EQuad News
Spring 2022
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PRINCETON

School of Engineering
and Applied Science

Design for Humanity

New perspectives, deep questions, better solutions

DEAN'S NOTE

Design for humanity

Each time I talk with Princeton colleagues and students, I come away with renewed excitement about the power of our work to bring long-term benefits to humanity.

That's not just because of our technological advances, which are truly transformative. It's because of the students, postdocs, and faculty at Princeton who thrive on interactions far outside their fields of studies and far beyond the confines of academia. As we develop innovations with the power to disrupt and remake so many elements of our lives and society as a whole, we need broad and interdisciplinary perspectives. In particular, collaborations across engineering, the social sciences, and the humanities, and with stakeholders of many backgrounds, are required to create the innovations that will improve lives, protect the environment, and avoid unintended pitfalls.

That is why, as we grow in our role as a hub for technology innovation and entrepreneurship, we are infusing our approach with the powerful practices of design. In this magazine, you'll read just a few examples of how design propels insights out of labs and into ventures that are making a positive difference. This is ongoing work. Our very popular course "Creativity, Innovation, and Design" (p. 6) has been a flagship of our entrepreneurship curriculum for more than five years and is now joined, through the generosity of Amy and Gordon Ritter '86, with an exciting collaboration with anthropology (p. 7) and other initiatives. We are creating an Innovation Hub that brings together people across the University and introduces them to the practice of design and innovation.

Please join us and share with us your own stories of innovation and design as tools for serving humanity.

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Photo by David Kelly Crow

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Note on alumni class years
Following Princeton University convention, undergraduate alumni are indicated by an apostrophe and class year; graduate alumni, whether master's or doctoral, are indicated with a star and class year.

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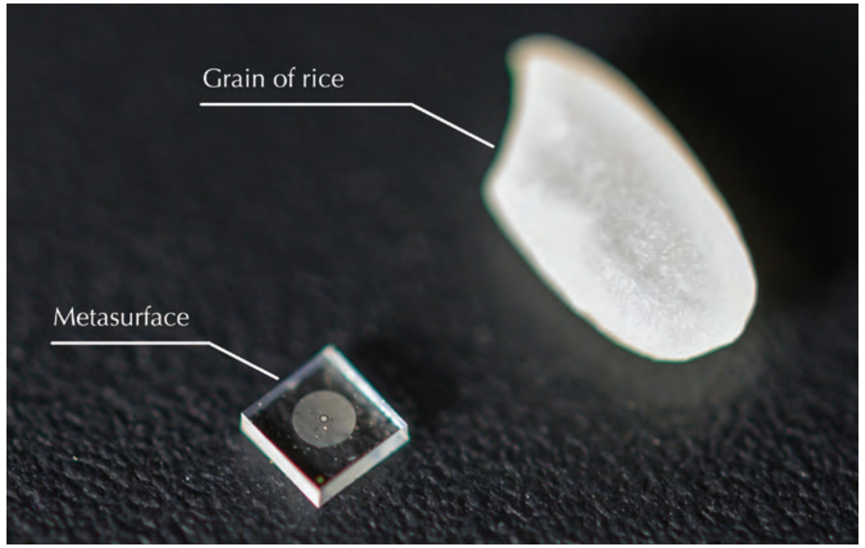
In the Nation's Service and the Service of Humanity



RESEARCHERS SHRINK CAMERA TO THE SIZE OF A SALT GRAIN

Micro-sized cameras have great potential to spot problems in the human body and enable sensing for super-small robots, but past approaches captured fuzzy, distorted images with limited fields of view.

Now, researchers at Princeton University and the University of Washington have overcome these obstacles with an ultracompact camera the size of a coarse grain of salt. The new system can produce crisp, full-color images on par with a conventional compound camera lens 500,000 times larger in volume, the team led by Felix Heide, assistant professor of computer science, reported in a paper published in Nature Communications.

Enabled by a joint design of the camera's hardware and computational processing, the system could enable minimally invasive endoscopy with medical robots to diagnose and treat diseases, and improve imaging for other robots with size and weight constraints. Arrays of thousands of such cameras could be used for full-scene sensing, turning surfaces into cameras.

