space Physics lab and can be adapted for use by other institutions worldwide.

"We're directly using this development from the student work to make a better instrument than we would have made otherwise," McComas said.

Jamie Rankin is an associate research scholar and the instrument lead for SWAPI. She collaborates with McComas in overseeing the Space Physics laboratory and the corresponding class for undergraduates at Princeton.

"We aim to provide students the most realistic, hands-on, practical experience in the lab that we can," Rankin said.

Rankin's research combines measurements from the Voyager mission, launched in the 1970s, with the more recent Interstellar Boundary Expedition (IBEX) mission's all-sky observations to investigate interactions between the heliosphere and the interstellar medium. She also studies the behavior of cosmic rays in the very near-sun environment using observations from another NASA mission, the Parker Solar Probe.

Only a limited number of organizations in the country build space instruments, and most of them are not educational institutions. For this reason, McComas and his team are working to create a program that will continue to train scientists and engineers for many years to come.

Rankin said she looks forward to seeing current and future space instruments built in the Princeton lab, and that now is only the beginning of a longer, more gratifying endeavor.

"It is truly an honor to play some small role in exploring, discovering and understanding some of the mysteries of the universe," she said.

John Teifert (left), a precision technical specialist at the Princeton Space Physics laboratory, wears protective clothing to prevent Earthly contamination of space-bound instruments. He talks via intercom to Jamie Rankin, associate research scholar and lead scientist for one of the instruments under development at the lab.

PHOTO BY SAMEER A. KHAN/FOTOBUDDY

From left: Lindsay Willmore, Annegret Falkner and Ilana Witten.

Bouncing back from adversity

Study finds that mice that fight back display greater resilience

By Allison Gasparini

Faced with climate change, a pandemic, and political unrest around the globe, it can feel all too easy to succumb to a sense of hopelessness. How do some people bounce back from adversity faster than others, and can those who struggle teach themselves to be more resilient over time?

A new study conducted in mice and published Oct. 19, 2022, in the journal *Nature* suggests resilience can be learned, and can even be reinforced. A team of researchers from the Princeton Neuroscience Institute placed small mice in close proximity with larger, aggressive mice and found that a display of defensive behaviors predicted the mice's ability to be resilient after the stressful event. Further, the team found that by activating dopamine while the mice fought back, they could further reinforce resilience.

From the research's inception, Lindsay Willmore, who earned her Ph.D. in 2022 and is lead author on the paper, was intrigued by the relatively rare subset of mice who would defend themselves tenaciously when faced with an aggressor.

"They'd turn back towards the aggressor, they'd throw their paws out, they'd jump on him, and they would just not give up," said Willmore. "I thought, wow, there's something going on in these guys' brains that's super interesting and could be the key to resilience."

In the study, the researchers gauged resilience by monitoring the mice's behaviors in the 10 days during which they sustained attacks by the aggressor.

The mice that tended not to defend themselves ended up displaying depression-like behaviors such as social avoidance following the stressful event. Meanwhile, the mice that fought back displayed greater resilience.

By stimulating dopamine while the mice were fighting back, the researchers found they could make the mice even more likely to become resilient. On the flip side, stimulating dopamine during avoidant behavior did not make the mice more resilient.

"It's a complicated environment where a mouse has to decide what to do around a bully mouse," said Ilana Witten, a professor of neuroscience and author on the study. "What decision it makes has profound consequences in terms of how it ends up."

While the defensive stances associated with fighting back were key in predicting a mouse's resilience in the face of attack, Willmore said, "Even more strongly related to resilience was how much dopamine the animals had in their reward system during the time when they were starting to fight back. That's what was really cool to me — that an animal that is not just fighting back but is rewarded for fighting back is the one that becomes resilient."

For the study, the researchers put a smaller mouse in a cage with a larger, more aggressive mouse that typically would attack its smaller cage-mate. Afterward, the two mice would stay in the enclosure but this time separated by a wall so that they could not interact physically.

A study conducted in mice and published in the journal *Nature* suggests resilience can be learned, and can even be reinforced.

"I'm very interested in the question of whether we can teach resilience," said Annegret Falkner, an assistant professor of neuroscience and author on the paper. The series of experiments the team conducted seemed to suggest the answer was indeed yes, that the mice could be nudged toward performing resilient behaviors.

While the researchers began the project before the start of the COVID-19 pandemic, Falkner said since the pandemic hit, she's been thinking more than ever about resilience. "We need to think about ways to help the people who seem to be more susceptible to cope with the stresses of the world," said Falkner.

As the researchers continue their studies on resilience, they hope that in the future such work could be applied beyond animals to human health. For example, devices such as smart watches could give real-time feedback about good habits to promote healthy mechanisms like resilience. "Information about our dynamic interactions with the environment will be useful for tracking our habits that might be helpful or harmful," said Willmore.

The study was funded by the New York Stem Cell Foundation, the Esther A. and Joseph Klingenstein Fund, the Simons Foundation, the Alfred P. Sloan Foundation, the National Science Foundation and the National Institutes of Health.

PHOTO BY DANIELLE CAPPARELLA

Do today: Find something new about the universe

Physicist Isobel Ojalvo explores the building blocks of matter at the world's largest particle collider

By Alaina O'Regan

"Understand the fundamental nature of the universe," reads the sticky-note on the desktop computer of Isobel Ojalvo, assistant professor of physics. It serves as a reminder of her greatest aspiration, her motivation to take steps each day toward uncovering something new.

Ojalvo recalls pondering such existential questions in a classroom at age 11. Having always been inclined toward math, she took to science as an avenue to explore the questions that kept her up at night.

"I've been kind of on a quest for my entire life of understanding the fundamental structure of the universe," she said.

This quest led to her interest in mysteries such as dark matter, cosmic inflation, and what happened at the very beginning of the universe.

Now, throughout a decade of research at the world's largest particle accelerator, the Large Hadron Collider (LHC) at CERN in Geneva, Switzerland, Ojalvo is making sizable contributions to the field of high-energy particle physics.

At the 17-mile-long underground tube, researchers accelerate protons toward each other at near the speed of light. The resulting debris can reveal much about the matter that makes up the universe. But with protons smashing together every 25 nanoseconds, these collisions create so much data that storing it all is impossible.

Ojalvo's work has focused on improving the electronic systems, called trigger systems, which run algorithms to decide which events in the detector are worthy of storing, and which can be thrown away.

Ojalvo spent many years working on the trigger systems at one of the LHC's two main detectors, the Compact Muon Solenoid (CMS) detector. For this system, Ojalvo has commissioned and installed hardware, developed new high-speed algorithms, written and managed online software, and spent many hours on call.

She began this work while she was a graduate student, spending her summers at CERN and the rest of the year studying at the University of Wisconsin-Madison. In 2012, during her second summer at CERN, the discovery of the Higgs boson — a long-predicted particle that gives the universe its mass — marked a dramatic turning point in the field of particle physics, and Ojalvo was there to witness it firsthand.

"It was pretty exciting to be there at the time," she said. "It was especially exciting to see what people working together could achieve."

To learn more about the Higgs and how it interacts with other particles, Ojalvo narrowed her focus to studying another elusive particle, the tau lepton. This particle is nearly identical to the electron, but has a much higher mass.

Because the strength of the connection, or coupling, of a particle with the Higgs boson is directly proportional to the particle's mass, the tau lepton is an ideal channel for understanding the Higgs coupling.

PHOTO BY SAMEER A. KHAN/FOTOBUDDY

But there is a catch. This particle decays very quickly and is thus difficult to detect.

"Every once in a while, somebody comes up to me and says, 'it's a particular type of crazy person who decides to look at the tau lepton,'" Ojalvo said.

To pin down the elusive tau, Ojalvo and her team had to develop special techniques as well as upgrades to the CMS trigger systems. The team wrote new algorithms that help the system work more efficiently in collaboration with engineers and physicists at the Institute for Research and Innovation in Software for High Energy Physics (IRIS-HEP), led by Princeton senior research physicist Peter Elmer.

Ojalvo is intentional about creating a diverse and supportive environment for other researchers, and she is aware of the adversity commonly faced by women and other minorities in her field. After learning from experience, she aims to show her lab members the importance of resilience, and of mutual support and respect.

Pallabi Das, a postdoctoral research associate who works with Ojalvo, said that the diverse backgrounds of Ojalvo's lab members contribute to the success of their work.

"It's a very collaborative environment, and all the students are very enthusiastic because Isobel herself is enthusiastic," Das said. "She encourages people to go forward, to be bold in whatever we do, and to speak up."

The LHC is currently the only high-energy collider in the world, and while it will operate for many years to come, Ojalvo hopes there will be future construction of a more powerful collider.

"I think in the long term that we have to not be complacent about the future of particle physics," said Ojalvo, whose work is funded by the U.S. Department of Energy. "We need to think about what future colliders can do, and what role the U.S. will play in this research."

Isobel Ojalvo, assistant professor of physics, explores the physics of an elusive particle called the tau lepton, one of the fundamental building blocks of matter being studied at the Large Hadron Collider.

Our fusion future:

Princeton Plasma Physics Laboratory aims to harness the sun's power to achieve climate goals

By Allison Gasparini

Brutal heat waves marked the summer of 2022, which brought us the hottest July ever recorded in the United States. Scientists and experts regard global warming as the crisis of our time, and with fossil fuel consumption at the center of climate change, deploying clean energy is one of the most important pursuits of the modern era.

Fusion, a process in which two lighter atoms collide to form one heavier atom, unleashes huge amounts of energy. As the world looks for sustainable alternatives to fossil fuels, fusion could be the ultimate clean energy answer.

"If the Earth becomes an inhospitable place for humans, that's a disaster," said Steve Cowley, director of the Princeton Plasma Physics Laboratory (PPPL) and a professor of astrophysical sciences. "Fusion can help change that."

Although fusion occurs naturally at the core of our sun, creating a similar process on Earth requires building complex machines that can contain the fuel and heat it to temperatures millions of degrees hotter than the sun.

At PPPL, researchers are leading the scientific charge to turn fusion into reality. If harnessed, the energy released in fusion reactions could provide electricity to power our homes and cities for thousands of years.

While excitement for wind and solar has inspired fields of turbines and panels, those energy sources depend on good weather. "The wind doesn't always blow and the sun doesn't always shine," Cowley said. "The combination of fusion plus renewables is probably the perfect energy system."

The fact that fusion energy can power homes around the clock isn't the only benefit. Fusion is also green. It requires just two ingredients or feedstocks, deuterium and tritium, both forms of hydrogen. Deuterium can be harvested from seawater while tritium can be produced through neutrons interacting with lithium inside a fusion reactor. Although lithium demand is high due to its use in batteries, new extraction technologies promise to make the element more available.

"Fusion is, in principle, a potentially very democratic source of power for the world," said Emily Carter, senior strategic adviser for sustainability science at PPPL and Princeton's Gerhard R. Andlinger Professor in Energy and the Environment. "The feedstocks are found in places that most countries have access to, which is not true for nuclear power."

Today's nuclear power reactors split atoms in a process called fission, whereas fusion reactors smash atomic nuclei together. Unlike fission, fusion doesn't create long-term hazardous waste or the potential for meltdowns like the Chernobyl disaster.

"With fusion, because of the very nature and the way in which the physical process takes place, there cannot be meltdowns," Carter said. When deuterium and tritium collide, they produce helium, an inert gas, and neutrons, which can fuel more fusion reactions by creating tritium from lithium, or be used to make steam for power plants to create electricity. "Moreover, tritium as fusion waste is much more short-lived than nuclear waste, and thus can be handled in a way that makes it much more attractive than nuclear power in the long run," Carter said.

The benefits of fusion energy have increasingly captured the interest of those looking for future sources of clean energy. In April, the Biden administration put forward a statement on its strategy to accelerate fusion energy research. The U.S. Department


IMAGE BY MANUEL ŠUMBERAC

of Energy (DOE), which funds PPPL, also announced $50 million to support partnerships between for-profit companies, national laboratories, universities and others for the design of a fusion pilot plant.

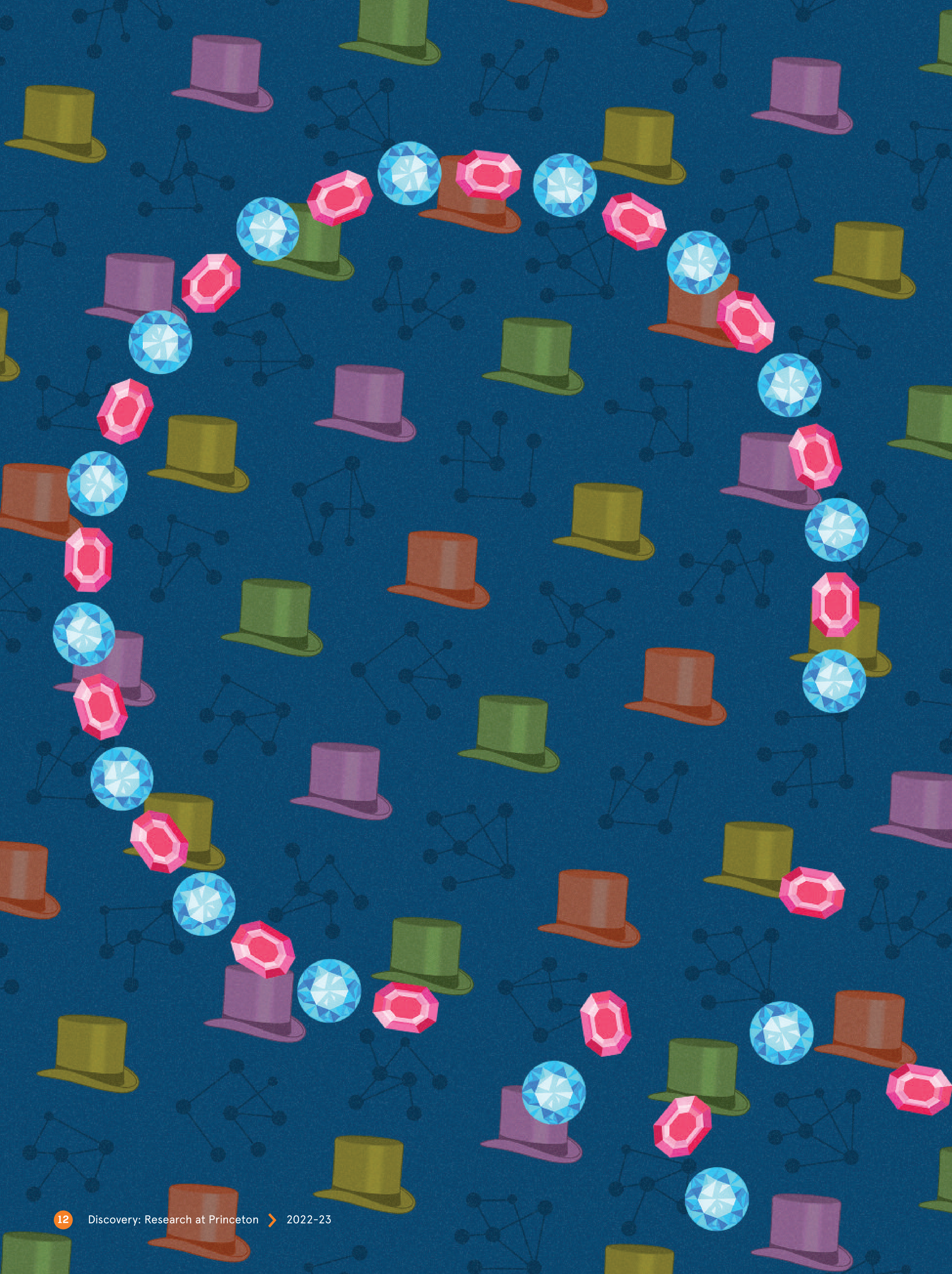
In recent years, private sector interest in fusion energy has soared. "One of the really exciting things that has happened is the amount of private money that's coming into fusion," said Elizabeth Paul, a Princeton presidential postdoctoral research fellow in astrophysical sciences. "For the first time, the private funding has surpassed public funding."

