Research | Penn State

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Mission Critical

Pennsylvania's mine waste could play an important role in the nation's green-energy future.

› ALSO IN THIS ISSUE:

SHAPING THE FUTURE

As we move into our "new normal," we are seeing an incredible appetite from our national leaders to fund large-scale research programs, including those driven by passage of the CHIPS+ Science Act. The time is right for Penn State to lead the nation in bold research directions, shaping the national narrative and forging new paths that involve exceptional partnerships with other universities, industry, and government. The breadth and depth of our research enterprise, combined with our unique interdisciplinary approach, make us ideally suited to define these directions and tackle the complex challenges we face.

This issue of *Research/Penn State* presents a sampling of these exceptional qualities and reflects on the remarkable dedication and accomplishments of our researchers.

Global geopolitics have heightened the importance of having a sustainable supply of the critical minerals used in virtually all of our high-tech products. These minerals, including rare earth elements, are indispensable to our green energy future, but currently the U.S. depends almost entirely on imports.

Penn State is a demonstrated leader in the search for domestic sources and the separation processes required. Our researchers are working with the Department of Energy and with industry partners to develop and analyze environmentally friendly technologies to extract these rare earth elements from coal byproducts and mine waste, thereby addressing national security priorities and affording significant economic opportunities for the state.

The Internet of Things (IOT), while offering unprecedented convenience in our daily lives, has also dramatically increased our online exposure, as cybercriminals threaten our institutions and even our national security. Addressing these constantly evolving threats requires a multipronged approach, understanding points of vulnerability and threat vectors, proactively addressing weaknesses, and raising awareness to change policy. Across Penn State, researchers are working on all these aspects.

We are changing public perception through research on microplastic pollution. Research identifying the presence of plastic microbeads in Lake Erie has been credited with spurring the Microbead Free Water Act. Subsequent studies have demonstrated the widespread presence of microplastics in drinking water and even bottled beer.

Through a major grant from the National Endowment for the Humanities we are pursuing cutting-edge art historical research, combining traditional archival methods and scholarship with materials characterization analysis to determine the composition of pigments used by Maya artists in a group of 16th century Mexican religious murals. This is a testament to the power of collaboration at Penn State.

Finally, there is a surprising range of water issues facing Pennsylvania, from flood to drought to drinking water, and these are being impacted by climate change. We are exploring where science intersects with policy and incorporating the human element into our research. To realize actual changes, science cannot be limited to the laboratory and must include leading the narrative for adoption by individuals in our communities, steered by leadership across our state, defining policy within our nation, and implementing solutions globally.

These are just a few examples that demonstrate how our researchers have pushed the boundaries of ideas whose impacts are significant and where the innovations are evident. You can read about these and more within this issue of *Research/Penn State*.

Thanks again to everyone for your continued commitment to fundamental discovery, knowledge creation, scholarly pursuits, and innovative applications. Your efforts are realizations of how we are shaping national and global directions.

Lora Weiss

LORA G. WEISS
Senior Vice President for Research

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ON THE COVER:
An acid mine sludge sample to be analyzed in the lab of Joey Cotruvo. See story on recovering critical minerals from Pennsylvania mine waste, page 10.

Photo by Patrick Mansell

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Drawing of a scientist working with human skeletal remains and ancient DNA.

Marija Stojkovic/Penn State

Early Farmers Did Not Measure Up

A combined study of genetics and skeletal remains shows that the switch from primarily hunting, gathering and foraging to farming about 12,000 years ago in Europe may have had negative health effects as indicated by shorter than expected heights in the earliest farmers, according to an international team of researchers.

“Recent studies tried to characterize the contribution of DNA to height,” said Stephanie Marciniak, assistant research professor of anthropology at Penn State. “We started thinking about the longstanding questions around the shift from hunting, gathering and foraging to sedentary farming and decided to look at the health effect with height as a proxy.”

Working with George H. Perry, associate professor of anthropology and biology, and more than 40 international researchers, Marciniak looked at the heights of individuals who lived before the Neolithic, and in the Neolithic, Copper, Bronze and Iron ages. The researchers measured the long bones of skeletal remains that were also being sampled or had already been sampled for ancient DNA testing by other researchers. They created a model that used adult height, indicators of stress seen in the bones and ancient DNA, and also looked at genetic indications of ancestry.

“Our approach is unique in that we used height measurements and ancient DNA taken from the same individuals,” said Marciniak.

The researchers found that individuals from the Neolithic, taking into account their genetically indicated potential heights, were an average of 1.5 inches shorter than previous individuals and 0.87 inches shorter than subsequent individuals. When they incorporated ancestral information, they found that the height decrease is reduced a bit so that it is not as extreme.

“This research requires more study with larger datasets,” said Marciniak. “Our work represents a snapshot of something that is very dynamic and very nuanced. We need to do more to see what is the cause of the decrease in achieved height versus predicted genetic height during the shift to farming.”

— A’NDREA ELYSE MESSER

WRITTEN IN THE ROCK ‹‹

Ancient rocks on the coast of Oman that were once driven deep down toward Earth's mantle may reveal new insights into subduction, an important tectonic process that fuels volcanoes and creates continents, according to an international team of scientists.

Subduction occurs when two tectonic plates collide, and one is forced under the other. Where oceanic and continental plates meet, the denser oceanic plates normally subduct and descend into the mantle.

Occasionally, oceanic plates move on top, or obduct, forcing continental plates down toward the mantle instead. But the buoyancy of the continental crust can cause the subduction to fail, carrying the material back toward the surface along with slabs of oceanic crust and upper mantle called ophiolites, the scientists said.

"The Samail Ophiolite on the Arabian Peninsula is one of the largest and best exposed examples on the surface of the Earth," said Joshua Garber, assistant research professor of geosciences at Penn State. "It's one of the best studied, but there have been disagreements about how and when the subduction occurred."

The team, led by Penn State scientists, investigated the timing of the subduction using nearby rocks from the Saih Hatat formation in Oman.

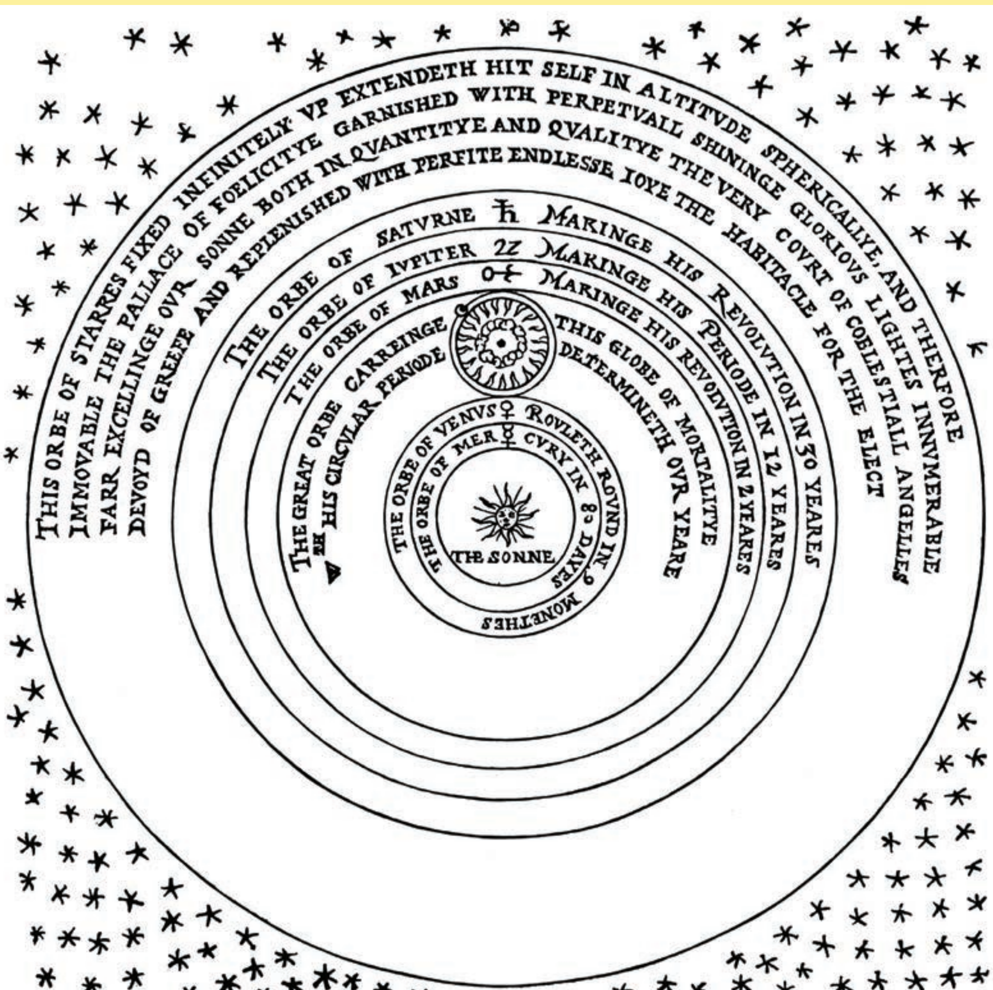
Heat and pressure from the process created garnet, zircon and rutile crystals in a key suite of highly metamorphosed rocks that saw the most extreme conditions during subduction. Using state-of-the-art dating techniques, including measuring isotopic dates and trace elements, the scientists determined these minerals all formed at roughly the same time 81 to 77 million years ago. The findings dispute previous results that estimated the event began 110 million years ago and happened in separate phases.

"What our findings suggest is that this continental material was not subducted deep into the mantle a long time before the ophiolite formed as previously thought," Garber said. "Our data supports a nice sequence of events that happened in a tighter window and that makes more geological sense."

—MATTHEW CARROLL

Joshua Garber/Penn State

Minerals visible in rock samples from the coast of Oman may reveal new information about subduction.



Courtesy Peter D. Usher

The Early Universe

This reproduction in the public domain is from *A Perfit Description of the Caelestiall Orbs according to the most aunciente doctrine of the Pythagoreans* (1576) by the English astronomer Thomas Digges (c. 1546 - 1595). It is the first depiction of a model of the universe that combines the Sun-centered planetary system proposed by the Polish mathematician Nicholas Copernicus (1473-1543) with an infinite universe of stars envisioned by Digges, and as such it is a precursor to the modern science of cosmology. In his new book, *Shakespeare's Knowledge of Astronomy and the Birth of Modern Cosmology* (Peter Lang, 2022), Peter D. Usher, professor emeritus of astronomy and astrophysics at Penn State, discusses the science behind the Digges model gleaned from a study of Early Modern literature.

IT'S THE HUMIDITY ‹‹

As climate change nudges the global temperature higher, there is rising interest in the maximum environmental conditions of heat and humidity to which humans can adapt. New Penn State research suggests that in humid climates, that temperature may be lower than previously thought.

It has been widely believed that a 35°C wet-bulb temperature (equal to 95°F at 100% humidity or 115°F at 50% humidity) was the maximum a human could endure before they could no longer adequately regulate their body temperature, which would potentially cause heat stroke or death over a prolonged exposure.

Wet-bulb temperature is read by a thermometer with a wet wick over its bulb and is affected by humidity and air movement. It represents a humid temperature at which the air is saturated and holds as much moisture as it can in the form of water vapor; a person's sweat will not evaporate at that skin temperature.

But in a new study, researchers found that the actual maximum wet-bulb temperature is lower—about 31°C wet-bulb or 87°F at 100% humidity—even for young, healthy subjects. The temperature for older populations, who are more vulnerable to heat, is likely even lower.

W. Larry Kenney, professor of physiology and kinesiology, said the results could help people better plan for extreme heat events.

"If we know what those upper temperature and humidity limits are, we can better prepare people—especially those who are more vulnerable—ahead of a heat wave," Kenney said.

He noted that using this temperature to assess risk only makes sense in humid climates. In drier climates sweat is able to evaporate from the skin, which helps cool body temperature.

"Our results suggest that in humid parts of the world, we should start to get concerned—even about young, healthy people—when it's above 31 degrees wet-bulb temperature," Kenney said.

—KATIE BOHN

Patrick Mansell

S. Tony Wolf, postdoctoral researcher, conducts a research session testing heat tolerance.

Penn State

To Eat or Not to Eat

It is often said that "children eat what they like," but the results of a new study suggest that it is more accurate to say, "children do not eat what they dislike." There is an important difference, according to Kathleen Keller, associate professor in nutritional sciences and food science.

