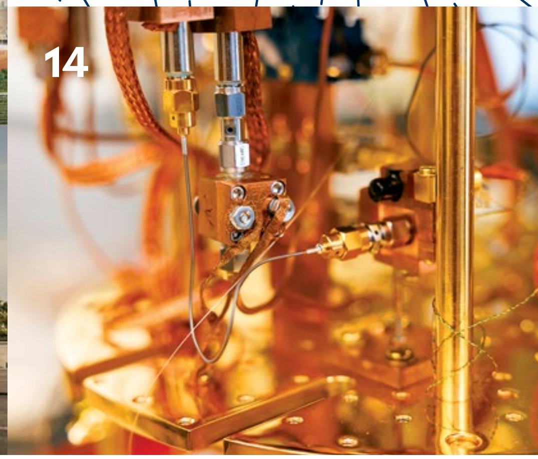
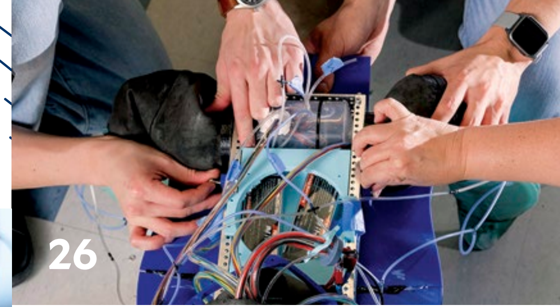
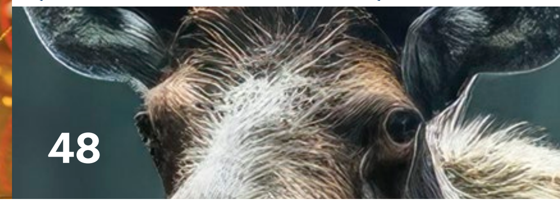
Y/ Yale Engineering

Robotics for humanity







In this issue

Yale Engineering 2024

Front cover: *Yale Engineering researchers are developing robots to assist in every-day settings and collaborate with humans, enhancing the integration of robotics into daily life for a better future.*
Photo by: *Tanner Pendleton*

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What's Next

Jeffrey F. Brock
Dean / School of Engineering & Applied Science
Zhao and Ji Professor of Mathematics

/ The transformation of Yale Engineering has begun, and in this issue, we show you what that looks like, with renderings of proposed new spaces — and some much-needed upgrades to familiar ones — providing a glimpse of what's next.

In the realm of quantum science, we highlight Katerina Sotiraki, whose work in lattice cryptography aims to develop new cryptographic protocols before the advent of quantum computing makes them an urgent necessity. We profile Hong Tang, whose lab developed the first chip-scale titanium-doped sapphire laser, and Shruti Puri's tailored error-correcting codes that protect fragile quantum states.

We profile the innovators — both Yale alums — behind Czinger Vehicles and Divergent 3D. From the gear box to the automotive assembly line, the Czingers have a way of evaluating existing systems with an eye to complete reinvention. The results are nothing short of dazzling.

On the AI front, we highlight Yale Engineering's Ruzica Piskac and Yale Law School's Scott Shapiro, whose "lawbots" help ordinary people navigate the legal system, answering plain-English questions about zoning codes, contracts, and more.

We profile Smita Krishnaswamy's MoirAI, which identifies "druggable" molecules in pursuit of new treatments for Alzheimer's, triple-negative breast cancer, and more. We speak with Arman Cohan and Sophie Chheang about CRAIG (Computed Radiology Reporting with AI-Assisted Generation), an imaging application with potential to reduce radiologist's workloads.

We look at what's next in robotics, under the rubric of Robotics for Humanity, where Ian Abraham's lab is developing robots that can learn independently, and thus can be reliably deployed in extreme environments where human supervision is impossible.

We consider the classic problem that, while complex manipulations of an object by human hands appear deceptively simple, replicating this ease with a robot hand is notoriously difficult, which inspired Aaron Dollar's work on next generation of dexterous robots, with applications for prosthetics, manufacturing, and more.

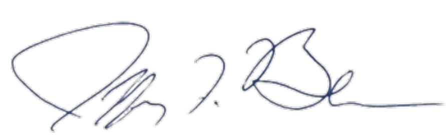
We consider Tesca Fitzgerald's work helping robots to adapt to human unpredictability in mixed human/robot settings; Rebecca Kramer-Bottiglio's morphing, adaptable robots, including "robotic skins;" Brian Scassellati's embodied computational models of human social behavior that train robots to engage with humans in comfortable, natural ways; and Marynel Vázquez's work to refine the ways that robots interpret their surroundings.

We take an in-depth look at Mark Saltzman's work with nanoparticles and targeted chemotherapy drug delivery, which has the potential to revolutionize cancer treatment, reducing side effects and improving efficacy of some of the strongest and most toxic therapeutic drugs.

We dive into Fameed Hyder's 3-dimensional brain energy atlas, a next-generation reference tool for biomedical research, diagnosis, and treatment for neurogenerative disorders created in collaboration with researchers at Fudan University in China, using positron emission tomography (PET) to map glucose use in active "resting" brains.

On the ecology front, we consider Aaron Dollar and Oswald Schmidt's Fluxbot, an open-source robot that monitors carbon soil flux rates in remote areas; Lea Winter's work developing electron-driven processes that can replace fossil-fuels in the manufacture of fertilizer, fuels, and other useful materials; and Menachem Elimelech's work to reclaim valuable minerals from wastewater, potentially reducing our dependence on mining while mitigating its high environmental and socioeconomic costs.

As we embark on a new era at Yale Engineering, these are just a few of the promising avenues of research ongoing here. We hope you'll find them as inspiring as we do.



Insights & impacts

IBM, Meta, Yale forge AI alliance

/ Yale Engineering joined the AI Alliance, an international coalition launched by IBM and Meta, dedicated to advancing open and responsible AI that positively impacts society.

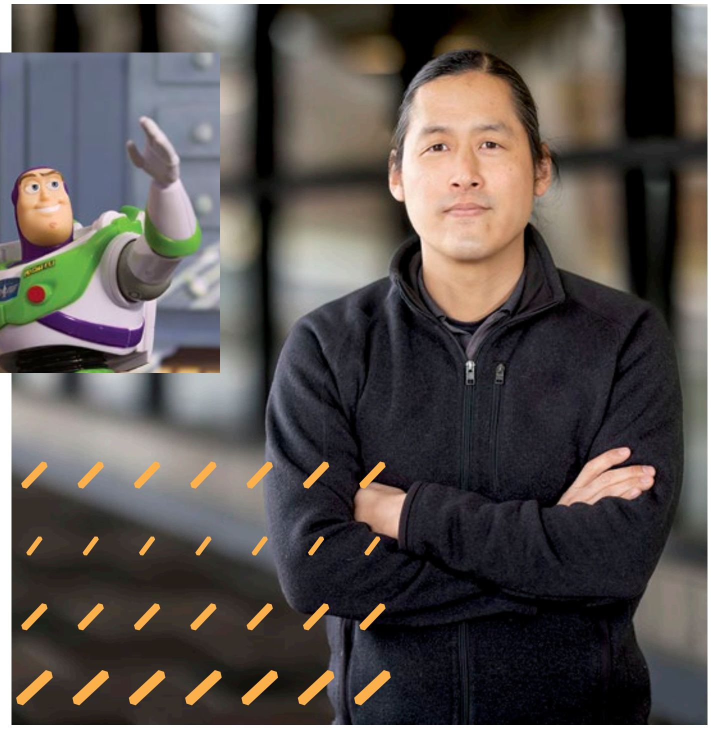
As a founding member, Yale collaborates with global leaders in technology, academia, and industry, focusing on collaborative research, policy formulation, and setting standards for safe, transparent, and trustworthy AI.

By bringing together leading developers, scientists, academic institutions, companies, and other innovators, the AI Alliance will pool resources and knowledge to address safety concerns while providing a platform for sharing and developing solutions that fit the needs of researchers, developers, and adopters around the world.

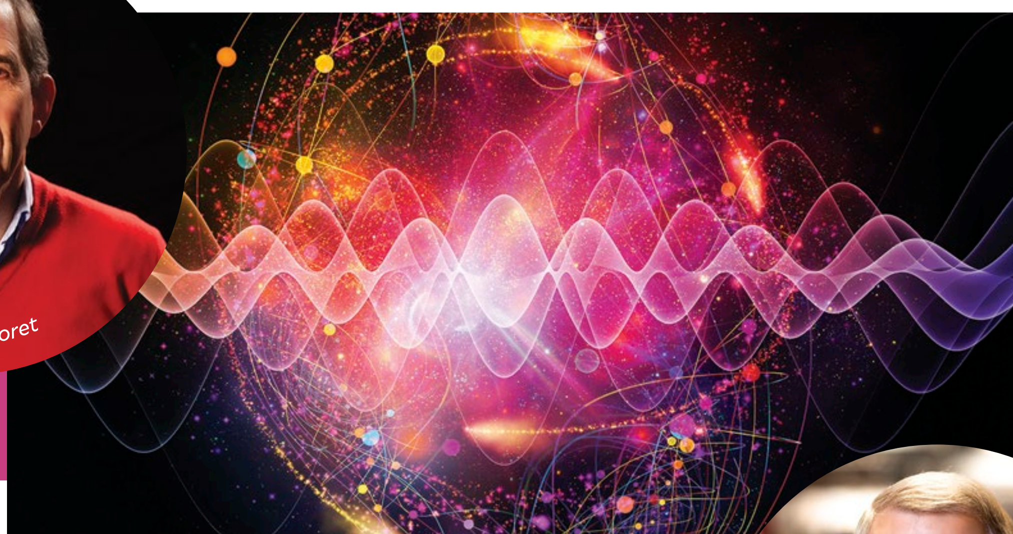
Sounding the alarm on oil sands emissions

/ Through aircraft-based measurements and laboratory experiments, researchers led by chemical & environmental faculty member Drew Gentner found that many air pollutants related to Canadian oil sands greatly exceed what had been previously reported. Teaming up with the Canadian government, Gentner used comprehensive data from aircraft measurements to capture the full range of organic pollutants generated by oil sands facilities, which produce about 3 million barrels of crude oil daily. Observed emissions were from 20 to over 64 times higher than previously known. Overall, the researchers said, that's equal to the emissions from all other human-related sources in Canada.

Kim wins second Academy Award



/ Theodore Kim, associate professor of computer science, received a Technical Achievement Award from the Academy of Motion Picture Arts and Sciences. The honor — Kim's second Academy Award — is for Fizt2, a program he co-developed. He describes the technology as "a simulator for all things soft and squishy" that makes things look natural when animators depict muscle, flesh, and cloth. Previous methods for animating soft materials were much more arduous. Before coming to Yale in 2019, Kim was a senior research scientist at Pixar. His work has been featured in *Harry Potter and the Sorcerer's Stone, Toy Story 4,* and many other films.



Devoret and Schoelkopf win Comstock Prize

/ The National Academy of Sciences awarded the prestigious Comstock Prize in Physics to applied physics faculty members Michel Devoret and Robert Schoelkopf for their groundbreaking work in quantum information processing and related fields. The $100,000 prize is awarded once every five years to one or more North American physicists whose recent work includes an innovative discovery or investigation in electricity, magnetism, or radiant energy. Many previous recipients have gone on to become Nobel laureates. The Academy cited the researchers for their development of technology that has paved the way for a growing number of applications in quantum computing and sensing.

Transforming Yale Engineering

At the heart of campus, a historic investment will propel innovation and collaboration

/ Over the next 10 to 15 years, Yale Engineering will oversee a $1 billion-plus transformation of its campus. With a series of major construction projects in the lower Hillhouse Avenue area, work on the new Engineering campus — one of the biggest investments in Yale history — will advance the university's strategy for hastening engineering, science, and technology breakthroughs.

Serving as a link between Yale's central campus and Science Hill, the combination of new and renovated spaces will reinforce the School's culture of innovation and collaboration. Here, researchers will have the resources to address the grand challenges of the 21st century, from access to clean drinking water to reliable artificial intelligence. The new campus will position Engineering for the future while staying true to its long history. Modern, glass-encased buildings will stand alongside the majestic architecture of centuries-old structures. Facades of revered buildings will remain intact, while their interiors will be brought up to date to meet the research and education needs of today and tomorrow.

School of Engineering & Applied Science Dean Jeffrey Brock said the revitalized engineering campus — concentrated on Hillhouse between Grove and Trumbull streets — in the heart

of Yale, will feature inclusive spaces that welcome the entire university community. This puts Yale Engineering in place to fully realize its aim to be the school of engineering and applied science "most integrally engaged with its larger university mission." The centrally located school will be well-positioned to create partnerships throughout the university. Providing Engineering with a strong visible identity and a hub of activity for the entire Yale community, the extensive work signals a new era for the School.

"It will provide a sense of place and identity for a thriving and growing enterprise, a re-envisioned school advancing Yale's reputation and its own standing alongside Yale's other great professional schools," Brock said.

The reimagined campus will boast new maker spaces, homes for centers and institutes, facilities supporting innovation and entrepreneurship, and room for future priorities. The plans prioritize interaction among faculty, staff, and students. As part of this goal, there will be a new outdoors quadrangle on the east side of Hillhouse envisioned as central to daily life.

The School's transformation goes beyond infrastructure. Along with modernizing its space, Engineering is currently ❯

17 Hillhouse

The centerpiece of the campus transformation is the construction of a new building at 17 Hillhouse. The four-story building will provide approximately 43,000 square feet and feature an open-floor plan and flexible lab spaces to accommodate future research needs.

1. The glass-heavy structures will showcase our researchers' innovations, as the work of the School will be visible to passers-by, including those walking along the Farmington Greenway Canal trail.

2. Inside, labs and makerspaces will also be glass-encased to engage students in engineering research and create a "must-visit" destination.

3. Serving as a focal point for the school, the quadrangle will act as a gathering place for the entire Yale community. This includes both everyday use as a place to meet and relax, as well as for special events like commencements and other occasions.

4. Laboratories inside will be dedicated to research in multiple disciplines, including Chemical, Environmental, Mechanical Engineering and Materials Science.

> "This reimagining of Yale Engineering facilities and its ambitions will benefit generations of scholars to come."
>
> Scott Strobel, Provost

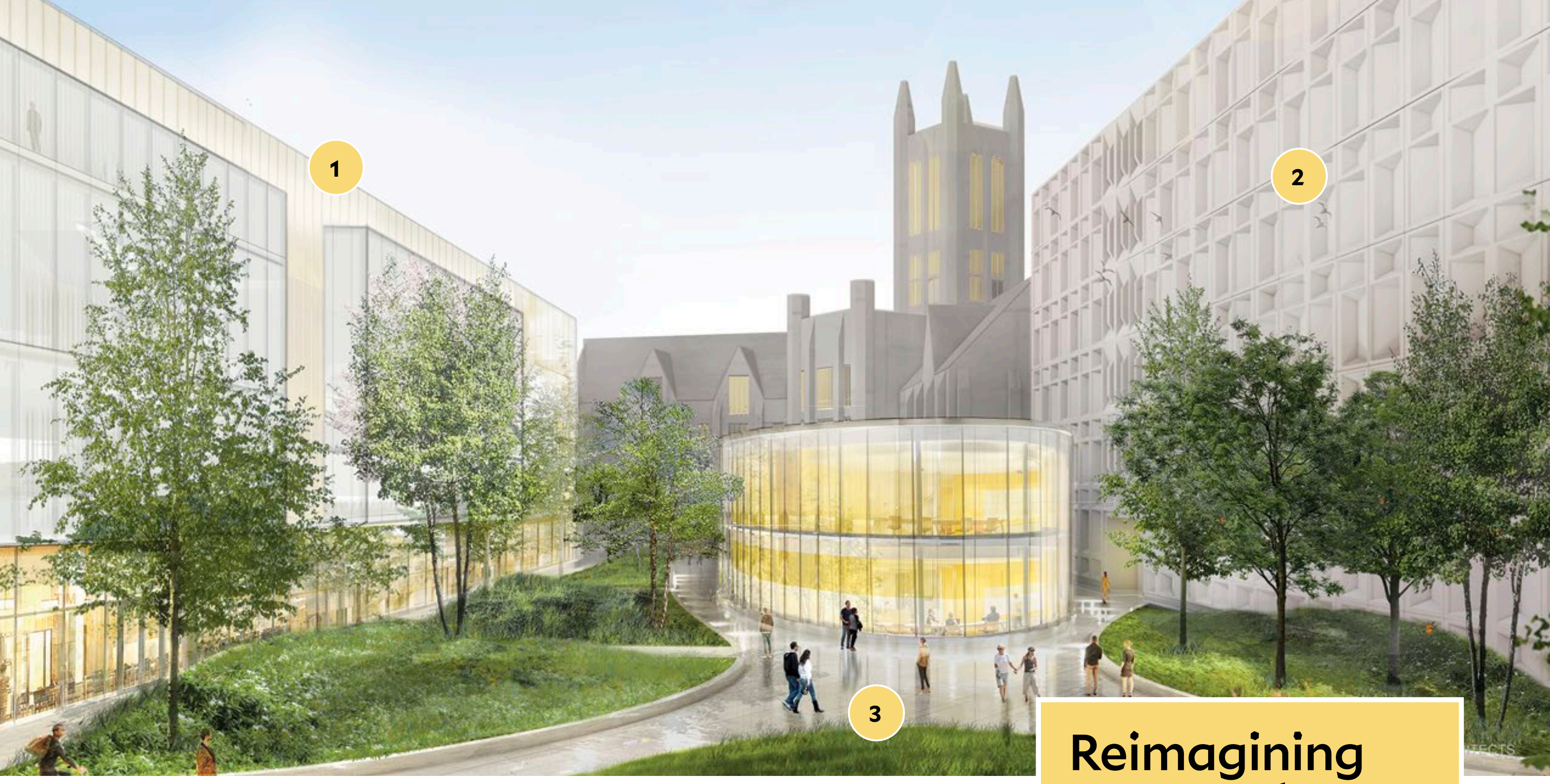
growing its faculty by 30 new positions, an investment that will allow the School to accelerate breakthrough research and enhance collaborative innovation. By making the needed investments now, Brock said this project will show what's possible in the areas of education, research, community building and sustainability.

