PRINCETON
INNOVATION

Accelerating impact *through* innovation *and* entrepreneurship

2023

PRINCETON
UNIVERSITY

WELCOME TO PRINCETON INNOVATION

It is common to think of entrepreneurship and innovation as "extracurricular" to the mission of a research university. I argue otherwise. As researchers and scholars, we seek ways to spread knowledge beyond our campus, whether through books and academic publications, public talks, or by starting a company. It's not enough to make a discovery or new insight, we want to share it with the world.

Princeton Innovation aims to advance the transition of research into the broader world by connecting our researchers and scholars with the entrepreneurial community. This initiative builds on a long tradition of innovation. We're consistently ranked among top innovative universities based on the discoveries made here, the startups formed, and the number of founders among our alumni.

But these activities are only part of the picture. Innovation spans the disciplines at Princeton, not only in the sciences and engineering but in the creative spirit and scholarship of the social sciences and humanities.

Across these pages, you'll learn how Princeton's innovative activities are making an impact, how we are fostering an inclusive environment by building connections between Princeton and the wider community, and how innovation is integral to everything we do across our campus. You'll meet faculty members and students who are bringing new ideas to the world.

We invite you to join us.

Craig B. Arnold
Vice Dean for Innovation
Susan Dod Brown Professor of
Mechanical and Aerospace Engineering

Join us for Celebrate Princeton Innovation, our annual reception honoring faculty innovators

Thurs., Oct. 12, 5 p.m.

Frick Chemistry Atrium

On the Cover: From top, cube-shaped sensors track surface temperatures to provide energy savings for indoor heating and cooling (page 16); graduate students in the humanities explore entrepreneurship (page 9); and a new approach targets the debilitating disorder known as fibrosis (page 20).

> **Connections between world-class research and the innovation ecosystem are more important than ever.**
>
> **Christopher L. Eisgruber,**
> *Princeton University President*

> **What is exciting right now is the way that Princeton is bringing together rigor and relevance to tackle major societal challenges.**
>
> **Jennifer Rexford,**
> *Princeton University Provost*

> **Many of our faculty and student researchers are energized by innovation — they want to do things that have a direct impact on people.**
>
> **Peter Schiffer,**
> *Dean for Research*

SOCIAL SCIENCES ARTS ENGINEERING NATURAL SCIENCES HUMANITIES

In the Nation's Service and the Service of Humanity

HIGHLIGHTS

Princeton Innovation is a ***campus-wide initiative*** that aims to **benefit humanity** *through* **innovation** *and* **entrepreneurship**.