Keller conducted an experiment involving 61 children ages 4-6 years to assess the relationship between their liking of foods and their subsequent intake. Children participated in two identical laboratory sessions, where seven foods—chicken nuggets, ketchup, potato chips, grapes, broccoli, cherry tomatoes and cookies—were included on a tray. Also included were two beverages, fruit punch and milk.

Before eating, children were asked to rate their liking of each food as either Super Bad, Bad, Maybe Good-Maybe Bad, Good and Super Good. After the children had eaten as much as they wanted, the researchers weighed what they ate and compared the results with what the kids said they liked and disliked.

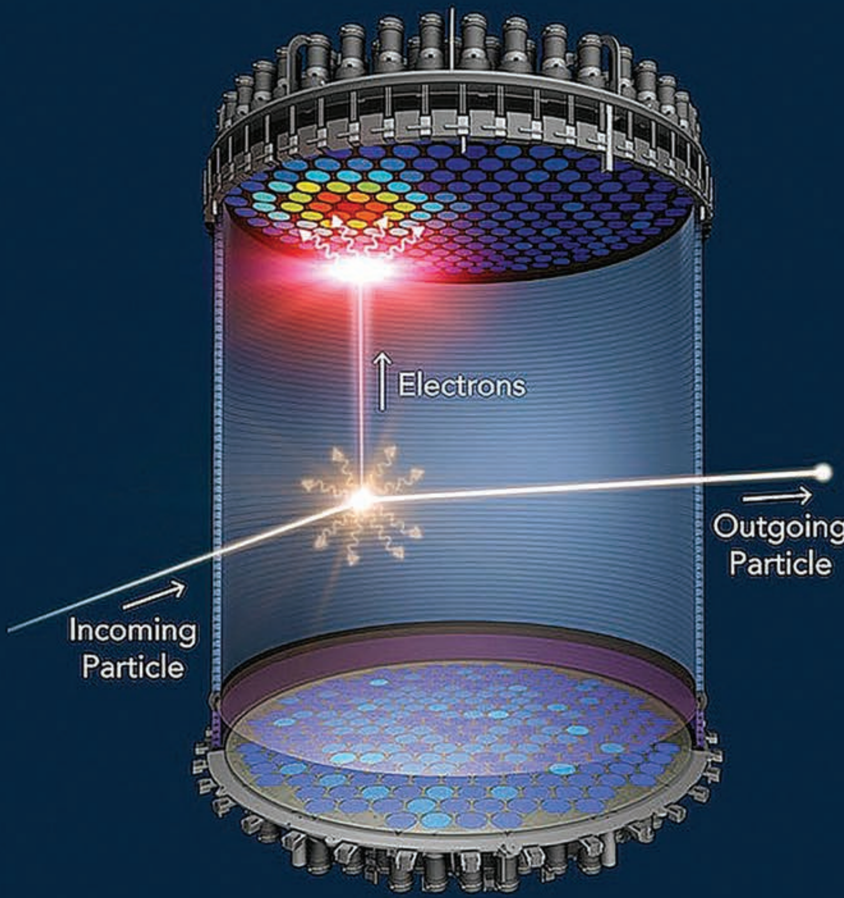
The relationship between liking and intake was not strong for most of the foods. However, there was a strong correlation between consumption—or non-consumption in this case—and the foods the children said they didn't like. Rather than eating what they like, these data suggest that children do not eat what they dislike, the researchers concluded.

"Lower-liking led children to avoid some foods and leave them on the plate," Keller said. "Kids have a limited amount of room in their bellies, so when they are handed a tray, they gravitate toward their favorite thing and typically eat that first, and then make choices about whether to eat other foods."

Study co-author John Hayes, professor of food science, puts it another way.

"In adults, we know that if you really like a food, you may or may not eat it. But if you don't like it, you'll rarely or never eat it. These new data show the same pattern is true in young kids."

—JEFF MULHOLLEM



LZ/SLAC

Diagram of an event in the LZ detector. An incoming particle interacts with a xenon atom, producing a small flash of light and electrons, which are extracted at the top of the detector and produce additional light. The flashes of light are detected by the top and bottom photomultiplier tube arrays and provide clues as to the incoming particle's makeup.

›› Up And Running

Deep below the Black Hills of South Dakota in the Sanford Underground Research Facility, an innovative and uniquely sensitive dark matter detector—the LUX-ZEPLIN (LZ) experiment—has passed a check-out phase of startup operations and delivered its first results. The LZ experiment, designed to observe the mysterious and as-yet undetected phenomenon known as dark matter, is led by the Lawrence Berkeley National Lab in conjunction with an international team of 250 scientists and engineers from more than 35 institutions, including Penn State.

"Dark matter is a fundamental part of the universe, but because it does not emit, absorb or scatter light, it cannot be observed in conventional ways," said Carmen Carmona-Benitez, assistant professor of physics and the LZ principal investigator at Penn State. "I'm thrilled to see this complex detector ready to address the long-standing mystery of what dark matter is made of."

Dark matter's presence and gravitational pull are fundamental to our understanding of the universe. For example, the presence of dark matter, estimated to be about 85% of the total mass of the universe, shapes the form and movement of galaxies, and it is invoked by researchers to explain what is known about the large-scale structure and expansion of the universe. Yet dark matter particles have never actually been detected.

HOW IT WORKS: A variety of cosmic particles collide with the Earth on a regular basis, and LZ is designed to detect theorized dark matter particles known as weakly interacting massive particles. The experiment is located about a mile underground to protect it from cosmic radiation at the Earth's surface that could drown out dark matter signals.

The heart of the detector is comprised of two nested titanium tanks filled with 10 tons of very pure liquid xenon. When particles collide with xenon atoms, they produce visible scintillation or flashes of light, which are recorded by two arrays of photomultiplier tubes. The collisions also will knock electrons off xenon atoms, sending them to drift to the top of the chamber under an applied electric field where they produce another flash permitting spatial event reconstruction.

"The characteristics of the light signals help determine the types of particles interacting in the xenon, allowing us to separate backgrounds and potential dark matter events," said Luiz de Viveiros, assistant professor of physics at Penn State, whose team is responsible for modeling and monitoring background signals in the detector.

Kelby Hochreither/Penn State

Penn State researchers used a new laser writing technique to develop the first highly customizable microscale gas sensing devices.

» The Nose Knows

Environmental sensors are a step closer to simultaneously sniffing out multiple gases that could indicate disease or pollution, thanks to a Penn State collaboration. Huanyu "Larry" Cheng, assistant professor of engineering science and mechanics, and Lauren Zarzar, assistant professor of chemistry, and their teams combined laser writing and responsive sensor technologies to fabricate the first highly customizable microscale gas sensing devices.

"The detection of gases is of critical importance to various fields, including pollution monitoring, public safety assurance and personal health care," Cheng said. "To fill these needs, sensing devices must be small, lightweight, inexpensive and easy to use and apply to various environments and substrates."

According to Cheng, the challenge is creating devices with the desired properties that still can be tailored with the infrastructure needed for precise and accurate sensing of different target gases at the same time. That's where Zarzar's expertise with laser writing comes in.

"Laser writing techniques give design freedom to a wide range of fields," Zarzar said. "Expanding our understanding of how to directly synthesize, pattern and integrate new materials—especially nanomaterials and nanomaterial composites—into complex systems will allow us to create increasingly more sophisticated and useful sensing technologies."

Her research group developed the laser-induced thermal voxel process, which enables the simultaneous creation and integration of metal oxides directly into sensor platforms. Metal oxides are materials that react to various compounds, triggering the sensing mechanism. With laser writing, the researchers dissolve metal salts in water, then focus the laser into the solution. The high temperature decomposes the solution, leaving behind metal oxide nanoparticles that can be sintered onto the sensor platform.

"Precise patterning is also a necessary component for the creation of 'electronic noses,' or arrays of sensors that act like a nose and can precisely detect multiple gases at the same time," said Alexander Castonguay, graduate student in chemistry. "Such precise detection requires the patterning of different materials in close proximity, at the thinnest microscale. Few patterning techniques have the resolution to do this, but the approach detailed in this study does. We plan to use the techniques and materials described here to develop electronic nose prototypes."

— ASHLEY J. WENNERSHERRON

Getty Images / Andy

Speeding Drug Development

A new machine learning method to model gene expression levels might improve the identification of genes that cause human diseases, according to Penn State College of Medicine researchers. Through information from the three-dimensional (3D) structure of genomes and epigenetics—how genes and environment jointly influence diseases—the investigators were able to identify genes associated with complex traits and diseases. These identified disease genes also help to nominate drugs that may be repurposed to treat new disorders.

Developing and approving new prescription medications can be a costly and time-consuming process. However, findings from this study could partially change that moving forward. According to investigators, instead of developing new medicines, pharmaceutical companies could save time and money by repurposing drugs that have already been FDA-approved for other disorders.

For the new data method, PUMICE (Prediction Using Models Informed by Chromatin conformations and Epigenomics), Penn State researchers integrated transcriptomic, epigenomic and 3D genomic data using a novel machine learning approach. According to the study, PUMICE was successful at identifying drugs that could reverse the expression level of disease genes and may be repurposed to treat several human diseases.

"Traditional approaches that analyze one drug and one disease at a time can be very inefficient," said Dajiang Liu, associate professor of public health sciences and biochemistry and molecular biology. "In contrast, a machine learning approach based on big data, such as PUMICE, can revolutionize biological and clinical research. It will greatly accelerate the process of identifying promising therapeutic targets, and fast forward drug development."

—TRACY COX

FOREVER YOUNG ‹‹

At 190 years old, Jonathan the Seychelles giant tortoise recently made news for being the "oldest living land animal in the world." Although anecdotal evidence exists that some species of turtles and other ectotherms—or 'cold-blooded' animals—live a long time, evidence is spotty and mostly focused on animals living in zoos. Now, an international team of 114 scientists, led by Penn State and Northeastern Illinois University, reports the most comprehensive study of aging and longevity to date, comprising data collected in the wild from 107 populations of 77 species of reptiles and amphibians worldwide.

Among their many findings, the researchers documented for the first time that turtles, crocodilians and salamanders have particularly low aging rates and extended lifespans for their sizes. The team also found that protective phenotypes, such as the hard shells of most turtle species, contribute to slower aging, and in some cases even "negligible aging"—or lack of biological aging.

The researchers applied comparative phylogenetic methods—which enable investigation of organisms' evolution—to mark-recapture data—in which animals are captured, tagged, released back into the wild and observed. Their goal was to analyze variation in ectotherm aging and longevity in the wild compared to endotherms (warm-blooded animals) and to explore previous hypotheses related to aging.

For example, the "thermoregulatory mode hypothesis" suggests that ectotherms—because they require external temperatures to regulate their body temperatures and, therefore, often have lower metabolisms—age more slowly than endotherms, which internally generate their own heat and have higher metabolisms.

The team's findings, however, reveal that ectotherms' aging rates and lifespans range both well above and below the known aging rates for similar-sized endotherms, suggesting that the way an animal regulates its temperature—cold-blooded versus warm-blooded—is not necessarily indicative of its aging rate or lifespan.

The team observed negligible aging in at least one species in each of the ectotherm groups, including in frogs and toads, crocodilians and turtles.

—SARA LAJEUNESSE

Getty Images / Ruth Black

Getty Images / Jeffrey Hamilton

THE FASCINATION OF WOLVES ‹‹

Graduate student Ellen Brandell examines wolf 969F, an adult female from the Junction Butte pack in Yellowstone National Park that was killed by her sister over a fight for alpha dominance.

Brandell, who earned a Ph.D. in biology in 2021, was studying how infectious disease influences pack behavior and how the population dynamics of the wolf population change the structure of the Yellowstone ecosystem. She is currently a Wildlife research scientist at Colorado Parks and Wildlife. This photo, by Willaman Professor of Biology Peter Hudson, won the "Ecology in Action" prize in the British Ecological Society's Capturing Ecology photograph competition in 2020.

Photo by Peter Hudson

Mission Critical

They aren't called 'critical minerals' for nothing.

Think of any technology that's part of a clean-energy economy: electric vehicles, wind turbines, solar panels. Think of the devices we depend on for work and play: smart phones, computer hard drives, flat screen monitors, rechargeable batteries. Or the systems that undergird our national defense: lasers and missile guidance, radar and sonar.

All of these depend on critical minerals.

The U.S. Geological Survey currently designates 50 minerals as critical to the U.S. economy or its national security or both. That number includes the so-called rare-earth elements—the 15 lanthanide metals at the bottom of the periodic table plus scandium and yttrium—along with the battery metals lithium, cobalt, nickel, and manganese, as well as platinum, aluminum, and graphite, among others.