"This momentous opportunity to re-envision and revitalize our dated infrastructure will help Yale Engineering attract additional premier faculty while supporting existing faculty and students through state-of-the-art spaces and facilities," Brock said. "A robust slate of major improvements will allow Yale Engineering to continue growing and will enrich both Yale and our surrounding community, furthering our pursuit of real-world impact and intensifying the spirit of innovation in the heart of Yale's campus."

The innovations enabled by an enhanced engineering campus will help the university as a whole achieve its aims, and ultimately yield benefits throughout society.

"At Yale, we are accelerating the pace of research and innovation in engineering and science," said President Peter Salovey. "The work of Yale Engineering over the coming decades will transform technological development across every sector. These investments will provide a platform on which to build next-generation solutions to the most pressing global challenges."

Community-based thinking will inform the design of labs, makerspaces, and classrooms. Collaborative spaces for faculty and communal gathering areas will sit alongside cutting-edge laboratory and instructional facilities, helping nurture new ideas and fruitful partnerships. In line with the School's Strategic Vision, all new spaces will be organized by research and teaching priorities rather than by academic department. Keeping the School's ambitions



in mind, there will be hubs dedicated to specific areas of emphasis, such as AI, computational and mathematical modeling, and robotics. Additionally, plans will provide space for existing strengths and for initiatives still to be imagined.

Immediate efforts focus on alleviating current space constraints within engineering buildings by bringing new state-of-the-art labs online as quickly and thoughtfully as possible. Doing so will allow room for maintaining Engineering's steady growth while minimizing relocations for existing faculty.

The project also serves Yale's sustainability goals, as buildings will be comprehensively renovated or demolished, and new structures built to Yale's zero-carbon-ready standard. A geothermal network will provide efficient, clean, and resilient thermal energy.

The first major work begins in 2025, at 19 Hillhouse. This new building will be dedicated to the School initiative Robotics for Humanity (see more about this on the previous page), and designed to foster a spirit of collaboration among robotics researchers. Like many other new spaces, this one will be defined by areas of research: Roboticists from Computer Science, Mechanical Engineering and Materials Science, and Electrical Engineering will all work together within the facility. The building will feature modern laboratories, state-of-the-art equipment, and floor plans that can be reconfigured to meet the changing needs of scientific inquiry. As the first phase to be completed in the campus transformation, 19 Hillhouse will be emblematic of Yale Engineering, and represent the kinds of changes to expect in the next decade.

The revitalization of lower Hillhouse will complement work already underway on the Physical Sciences and Engineering Building (PSEB), which will be located on the north end of Science Hill, where many of Engineering's close collaborators work. That building — also one of the largest facilities projects in university history — will house numerous engineering and science initiatives, including quantum computing, quantum engineering, and materials science.

Provost Scott Strobel said that, together with the PSEB, the plans for lower Hillhouse signal Yale's resounding commitment to engineering. Alongside other recent investments across campus, he said "this reimagining of Yale Engineering facilities and its ambitions will benefit generations of scholars to come."

Reimagining Becton Plaza

Renovation to the Becton Plaza will complement Yale's "innovation corridor" — which includes the Center for Engineering Innovation and Design, the Greenberg Engineering Teaching Concourse, and the Tsai Center for Innovative Thinking at Yale.

1. **With an expanded footprint, Dunham Laboratory will allow for more makerspaces and facilitate initiatives for innovation and faculty entrepreneurship.**
2. **Renovations to Becton Laboratory will support the School's goal for expanding Materials Science — an expansion complemented by space in the PSEB building.**
3. **Walkways will connect to all parts of the engineering campus, bringing an added sense of community to the School.**

"It will afford the School the kind of flexible, well-equipped spaces it needs to conduct world-class teaching and research, and to develop elegant, sustainable solutions to global challenges."

Accelerating innovation

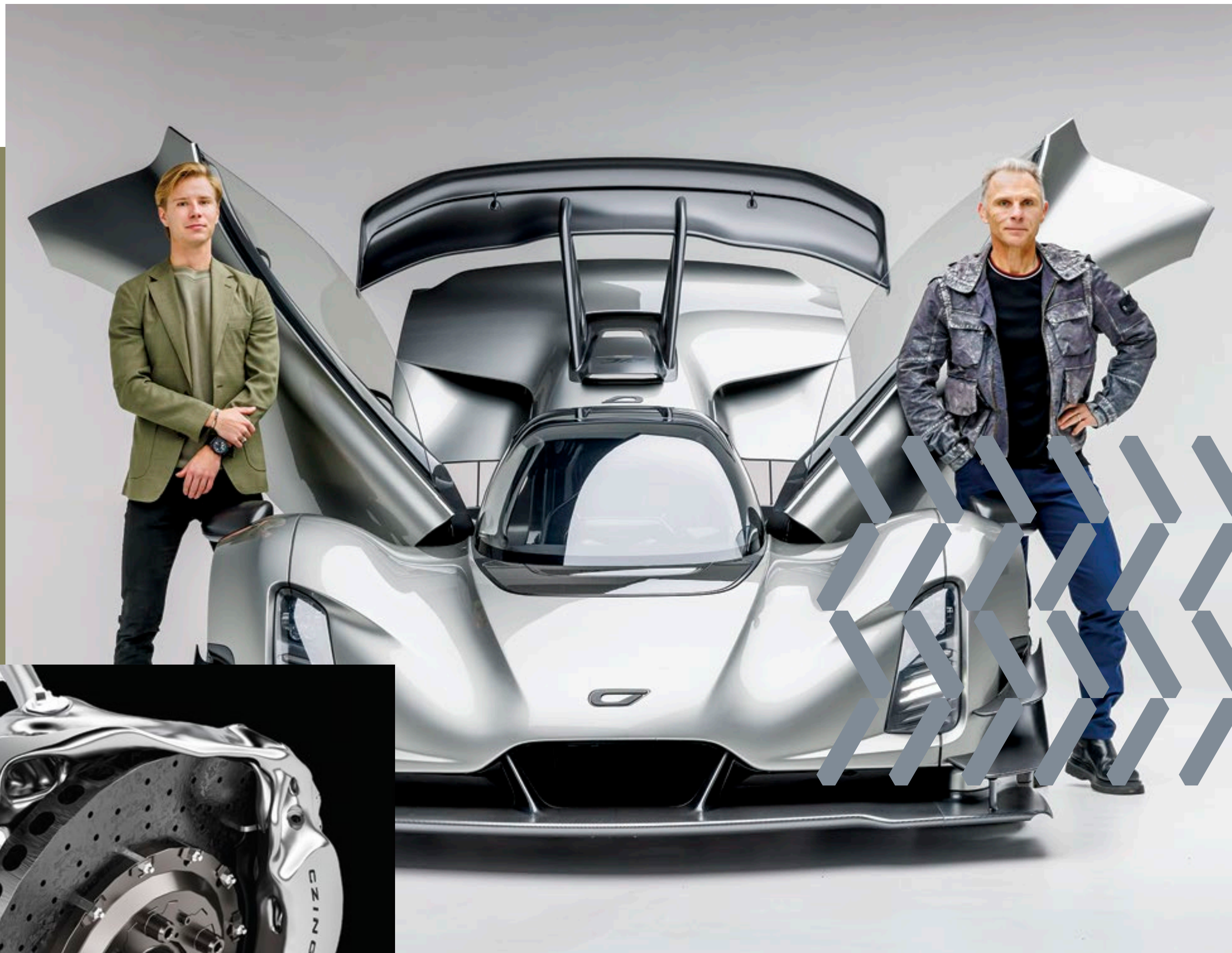
Photo by Robert Grubbs

The Czingers are disrupting manufacturing at top speeds–253 mph, specifically

The first thing people typically know about the father-son team of Kevin Czinger ’82 B.A, ’87 J.D and Lukas Czinger ’17 is the car.

Known as the Czinger 21C, it’s sleek, sporty, and extremely fast. And it has the numbers to back up its futuristic look: 1,350 combined horsepower, an acceleration of zero to 60 miles per hour in 1.88 seconds, and it’s able to reach a speed of 253 miles per hour. The flagship product of their company, Czinger Vehicles, it has set records and earned such superlatives as “the World’s first Human/AI-designed and 3D-printed hypercar.” And, as Kevin Czinger puts it, the 21C will be the “fastest street-legal car when it’s delivered in the near future.”

And as impressive as the 21C is, the car also demonstrates the even greater ambition of the Czingers’ other company, Divergent 3D: changing how motor vehicles are made, from their design and development to how they’re assembled. With a combination of innovative software and 3D metal printing, the Czingers have created a system to radically speed up and streamline the process of making vehicles, and potentially transform the automotive industry. It applies artificial intelligence to develop car parts, and 3D printing to manufacture them.



Photos by Ted7 Photography (top) and Czinger Vehicles (bottom)

***Top:** Lukas and Kevin Czinger in front of the Czinger 21C. **Bottom:** With a combination of innovative software and 3D metal printing, the Czingers' manufacturing process can transform the automotive industry.*

The Los Angeles-based company's own Divergent Adaptive Production System (DAPS) was developed by a team that includes engineers formerly from Tesla, Apple, and other tech heavyweights. It's a complete software-hardware solution designed to replace traditional vehicle manufacturing. With artificial intelligence, it can computationally design any structure, no matter how complex. The system then additively manufactures and assembles these parts, optimizing every component for minimum weight and maximum strength. And it can seamlessly switch from manufacturing cars to drones and beyond.

"That software designs the parts and designs it to be its most efficient and to print in the most effective way on our hardware," said Lukas Czinger, who majored in electrical engineering as a student at Yale College. "Then it also designs it to be assembled in the lowest possible cycle time while meeting all the requirements of our modular, fully fixtureless assembly process. Those three things together — design software, printing, and assembly — is really what Divergent is."

The company, which began only seven years ago with Kevin as its sole employee, now employs almost 300 people and has received more than 550 patents. And the Czingers and their grand vision are getting noticed: The company has garnered more than $500 million from investors. Board members include John Thornton, lead director of Ford Motor Company and former Goldman Sachs president (and a 1980 graduate of Yale School of Management), and retired General Peter Pace, former chairman of the Joint Chiefs of Staff. The company currently has vehicle and structure production programs with Aston-Martin, Mercedes, and five other major auto OEMS (original equipment manufacturers) as well as with General Atomics and several other U.S. aerospace and defense companies.

"These larger companies, like Mercedes for instance, they're saying 'We have all of these EV platforms, and we need lighter, more efficient vehicles,'" Kevin Czinger said.

With the advance of 3D printing, the potential form that parts can take is unlimited, and the software-hardware system ensures that there's no wasted material. The difference between conventional car parts and those made by Divergent is apparent at first glance. Instead of the smooth, geometric structures of your typical motor vehicle, Divergent 3D's parts look like they could have grown out of the ground (minus the metallic hues), honed by millennia of evolution.

"We're using neural networks and machine learning to reduce the processing power by coming up with solutions sooner and in some cases, coming up with novel solutions," Kevin Czinger said. "No human could engineer these structures. They're perfectly optimized. We're literally taking 20% to 40% of the mass out of structures."

Adding to the sustainability of the process, each part is made from used metal and can be broken down and recycled into another component.

From an environmental standpoint, the implications are huge. One of the big selling points of electric vehicles is that they run on clean energy. But the amounts of resources spent at the manufacturing level also need consideration. As the global demand for motor vehicles increases, Kevin Czinger notes, society is at risk of being locked into an "economically and environmentally broken" system of manufacturing that wastes materials and is fundamentally bad for the planet.

"Nothing is optimized for material and energy from a product design or materials input standpoint, so you're consuming more and more per product," he said. "More people are consuming less efficient, heavier, more material- and energy-consuming products, which in turn need more power generation, fuel creation, and consumption."

If you're interested in getting behind the wheel of the 21C, it'll be out soon. With a $2 million price tag, you might not see many of them, but its benefits could greatly outweigh its sales numbers.

"Really, the car does two things for Divergent," Lukas Czinger said. "One is application-specific technology: We get the guy that knows brake system design or transmission design, or knows combustion engines very well — he's going to feed that back into the Divergent system that knows software, 3D printing and assembly. Then you're going to end up with some sort of unique transmission that's never been seen before. And it's the brainchild of Czinger engineering, and the Divergent system."

The second benefit is that it "attracts a lot of eyes"— particularly of people who Divergent wants to work with, he said.

"It goes really fast, and it looks really cool, and it has all the 3D-printed parts. When you pop the engine bay, that's when McLaren and Rolls Royce and Bentley CEOs walk by and definitely take notice as well."

Reinventing manufacturing

If the Czingers' vision for Divergent pans out, the benefits will extend well beyond one car model, no matter how cutting edge it may be. The Czingers see the technology used to make the car as eventually democratizing manufacturing.

Growing up, Kevin Czinger remembers watching the automotive industry get wiped out because its manufacturing equipment couldn't adapt to changing needs. "So rather than rebuilding in Cleveland," he said, "all of that got moved to some low-cost area."

A system like theirs, though, could prevent that kind of job loss, the Czingers say. "This is a machine that can be set up regionally, collapses the supply chain, collapses the number of parts, optimizes material and energy, and provides a permanent manufacturing footprint," Kevin Czinger said.

The DAPS system entails a series of printer modules and assembly modules that are completely design-agnostic. And unlike a traditional assembly line, the Czingers' system can take on entirely different tasks with no trouble.

"One minute you're going to be sending data for a drone, the next minute for a Mercedes SUV, the next minute for a Ferrari," Kevin Czinger said. "The same thing on the assembly side. So you're just looking at volume into a structure. You can set that up regionally. It's a multi-customer, multi-industry facility."

They saw that no one else was building software to optimize parts or the assembly process. In four years, they had built the system that has given the company its niche.

Two generations at Yale

Kevin Czinger, who grew up in Cleveland, was the first in his family to attend college. He places attending Yale — alongside meeting his wife, Katrin (at Yale as a visiting scholar from the Freie Universitaet Berlin), and having the opportunity to work with his son — among his greatest blessings. When he was young, his older brothers taught him the basics of auto maintenance. "I'm a kid who grew up in a working-class family building American muscle hot rods."

He was recruited to Yale for the football team in 1978, and by the time he was a senior he was named Ivy League Player of the Year. As an undergrad, he majored in classical civilization and premed. After graduating, he attended Yale Law School, and later studied electrical engineering at Arizona State

University. His career took a circuitous path: He was a federal prosecutor in New York City and a senior executive with Goldman Sachs in Europe and Asia before embarking on a 25-plus-year journey as a technology company founder, inventor and CEO, including a stint as entrepreneur-in-residence at Benchmark Capital in Silicon Valley. Prior to creating Divergent, he co-founded a pioneering electric vehicle company and an electric vehicle battery manufacturing company as joint ventures in China. He was also an infantry rifleman in the U.S. Marines Reserves.

At Yale, he approached academics pretty much how he approached everything else — he found something that interested him and threw himself into it. "I never thought you couldn't do anything," he said. "You want to learn something? You just teach yourself and learn it."

Like his father, Lukas Czinger also excelled at sports, and played varsity soccer at Yale. And he applied a similar attitude toward academics.

"I've always been best at just throwing myself into the deep end and then coming out with quite a lot of knowledge from some torture and some learning and a lot of experience," he said.

For him, that meant taking on electrical engineering as his major. He figured it was one of the tougher majors, but also one that could be most widely applied and provide him with valuable knowledge in mechanical engineering, physics, and math.

"The professor I probably spent the most time with was Mark Reed [the late Harold Hodgkinson Professor of Electrical Engineering & Applied Physics]," he said. "He had a couple of classes that really got to me, and I was interested in photovoltaics and all of that. That was really good learning for me."