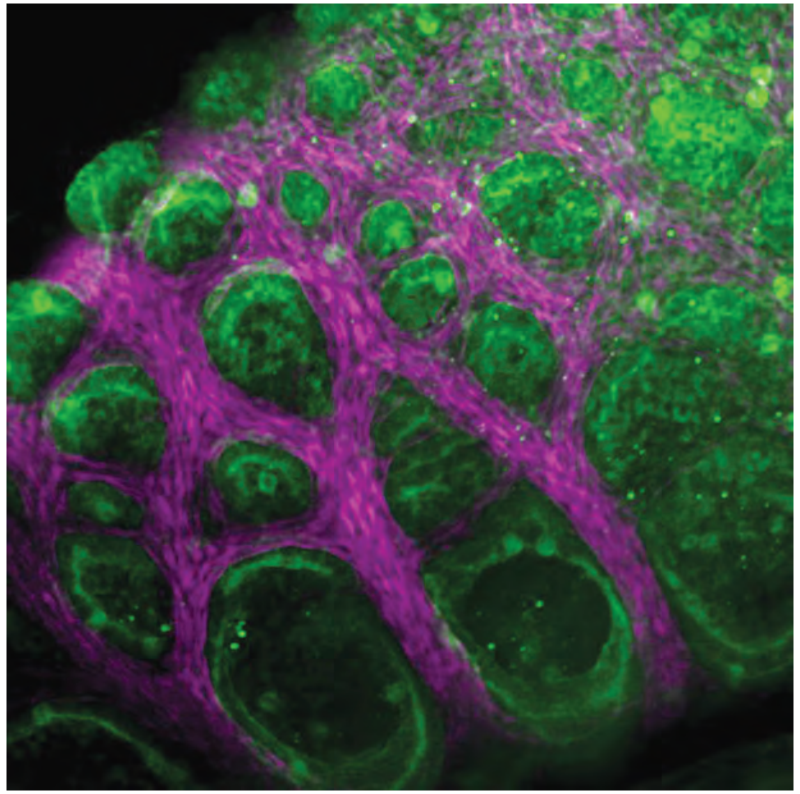
While a traditional camera uses a series of curved glass or plastic lenses to bend light rays into focus, the new optical system relies on a technology called a metasurface, which can be produced much like a computer chip. Just half a millimeter wide, the metasurface is studded with 1.6 million cylindrical posts, each roughly the size of the human immunodeficiency virus (HIV).

Each post has a unique geometry, and functions like an optical antenna. Varying the design of each post is necessary to correctly shape the entire optical wavefront. With the help of machine learning-based algorithms, the posts' interactions with light combine to produce the highest-quality images and widest field of view for a full-color metasurface camera developed to date.

A key innovation in the camera's creation was the integrated design of the optical surface and the signal processing algorithms that produce the image. This boosted the camera's performance in natural light conditions, in contrast to previous metasurface cameras that required the pure laser light of a laboratory or other ideal conditions to produce high-quality images, said Heide. **– by Molly Sharlach**

Researchers at Princeton University and the University of Washington have developed an ultracompact camera the size of a coarse grain of salt. The system relies on a technology called a metasurface, which is studded with 1.6 million cylindrical posts and can be produced much like a computer chip. Photo courtesy of the researchers

HUMBLE LIZARDS OFFER SURPRISING APPROACH TO ENGINEERING ARTIFICIAL LUNGS



Princeton researchers found that lizard lungs offer a fast and simple model that engineers can use to develop advanced biotechnology for regenerating and engineering tissue. The lung of a developing brown anole, above, forms through a physical process the researchers liken to a mesh stress ball, the common toy, where fluid pressure causes an inner membrane (green) to bulge through a muscular mesh (pink) to form cavities where gas exchange can occur. Above image courtesy of the researchers, lizard photo from iStock

When it comes to studying lungs, humans take up all the air, but it turns out scientists have a lot to learn from lizards.

A new study from Princeton University shows how the brown anole lizard solves one of nature's most complex problems — breathing — with ultimate simplicity. Whereas human lungs develop over months and years into baroque tree-like structures, the anole lung develops in just a few days into crude lobes covered with bulbous protuberances. These gourd-like structures, while far less refined, allow the lizard to exchange oxygen for waste gases just as human lungs do. And because they grow quickly by leveraging simple mechanical processes, anole lungs provide new inspiration for engineers designing advanced biotechnologies.

"Our group is really interested in understanding lung development for engineering purposes," said Celeste Nelson, the Wilke Family Professor in Bioengineering and the study's principal investigator. "If we understand how lungs build themselves, then perhaps we can take advantage of the mechanisms Mother Nature uses to regenerate or engineer tissues."

The study, published in the journal Science Advances, is the first to look at the development of a reptile lung, according to the researchers. While avian and mammalian lungs develop great complexity through endless branching and complicated biochemical signaling, the brown anole lung forms its relatively modest complexity through a mechanical process the authors likened to a mesh stress ball — the common toy found in desk drawers and DIY videos.

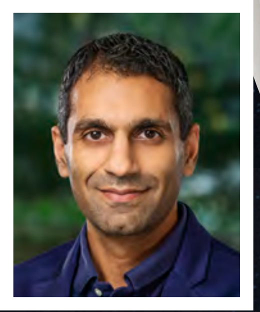
The whole process takes less than two days and is complete within the first week of incubation. After the lizard hatches, air comes in at the top of the lung, swirls around the cavities, and then flows back out.

For engineers looking to crib nature's shortcuts on behalf of human health, this speed and simplicity make for a radical new design paradigm. The study also breaks new ground for scientists to study reptile development in far greater detail.