With the accelerating shift toward renewable energy, need for these materials is rising sharply. By 2030, according to Bloomberg, demand for nickel and aluminum will increase 14-fold, with graphite and lithium not far behind.

"The problem is we are highly dependent on other countries for both production and processing," says Sarma Pisupati, professor of energy and mineral engineering and director of the Center for Critical Minerals at Penn State. According to USGS, the U.S. imported almost all the rare earth elements it used in 2018, with 80% coming from China. Department of Energy figures show over 50% import reliance for the remaining critical minerals, and 100% reliance for 14 of them.

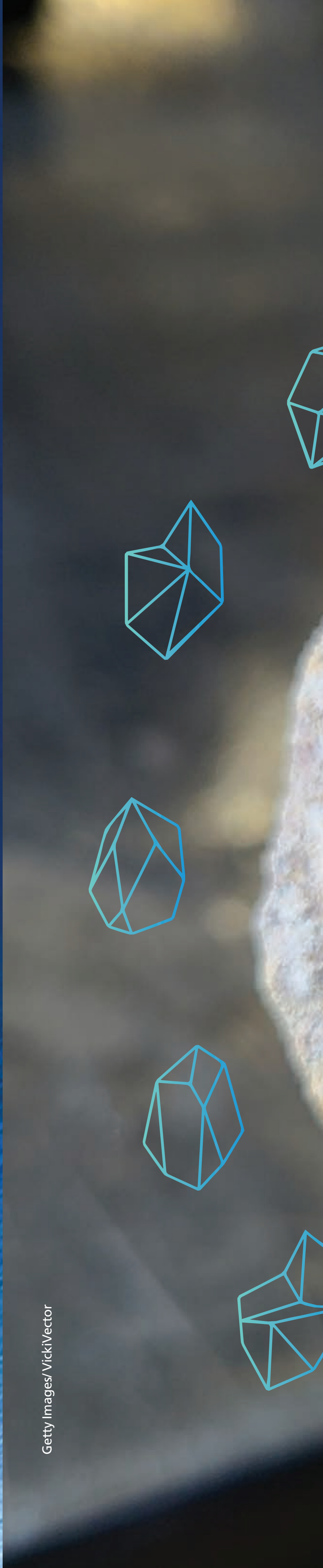
This dependence was a serious concern even before the COVID pandemic revealed major gaps in U.S. supply chains, and mineral-rich Russia's invasion of Ukraine has only exacerbated the problem. The federal government has responded with executive orders directing increased efforts to find and develop domestic sources, but new mining poses steep environmental and political costs, and primary deposits of many of these minerals are limited in the U.S.

"There is a need for secondary resources," says Pisupati. Fortunately, he adds, "Pennsylvania is rich in these resources." Pennsylvania's legacy as a coal-mining state, he says, could be to turn a problem into an important part of the solution.

Decades of industrial mining have left behind literal mountains of waste across the Commonwealth, Pisupati explains. Mine tailings, sludge ponds, and acid mine drainage are an ongoing environmental concern. But locked inside those waste streams are significant quantities of rare earth elements and other critical minerals, he says. All we have to do is figure out how to safely and economically extract them.

"We already have to treat this stuff before releasing it into the environment," Pisupati says. "By modifying existing treatment processes, we can address multiple problems: getting the material we need for national security and remediating long-standing environmental problems at the same time. If we do it right, we can create jobs and an economic boost for the communities coal has left behind."

By David Pacchioli



Getty Images/ VickiVector

Pennsylvania's mine waste could play an important role in the nation's green-energy future.

A core sample of clay in the lab. The Mercer Clay, a large deposit in central Pennsylvania, may be a secondary source of lithium.

Patrick Mansell

BUILDING ON HISTORY

Penn State's involvement in the state's coal-mining industry traces back to the 19th century. The University established a mining engineering degree program in 1890, training graduates in mine mechanization and safety. Its programs in mining geology, mineral processing, and extractive metallurgy have long been recognized among the best in the world.

University experts were early to recognize the untapped potential in coal byproducts. In 1952, Edward Steidle, dean of what was then the College of Mineral Industries, wrote, "By the year 2000 we will not be wasting our coal ash, in which geochemists have shown there is a notable concentration of rare elements, such as germanium and rare earths. We will be recovering these elements."

Today, Penn State's research and teaching capabilities span the entire supply chain for critical minerals, from resource exploration and evaluation to raw material processing to extraction and refining of metals to the manufacturing of end products like lithium-ion batteries, magnets, and advanced carbon fibers. "No other university has that breadth," says Pisupati.

The Center for Critical Materials that he directs was formed by the College of Earth and Mineral Sciences in 2019 to take full advantage of this expertise. Its research core now includes over 25 faculty from departments across Penn State, including geosciences, energy and mineral engineering, materials science and engineering, chemistry, chemical engineering and energy business and finance. A memorandum of understanding signed in 2020 with the Colorado School of Mines further expands that reach.

Last year Penn State was tapped by the U.S. Department of Energy to lead a regional consortium to assess and catalog critical mineral resources in Pennsylvania and surrounding states, to develop strategies to recover these materials, and to identify potential gaps in the supply chain. The Consortium to Assess Northern Appalachian Resource Yield, or CANARY, is part of a national effort to ramp up domestic production.

"Critical mineral recovery from coal waste and its associated environmental remediation present a tremendous opportunity for the college, university, Commonwealth and nation," says Lee Kump, dean of the College of Earth and Mineral Sciences. "Our research will guide the development of advanced green technologies that will ensure that this new industry will be a boon for the Appalachian economy and environment and create a domestic supply chain of minerals needed for energy transition to renewables, high-tech manufacturing, and national security."

ASSESSING WHAT'S OUT THERE

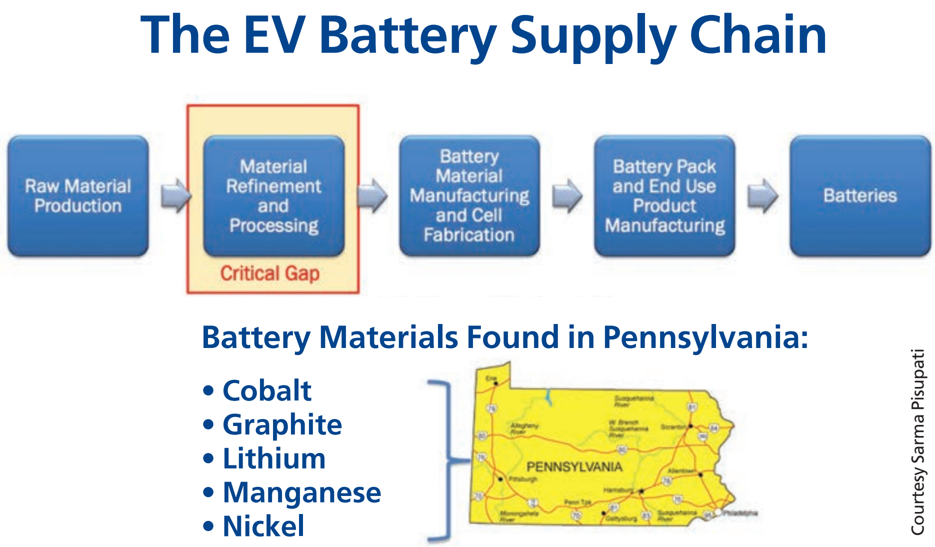
Much like other critical minerals, "Rare earths aren't exactly rare," says Barb Arnold, professor of practice in mining engineering and CANARY's managing director. "But they're rarely found in high concentrations, so mining for them often isn't economically viable."

In places like Pennsylvania, these metals accumulated by various means in rock associated with coal over the millions of years of coal's formation. "Some of the heavy stuff seems to have settled down into clays that were underlying the peat bogs," Arnold says. "That's why we have all these elements present in coals." Over decades of mining, these minerals were routinely tossed aside with the rest of the detritus. Now, however, coal's waste streams hold enough potential value to be worth exploring. Acid mine drainage, the acidic runoff from abandoned mine lands, impacts over 5,500 miles of the state's waterways. This literal waste stream, along with the acidic sludge held in treatment ponds, the vast piles of coal refuse, and the fly ash associated with coal-fired power plants, is a potential source of critical minerals.

The first step is assessing what's out there. Arnold and the rest of the CANARY team, including Pete Rozelle, a Ph.D. alum and former project manager for the DOE who is now an adviser for the College of EMS, have begun the task of evaluating concentrations of cobalt, lithium, manganese, nickel, and rare earths likely to be present around the state. That means digging into the history of mining, scouring century-old government records and other publicly accessible databases as well as University archives. "We have a head start," Rozelle says, "because Penn State was a leader in the U.S. in inventorying mine refuse in the 1960s."

Coal mines are not the only object of interest. Mining for metals, including chromium, zinc, iron, and nickel, has been ongoing in Pennsylvania for 200 years, up until the 1980s. Waste dumps left behind by the metallurgical and metal-processing industries are another potential source of critical minerals.

> "Pennsylvania's legacy as a coal-mining state could be to turn a problem into an important part of the solution."
>
> —Sarma Pisupati



Left: A byproduct of coal mining, acid mine drainage sludge sites like this one in central Pennsylvania are rich in critical minerals. Right: Diagram of the supply chain for production of lithium-ion batteries for electric vehicles. The lack of U.S. domestic processing capacity, in particular, creates a critical gap.

Left: Potential critical mineral feedstocks are crushed and tested on a concentrating table that separates minerals by specific gravity. Many of the critical minerals—including rare earths—are "heavy" and can be separated from lighter minerals. Right: A sample of coal measure rock to be analyzed for potential recovery of critical minerals.

Rare earths aren't exactly rare. But they're rarely found in high concentrations.

—Barb Arnold


Patrick Mansell

Mohammad Rezaee

Analyzing historical data brings special challenges, Arnold says. Assays relied on back in the day may not yield accurate results by today's standards. "The USGS has qualified some of the numbers in its historical data," she says. "In some cases, we have to go back and do our own assessment."

Still, early results have been encouraging. In November 2021 the team released a preliminary estimate of the amounts of cobalt and manganese present in mine dumps and acid mine treatment ponds around the state. Both metals are essential ingredients in the lithium-ion batteries that power electric vehicles, and for both, the U.S. is highly dependent on imports from countries including the Democratic Republic of the Congo and China.

Pennsylvania once led the nation in cobalt production, Rozelle notes. "It was a byproduct of the steel industry." So it was no surprise to find that there is as much of the stuff locked up in the state's mine waste—some 52,000 metric tons—as exists in the entirety of U.S. primary reserves.

The same report estimates over half a million metric tons of manganese, with additional amounts of both metals leaking into waterways via acid mine drainage every year. Recovery and sale of these materials, Pisuapti says, could not only provide a domestic source for the battery industry, but could help offset the costs of reclaiming abandoned mine lands and restoring polluted streams.

THE SCIENCE OF EXTRACTION

Accessing these dormant resources, however, will require bold advances in mineral processing—finding ways to make extraction and separation of the desired materials both environmentally friendly and economically feasible. It's a tall order, which is why Pisupati and his colleagues are exploring every possible avenue.

"We're looking at various approaches, and many different feedstocks," he says. These include not only mine tailings, acid mine drainage and fly ash, but also waste piles associated with the Mercer Clay, a large clay deposit in central Pennsylvania that once supplied the refractory industry and may yet be a viable source of alumina and lithium. "We're also looking at electronic waste recycling," Pisupati says. "Our approach has been to try to recover multiple metals from a given waste stream in order to make the process economically feasible."

He and Mohammad Rezaee, assistant professor of mining engineering, have already developed a process for extracting critical minerals from acid mine drainage via a modification of the method currently used for environmental treatment.

"Acid mine drainage is required to be neutralized before it is released into waterways," Rezaee explains. "Generally, the practice is to add caustic soda to raise the pH. At neutral pH, the majority of toxic metals dissolved in the water will precipitate out of the solution as sludge."

By substituting soda ash for the caustic soda or purging CO_2, he and Pisupati found, they could cause iron, aluminum, and rare earth elements present in acid mine drainage to precipitate separately at pH values at or below those required for environmental compliance. "We also use a chemical-free process by purging ozone to recover cobalt and manganese," Rezaee says. "This process produces multiple high-purity valuable products from these waste streams."