Jeffrey Brock, dean of the School of Engineering & Applied Science, noted that the Czingers' radical overhaul of how things are done in the automotive world reflects a paradigm-shifting vision that is infused with a depth of

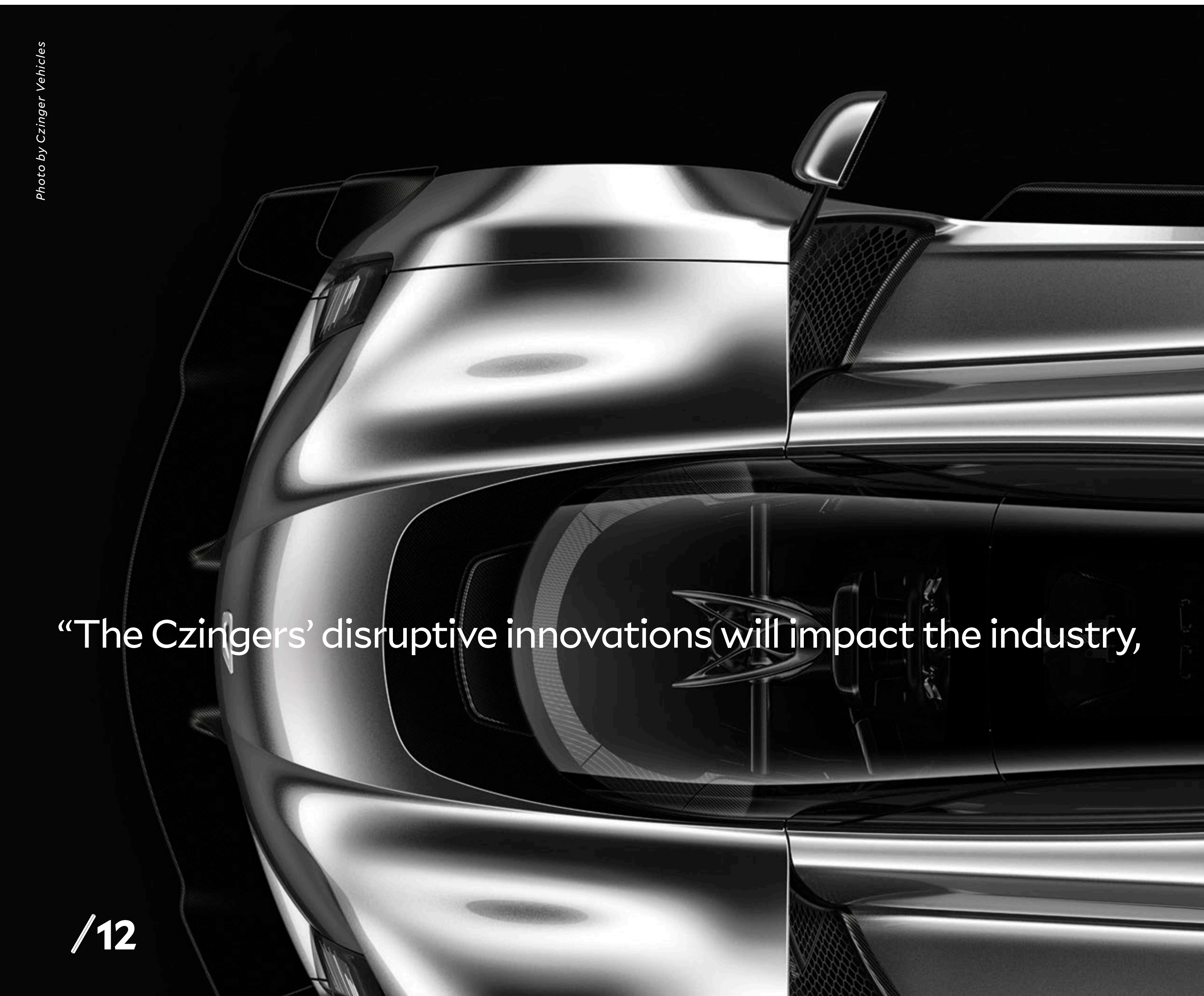


Photo by Czinger Vehicles

"The Czingers' disruptive innovations will impact the industry, understanding of global norms and constraints that limit innovation.

“The Czingers’ disruptive innovations will impact the industry, and likely the entire world, for generations,” he said. “We’re eager to see what they do next, and to bring their example into practice at Yale.”

After graduation, Lukas Czinger was already establishing himself in a career in finance when he decided to attend a talk that his father was giving at a tech conference about Divergent 3D. Impressed, he approached his father about coming to work at the company.

Working as a father-son team wasn’t something either had anticipated. In the seven years since, though, it’s worked out well.

“We both have a very logical thought process that allows us to usually be on the same terms,” he said. “But we also have pretty unique differences that allow the company to operate in the right way.”

Kevin Czinger sees the family dynamic as one of the things that tempers the “megalomaniacal craziness” that sets the tone for many other ambitious start-ups — “especially in this era of ‘I’m the genius that’s going to save the entire world.’”

“To have somebody as a partner who is that talented, that you can totally trust — that’s unique, and obviously it’s fun,” the elder Czinger said. “When things work right and when they don’t work right, it’s a strengthening thing because you know you can trust the person.”

Lukas Czinger also has no regrets about teaming up with his dad. For one thing, they don’t have to navigate the internal politics and bureaucracy found at a lot of other companies.

“When you’re working with family, there’s absolute trust,” he said. “And you’re just trying to move the ball forward and make the company a success, and there’s no politics around that. So I feel just very fortunate to be in that sort of position.”

*To learn more about **Czinger Vehicles**, visit www.czinger.com.*
*For **Divergent 3D**, visit www.divergent3d.com.*

and likely the entire world, for generations.”

Jeffrey Brock, dean of the School of Engineering & Applied Science

Pioneering quantum futures

Yale Engineering faculty are paving new paths in quantum exploration

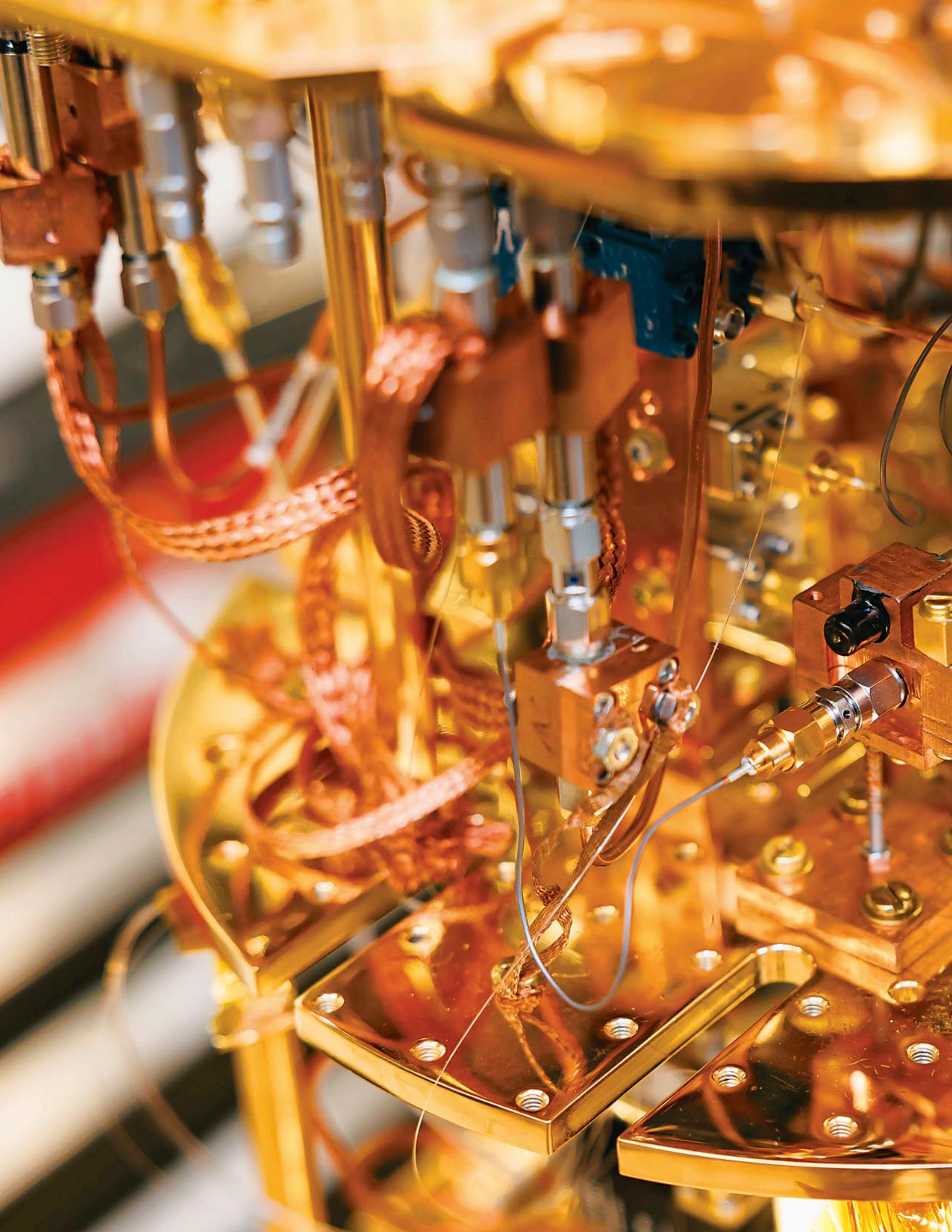
In classical computing, information comes in the form of bits corresponding to ones or zeros. In quantum computing, information is stored in special devices with quantum properties that are known as quantum bits, or "qubits."

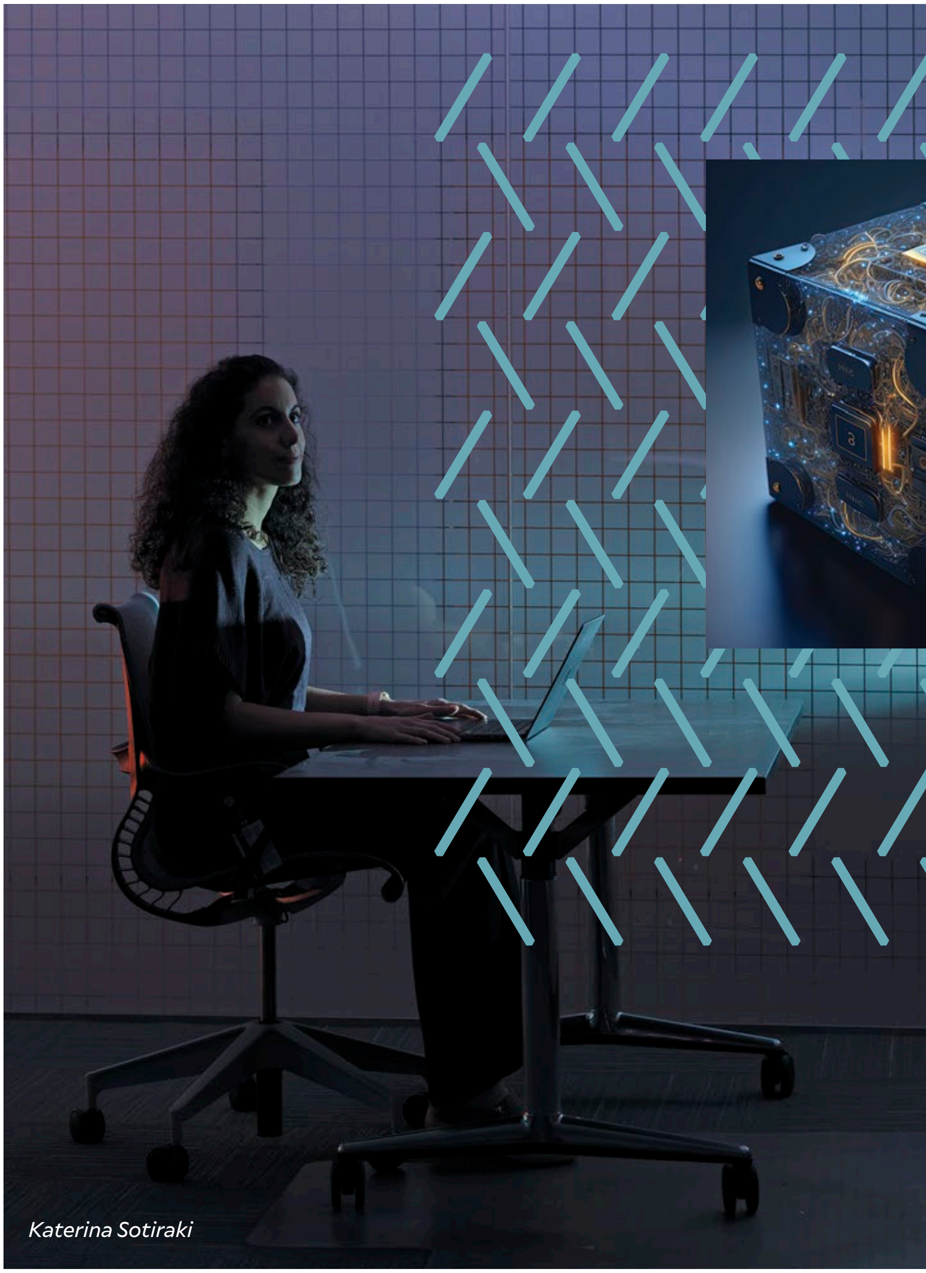
The qubits can each represent a one or a zero, or — confoundingly — both one and zero at the same time. This "quantum parallelism" is one of the properties that enables quantum computers to make calculations that will potentially be orders of magnitude faster than what is possible on classical supercomputers, which will in turn transform multiple industries and revolutionize everyday life.

But achieving even one stable qubit is tricky. Even trickier is getting enough to build an error-free, truly useful quantum computer. The consensus among those in the field is that we're some ways off from that point, but progress is being made. At Yale Engineering, several faculty in Computer Science, Electrical Engineering, and Applied Physics are working to pave the way toward practical quantum computing and preparing for when it arrives. Among them are Katerina Sotiraki, Hong Tang, and Shruti Puri — here's a look at some of the work they're doing:

Katerina Sotiraki

In recent years, consumers of technology news may have come across ominous headlines warning us of the imminent "Q-Day." In theory, that's when quantum computing has advanced to a level that it can easily dismantle even the most complex and sophisticated computer security systems currently in place. Encryption ›





Katerina Sotiraki

keys that today's classical computers require trillions of years to solve, for instance, could be broken by a fully powered quantum computer in mere seconds.

Katerina Sotiraki, one of the most recent additions to the Computer Science Department, is working to ensure that Q-Day never arrives.

Thanks to computer cryptography, we're able to use digital technology without fear of getting hacked. And over the last few decades, cryptography has made a great deal of progress over the last few decades, as the field has developed many powerful protocols with provable security such as public-key encryption schemes and signature schemes.

The arrival of quantum computing throws a wrench into all of this work. Once quantum computing has advanced to a certain degree, and an attacker has access to a quantum computer, today's cryptographic protocols will be at risk.

Preparing for that eventuality, Sotiraki's research uses tools from mathematics and theoretical computer science to build cryptographic protocols that could hold up against quantum attacks. This includes understanding the complexity of widely used cryptographic assumptions — that is, the problems designed to foil hackers — and constructing security protocols that can defend against future and more advanced quantum computers.

"One of the main approaches is that we try to build new protocols based on assumptions that we believe will resist quantum attacks," she said.

Current security systems tend to be based on computing prime factors or discrete logarithms, she said.

"Theoretically, if we had a very powerful quantum computer, we could break these assumptions," she said. "So for my work, I use different types of assumptions — specific assumptions that we believe will keep us quantum-secure in the sense that people have tried to break them using quantum algorithms and they have not succeeded."

Specifically, Sotiraki is working on what's known as lattice cryptography, a concept based on multidimensional grids. Because it's extremely difficult to find information embedded within multiple spatial dimensions of a lattice, it could be key to developing a system that can withstand attacks from both classical and quantum computers.

But there's still work to be done.

"One challenge right now is that these assumptions are not as efficient as the protocols that we use right now," she said. "Which makes sense — for the protocols that we use right now, there has been a lot of time and people have really optimized them. And for the new protocols, we are just starting."

But even in a worst-case scenario, experts believe we're years if not decades away from a possible Q-Day.