The White House estimates that $4 billion in fusion investment is coming from the private sector. "Continuing to push engagement from private companies would accelerate fusion research and fusion energy on the grid at a reasonable cost," said Ahmed Diallo, a principal research physicist at PPPL and a program director for the DOE Advanced Research Projects Agency-Energy (ARPA-E).

Last year, 2021, was a pivotal year in fusion energy research. In the United Kingdom, researchers at the Joint European Torus broke the record for the most energy produced during a fusion experiment. Then, at the National Ignition Facility in California, researchers reported creating a self-sustaining fusion burn using an array of high-powered lasers. The multinational fusion demonstration project ITER, located in France and funded by countries including the United States, will begin operating in the next decade.

Between the increase in private efforts, and innovations led by PPPL and collaborators across the globe, it appears the future of fusion-based clean energy is brighter than ever.

Fusion, a process in which two lighter atoms collide to release energy, could become the ultimate clean energy solution.



Beyond guess and check

Some problems are so complex that they could take trillions of years to solve

By Alaina O'Regan

C

Consider a traveling salesperson who has to visit several cities scattered across the country. What route would minimize the distance that the salesperson has to travel? There is no formula, no simple algorithm, for finding the answer, and adding more cities makes the answer take exponentially longer to find.

This conundrum falls into the category of problems that, once you find the solution, are easy to check to see if you were right. However, finding the solution in the first place is virtually impossible because of the time it would take even a powerful computer to guess and check all the possibilities.

In Princeton's mathematics department, researchers tackle a range of questions about the structure of our world, delving into problems that can have profound impacts at the theoretical level as well as in practical applications such as the design of computer algorithms to solve problems efficiently. In this feature, we meet two professors who are fascinated by why some problems resist mathematical solutions and who look for ways to move beyond guess and check.

Hat guessing games

Whether the debate is about politics, popular culture or even science, it can be difficult or impossible for one person to convince another to change sides in an argument.

But in mathematics, once something is proven true, it remains true forever. It ceases to be up for interpretation. This unique feature is part of what intrigues Noga Alon, a professor of mathematics and applied and computational mathematics at Princeton.

Much of Alon's work is in the crossover of mathematics and computer science, and he is interested in whether computers can solve certain problems in math efficiently. To solve a problem efficiently goes beyond simply coming up with an answer, but refers to the time and effort it takes for a computer to come up with and solve an efficient procedure, or algorithm, that avoids a systematic guess-and-check process. A proof that provides an efficient procedure for solving a problem is known as a constructive proof.

Many of the problems that Alon works on deal with quantities whose answers can be verified quickly but that, like the traveling salesperson problem, are extremely time-

ILLUSTRATION BY DAN PAGE

Children guessing at the color of each other's hats and thieves squabbling over how to divide a stolen necklace are a few of the problems that intrigue Noga Alon.

consuming to solve. These problems are known as NP-hard problems. [See P vs NP box, page 17.] If a computation for *any* NP-hard problem can be done efficiently, it would mean *every* NP problem could be solved using an efficient algorithm.

One problem that intrigues Alon involves the "four-color theorem," which states that any map that can be drawn on a plane, or on the surface of a sphere, can be filled in using four colors so that no two bordering regions share the same color.

This theorem has a constructive proof, as it answers the "yes" or "no" question of whether or not four colors are always enough to fill in any planar map, and the proof that four colors always suffice provides an efficient algorithm to find the required coloring. It's a simple concept, but this statement took well over 100 years to prove.

Alon took this theorem a step further with a proof for a related formulation of the problem with more restrictions. In this version, only the region's edges are colored, and each edge is assigned a random list of three colors it is allowed to have.

For example, one edge may have a list that says "green, blue or yellow," while its neighbor has a list that says "green, red or orange." Alon used algebraic methods to show that a map can be shaded under these conditions so that no two bordering edges share the same color.

Unlike the simpler four-color problem, Alon's proof that this can be accomplished is not a constructive proof.

If we wanted to ask exactly how to color in this map, that would be difficult. Many mathematicians believe it is highly unlikely that a constructive proof could exist for this problem.

Alon applied a related algebraic approach for tackling another problem that he calls the "hat guessing game." Imagine a room full of 100 boys and 100 girls, each lined up on opposite walls and each wearing a hat of a specified color. All of the boys can see all of the girls but cannot see each other (or themselves), and vice versa. Provided information about how many different colors of hats there are, can we ensure that at least one person will be able to correctly guess the color of their own hat based on what they see? And if so, how might this be done?

Alon discovered that both the answer and the approach change depending on the number of hat colors. If there are fewer than four hat colors, the problem can be solved using a simple linear guessing function. But when there are four colors or more, the problem becomes more complicated and requires nonlinear functions. This means that rather than a simple formula for the function as a whole, each person now has their own distinct, "random-looking" formula that they will use to make their guess. The solution becomes more complex as we increase the number of people and of different hat colors.

There is another set of problems that Alon has famously contributed to, called "necklace splitting." Picture a necklace composed of rubies and diamonds, strung together in random order. The question is, how can two partners, or thieves, share this necklace evenly by making the fewest number of cuts in the necklace?

This problem becomes more difficult when there are more thieves and a larger variety of gemstones. Alon discovered that at a certain point, the problem takes a surprising turn by changing from a question of combinatorics — how many possible combinations of elements and how are they related to each other — to a question of topology, an entirely different branch of mathematics that studies continuous structures.

"The question is not that difficult, but you have to realize that it should be treated by using tools from topology," he said. "It's always nice to find connections between areas that appear to be totally unrelated."

Alon pursues this work because he finds it interesting to think about. Whether or not practical applications stem from it, or whether or not he will be able to contribute to the P versus NP problem, is not the main motivation behind his research.

His passion for math has led him to publish more than 500 research papers throughout his career, many of which have laid important groundwork for the research of thousands of mathematicians all over the world. His contributions to math and theoretical computer science earned him the 2022 Shaw Prize in Mathematical Sciences.

"The nice thing about being a mathematician is that you are free to pursue whatever you find interesting," Alon said.

Alon encourages his graduate students and other young researchers to choose a specialty that is interesting to them, and not base that choice on their perception of what might seem to be important.

These problems can have profound impacts at the theoretical level as well as in practical applications such as the design of computer algorithms.

"What is and is not important in mathematics changes all the time," he said. "The most important thing is that you go into what appeals to you because if you are passionate, you are more likely to be successful."

The sparsest cut

When faced with a large task, it is natural to want to break it into manageable pieces that can be tackled one at a time.

For this approach to work, the problem needs to be broken up in a way that makes sense. If the individual pieces have too many connections or are too reliant on one another, solving them individually isn't going to work.

This situation describes a problem that mathematicians and computer scientists have been working on for decades, called the "sparsest cut problem."

The goal of the sparsest cut problem is to divide a "universe" into two pieces so that they have the least total connection between them relative to their size. Each piece can then be partitioned repeatedly until they are all small enough to handle.

This "universe" could be any collection of objects with pairwise interactions, such as a network of people, a collection of molecules or a collection of websites. A universe is defined simply as a system of elements with measurements of the strength of the interactions between each pair of elements.

PHOTO BY SAMEER A. KHAN/FOTOBUDDY

One of the questions that Assaf Naor explores is how to design computer algorithms that partition a "universe" of elements into pieces so that they have the fewest connections between them.

"Understanding the power and limitations of algorithms for the sparsest cut problem leads to questions which you can choose to approach either from the mathematics or the computer science perspective, and they're both equally interesting," said Assaf Naor, professor of mathematics.

Finding a foolproof algorithm — a set of steps to take to solve a problem — that will allow a computer to find the best possible partition has proven extremely difficult. So difficult, in fact, that the sparsest cut problem falls into the category of "NP-hard" problems, which consists of tasks that are thought to be impossible for a computer to solve in any reasonable amount of time. [See P vs NP box, page 17.]

For the sparsest cut problem, along with many other problems that fall under the umbrella of NP-hard, researchers are working to find algorithms that come as close as possible to the optimal solution, but do not hope to find it exactly.

"The game here is not to find the best way to partition the universe, the game is to come close to it," Naor said. "That's what's called an approximation algorithm."

The best-known approximation algorithm for this problem was proposed in the mid-1990s by Michel Goemans and Nathan Linial, the latter one of Naor's teachers at the Hebrew University of Jerusalem.

Their method, known as the Goemans-Linial algorithm, was successful in partitioning a universe into pieces, but it was unknown how close the algorithm actually was to finding the best, or sparsest, cut.

"It's a concrete algorithm that does partition the world into pieces but they didn't know how well this algorithm performs," Naor said. "They suspected, or hoped, that this algorithm would actually solve the problem, and that it would get close to the minimum up to a certain factor."

It took 20 years, but in 2017, Naor and his colleague Robert Young of New York University were able to show precisely how well this algorithm works.

"I can cook up a universe for which I can prove that this algorithm messes up in the worst-possible way," Naor said. "And the bad guy here is something called a Heisenberg group."

Heisenberg groups are mathematical objects that arise in both classical mathematics and physics. When Naor and Young wanted to find out if the Goemans-Linial algorithm would successfully partition this complicated structure, it turned out that the Heisenberg group fooled the algorithm.

This result departs completely from traditional computer science, and they could have only found it from a vantage point of high level, abstract mathematics.

This is partly because the Heisenberg group that works for their purpose is a mathematical object that exists in five dimensions, meaning you probably will never see one sitting on the sidewalk on your way to work.

But just because it doesn't physically exist in our world doesn't mean it isn't "real," in the sense that mathematicians and physicists can use it to deepen their understanding of mathematical theories, and to learn things about our world.

A few years later, in 2020, Naor and Young figured out how the issue that they understood in five dimensions plays out in three dimensions. They used this knowledge, which arose initially from the need to solve an algorithmic question, to solve even older open questions in pure mathematics.

Finding algorithms for the sparsest cut problem has implications for computer scientists, for example by helping to manage large data sets, among other things. For Naor, the possible application is not what drives him to pursue the research.

"The application is a huge plus. It excites me, but I would have thought about it anyway," he said.

Many of the problems Naor thinks about have potential for real-world application, such as the sparsest cut problem, while others remain in the realm of the theoretical. Naor emphasizes, however, that these two are not necessarily mutually exclusive.

"There are objects that are abstract to imagine, but oftentimes you're using them to answer concrete questions," Naor said.

P versus NP:

A million-dollar question

Computer scientists place problems into categories, called complexity classes, based on how difficult they are to solve. Of many defined complexity classes, two of the most relevant are "P" and "NP."

There is a one million-dollar prize on the line offered by the Clay Mathematics Institute to anyone who can prove, or disprove, that P and NP actually refer to the same set of questions.

P stands for polynomial time. It refers to problems that are considered "easy" for a computer to solve. The time it takes does not increase exponentially when the problem has more elements to consider.

Example: Identifying the largest number in a given list. A computer can use an algorithm to run through a list of numbers, and keep note of the largest number it has recorded so far. The more numbers on the list, the longer this problem takes, but the amount of time it takes is directly proportional to how long the list is.