"Different organisms have different organ structures, and that's beautiful, and we can learn a lot from it," Nelson said. "If we appreciate that there's a lot of biodiversity that we can't see, and we try to take advantage of it, then we as engineers will have more tools to tackle some of the major challenges that face society." **– by Scott Lyon**

DESIGNING FOR SOCIETAL IMPACT

by Naveen Verma, Professor of Electrical and Computer Engineering. Director, Program in Technology and Society. Director, Program in Entrepreneurship. Director, Keller Center for Innovation in Engineering Education.



Naveen Verma. Photo by David Kelly Crow

The urgent challenges facing our planet demand new cooperation and new solutions.

There is great hope for overcoming these urgent challenges, particularly by harnessing the engineered technologies we are creating, which place in our hands disproportionately greater capabilities and reach than ever before.

But as our technologies grow more powerful, so do the potentials for unintended consequences. As we enter an era of engineering new forms of societally-embedded intelligence, planetary processes, and basic mechanisms of life, there is simply no room for unintended consequences.

With long traditions of scholarship, discovery, and commitment to society, Princeton stands ready to respond. Recognizing the complexity of the challenges before us, we are pursuing meaningful societal impact through the practice of design. Design is deliberated change — a rigorous process for gathering perspectives and asking deep questions to unleash greater creativity and to meet real-world constraints and values by eliminating the blind spots born of narrow thinking.

Design at Princeton leverages our strengths in engineering, natural sciences, social sciences, and humanities to form the foundation for achieving positive societal impact through innovation and entrepreneurship.

The Keller Center serves as a hub for this convergence, with a broad range of on- and off-campus partners and stakeholders. Working across academic disciplines, communities, businesses, and governments is powerful, but fraught with barriers. Anyone who has worked with experts and stakeholders from widely varying viewpoints can attest to the frictions that can result. But we are discovering new ways of working together through projects led by Princeton researchers — projects that place urgent problems directly in their crosshairs, but also serve to establish new models for academic and real-world collaboration.

Just one example of such a collaborative project is led by Carolyn Rouse, the chair of the anthropology department and Princeton's inaugural Ritter Professor, a new position that connects faculty to the Keller Center to encourage human-centered approaches to solving societal problems. Carolyn (see page 7) is establishing a project for stormwater management in the municipality of Princeton by collaborating with expert colleagues and students in civil and environmental engineering, computer science, and anthropology, together with municipal managers in city planning, engineering, and policy.

Students and faculty continue to create incredibly differentiated technologies through ideas that are only possible because of deep disciplinary expertise. In this magazine we see new ventures spinning out of Princeton Engineering to deliver life-saving drugs and vaccines, instantly detect COVID, solve the problem of spent batteries in our emerging electric economy, and more. While our technologies incorporate the deepest levels of engineering design, we as a community move toward the design of societal impact, through understanding derived from classes (see page 6) and projects like Carolyn's.

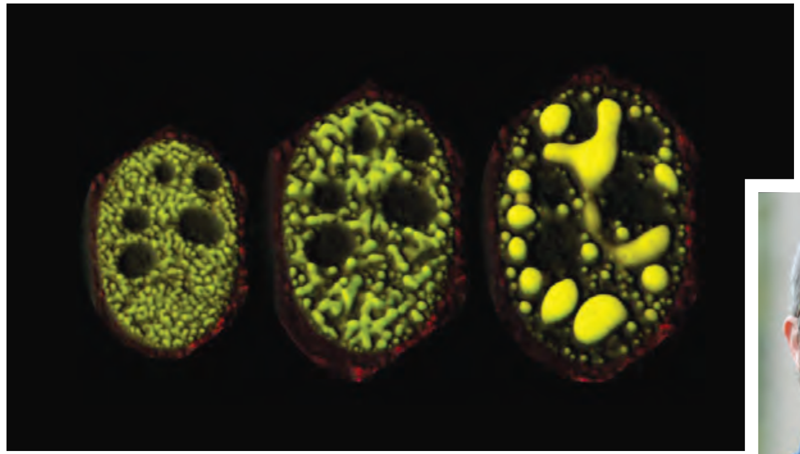
Empowered by design, we see innovation and entrepreneurship as tremendous vehicles for such societal impact. We have just begun to scratch the surface, and I hope you will bring your ambitions and perspectives to this initiative — as with all forms of engineering, our success will be derived directly from the diversity of perspectives we bring. **E**

INNOVATION HUB

The School of Engineering and Applied Science is creating an innovation hub to accelerate and broaden participation in innovation, entrepreneurship, and design across the whole campus.The hub, bolstered with hiring now underway for several faculty and staff positions, will provide faculty, students, and postdoctoral researchers in all disciplines with the projects, programs, places, and people to help support their innovation ambitions. This includes access to a network of advisers, alumni, and practitioners. The maker space in the Engineering Quadrangle pictured here brings together graduate and undergraduate students from across the University for courses in creativity, innovation, and design as well as for independent projects. Photo by Sameer A. Khan/Fotobuddy

TECH AND SCIENCE ADVANCE IN CONCERT

by the Office of Engineering Communications



In recent work, Brangwynne's research team has developed new tools using light to examine how liquid matter inside cells transforms into functioning cellular compartments called membraneless organelles. Photo of organelles by the researchers, Brangwynne photo by Sameer A. Khan/Fotobuddy

For Clifford Brangwynne, director of the Princeton Bioengineering Initiative, it's impossible to choose between scientific discovery and technological innovation.