Pisupati estimates that this simple modification can recover over 90% of the high-grade aluminum, cobalt, and manganese present in acid mine drainage and sludge ponds, as well as over 85% of the rare earth elements. "It also works for lithium-rich Mercer clay to pull out over 90% of lithium from the feedstock," he says.

Across campus, Joey Cotruvo, associate professor of chemistry, is taking a different approach. As a bio-inorganic chemist, Cotruvo studies the important roles that metal ions play in the chemistry of life. "All organisms require certain metals to accomplish cellular processes," he says. "They all have to figure out how to selectively bind the metals they need."

In 2018, while studying this basic problem, he discovered a bacterial protein that binds extremely well to lanthanides, the class of rare earth metals, without appreciably binding other metals. He quickly realized that this protein, which he subsequently named lanmodulin (because its shape is modulated by lanthanides), might be useful for extracting rare earths from environmental sources.

Patrick Mansell (2)

Top: Acid mine sludge sample being analyzed in Joey Cotruvo's lab.

Joey Cotruvo

Working with colleagues at Lawrence Livermore National Laboratory, Cotruvo and his team recently demonstrated a process that does exactly that: not only successfully extracting all the rare earth metals, and only the rare earths, from complex solutions but also separating the lighter rare earth metals present from the heavier ones. His team is currently fine-tuning the separations aspect to the point where it can isolate individual metals, in high enough purity to be sold. He believes this method will eventually be useful for recovering some of the most critical and valuable rare earths, like scandium, neodymium, dysprosium, and yttrium, from low-grade sources.

Meanwhile, Amir Sheikhi, assistant professor of chemical engineering and biomedical engineering, is applying nanotechnology to the problem. Sheikhi and his team engineer soft materials, mostly bio-based, for biomedical and environmental applications. "One of the platforms that we are very excited about it is hairy cellulose nanocrystals, which are highly functional nanoparticles derived from a broad range of cellulose sources," he says.

Hairy cellulose nanocrystals, he explains, have a crystalline core with amorphous regions of cellulose attached at either end. "Those regions we call hairs, and we can engineer them to perform critical chemical functions." Potential applications include removing residual drugs from the body after chemotherapy—and, it turns out, extracting critical minerals from the environment.

Recently Sheikhi and graduate student Patricia Wamea negatively charged their nanoparticles to attract and bind with positively charged ions of neodymium, effectively salvaging this highly sought-after rare earth element from samples of electronic waste. Unlike current recycling methods, the nanocrystals worked without the use of harsh chemicals or extreme pH levels. "Using cellulose as the main agent is a sustainable, cost-effective, clean solution," Sheikhi says. "And we can adapt it to extract other elements." Sheikhi has filed provisional patent applications on the technology.

JOINING FORCES

The goal of the Center for Critical Minerals, Pisupati says, is to act as a catalyst, integrating Penn State's wide-ranging expertise and its world-class facilities in support of industry's efforts to establish domestic production. A stakeholders' group including representatives from industry and government meets regularly to discuss needs and priorities and share progress. At a recent workshop, held as part of Energy Days 2022 at University Park, attendees debated next steps.

"A lot more characterization is needed," Pete Rozelle told the assembly, in order to get beyond broad estimates of how much resource is currently "on the ground." Variability in quality is an issue, he said, and so is ease of access. Encouraging the private investment that will be necessary to develop these resources will require both sophisticated modeling and careful geological exploration.

In addition to the geoscience, center researchers are taking stock of existing infrastructure across the state, everything from manufacturing and processing capabilities to transportation logistics to the available workforce. "If we're going to set up a new critical minerals industry in the U.S.," Arnold says, "we're going to have to rebuild the supply chain."

> "All organisms require certain metals to accomplish cellular processes. They all have to figure out how to selectively bind the metals they need."
>
> —Joey Cotruvo

At the same time, Pisupati says, the time is ripe to scale-up some of the novel extraction technologies that have shown such promise in the lab. He hopes to attract funds for a demonstration facility in University Park "to integrate all that we are learning and show potential investors that this can actually work," he says. He and Arnold have begun working with partner companies on optimal designs for processing plants tailored for various feedstocks.

There are special challenges involved in dealing with secondary mineral sources, Pisupati acknowledges. One is the potentially complex legal issues associated with property rights pertaining to decades-old waste streams. But there is also strong precedent at Penn State for the kind of academic-industrial partnership that is now taking shape, he says.

In the 1980s, when the U.S. power industry was deregulated, Penn State research into fluidized-bed combustion technologies played a key role in the emergence of the independent power industry, Pisupati says, enabling the use of coal waste as fuel and thereby also effecting substantial environmental remediation across the state.

"We have had success at this scale," he says. "We changed an industry. And we're ready now to make that kind of impact in critical minerals."

"The need is urgent, and Penn State is ready and able to help."

Patrick Mansell (2)

Top: Amir Sheikhi transforms waste products like shredded paper into nanoparticles capable of extracting critical minerals from the environment.

SOUNDING THE ALARM

5 Gyres Institute

Sherri Mason's work on microplastic pollution has influenced federal legislation and changed public perception.

There are four basic ingredients in beer: grain, hops, yeast, and water. The water often introduces a fifth, which passes unfiltered into a typical pilsner.

In 2017, working with two colleagues, Sherri "Sam" Mason, then a faculty member at the State University of New York at Fredonia, analyzed 12 brands of beer brewed using water drawn from the Great Lakes. Every sample she tested contained small particles of plastic—tiny pieces of synthetic debris. We ingest that plastic when we drink the beer.

Cheers!

It is not clear what effect, if any, that plastic has in our bodies. Some of it passes through undigested: In 2018, researchers in Austria found microplastics—polymer particles smaller than 5mm—in the stool samples of people in eight countries.

New research at the University of California, Irvine, and in the Netherlands found microplastics in volunteers' lungs and blood. Other studies have found plastic particles in hair samples and fingernail clippings.

"There is absolutely no doubt this material is getting into our bodies," says Mason, who is now the director of sustainability at Penn State Behrend, in Erie, Pennsylvania. "What we don't yet fully understand is what it's doing to us." Microplastic fibers, which are believed to be associated with polymers in clothing, including fleece, are more likely to attach to or entangle in the body, due to their elongated shape, Mason says. She has found plastic fibers attached to the digestive systems of fish.

"They weave themselves into the intestinal tract," she says.

Plastic particles enter our bodies when we drink, when we eat, and even when we breathe, Mason says. Most are too small to see.

Much of that plastic begins as packaging: grocery bags, water bottles, and take-out containers. Since the 1950s, when the material was introduced, approximately 10 billion metric tons of plastic waste has been generated, according to the United Nations Environment Programme. Less than 10% of that has been recycled.

As plastic enters the environment, including water systems, it often drifts, moved by currents, runoff, and prevailing winds, degrading into ever-smaller pieces.

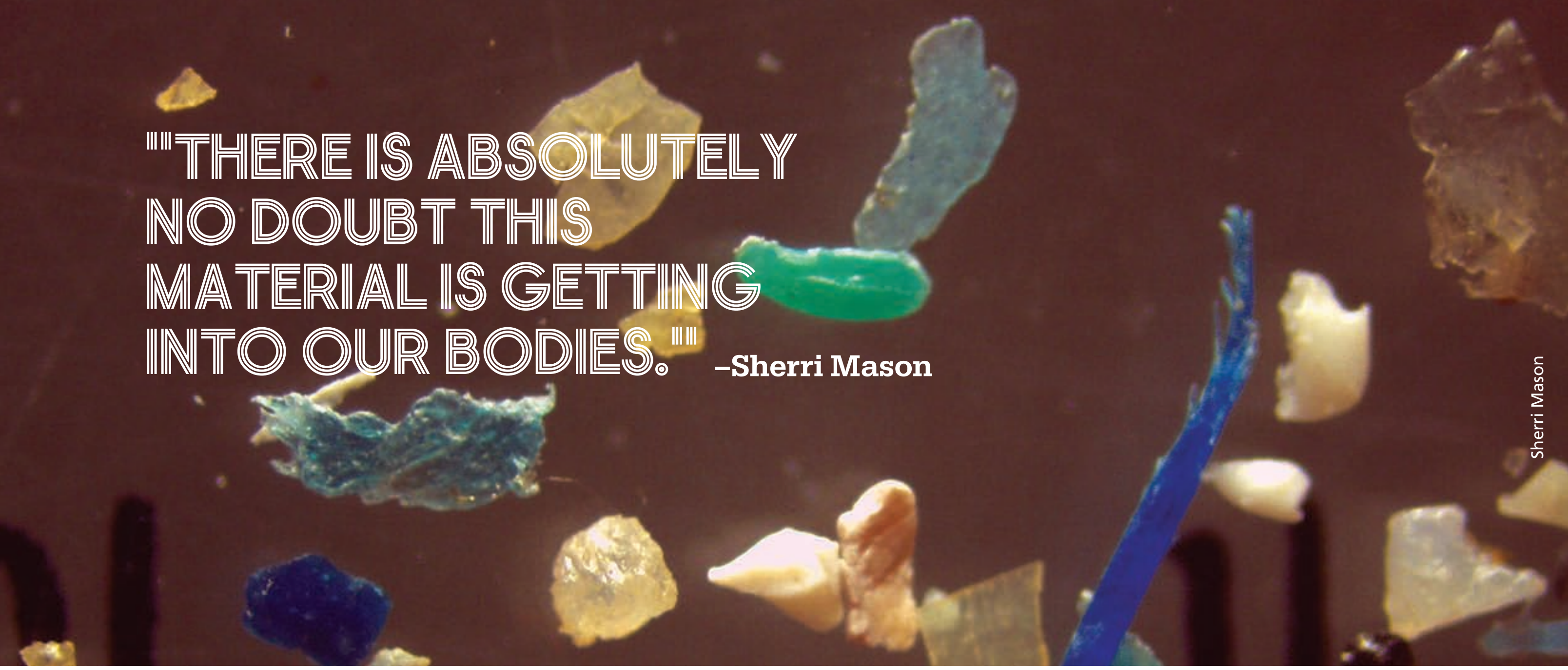
"The size of the particles surprised me," says Mason, who netted plastic debris from the surfaces of lakes Superior, Huron, and Erie in 2012. She found additional plastic material in all five of the Great Lakes in 2013 and 2014.

by Robb Frederick

Nate Drag/NY Sea Grant

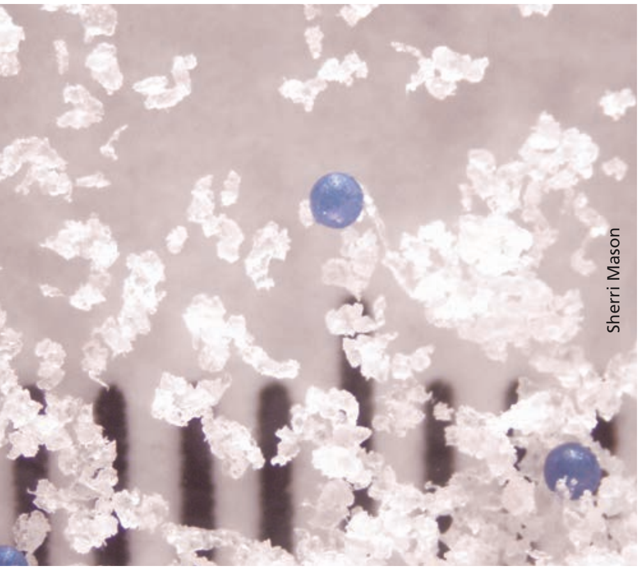
Opposite: Sherri Mason's 2012 study was the first survey for plastic pollution within the open waters of the Great Lakes. Here, shown on a penny for scale, are samples of the plastic microbeads she found in the water.

Mason holds a "nurdle"—a pre-production plastic pellet—found during a beach clean-up at Presque Isle State Park in Erie, Pa.



"There is absolutely no doubt this material is getting into our bodies." –Sherri Mason

Sherri Mason



Sherri Mason

Nicholas Gunner/Orbitist.com

Top: These microplastic particles were extracted from one of the 29 major tributaries into the Great Lakes during a 2016 study completed in collaboration with the U.S. Geological Survey. The background scale is 1 cm, with millimeter gradations. Above left: Plastic microbeads can include both perfectly spherical and rough-edged pellets. These samples, shown on a background scale with millimeter gradations, were extracted from a personal care product in 2013. Sherri Mason's work subsequently led to legislation prohibiting the use of plastic microbeads in cosmetics and personal-care products. Above right: Mason, right, shows plastic particles collected in a manta trawl to a film crew from Al Jazeera America during an excursion in the outer harbor of Buffalo, New York.