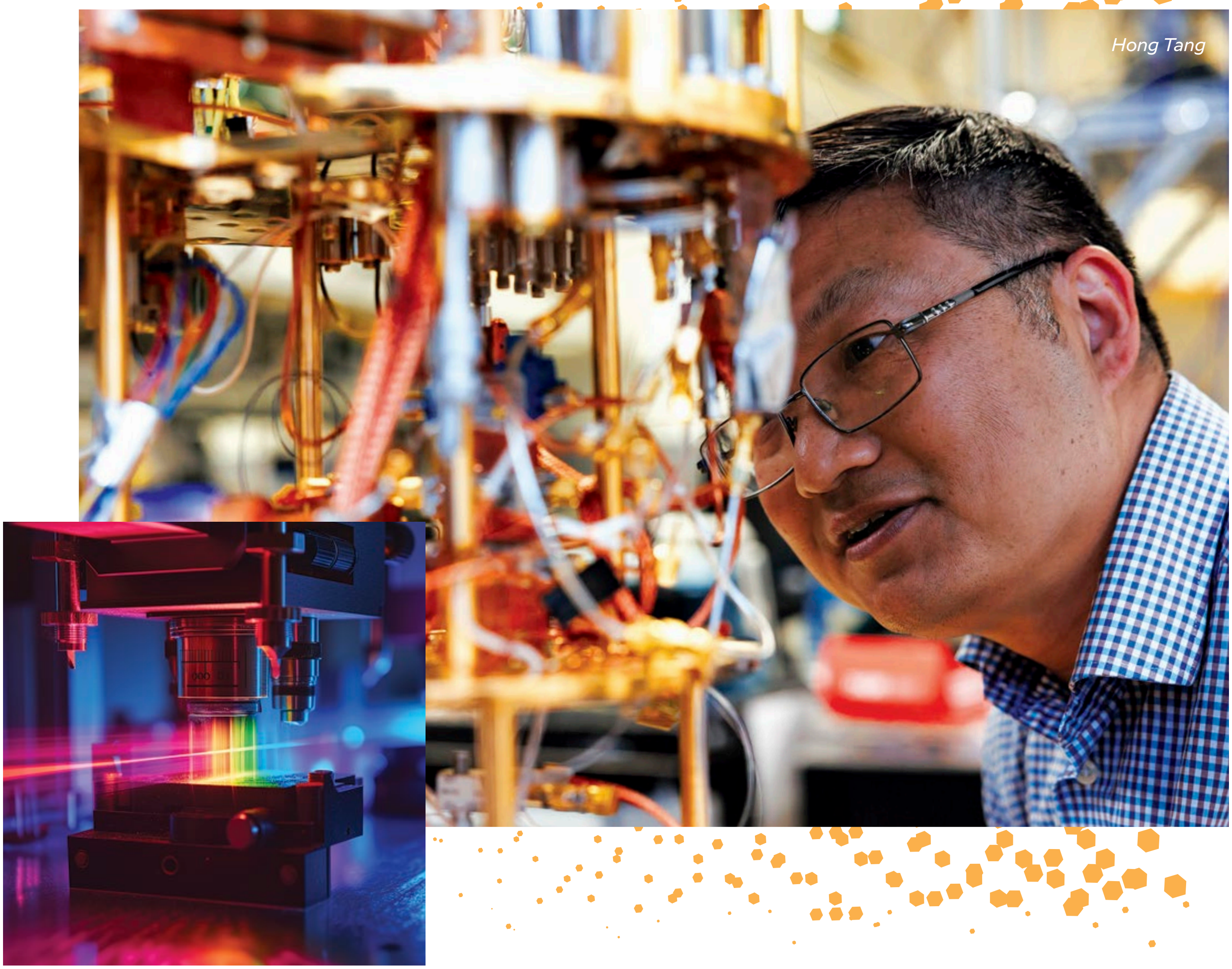
"My understanding is that we are a long way from having quantum computers that would break the current assumptions, which is a good thing, because it allows us to have some time for this transition," she said.

Hong Tang

The research of Hong Tang, the Llewellyn West Jones, Jr. Professor of Electrical Engineering, Applied Physics and Physics, has involved numerous projects that could lead to advances in quantum computing. Recently, his lab developed the first chip-scale titanium-doped sapphire laser, which could go a long way toward making a critical technology much more accessible to researchers.

Combining the efficient performance of titanium-sapphire lasers with the small size of a chip, it could boost the development of quantum computing chips as well as atomic clocks, portable sensors, and other applications.

When the titanium-doped sapphire laser was introduced in the 1980s, it was a major advance in the field of



Hong Tang

lasers. Key to its success was the material used as its gain medium — that is, the material that amplifies the laser's energy. Sapphire doped with titanium ions proved to be particularly powerful, providing a much wider laser emission bandwidth than conventional semiconductor lasers. The innovation led to fundamental discoveries and countless applications in physics, biology, and chemistry.

The table-top titanium-sapphire laser is a must-have for many academic and industrial labs. But these lasers are costly and take up a lot of space, which means you rarely see them outside of a well-resourced laboratory. Tang's chip-scale laser, which was headed up by Yubo Wang, a graduate student in Tang's lab, could help change that.

"Without becoming more widely accessible, these devices will remain a niche item, limiting the potential breakthroughs that they could help produce," Tang said.

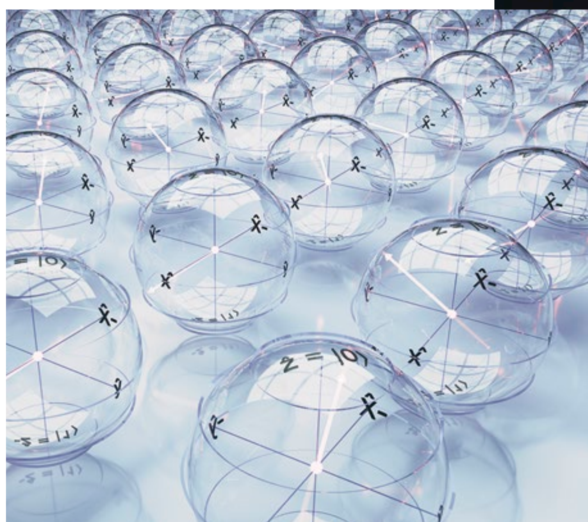
Just weeks before the results of that project were published, Tang's lab also unveiled the first on-chip device that can detect up to 100 photons at a time.

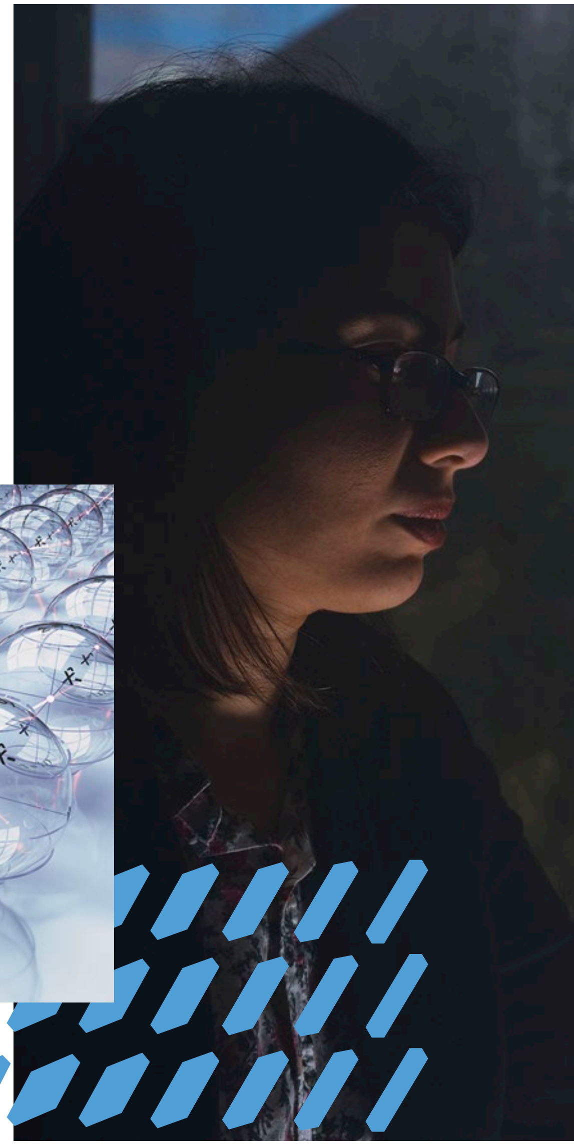
With very high sensitivity, photon detectors can detect the number of photons even in an extremely weak light pulse, and are essential to many quantum technologies, including quantum computing, quantum cryptography and remote sensing. However, current photon-counting devices are limited in how many photons they can detect at once—usually only one at a time, and not more than 10. By increasing the capability by up to 100, the Tang lab's device allows for a broader range of quantum technology applications. The project was led by Risheng Cheng, and Yiyu Zhou, both postdoctoral associates in Tang's lab at the time.

Not only does Tang's device detect more photons, but the rate at which it counts them is also much faster. Plus, it operates at an easily accessible temperature.

Because of this, the device allows for a broader range of applications. This is true, Tang said, "especially in lots of fast-emerging quantum applications, such as large-scale Boson sampling, photonic quantum computing, and quantum metrology."

The complexity of the device required years of design and fabrication, in addition to the time it took to verify its performance. And they're not done yet. Tang and his team plan to make the device smaller and increase the number of photons it can detect — possibly up to more than 1,000.





Shruti Puri

When she entered the field of quantum research, Shruti Puri was surprised by the division between those working on system architecture and those working on hardware. Because they were working separately, it meant that assumptions had to be made about what kind of errors could potentially happen — assumptions that aren't always accurate. As a result, systems are often designed to protect against a broad range of potential errors — many of which very likely will never happen – leading to an inefficient use of the system's resources.

Puri's research is at the intersection of quantum optics — that is, how light interacts with matter — and quantum information theory. It's a background that gives her a good understanding

Shruti Puri

of the hardware physics and the actual noise in the system. And that provides a clearer picture of potential errors to anticipate and correct.

Because they're so incredibly small, qubits — fragile bits of quantum information — are particularly susceptible to any perturbations in their environment. Electromagnetic fields, pressure changes and other disturbances — referred to as noise — can destroy the phenomena that make quantum computing so potentially powerful.

"The errors are quite large in the system, so you need to really think about how to optimize your error-correction code more than you do in the classical systems," said Puri, assistant professor of applied physics.

The eventual successful application of quantum technology, she said, will require efficient and active quantum error correction to protect the fragile quantum states. Puri is working toward this goal with a combination of robust quantum circuit engineering, tailoring error correction codes for specific noise models, and engineering qubits with inherent noise protection.

"For a long time, people would usually design codes to correct for noise in a quantum system, just assuming a general kind of noise model to describe the system," she said. "But because I was coming from more of a hardware physics background, this was just bizarre to me. How can you make codes to correct noise when you don't understand the noise that's particularly affecting the hardware?"

Puri designs hardware in such a way that the noise is of a very specific nature, and easier to correct. Once the hardware has been tailored, she can design much more effective error-correcting codes. In 2020, Puri and her research group published a paper introducing a specific quantum element that enabled the realization of a tailored error-correcting code, which could perform much better than a general code. That helped revive interest within the field in the idea of tailoring a system for more effective error correction.

"Since then, we have identified other sorts of physical hardware where you can design other types of noise and then develop how to do error correction for that specific tailored noise," she said.

AI's legal revolution

Legal expertise at your fingertips with AI lawbots

The law can be a complicated thing, even for seemingly simple matters. Wondering if the oak tree in your front yard is in violation of local zoning ordinances? Figuring that out could mean wading through a tall pile of regulations, all written up in confounding legalese.

A city zoning code can contain tens of thousands of meticulously detailed rules, regulations, and guidelines. Even if the 60-megabytes-plus size of the documents doesn't crash your computer, you still have to try to understand it all. This is a daunting task even for legal experts. For laypeople, deciphering such a Byzantine set of rules borders on the impossible.

To that end, professors Ruzica Piskac and Scott Shapiro – from Engineering and the Yale Law School respectively — are putting artificial intelligence (AI) to work on your behalf. With advanced AI-powered tools, they've developed a system – known as a "lawbot" — that can review and parse zoning laws, tax provisions, and other intricate legal codes much faster than human lawyers. They named their start-up Leibniz AI, after the 17th century polymath who dreamed of an automated knowledge generator. ›

Left: *Yale Engineering's Ruzica Piskac and Yale Law School's Scott Shapiro in Yale Legal Laboratory, the Lillian Goldman Law Library.*

To the user, the concept behind the lawbot is fairly simple: ask it a legal question, and it provides you with an understandable and accurate answer.

More than just offering helpful advice, the two professors see their system as helping to democratize the legal system. Getting reliable information that isn't cost- or time-prohibitive empowers the average person to understand their rights and make more informed decisions.

The system harnesses the power of large language models, which can understand and generate human language — essentially, they streamline legal analysis and allow users to ask questions and get answers in plain language. Crucially, the system also applies automated reasoning, a form of AI that uses logic and formal methods to reliably solve complex problems. Today's popular chatbots have shown a tendency toward "hallucinating" — that is, asserting false statements as true. Obviously, this isn't something you're looking for in a lawyer. But thanks to automated reasoning, the Leibniz AI lawbot offers only clear-headed responses. By systematically verifying and validating each step of the reasoning process, it significantly reduces the potential for errors.

"We want to use those insights that we already learned about reasoning in the legal setting," said Piscak, associate professor of computer science. "Then we can apply them to real-world settings so that regular users like me or someone else can ask their questions. For instance, if I have an extra room, am I allowed to rent it on Airbnb?"

There are currently AI-based start-ups focused on providing legal services. Unlike Piskac and Shapiro's system, though, none use automated reasoning or any other sorts of formal validation of their results. Instead, they tend to rely mainly on unreliable large language models.

Shapiro, the Charles F. Southmayd Professor of Law and Professor of Philosophy, said developing a lawbot seemed like a great opportunity to show the promise of AI technology. But increasing access to legal information through large language models brings the obligation to ensure that the information is accurate — the stakes are high when it comes to the law. That's where the system's techniques of automated reasoning, verification, and logic solvers come into play. The result is nuanced legal information delivered quickly and accurately at the user's fingertips.

A "deeply interdisciplinary" collaboration

Piskac and Shapiro began working together after a Ph.D. student in Piskac's class, Samuel Judson, proposed applying for a research grant from the National Science Foundation. The proposal called for developing accountable software systems, a project that required legal expertise. Piskac emailed Shapiro, whom she'd never spoken with before.

"I'm like, 'Hey, I'm a person who likes logic. Would you like to work with me on a project involving logic and the law?' And Scott answered within a couple of minutes: 'Yes. I like logic, too.'" Soon after, together with Timos Antonopoulos, a research scientist in Piskac's group, they applied and were awarded a research grant from the National Science Foundation for their project on accountability.

The work they've accomplished wouldn't have been possible without both researchers participating, Shapiro said.

"One of the things that I really love about this project is how deeply interdisciplinary it is," he said. "I had to learn about program verification

Left: *Piskac and Shapiro's "lawbot" can review and parse zoning laws, tax provisions, and other intricate legal codes much faster than human lawyers.*

Right: *A common thread in Piskac's research is improving software reliability and trustworthiness using formal techniques.*

and symbolic execution, and Ruzica and her team had to learn about legal accountability and the nature of intentions. And in this situation, we went from a very high level, philosophical, jurisprudential idea all the way down to developing a tool. And that's a very rare thing."

Each field of study comes with its own terminology and ways of thinking. It can make things tricky at first, Piskac said, but having a common interest helped overcome those obstacles.

"Scott would say something, and I would say 'No, this is not correct from the computer science perspective.' Then I would say something and he would say 'No, this is not right from the legal perspective,'" she said. "And just this immediate feedback would really help us. When you're sitting close to each other and comparing and discussing things, you realize that your goals and ideas are the same. You just need to adapt your language."

Yale Engineering Dean Jeffrey Brock said the collaboration is a great example of how the School can direct the conversation around AI and make impactful contributions to the rapidly evolving field. In addition to AI-related projects with the Law School and School of Medicine (see sidebar on page 24), he noted that Engineering has been working with the Jackson School of Global Affairs on cybersecurity, and more collaborations are in the works.

"Engineering is lifting Yale by helping other schools and disciplines on campus to thrive," Brock said. "In the era of generative AI, fields like law and medicine will become inextricably intertwined with technology development and advanced algorithms. For these schools at Yale to maintain their preeminence, they are increasingly engaged with our mission, and we want to help make their work even better. That's happening now, and we expect it to continue to an even greater degree in the future."

He also noted that the cross-disciplinary approach is reflected in the School's curriculum. Piskac and Shapiro, for instance, co-teach Law, Security and Logic, a course that explores how computer-automated reasoning can advance cybersecurity and legal reasoning. And AI for Future Presidents, a newly offered course taught by Prof. Brian Scassellati, is designed for all students and takes a general approach to the technology and its societal impacts.

Putting the car on the stand

Our lives are increasingly entwined with the automated decision making of AI. Autonomous vehicles use AI to share our roads, healthcare providers use it to make certain diagnoses and treatment plans, and judges can use it to decide sentencing. But what happens when — even with the best intentions — things go wrong? Who's accountable, and to what degree?

Harnessing AI to transform healthcare diagnosis and treatment

Yale Engineering's researchers are finding ways to apply AI to numerous fields, from law to history to museums' preservation efforts.

Below are two examples of AI medical applications headed up by our faculty:

MoirAI

Smita Krishnaswamy

Like the cells that make up who we are, diseases are characterized by dynamics. Neurodegenerative diseases like Alzheimer's disease, for instance, have immune cells that change from homeostatic states to inflammatory degenerative states. Most diseases undergo some kind of progression, which makes them extremely hard to control. MoirAI, a start-up led by Smita Krishnaswamy, has assembled a team with joint expertise in mathematical artificial intelligence (AI), machine learning, and various biomedical fields with the goal of controlling cellular dynamics and identifying druggable molecules that drive diseases.

The system involves inputting longitudinal single-cell data collected on a disease progression system into MoirAI's neural ordinary differential equation models, which automatically learn the disease dynamics.

"These inferred dynamics give different trajectories for each and every single cell," said Krishnaswamy, associate professor of computer science and genetics. "So we learn the different states to which cells transition. This allows us to build underlying gene regulatory networks that give rise to these dynamics, and this is how we identify the target."

The system has a wide range of potential applications. The first disease that the company is targeting is triple-negative breast cancer, one of the most diagnosed diseases in the U.S. among females, and one that is very difficult to treat without targeted therapies.

CRAIG

Arman Cohan

Imaging studies are vital to many decisions about treatment, and the need for these studies is rapidly increasing. Radiologists, critical members of the medical community, are typically in demand, overworked, and underpaid. So any technology that can help them out is welcome. That's where CRAIG (Computed Radiology Reporting with AI-assisted Generation) comes in. Led by co-principal investigators Arman Cohan, assistant professor of computer science, and Sophie Chheang, assistant professor of clinical radiology and biomedical imaging, CRAIG provides a system that uses AI to automatically generate the summary, or impression, of the radiology report.