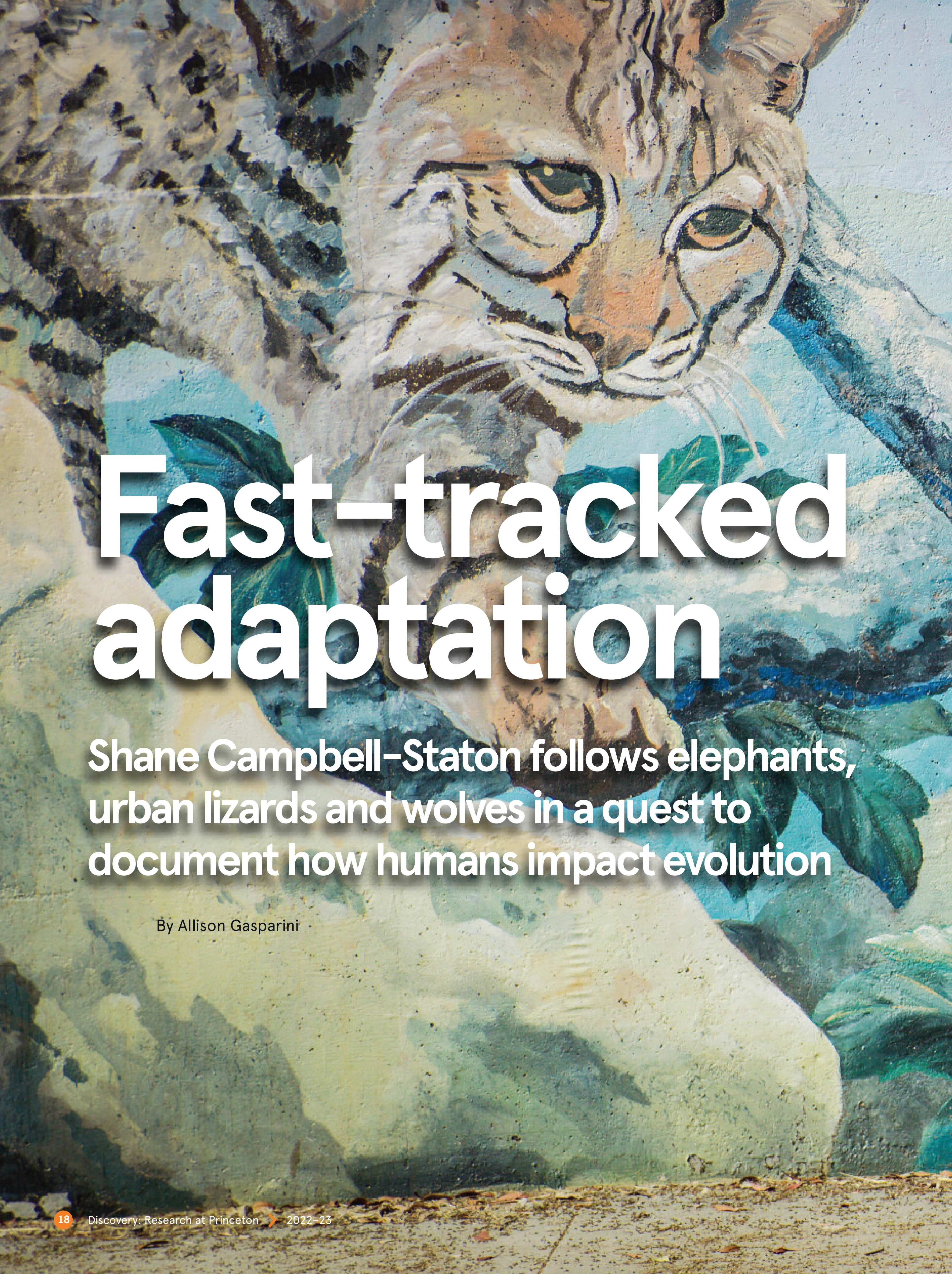
NP stands for nondeterministic polynomial time. These are problems for which a proposed solution can be quickly verified by a computer, but that could take an unreasonable amount of time for a computer to solve.

Example: Finding all prime factors of a large number. A computer can use some cleverly developed methods to solve this, but even the best-known ones could take trillions of years for numbers with several thousand digits. A computer can, however, quickly verify the correctness of a proposed solution.

Naor said he is happy with the progress he's made with the sparsest cut problem, but says that there is more to understand about it, yet he has "no idea" what the next steps are.

That may sound intimidating to some, but to Naor and many mathematicians, the "not knowing" is what makes it attractive.

"Mathematical research is partly about embracing questions," Naor said. "This feeling of being surrounded by the unknown is a positive. It doesn't scare us, it attracts us."



Fast-tracked adaptation

Shane Campbell-Staton follows elephants, urban lizards and wolves in a quest to document how humans impact evolution

By Allison Gasparini

PHOTO BY DAY'S EDGE PRODUCTIONS

One night back in 2016, Shane Campbell-Staton couldn't sleep. Doing what any person who feels inexplicably restless at 3 a.m. might do, biologist Campbell-Staton embarked down a YouTube rabbit hole. A few videos deep, he came across a clip about the tuskless elephants who live in Gorongosa National Park in Mozambique.

Much of Campbell-Staton's career up to this point had revolved around the study of small green anole lizards native to the southeastern United States. Specifically, he was studying how the reptiles adapt to changes in temperature, especially when faced with human-made changes to their environments. But the phenomenon of elephants rapidly evolving without tusks to adapt to human activity such as poaching resonated with Campbell-Staton's research interests. He became so curious about the tuskless elephants that he reached out to some scientist friends to see who — if anyone — was researching them. On the email chain was Princeton ecology professor Rob Pringle, who happened to be planning an expedition to Mozambique as part of a long-term study on the ecology of large mammals in Gorongosa National Park. Pringle invited Campbell-Staton along. By 2018, Campbell-Staton, who was then an assistant professor at the University of California-Los Angeles, was driving around Gorongosa in search of tuskless elephants from which to collect genetic samples.

The accidental foray into elephant tusk research was one of many unusual paths that anyone who knows Campbell-Staton, who joined Princeton as an assistant professor in the Department of Ecology and Evolutionary Biology in 2021, might expect him to take. He's a researcher described by colleagues as a rising star. "Right now, he's full throttle," said Pringle. "Every time we talk, he's got a new idea."

Campbell-Staton imagines that his career likely will be filled with exciting twists and turns akin to the path leading him to work with elephants. "What attracts me to projects are stories that I find fascinating, mysteries that I find fascinating," he said. "Chasing those mysteries and trying to understand the questions that go along with the stories and the answers to those questions leads me down all sorts of unexpected roads."

When following Campbell-Staton's research, it's best to expect the unexpected. From looking for tuskless elephants in Mozambique, to studying how urban lizards in Puerto Rico adapt to rising temperatures, to joining a new collaboration to investigate radiation's impact on the wolves of Chernobyl, Campbell-Staton's interests take him in many directions.

A biologist begins

Ask a biologist how they got into the field, and they'll probably recount a story about encountering salamanders while hiking through the woods or splashing around with anemones in tidal pools off the beach. Campbell-Staton isn't one of those biologists. "I grew up in the 'hood in South Carolina," he said. "My pathway into science was actually through television."

> "Typically, when you think about evolution, you think about it playing out over thousands or millions of years," explained Campbell-Staton. "The idea of being able to track selection in real time became fascinating for me."

A self-described latchkey kid, Campbell-Staton said he spent a lot of time at home, taking care of his little sister while his mom worked shifts up to 72 hours long as a taxicab driver. "I didn't have a whole lot of experience with the outdoors at all," he said. During these after-school hours, he spent time watching crocodile hunter Steve Irwin and biologist-slash-television host Jeff Corwin. TV introduced Campbell-Staton to the amazing animals and incredible places of planet Earth.

The love he found for the natural world led Campbell-Staton to the University of Rochester, where he completed his bachelor's degree in ecology and evolutionary biology. It was here that he began blending his interests in genomics and lizards. In the laboratory, Campbell-Staton used DNA sequencing to trace the evolutionary origins of bearded dragons. After completing an honors thesis on the subject, Campbell-Staton went on to pursue his Ph.D. at Harvard. Again he studied lizards, but it wasn't until toward the end of his Ph.D. that Campbell-Staton had the opportunity to explore the phenomenon that would become the hallmark of his research: how human activity can impact evolution.

That opportunity arrived after a winter storm passed through Texas where Campbell-Staton had been studying several different populations of lizards. "I decided to go back and look at how these populations responded to the single extreme weather event," he said.

What he found astounded him. The lizard populations experienced a number of shifts in gene expression that allowed them to better tolerate the cold, much like their northern counterparts. "Typically, when you think about evolution, you think about it playing out over thousands or millions of years," explained Campbell-Staton. "The idea of being able to track selection in real time became fascinating for me."

"Shane has a really great ability of seeing things in a different way than other people see things," said Kristin Winchell, who collaborates with Campbell-Staton and is an assistant professor at New York University. "He can identify these big picture ideas and problems and envision how he would test them very clearly."

Chasing the story around the globe

From living vicariously through the adventures of conservationists on-screen, Campbell-Staton now gets to experience Earth's extraordinary habitats firsthand. His work has taken him to Puerto Rico, Australia and South Africa. The trip to Mozambique to study tuskless elephants in 2018 was his first excursion to continental Africa.

If you'd asked Campbell-Staton five years ago whether he'd ever be interested in studying the tooth development of elephants, he'd have answered with a resounding, "No, not particularly." Pringle, however, who invited Campbell-Staton to research elephants alongside him, was less surprised at the latter's move from lizard thermal biology to tusks.

"My own research program is sprawling," said Pringle. "I think that's one of the reasons that Shane and I can collaborate so well, because we both have this sort of expansive sense of what's possible."

PHOTO BY KRISTIN WINCHELL

Campbell-Staton's task was to collect fecal samples from tuskless elephants to extract and test their DNA. Upon arriving in Mozambique, Campbell-Staton said he drove around for three weeks in search of elephants — and encountered none at all. Luckily for Campbell-Staton, Pringle and his team had arranged a helicopter to track down and tranquilize elephants to collect their blood, which ultimately provided the crucial DNA.

In 2021, Campbell-Staton, Pringle and colleagues published a paper in the journal *Science* drawing a connection between the relatively large proportion of female elephants born without tusks following the 20-year Mozambican civil war and the genes associated with tusklessness. During the war, elephant populations declined 90% due to poaching for their valuable ivory tusks. The study provided evidence for the role of poaching in tuskless-elephant survival and population growth.

If studying how animals adapt in the face of human activity is the body of Campbell-Staton's research, then his collaboration with other scientists is the beating heart. "Shane cares about the people he collaborates with," said Winchell. "And I think when you place the people as a priority in your scientific collaborations, that leads to better science."

The human impact on the tree of life

When Campbell-Staton is not traveling for his research, he spends his time in his laboratory at Princeton, typically at a computer completing statistical analysis. He described his graduate students and postdoctoral fellows as the "boots on the ground" — in the work they do preparing DNA samples for sequencing and carrying out genomic studies.

"My role is to provide these young, ambitious scientists with as many opportunities as possible," said Campbell-Staton. "And to help them think of the coolest, craziest stuff that could possibly be done to get at some of these really important and pressing questions."

His experience with studying rapid evolution in Texas lizards as a Harvard graduate student bloomed into a collaboration with Winchell, who at the time was pursuing her doctorate across the river at the University of Massachusetts, Boston, while also visiting a laboratory at Harvard. Campbell-Staton heard about her research with lizards in urban environments and their partnership grew from there.

In 2021, Winchell worked as a postdoctoral researcher in Campbell-Staton's

Urban lizards are some of the animals that have adapted rapidly to human-made environmental changes.

Princeton laboratory, and then began her position at New York University as an assistant professor. She continues to study how anoles adapt to city living. "I think of [urban environments] as both relevant to conservation in a changing world and also as an evolutionary testbed to understand fundamentally critical questions of evolutionary processes," she said.

PHOTO BY CHARLIE HAMILTON JAMES

Research in Mozambique provides evidence for the role of poaching in the evolution of tuskless elephants.

Campbell-Staton and Winchell agree that urban environments are crucial for understanding biodiversity. Winchell's dissertation research concluded that lizards in urban areas had adapted to develop longer limbs and larger toe pads. These genetically based shifts allowed the lizards to better navigate their urban environments.

Together, Winchell and Campbell-Staton are exploring how lizards respond to the urban heat island effect — when urban environments tend to be several degrees warmer than forest environments. In addition to gauging how the reptiles tolerate hotter environments, the researchers also are testing how their physical performance differs at higher temperatures. For example, the researchers put the lizards on racetracks to see if they've adapted to run faster when experiencing hotter conditions.

Across all systems and scenarios studied by the researchers in Campbell-Staton's lab, a common theme comes up again and again. "Life is both incredibly fragile and incredibly resilient," said Campbell-Staton. "And it plays out every single day." Species are plummeting to extinction due to human activity, and at the same time species are finding unique and strange ways to adapt and survive.

"Everything we do — whether it's intended or unintended — has cascading consequences," he said. Campbell-Staton says his research shows how deeply rooted we are to the tree of life, even when we humans may think of ourselves as separate from the animal kingdom. "We have become a force of evolutionary change in a lot of different ways, and we've also become a force of evolutionary change for ourselves," he said.

The theme of human-induced evolutionary change is present throughout all the animal populations Campbell-Staton has studied. While the research is fascinating, it's also heartbreaking, said Campbell-Staton. The most difficult challenges he has faced in his research career have been emotional, rather than technical. "There is inherent value in trying to understand our human footprint, but the reality is our human footprint is not a pretty thing," Campbell-Staton said.

He recalled observing a sedated elephant in Mozambique and realizing he was looking not just at a study subject, but at a matriarch of a herd. And not only was the elephant a matriarch, she had survived the Mozambican civil war, during which 9 out of 10 members of her species died within a 15-year period. And throughout all the stress, the elephant had gone on to have her own offspring and grandchildren.

The fragility and resilience of life also plays out in the animal populations still living in Chernobyl after the 1986 nuclear accident, one of the worst in history. Campbell-Staton recently started collaborating with postdoctoral research associate Cara Love at Princeton to study the wolves that hunt in the Chernobyl exclusion zone. Love brought the research idea to Campbell-Staton, and they are working on their first paper. Despite the chronic radiation in the Chernobyl exclusion zone, wildlife, including wolves, has returned to the area. The animals are not just surviving — they appear to be thriving.

With funding from the Pew Research Center, the Princeton Branch of the Ludwig Institute for Cancer Research, the Princeton Catalysis Initiative and the therapeutics company Genmab, Love and Campbell-Staton are asking how the wolves of Chernobyl have adapted to dangerous levels of radiation. Their ultimate hope in studying the wolves is to understand cancer biology, and, in this way, potentially find "novel therapeutics for cancer using the solutions that natural selection has come up with," said Campbell-Staton.

Just as he followed the story about tuskless elephants all the way to Mozambique, Campbell-Staton's move into cancer biology is in line with his ever-growing range of research interests. "I am not a cancer biologist by any means whatsoever," he said. "But again, it's one of those things where the story requires questions and those questions lead you down all sorts of scientific pathways."

Expanding horizons

Over the past year, Campbell-Staton has continued to travel frequently, but not just for fieldwork. He's been filming, producing and hosting an upcoming science-travel television show for PBS. The details of the production are still very much under wraps, but it's a fitting turn for a biologist who found his own passion for science by watching others on screen.

This past summer, Pringle went to lunch with Campbell-Staton. Having come to Princeton as an assistant professor a decade ago, Pringle had completed many of the projects he set out to do early in his career and was searching for fresh inspiration. He found it while listening to Campbell-Staton brimming with excitement about all his latest ideas. "I'm over the moon that Shane is a colleague," said Pringle. "He's a phenomenal person, a phenomenal scientist, and I think he's a real credit to the department and the institution."

Campbell-Staton maintains that it is his collaborations with others, like Pringle, Winchell and Love, that have been integral in the creativity pushing forward his science. The researchers each bring their own expertise, and by working together they can expand the horizons of scientific understanding.

"As scientists, it's our job to stand on the horizon of our collective human knowledge and look out into the darkness that is the unknown," said Campbell-Staton. From anoles to elephants to wolves, there is one thing that is certain about his future as a scientist — Campbell-Staton will be found at the edge of that darkness, finding ways to illuminate new knowledge.