RESEARCH

$298M
in external funding for research from all sources

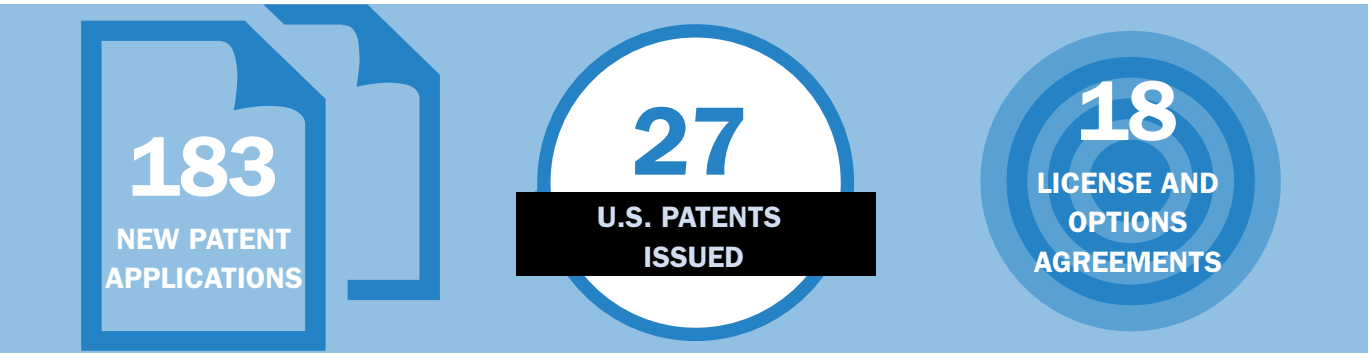
INNOVATION

113
NEW INVENTIONS DISCLOSED

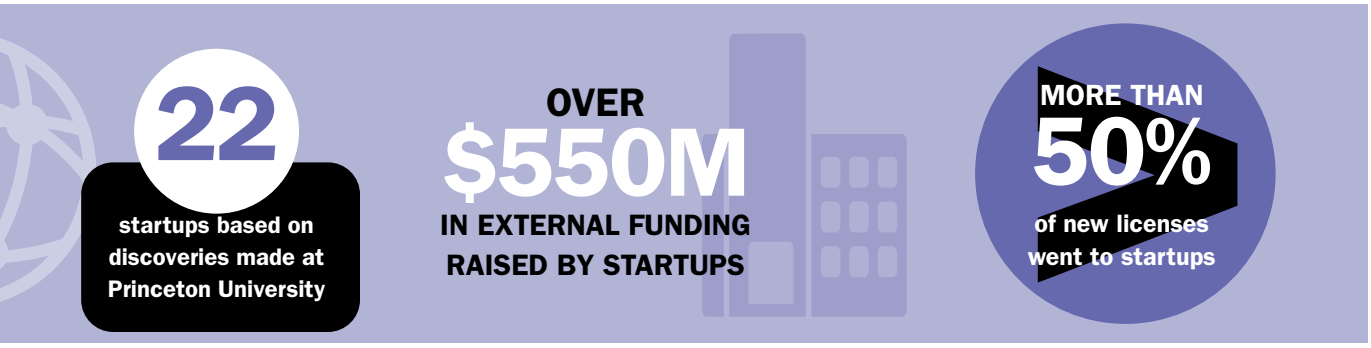
STARTUPS

ENTREPRENEURSHIP

Source: Office of Research and Project Administration, fiscal year 2023



Source: Office of Technology Licensing, fiscal year 2023



Source: Office of Technology Licensing, since founding of Princeton Innovation in 2020

Source: Northeast I-Corps Hub, since Hub formation in 2022; Princeton Entrepreneurship Council, fiscal year 2023

IMPACT

We *spark* **connections** and *grow* **opportunities** to *support the translation of discoveries* into **breakthrough products** and **services.**

Fostering breakthroughs: Office of Technology Licensing

Research and creativity are at the heart of what makes Princeton one of the world's leading universities. Countless technologies and everyday products trace their roots to University-led discoveries.

Princeton's **Office of Technology Licensing** connects innovative faculty-led discoveries with companies, investors and entrepreneurs who transform them into products and services, ensuring that Princeton research benefits the world.

Connect with us at:
patents.princeton.edu

> **Princeton's support for new technologies has a multiplier effect on the societal impact of University research.**
>
> **John Ritter,**
> *Executive Director, Office of Technology Licensing*

61
number of research projects funded by Princeton's IP Accelerator Fund in its first decade

The IP Accelerator Fund

Sometimes an extra bit of lab work or prototyping makes all the difference when demonstrating the value of a discovery for society. **Princeton's Intellectual Property Accelerator Fund,** now celebrating its 10th year, supports this research.

Among the projects funded in 2023:

Assessing microbiome-derived drug metabolism for drug development and personalized medicine.

Mohamed Abou Donia,
Associate Professor of Molecular Biology

Curing chronic hepatitis B virus infection with small molecule therapeutics.

Alexander Ploss,
Harry C. Wiess Professor of Life Sciences and Molecular Biology

Accelerating the sorting of viral and drug-delivery nanoparticles by DNA barcoding.

Haw Yang,
Professor of Chemistry

Charting the startup path:
I-Corps Northeast Hub

Led by Princeton, the National Science Foundation-sponsored I-Corps Northeast Hub helps researchers and community innovators across the region explore the value of their discovery or innovation by talking to potential customers.

With dedication to inclusive innovation and an emphasis on identifying how discoveries can benefit society, I-Corps stands apart from many entrepreneurial programs. All trainings are free and open to qualified applicants. Teams that complete the training are well-positioned to qualify for federal small-business seed grants and further investments.

Learn how you can get involved as a mentor or participant:
icorpsNE.org

27%

of instructors and mentors are from backgrounds underrepresented in entrepreneurship

> **Innovation thrives when we bridge the gap between knowledge and real-world impact.**
>
> **Christina Pellicane**,
> *Assistant Director, Princeton Innovation and Lead Instructor for the I-Corps Northeast Hub*

I-Corps snapshot: Sóliome

Sóliome, a startup founded by Princeton researchers, develops new sunscreens and UV-protective products that are safer for both humans and the environment. The company's sunscreen ingredients are photo-stable, biodegradable and resist absorption by the skin. The compounds are based on research conducted in the lab of Professor John T. Groves, Hugh Stott Taylor Chair of Chemistry at Princeton, where Sóliome co-founder and CEO Micah Nelp was a postdoctoral researcher. Produced at relatively low cost, Sóliome's compounds are attracting interest from the $13 billion sunscreen industry. **soliome.com**

Co-Founder Denise Koller, a doctoral student in art and archaeology at Princeton, represented Sóliome at the 2023 Empower pitch competition.

INCLUSIVE

Through our **leadership,** *we are building* a broad **community** across our **region** and the **world**.

Catalyzing collaborations:
Corporate Engagement and Foundation Relations

Collaborations with industry and foundations are often instrumental in identifying challenges facing society.

Princeton's **Corporate Engagement and Foundation Relations** office helps build research relationships between our faculty and external partners in industry, foundations, government and academia to advance research.