"The scientific enterprise is often snail-paced, and then something comes along and catapults it to the next level," said Brangwynne, the June K. Wu '92 Professor of Chemical and Biological Engineering. "Usually, that something is technology."

Asked for a few examples, Brangwynne rattles off a string of breakthroughs: green fluorescent proteins that allow scientists to probe cellular operations; super-resolution microscopes, "suddenly, the glasses are not foggy;" RNA interference and CRISPR, which allow science to explore changes to cellular function.

"All of these are transformative," Brangwynne said.

Brangwynne has direct experience. As a postdoctoral researcher in 2009, he postulated the concept that key organelles performing functions inside cells form through phase separation, like raindrops condensing from water vapor. The insight has proven central to both understanding how cells operate and how they can misfire in ways that lead to disease.

Over the next decade, Brangwynne's lab has developed new techniques that allowed researchers to further explore his theory. Among them, harnessing light-sensitive proteins for triggering phase separation with lasers.

Brangwynne and colleagues have recently started a company, Nereid Therapeutics, to translate technical and scientific advances to the market. Nereid is deploying technologies from the Brangwynne lab to developing therapies for cancers and neurodegenerative diseases.

Embracing technological innovation as central to scientific discovery is a priority for the Bioengineering Initiative, Brangwynne said. "Once you develop new technologies in the service of discovery, you are going to find there are a lot of other potential applications," Brangwynne said. "This is at the heart of Princeton Bioengineering." **E**

DON'T JUST **THINK** OUTSIDE **THE BOX,** RETHINK **THE BOX**

by Sharon Waters

Majora Carter works to help students expand their thinking on ways to develop Princeton's Palmer Square. Photos by David Kelly Crow

Majora Carter, an instructor of the Keller Center's core design course, works to dispel the myth that creativity is pure inspiration that flashes like lightning across the imagination.

"The course focuses on the fact that creativity isn't this inborn talent that only a few of us have, but you can literally learn to access it, if you're willing to put in the work and develop the confidence to do so," said Carter, who received a MacArthur fellowship in 2005 as the founder of the urban revitalization group Sustainable South Bronx. "The class allows students to work side by side with faculty partners — anthropologists, engineers, humanists, and scientists — on projects that can significantly impact society."

Carter is one of the instructors of "Creativity, Innovation, and Design," a course required for the University's entrepreneurship certificate. Largely formed by the center's entrepreneurship specialist and iSuppli founder Derek Lidow, the course challenges students to think of novel ways to approach a range of problems.

In a recent session in a classroom in the University's Entrepreneurial Hub on Chambers Street, instructor Jessica Leung posed a series of brain twisters to a class of 12 students. The first — what happened to three bodies in a cabin on a mountainside? — stumped the group. But by the third question — how does a bus driver avoid a ticket passing a stop sign, turning the wrong way? — the students were ready.

"He's walking," one said.

"You guys are getting better," said Leung, who directs and teaches the Keller Center's human-centered design program, Tiger Challenge. "You're really starting to think!"

The course, Leung explained, presents students with new lenses through which to view problems.

"The goal is to broaden your perspective, to overcome your assumptions before they limit your options," she said.

And the cabin question? It was a plane crash. **E**

NEW PROFESSORSHIP **IMBUES** HUMANITY **IN DESIGN**

by Beth Jarvie

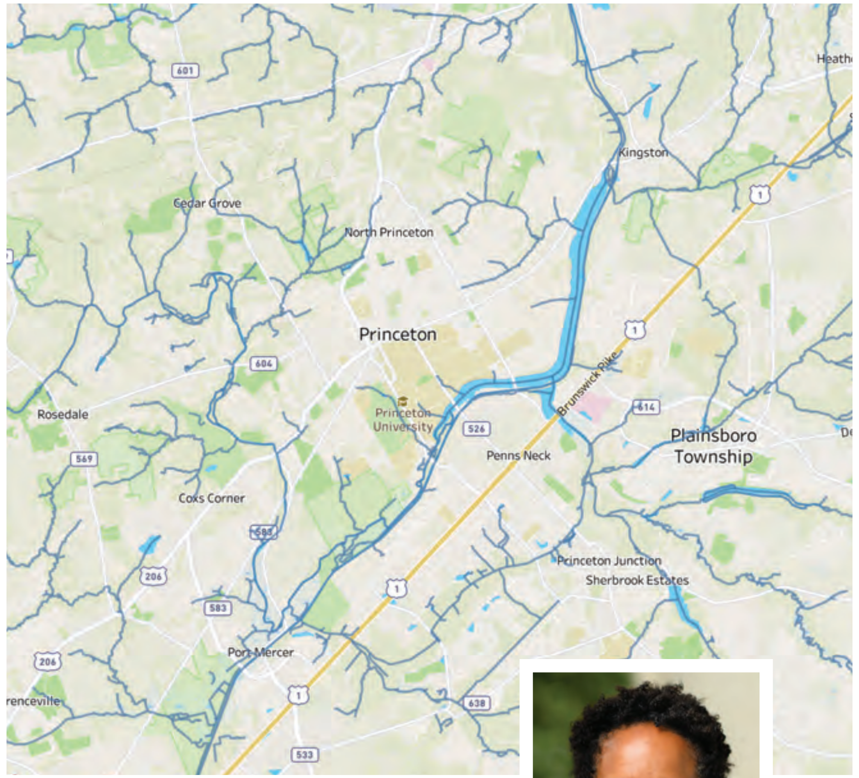
Carolyn Rouse, chair of the anthropology department, will serve as Princeton's inaugural Ritter Professor, an endowed chair that supports transdisciplinary approaches to addressing society's most important and complex challenges. Her objective is to engage Princeton faculty and students in projects and curricula that broaden the use and awareness of design that puts people first.