> "My role is to provide these young, ambitious scientists with as many opportunities as possible. And to help them think of the coolest, craziest stuff that could possibly be done to get at some of these really important and pressing questions."
>
> — **Shane Campbell-Staton**, assistant professor in the Department of Ecology and Evolutionary Biology at Princeton University

PHOTO BY DAY'S EDGE PRODUCTIONS

Art History (Hx)

Scholars examine British colonialism's enduring influence on medicine and race

By Ashia Reid

For nearly five centuries, a small European island exerted a profound influence on millions of people, imparting a cultural legacy that continues today. A decorative map created in the 1850s illustrates the British Empire's vast possessions, not only of land but of the colonial subjects who lived within its borders.

Now a Princeton-led project is using works of art such as this map as a portal for the exploration of British colonialism's impact on our modern perceptions of racial differences, disease and health.

The project, *Art Hx: Visual and Medical Legacies of British Colonialism* (Hx is medical shorthand for history) brings together scholars and artists to examine the intersection of colonialism, medicine, and works of historical and contemporary art.

"There are missing links between art history, the histories of medicine, and the histories of colonialism," said Anna Arabindan-Kesson, associate professor of art and archaeology and African American studies, and Art Hx's leader. "We wanted to create a project that would bring these concepts together," she said.

Through the project, scholars explore modern attitudes that are rooted in colonial notions of superiority over non-British people. These attitudes encompass themes such as stereotypes about Black women's healthcare, distrust of Indigenous medical knowledge, and false information about genetics and racial superiority.

The researchers have posted works of art and essays, including work by Art Hx graduate students, scholars and collaborators, on the public website **artandcolonialmedicine.com**. The project features art from colonial times as well as more contemporary works.

The era of British colonization spanned the 1500s to the second half of the 20th century, and led to the forced migration of millions of people, including via the trans-Atlantic slave trade. To rationalize the exploitation of peoples and justify punishment and neglect, colonizers invented medicalized theories of racial differences that continue to influence modern physicians.

Nineteenth-century physician James Marion Sims, sometimes referred to as "the father of gynecology," is one historical figure being studied. By examining drawings that appeared in surgical publications during the 1870s, Art Hx interpretive fellow Edna Bonhomme, a historian of science who earned her Ph.D. at Princeton in 2017, explored Sims' complicated legacy.

Sims developed surgical tools and procedures through operations on poor Irish and enslaved Black women. Although Sims' discoveries benefited the medical profession, his surgeries on enslaved persons who lacked the legal right to consent to treatment raise significant ethical questions about racialized medical treatment and the right to make reproductive healthcare decisions, two issues very much in the news today.

Empire's medical legacy

Jessica Womack, a graduate student in Princeton's Department of Art and Archaeology, began working with Arabindan-Kesson on Art Hx in 2020 as the project manager. During the early months of the

SOURCE: LIBRARY OF CONGRESS

The map titled *British empire throughout the world exhibited in one view*, 1850, by the cartography firm of John Bartholomew, illustrates the British Empire's vast holdings of land and people.

pandemic, she watched as the COVID-19 cases rose, particularly within the Black community.

"Black people were dying of COVID," Womack said. "It was terrifying, overwhelming and suffocating to see that. So when Professor Anna Arabindan-Kesson brought me onto the project, I'd already been thinking about issues of racial disparities, healthcare access and healthcare outcomes."

Womack was struck by the parallels between racial disparities in modern medical care. "The disparate effects of COVID-19 on Black, Brown and Indigenous communities point to the structural racism embedded in systems of healthcare," Womack said.

The impact of COVID-19 on Black communities is not the only example of modern racial disparities in healthcare outcomes, Womack said. Black women are three times more likely to die from a pregnancy-related cause than White women, according to the U.S. Centers for Disease Control and Prevention.

Womack said that art helps illuminate medical care in the past, and can reveal much about the present.

"Art-historical approaches can help us understand the visual aspects of communication, which is so important in the circulation of medical knowledge," Womack said.

One example of how colonial art circulated medical knowledge was through illustrations of tropical plants. Such plants

SOURCE: YALE CENTER FOR BRITISH ART

The need for laborers to work vast sugar cane plantations in the British-colonized Caribbean led to the creation of medicalized theories of racial differences that continue to influence physicians during the postcolonial period and today. *Cutting Canes*, by Richard Bridgens, a British artist working in the 1850s, depicts scenes from a sugar plantation in Trinidad where the artist's wife had inherited land.

were of interest to the European scientific community due to their potential medical uses, even as many colonial physicians looked down on Indigenous medical practices. Anna Reid, a historian of art and an Art Hx interpretive fellow, describes artworks created by German-born naturalist Maria Sibylla Merian, who documented plants and insects during a visit to Suriname in 1701.

Suriname was home to coffee and sugar plantations worked by enslaved Africans and ruled alternately by the British and Dutch. In notes accompanying her illustration of a plant known locally as the "peacock flower," Merian reported that enslaved Black women used the seeds to abort their pregnancies, employing their botanical knowledge to assert control over their bodies.

Arabindan-Kesson's own experience in the medical profession inspired her interest in the relationship of art and history. She was born in Sri Lanka and grew up in Australia and New Zealand, where she became a nurse after high school. Like millions of people around the globe, she has lived most of her life in the former British Empire.

"Working and traveling in these countries as a nurse highlighted for me how constructions of race and racism play out in the ways in which communities are marginalized and subjected to various kinds of discriminatory social, political and legal structures," Arabindan-Kesson said.

She credits her interest in colonial influences on medical care to the figures in her life who educated her on her nursing journey.

"As a nurse I was trained by Maori and Pacific Islander women in New Zealand," she said. "They taught me to see how colonial histories contain perceptions of difference that play out in the way that people still treat each other."

Ultimately, these perceptions of difference inspired her to leave nursing and return to the university environment to study art history. In 2014, she received her Ph.D. in the history of art and African American studies from Yale University. "I think what's fundamental to art history is figuring out the ways in which people see," she said, "and how vision is shaped by all of these other structures, histories and frameworks."

Arabindan-Kesson joined the Princeton faculty in 2015 and in 2020 created the Art Hx project in part due to the difficulties in bringing together different types of historical objects. Visual art is housed in museums, while historical documents are stored in libraries or archives. The website, which serves to connect many of these items, was launched in 2021.

"Often, because of the way that objects are categorized, or filed or collected, it's hard to find connections between objects," Arabindan-Kesson said. "The [Art Hx] website is a way to start aggregating different objects together to allow people to see how these objects tell interconnected stories."

Bringing stories to life

Sarah Khurshid Khan was the project's inaugural artist-in-residence from 2021-22. With a background in public health and nutrition and a Ph.D. in plant sciences and traditional ecological knowledge, Khan creates artworks that explore food, culture, migration and healing.

Khan said that Art Hx presents objects in ways that provide a different angle of storytelling. For example, artists highlighted through the project can tell the story of sugar cane from a culinary viewpoint, or from a healthcare viewpoint, or by showing the crop's impact on the enslaved people who planted and harvested it on vast Caribbean plantations.

"They are the same stories but we're looking at them from different angles that suddenly reveal all of this other information that we haven't paid attention to," Khan said. "This is information that brings to life the lives of those who actually did the labor."

Art Hx is supported with a two-year Collaborative Humanities grant from the Princeton University Humanities Council, which provides the primary support for the project. The project also receives support through the Dean for Research Innovation Fund and is affiliated with Princeton's Center for Health and Wellbeing and the Center for Digital Humanities.

Both Arabindan-Kesson and Womack agree that Art Hx is a resource not only for scholars but also for the public.

"We're exploring working with community partners and activists to offer education and policy toolkits for K-12 educators, healthcare professionals and university educators," Arabindan-Kesson said.

"We hope that what we are creating is an accessible resource," Womack said, "not only for academics but something that impacts society."

SOURCE: THE TRUSTEES OF THE BRITISH MUSEUM

Art Hx, a project examining the lasting impact of colonialism on medicine and healthcare, explores themes that range from slavery's influence on modern medical care for Black women to colonial attitudes about indigenous botanicals for the treatment of illness. In German naturalist Maria Sibylla Merian's 1701 illustration of the peacock flower, the artist notes that this medicinal plant was used by enslaved women in Suriname to abort their pregnancies.

Artificial intelligence enters a new era

Computers that can see the world and understand our language are taking on new challenges

By Allison Gasparini

A Covid-19 patient is rushed to the emergency room for trouble breathing and placed on a ventilator. The ventilator senses various conditions including the pressure in the patient's lungs and injects the appropriate amount of oxygen to help the patient breathe normally again.

It's a real-life scenario — and it's one in which artificial intelligence (AI) could make all the difference. By harnessing computers to learn the patient's needs, calculate the amount of oxygen needed, deliver it, and automatically adjust to the patient's changing status, all on the fly, Princeton researchers hope to improve the control of ventilator activity and enhance patient outcomes. This project, a collaboration between Princeton and Google scientists, is one of many examples where Princeton researchers are pushing computers to mimic the intelligence and skills displayed in nature by humans and animals, all with the goal of building a better world.

However, for AI to realize its potential — to relieve humans from mundane tasks, make life easier, and eventually invent entirely new solutions to our problems — computers will need to surpass us at two things that we humans do pretty well: see the world around us and understand our language.

"Learning to see and learning to read are the two main things we need for the computer to do to gain knowledge," said Jennifer Rexford, chair of Princeton's computer science department and the Gordon Y.S. Wu Professor in Engineering. "We call these fields computer vision and natural language processing. These two fields have evolved independently but our faculty are bringing them together in interesting ways."

In recent years, researchers at Princeton and beyond have made major strides in these two fields, opening up rapid progress across a variety of applications. "There's been this huge transformation in the last decade," said Olga Russakovsky, an assistant professor of computer science who works with computer vision. "We're entering this second decade of things actually working."

PHOTO BY SAMEER A. KHAN/FOTOBUDDY

Seeing our world

Improving our ability to capture and analyze images is an essential part of bringing human, or even superhuman, visual abilities to machines such as cellphones, robots and health devices.

Felix Heide is one of the researchers who is developing AI methods to improve the computer's eye, the camera. His goal is to help cameras evolve to the point where their vision capabilities match or surpass those of humans or animals.

"Cameras are a ubiquitous interface between the real world and machines," said Heide, an assistant professor of computer science who works at the interface of AI, physics and optics.

Heide and collaborators at the University of Washington recently built a camera so small that it is about the size of a grain of salt. The device consists of more than a million nanoscale cylindrical posts that interact with light to produce an image. The camera combines image processing and software on the same computer chip.

The team used AI to optimize the shape and position of the posts to modulate light so that the best picture is recorded when using AI to reconstruct and refine the resulting image.

The team's approach relies on a type of AI known as an artificial neural network, modeled after the neurons and connections of the brain, combined with a model of the physics of light transport. The neurons in the model are actually computer algorithms called nodes that take in information, perform a calculation, and produce an output.

"Combining physical models with artificial neural networks is a new paradigm for designing cameras," Heide said. "We're able to use AI to open up an entirely different design space on the optical side."

Future applications of such AI-driven cameras are very broad, Heide said. Placing thousands of such cameras in an array could turn entire surfaces into full-scene cameras. The tiny cameras could be built into ultra-thin endoscopes for medical diagnoses from within the body. With imaging and information processing combined in a single device, the cameras could be ideal for security applications.

AI also is helping us see objects that we've never seen before, such as individual proteins, life's building blocks and sometimes the cause of diseases including Alzheimer's. Proteins are far too tiny to visualize in detail, even with the most powerful equipment. AI could change that.

Ellen Zhong, a new assistant professor of computer science, has developed machine-learning techniques to obtain three-dimensional structures of proteins. She works with images captured using a cryo-electron microscope, which involves first freezing the proteins to quell their vibrations before imaging the sample with an electron microscope.

PHOTO BY DAVID KELLY CROW

The resulting images contain a series of two-dimensional snapshots of the molecules from all directions. Researchers then use complex algorithms to synthesize the different views and stitch together the 3D structure, which can reveal the positions of the atoms in these complex molecules.

Zhong uses machine learning to make sense of the patterns of complex data in cryo-EM images, helping researchers get closer than ever to accurate representations of proteins. But she doesn't plan to stop there.

"One of the exciting future-looking areas of my research is being able to visualize full cells instead of single proteins," said Zhong. "Right now, we can do 3-D reconstructions to visualize individual molecules, but that's just such an isolated piece of the puzzle."

Zhong is one of many researchers who believe that AI may be an important key to tackling the larger goal of understanding how individual proteins interact with each other within the cellular landscape. With a better understanding of these interactions, biologists can help to create new therapeutics for a number of diseases involving protein malfunction.

AI is not only helping us see new things, it is also helping us communicate through improvements in natural language processing.

Helping computers understand us

AI is not only helping us see new things, it is also helping us communicate through improvements in natural language processing. Such systems are behind the ability of computers to translate languages, convert speech into text, and answer spoken questions.

Princeton's Natural Language Processing group aims to make computers understand and use human language effectively. The group was started by two assistant professors of computer science, Danqi Chen and Karthik Narasimhan, and includes Sanjeev Arora, Princeton's Charles C. Fitzmorris Professor in Computer Science.

Chen is working to develop machines that can access human knowledge through interactions with written and spoken language, and that have the power to comprehend, reason, and make decisions and judgments with little or no outside guidance.

"I study basic questions like how we should represent text in neural networks, how we should extract and encode information that is written in the text, and how we can retrieve relevant information and utilize it for downstream applications such as question answering and dialogue systems," Chen said.

Over the past two to three years, the natural language processing field has transformed through the introduction of large language models (LLMs), which have started a new era of open-ended human-machine interactions via simple natural-language instructions. Despite the excitement, these LLMs may contain hundreds of billions of parameters, making them a thousand times larger than previous models. Training these models comes at a massive financial and environmental cost, and therefore has been limited to only a handful of large corporations and well-funded research labs.

"One of the major problems I am currently tackling is how to scale down these models and develop more efficient solutions for training and adapting these very large models," Chen said.

Narasimhan is developing autonomous systems that can acquire language through interactions with their environments. He also wants to grow the capability for computers to take in textual information and use it to drive decision-making.

"Most of today's natural language processing models focus on learning semantic

PHOTO BY DAVID KELLY CROW

representations from text alone, but deep understanding of natural language requires situational and contextual awareness for an AI system to resolve ambiguities, avoid misunderstandings and provide appropriate responses," Narasimhan said. "Our lab focuses on embodied language understanding, with the goal of teaching machines to understand and use language in interactive, multi-modal environments."