Find out how you can partner with Princeton at
partnerships.princeton.edu

> **We are driven to create enduring strategic research partnerships that foster a culture of innovation, leaving a transformative ripple effect on a global scale.**
>
> **Coleen Burrus**, *Executive Director, Corporate Engagement and Foundation Relations*

58%

increase in research funding from corporations (awards greater than $50,000) from fiscal year 2017 to 2021

Driving the regional innovation ecosystem

A Princeton-led collaboration to drive economic growth and technological advancements in photonics — the branch of science that includes lasers, optical fibers and cutting-edge light-based innovations — has received a prestigious development grant from the **National Science Foundation's Regional Innovation Engines** program.

With co-lead Rowan University, Princeton will work with partners throughout New Jersey, Delaware, Pennsylvania and New York at universities, community colleges, photonics companies, workforce development programs and technology incubators.
advancingphotonics.org

Building a broad community:

Princeton Entrepreneurship Council

The Princeton Entrepreneurship Council brings together entrepreneurs from throughout the campus and the alumni body to educate, engage and connect the entrepreneurial community through a variety of events and programs.

Our annual Empower conference attracts academic entrepreneurs and national thought-leaders, including those from historically underrepresented groups, to share knowledge, skills and tools.

55

active investors attended the 2023 Empower pitch competition

Join our community at:
entrepreneurs.princeton.edu

> **Our efforts focus on two global groups — Princeton-connected entrepreneurs and academic founders from underrepresented groups.**
>
> **Anne-Marie Maman**, *Executive Director, Princeton Entrepreneurship Council*

Empowering entrepreneurs: PolyGone Systems

PolyGone Systems is developing technologies for the removal of microplastics from aquatic environments. Founded by Yidian Liu and Nathaniel Banks, who earned their master's degrees in architecture at Princeton, the company was recently selected to be part of a $1.9M grant from the National Oceanic and Atmospheric Administration in collaboration with New York Sea Grant. The woman-co-led company is headquartered at **Princeton Innovation Center BioLabs**, which provides space for startups throughout the region.
polygonesystems.com

Left: Vice Dean for Innovation Craig Arnold presents winning check to Yidian Liu, co-founder of PolyGone, at the 2023 Empower pitch competition.

INTEGRAL TO EVERYTHING WE DO

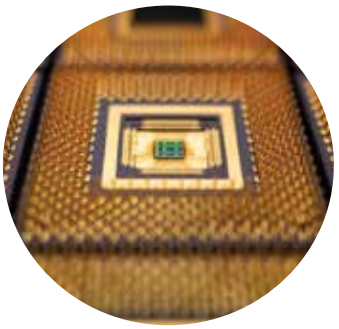
We *unite* **the campus** *across* the **sciences** and **engineering** as well as the **humanities**, **arts** and **social sciences.**

Creating social impact:

Keller Center

Serving undergraduates, graduate students and faculty across the campus, the Keller Center creates societal impact through educational opportunities that bridge engineering and the liberal arts at the intersection of technology and society. Many Keller events are open to the greater entrepreneurial public, including the Innovation Forum, a competition and networking event showcasing Princeton projects in technology and the humanities.

kellercenter.princeton.edu



Encharge AI, a startup based on research led by Naveen Verma, Director of the Keller Center and Professor of Electrical and Computer Engineering, is rethinking computer-chip design to boost performance and meet the needs of artificial intelligence. **enchargeai.com**

> **We serve students and faculty from across campus who spread their wings and embark on their innovation journeys.**
>
> **Cornelia Huellstrunk**,
> *Executive Director, Keller Center*

Preparing a new generation

Omenn-Darling Bioengineering Institute

Announced in July 2023, this institute will promote new directions in research, education and innovation at the intersection of engineering and the life sciences. A newly created doctoral program in bioengineering will include a component focused on innovation, organization and entrepreneurship to give students a behind-the-scenes look at how discoveries move from labs to wider societal use, including via startup ventures. The institute is supported through a gift from alumni Gilbert Omenn, Class of 1961, and Martha Darling, Masters of Public Affairs, 1970.

bioengineering.princeton.edu

To combat the growth of antibiotic resistance, researchers in the lab of Mark Brynildsen, Professor of Chemical and Biological Engineering, are searching for treatments that weaken bacterial defenses against the body's immune system.

GradFUTURES

At **GradFUTURES**, graduate students explore their futures through broad offerings in training, mentorship, experiential opportunities and interdisciplinary learning. One of the newest programs, the Humanities Expedition & Lab, is co-organized by the Princeton Entrepreneurship Council and exposes students to the many ways that a graduate degree in the humanities and social sciences can have an impact on the broader world.

gradfutures.princeton.edu

Sugarman Practitioners

Like an “artist-in-residence” program, the **Sugarman Practioner in Residence** program supports individuals pursuing breakthrough solutions to society-relevant problems by addressing aspects of human behavior. Established through a gift by Jay S. Sugarman, Class of 1984, and housed in Princeton’s Kahneman-Treisman Center for Behavioral Science and Public Policy, the program offers support and mentorship to early-career entrepreneurs and leaders.

behavioralpolicy.princeton.edu

Center for Digital Humanities

Drawing on a rich humanities tradition at Princeton, the **Center for Digital Humanities** brings together faculty, staff and students working at the intersection of humanities and technology. One new offering is the Humanities + Data Science Institute, supported by a Magic Grant for Innovation from the Princeton Humanities Council. The institute empowers scholars from the humanities to engage with the conceptual, practical and ethical aspects of data science.

cdh.princeton.edu

STARTUP SPOTLIGHT

Liminal Insights envisions the future of lithium-ion batteries

The technology behind startup company Liminal Insights was inspired by an internet video that bounces batteries against a surface to tell if they are charged.