Essentially, the researchers say, the system supports the radiologists' workload as a way to help hospitals take care of more patients.

Radiology reports have two important components. The first is the objective description of the imaging, known as the findings. The second is the impression, which summarizes the findings and identifies its most clinically important aspects. Pretrained on a very large corpus of medical reports, the CRAIG system automatically generates the impression, thereby saving the radiologists a significant amount of time. Numerous radiologists have tried out and praised the CRAIG system. One private practice radiologist described the system as "surprisingly accurate, given that it wasn't trained on my data."

Right: *In addition to the "lawbot," Shapiro and Piskac have created a tool that uses formal methods to "put the algorithm on the stand" to better hold them accountable.*

Algorithms can fail — they can cause fatal accidents, or perpetuate race- and gender-based biases in court decisions.

In a project that combines computer science, legal rules, and philosophy, Piskac and Shapiro have developed soid, a tool that uses formal methods to "put the algorithm on the stand."

To better understand how to hold an algorithm accountable, Piskac and Shapiro consider a case in which one autonomous car hits another. With human drivers, lawyers can ask direct and indirect questions to get to the matter of who's at fault, and what the drivers' intentions were. For example, if a human driver can testify convincingly that the crash was unforeseeable and unintentional, the jury might go easier on them.

Just as human drivers do, automated decision-making systems make unsupervised decisions in complex environments — and in both cases, accidents can happen. As the researchers note, though, automated systems can't just walk into a courtroom and swear to tell the whole truth. Their programs, though, can be translated into logic and subjected to reasoning.

Using automated reasoning, Piskac and Shapiro developed a system that can rigorously "interrogate" algorithmic behaviors in a way that mirrors the adversarial approach a lawyer might take to a witness in court. This method is a provable approach, they say, that guarantees accurate and comprehensive answers from the decision algorithm.

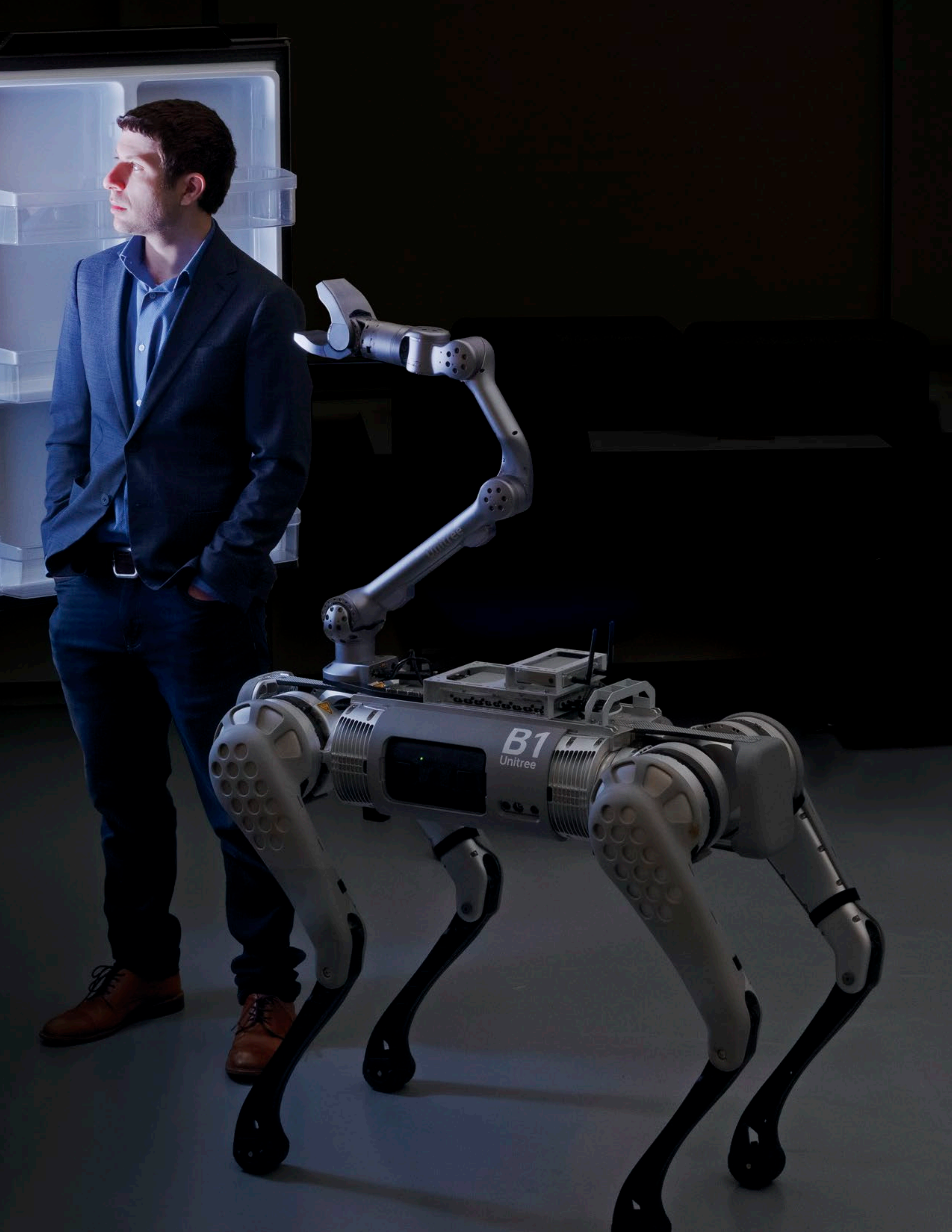
"The basic idea is that we developed a tool that can almost mimic a trial, but for an autonomous system," Piskac said. "We use a car because it's something that people can easily understand, but you can apply it to any AI-based system."

In some ways, an automated decision-making system is the ideal witness.

"You can ask a human all of these questions, but a human can lie," she said. "But this software cannot lie to you. There are logs, so you can actually see — 'Did you see this car?' If it's not registered in the log, they didn't see the car. Or if it is registered, you have your answer."

Using soid, built by Judson in Piskac's lab, an investigator can pose factual and counterfactual queries to better understand the functional intention of the decision algorithm. That can help distinguish accidents caused by honest design failures versus those by malicious design practices — for instance, was a system designed to facilitate insurance fraud? Factual questions are straightforward ("Did the car veer to the right?"). Counterfactuals are a little more abstract, asking hypothetical questions that explore what an automated system might or would have done in certain situations.

"Then, when you ask all these counterfactual questions, you don't even need to guess if the AI program is lying or not," Piskac said. "Because you can just execute the code, and then you will see."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Unitree

Robotics for humanity

In Yale Engineering labs, robots and humans are working together

Photography by Tanner Pendleton
Yale School of Art MFA Photography Program

Left: *Danny Rakita and fellow Yale Engineering roboticists are working to integrate robots seamlessly and beneficially into the home, the workplace, in healthcare and other aspects of our lives.*

With an oven, a coffee maker and fridge, the far side of Danny Rakita's lab on the third floor of A.K. Watson Hall looks a lot like any workplace break room. Here, though, robots will be doing the meal preparations. It's part of Rakita's effort to program robots to become accustomed to helping out in home care settings.

"We want to make deploying kinds of devices a lot more effective in the real world," said Rakita, assistant professor of computer science.

Walk upstairs to the lab of Marynel Vázquez and you'll see a device that she's programming to help make pizza, as part of a robot-human cooking team. She's developing ways for robots and humans to work together naturally, attuned to the sort of nuances that come with any seasoned partnership—where all parties are able to pick up on each other's cues, like tone of voice or facial expressions.

"One of the things that drives a lot of our work is advancing how robots make sense of the social world that they're in," said Vázquez, assistant professor of computer science.

The number of roboticists in the School has more than doubled in recent years, and Rakita and Vazquez are just two of the faculty driving the new Engineering initiative known as Robotics for Humanity. As the field of robotics is poised to make an impact on modern life as pervasive and revolutionary as computers did a few decades ago, Yale Engineering is working to help integrate them seamlessly and beneficially into the home, the workplace, in healthcare and other aspects of our lives.

The Robotics labs are already immersed in interdisciplinary collaborations both within the School as well as with Law, Psychology, Medicine, Environment, Architecture, Management, and the Humanities, making Yale uniquely positioned to take on essential human challenges.

The School and the University are investing both resources and space in robotics (see story on page 4) helping to cement Yale as a leader in Robotics, enhance on-campus visibility and create a "must visit" space for students and visitors. Here's a look at our roboticists, and some of the groundbreaking work that's happening in their labs:

Ian Abraham
Giving robots independence

Robots often encounter situations unanticipated by the robot designer and software developer, and in most cases, that causes problems. Ian Abraham, assistant professor of mechanical engineering & materials science, wants to make the unexpected no big deal for robots.

"The mission of my lab really is just getting robots less dependent on humans when we deploy them," he said. "We want to get them operating in extreme environments, and we can guarantee that they're doing exactly what we're telling them to do."

That involves developing algorithmic methods that enable robotic systems to intentionally learn and experiment to become self-sufficient autonomous agents. Abraham wants them to operate seamlessly even in unfamiliar environments. It's an ambitious goal, considering that even routine tasks can be tricky for robots. Abraham points to the example of picking up a set of keys — the kind of thing that humans do with ease but can be deceptively complex for robots.

"What we're figuring out is: 'How can we solve for these behaviors?'" he said. "What are those behaviors, and can we optimize for it? So we're sort of doing the problem backwards. We're saying, 'Let's formulate what we think the solution should be and investigate mathematical principles that answer why some behaviors are more reliable than others.'"

Top left: *Ian Abraham is developing algorithms that allow robots to reason about interactions with the environment that optimize learning manipulation and locomotion skills.* ***Right:*** *This can include picking up a set of keys, reaching for an unknown object, or robotic search and exploration utilizing drones.*


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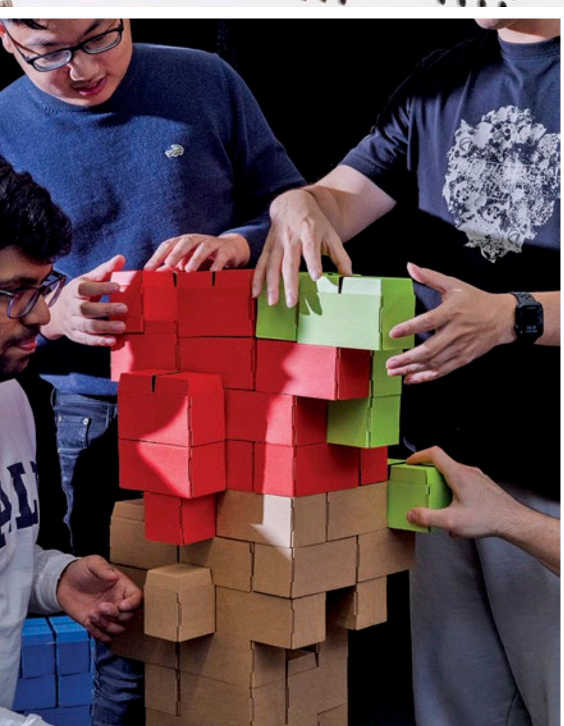
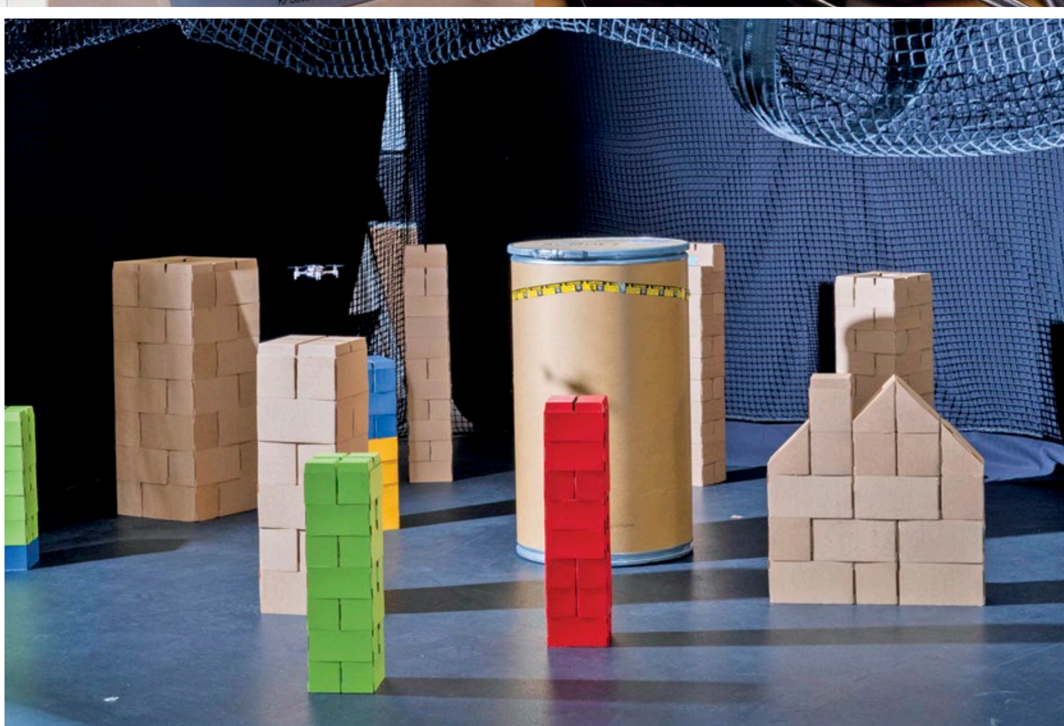


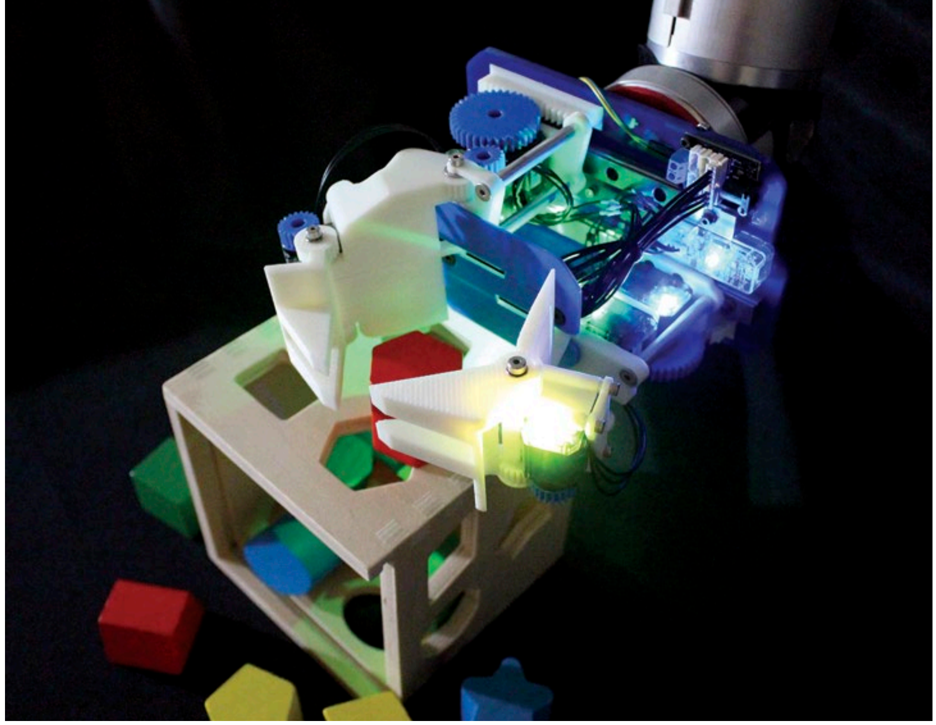


Aaron Dollar

Grasping a complex task

These days, you can occasionally find robots that can reliably pick things up and put them down. But for a robot to manipulate an object within its grasp - for instance, rotate it without dropping it - that's a whole other level of dexterity. The lab of Aaron Dollar, professor of mechanical engineering & materials science & computer science, is building devices capable of those kinds of complex tasks.

"We primarily focus on finding novel ways to address the toughest challenges in robot manipulation, especially regarding robotic hands," Dollar said.



"We primarily focus on finding novel ways to address the toughest challenges in robot manipulation, especially regarding robotic hands."

Top: *Aaron Dollar's is building robotic hands capable of complex manipulations, redefining finesse in robotics by rotating objects without letting them slip away.* ***Bottom:*** *An advocate for open access to research, Dollar has provided numerous designs to the public that are available to download.*

"We're asking 'How can we impart human-like dexterity onto robots?'"

Projects that have come out of his lab include dexterous prosthetic hands for amputees; grippers for "floating" vehicles (aerial, underwater, or space); and hands that can reorient objects within their grasp, along with computing approaches that allow them to be controlled with minimal sensing.

Dollar has long advocated for open access and established the Yale OpenHand Project, which offers several 3D-printable designs for download. He's also the co-creator of the Yale-CMU-Berkley Object and Model Set, a group of everyday objects to be used as universal benchmarks for testing robotics and prosthetics.

Dollar's boundless curiosity has expanded his lab's mission to well beyond robotic hands, and his list of projects now includes numerous conservation-related efforts (for more on these, see page 48).