Narasimhan's team also develops new methods to get computers to learn via a combination of "doing" and "reading" — just as humans do — as opposed to the "trial and error" nature of predominant AI paradigms like reinforcement learning, a training method based on rewarding desired behaviors. As an example, say you decide to pick up tennis as a sport. You could just hit balls in the court every day without any external inputs and improve slowly, but it is more likely that you would get tips from the internet or through verbal feedback from a coach to make more rapid progress.

"I imagine a not-too-distant future where AI systems can similarly use language as a way to receive distilled knowledge and guidance from human experiences through books, manuals and the internet," Narasimhan said.

Over the last several years, Arora has been captivated by questions about how AI works, why some methods of AI work better than others, and what is happening when AI systems are learning. Arora is interested in figuring out what is going on inside of the neural network as it processes the world around it.

"My work is to understand — at a more rigorous and mathematical level — what is going on inside the training of the artificial neural net," Arora said. "We say our goal is to open the black box." This will help understand the answers that the neural net gives, and also may lead to better training algorithms and more robust learners.

In understanding what happens when neural nets are running, Arora hopes to help engineers better plan and design their algorithms.

Making AI smarter

AI has caught up with humans in many ways, becoming as good as we are at recognizing familiar images, translating languages and converting text to speech. And AI can do these things faster than most humans can. But can AI really help people create, and innovate?

In Ryan Adams' laboratory, the question researchers are chasing is, can they design new things using AI?

"We have generative models that synthesize new pictures and text," explained Adams, a professor of computer science and director of Princeton's undergraduate program in statistics and machine learning. "But we're also working on how you can use AI to create new kinds of designs for real-world objects, for example, inventing new antibiotic molecules, new mechanical systems, or new materials. Even more than just design, we want AI to help us make these things, too."

> AI can do these things faster than most humans can. But can AI really help people create, and innovate?

One recent innovation to come out of Adams' research is the application of AI models to computer aided design (CAD) tools. Adams and his team created AI software trained with human-designed CAD sketches that can automate suggestions of new inventions on its own. "Think about using Microsoft Word and you misspell something and it autocorrects or it suggests new text," explained Adams. "What if we could do that for design?"

Across the hall from his office, Adams has a laboratory space filled with machine tools, 3-D printers and laser cutters. It's a highly physical set up, unlike most AI labs where researchers do the bulk of their work behind computer screens. "We have some fun chaos," he said.

PHOTO BY DAVID KELLY CROW

One of the most impactful things Adams believes he and his colleagues are doing in their research is thinking deeply about the interaction between physics and AI. "Invention is about physical embodiment," said Adams. "It's about making things, and you can't be blind to the physics behind it."

Adji Bousso Dieng is also thinking deeply about the intersection of science and AI — but in a different way.

Dieng leads Vertaix, an interdisciplinary research lab at Princeton working at the intersection of AI and the natural sciences.

"We are looking at every step involved in the scientific discovery process and developing AI methods motivated by problems arising from that process," said Dieng, an assistant professor of computer science.

One core part of that discovery process is to ensure that machine learning algorithms are able to generate solutions or outcomes that contain the diversity that we see in natural world.

One core part of that discovery process is to ensure that machine learning algorithms are able to generate solutions or outcomes that contain the diversity that we see in the natural world. Dieng and her collaborator Dan Friedman, a Ph.D. student in the computer science department at Princeton, drew on definitions of diversity used in the field of ecology to develop a metric called the Vendi Score to measure diversity of models.

PHOTO BY SAMEER A. KHAN/FOTOBUDDY

The Vendi Score looks at the similarity between elements in a sample — in one example, a large number of scent molecules — and returns a score of how diverse or different from each other the molecules are. If all the scent molecules were of the category "herbal," for example, the score would be lower than if many more scent categories were shown.

Unlike other estimates of diversity in machine learning, the score can be used in any problem where similarity can be defined. It is unsupervised, in that it doesn't require a human to add labels to the dataset. "For AI to enable discovery, we ought to be able to measure and incorporate diversity into the methods we develop," said Dieng.

The interest in AI for science is rapidly growing, said Dieng. "In 10 years, the biggest impact from AI will be from the sciences."

In the Google AI Lab, a research center near campus where Princeton and Google researchers collaborate, Elad Hazan, a professor of computer science, and his team are working on challenges such as controlling ventilators for patients as well as other situations in which machines control technologies. To do this, they are developing new algorithms to advance machine learning methods as well as make them more efficient. The fastest known methods for training neural networks stem from Hazan's work on optimization and are widely used in academia and industry. Hazan's current research is concerned with the field of control, with the goal of manipulating a physical system, such as the medical ventilator, using observable signals.

"The field of control goes back decades, even centuries," said Hazan. "Our take on it is new because we're using AI and deep learning, which are new tools and give rise to new methods."

In his laboratory, he and his collaborators are working on developing methods to train neural networks to perform in a certain way. For example, Hazan's methodology could be applied to controlling autonomous vehicles and robotics. "Generally, innovations in the field of control have implications to robotics," said Hazan. "Control theory concerns manipulating a physical system in generality. It can be a ventilator, robot, drone or autonomous vehicle."


Elad Hazan

PHOTO BY DAVID KELLY CROW

Expanding the community

The rapid adoption of AI must be accompanied by addressing questions about racial and gender biases in AI algorithms.

Russakovsky is one of the researchers in the field grappling with ethical questions from the engineering perspective. "We're starting to ask — as engineers, as builders of these systems — what can we do to ensure that they are equally accurate for all people," Russakovsky said.

Previous research has found striking biases embedded in AI-driven processes. For example, facial recognition systems performed vastly more accurately when identifying men with lighter skin versus women with darker skin.

Russakovsky and her group are engineering solutions to these problems. She helped build a tool known as REVISE, which analyzes visual datasets for signs of biases, including racial and gender biases.


Olga Russakovsky

PHOTO BY DAVID KELLY CROW

"It's a very complicated space, and approaching it from a tech standpoint is kind of a Catch-22," said Russakovsky. "You have to design technical solutions, but any technical solution you design is inherently a simplification of the underlying issue."

Despite the challenges, Russakovsky is excited about the progress AI has made. Now that researchers know how well these visual learning applications can work in the real world, they want to push forward the limits of what they may actually achieve. "Now the question is: what are the new frontiers we can tackle?" said Russakovsky.

Now that researchers know how well these visual learning applications can work in the real world, they want to push forward the limits of what they may actually achieve.

Attracting the next generation of AI researchers to Princeton will be important as researchers across the University continue to innovate and move into the next generation of machine learning. The collaborative opportunities are only growing. Adams, for his part, believes the University is in a position to make things possible in the AI space that may have seemed impossible even just last year. "We sort of have this balance of size and quality," said Adams.

Princeton is small enough that an AI researcher can walk across campus to collaborate with engineers and researchers in robotics while also delivering world-class teaching and research, Adams said. "Princeton is just absolutely uniquely positioned to take things to the moon."

Bridging the divide

Two newly hired professors bring expertise in development economics to solving global challenges

By Christopher Hann

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Pascaline Dupas' first job in research was, in her words, "at the very bottom of the pecking order." She'd traveled to Kenya to work for a year as a field research assistant to Michael Kremer, a pioneer in development economics. Her first task was to help measure parasite levels in Kenyan children, in part by examining their stool samples. It fell to Dupas to label those samples. "I put their poop in a plastic jar," she said. "We needed to know whose poop was whose. I learned so much from this."

For Dupas, the experience proved inspiring. Her year in Kenya bolstered her desire to alleviate poverty globally, and she returned home convinced that through research she could help devise solutions to the many challenges facing the world's poorest people. After earning a Ph.D. at the Paris School of Economics, she embarked on such research, focused primarily on issues of health and education in Africa, and over the ensuing two decades has emerged as a leader in the field of development economics.

Seema Jayachandran tells a similar tale. Like Dupas, she can trace her career path to Michael Kremer, with whom she took a course in development economics at Harvard, where she earned a Ph.D. in economics. The course was inspiring. "Something sparked intellectually," Jayachandran said.

Over the past two decades, she, too, has dedicated her life to development economics, with much of her work focused on environmental conservation, gender equality, health and the economic issues that impact everyday life in developing countries.

Their shared interests brought Dupas and Jayachandran together to become research collaborators: A current project in Burkina Faso, in West Africa, seeks to determine how the perception of child mortality affects women's fertility decisions. Said Dupas, "We were on Zoom way before the pandemic."

These days the two scholars stand poised to embark on their most ambitious collaboration yet: Together they will lead Princeton's newly launched Research Program in Development Economics, a joint endeavor between the School of Public and International Affairs (SPIA) and the Department of Economics.

Jayachandran arrived at Princeton in fall 2022 from a faculty position at Northwestern University. Dupas, who is now at Stanford, will arrive at Princeton in July 2023. Dupas and Jayachandran will each hold the title of professor of economics and public affairs, and will be appointed in both SPIA and the Department of Economics.

Princeton has long been a leader in this interdisciplinary field, which explores the breadth of factors — health, education, working and market conditions, domestic and international policies — that drive economic and social conditions in the developing world.

To Amaney Jamal, the dean of the School of Public and International Affairs, the arrival of Dupas and Jayachandran heralds a new chapter in the University's longstanding commitment to development economics research.

Jamal said the new leadership will guide SPIA's effort to internationalize its research program, enhancing the school's global footprint. "We are extending our rigorous research to all parts of the world," Jamal said. "We want to make sure we're paying attention to how international affairs affect curriculum. Is it only about the U.S. experience? Is it only about the European experience? Or can we talk more universally about the global experience?"

Wolfgang Pesendorfer, Princeton's Theodore A. Wells '29 Professor of Economics and chair of the Department of Economics, said the two new professors will pioneer work that can serve as a bridge for Princeton economics students and researchers to collaborate with colleagues across campus and around the world.

"What is nice about economics is that, because we share common methods across fields, the boundaries of the fields are flexible," Pesendorfer said. "Many people in the department will do some work in various fields, among them development economics. Whenever we bring in exciting new people, it has a direct effect on all of us."

Dupas and Jayachandran said the hiring of each other made the move to Princeton even more appealing.

"Our mandate," Jayachandran said, "is to modernize the development economics program, to bring it to where the frontier is."

"I know we can do more together," Dupas said, "than either one of us could do on our own."

The price of bed nets

Dupas summarizes her life's work in this simple passage on her website: "I am a development economist," the page reads, "seeking to better understand challenges facing poor households in lower income countries. My aim is to identify tools and policies that can help overcome these challenges and reduce global poverty."

In Kenya, Dupas studied the efficacy of providing free, insecticide-treated bed nets to people in poor villages. The bed nets serve as vital shields in the prevention of malaria, which, according to the World Health Organization, killed 627,000 people globally in 2020, nearly all of them in Africa.

In her research, Dupas delved into a long-running debate among public-health experts over the most effective methods for distributing essential healthcare products.

Pascaline Dupas

PHOTO BY ROD SEARCEY

Research led by Pascaline Dupas, a newly appointed professor of economics and public affairs, found that providing free, malaria-preventing bed nets to people in poor villages in Kenya led to increased usage, helping to settle the debate over whether user fees should be charged for access to life-saving health care products.

PHOTO BY SALVADOR-AZNAR/ISTOCK

Seema Jayachandran

PHOTO BY TEAMWORKS

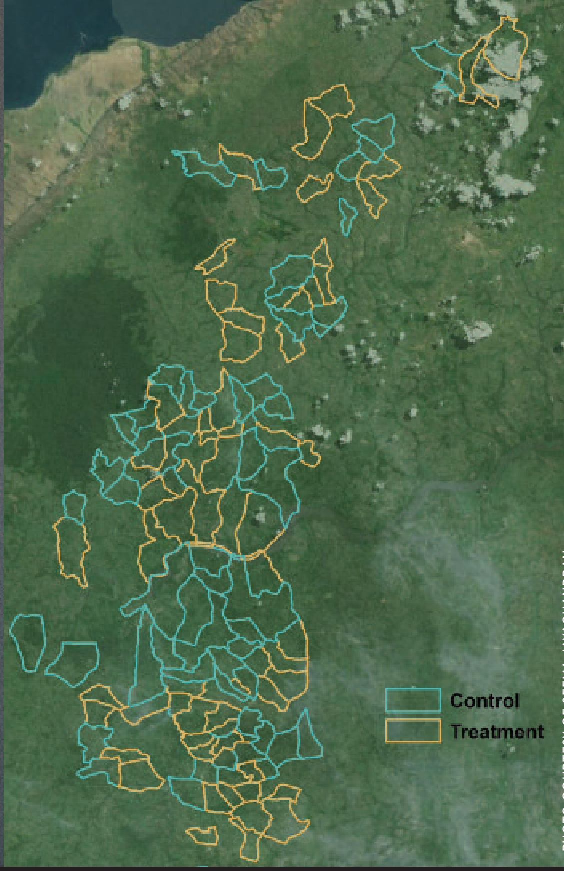


PHOTO COURTESY OF SEEMA JAYACHANDRAN

Newly appointed Princeton professor of economics and public affairs Seema Jayachandran's research showed that paying forest owners in western Uganda not to cut down their trees can be a cost-effective way to mitigate climate change.

Should recipients be charged a nominal price for bed nets, to save resources by screening out those who might not use them? Would charging fees raise revenues and thus make distribution programs more sustainable? Or should essential healthcare products be provided free of charge to anyone in need?

With a fellow researcher, Dupas studied the impact of different subsidies on the use of bed nets delivered to pregnant women at 16 health clinics in Kenya. They found that charging for bed nets dragged down overall usage. Even when the bed nets were sold at a 90 percent discount, the use of bed nets dropped by 60 percent compared to when the bed nets were offered free of charge.

Dupas' research helped shift policy on the distribution of healthcare products, according to a review by the Abdul Latif Jameel Poverty Action Lab (J-PAL), a research institute dedicated to ensuring that policy is informed by scientific evidence. "A number of influential organizations now recognize that the elimination of user fees is the most effective way of quickly increasing take-up of key preventive health products," J-PAL wrote.

In 2008, working with Kremer and Esther Duflo — who together won the 2019 Nobel Prize for experiment-based solutions to global poverty — Dupas began a longitudinal study on the impact of free secondary education in Ghana. The study, a randomized controlled trial, provided scholarships to 682 students who had been admitted to a public high school but had not enrolled because of the prohibitive cost. By 2016, the study found, 74% of scholarship recipients had completed senior high school, compared to 47% of nonrecipients from the same demographic.