Liminal Insights, a startup company founded on discoveries made at Princeton, uses ultrasound to evaluate the reliability of battery cells, helping to contain costs and meet production goals faster.

Today, the company applies similar principles to improve the quality of lithium-ion and other batteries at the heart of the shift toward greener transportation. Their patented technology, known as EchoStat, uses ultrasound to check the fitness and reliability of battery cells, helping to contain costs and meet production goals faster.

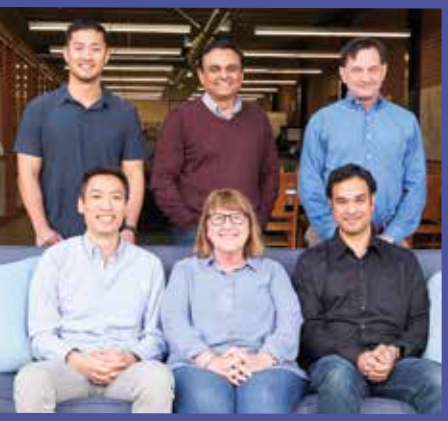
Andrew Hsieh, Liminal's CEO and co-founder, said the expected surge in demand for electric vehicles will require the expansion of battery production by 10- to 20-fold over the next decade.

"We're helping electric-vehicle manufacturers buy and make batteries that are safer, more reliable, and lower cost, so that people everywhere can afford an electric vehicle," Hsieh said.

EchoStat pulses sound waves through the battery, while a machine-learning-based algorithm evaluates how the waves travel to diagnose defective units. Prior to EchoStat, the industry lacked a non-destructive method to detect whether a battery's electrolyte — the chemical inside the cell — was performing, Hsieh said. Liminal's technology predicts cell performance in seconds, in a non-invasive and non-destructive manner, enabling manufacturers to identify and correct defects.

Hsieh, who earned his Ph.D. at Princeton in 2014, led the development of the ultrasonic battery diagnostics technology while a postdoctoral research associate at Princeton, working with Daniel Steingart, then an assistant professor of mechanical and aerospace engineering.

Steingart, who is a Liminal co-founder, wondered if the height of a battery's bounce — which increases as the battery is used — could suggest a more systematic way to test a battery's charge level. Bouncing a battery against a surface induces vibrations to travel through the battery in a manner similar to how sound travels through an object. The team decided to try pushing high-frequency sound waves through batteries, and discovered that charged batteries have a distinctive ultrasonic signature compared to depleted batteries.



From left, top row:
Darren Lim, Director of Strategy and Operations; **Vivek Bhagat,** Vice President of Product Engineering; **James Carrington,** Vice President of Business Development.

Bottom row:
Andrew Hsieh, CEO and Co-Founder; **Laurie Terzolo,** Director of People and Culture; **Shaurjo Biswas,** CTO and Co-Founder.

"It's almost mind-boggling to think that an internet video was the genesis for what we're doing now," Hsieh said. "It turns out that there was this huge, unsolved need that existed that could be solved with this kind of wild idea." To explore how this idea could benefit society through better batteries, Hsieh, Steingart and Princeton postdoctoral researchers Shaurjo Biswas and Barry Van Tassell founded the startup firm Feasible, which later became Liminal Insights.

Expansion phase

The team received early funding from Princeton's Intellectual Property Accelerator Fund, which supports prototyping and other research to demonstrate the technology's capabilities. After receiving seed capital from Princeton's Alumni Entrepreneurs Fund, the fledgling company got a major boost when it won a prestigious spot in a California-based clean-energy technology accelerator funded in part by the U.S. Department of Energy.

The company began to attract federal small-business and investment funding, including from ARPA-E and the National Science Foundation. Since its founding, the company has also received support from Chrysalix Ventures, ArcTern Ventures, Good Growth Capital, UTEC Ecosystem Integrity Fund, Incite Labs, Elemental Excelerator, and battery manufacturer Northvolt.

Last year, the team deployed the first system into a customer's factory. They will deploy a semi-automated system in 2023, and are working towards a fully-automated, fully-integrated solution in 2024. The company, now located in Emeryville, California, employs 50 people. Hsieh hopes to expand the company's offerings beyond electric-vehicle lithium-ion batteries to all types of battery cells, including newer lithium-based formulations and sodium-based batteries.