"I thought we would be capturing bags and bottles, identifiable items," Mason says. "What we saw was much smaller."

The largest known accumulation of aquatic plastic pollution is the "Great Pacific Garbage Patch," which was discovered by oceanographer Charles Moore in 1997. The patch, located in the waters off California, is, in fact, two distinct debris fields, which together cover an estimated 1.6 million kilometers—an area roughly three times the size of France. The debris constantly churns, as if in a washing machine, held in place by the currents of the North Pacific Subtropical Gyre.

The debris is buoyant. Some of it is still identifiable—fishing nets, for example, and rubber from vehicle tires—but the majority is microplastics. Those smaller particles are suspended in the water column, "like flecks of pepper floating throughout a bowl of soup," according to the National Oceanic and Atmospheric Administration.

Similar materials litter the Great Lakes. You'll need to give up more than beer to keep them out of your body: Mason's 2018 study, published in the journal PLOS ONE, also found microplastics, or "anthropogenic contamination," in sea salt and tap water.

5 Gyres Institute

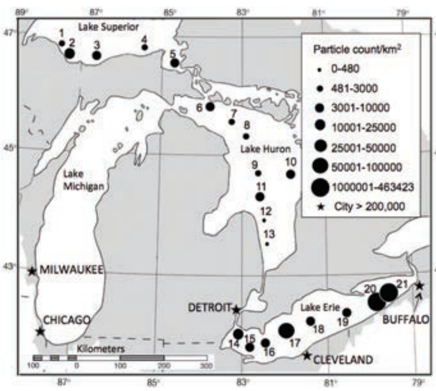
Previous research had found polymer fragments in German beers. No one had looked for those contaminants in tap water, however. Mason and her colleagues analyzed 159 water samples, collected from 14 countries. They found plastic in 81% of the samples. The water sourced from developed nations, including those in the European Union, contained more plastic—6.85 particles per liter, on average, compared to 4.26 particles per liter in lesser-developed nations. The water from U.S. taps was the most contaminated: 9.24 particles per liter.

Mason's team determined that the typical American, consuming an average amount of water, beer, and sea salt, ingests more than 5,800 particles of plastic every year from those sources alone.

In a follow-up study, also published in 2018, Mason analyzed 11 brands of bottled water. She found plastic in 93% of the samples.

"That was part of a larger a-ha moment, when we began to better understand how much of what we eat and drink contains microplastics," says Mary Kosuth, a co-author of the study of tap water, beer, and sea salt.

"Scientists had been finding plastic debris in wildlife since the 1960s, when it began to appear in seabirds," says Kosuth, now a research assistant at the University of Minnesota. "Then it was in the Sargasso Sea. Then it was in freshwater. As we learned that plastic was also in the fish we were eating and the water we were drinking, more people started to pay attention. Even the titles of the academic papers changed. The sentiment went from 'ho hum' to 'Oh, my goodness!'"



Marcus Eriksen, 5 Gyres Institute

Distribution of plastic particles by count for 21 samples collected in lakes Superior, Huron, and Erie during an expedition aboard the U.S. Brig Niagara in July 2012.

"THIS IS DISGUSTING"

Mason's passion for science and the environment began with an episode of the TV show "Diff'rent Strokes." In season four, Kimberly, the sister of Arnold and Willis, washes her hair with contaminated water. When she takes the towel off, she screams: Her hair is green.

"That was the first time I realized that humans could have an adverse effect on the environment, and that there can be consequences for us," Mason says.

She was 10 years old. The next year, for a school presentation, she squirted motor oil into a beaker filled with water. She swirled it, showing that the liquids wouldn't mix. The teacher told her that was chemistry. It was the first time she had heard the word.

"From that point on, I always knew that I was going to be an environmental chemist," she says.

Years later, at the University of Montana, where she would earn a Ph.D. in physical chemistry, Mason studied the chemicals that are present in the smoke plumes from forest fires. Her work was funded in part by NASA's Earth System Science Fellowship Program.

By 2012, she was teaching at the State University of New York at Fredonia, near the southern shore of Lake Erie. Her first impression of the Great Lakes wasn't a good one: Algal blooms were fouling the water and killing fish.

"I didn't yet have an appreciation for the lakes," she says. "I was more like, 'This is disgusting.'"

That changed when she was invited aboard the U.S. Brig Niagara, a replica of Oliver Hazard Perry's 1812 flagship, for a three-week teaching trip. The ship's home port is in Erie, but in the summers, the Niagara sails the Great Lakes, often with students and research teams aboard.

"When you look at Lake Erie on a map, you think, 'Yeah, that's a lake,'" Mason says. "But when you're out there on the water and you can't see land, you get a very different sense of the size and scope of it. These lakes are enormous, and they're all connected, but each is unique in some way. It just overwhelmed me, how beautiful they are."

Her research would shift public perception again, upending what boaters, swimmers, and anglers know about the Great Lakes. Using a manta trawl, a fine-mesh net towed from a spinnaker pole, beyond the ship's wake, she collected debris from the surfaces of lakes Erie, Huron, and Superior. All but one of the 21 samples contained plastic, which she sorted into categories: fragments, foamed polystyrene, line, pellets, and films.

Pellets and fragments were the most common form of plastic in the water. They accounted for 81% of the debris. Most of the pellets were blue, green, or purple—colors that are common in "rinse-off" cosmetic products, such as face-scrubs. Through microscopy and chemical analysis, Mason's team determined that the pellets were microbeads, polymer abrasives that were added to personal-care products, including soaps and toothpaste, beginning in the 1990s. The plastic was cheaper and less abrasive than previous exfoliants, which had included salt, sugar, and ground-up walnut shells.

When consumers used those personal-care products, the microbeads were washed down the drain and into municipal wastewater systems, which do not screen for debris that small. The plastic became part of our environment.

A PRETTY BIG SPLASH

Before her study of plastic in the Great Lakes was published—before she even stepped onto the ship, actually—Mason was fielding calls from journalists who wanted to know what was in the water. A writer for the Associated Press had learned about the project and wrote a story that appeared in regional newspapers. That led to additional stories, including a feature in the New York Times.

"It made a pretty big splash, which surprised all of us," she says. "We hadn't even begun the work."

When the sail ended, Mason shared her data with media outlets, including the Buffalo News. A scientist in the Environmental Protection Bureau, a unit in the New York Attorney General's office, read one of those stories and asked Mason for a meeting.

The scientist wrote a white paper, which amplified Mason's overarching concern: Many plastic products include chemical additives—UV stabilizers, colorants, and flame retardants—that are mixed into the polymers. Those chemicals can leach out when exposed to weathering and heat.

Immersed plastics also attract "hydrophobic pollutants" —chemicals that are present in the water and will quickly bind to a new host. Those pollutants, which include polycyclic aromatic hydrocarbons (PAHs), polychlorinated biphnenyls (PCBs), and pesticides, all of which are believed to be toxic, are attracted to plastic. They accumulate on microbeads and polymer fibers until the chemical presence on the plastic is as much as one million times higher than it is in the water in which that plastic floats.

"Those chemicals are exceedingly long-lived," Mason says. "We know they stick to plastic, at concentrations much, much higher than we find in the water, so that elevates the risk. When we ingest plastic, some really nasty stuff is coming in with it."

The New York white paper spurred a legislative effort to ban the manufacturing, packaging, and distribution of cosmetic products that included plastic microbeads. Seven states, including California and New Jersey, enacted bans. Eight counties in New York followed suit.

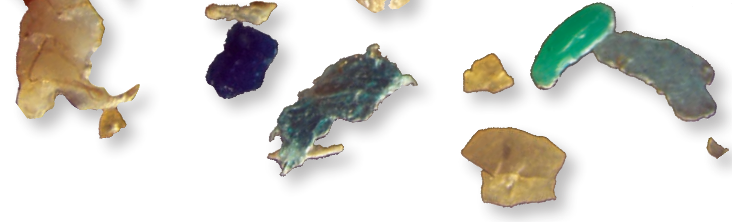
"We were already close to a tipping point, in terms of public awareness of plastics pollution," says Marcus Eriksen, director of research at the 5 Gyres Institute and a co-author of Mason's 2012 study. He provided the manta trawl and other equipment for the three-week Great Lakes excursion.

"Finding all those microbeads in the water—that was sort of the smoking gun," Eriksen says. "It drew a straight line from the products we were buying to the pollution in the water."

U.S. Sen. Kirsten Gillibrand, a Democrat from New York, proposed federal legislation, the Microbead-Free Waters Act of 2015, to balance the patchwork state-by-state approach to regulation. It passed unanimously, and with the support of cosmetic companies, which by then were under pressure from consumers to use alternative materials. President Barack Obama signed it into law on Dec. 28, 2015.

For Mason, that moment brought an immense sense of achievement.

"I felt a huge surge of humility, and appreciation, and accomplishment, all combined at the same time," she says. "That 10-year-old in the back of my mind, that little girl who wanted to lessen human impact on the environment, she was just beaming."



Sherri Mason

SCIENCE IN THE PUBLIC INTEREST

When the Niagara returned to port, Mason took an unusual step, for an academic: She shared her findings in real time, before the peer-review process was complete. A few colleagues questioned that decision, but Mason pressed forward. To her, it didn't make sense to wait.

"Scientists tend to be very guarded in the way we present information," she says. "My style is a little different, I guess. I'm going to sound the alarm."

At Penn State Behrend, Mason has fully embraced the public-facing approach. She still teaches, and she continues her research—a current study is focused on the debris that accumulates in litter booms and municipal street-sweepers—but she also manages broader sustainability initiatives across the college.

She was drawn to Behrend in part because of Wintergreen Gorge, a Natural Heritage Area with more than 14 miles of hiking and biking trails. The college has preserved much of that land, which is used for public recreation and as an environmental teaching space.

She also saw an opportunity to more broadly engage with students, faculty, and staff on varied but environmentally connected projects: a composting program in two student dining facilities, a season-extending high-tunnel greenhouse, a recycling system for filament from the college's 3D printers, and a new hub site for the annual Worldwide Teach-In on Climate and Justice.

For that work, and for her continued study of microplastics, Mason was awarded the 2021 Great Lakes Leadership Award, which recognizes science and outreach efforts that raise awareness of critical issues in the Great Lakes ecosystem.

"My approach now is more holistic," she says. "Every day, I meet people who care about these issues, who see the impact we are having on the planet and want to do better but aren't sure where to start. I give them options. I find projects that fit their interests. I connect them to this broader community, so they know they aren't alone."

Every project she selects aligns with the 2030 Agenda for Sustainable Development, an environmental call to action by the United Nations member states. The document's 17 goals expand the traditional "green" messaging—clean water, climate action, and habitat preservation—and map the ways other societal challenges, such as poverty and gender inequality, can hinder sustainability efforts.

"For me," Mason says, "it's always about science in the public interest. It's about doing things that help to push our society in a better direction. Plastic pollution is a huge issue, with very real and proven consequences, and we need to find a solution. But plastic isn't the only issue. To solve that problem—to solve any environmental problem, really—you have to be thinking about and trying to solve all these other, bigger issues. My goal is to make those connections, to engage people who want to make a difference, and to look for and support opportunities that move us all forward."

ON THE MOVE

Microplastic pollution has existed since plastics came into widespread use in the 1950s. Our awareness of its ubiquity, and our ability to measure its presence, have expanded over the past 10 years, thanks to the work of Sherri Mason and many others. But once microplastic finds its way into a freshwater system, where does it go? How does it move? Where does it wind up?

Margaret Byron took up these questions on a recent episode of "Growing Impact," a podcast produced by the Institutes of Energy and the Environment at Penn State.

Byron, an assistant professor of mechanical engineering, studies "particle laden flows," and is particularly interested in the physical transport of organisms and objects within aquatic environments. She and colleague Jay Regan, professor of environmental engineering, recently received an IEE seed grant to study the "Effects of biofilms on the transport of microplastics."

Microplastics come in a huge variety of shapes and sizes, Byron points out. They aren't uniform, which makes their movement more complicated to understand. The attachments they make can render them even more irregular.