Within the same time frame, another 12% of scholarship recipients had enrolled in tertiary education, compared to 9% of nonrecipients. Women who won scholarships married later and delayed childbirth, and avoided unwanted pregnancies, compared with women who did not win scholarships. In 2017, informed by the study's findings, the government of Ghana made secondary education free for all.

Dupas and her colleagues continued to follow the study's participants up to this year. Dupas reports that girls who received the scholarship "were better insulated from the negative economic shock created by the COVID-19 pandemic." Importantly, their children, she reports, were more likely to survive to their third birthday.

"To me," Dupas said, "working towards improving the lives of people around the world who live in poverty is very important. There is no other thing I would like to do."

Paying for trees

While Jayachandran's research has focused on India, she has also worked in Africa. In 2017 she was the lead author of a study that showed the benefit of paying forest owners in western Uganda not to cut down their trees. The study was published in the journal *Science* and reported in *The New York Times* and other major news outlets.

Jayachandran and her colleagues offered owners of forested land in 60 villages the equivalent of $11.20 an acre a year if they did not cut their trees. They compared the forested land in those 60 villages to similar property in 61 "control" villages, where landowners had not been offered the subsidy. Two years later, they found the forest cover dropped by 9.1 percent in the control villages but only 4.2 percent in the villages whose landowners were offered payments. The result showed that preserving forests' ability to capture and store carbon can be one of the most cost-effective ways to mitigate climate change.

More recently, Jayachandran helped design a program intended to reshape attitudes toward girls and women among adolescent students in the Indian state of Haryana. Jayachandran and colleagues studied the results of a classroom program designed to teach gender equality to seventh- to tenth-graders. The students received a 45-minute lesson — in gender stereotypes, gender roles at home, and harassment, among other topics — every three weeks for two and a half years. The study found the program "made attitudes more supportive of gender equality," even two years after it ended. Jayachandran's research team took their findings to government officials, and the program has since been adopted in two other Indian states, reaching an estimated one million students a year.

"It's kind of exciting," Jayachandran said. "Ten years ago, I had this idea that the way to solve this problem was that governments should try using schools to change attitudes. We turned that into a concrete research project, and now very recently we see the research affect policy."

Helping people flourish

Jamal herself is a leading researcher in global development. Now in her second year as SPIA dean, she expects to return to her own research with renewed vigor this academic year — namely, a book about economic segregation around the world. "Why is it," she asks, "in this particular moment, we are seeing poor people in more exclusively poor areas and rich people in more exclusively rich areas. Not only in the United States, but globally." Her book is tentatively titled *The Global Segregation of the Poor*.

Jamal is excited about the prospect of Dupas and Jayachandran creating opportunities for existing faculty and Princeton students to take part in research that expands our understanding of global topics, affects public policy, and, ultimately, improves lives. "No doubt they're going to do remarkable things with the program," Jamal said.

"If I can train the next generation of graduates to design better policy because they understand the framework of economics, they're going to have a huge, concrete impact on the world."

Jayachandran and Dupas say they look forward to collaborating with new colleagues, bringing visiting scholars and foreign government officials to Princeton, and especially working with students. "A lot of the impact you can have is by helping other people flourish," Jayachandran said. "If I can train the next generation of graduates to design better policy because they understand the framework of economics, they're going to have a huge, concrete impact on the world."

Shariffa Ali, theater maker

When a two-week trip to the U.S. fell through, Ali created new spaces of possibility

By Ashia Reid

Shariffa Ali watched as thousands of girls swayed their arms and legs in rhythm to the music, their voices raised in a high-pitched, undulating song. She was 6 or 7 years old, and had come to watch the Reed Dance, an annual cultural celebration in Swaziland (now Eswatini), in which tens of thousands of girls dance, sing and place reeds in front of the Queen's palace.

"Witnessing the immense spectacle and pageantry of the event planted in me a love of gathering, and a love for viewing performance," said Ali, who today is a writer, director, creator and filmmaker, as well as a lecturer in theater at Princeton's Lewis Center for the Arts.

Ali's early experiences in Eswatini set the foundation for a deep passion for the arts, and for finding ways to bring out creativity in others. Through her journey from the southern African country to Princeton, with stops in Pittsburgh, Washington Heights and New Haven, Ali has inspired people young and old. From college students to senior citizens, she has helped others look for meaning through embracing the arts and turning setbacks into opportunities.

Ali describes herself as "a planter of seeds, of proposals to humanity."

"I believe that our art can reflect our world but also project a proposal to humanity on what our world could be one day," Ali said during an interview in Princeton, reflecting words from one of her mentors in public theater. "It is in that space of possibility that I most creatively thrive."

Born in Nairobi to Kenyan and Ethiopian parents, Ali spent her early life in Eswatini, and then moved with her family to South Africa. There, she faced bullying from other high school students over skin that was darker than that of her South African classmates. "Colonialism and white supremacy culture have infected the minds of young people, and as a result we don't equate ourselves with being beautiful and celebrated," she said, recalling that experience.

The bullying pushed her to move to a high school focused on academics and the arts, and she found herself drawn to the school's theater program. Inspired to become an actor, Ali applied to the University of Cape Town's prestigious theater and performance program. When she received her acceptance letter, however, she found that she'd been placed not in the acting program, but in a program that trains people to become "theater makers," which she said encompassed everything from directing to marketing and producing.

Although disappointed at first, she enrolled in the program and soon found she was

PHOTO BY MIGUEL HERRERA

Shariffa Ali

Ali first came to Princeton as the guest director of *Eclipsed*, a play that formed the basis of a senior thesis project by undergraduate Ugonna Nwabueze, Class of 2018 (left), shown performing with another student.

exactly where she belonged. "I didn't choose theater," she said with a laugh. "Theater chose me, and I accepted the invitation."

While in college, Ali met an exchange student from the U.S. who invited her to come, upon her graduation, to Pittsburgh for two weeks to co-create a theater piece called *Still*, which was about a young Black man born into an unwelcoming world.

When she stepped off the plane in the United States, however, her friend had bad news. The theater where the program was to be held was closing due to financial struggles.

Rather than boarding the next plane home, the 22-year-old was determined to find a way to stay in the U.S. She convinced her mother to give her a few weeks to experience life in the U.S. before heading home. "My ego did not allow me to return home without doing something," she remembers, smiling. She headed to New Rochelle, a town just north of New York City, where an aunt lived. She slept on the couch, as the weeks turned into months.

While staying with her aunt, a new friend invited Ali to watch a reading of a play. Ali, seated at a large table, turned to her right and met a man who she thought moved with the grace of a gazelle and, it turned out, was Gentry George, a dancer with the Alvin Ailey Dance Theater, founded by the iconic choreographer and activist.

Ali asked George if he would be interested in collaborating with her in continuing the production of *Still*. He agreed, and for the next several weeks, Ali, her newfound friend and a handful of others met regularly, first in Washington Heights and then in Brooklyn, to develop the piece. They rehearsed on rooftops, at the YMCA, at the nearby sports center, anywhere they could find a quiet space. Finally, they were ready to put on the performance, for which they charged $10 per person admission. "We each made 50 dollars, which was huge since we'd built it from the ground up," she said.

Having convinced her worried mother that she could make it in her newly adopted country on her own, Ali found an internship at New York City's Public Theater, one of the nation's oldest nonprofit theaters and a center for community performances, including New York's free Shakespeare plays in Central Park. Ali's internship led to a permanent position as a public works coordinator, helping to introduce theater and creative works across New York's five boroughs. "We were teaching theater classes, voice classes, movement, dancing," she said. "We were involved in a giant summer pageant that featured 200 people."

During her fourth year at the Public Theater, Ali got the chance of a lifetime: the opportunity to direct a production at Yale University of *We Are Proud to Present a Presentation About the Herero of Namibia, Formerly Known as South West Africa, From the German Südwestafrika, Between the Years 1884-1915*.

Described as intense and revelatory, the play explores what happens when a group of actors confronts the genocide of the Herero people of southern Africa.

Working days at the Public Theater and commuting to Yale in New Haven, Connecticut, to rehearse with students meant a grueling schedule. Ali woke up at 6 a.m., took the 7 a.m. train to New York City where she spent the day at the Public Theater, and then took a two-hour train ride to New Haven so she could arrive for rehearsals that stretched until 11:30 at night.

"Four hours a day were spent on the train, but it enabled me to say yes, I am capable," she said. "It proved to me that maybe there is a space for me as a creative person here in the U.S."

One of the people who heard about the performance was Ugonna Nwabueze, a Princeton University student. When Ali and Nwabueze met, the two connected immediately.

When it came time for Nwabueze to propose her senior thesis project, she chose to produce and act in a play called *Eclipsed* about five Liberian women who confront civil war with resilience, resistance and hope. Nwabueze felt that the play's sensitive topic required a director with experience living in Africa, and Ali was at the top of her list.

Jane Cox, Professor of the Practice in the Program in Theater in the Lewis Center for the Arts, and director of the program, was one of Nwabueze's advisers and led the committee that approved Ali's appointment as a guest director at Princeton in 2017.

"I'll never forget the first meeting that I had with Shariffa," Cox said. "I just felt like this person is in charge and this person is going to take care of things. This person is wise. This was really wonderful for that project because the piece is about people who are surviving war and turmoil, and for Ali to be able to bring that sort of energy to the room with the students was really helpful in dealing with really traumatic material."

Elena Araoz, senior lecturer in theater and the Lewis Center for the Arts, praised Ali's ability to create an exciting piece of theater based on the singular talents of who is in the rehearsal room rather than trying to fit people into preexisting expectations.

"Black women are fierce. We care for each other deeply. We belong everywhere."

"I appreciated that she was asking, Who is in the room with us, who are all of our collaborators, students, professionals and colleagues, and how we are going to make something that comes from the best of what we have to offer?" Araoz said.

Since arriving at Princeton to direct *Eclipsed*, Ali has directed numerous productions including the original musical *We Were Everywhere*, developed by Ali, Avi Amon and Joanna Evans with Princeton students during a theater course in 2019, and Lynn Nottage's *Intimate Apparel*. She has produced several new works written by Princeton seniors in the theater and music theater programs, and she teaches on topics ranging from introductory art making to South African protest theater.

"This film began as a love letter to my mom — all her passion, quirks and resilience. Throughout the pandemic, it has morphed into therapy."

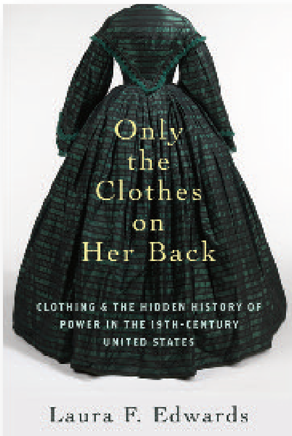
Ali also expanded her work to include film writing and directing with a 13-minute Sundance Film Festival short called *You Go Girl!* The film is about a young Black woman who travels to a desolate part of Oregon where she confronts challenging terrain inside herself and in her surroundings.

"This film began as a love letter to my mom — all her passion, quirks and resilience," Ali wrote in the film's description. "Throughout the pandemic, it has morphed into therapy. Black women are fierce. We care for each other deeply. We belong everywhere."

Although only 31, Ali draws on substantial life experiences when advising students who want to succeed in the arts. One of her main pieces of advice is not to wait.

"Do not wait for an institution or individual to give you an opportunity, but rather make theater with whatever you have, wherever you have it," Ali said. "Understand that you have plenty of opportunities based on the people that you already know, and the friends that you have met. Create constantly, because that's the way you get noticed."

Above all, she tells young people to follow their inner compass, just as she did when, nine years ago, she chose to stay in the U.S. despite the cancellation of her first big opportunity. "We live in a world that has groomed us to ignore our instincts, to say yes when we really mean no, to act against our best interests," Ali said. "You have to make space for the inner voice to be heard." ●



Only the Clothes on Her Back: Clothing and the Hidden History of Power in the Nineteenth-Century United States

Oxford University Press, Feb. 2022

Laura F. Edwards, Class of 1921 Bicentennial Professor in the History of American Law and Liberty

What can dresses, bedlinens, waistcoats, pantaloons, shoes and kerchiefs tell us about the legal status of the least powerful members of American society? In the hands of eminent historian Laura Edwards, these textiles tell a revealing story of ordinary people and how they made use of their material goods' economic and legal value in the period between the Revolution and the Civil War.

Only the Clothes on Her Back uncovers practices, once commonly known but now long forgotten, which made textiles a unique form of property that people without rights could own and exchange. The value of textiles depended on law, and it was law that turned these goods into a secure form of property for marginalized people. Edwards grounds the laws relating to textiles in engaging stories from the lives of everyday Americans. Wives wove linen and kept the proceeds, enslaved people traded coats and shoes, and poor people invested in fabrics, which they carefully preserved in trunks. Edwards shows that these stories are about far more than cloth and clothing; they reshape our understanding of law and the economy in America.

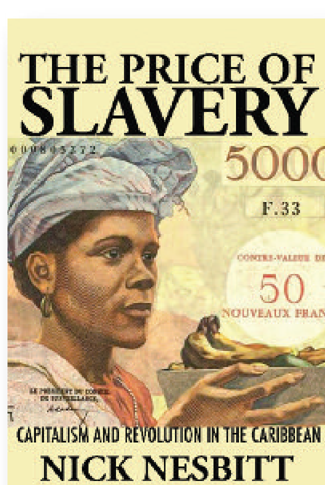
The Price of Slavery: Capitalism and Revolution in the Caribbean

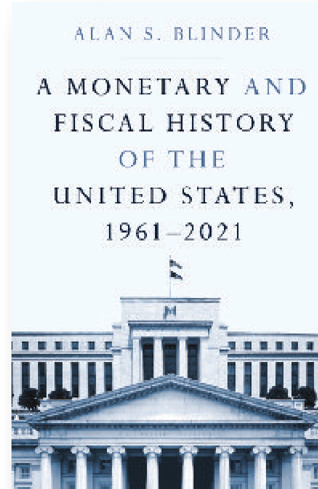
University of Virginia Press, March 2022

F. Nick Nesbitt, Professor of French and Italian

The Price of Slavery analyzes Marx's critique of capitalist slavery and its implications for the Caribbean thought of Toussaint Louverture, Henry Christophe, C. L. R. James, Aimé Césaire, Jacques Stephen Alexis, and Suzanne Césaire.