In addition to the research led by Steinhart, the company's technology also includes discoveries led by engineering professor Craig Arnold, Princeton's Vice Dean for Innovation and the Susan Dod Brown Professor of Mechanical and Aerospace Engineering. "The path of this company is a great example of how researchers can take a laboratory finding and transition it into an actual product," said Arnold. "The role of university-based startup companies cannot be overstated — this is one of the great ways that Princeton research has the potential to benefit humanity."

CELEBRATE PRINCETON INNOVATION

Meet the faculty members and researchers featured at our annual reception, Celebrate Princeton Innovation.

A planet-friendly way to make pure oxygen from water

Emily Carter,
Senior Strategic Advisor and Associate Lab Director for Applied Materials and Sustainability Sciences at the Princeton Plasma Physics Laboratory; Gerhard R. Andlinger Professor in Energy and the Environment and Professor of Mechanical and Aerospace Engineering, the Andlinger Center for Energy and the Environment, and Applied and Computational Mathematics at Princeton University

A new approach to making pure oxygen by splitting water molecules could provide inexpensive and planet-friendly supplies of the gas for medical and industry uses.

Research engineers from Princeton and the Indian Institute of Science have developed a protocol for obtaining high yields of oxygen by splitting water into its core ingredients, hydrogen and oxygen. Unlike today's method of generating oxygen, this new industrial technology employs inexpensive iron and nickel catalysts combined with renewable electricity from solar, wind or other sources to break the bonds between hydrogen and oxygen atoms, and then join two oxygen atoms to produce oxygen gas.

The chemical reaction produces pure oxygen gas as well as pure hydrogen gas, which is valuable as a fuel. Most industrial hydrogen is obtained from steam methane reforming, which results in a significant amount of carbon dioxide. When applied to hydrogen production, the new method would reduce the release of carbon dioxide into the atmosphere.

To develop their protocol, the researchers created theoretical models that evaluate how various factors improved the amount of oxygen produced during water electrolysis. The team determined the ideal amounts of input electricity, pH, temperature and pressure to produce the greatest amounts of pure oxygen. The model also allows the team to minimize the amount of alkali needed, improving the environmental impact of the process.

> "Our research on fundamental energy science has the potential for significant impact on how we think about future energy usage globally."
>
> —John Mark P. Martirez

John Mark P. Martirez, *Staff Research Scientist and Deputy Advisor for Sustainability Science, Princeton Plasma Physics Laboratory*

Ananth Govind Rajan, *Assistant Professor of Chemical Engineering, Indian Institute of Science*

Development status:
Patent issued in India and pending in United States. Princeton is seeking outside interest in developing this technology.

Funding:
Air Force Office of Scientific Research

Learn more:
martirez@pppl.gov

Licensing contact:
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A behavior-centered architectural reinvention of public toilets

Chukwuemeka V. Chukwuemeka,
Sugarman Practitioner in Residence, Kahneman-Treisman Center for Behavioral Science and Public Policy

A reinvented public toilet would enhance access to safe, clean and sustainable sanitation facilities worldwide while minimizing the risk of spreading infection.

Almost 2.3 billion people do not have toilets, and about 4 billion people still lack access to safely managed sanitation. Public toilets are critical in the fight against the spread of diseases, and yet public toilet design has not changed in the last 200 years. Today's public toilets can be claustrophobic and inaccessible, are difficult to clean and maintain, feel unsafe, and are not user friendly, especially for women, children, the disabled and senior citizens.

An improved redesign and reconfiguration would address the problems associated with maintaining public toilets and also mitigate the prevalence of over 50 different infectious diseases, while reducing the risk of epidemics. Drawing on his background as an architect and designer, Chukwuemeka V. Chukwuemeka is reimagining the spatial configuration of public toilets to include ventilation systems, bio-aerosols elimination, sterilization of microbial activity on surfaces, and motion sensing to detect body activity patterns.

Chukwuemeka is creating a behavior-centered redesign through the exploration of human motivation, judgement, decision-making and perceptions at the individual and collective level. By combining observations of human behavior with sanitation and maintenance requirements, Chukwuemeka is pioneering a new public toilet design that is easy to clean and maintain while enhancing user comfort, safety and health.

Collaborator:
Eldar Shafir, *Class of 1987 Professor in Behavioral Science and Public Policy. Professor of Psychology and Public Affairs*

> "Sanitation is a primary element of our humanity. By creating a design that factors in human behavior, we can improve the human experience and reduce the transmission of disease."
>
> **—Chukwuemeka V. Chukwuemeka**

Development status:
This idea is in the prototyping stage. Princeton welcomes outside interest in developing this technology.