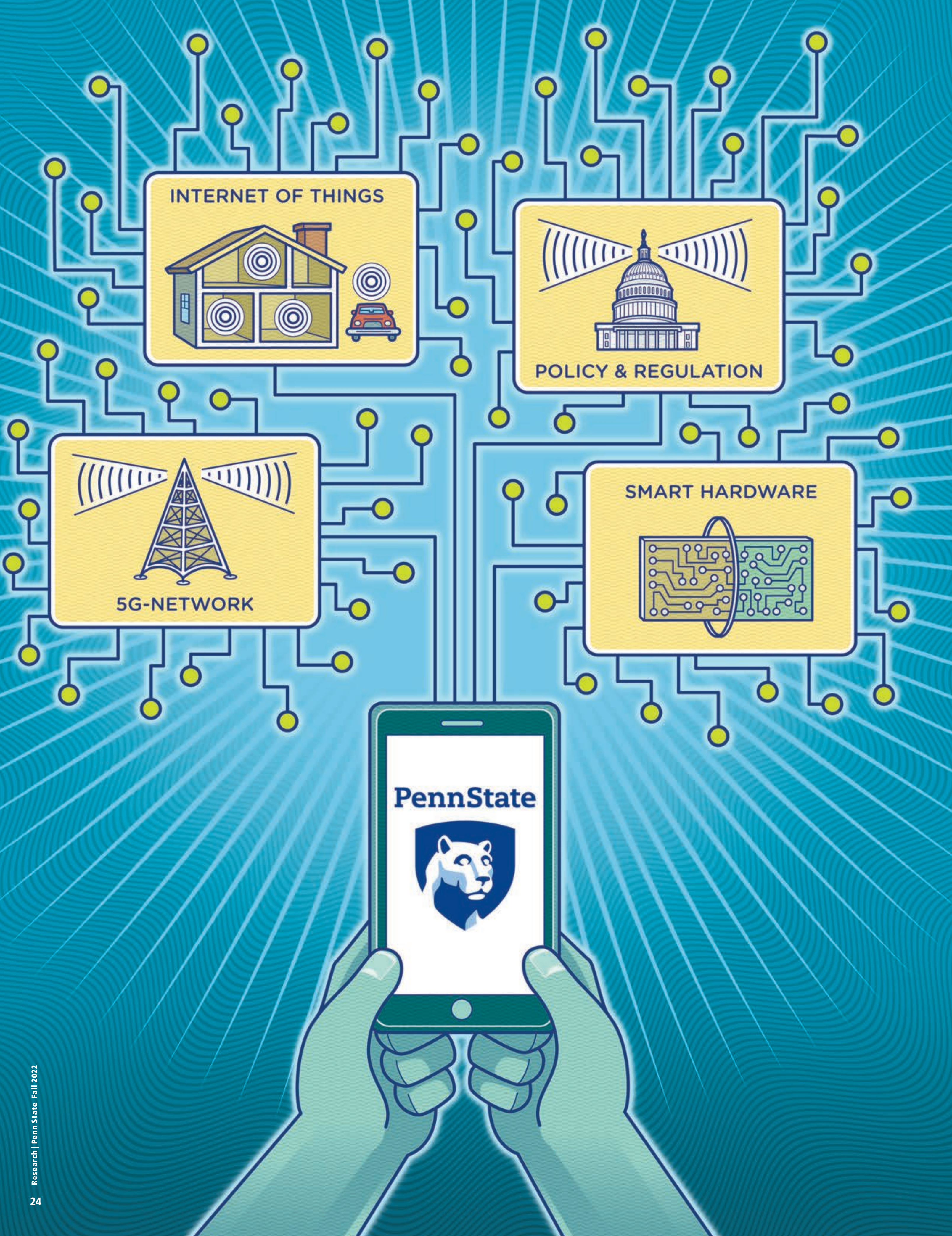
As Byron explains, once a piece of microplastic enters the water, "it doesn't exactly go with the flow." Rather, it becomes "an active participant in the environment," that is, it starts to interact with thin films of bacteria, algae, even larger organisms present in the water that attach to it and start to grow.

"You can imagine if it's got a barnacle attached to one side—maybe it's bottom-heavy. Or it's got bacteria growing on it, maybe it's a little gooey, a little slimy," she says. "How does that change the velocity, the speed at which it settles through the water? And then how does that change these questions of physical transport?"

If she can come to understand how microplastics are transported, Byron suggests, maybe she can start to make predictions that can inform mitigation strategies—not just for the removal of what's already present in a river or a lake but for the prevention of more from entering.

"If we can track back how it got to where it is," she says, "maybe that helps us to prioritize how to turn off the spigot."

—DAVID PACCHIOLI


INTERNET OF THINGS
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SMART HARDWARE
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Internet of Threats

by SARA LAJEUNESSE

PENN STATE RESEARCHERS TAKE ON THE EVOLVING, MULTI-FACETED CHALLENGE OF CYBERSECURITY.

With the increasing availability of virtual-assistant alarm clocks, smartphone-controlled coffee makers, and pressure-sensing yoga mats, an ever-growing array of smart devices now assists us with many of our daily tasks—often before we set foot out the door in the morning. Indeed, we live in a time of constantly accelerating technological advance, with each new product and network promising to make our lives easier and better.

But there's a dark side to connectedness. Every advance means increased exposure and increased risk.

On a personal scale, most people are at least dimly aware of the security threats associated with their computers and smartphones. Most of us have received phishing emails or texts, in which attackers attempt to trick us into clicking on malicious links could lead to malware being installed on our devices or our sensitive information being revealed.

But what about all the so-called Internet of Things (IOT), all those innocent-looking devices— coffeemakers, yes, but also lamps, thermostats, and televisions—embedded with sensors, software, and other technologies for connecting and exchanging data over the internet? Many of us are unaware that these devices can be transformed into tools for cyber criminals to steal our bank and credit card details, stalk our movements and conversations, and generally cause chaos in our lives.

It's not just our homes. Cyber criminals threaten our institutions and even our national security. In the summer of 2021, hackers stole files containing the first and last names, Social Security numbers, birth dates, and driver's license numbers of more than 50 million T-mobile customers. A 21-year-old American man admitted to the crime, which he pulled off via an unprotected router. And in February, a cyberattack attributed to the Russian military intelligence agency knocked out websites belonging to the Ukrainian Defense Ministry and two of that country's largest banks. The following month, hackers linked to the Chinese government penetrated the networks of multiple U.S. state government agencies.

Addressing this constantly evolving threat, on whatever scale, requires a multipronged approach, one that includes understanding points of vulnerability, designing and implementing tools to address those vulnerabilities as proactively as possible, raising awareness of the magnitude and urgency of the problem, and implementing policies that protect consumers. Across Penn State, researchers are working on cybersecurity issues related to all these aspects.

Sascha Meinrath, Palmer Chair in Telecommunications, is a technology policy expert and the director of X-Lab, a non-profit public policy think tank based at Penn State that aims to define the trajectory of technology's place in modern society. Much of Meinrath's work is focused on raising awareness of cyber threats, both among the public and within government agencies.

As a regular consultant to both private industry and multiple government officials and agencies, he often finds himself separating fact from fiction, especially since many of the exploits used by cyber criminals—segments of code that maliciously take advantage of vulnerabilities or security flaws in software or hardware—are both highly technical and unprecedented.

"Cybersecurity is a relatively new phenomenon," says Meinrath. "In my youth, we didn't have cybersecurity because nothing was really 'cyber,' whereas, for my kids, everything is connected. We've created a whole new domain, and we are experimenting with what it even means to have to address this new problem we created. It's a society-wide problem that can only be solved with a society-wide intervention."

ILLUSTRATIONS BY PETER HOEY

Patrick Mansell

PROTECTING THE INTERNET OF THINGS

Although living in a “smart home” is all the rage, the more internet-connected gadgets and gizmos we have, the more vulnerable we are to cyberattacks. “Most of the technologist experts I know have one of two kinds of homes—a dumb home without any smart gadgets, except for maybe a laptop and a cell phone, or a smart home where they’ve set up extra IT infrastructure to prevent the loss of personal information,” says Meinrath. “I have a dumb home because I know how terrible the cybersecurity for the internet of things is, and I don’t want the headaches that would come with an attack.”

Meinrath is not being dramatic. According to the anti-virus and cyber security provider Kaspersky, the first half of 2021 saw more than 1.5 billion breaches of IoT devices.

“Imagine a smart home programmed in such a way that whenever the home temperature rises to a given threshold, the windows automatically open,” says Peng Liu, director of the Center for Cybersecurity, Information Privacy, and Trust at Penn State. “If an attacker obtains access to this system, they could turn the temperature up and enter the home through the windows.” More simply, an attacker could access and open the smart lock securing the front door.

Liu, who is Raymond G. Tronzo, MD, Professor of Cybersecurity, is investigating the security of IoT devices with a goal of developing tools that protect consumers. In a recent study, he and his colleagues specifically examined security vulnerabilities in several widely used smart home platforms, including Samsung SmartThings, TP-LINK KASA, and Ali Alink.

“Smart home platforms tend to consist of three entities that interact with each other: an IoT cloud, a smart home device, and a mobile app,” says Liu, explaining that the mobile app provides users with an interface to manage the device, and the IoT cloud provides the external space and processing and automatic control capabilities using the information generated by the device.

Liu notes that while most studies focus on the individual entities, many security vulnerabilities arise in the interactions between them. To uncover some of these vulnerabilities, the team played the role of a hacker, conducting what Liu calls “man-in-the-middle monitoring,” in which they interjected themselves into the communication process to intercept the data. To confirm the vulnerabilities they discovered, the researchers implemented a phantom device—essentially a computer program that mimics an actual device—and instructed it to intervene in the normal interactions between the three types of entities.

“By carefully constructing attacks that exploited the security flaws we found, we showed that serious previously unrecognized security hazards are possible,” says Liu. For example, IoT clouds sometimes accepted and executed sensitive commands from fake devices.

Remotely hijacking control has been a staple of Mission Impossible movies for years. Liu's results show, however, that adversaries can now take over a system or device in real life. "The adversary can access the user's private data and, in turn, manipulate data that is sent to the user, thus deceiving or misleading the user," he says. "For example, an adversary can harvest sensor readings from a smart home device to monitor the victim's home or even manipulate the device, such as by turning up the heat, which could endanger the victim."

Liu notes that these newly discovered hazards have significantly enlarged the previously known 'attack surface' of smart home platforms. "All the vulnerabilities described in this paper have been reported to the corresponding vendors, and many of them have been addressed," he says, "but more vulnerabilities are always surfacing as new products are created and as cyber attackers find new ways to get in."

THINK LIKE A HACKER

To identify vulnerabilities in smart home platforms, Liu and his colleagues essentially hacked into the systems to see if and how they could do it. Indeed, ethical hacking into systems (e.g., penetration testing) is a common strategy for cybersecurity experts. Researchers at Penn State's Applied Research Laboratory (ARL) used this approach to build their Automated Attack Framework for Test and Evaluation (AAFT).

"Most commercial systems have many known vulnerabilities, and there are open-source tools that any person can use to exploit those vulnerabilities," says Isaac Porche, ARL deputy director. Porche leads the lab's Communications, Information, and Navigations Office, which, among other research areas, focuses on cybersecurity.

Isaac Porche

Patrick Mansell

A former senior engineer at the RAND Corporation and program director for the federal government's Homeland Security Operational Analysis Center, Porche notes that to outwit a cyber attacker, one must think like a cyber attacker. "Understanding what's at risk is where the expertise is, and that's what we have at ARL," he says. "In addition to programmers and electrical engineers, we have people who are experts on equipment—whether military equipment, commercial vehicles, or even pleasure boats. You want people who have an understanding of what that target is, so it takes all types."

Porche explains that ARL's mission is to provide its sponsors, including the U.S. Navy, with innovative, cost-efficient solutions that enable them to achieve their national security missions. "This includes ensuring that the military's devices are as secure as possible," he says. "Fortunately, some of the work we do can also benefit civilians."

To that end, Porche's office created AAFT, an automated hacker that the military and civilian organizations can use to check all the known vulnerabilities for any new system they produce. "Electronics, laptops, handhelds, and computers are so ubiquitous that no one can claim that their system is totally locked down," says Porche. "Our hope is that folks can use AAFT to handle the low-hanging fruit. Is it insurance that they're systems will be impenetrable? Absolutely not. But at least they will know they don't have something that can be exploited by a tool that can be bought off the internet."

Porche says that the best time for organizations to use AAFT is during the development of new systems, rather than after a system has been deployed. "We are often in a situation where we have to retrofit existing systems with increased security measures," he acknowledges, "but doing the work ahead of time can be much more effective."