Rouse is currently developing a new course focused on using ethnographic methods taken from anthropology to approach problems of design and innovation. The goal is to produce solutions strengthened by deeper observations of people and systems affected by the design. The class will allow students to work side by side with faculty partners — anthropologists, engineers, humanists, and scientists — on projects that can significantly impact society.

"You get them to set aside their values and expectations and presumptions in order to ask better questions, to get to a better place, an ethical place," Rouse said.

As a Ritter Professor, Rouse will also be leading a design solution project which addresses stormwater and flooding devastation due to climate change. The project, called "High-Water Mark: Designing Flood Resiliency in New Jersey," will bring together anthropologists, environmental engineers, and entrepreneurs to mitigate future flood damage to the Princeton community due to rising stormwater levels.

In bridging engineering and the humanities through design initiatives, Rouse sees an excellent opportunity to "bring the intellectual power of Princeton together with practice in building sustainable solutions." **E**



A project spearheaded by Professor Carolyn Rouse, newly appointed as Princeton's Ritter Professor of Anthropology, is bringing engineers, artists, and anthropologists together with local community members and leaders to design a multi-year plan to mitigate flooding in the Princeton area, while building a model for tackling complex problems through the tools of design thinking. Image courtesy Jeff Himpele, director of Princeton's Ethnographic Data Visualization Lab, photo of Rouse by Sameer A. Khan/Fotobuddy

STARTUP FAST-TRACKS BATTERY RECYCLING

by Molly A. Seltzer

Mechanically shredded batteries at the Princeton NuEnergy facility in Bordentown, New Jersey. Photo by Molly A. Seltzer

Billions of dead lithium-ion batteries, many from electric vehicles, accumulate because there is no cost-effective process to revive them.

Now, Princeton researchers have developed an inexpensive, sustainable way to make new batteries from used ones and have spun off a company to scale up the innovation.

Current technologies for recycling lithium-ion batteries rely on harsh chemicals and energy-intensive processes to deconstruct spent batteries to their elemental components. Princeton NuEnergy uses a process developed by two faculty members who combined expertise from different fields to solve a long-standing problem: how to recycle batteries' cathode materials, which include expensive elements such as cobalt, nickel, manganese, and lithium.

The method runs cathodes through a reactor driven by low-temperature plasma. Because of plasma's inherent reactivity, it can remove contaminants directly while maintaining much of the structure and composition of the original cathode. This method reduces water use by approximately 70% and energy use by 80%, the researchers said.

"People would be willing to give us their dead batteries that are currently just sitting around. They receive back from us new pristine cathode materials for new batteries cheaper than they could manufacture," said Chao Yan, cofounder and CEO of Princeton NuEnergy and a postdoctoral research associate in the Department of Mechanical and Aerospace Engineering.

Xiaofang Yang, who was an associate research scholar at Princeton, is a cofounder and CTO of the company. Yiguang Ju, the Robert Porter Patterson Professor of Mechanical and Aerospace Engineering, and Bruce Koel, professor of chemical and biological engineering, are cofounders and technology advisors.

"We think there is a massive opportunity to transfer our technology into a real industrial project that will allow us to recycle and repurpose lithium-ion batteries at scale," said Yan. The startup is working with a Taiwan-based company to build a pilot plant in Texas to process at least a ton of material a day.

Koel said the team considered other pursuits based on their electrochemistry expertise, but decided battery recycling would be the most useful.

"This was an important problem to society and it looked like there was room for innovation," said Koel.

The researchers noted that cheap and sustainable recycling could address many problems, such as labor and environmental concerns associated with mining.

"This was something we could really do differently and have a real impact on sustainability and impact the energy landscape," said Koel. **E**

AI USES SMARTWATCH TO DETECT COVID

by Molly Sharlach

Combining questions about a person's health with data from smartwatch sensors, a new app developed using research at Princeton University can predict within minutes whether someone is infected with COVID-19.