Funding:
Kahneman-Treisman Center for Behavioral Science and Public Policy

Learn more:
chukwuemeka@princeton.edu

Licensing contact:
Anthony Williams
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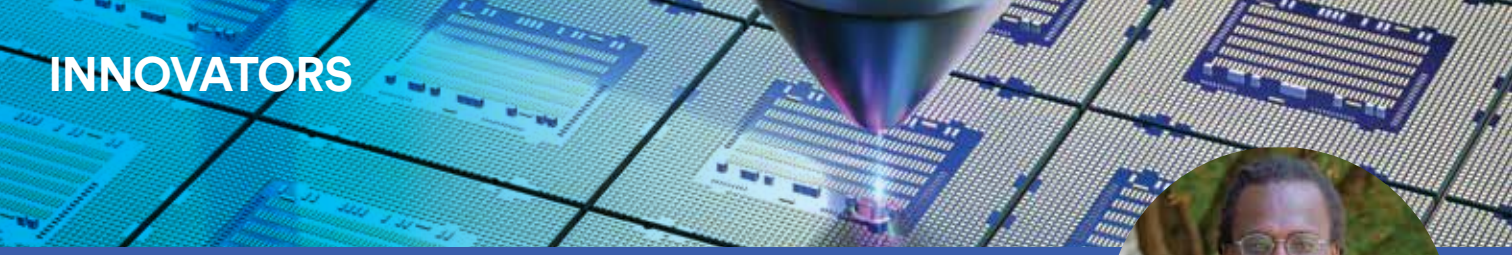
anthonyw@princeton.edu



Vanishing magnetic fields improve chip manufacturing

Ahmed Diallo,
Principal Research Physicist, Princeton Plasma Physics Laboratory; Program Director, Advanced Research Projects Agency-Energy (ARPA-E)

A new method that prevents damage to the highly sensitive mirrors used in semiconductor chip manufacturing could lead to cheaper and more reliable technologies.

The team's solution involves creating a magnetic-free zone — an area where all magnetic fields cancel each other out — in front of the mirrors to guide particles away from the reflective surfaces and into a collection area. The solution, created by Princeton Plasma Physics Laboratory scientists, is highly cost-effective, simple, and could increase efficiency by reducing the need to clean and replace dirty or blistered mirrors.

Today's chips contain features that are so tightly packed together that there are only a few nanometers between each object. Manufacturers etch fine-resolution structures onto chips by shrinking the wavelength of light into the extreme-ultraviolet (EUV) range in a process that involves shooting lasers at microscopic droplets of tin. However, the exploding tin droplets send charged particles flying in all directions, including toward the mirrors.

Current preventions, such as placing a protective gas in front of the mirror to slow the particles, are expensive and can block light from reaching the mirror. The new strategy involves creating a region in front of the mirror where magnetic fields cancel each other out. This "magnetic null" sends particles in random directions, including toward traps on the side or bottom of the chamber where they can be removed.

> **"Our solution has the potential to reduce downtime and effectively increase overall efficiency for chip manufacturing."**
> **—Ahmed Diallo**

Marien Simeni Simeni, *Assistant Professor of Mechanical Engineering, University of Minnesota*

Christopher Smiet, *Postdoctoral Scholar, École Polytechnique Fédérale de Lausanne*

Ben Israeli, *Graduate Student in Astrophysical Sciences, Princeton Plasma Physics Laboratory*

Development status:
Patent pending. Princeton is seeking outside interest in developing this technology.

Funding:
U.S. Department of Energy Laboratory-Directed Research and Development grant

Learn more:
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Package delivery robot for the ‘last 50 feet’

Jaime Fernández Fisac,
Assistant Professor of Electrical and Computer Engineering

A new robotic system that carries packages from delivery vehicles to customers’ doorsteps could double the efficiency of human drivers by 2030.

The design fluidly combines two common modes of robot mobility: legs and wheels. The robots’ unique configuration allows them to strategically navigate curbs, stairs and irregular terrain.

Numerous organizations are working to address the “last-mile delivery problem,” the expensive and time-consuming transportation of goods from a distribution hub to their final destinations. The new design specifically tackles the final 50 feet of the last-mile problem through a squad of modular robots that ferry items from the delivery van to the customer’s doorstep.

Under this approach, vans will transport, dispatch and retrieve delivery robots along a route. Using a combination of wheels and legs, each robot can swiftly roll up over curbs, veer around obstacles and climb stairs under a range of environmental conditions. Incorporating technologies developed in Princeton’s Safe Robotics Laboratory, each robot plans and executes highly dynamic trajectories with clear-cut safety guarantees.

Unlike other approaches such as drones or curbside “lockers on wheels,” the team’s van-to-door robot fleet combines multiple robot units to provide the flexibility to carry heavy, large or irregularly shaped items including meals, groceries and parcels. The goal is to streamline the package delivery pipeline with a tailored, safety-focused robot solution.

Robert Shi, *Princeton Class of 2021 and Master of Engineering 2022*

> “Our solution boosts agility while reducing the resources needed for package delivery, providing benefits for the consumer, companies and the environment.”
>
> **—Jaime Fernández Fisac**

Development status:
Patent pending. A startup company, Vault Robotics, Inc., is developing this technology.