SECURING THE 5G NETWORK

Syed Rafiul Hussain, assistant professor of electrical engineering and computer science, is also concerned about the still-common practice of viewing security as an afterthought. "The rate of technology creation and adoption outpaces the protections that we can put into place," he says. "This has resulted in retrofitting security solutions that patch vulnerabilities as they emerge, but sometimes fail to address the root cause of the vulnerability, leaving the network exposed to sophisticated attacks."

Hussain is particularly interested in the security of 5G and NextG (6G, 7G, and 8G, etc.) networks.

"5G cellular networks provide faster connectivity and greater bandwidth," says Hussain. "As a result, they have the potential to contribute to the transformation of cities, homes, healthcare, manufacturing, transportation, and robotics."

Because 5G promises to make cellular networks so fast and so pervasive, ensuring its security is highly critical, says Hussain. "Certain attacks carried out on 5G cellular networks could paralyze entire communities and service infrastructures with disastrous consequences," he says. Using 5G's heightened connectivity, for example, attackers could more quickly spread malware through its networks, triggering massive supply chain disruptions or power outages.

Hussain and his colleagues aim to change the security landscape of NextG cellular networks by improving NextG security from the ground up, incorporating security analysis beginning with a product's design and continuing all the way through its deployment.

In one recent study, the team investigated vulnerabilities in the way individual devices such as smart phones connect with 5G base stations, the hubs for local 5G wireless networks.

"To advertise their presence, base stations periodically broadcast information about the network, and cellular devices listen to these broadcast messages and connect to suitable base stations," says Hussain. "Unfortunately, there is no mechanism to ensure the authenticity of these broadcast messages, therefore, devices cannot differentiate between legitimate and fake base stations. This could allow an adversary to send messages from a fake base station, luring cellular devices to connect to it and then launching security and privacy attacks."

Hussain notes that this vulnerability has been widely acknowledged but not adequately addressed, thus enabling motivated adversaries to carry out attacks against targeted users.

Although 5G cellular protocols have been enhanced to prevent some of these attacks, he says, the root vulnerability still exists. In their study, he and his team created a custom tool called 5GReasoner that identified the root causes for several vulnerabilities, including some with the potential to reveal people's locations; run up their wireless bills; and track their internet browsing, phone calls, and texts.

The team shared its findings with the Global System for Mobile Communications Association (GSMA), a global standards body for mobile technologies, which in turn used the findings to implement some of the solutions they suggested. "Our work has led to changes in standards that have affected every network operator and every device in the world," says Hussain. "It's a huge impact."

NEEDED: A NEW SOCIAL CONTRACT

Sascha Meinrath and his colleagues briefed U.S. Senators on a similar wireless network vulnerability nearly a decade ago. "We set up a 'rogue' cellular base station inside the Capitol and captured Senators' text messages in real time during our briefing to show just how easily this could be done," he remembers. "Unfortunately, regulations like the Communications Assistance for Law Enforcement Act make it extremely difficult to secure our cellular networks."

Indeed, in some cases, government regulations are the sources, rather than the solutions, of cybersecurity problems. For example, says Meinrath, "Legacy code and poor national policy can often create major headaches, as we saw with the 'Factoring RSA Export Keys,' or 'FREAK,' exploit." During the 1990s, he explains, U.S. export regulations required weak encryption in many applications purchased by foreign countries so that their governments, or hackers, could not easily launch attacks. "Decades later, this code inadvertently ended up in many mainstream applications—including Apple, Microsoft, and Google browsers—and has affected over a third of all HTTPs-secured websites, including those of the Federal Bureau of Investigation, the National Security Administration, and the White House," says Meinrath, noting that many of the issues are in the process of being fixed.

Although the research of Hussain, Porche, Liu, and their colleagues at Penn State and other universities is providing answers to some of the most pressing cybersecurity threats, Meinrath underscores that an important part of the solution must come from government itself. "Many of our laws and policy frameworks are from a pre-internet era, and often don't map on to today's technological realities," he says. "The government needs to modernize its systems, but also its policies and regulations to address these issues."

Finally, Meinrath adds, "We need to improve digital literacy training and educate students about best practices for securing their own data, devices, and communications while we advocate for the government to catch up."

Ultimately, he says, a new social contract is needed to protect consumers from potential cyberattacks and privacy infringements. "In the 1930s, we established Medicaid and Social Security. In the 1960s, we aimed to eliminate overt racism. Now many decades later, we need a social contract that addresses digital technologies," he says.

"I'm an optimist. These are solvable problems, but we have to acknowledge the problems first, before we can meaningfully address them."

Syed Hussain

Patrick Mansell

Patrick Mansell

"MANY OF OUR LAWS AND POLICY FRAMEWORKS ARE FROM A PRE-INTERNET ERA, AND OFTEN DON'T MAP ONTO TODAY'S TECHNOLOGICAL REALITIES."

—SASCHA MEINRATH

2D to the Rescue

by MARIAH CHUPRINSKI

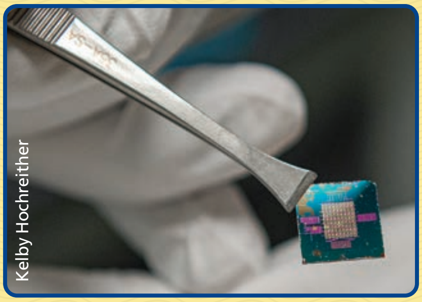
With the growing proliferation of smart technology, securing digital data on handheld devices requires massive amounts of energy, according to an interdisciplinary team of Penn State researchers, and is a greater concern than ever before.

Led by Saptarshi Das, associate professor of engineering science and mechanics and affiliate of the Materials Research Institute, the team has developed a smart hardware platform, or chip, to mitigate energy consumption while adding a layer of security.

"Information from our devices is currently stored in one location, the cloud, which is shared and stored in large servers," says Das. "The security strategies employed to store this information are extremely energy inefficient and are vulnerable to data breaches and hacking."

"Although software-based security modules are powerful, there exists a multitude of challenges with them," adds Akhil Dodda, a doctoral student in engineering science and mechanics. "We developed a cryptographic platform using a two-dimensional material to overcome these limitations."

Instead of the standard silicon, they turned to 2D materials, specifically molybdenum disulfide (MoS_2), which is less than one nanometer thick, to create a low-power cryptographic chip. Penn State collaborators Joan Redwing, distinguished professor of materials science and engineering and electrical engineering, and Nicholas Trainor, a doctoral student in materials science and engineering, worked together to synthesize the MoS_2 needed to create the chip.



Kelby Hochreither

The chip employs 320 MoS_2 transistors that each have a sensing unit, a storage unit and a computing unit to encrypt data. To test the strength of the encryption process, the researchers used machine learning algorithms.

"We found that the advanced machine learning techniques couldn't decode the encrypted information, reinforcing the resilience of the encryption process against machine learning attacks," Das says. "Without prior knowledge of the information channels and decoding variables, it is extremely difficult to decode the information."

Additionally, the energy consumed in encrypting the information was significantly less than silicon-based security methods. The result was a low-power, all-in-one chip that could sense, store, compute and communicate information among connected devices—a potential solution for users who want added security but cannot afford to drain their handheld device batteries in day-to-day use.

Entrance to Cloister (Porteria), Monastery of San Antonio de Padua, Izamal. Opposite: Mural painting of Santa Barbara, Monastery of San Antonio de Padua, Izamal.

WORLDS COLLIDE

ART HISTORY AND MATERIALS SCIENCE COMBINE TO UNCOVER A 16TH-CENTURY CULTURAL CROSSROADS.

In the summer of 1991, a 13-year-old Amara Solari set off on a more than 3,000-mile family trip from the Napa Valley in California to the Yucatán Peninsula in Mexico. In a rented Volkswagen bus, Solari, her parents and her sister toured the tropical destination that would become not only an enduring source of wonderment and discovery, but eventually the focal point of her academic research.

For the last five years, Solari, now professor of art history and anthropology at Penn State, has led a research team on an historical and, unexpectedly, scientific journey in the Yucatán.

Working closely with colleague Linda Williams of the University of Puget Sound, she has scoured the peninsula to identify, document, interpret and analyze murals painted inside churches by Maya Christian artists more than 400 years ago, combining art history and cutting-edge materials science in the only known cohesive study of these fragile artworks.

Solari's affinity for the Yucatán resurfaced shortly after she earned a bachelor's degree in anthropology in 2000 from the University of California, Berkeley. She spent a couple of field seasons after graduation on archaeological digs in Honduras, but her thoughts kept drifting back to that family trip and a place she still felt connected to.

For Solari, the history of the colonial era, which began in 1521 when Hernándo Cortés and a ragtag group of Spanish conquistadors invaded the Aztec empire and ended in 1821 with Mexican independence from Spain, always had an appeal—and she was specifically interested in the conversations through art between the Indigenous Maya people and the Spaniards who oversaw the campaigns to convert them to Catholicism.

"The Yucatán Peninsula is perfect for an art historian who wants to study those moments of interaction," Solari says. "Unlike other areas of Latin America, largely because of a lack of modern economic growth, Yucatecan architecture and its associated artworks have remained like a time capsule of the 16th century."

BY LEON VALSECHI

Courtesy Amara Solari

Porteria mural of the Immaculate Conception in the Monastery of Santa Clara in Dzidzantún, Yucatán. Left to right are Claudia Garcia, Linda Williams, and Amara Solari.

"YUCATECAN ARCHITECTURE AND ITS ASSOCIATED ARTWORKS HAVE REMAINED LIKE A TIME CAPSULE OF THE 16TH CENTURY."

— AMARA SOLARI

A WORKING BOND

Over the last 20 years, Solari has explored the history of this cultural crossroads. She has authored or co-authored six books, been published in numerous journals and delivered dozens of lectures on her research. In 2010, soon after she was contacted by Williams to speak at a conference, a partnership was born.

"I read one of her first articles and was absolutely thrilled to see that there was anyone, let alone another art historian, working on that time period in Yucatán," remembers Williams, a specialist in sixteenth and seventeenth-century Mexico. "There just aren't that many of us."

The connection opened endless research possibilities, and the two eventually focused on the murals: initially 22 artistic treasures that Solari and Williams had both observed resurfacing piece by piece from behind centuries-old plaster. Each research trip revealed a more complete view of the paintings that told a visual story of Spanish and Maya cultural interaction and the development of Mexican Catholicism.

Patrick Mansell

Amara Solari

After finally meeting at the conference, the two developed a working bond that evolved into a sisterhood, with dreams of writing a book that would finally offer to the world and, perhaps more importantly, to indigenous Mayas themselves, a comprehensive account of the religious, cultural and historical importance of the murals.

That dream became a reality when the duo submitted a grant proposal to the National Endowment for the Humanities in 2018. The following year, their project, "Maya Christian Murals of Yucatán: Indigenous Catholicism in Early Modern New Spain," was awarded $200,000, the highest amount allocated to research in the humanities.

BURIED TREASURES

The towns and villages of the Yucatán vary widely in size and level of economic development, but one common characteristic is the imposing presence of colonial churches, built by Indigenous stonemasons in the 16th century at the direction of Spanish Franciscan friars. These churches were and are the town centers, and the murals their showpieces.

Using vibrant blue, green, yellow and red pigments, all locally sourced and used by native artists for centuries, the artworks featured Christian iconography: Images of Christ, the Virgin Mary and various saints depict the central tenets of early modern Catholicism and were used as a tool of evangelization.

"The Counter-Reformation is in full swing by the end of the 16th century, the very moment when these murals are created," Solari explains. "The Protestants are accusing the Catholics of idolatry for venerating the same kind of images that are being used in these indigenous missions."

By the 18th century, these murals had been systematically covered under plaster whitewash by clergymen eager to alter the aesthetic of the churches and, Solari says, to simplify their Christian messages.

The whitewash was enduring. Over the last 30 years, however, by a combination of tropical climate and human intervention, the plaster has begun to peel, gradually revealing the murals beneath. The size and quality of the exposed artworks vary from brightly colored scenes that cover an entire wall to a single fragment of the Virgin Mary that is barely visible. Since the project began, Solari and Williams have discovered mural cycles in three additional churches, bringing the total from 22 to 25. According to Solari, there are likely dozens more.

Today, the churches continue to be used for baptisms, marriages and Sunday services, but most of the townspeople don't even know the murals are there, says Claudia García-Solís, a conservator and restorer assigned to the project by the Instituto Nacional de Antropología e Historia (INAH), the agency tasked with preservation of Mexican cultural heritage. For García-Solís, this highlights the importance of the project.

"It is incredibly meaningful to have and share a record of these paintings," she says. "Preservation is ideal, but explaining and understanding their relevance, even for the people of the Yucatán, is very important for Mexico."