This new breed of diagnostic tool stems from research led by Niraj Jha, a professor of electrical and computer engineering at Princeton University. His team is developing artificial intelligence (AI) technology for COVID-19 detection, as well as diagnosis and monitoring of chronic conditions including depression, bipolar disorder, schizophrenia, diabetes, and sickle cell disease.

NeuTigers, a company founded to commercialize Jha's work, applied to the U.S. FDA, under the agency's provision for "software as a medical device," for clearance for its CovidDeep product. Shayan Hassantabar, a Ph.D. student in Jha's group, is the lead author of a paper in IEEE Transactions on Consumer Electronics describing the development and testing of CovidDeep. The software integrates smartwatch sensor readings of heart rate, skin temperature, and galvanic skin response with blood pressure and oxygen saturation levels, as well as a questionnaire on COVID symptoms.

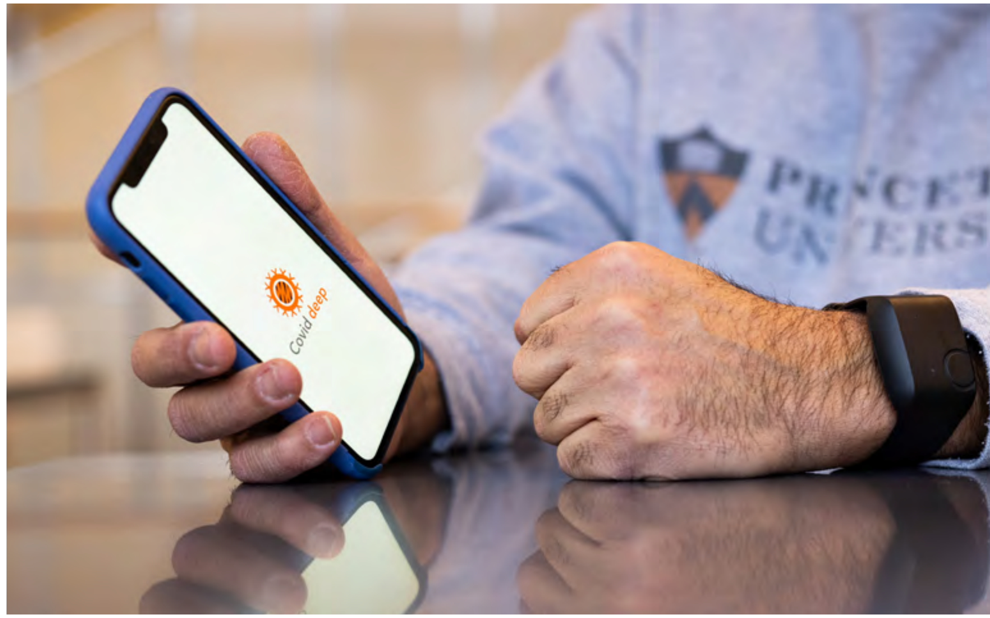
Jha's research group at Princeton has long focused on adapting a type of AI called deep learning, which is typically energy-intensive, to function on low-power electronic devices such as phones and watches instead of centralized cloud computing centers. This approach, known as edge AI, has the added benefit of helping to preserve users' privacy and increase security. A key innovation is pared-down neural networks (the "neu" of NeuTigers) that mimic human brain development.

"It's a very generalizable framework," said Jha. "Smart health care is just one application. We are also applying it to cybersecurity and other internet-of-things applications." Similar to preventive medical interventions, machine learning models could spot aberrant patterns and help fix software vulnerabilities before a cyberattack ever occurs, he said.

In recent years, Jha's team has explored edge AI for health care applications such as noninvasive detection of diabetes and mental health disorders from smartwatch and smartphone sensor data.

In fall 2017, former pharmaceutical executive Adel Laoui audited Jha's class on "Machine Learning for Predictive Data Analytics" and was intrigued by the technology. Laoui, who had experience developing and deploying new technologies for disease management, approached Jha after the course ended. After further discussions with Jha's Ph.D. students, they launched NeuTigers in June 2018.

"We saw a lot of intersections in our interests," said Jha. "Smart health care with the help of edge AI was taking off, so it was an opportune moment for a startup in this area. Adel had a lot of connections with angel investors, and so it ramped up very quickly." **E**



New technology uses smartwatch data to improve patients' health. Photo by Sameer A Khan/Fotobuddy

TINY PARTICLES LEAD TO BIG GAINS IN PUBLIC HEALTH

by Scott Lyon

Researchers in Robert Prud'homme's lab have pioneered techniques for precisely mixing chemicals that have served as a basis for modern pharmaceutical delivery.

For 20 years, researchers in Robert Prud'homme's lab have fine-tuned technology that is revolutionizing drug manufacturing, enabling everything from mRNA-based COVID-19 vaccines to malaria drugs that can be distributed across rural Africa.

Prud'homme, a professor of chemical and biological engineering, is a master of the incredibly precise art of packaging drug molecules for delivery. It's an area often ignored in popular discussion, but without a vehicle, many of today's crucial medicines would be little more than lab curiosities, adrift in a sea of potential. Putting them where they need to be is half the job.