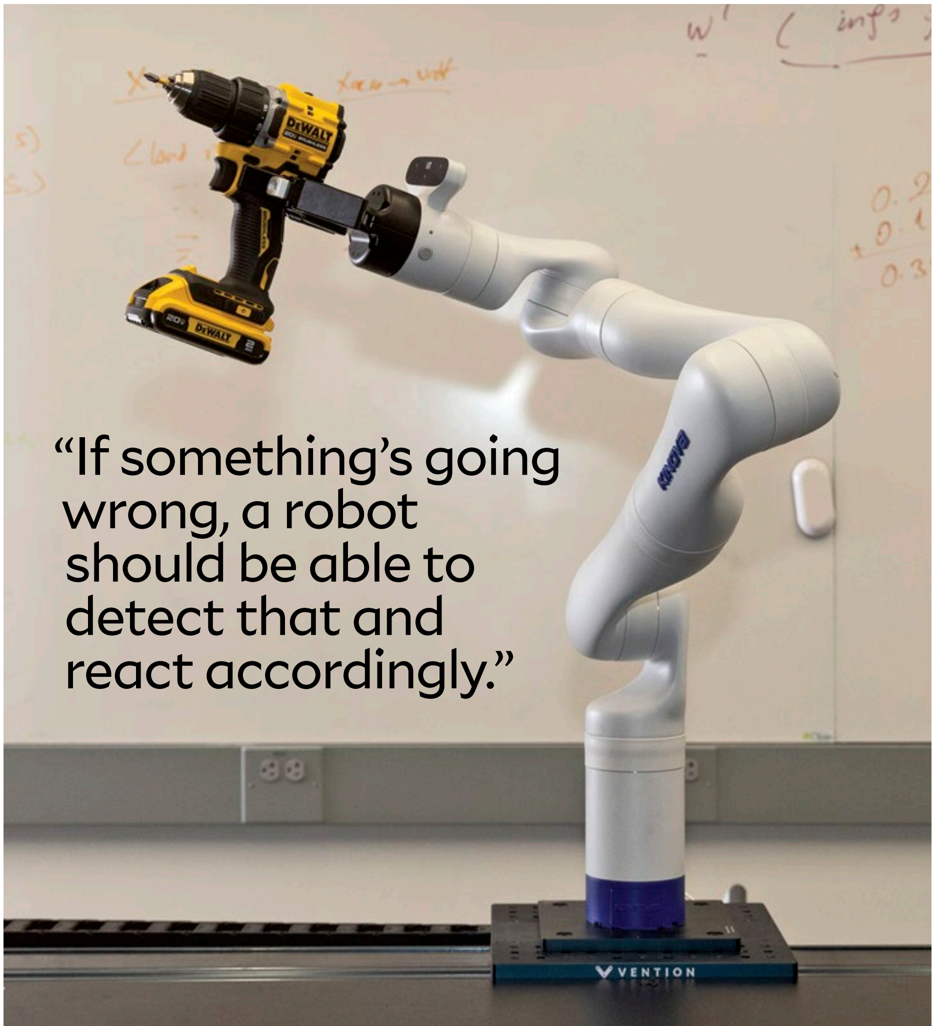
Tesca Fitzgerald
Helping robots ask for help

Whether it's helping with everyday tasks in the home or among workers in a factory, we need to think about robots as teammates.

"We want robots to be flexible to changes within that team," said Tesca Fitzgerald, assistant professor of computer science. "If something's going wrong, a robot should be able to detect that and react accordingly."

Historically, robots have thrived in settings that don't change much — working at a conveyor belt, for instance. But when people become part of those settings, changes are frequent and can often throw a robot off its game. Fitzgerald's research focuses on helping robots adapt to those changes — an increasingly critical ability as robots become more common in human environments. Even small changes in a task — like a jar made from different material — can be tricky if a robot hasn't been trained for that variation.

Photography by Shelli Weiler / Yale School of Art MFA Photography Program (top & bottom)



"If something's going wrong, a robot should be able to detect that and react accordingly."

__Top:__ Tesca Fitzgerald, who came to Yale in 2022, is among a recent cohort of roboticists who have greatly bolstered Yale Engineering's ranks in the field of robotics. __Bottom:__ Fitzgerald's research aims to give robots the ability to improvise and be able to adapt to changing circumstances and environments. This can even include knowing when to ask a human for help.

Fitzgerald develops algorithms that allow a robot to interpret its interactions with a human teacher and enable that robot to ask for help with unfamiliar problems. Part of her research considers Human-in-the-Loop Machine Learning, a widely adopted paradigm for instilling human knowledge in robots. In doing so, Fitzgerald is developing methods for robots to actively learn and adapt to novelty.

"If we assume that these robots will work around people, why not help a robot to ask us for help?" she said.

“We’re creating robots that can adapt their morphology and behaviors on demand.”

Rebecca Kramer-Bottiglio

Taking cues from nature

Robots are typically designed to perform a finite collection of tasks in a known context. In contrast, the natural world is filled with soft, adaptive systems capable of performing many tasks in varied environments. Rebecca Kramer-Bottiglio is bridging the gap.

“Biological organisms possess an exceptional capacity to adapt to new contexts, tasks, and environments, and we want to realize robots that can do the same,” said Kramer-Bottiglio, the John J. Lee Associate Professor of Mechanical Engineering & Materials Science. Her lab designs novel multi-functional materials and uses them to build soft, morphing robots.

With innovations in materials and fabrication techniques, Kramer-Bottiglio’s team is pushing forward the capabilities of soft-material robots. Her lab has produced a number of attention-getting technologies, including an amphibious turtle-inspired robot featuring morphing limbs that switch from legs to flippers, allowing the robot to move efficiently both on land and in water. They have also pioneered “robotic skins” — flat, skin-like robots made of elastic sheets embedded with sensors and artificial muscles. The team previously demonstrated robotic skins wrapped around soft deformable objects to easily turn such inanimate objects into animate robots. Robotic skins can be applied to and removed from different objects to generate robots with different functions.

“We’re creating robots that can adapt their morphology and behaviors on demand,” she said. “Changing both the body shape and the way it moves helps the robot to overcome obstacles or continue task performance despite changing terrains and environments.”

Left: *Rebecca Kramer-Bottiglio is pioneering soft-material robots, designing materials for robots to shapeshift and maneuver across diverse terrains.*

Danny Rakita

Preparing robots for the real world

__Above:__ Danny Rakita is developing cutting-edge algorithms enabling robots to move intelligently and interact safely, ensuring their actions are understandable to humans for effective collaboration across numerous critical sectors.

Unlike people, robots have no common sense or intuition for their own motions. Without corrective measures, a robot might naively drive its elbow into a table or over-rotate a cup and spill water on the floor. Danny Rakita, assistant professor of computer science, sets them on course.

"At a high level, I develop algorithms that allow robot manipulators to effectively move in the world around us," he said.

Specifically, these algorithms are designed to efficiently generate multi-step, long-horizon robot motions that achieve some high-level goals, all while satisfying key objectives and sub-goals along the way. Such objectives and sub-goals could include avoiding collisions, visually finding objects that are currently unseen, or gently nudging secondary items out of the way in a cluttered refrigerator. Further, Rakita aims to make sure that anyone working with or alongside the robot is able to intuitively specify new goals for the robot and correctly interpret what the robot will do next. That way, even people who aren't experts can operate or collaborate with these robotics systems. It's an interdisciplinary approach that uses techniques across robotics and computer science, such as optimization, planning, and machine learning.

"Overall, the goal of my work is to enable robots to help people with critical tasks," he said. He notes that doing so can help advance the use of robots in numerous fields, including full-time homecare, home assistance, telenursing, robot surgery, disaster relief, large-scale manufacturing, nuclear materials handling, and space robotics.

Brian Scassellati

Social engagement through robotics

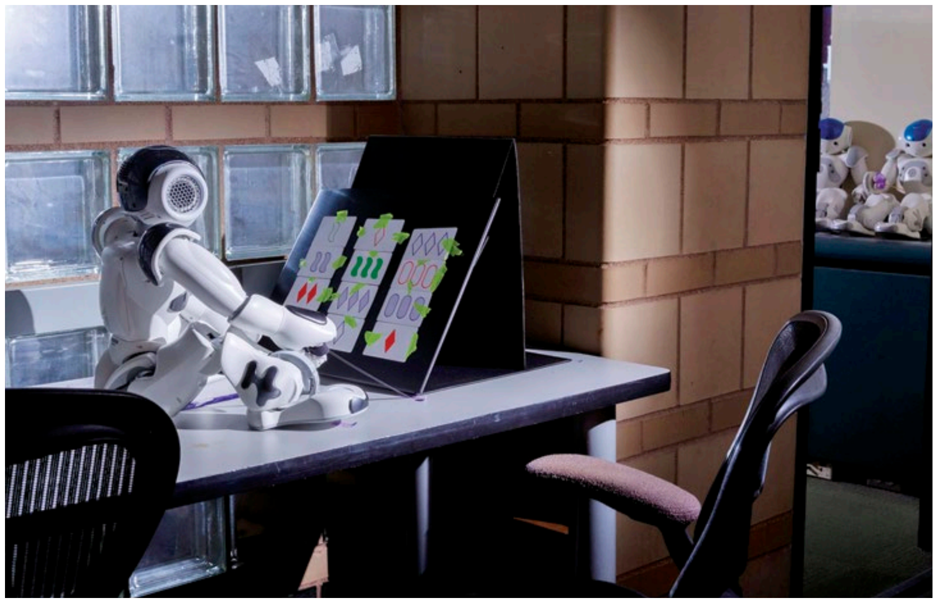
Human behavior has been studied from many perspectives and at many scales. Psychology, sociology, anthropology, and neuroscience each use different methodologies, scope, and evaluation criteria to understand aspects of human behavior. Brian Scassellati uses computer science, and robotics in particular, to provide a complementary perspective on the study of human behavior. His research focuses on building embodied computational models of human social behavior, especially the developmental progression of early social skills.

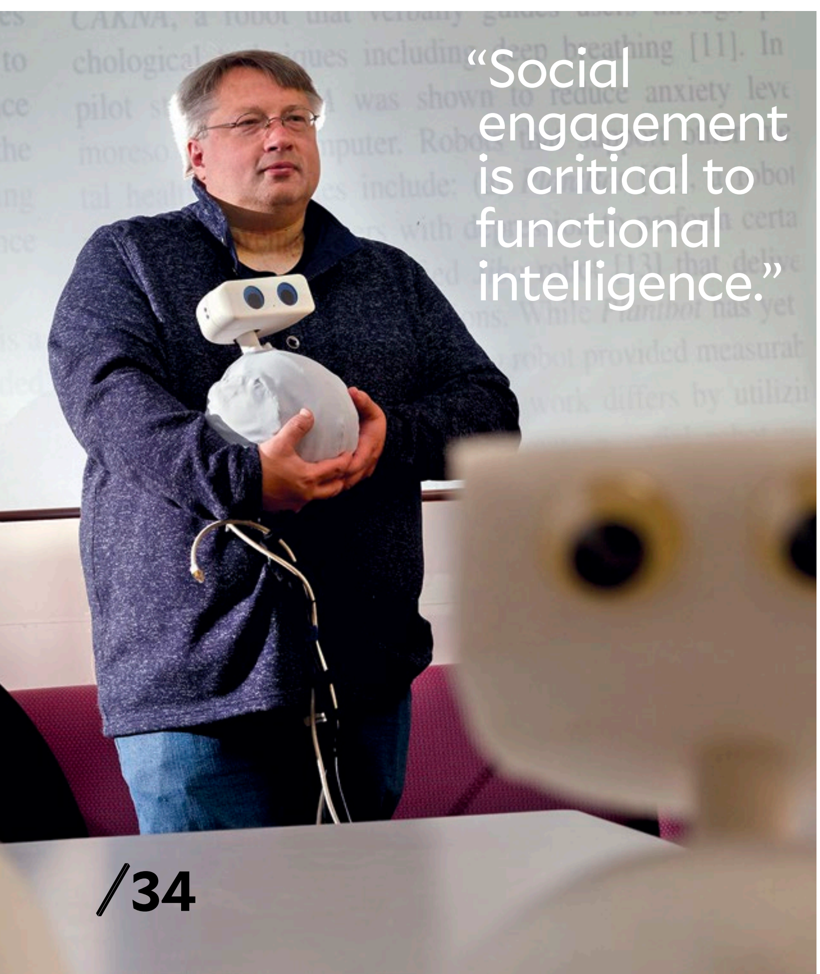
"Social engagement is critical to functional intelligence," said Scassellati, the A. Bartlett Giamatti Professor of Computer Science and Mechanical Engineering & Materials Science.

His work uses computational modeling and socially interactive robots to explore questions about social development. To do so, his research team takes on the considerable challenges in building interactive robots. As robots move out of controlled settings and into the settings of everyday life, there is a critical need to engage untrained users in ways that are comfortable and natural. Scassellati and his team are providing a structured approach to constructing robotic systems that elicit and respond to the natural behaviors of people.

"Even though they have a serious amount of engineering and computational effort behind them, these robots have real impacts on real people in the real world — in schools, in hospitals, in malls, and on the streets," Scassellati said.

*Brian Scassellati designs robotic systems that elicit and respond to the natural behaviors of people. These include **Top:** Using games to improve a robot's ability to learn from humans; **Bottom left:** Aid in anxiety management through deep breathing exercises and; **Bottom right:** Making human-robot interactions more seamless and intuitive in various scenarios.*





"Social engagement is critical to functional intelligence."

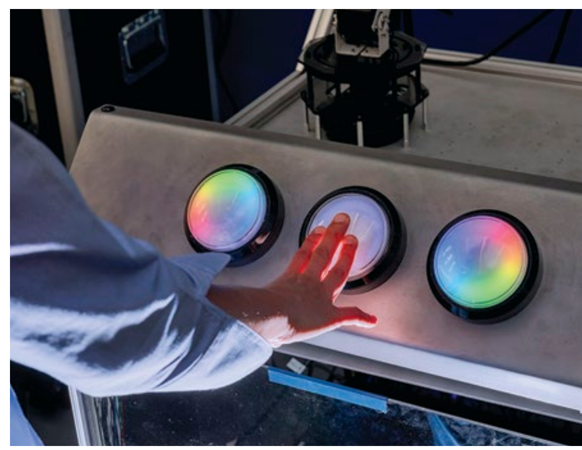
> "It's not just enough for the robots to work and function. Robots and humans have to actually understand each other."

Marynel Vázquez

Robots in group settings

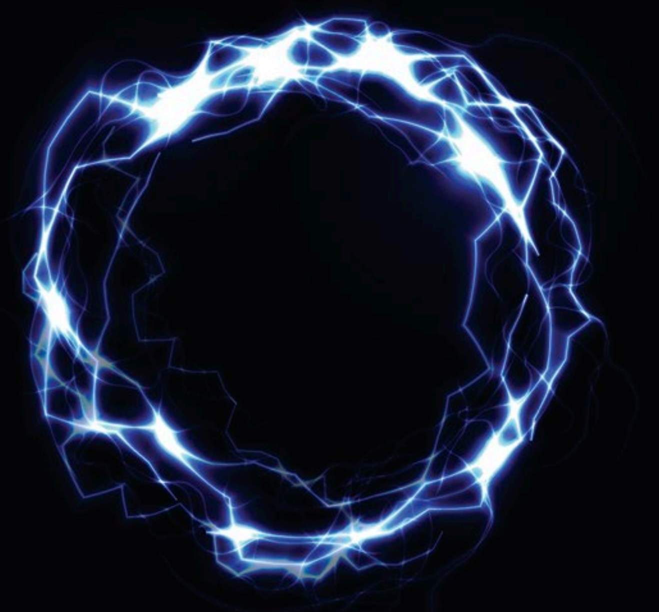
As more robots begin sharing our spaces, the more important it is that we get along with them. That's where Marynel Vázquez comes in. The assistant professor of computer science specializes in Human-Robot Interaction. One example of her work can be seen with Shutter, a robot designed in her lab that interacts with passersby and offers to take a photo as a memory of their time on campus. The researchers track when passersby choose to interact with Shutter, and how they behave toward the robot.

It's one of the projects designed to help robots understand the many different social settings they could find themselves in. With an interdisciplinary approach that combines computer science (especially artificial intelligence), behavioral science, and design, Vázquez is helping robots make sense of their surroundings and how to respond appropriately. That means a lot of her studies involve social group settings. One-on-one encounters tend to get more attention in the robotics field, but Vázquez notes that multiple-party situations happen everywhere — on campus, in homes, and in workplaces.



Top, bottom right: *Marynel Vázquez specializes in Human-Robot Interaction, emphasizing the importance of robots to understand and respond appropriately in various group situations to coexist with humans effectively.* ***Bottom left:*** *Vázquez has extended her work into simulation platforms to evaluate social navigation algorithms.*

"Chances are the robots are going to see these multiparty encounters over and over again the more they are deployed in unstructured environments, doing things for people in the future," she said. "So it's not just enough for the robots to work and function. Robots and humans have to actually understand each other."



Electrifying clean energy

Lea Winter looks to spark a sustainable future

Walking through her lab, Lea Winter points to a contraption resting on the counter, featuring a slim glass tube wrapped in a coil. A lightning bolt shoots through the device. It looks like a cool desk toy, but it has the potential to play a big role in the future of renewable energy.