Funding:
Princeton Intellectual Property Accelerator Award;
Faculty New Ventures Fund;
NSF I-Corps Northeast Hub

Learn more:
contact@vaultrobotics.ai
www.vaultrobotics.ai

Licensing contact:
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Technology Licensing Associate
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Cube-shaped sensor boosts energy-efficient heating and cooling

Forrest Meggers,
Associate Professor of Architecture and the Andlinger Center for Energy and the Environment; Co-Director of the Program in Architecture and Engineering

A simple cube-shaped sensor could reduce the energy required to heat and cool indoor spaces while prioritizing the comfort of its occupants.

Most heating and cooling systems adjust the temperature of a room's air, but with recent technological advances, comfort can be achieved more efficiently by responding to additional factors such as humidity, air speed, clothing, metabolic rate and radiant temperature. This last factor, radiant temperature, describes the warmth or coolness of surfaces such as windows, floors, desks and chairs.

About half of the body's thermal sensation is due to the transfer of heat between the body and nearby surfaces. Heating and cooling systems typically work by adjusting a room's air to a specific temperature set at a thermostat. However, new systems that make people comfortable, rather than reaching a preset air temperature, could produce dramatic energy savings while improving satisfaction.

The new cube sensors enable researchers to measure surface temperatures throughout a room. Each face of the cube contains a point detector that can "see" the temperature across a 90-degree field of view, without requiring contact with the surfaces. Algorithms then integrate the information to produce a three-dimensional picture of the room's surface temperatures.

The new cube sensors demonstrated substantial gains in resolving the thermal variations caused by surfaces radiating at different temperatures, opening possibilities for responsive energy-efficient thermostats that improve human comfort.

> "Our focus is on making people — not rooms — more comfortable in ways that conserve energy and are good for the planet."
>
> —Forrest Meggers

Alexander Kim, *Class of 2024*

Coleman Merchant, *Class of 2019*

Eric Teitelbaum, *Princeton Ph.D. 2020*

Collaborators:
Sean Rucewicz, Master of Architecture 2019; **Kianwee Chen**, former Visiting Research Scholar, Andlinger Center for Energy and the Environment

Development status:
Patent pending. Princeton is seeking outside interest in developing this technology.

Funding:
Princeton Intellectual Property Accelerator Fund

Learn more:
fmeggers@princeton.edu
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chaosense.com

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Neural networks that are faster, more energy-efficient

Karthik Narasimhan,
Assistant Professor of Computer Science

A new technology makes it possible to run a deep neural network — the software at the heart of today's artificial intelligence (AI) — at least 10 times more efficiently while sacrificing only 2% accuracy.

The approach, called DataMUX, could reduce energy consumption and make powerful computing more widely available.

Large AI systems consume a great deal of energy and computing power. A state-of-the-art natural language model can produce around 14,000 pounds of greenhouse gas in just three months.

The team realized that when creating a deep neural network, the size of the network required for training the model does not always translate to the size required to accomplish a task. Once a large network is trained for any specific task — such as sentiment analysis, question-answering or image classification — the computations don't actually require such a large model.

Current solutions to making large networks more efficient after training focus on creating sparser or smaller neural networks. The DataMUX technique takes the opposite approach. It allows neural networks to process multiple text and image inputs simultaneously, making them denser. This allows the model to perform complex tasks with less computing power.

The model can be used with any type of data — including images, text, video, speech and genes — and in a variety of AI applications.

> "Our goal is to make AI cheaper, more energy-efficient, and to democratize it, giving more people access to the best models."
>
> —Karthik Narasimhan

Vishvak Murahari, *Graduate Student*

Carlos Jimenez, *Graduate Student*

Runzhe Yang, *Graduate Student*

Collaborators:
Ameet Deshpande, *Graduate Student;*
Yushan Su, *Princeton Ph.D. 2023;*
Kai Li, *Paul M. Wythes '55 P86 and Marcia R. Wythes P86 Professor in Computer Science*

Development status:
Patent pending. Princeton is seeking outside interest in developing this technology.

Funding:
Samsung Global Research Outreach; 2022 Bell Labs Prize

Learn more:
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Lithium extraction from high-salt water using solar power

Z. Jason Ren,
Professor of Civil and Environmental Engineering and the Andlinger Center for Energy and the Environment

Sunxiang (Sean) Zheng, *Professional Specialist, Andlinger Center for Energy and the Environment*

Xi Chen, *Former Associate Research Scholar in Civil and Environmental Engineering*

A technology that uses solar power to extract lithium from salty water could help advance the nation's goal of net zero emissions by 2050.

Renewable electricity is on track to replace fossil fuels to decarbonize many industries, but the supply of lithium for batteries and electric vehicles falls short of meeting its rapidly increasing demand.

The new technology, which is powered by energy from the sun, has demonstrated an improvement of more than 10 times the standard rate of lithium extraction from bodies of water with high salt concentration, known as brine.

The approach involves cellulose fiber crystallizers that take advantage of the high solubility and mobility of lithium salts in water. The crystallizer's unique structure provides optimal characteristics for selective extraction and spatial separation of lithium from other ions. The team has shown that their crystallizer can accelerate the evaporation speed by more than 20 times compared to evaporation ponds.