Nick Nesbitt assesses the limitations of the literature on capitalism and slavery since Eric Williams in light of Marx's key concept of the social forms of labor, wealth, and value. To do so, Nesbitt systematically reconstructs for the first time Marx's analysis of capitalist slavery across the three volumes of *Capital*. The book then follows the legacy of Caribbean critique in its reflections on the social forms of labor, servitude, and freedom, as they culminate in the vehement call for the revolutionary transformation of an unjust colonial order into one of universal justice and equality.





A Monetary and Fiscal History of the United States, 1961–2021

Princeton University Press, Oct. 2022

Alan S. Blinder, Gordon S. Rentschler Memorial Professor of Economics and Public Affairs

Alan Blinder, one of the world's most influential economists and one of the field's best writers, draws on his deep firsthand experience to provide an authoritative account of sixty years of monetary and fiscal policy in the United States. Spanning twelve presidents, from John F. Kennedy to Joe Biden, and eight Federal Reserve chairs, from William McChesney Martin to Jerome Powell, this is an insider's story of macroeconomic policy that hasn't been told before — one that is a pleasure to read, and as interesting as it is important.

Focusing on the most significant developments and long-term changes, Blinder traces the highs and lows of monetary and fiscal policy, which have by turns cooperated and clashed through many recessions and several long booms over the past six decades. From the fiscal policy of Kennedy's New Frontier to Biden's responses to the pandemic, the book takes readers through the stagflation of the 1970s, the conquest of inflation under Jimmy Carter and Paul Volcker, the rise of Reaganomics, and the bubbles of the 2000s before bringing the story up through recent events — including the financial crisis, the Great Recession, and monetary policy during COVID-19.

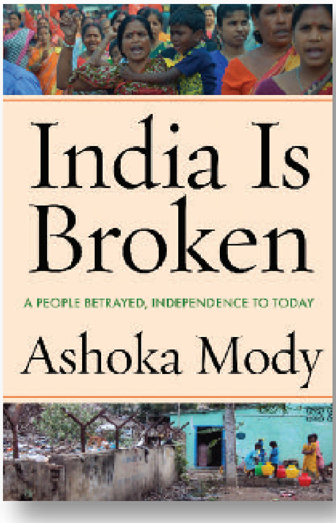
India Is Broken:
A People Betrayed, Independence to Today

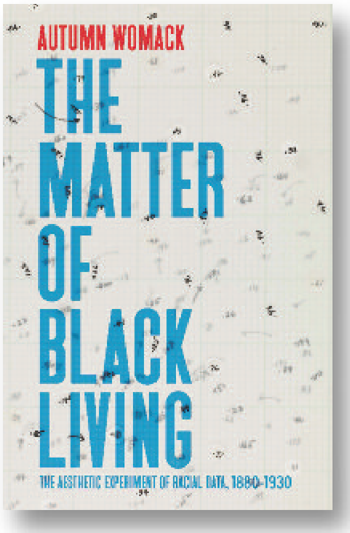
Stanford University Press, Feb. 2023

Ashoka Mody, Charles and Marie Robertson Visiting Professor in International Economic Policy

When Indian leaders first took control of their government in 1947, they proclaimed the ideals of national unity and secular democracy. Through the first half century of nation-building, leaders could point to uneven but measurable progress on key goals, and after the mid-1980s, dire poverty declined for a few decades, inspiring declarations of victory. But today, a vast majority of Indians live in a state of underemployment and are one crisis away from despair. Public goods — health, education, cities, air and water, and the judiciary — are in woeful condition. And good jobs will remain scarce as long as that is the case. The lack of jobs will further undermine democracy, which will further undermine job creation. *India is Broken* provides the most persuasive account available of this economic catch-22.

Combining statistical data with creative media, such as literature and cinema, to create strong, accessible, people-driven narrative, this book is a meditation on the interplay between democracy and economic progress, with lessons extending far beyond India. Mody proposes a path forward that is fraught with its own peril, but which nevertheless offers something resembling hope.





The Matter of Black Living:
The Aesthetic Experiment of Racial Data, 1880 – 1930

University of Chicago Press, April 2022

Autumn Womack, Assistant Professor of African American Studies and English

As the nineteenth century came to a close and questions concerning the future of African American life reached a fever pitch, many social scientists and reformers approached post-emancipation Black life as an empirical problem that could be systematically solved with the help of new technologies like the social survey, photography, and film. What ensued was nothing other than a "racial data revolution," one which rendered African American life an inanimate object of inquiry in the name of social order and racial regulation. At the very same time, African American cultural producers and intellectuals such as W. E. B. Du Bois, Kelly Miller, Sutton Griggs, and Zora Neale Hurston staged their own kind of revolution, un-disciplining racial data in ways that captured the dynamism of Black social life.

The Matter of Black Living excavates the dynamic interplay between racial data and Black aesthetic production that shaped late nineteenth-century social, cultural, and literary atmosphere. *The Matter of Black Living* charts a new genealogy from which we can rethink the political and aesthetic work of racial data, a task that has never been more urgent.

The Entrepreneurs:
The Relentless Quest for Value

Columbia Business School Publishing, Nov. 2022

Derek Lidow, Professor of the Practice in the Keller Center for Innovation in Engineering Education

Entrepreneurs are among the primary shapers of our culture, yet their role in driving progress and influencing society has often been overlooked. Almost five millennia ago, copper tool manufacturers set up a factory in what today is southwest Spain, profiting for hundreds of years from trade around the Mediterranean. Papyri document the diverse investments of an ancient Egyptian businessperson, from grain-yielding land to flax for linen cloth. What do these figures have in common with renowned modern entrepreneurs, and how do their similarities help us achieve a deeper understanding of entrepreneurship as well as the potential for a healthier, wealthier, and more equitable and sustainable future?

Derek Lidow delves into the deep history of innovation to deliver essential new insights into how entrepreneurs create value and bring about change. Lidow emphasizes how entrepreneurship can harm society as well as benefit it, and he underscores ways to mitigate its harmful side and harness its positive effects. By highlighting the fundamental qualities of innovation throughout history, this book provides indispensable new perspective on how it is shaping our present and future.

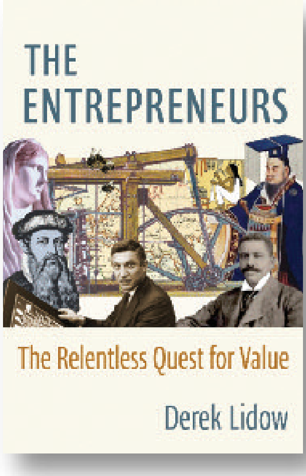


PHOTO BY STEVEN FREEMAN

Breakthrough Prize goes to Cliff Brangwynne

Princeton bioengineer Clifford Brangwynne won the 2023 Breakthrough Prize for Life Sciences in recognition of his contributions to the study of living cells. Brangwynne's research has changed how scientists understand cellular organization, leading to foundational insights about cell functions and suggesting new ways to treat diseases such as cancer, amyotrophic lateral sclerosis (ALS) and Alzheimer's disease.

Brangwynne, the June K. Wu '92 Professor of Chemical and Biological Engineering, shares the $3 million prize with Anthony Hyman of the Max Planck Institute of Molecular Cell Biology and Genetics. The Breakthrough Prize cited the researchers' discovery of "a fundamental mechanism of cellular organization mediated by phase separation of proteins and RNA into membraneless liquid droplets."

Before Brangwynne and Hyman's 2009 paper, scientists believed the primary structures that organize molecular machinery within cells were like soap bubbles, with a distinct membrane separating inside from out. The researchers showed that many structures within cells are more like raindrops, where molecules condense from their surroundings and band together due to the physics of phase separation. Over the past decade, this paradigm, sometimes called liquid-liquid phase separation, has been shown to drive many basic cellular functions, including protein aggregation, gene expression, the immune response to viruses, cell growth and cancer, and a host of other processes. ***–Scott Lyon***

Wolf Prize goes to Bonnie Bassler and Elizabeth Diller

Bonnie Bassler, the Squibb Professor in Molecular Biology and a Howard Hughes Medical Institute Investigator, shares the Wolf Prize in Chemistry with Carolyn Bertozzi of Stanford University and Benjamin F. Cravatt III of the Scripps Research Institute.

Elizabeth Diller, professor of architecture, has been named a Wolf Prize Laureate in Architecture for 2022. She was selected "for her exceptional and influential work connecting architecture to artistic practice, engaged in the public domain."

Bassler received the award "for her work elucidating the role of chemical communication between bacteria. She has made important discoveries revealing how quorum sensing is used by bacteria both for virulence and for communicating across species."

Diller, a Polish-born American architect, has completed groundbreaking projects in the connected worlds of art and architecture. Her efforts have radicalized the relationship between architecture, art and the engagement of a larger audience.

Bestowed by the Wolf Foundation in Israel since 1978, the Wolf Prize is awarded to outstanding scientists and artists from around the world. The prize laureates are selected by international jury committees of experts.
–Liz Fuller-Wright and Jamie Saxon

[BASSLER] PHOTO BY ALENA SOBOLEVA

[DILLER] PHOTO BY GEORDIE WOOD

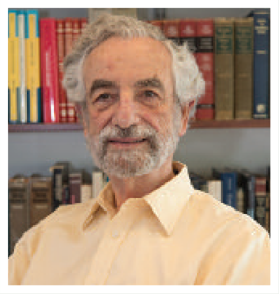


PHOTO BY DENISE APPLEWHITE

Elliot Lieb wins American Physical Society's highest honor, and mathematics' Gauss Prize

Elliott Lieb, Princeton's Eugene Higgins Professor of Physics, Emeritus, and professor of mathematical physics, emeritus, received the 2022 American Physical Society (APS) Medal for Exceptional Achievement in Research for "major contributions to theoretical physics through obtaining exact solutions to important physical problems, which have impacted condensed matter physics, quantum information, statistical mechanics and atomic physics."

Awarded annually, the medal is the highest honor the APS bestows upon researchers across all of physics, recognizing contributions of the highest level that advance our knowledge and understanding of the physical universe in all its facets.

Lieb also received the 2022 Carl Friedrich Gauss Prize, named for the German mathematician and physicist and awarded jointly by the German Mathematical Union, which recognizes outstanding mathematical contributions that have found significant applications outside the field. Lieb was honored for contributions to physics, chemistry and pure mathematics.

"His profound and lasting influence has changed and in some cases redefined multiple branches of mathematical physics, including quantum mechanics, statistical physics, computational chemistry and others," said Igor Rodnianski, professor and chair of the Department of Mathematics.
–Liz Fuller-Wright

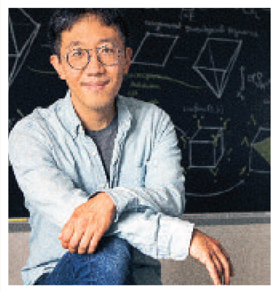


PHOTO BY DENISE APPLEWHITE

Fields Medal and MacArthur Fellowship go to June Huh

June Huh, professor of mathematics, was awarded the 2022 Fields Medal, often referred to as the "Nobel Prize of mathematics," in recognition of his work in combinatorics.

He was awarded a 2022 MacArthur Fellowship for "discovering underlying connections between disparate areas of mathematics and proving long-standing mathematical conjectures."

Huh's research focuses on geometry, topology, and the combinatorics of algebraic varieties. He is known for proving long-standing mathematical conjectures by building bridges between different branches of math, especially combinatorics and algebraic geometry.

Algebraic geometry involves the properties of geometric structures — like curves or surfaces — that are described using polynomial equations. Combinatorics concerns counting, arranging and combining sets of elements within a discrete system. Most mathematicians consider algebraic geometry and combinatorics distinct, almost unrelated branches of mathematics, but Huh saw how these widely different fields could answer each other's long-standing questions. *–Liz Fuller-Wright*

PHOTO BY DENISE APPLEWHITE

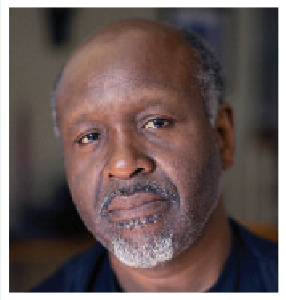


PHOTO BY CHIKA OKEKE-AGULU

Simon Gikandi and Chika Okeke-Agulu elected to British Academy for contributions to the humanities

Simon Gikandi, the Class of 1943 University Professor of English, and Chika Okeke-Agulu, professor of art and archaeology and African American studies, have been elected corresponding fellows of the British Academy, in recognition of their contribution to the humanities.

Gikandi is recognized for his work in the literatures and cultures of Africa and its Black Diasporas in the Americas and Europe; cultures, histories and institutions of slavery; literary history and comparative literature; and global modernism.

Okeke-Agulu is recognized for his work in modern and contemporary African and African diaspora art; classical and traditional African art; postcolonial theory and art criticism; and art and politics. *–Jamie Saxon*




Manjul Bhargava (left), Katja Guenther, Esther Schor and Judith Weisenfeld

PHOTOS OF MANJUL BHARGAVA, KATJA GUENTHER AND JUDITH WEISENFELD BY DENISE APPLEWHITE; PHOTO OF ESTHER SCHOR BY ISOMETRIC STUDIO

Bhargava, Guenther, Schor and Weisenfeld receive 2022 Guggenheim Fellowships

Four Princeton University faculty members received 2022 Guggenheim Fellowships:

Manjul Bhargava, the Robert C. Gunning *55 and R. Brandon Fradd '83 Professor in Mathematics, was awarded the Guggenheim in the field of mathematics. Bhargava's research focuses on number theory, the study of whole numbers and their relationship to each other.

Katja Guenther, professor of history, was awarded the Guggenheim in the field of history of science, technology and economics. She specializes in the history of modern medicine and the mind sciences.

Esther Schor, the John J.F. Sherrerd '52 University Professor, professor of English and chair of the Humanities Council, was awarded the Guggenheim in the field of intellectual and cultural history. Her scholarship focuses on modern Jewish culture and British romanticism.

Judith Weisenfeld, the Agate Brown and George L. Collord Professor of Religion, was awarded the Guggenheim in the field of religion. Her research and teaching focus on African American religious history, religion and race, and religion in modern American culture. *–Jamie Saxon*

Bryan Grenfell wins Kyoto Prize

PHOTO BY SAMEER A. KHAN/FOTOBUDDY

Princeton University's Bryan Grenfell, the Kathryn Briger and Sarah Fenton Professor of Ecology and Evolutionary Biology and Public Affairs, is one of three recipients of the Kyoto Prize in 2022. Grenfell won the basic science category, for "development of an innovative methodology for integrative analysis of pathogen evolution and epidemics."