Winter's lab is taking on a complex and important challenge: Reimagining how we produce useful materials from carbon dioxide and nitrogen from the air or nontraditional water sources. Doing so could go a long way toward reducing and adapting to climate change. Typically, the chemical processes used to produce these materials have been activated by heat from burning fossil fuels. Winter, who places her research at the nexus of food, energy, water, and climate, is instead leveraging electron-driven processes such as plasma and electrochemistry.

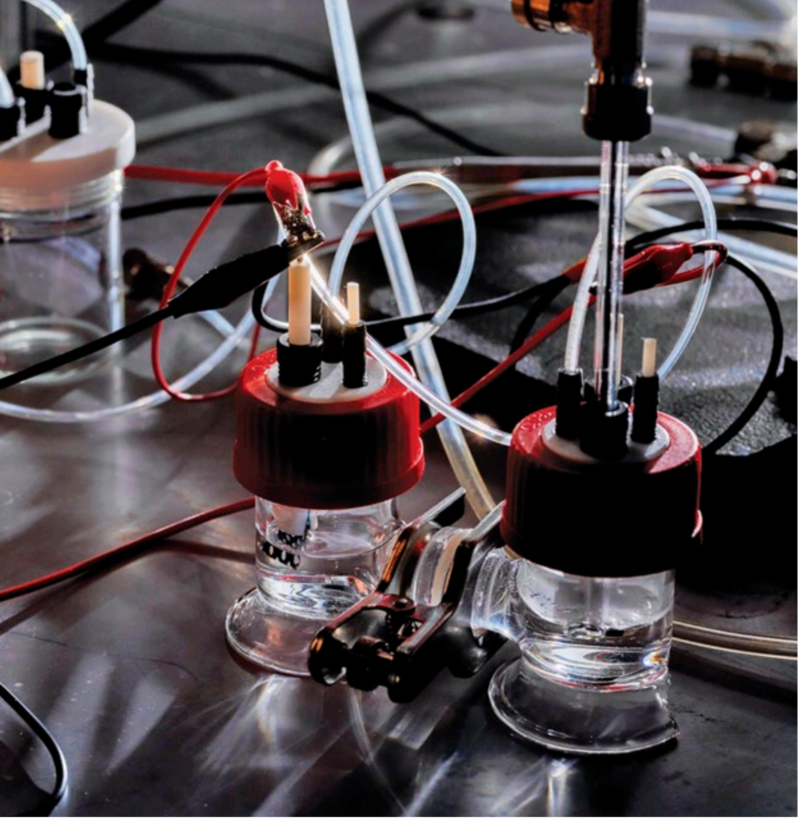
"We are moving towards an electrified, renewable energy future, where we have all these energy sources that are driven by electrons and electricity-based sources like solar and wind," said Winter, assistant professor of chemical & environmental engineering. "So we are thinking about how we can make fertilizers, fuels, water, and various types of chemicals that we use through processes that are driven by electrons and don't rely on fossil fuels."

Winter's research team designs catalysts and membranes to control these processes. One of her go-to tools is plasma, often referred to as the fourth state of matter. It's an ionized gas made of electrically charged particles — it's what lightning is made of. In her lab, they create it with a high-voltage electrode and a ground electrode to generate an electric field. "So you have electrons and ions and radicals and photons and all of these reactive species in your gas mixture."

With the particular type of plasma they're using, nonthermal plasma, the electrons are much smaller than the rest of the gas molecules. They move quickly, effectively at thousands of degrees Kelvin. The gas molecules, though, move much slower and stay at room temperature.

"This means that we can do reactions at room temperature in a gas

Lea Winter, assistant professor of chemical & environmental engineering



Left: *One of Winter's go-to engineering tools is plasma, created with a high-voltage electrode and a ground electrode to generate an electric field.* ***Right:*** *Conventional membranes separate contaminants from water supplies but don't break them down. Winter's electrified membranes can transform contaminants into harmless by-products like nitrogen or useful materials like ammonia.*

phase by using these hot electrons to activate our reactants and do subsequent reactions."

Winter has been on the Yale faculty since 2022, but her Yale and New Haven roots go much deeper:

"My dad grew up here. His parents originally moved here since my grandfather was a metallurgist, and I guess there was a lot of metallurgy going on in New Haven about 75 years ago. My dad ended up coming back here for his Ph.D. at Yale. He was in Applied Physics working with (Mechanical Engineering & Materials Science professors) Marshall Long and Mitchell Smooke, both of whom I took classes from when I was an undergrad. So my family's been in New Haven for three generations now."

When she was a senior at Wilbur Cross High School, Winter asked a volunteer from Teach for America about the reaction of two chemicals during an AP chemistry class. Unsure of the answer, the teacher told Winter to conduct her own experiments to find out for sure.

"That sparked in me this idea that you could figure out how to ask the right questions and design your own experiments to find the answer to how things work."

And that led to her designing her own research project, in which she synthesized her own chemicals, and entering the New Haven Science Fair. She also took part in a program that allowed students to take classes at Yale. She contacted Prof. Anjelica Gonzalez about taking her course Biotechnology in the Developing World. Gonzalez, who was teaching the course for the first time that year, was impressed by the student's initiative.

"Lea had reached out to ask if I would admit a high school student — and because, one — I wasn't even sure I would have any interest from Yale students and — two — Lea is tenacious and persistent, I said yes," said Gonzalez, professor of biomedical engineering. "And it was one of the best decisions I ever made."

As Gonzalez recalls, Winter did all the readings, asked questions, and led discussions. She challenged ideas presented in the class, pressed for more information on specific technologies — "AS A HIGH SCHOOL STUDENT!" Gonzalez wrote in an email.

"She is a thoughtful individual who was a superstar even then. I was lucky to have her as a student in that class... I learned as much from her as she might have from me."

And for Winter, it was a pivotal point in her academic career.

"That's where I really started to learn about all these challenges that exist, both in the developing and the developed world for access to health care," she said. "And I started to realize that a big reason why so many people were sick was that they didn't have access to enough nutrition or clean water, leading to all these waterborne illnesses."

Climate change also figured into this, she said. In situations of extreme heat or lack of electricity, there needs to be a way to keep vaccines viable.

Right: *From a young age, Winter was resolute in her quest to pose pertinent questions and craft her own experiments to unravel the mechanics behind how things function.*

After high school, she received her B.S. in Chemical Engineering at Yale, and then her Ph.D. in Chemical Engineering at Columbia. From there, she served as a NEWT Distinguished Postdoctoral Fellow at Yale in the lab of Menachem Elimelech, the Sterling Professor of Chemical and Environmental Engineering. That's when she began researching electrified membranes for the transformation of nitrate in wastewater.

"Meny's group specializes in membranes and water treatment," she said. "This was something that I was really excited about and had always cared about — that had really been sparked during my time as an undergrad at Yale."

Conventional membranes separate contaminants from water supplies, but don't break them down.

"So you've been able to clean your water, but you're left with this concentrated waste stream that ends up back out in the environment, usually where it's going to go back to contaminating groundwater that's used for drinking," she said.

The electrified membranes that her lab develops, though, can transform these contaminants into a harmless by-product like nitrogen, or useful materials like ammonia.

"I thought 'What if we take conductive materials and catalysts and put them into water treatment membranes, and then we can get all of these new advantages,'" she said. "And there were some people in Meny's group who were also thinking about the same ideas at the same time. So it was a really good time to come here to start to work on these systems and figure out how they work and how to make them."

Growing up in New Haven, Winter showed an early interest in science and how things work. She dug for fossils in her backyard, disassembled and reassembled pens, read and re-read her favorite picture book on the La Brea Tar Pits.

"I enjoy tinkering and problem-solving, and I've always been fascinated with understanding how things work," she said. "When I got older, I realized that I wanted to apply science and engineering to safeguard people, animals, and the environment. I was inspired to find ways to use fundamental chemistry and physics to design environmentally responsible technologies that prevent illness by improving access to clean water, reliable energy, and food, while maintaining a clean and safe environment."

From thoughts to watts

Where does your brain's energy go? A brain atlas offers answers

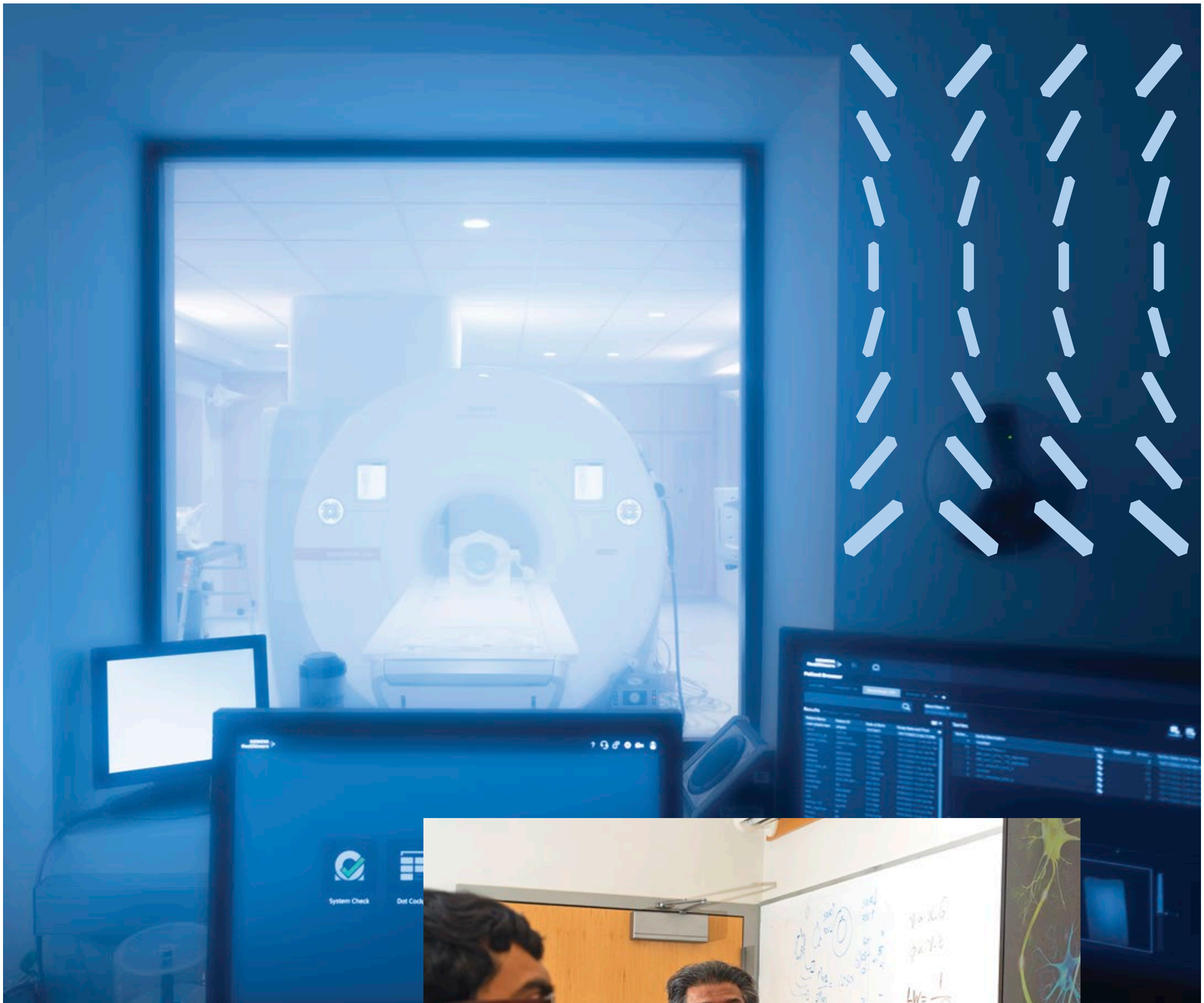
A conscious human brain takes up a lot of energy. Powering thoughts, memories, and every conscious moment, the human brain, a mere two percent of our body weight, consumes nearly a quarter of our body's glucose—that's what kickstarts the brain's fuel system.

"Along with a few other labs around the world, we've observed that brain activity is very energy-demanding," said Fahmeed Hyder, professor of biomedical engineering & radiology and biomedical imaging. "It consumes a lot more energy than what the size of that organ would indicate."

Every living brain has its own internal rhythm of activity created by periodic electrical discharges. Over time, that rhythm can vary across regions due to numerous factors, both in health and in disease. But exactly how these rhythms of brain activity and spatial distribution of brain energy vary is unclear. To get a better understanding of this, Hyder and his collaborators created a 3-dimensional brain energy atlas. Working with researchers at Fudan University in China, Hyder's aim for the atlas is to serve as the next generation of neuroscientific tools — a reference that explains exactly how much and where in the brain this energy is being consumed. Developed computationally, or *in silico,* a 3D energy map brings not only a better understanding of the brain's inner workings, but potentially better ways to study and treat Parkinson's disease and other brain-related maladies.

The researchers, who published their results recently in *Cerebral Cortex,* used positron emission tomography (PET) scans to measure the glucose oxidation of healthy subjects' "resting" brains (awake, eyes closed, with no cognitive tasks assigned). With this, they created a map of how much and where the brain processes glucose to produce adenosine triphosphate (ATP), the cells' main fuel source. Combining that map with existing maps of cellular and synaptic densities of other healthy subjects, Hyder and team assembled an atlas that charts the brain's energy consumption with unprecedented precision given the cellular architecture of the healthy brain. With their model, the researchers were able to determine that much of the brain's electrical activity clocks in at about

Fahmeed Hyder, professor of biomedical engineering & radiology and biomedical imaging



Top: *Hyder and his team used PET scans to measure the glucose oxidation of healthy subjects' "resting" brains (awake, eyes closed, with no cognitive tasks assigned).* ***Bottom:*** *Combining their results with existing research, the group created the Brain Energy Atlas, a publicly available toolbox for others in the field to gain new insights into the energy workings of both healthy and diseased human brains.*

1.2 Hz — surprisingly close to the rare *in vivo* measurements of human brain activity made in neurological patients.

In future work, the researchers plan to apply the model to other brain states (with eyes open, for example, or under sedation).

Calling it the Brain Energy Atlas, the researchers have made their atlas publicly available as a toolbox for other scientists in the field to gain new insights into the energy workings of both healthy and diseased human brains.

Much of what we currently know about shifts in the brain's internal rhythm of electrical activity comes from animal studies. That's because *in vivo* measurements of such electrical signals requires invasive electrodes, which are not feasible in the human brain. The Brain Energy Atlas provides a way to noninvasively estimate the human brain's internal rhythm of electrical activity.

It also opens the way toward simulating effects of various diseases that can affect specific ways that the brain consumes energy. For instance, depression can decrease the brain's pumping of sodium and potassium across the cell membrane. Now researchers can pinpoint such outcomes by comparing *in silico* predictions with *in vivo* measurements of brain metabolism.

The atlas takes into account what are essentially the brain's software and hardware components. The software is made up of the electrical signals that the brain processes. The hardware is the neuropil, composed of neuronal and glial cells with their associated synapses (that is, cellular and synaptic densities), which facilitates the electrical signals. Some regions of the brain have higher neuropil density, while others have higher neuronal activity. These variations make for a very complex interplay between the brain's hardware and software. The atlas Hyder and his team created captures that complexity.

Taking on this aspect of the brain is an arduous process that involves a lot of very dense calculations, something that has limited the number of labs delving into the field.

"There are billions of neuronal/glial cells that consume billions of molecules per second," Hyder said. "But it's very important to estimate these exactly, because it tells us: How far off are we in our understanding of what these cellular needs are?"

Specifically, Hyder's team is looking at ATP, the source of energy at the cellular level, and how much of it is needed by cells at the synaptic level and beyond. They've been able to determine that there's some metabolic heterogeneity — that is, some cells need more ATP than others. In doing so, they were able to create an "energy budget" of the brain — something that doesn't just determine how much energy the brain needs, but how much the brain is spending on each cellular and synaptic function.

"We can look at the amount of energy devoted to electrical activity versus the amount to non-signaling activity," said Adil Akif, a biomedical engineering graduate student in Hyder's lab, and a co-author of the study. "Or we can look at the amount of energy being used by synapses versus neurons. This energy atlas that we've developed allows us to ask in-depth how this crucial resource is used and distributed throughout the brain."

It's a question that could only be asked in the last 15 or so years, thanks in part to the BigBrain Project. That, in turn, is the work of a team of Canadian and German scientists who sliced a human brain into 7,400 sheets and then digitally reconstructed it to create a very high-resolution, 3D cellular map of the human brain.

A few years later, labs at Yale and a few others in the world developed PET measurements of synaptic density, a crucial component of Hyder and team's Brain Energy Atlas. Further, they teamed up with researchers in Denmark to conduct quantitative measurements of glucose oxidation in the brain.

With these very large sets of data, they can now look into the origin of the brain's metabolic variations. Besides shedding light on longstanding questions about the human brain, the project may lead to better and more individualized treatment of brain diseases. For example, Hyder said, if a brain lesion suggests that it could be caused by either neurodegeneration or by gliosis, typical medical imaging won't determine the origin.

"But using our budgets, we can ask 'What if this lesion was purely due to neuronal degeneration?' We can test that to give us a more cell-specific idea of the origin of these metabolic dysfunctions."