In a 2003 paper, Prud'homme and former graduate student Brian Johnson described a technique called "flash nanoprecipitation" that mixes liquids to create invariably precise solids — perfectly sized, perfectly shaped, perfectly layered polymer grains, one million times smaller than a grain of table salt. To arrive at the results, the researchers created a device called a confined impinging jet mixer that takes in two unlike liquids, mixes them in a flash of turbulent swirling, and pumps out a stream of bespoke nanoparticles like warm water from a tap. Each particle contains an active ingredient — such as a drug molecule, a strand of RNA, a protein — wrapped in a package that delivers the payload to its target, whether blood cells, liver cells, or a metastasizing tumor.

The secret to this mixing, according to Prud'homme, lies in empty space.

"You need a confined volume where the turbulence can evolve," he said. "Think of stirring cream into a coffee cup. That stretching, swirling process is how turbulence does the mixing."

Other methods either take the coffee cup analogy literally, stirring the solutions in vessels, or use a T-shaped geometry to flow two streams together and sluice them out the bottom. The vessel approach limits production to single batches at a time and fails when applied to large volumes. The T-mixer gets clogged easily at both large and very small scales. Both approaches, while fine for research, produce inconsistent and unstable particles when used at large commercial scales.

The confined impinging jet mixer avoids the limitations of both approaches to produce precision medicines at global scales. It allows continuous flow of large volumes for long periods of time, while avoiding clogging by engineering a cavity where the two liquid jets strike each other in the middle of the open space, away from the walls. The particles form and drop out of the device in less than 50 milliseconds – hence the "flash" in "flash nanoprecipitation."

"The real innovation was in how to make small particles in large volumes," said Rodney Fox, a leading fluid-dynamics expert and professor at Iowa State University. Fox headed a team that later simulated the process in molecular detail and proved how it worked computationally. He said the rapid timing put Prud'homme's technique in a class by itself. If mixing doesn't happen fast enough, particles clump together. But with flash nanoprecipitation, the complex particles form before they can clump. Prud'homme had figured out to combine materials that normally refuse to combine by mixing them so fast they don't have time to react otherwise.

The method has led to its widespread adoption. Since 2016, the Gates Foundation has sponsored work in the Prud'homme laboratory to produce low-cost and highly effective drugs for use in global health applications. They have demonstrated production of highly stable treatments for malaria, diarrhea, and tuberculosis. One of the world's largest contract research organizations, WuXi AppTec, is building a manufacturing capability based on this technology. Merck also adopted it for work with RNA cancer therapies.

In recent CNN coverage of plants producing the COVID-19 vaccine, Mike McDermott, Pfizer's chief of global supply, said "the heart of this whole machine is what's called an impingement jet mixer."

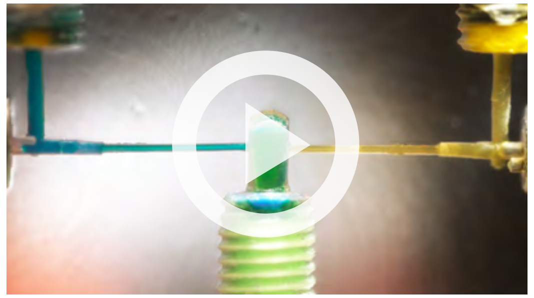
While many scientists and engineers around the world contributed, the basis of the technology originated with insights from Prud'homme's lab, Fox said. "He's the father of this idea."

Carsten Losch, chief executive of KNAUER Wissenschaftliche Geräte GmbH, the Berlin-based company that created the skids of high-tech mixers used for encapsulation of COVID mRNA vaccines, said his firm had invested a lot of effort perfecting the devices to meet the exacting specifications of the pharmaceutical industry.

"It would be fair enough to say the basic research of Professor Prud'homme resulted years later in a technology that manufacturers of lipid nanoparticles use in a similar way today," Losch said.

Prud'homme also cofounded a startup company called Optimeos, in 2016, with Shahram Hejazi, a lecturer at Princeton's Keller Center for Innovation in Engineering Education. Optimeos focuses on bringing next-generation RNA-based therapies to market to treat cancer, diabetes, and other diseases using the technology developed in Prud'homme's lab.

"It is incredibly rewarding to be a part of the path from fundamental academic research to major advances in public health," Prud'homme said. **E**



Watch Robert Prud'homme describe how mixing liquids in a precisely controlled way is yielding global health benefits. Video stills by Nick Donnoli/Orangebox Pictures