Courtesy Amara Solari

Drone photo outside the Monastery of Santa Clara in Dzidzantún, Yucatán. Left to right are Claudia Garcia, Amara Solari, Emily Floyd, and Linda Williams. Below left: Arma Christi mural at Monastery of Santa Clara of Dzidzantún. Below right: Emily Floyd teaching the children of Tabi, Yucatán, about drone photography.

Photography by Emily C. Floyd for MAVCOR. Reproducción autorizada por el Instituto Nacional de Antropología e Historia (INAH), México

Courtesy Amara Solari

INTO THE FIELD

As the cultural significance of the research became clear, Solari knew that capturing the work with digital photography and video would be an essential preservation component of the project.

She was familiar with Yale's Center for the Study of Material and Visual Cultures of Religion (MAVCOR), an open-access collection of high-resolution media documenting religious, cultural and archaeological sites around the world. Through the center's website, Solari connected with editor and curator Emily Floyd.

With Floyd and her technical ability on board, an intensive research trip was scheduled for April 2018. The goal was to visit churches in the villages of Maní, Tabí, Izamal, Temax and Dzidzantún, all located in the northern Yucatán, and to gather digital images, videos and, perhaps most importantly, small fragments of the murals for materials analysis.

Having what Solari calls "the dream team" in place, she, Williams and Floyd flew to the Yucatán, rented a car, filled it with gear, "loaded up on Cheez-its and Coca Cola," and went to work.

As they entered each town, the team would seek out the sacristan to gain access to the church while Floyd prepped her recording gear. One piece of equipment always caught the attention of the local children: the DJI Phantom 4 Pro drone she used to capture aerial images of the church and its surroundings. "They would all gather around as I explained what it is and what it does," Floyd remembers.

For one busy week, the team travelled church to church, logging 8- to 10-hour days to gather dozens of hours of footage, hundreds of photos and fragments of pigment for analysis.

Using a scalpel, García-Solís deliberately excised from nondescript sections of the murals, careful to maintain their integrity. The removal of samples, which are about the size of a pin head, was a tedious process requiring multiple government permits.

Photography by Emily C. Floyd for MAVCOR. Reproducción autorizada por el Instituto Nacional de Antropología e Historia (INAH), Mexico (2)

Courtesy Amara Solari

Top left: Mural painting of the Flagellation of Christ, Monastery of San Miguel Arcángel of Temax. Bottom left: Several layers of mural painting, Church of San Miguel Arcángel, Mani. Right: Pigment sample of "Maya Blue" taken from the apse murals of the Monastery of San Miguel Arcángel, Mani, Yucatán.

"THIS RELATIONSHIP WITH AMARA AND PENN STATE PRESENTED AN OPPORTUNITY TO SAFELY PRESERVE THESE PAINTINGS."

— CLAUDIA GARCÍA-SOLÍS

This legal framework for sampling murals is well-defined in Mexico. "These tiny fragments are rightfully deemed cultural patrimony and it is thus usually illegal to remove them the country," Solari says. However, for García-Solís and INAH, Penn State's international research reputation and its advanced technological capabilities created a natural partnership that she says is beneficial to Mexico's preservation efforts.

Protecting the artifacts is of paramount importance. Simply cleaning a mural with the wrong product can cause a chemical reaction that could destroy the painting. Even more difficult can be choosing the right sealant to protect against deterioration.

The only way to guarantee safe interaction with the murals, the team realized, is to identify the materials used in their creation. That's where Penn State's Materials Characterization Lab (MCL) comes in. Housed within the Materials Research Institute at Penn State, MCL is a world-class facility offering state-of-the-art scientific analysis of materials samples.

"This process can be very expensive, and the one thing that INAH doesn't have much of is money," García-Solís says. "This relationship with Amara and Penn State presented an opportunity to safely preserve these paintings."

After the first successful first trip, the team returned to the Yucatán three more times on fragment-gathering missions, with the final one coming in March of 2020.

Throughout that fateful week, the team, like much of the world, began to hear news reports about the spread and severity of a virus named COVID-19, adding a sense of urgency to their work. At week's end, with ample data and samples gathered, Solari nervously boarded a plane for the journey home, one of the last flights before the U.S. closed its borders to international travel.

A NEW DIMENSION

A few days after her return, Penn State announced that all international travel was on hold indefinitely, clouding the future of the project.

"For an art historian, the next step would have been to travel to Seville, Spain and the Archive of the Indies to research the Mexican colonial documents," Solari explains. "The archive is where any correspondence sent from the colonies back to Spain was collected and housed."

The inability to gather textual information that could help to date the murals and tell their story caused her to shift her focus and become more dependent on the scientific analysis, a task she says was not only out of her comfort zone, but "completely foreign."

Solari delivered the collection of mural fragments to the MCL, where Nichole Wonderling, X-ray scattering manager, and Julie Anderson, research technologist, invited her to take part in the analysis.

Amara Solari in the sacristy of the Ex-Convent of San Ramon, Chancenote, Yucatán.

Courtesy Amara Solari

"WE'VE BEEN ABLE TO BASICALLY RECONSTRUCT THE ENTIRE COLONIAL PALETTE BECAUSE OF THESE SAMPLES."

— AMARA SOLARI

Wonderling's goal was to find traces of the clay mineral palygorskite, which when heated together with indigo creates the pigment known as Maya blue. The process dates back to A.D. 300 and the pigment, which is virtually impervious to time and weather, was commonly used in the Yucatán throughout the Colonial period.

Using the lab's X-ray diffractometer, Wonderling and assistant research professor Beth Last explored the samples in what they call a "hunt and peck" mission. The process proved difficult at first because of the presence of calcite in the plaster attached to the paint, but after employing a more focused microdiffraction technique, they found what they were looking for.

Anderson has since been using an electron microscope to scan the fragments. To determine the chemistry of the pigments used, she has worked with Energy Dispersive Spectrometry. The lab employed an ion milling process to remove the top amorphous layer from the fragments and reveal a pristine sample surface. This has allowed the team to analyze cross sections to eliminate the intrusion of materials that could have been added later to alter a mural or add a protective layer.

Throughout the analysis, Wonderling says that Solari has been a welcome addition to the team, her keen interest a breath of fresh air.

"She was just so excited about what we were doing and mesmerized with what was possible," Wonderling says. "It was fun to work with her, and I hope this success can let that person who maybe isn't comfortable with science and technology know that there are people here who can help them."

THE POWER OF COLLABORATION

So far, the MCL's findings have allowed Solari and Williams to declare with certainty that all the murals they have sampled were created during the Colonial period, using not only Maya blue, but also yellow and red ochres and carbon black. As the research continues, Solari expects to confirm the origins of additional murals, thanks in part to the pigment analysis.

"We've been able to basically reconstruct the entire Colonial palette because of these samples," Solari says. "I just keep thinking, 'this is the power of collaboration at Penn State.'"

She and Williams are writing that long-planned book, expected to be completed in 2022. In the meantime, Floyd and the MAVCOR team have created "Colonial Maya Churches of the Yucatán," a stunning, high-resolution 360-degree online tour of the churches and their murals, available on the MAVCOR website.

Additional work on the samples combined with post-pandemic access to the Archive of the Indies will likely result in more discoveries. The scientific data will aid García-Solís and INAH as they devise proper cleaning and preservation methods. For Solari, however, these data open up an even larger interpretation.

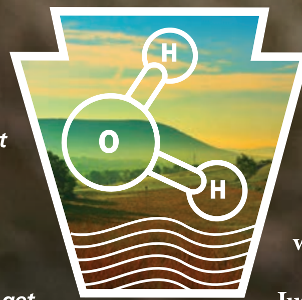
"The science can tell me that this pigment is composed of 'x' and then we determine that 'x' does not come from Yucatán. In determining its place of origin, I am able to reconstruct an entire economic network premised upon the movement and exchange patterns of native people," Solari explains. "By illuminating the contours of daily life in the colonial period, we're revealing the agency of Indigenous actors during this historical moment and beyond."

There's another, more personal, dimension for Solari as well. In December of 2021, she returned to the Yucatán for a research trip, this time with a new research assistant—her 5-year-old daughter, Catalina.

The days spent driving through the Yucatán on bumpy jungle roads were a little sweeter this time, Solari says. Some of the usual art-hunting gear was replaced by a car seat and a new research assistant who adds a whole new perspective to her work.

"This is my favorite area of the world," Solari says. "My parents brought me here when I was a girl and because of that, I know it's important to share it with my own child. The amazing thing is, she absolutely loves it."

Lara Fowler on Water Issues in Pennsylvania



Water lawyer and mediator Lara Fowler is a senior lecturer at Penn State Law, where she teaches water and energy law, environmental mediation, and dispute resolution; and assistant director of the Institutes for Energy and the Environment. She was recently named interim director of the Sustainability Institute and the university's chief sustainability officer.

"Where science meets policy meets how do we get things done, bringing in the human element, is kind of the core thread of the work that I do," she says. Fowler grew up in Idaho and Oregon, and worked on water issues in Oregon, Washington, and California before coming to Penn State in 2012.

WHAT WAS IT LIKE COMING FROM WEST TO EAST?

The patterns of development are older here, but I think the tenor and personality of Oregon, Washington and Pennsylvania are more similar than I would've expected. The West knows they have a water problem—they're staring down a 1,200-year drought—but I think there's a dawning realization that water is more of an issue here than people maybe realized.

Flooding was very fresh on people's minds when we came in 2012. Everybody was talking about Tropical Storm Lee, which had a huge impact in Pennsylvania. One of my early projects looked at impacts of the National Flood Insurance Program on Pennsylvania. The NFIP was created in 1968, but growth and development in Pennsylvania dates to the 1700s, when rivers were the transportation system. The legacy of that with our long ridges and valleys is that a lot of settlements, towns, boroughs are right next to rivers and streams. And the Susquehanna is unusually shallow, with hard rock underneath. It's one of the most flood-prone rivers in the country.

WHAT ARE SOME OTHER WATER-RELATED ISSUES IN PENNSYLVANIA?

There are layers of them. I started with flood, but soon realized there's also drought. If you talk to farmers, they'll tell you we're getting huge fluctuations in rainfall in any given summer. Our averages are hiding the fact that we have changing patterns between flood and drought that are incredibly detrimental.

Water quality is another issue. We think we have plenty of water, but if you look on a map at where all the nitrate pollution is, and where the PFAS contamination is, and the acid mine drainage, I think we have much less [usable] water than we think we do. And in Pennsylvania, 25% of people rely on private backyard wells, yet there are no state well-drilling standards.

WHAT ARE THE CHALLENGES TO ADDRESSING THESE ISSUES?

There are lots of discussions across the U.S. about integrated water resource management. Can we get out of our silos of thinking about water as drinking water or wastewater or storm water or flood water?

Just as importantly, to fix some of these problems you have to go and talk with the folks at ground level, see what they think. Farmers know very well what's impacting them locally.

This coming together across disciplines, across ways of knowing, requires getting a bit out from the academic side. It is not fast. But I have more hope in this sort of bottom-up work having longevity to make a difference. I spend a lot of time trying to get people to learn how to talk with each other.

HOW ARE THE STATE'S WATER ISSUES IMPACTED BY CLIMATE CHANGE AND OTHER FACTORS?

Climate change is water change. What was predictable 20-30 years ago is no longer predictable. Even the temperatures we've seen this Spring – our systems aren't set up to deal with that.

I also don't think we fully understand how interconnected we are, how what's happening with loss of agriculture in California, or now in Ukraine, drives and will drive the need for better and more robust agriculture in Pennsylvania. How do these [far-off developments] affect water allocation and water supplies in this area?

WHAT COMES NEXT?

There are opportunities for creative solutions to be found in bringing together projects that benefit people, wildlife, habitat, and rivers at the same time. If we can articulate the co-benefits of these projects, we can leverage funding sources from a lot of different areas. There's money available, but right now there are gaps in capacity at the local level. I think Penn State can start to convene discussions to bridge some of those gaps.

Editor's note: Penn State is developing a university-wide Water Consortium, building on the University's long and rich history of engaged, innovative, and impactful water-related research. To find out more, visit https://iee.psu.edu/programs/consortia/water-consortium.

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Randall McEntaffer, head of Penn State's Department of Astronomy and Astrophysics, makes adjustments to the flight electronics and power supply of the X-ray spectrometer that he and his team built for a September launch with NASA. Credit: Patrick Mansell / Penn State. Creative Commons.