The Kyoto Prize, a major international distinction, is presented by the Inamori Foundation of Japan to honor the lifetime achievements of those who have contributed significantly to the scientific, cultural and spiritual betterment of humankind.

"It has been a privilege and pleasure to spend my career exploring the spatiotemporal dynamics and evolution of infectious disease epidemics, and the impact of control measures," said Grenfell, who is also associated faculty in the High Meadows Environmental Institute (HMEI) and a leader in HMEI's Climate Change and Infectious Disease Initiative, which has published numerous studies on the dynamics of COVID-19. *–Liz Fuller-Wright*

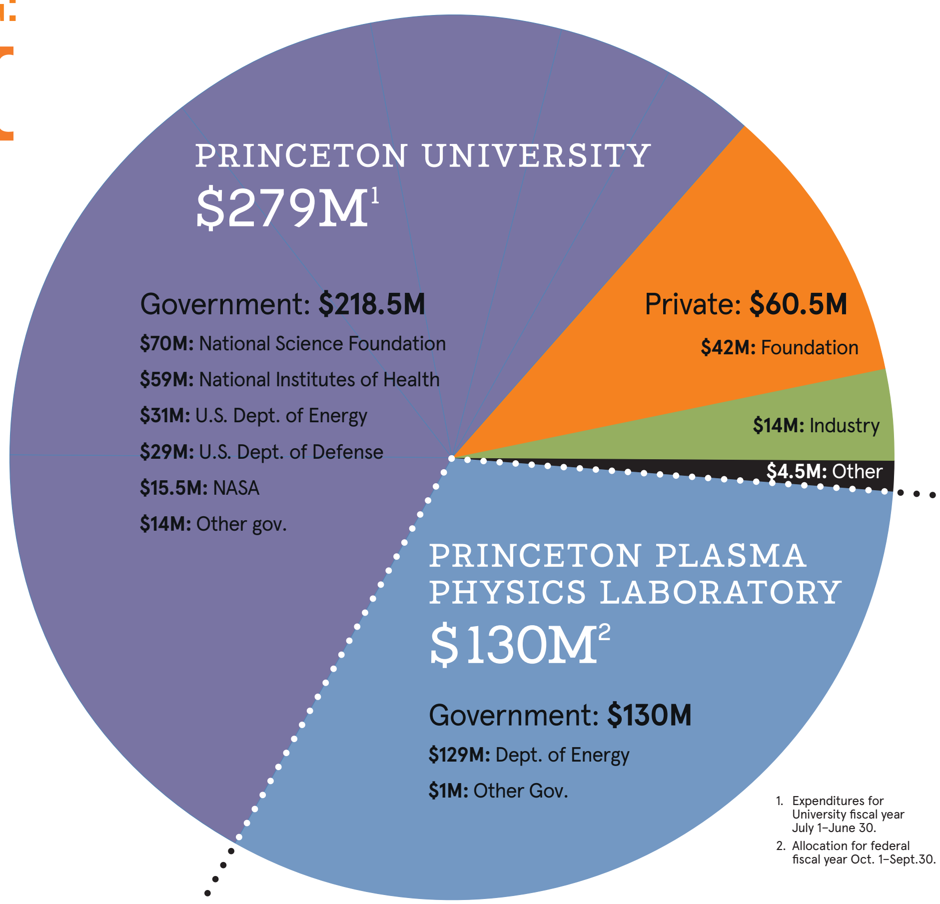
Princeton University is home to a thriving research and innovation ecosystem. Each year, the University receives funding from federal agencies as well as corporate, foundation and other sources. The University also allocates internal funding to research projects and infrastructure across the sciences, engineering, social sciences and humanities.

TOTAL FUNDING: $409M

in research spending, fiscal year 2022

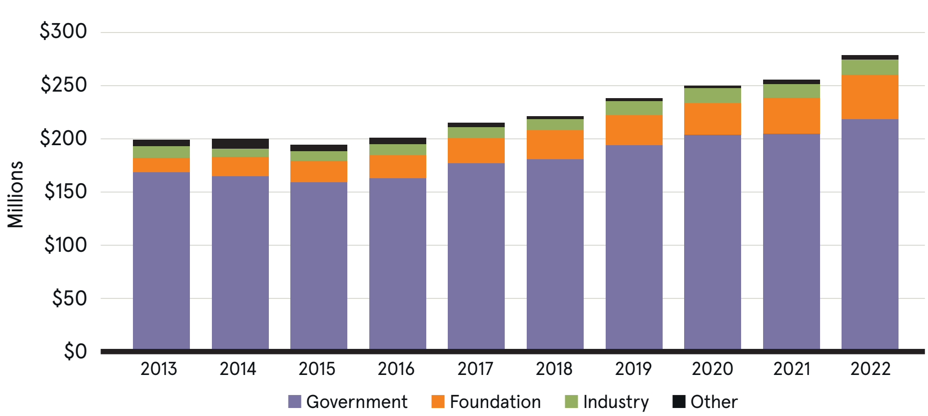
The superlative quality of research at Princeton is reflected in its ability to attract a significant amount of external funding. This chart shows research expenditures by funding source, excluding gifts and internal sources.

Source: Office of Research and Project Administration Annual Report.



1. Expenditures for University fiscal year July 1–June 30.
2. Allocation for federal fiscal year Oct. 1–Sept.30.

CAMPUS RESEARCH SPENDING



Source: Office of Research and Project Administration Annual Report, fiscal years 2013–22. Excludes gifts and internal funding.

A LEADING RESEARCH UNIVERSITY

Princeton is home to eminent scholars across the sciences, humanities, engineering and social sciences.

31 NOBEL PRIZES

19 NATIONAL MEDALS OF SCIENCE

11 NATIONAL HUMMANITIES MEDALS

13 FIELDS MEDALS (MATHEMATICS)

9 PULITZER PRIZES

Faculty, student and staff recipients listed here performed their award-winning work at Princeton, were employed by or studying at Princeton when they received their award, or are currently working at the University.

GROWING OUR RESEARCH ECOSYSTEM

Princeton's research activities have increased steadily as measured by dollars spent on research.

21% ↑ TOTAL RESEARCH SPENDING from all sources

28% ↑ FOUNDATION FUNDING spent on research

30% ↑ PRINCETON UNIVERSITY FUNDS spent on research

Source: University data submitted to the National Science Foundation Higher Education Research and Development Survey (HERD) for fiscal years 2017-21.

EXPANDING COLLABORATIONS WITH INDUSTRY

Our researchers have increasingly collaborated with scientists in industry to create solutions to real-world challenges.

OF AWARDS ↑ 44%

INDUSTRY FUNDING ↑ 58%

*All numbers refer to awards of more than $50,000, fiscal years 2017-21.
Source: Corporate Engagement and Foundation Relations

INNOVATION

Faculty-led discoveries inspire new products and technologies that can benefit humanity. Fiscal year 2022 activities include:

104 INVENTION DISCLOSURES

190 PATENT APPLICATIONS

51 PATENTS ISSUED

28 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.

17 STARTUPS FORMED

40% OF NEW LICENSES WENT TO STARTUPS

$500M IN FUNDING RAISED BY STARTUPS

Source: Office of Technology Licensing

Princeton Research > Office of the Dean for Research

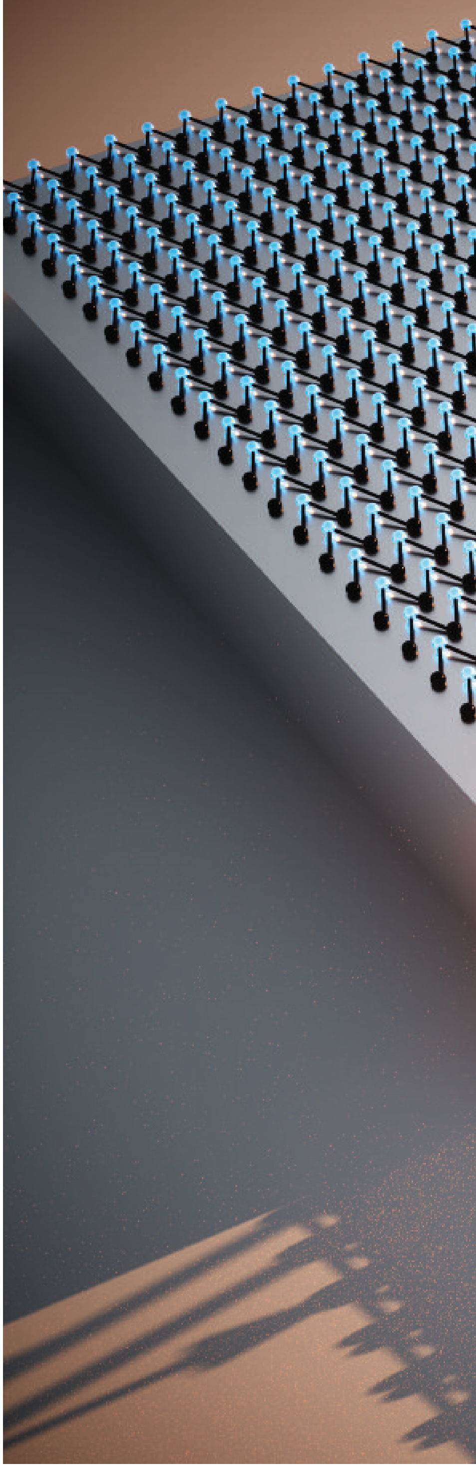


PHOTO BY SHAFAYAT HOSSAIN AND M. ZAHID HASAN

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.

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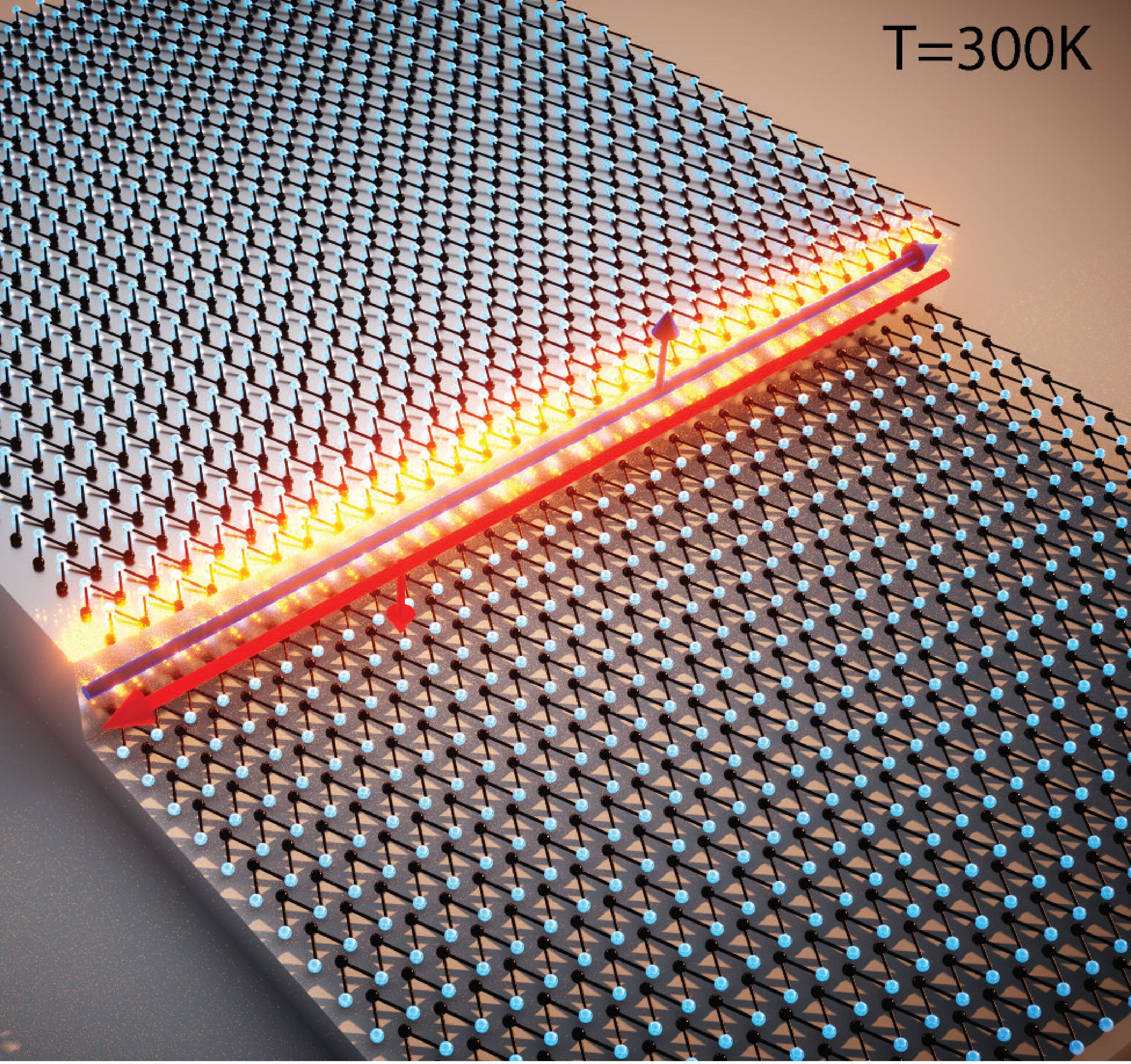

Scientists discover exotic quantum state at room temperature

Princeton researchers are leaders in many fields, including quantum science and engineering. In a paper published in the October issue of *Nature Materials*, researchers observed quantum behaviors in an exotic material called a topological insulator at room temperature for the first time. Typically, inducing and observing quantum states in topological insulators requires temperatures around absolute zero, which is equal to minus 459 degrees Fahrenheit.

"The novel topological properties of matter have emerged as one of the most sought-after treasures in modern physics, both from a fundamental physics point of view and for finding potential applications in next-generation quantum engineering and nanotechnologies," said M. Zahid Hasan, the Eugene Higgins Professor of Physics at Princeton University, who led the research.

Hasan's team fabricated a new kind of topological insulator made from bismuth bromide, an inorganic crystalline compound sometimes used for water treatment and chemical analyses.

Princeton Research > Office of the Dean for Research

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Shane Campbell-Staton studies the rapid evolution of animals such as elephants, urban lizards and wolves in response to human activity (page 18).

PHOTO COURTESY OF KNYSNA ELEPHANT PARK