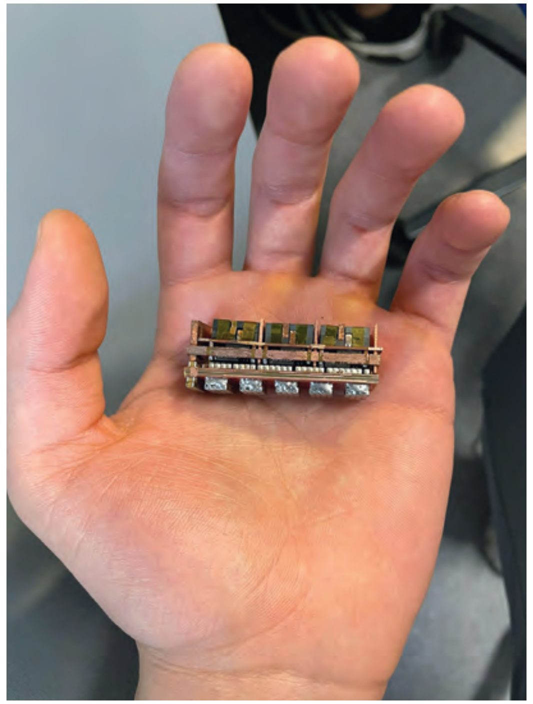
BREAKTHROUGH POWERS HIGH-PERFORMANCE COMPUTERS

by John Sullivan

Working with Intel, Google, and colleagues at Dartmouth College, Princeton researchers have completely redesigned the technology for powering high-performance computers, resulting in systems that increase power delivery 10 times beyond the current state of the art.

The demand for power ultimately comes from the demand for computing. With designers cramming more circuits into microscopic sections of microchips, the power delivered to tiny clusters of circuits is approaching levels equivalent to the interior of a nuclear reactor. Engineers call the amount of power delivered to an area power density. Supercomputers' power density is reaching nuclear levels not primarily because of the computing demands but because of the tiny spaces of computer chips.

This demand for highly controlled power has proven to be a limit to chip designers and a major challenge for power electronics engineers. Sending large amounts of power to tiny areas generates heat, which is not only inefficient, but can also be fatal to computer components.



Princeton researchers have discovered how to increase power delivery to high-speed computers with a compact, efficient device. Photo courtesy of the researchers

"It has to be clean power with very low noise, precisely controlled to a very tiny area," said Minjie Chen, assistant professor of electrical and computer engineering and the leader of the Princeton research team. "If the efficiency is not high enough, you will overheat. If the components overheat, you will not be able to deliver the power."

To meet the demands of new computer systems, the team had to overcome three challenges: Deliver power to smaller areas to allow microprocessors to sit ever-closer together; operate with high efficiency both to cut costs and to prevent overheating; and switch power among components with blinding speed to match the demands of microprocessors. "Google and Intel originally asked 'How do you deliver 10 times more power to a millimeter square of silicon without sacrificing speed or efficiency?'" Chen said.

The research team accomplished all three by rethinking everything from power delivery components to their architecture and control. They used capacitors instead of the traditional method of magnetics to process power, and they built the systems vertically instead of the traditional horizontal construction. Both features introduced significant design challenges, but once the researchers solved those, they were able to deliver a superior system.

"We have tested the efficiency up to full power, and we have tested the dynamics,"Chen said. "It is a fully functioning system 10 times smaller than the best off-the-shelf." **E**

TOOL HELPS CITIES DESIGN A NET-ZERO FUTURE

by Liz Fuller-Wright

To get to net-zero carbon dioxide emissions, what actions should cities prioritize?

A new tool for city planners helps them design a portfolio of actions that encompasses compact development, smart electric mobility, electric heating systems, mass timber construction, urban reforestation, and technologies that allow resources to circulate efficiently through food, waste, and energy sectors.

"In cities, environmental health and human well-being intersect," said Anu Ramaswami, leader of the development team and Princeton University's Sanjay Swani '87 Professor of India Studies and a professor in three other programs — the Department of Civil and Environmental Engineering, the Princeton Institute for International and Regional Studies, and the High Meadows Environmental Institute — as well as the director of the M. S. Chadha Center for Global India.

"About 55% of the world's population lives in cities, and more than 90% of the world's gross domestic product is generated in cities," said Ramaswami. "If you can figure out zero-carbon pathways at the city scale, for cities of different types across the globe, there's potential to solve global challenges with local benefits to health and social equity."

At a UN climate summit last fall, 1,049 cities with a collective 722 million occupants joined the "Cities Race to Zero" campaign, committing to halve emissions by 2030 and reach net-zero by 2050.

Ramaswami is working to help these cities reach carbon "net-zero," sometimes called "carbon neutrality," balancing the amount of carbon dioxide emitted with the amount absorbed from the atmosphere. Cities that emit no more greenhouse gases than are permanently removed are essential to avert the worst consequences of climate change, say experts.

To that end, Ramaswami and her team developed the Zero Emissions Calculator for Communities. They then took it a step further by partnering with Mauricio Leon, senior researcher at Minnesota's Twin Cities Metropolitan Council, incorporating high-resolution local data to create a "Greenhouse Gas Scenario Planning Tool" for every city, town, and rural community in the Minneapolis-St. Paul region — all 182 of them.

"The creation of the new Scenario Planning Tool could be really valuable for us. We're always trying — literally month to month — to figure out the best use of our time in reducing greenhouse gas emissions," said Russ Stark, the chief resiliency officer for the City of Saint Paul. "It can really help us decide which ones we need to do first, which actions can have the most impact, and how to stage those over time." **E**

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