The approach is particularly advantageous for use in the U.S., which currently mines and processes less than 1% of the global lithium supply, yet is one of the largest consumers of the mineral. Because of this disparity, securing domestic sources of lithium has become a priority for national security.

The team is launching a startup and is working with a leading lithium producer on prototype testing.

> "Our process is fairly unique. We take advantage of nature by using sunlight to concentrate and separate lithium out of brine water."
>
> —Z. Jason Ren

Collaborators:
Meiqi Yang, *Graduate Student;* **Fernando Temprano-Coleto**, *Distinguished Postdoctoral Fellow in the Andlinger Center for Energy and the Environment;* **Howard Stone**, *Donald R. Dixon '69 and Elizabeth W. Dixon Professor of Mechanical and Aerospace Engineering;* **Nan Yao**, *Senior Research Scholar at the Princeton Materials Institute and Director of the Imaging and Analysis Center;* **Liangbing Hu**, *University of Maryland*

Development status:
Patent pending. A startup company, PureLi, has been formed to develop this technology.

Funding:
Princeton Intellectual Property Accelerator Fund; START Fellowship; Princeton Catalysis Initiative; NSF I-Corps Northeast Hub; National Science Foundation

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Superconducting ink provides greater flexibility in electronics

Leslie Schoop,
Associate Professor of Chemistry

A simple method for producing electricity-conducting ink could enable the printing of circuits for wearable electronics and quantum computers.

Superconducting ink — a single-molecule-thin substance that conducts electricity without resistance — has a wide range of potential applications, from a thin bandage that measures heart rate to a phone made from a thin piece of film worn around the wrist. However, previous methods for creating this material have not lived up to expectations.

A new approach created by Princeton scientists produces stable superconducting ink using a process called chemical exfoliation, in which researchers dip a chemical compound into a corrosive acid to separate it into layers. Chemical exfoliation has been used to create these inks in the past, but the product was unstable and highly sensitive to air, and the process was not replicable at large scale.

The new variation of this method produces a product that remains stable in ambient conditions for at least 30 days without any protective agents. The scalable method produces a stable superconducting ink made of a chemical compound called tungsten disulfide.

The ink is metallic at room temperature and superconducting at seven degrees above absolute zero, a notable development compared to the temperature requirements for other known superconducting materials. This proof-of-concept development for the first time opens the door for large-scale development of nanosheet electronics.

> “It’s a bit like printer ink, except you’re not printing a picture, you’re printing electronics.”
>
> —Leslie Schoop

Xiaoyu Song, *Princeton Ph.D. 2022*

Collaborators:
Brianna L. Hoff and **Joseph W. Stiles**, *Graduate Students;* **Yao-Wen Yeh**, *Princeton Ph.D. 2017 and former Senior Research Specialist;* **Guangming Cheng**, *Associate Research Scholar;* **Jason F. Khoury**, *Postdoctoral Research Fellow;* **Ratnadwip Singha**, *Postdoctoral Research Associate;* **Nan Yao**, *Senior Research Scholar at the Princeton Materials Institute and Director of the Imaging and Analysis Center;* **Philip E. Batson**, *Rutgers University;* **Franziska Kamm** and **Florian Pielnhofer**, *University of Regensburg.*

Development status:
Patent pending. Princeton is seeking outside interest in developing this technology.

Funding:
U.S. Department of Defense; National Science Foundation; Gordon and Betty Moore Foundation

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Strategy for slowing fibrosis

Jean Schwarzbauer,
Eugene Higgins Professor of Molecular Biology

A strategy for targeting a protein that drives rapid cell growth could prevent or slow fibrosis, the disordered growth of connective tissue that harms major organs, including the lungs and kidneys, and causes blindness in diabetes patients.

The protein, called fibronectin, is part of a large network of proteins and other molecules that make up the extracellular matrix, which supports and gives structure to the organs and tissues in the body.

Many injuries and illnesses promote the growth of extracellular matrix as part of the body's efforts to repair wounds or control disease. But when growth is irregular and faster than normal, proteins in the matrix can accumulate in a disorganized fashion, resulting in fibrosis. Fibrosis can cause blindness when it happens in the retina of the eye, a common concern for diabetes patients.

Schwarzbauer is developing strategies that can prevent or slow down fibrosis in its beginning stages. The team is developing a compound to inhibit fibronectin matrix production with the goal of preventing or slowing down fibrosis as soon as the extracellular matrix begins to form irregularly.

The researchers will test the ability of the molecules they've developed to inhibit matrix development in a model cell system that mimics an early fibrotic lesion. The application of strategies that target fibronectin could lead to effective therapies to treat fibrosis.

Henry A. Resnikoff,
Graduate Student

Collaborator:
Charles G. Miller, *Princeton Ph.D. 2014, Rutgers M.D. 2016*

> "We know about the interactions that happen between proteins that are essential for the matrix to form. So why not try to inhibit these interactions as a way to slow down fibrosis?"
>
> **—Jean Schwarzbauer**

Development status:
Patent pending.

Funding:
Foundation for Health Advancement Innovation

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