Armed with that knowledge, doctors can then determine the best course of therapy.

The brain is a complicated and mysterious organ, and Hyder acknowledges that there's a lot more to learn about how it works. He hopes that the Brain Energy Atlas will be more widely adopted within the field and used for new studies that will shed more light on brain energetics.

"This field of energy budgets of cells has been a very small subfield in neuroscience, but the true meaning and the true purpose of that field really has been a question mark," he said. "Other steps will have to follow, but this study is that one first step."


HOOD CONTROLLER
ALARM
PURGE
AFC5000
Hood 5-5
CO2
NIT
Elimelech
YALE

Critical resources, sustainable solutions

Yale environmental engineers are charting a sustainable course for mineral supply

Due to their essential role in electric vehicles, renewable energy systems, defense equipment and other applications, Menachem Elimelech says, the supply of critical minerals is vital for advancing technology, helping the environment, and even bolstering national security.

We just need to be smarter about how we maintain that supply, he says.

"I was just listening to one of these podcasts, and they're talking about deep-sea mining of all these minerals, which is a very bad idea in my opinion, and very destructive to the environment," said Elimelech, the Sterling Professor of Chemical and Environmental Engineering.

Elimelech urges his fellow scientists to tailor their efforts to specific materials and from specific resources. "Securing the domestic supply of critical minerals like lithium, cobalt, and rare earth elements is crucial to reduce reliance on foreign sources and maintain competitiveness in key industries necessary for economic growth and defense capabilities," he says.

Left: *Menachem Elimelech, Sterling Professor of Chemical & Environmental Engineering*

Even though conventional recycling methods have been fairly effective in recovering some common metals, like copper and lead, projections about their supply in the next 20 to 30 years are bleak. And recycling specialty metals, such as rare-earth

Left: *The mining of critical metals such as copper, lithium, cobalt, and nickel can be destructive to the environment.*
Right: *Elimelech's device uses a nanoporous membrane that serves as a molecular filter, helping distinguish the various materials in the mixture.*

elements, is particularly tricky because these materials are used in such small quantities for computer chips and other products with complex elemental compositions.

To meet the rising demand over the next few decades for both common and specialty metals, new thinking and new methods are needed to improve the reuse rates. The high consumption rate of these materials not only jeopardizes their supply chains but is also detrimental to the environment. For instance, the increased need for batteries has jeopardized the supply of lithium, an essential element for low-carbon energy technologies.

Elimelech says that it's crucial that we shift away from heavily relying on mining, single-use consumption, and disposal. Rather, there's a lot of very valuable minerals that can be found in the overlooked source of industrial wastewaters—that is, the by-products that result from industrial processes. The oil and gas industry, for instance, discharges wastewater containing various metals at a concentration much higher than what's found in natural bodies of water. Go to a battery-making plant, and you'll find an abundance of lithium in the wastewater.

"You need to go to the industries," Elimelech said. "If you want to recover cobalt or nickel, don't try more mining. Go to wastewater, recover it and reuse it and it will be less damaging to the environment."

Focusing on industrial wastewater isn't just environmentally friendly, it's also a lot more efficient. "Because the concentration in the ocean is so low, you need to process millions of gallons of water and it's not economical," Elimelech said.

Elimelech's lab has recently begun work that aims to steer industry and the research community toward best practices for effectively extracting these valuable resources.

"We want to give direction about when it would be viable to recover all these critical metals, because many people talk about recovering them from the ocean and the sea, and we're showing that it's completely not viable."

For one project, the Elimelech lab has collaborated with the Yale School of the Environment to focus on prioritizing which metals should be recovered from wastewater and brine.

"We want to recover some of these metals that are otherwise being wasted because they're high-value and in potentially short supply, especially as metals are becoming more and more widely used with the energy transition," said Ryan DuChanois, a former Ph.D. student in Elimelech's lab who led a study on the project that was recently published in *Nature Water*.

But there's a wide range of metals that could potentially be recovered, and only so many available resources to do this kind of work.

"Because there are so many different metals across the periodic table, we can't focus on all of them," said DuChanois, now a postdoctoral research associate at Rice University.

Right: Elimelech believes priority should be given to metals that are geologically scarce and vital to essential industries.

"So we saw this need to try to identify which metals are the most important. Through this process, we're slowly narrowing down our list."

As collaborator Prof. Thomas E. Graedel notes, these sources are so rich in metals that it can be difficult getting what you want.

"It's quite important that you understand which materials are worth going after, and then from a standpoint of water treatment, which ones you can be successful going after," said Graedel, the Clifton R. Musser Professor Emeritus of Industrial Ecology, Professor Emeritus of Chemical Engineering.

For the study, the researchers assess the feasibility of recovering these metals from various water sources by comparing the estimated costs to market prices. It also highlights materials and processes that, with further research and development, could serve as more sustainable alternatives to metal recovery.

The researchers acknowledge that their goal is an ambitious one. Various geopolitical factors make it tricky for the scientific community to agree on which metals to prioritize for recovery. But the researchers are hopeful that guidelines are a good start. For instance, they advise that priority should be given to metals that are geologically scarce and vital to essential industries. Examples include rare-earth metals, battery materials, gallium, and vanadium.

Going forward, Elimelech said he hopes to narrow the list of prioritized metals even further and to see more efforts in developing recovery technologies that have low chemical demand and low-energy consumption.

• • • • • • • •

To help separate the right metals from the unwanted ones in these wastewater sources, Elimelech's lab is also focusing on the use of specially developed membranes for extracting critical materials from water — a method known as nanofiltration.

"Nanofiltration is used widely at the moment, but we think that there's still a lot of potential that we cannot untap yet just because we don't have the right membranes," said Luis Francisco Villalobos, a postdoctoral associate who headed up a study in this research area in Elimelech's lab.

The technology employs a nanoporous membrane that serves as a molecular filter, distinguishing between various materials in the mixture. Unlike reverse osmosis membranes, which reject most ions and uncharged molecules, nanofiltration membranes allow some solutes to pass through the nanopores, allowing for the recovery of the most critical materials.

To fully unleash nanofiltration's environmental benefits, though, the researchers say it is necessary to optimize the membrane properties to better differentiate between dissolved components.

"Nanofiltration can be viewed as a platform for membranes that can be eventually selective for these similar species, because the way we manufacture them is relatively easy and we know how to work with them," Elimelech said. "And with some slight modification for this platform, I think we can make them selective."

To create next-generation nanofiltration membranes, the field needs to advance its fabrication of single-species selective membranes.

"If the membranes are better designed, then we can use them to separate more complex solutes that are very similar to each other," said Villalobos, whose research was published last year in *One Earth*. "And this can have a huge potential to increase the circularity of certain critical materials."

For example, he said, if the pores of a nanofiltration membrane were designed so that they could differentiate between lithium and other ions, then the process could potentially be used to recover lithium from unconventional sources, such as from the brine that results from oil and gas production.

Elimelech said the field can draw from biological systems for inspiration. For instance, our bodies contain membranes that can separate between potassium and sodium, which are very similar.

"If you can incorporate such chemistry in these membranes, I think we can do these kinds of things," he said.

Fluxbot

With robotics, insight into a moose population and the state of a Newfoundland forest

About 100 years ago, moose were introduced to Newfoundland, Canada as a means of bringing more hunting to the island. At about the same time, the island's wolves had been eradicated. With an island full of arboreal trees and no natural predators, the moose population grew to one of the densest in the world. Now, a team of environmental researchers want to understand exactly how this has changed the ecosystem. So they called a roboticist.

Since at least the Industrial Revolution, much of technology has emerged to make various tasks faster and easier for humans. However, it's also made it easier to quickly consume the Earth's resources. Prof. Aaron Dollar, whose research in robotics places him squarely in the technology-advancing world, wants his lab to be part of an effort to benefit the natural world.

"I consider myself an amateur naturalist, essentially," said Dollar, who, as it happened, was speaking by phone while hiking trails in Guilford, CT and offering occasional commentary on noteworthy plants he encountered. "I love being immersed in the natural world and learning about the endless interconnections between parts of ecosystems. So I wanted to start doing work that aligned with that passion."

To that end, he's developed numerous seed projects designed for collaborations with researchers in other disciplines. Among these efforts, his lab has conducted projects ranging from biomechanical analyses of bird talons to using machine learning to categorize millions of plant images to provide additional scientific detail to museum collections.

"I want to use my skills for something that helps the planet rather than something that's going to hurt it. So I'm still kind of wrestling with that dichotomy there."

Dollar found that some of the biggest needs for environmental projects were in data collection and processing.

"We're definitely in the age of data – collection and the processing of data. So I started to explore some projects here and there."

One of these projects is a collaboration with the lab of Oswald Schmitz, the Oastler Professor of Population and Community Ecology, in the Yale University School of the Environment. Together, they're taking a very close look at how Newfoundland's increasing moose population is affecting the area's forests and its ecosystem.

Dollar and Schmitz first collaborated, years earlier, on developing a device that pounds the ground as a way to bring earthworms to the surface to monitor for invasive Asian Jumping Worms. The two labs merged again for the Newfoundland project by way of Connor Pan, a Ph.D. student in Dollar's lab. Pan was taking one of Schmitz's courses and mentioned that his advisor was interested in taking on some environmental science. As it turns out, Schmitz's lab was working on a project — the Newfoundland moose population question — that required some engineering expertise. Pan began working with Elizabeth Forbes, a postdoctoral associate in Schmitz's lab, on optimizing a device for the project.

It's the kind of collaboration for which Yale is uniquely suited, Schmitz said. With this kind of project, it's not enough for the environmentalists to specify what kind of technology they need — they need partners who can offer their own ideas.

"What's different here is that we're innovating," Schmitz said. "We have an idea of what we want as ecologists, but the engineers say 'OK, here's the technology that we can apply to hat.' And together, we've designed the instruments to actually serve a specific role. There's a lot of invention going on."


Fun fact: *This image was generated with artifical intelligence.*


LI-840A

The Dollar-Schmitz research team is combining traditional ecology methods like testing soil samples for carbon content as well as measuring the rate of carbon exchange with the atmosphere. Soil carbon flux, the rate at which carbon dioxide is exchanged between soil and the atmosphere, is a key feature of an ecosystem's carbon budget. Getting detailed measurements of soil carbon flux rates, though, is tricky. Commercial sensor systems are pricey, and manually collecting the data comes with all kinds of logistical issues.

Fluxbots: Robotic, autonomous devices outfitted with sensors that collect hourly data for as long as they are deployed.

Because the moose of Newfoundland are dispersed across a wide area, the researchers need to take these measurements in many locations simultaneously. Previously, researchers would either bring handheld devices that take "snapshot" measurements, or use large structures known as eddy flux towers that measure the gas exchange between the forest and atmosphere. These methods, though, lack a crucial precision — that is, they don't home in on exactly when and where these gas exchanges are happening.

To get around this, the Dollar and Schmitz labs developed numerous "fluxbots" — robotic, autonomous devices outfitted with sensors that collect hourly data for as long as they are deployed. For 55 minutes every hour, the devices' sensors take ambient readings of the temperature, humidity, and average atmospheric carbon dioxide. And for five minutes per hour, a chamber in the device mechanically closes and a sensor measures the buildup of carbon dioxide inside that sealed volume.

***Top:** The fluxbots have deployed in Newfoundland, Canada and the Harvard Forest. **Middle:** The fluxbots are more durable, flexible, and utilizing off-the-shelf parts, much less expensive than other devices. **Bottom:** After taking ambient readings of temperature, humidity, and average atmospheric carbon dioxide for 55 minutes, the chamber mechanically closes for five minutes and a sensor measures the buildup of carbon dioxide inside that sealed volume.*

"So at this point in the soil where we've installed this fluxbot, we can regularly measure how quickly CO_2 is being emitted to the atmosphere from microbial respiration, from root respiration, from the physics of the soil," Forbes said. "We can ask 'Are there cracks in the soil? How dense is the soil?' and all sorts of things that contribute to the rate of carbon dioxide emissions."

The numerous and consistent measurements provide a much clearer picture of what's happening in the forest than the conventional technology for this research.

"Traditionally, with those handheld units, they're very precise, but you can only get one measurement a day, basically," Pan said. "Whereas these produce 24 measurements a day."

Further, the fluxbots are relatively inexpensive to make and are designed to survive in the soil over months of Canadian weather. The devices are a refined version of ones that Forbes used in an earlier research project in Kenya.

"What this new technology helps us do is really isolate what the soil is doing, and really get down and spread the sampling over a vast area, because you've got lots of little instruments that you're measuring soil with simultaneously," Schmitz said. "The engineering has been a breakthrough because we can get real-time, very accurate, and continuous time readings of soil CO_2 emissions. That improves the quality of the data."

Dollar notes that any results that come out of the study will have implications well beyond Newfoundland about how carbon enters and exits the atmosphere, and what kinds of environmental effects it can have.

"There's a lot of interest in the carbon cycle because carbon is the main driver of climate change and carbon is cycled through the ecosystem," he said. "And nobody's really studied much about how animals affect that process. Animals, especially big animals like moose, can come in and completely graze down an area and obviously affect the plant life there."

Dollar has been an avid bird watcher for about a decade and has "always just been kind of infatuated with understanding nature." Besides the School of the Environment, his interest in nature has led to connections with Yale's Ecology and Evolutionary Biology Department as well as organizations outside Yale, like the Smithsonian and the World Wildlife Nature Conservancy.

"All of my hobbies are nature-based, and I've become super passionate about the planet so for quite a few years now I've been purposely looking into ways I can help through my research," he said. That interest took on an even greater urgency about 10 years ago when the first of his three children was born.

"It certainly changed me," he said. "We're at a point where just a single generation of humans with huge consumption appetites can irrevocably damage our ecosystems. I definitely want to leave a planet for them that is in a healthy state."

Tiny particles, big impact

W. Mark Saltzman, the Goizueta Foundation Professor of Biomedical Engineering, Chemical & Environmental Engineering and Cellular and Molecular Physiology

Mark Saltzman is pioneering medical marvels at the cellular level

Nanoparticles — roughly defined as particles between 1 and 100 nanometers — have always occurred in nature. Thanks to nanotechnology, though, they're also being produced in the lab. This has increasingly been the case in the last two decades, in which scientists have been creating them for everything from scratch-free eyeglasses to graffiti-proof wall coatings. The lab of W. Mark Saltzman, the Goizueta Foundation Professor of Chemical and Biomedical Engineering, and Cellular and Molecular Physiology, is fabricating nanoparticles to improve medical treatments for numerous maladies, as well as to prevent disease.

Saltzman began working on nanomaterials while on the faculty at Cornell University, a few years before coming to Yale. There, he focused on making nanoscale structures from materials to control cell interactions as well as making nanoparticles to administer gene therapy to cells. It was at Yale, though, when these efforts converged and led to a *eureka!* moment. He and his team realized that there was a relationship between the nanostructure of materials and their uptake by cells, which could lead to a breakthrough in gene delivery. ›

Above: *Of the 33 PhD students who have passed through Saltzman's lab at Yale almost half of them have had "nano" in their thesis titles — and plenty more were similarly immersed in nanoscience.*

"One of the students who came with me from Cornell — Amaryllis Sanchez-Santos — did the first experiments with nanoparticles for delivering drugs, and startled me with the effectiveness of nanoparticle delivery systems for chemotherapy drugs in a variety of experiments," Saltzman says.

Sanchez-Santos graduated in 2004, and 33 PhD students have since passed through Saltzman's lab at Yale. Almost half of them have had "nano" in their thesis titles — and plenty more were similarly immersed in nanoscience.

"It has been a trend that persisted because, one, we perfected techniques for making nanoparticles with controlled properties and, two, nanoparticles have the right properties for the effective delivery of agents in many situations."

The wide range of potential applications of nanoparticles has also led to numerous collaborations. For instance, Saltzman recently teamed up with Prof. Mingjiang Zhong in Chemical Engineering to explore how to improve the uptake of the particles by changing their surface topographies. Another collaboration, with David Stitelman in the department of surgery, demonstrates the use of nanoparticles in treating congenital diaphragmatic hernia, a condition that affects lung development in infants.

Here are some of the many other ways that the Saltzman lab is using nanoparticles to make important innovations.

Battling Multiple Cancers

Brain Cancer: One obstacle that has thwarted conventional treatment of brain tumors is the blood-brain barrier. It protects the brain's sensitive tissue from foreign elements, but it also blocks drugs that could otherwise be very effective for treating tumors. Researchers have managed to bypass this barrier with a method known as convection-enhanced delivery, in which the drug is delivered directly to the tumor. However, this procedure is complex and invasive and can only be performed a limited number of times. Also, most small molecules delivered directly to the brain are quickly flushed away by the cerebrospinal fluid.

A collaboration between Saltzman's lab and Ranjit Bindra, associate professor of therapeutic radiology and of pathology, may offer a solution. Their research has led to a promising drug delivery system that uses nanoparticles to fight particularly aggressive and hard-to-treat brain cancers. They have developed a delivery system that uses nanoparticles to get drugs past the blood-brain barrier and remain longer around the tumor. One variation of the method has been tested on mice with glioblastoma, the most aggressive form of brain tumor. Another was tested on mice with medulloblastoma, a cancer that mostly affects children and is particularly hard to treat because the tumors spread into the cerebrospinal fluid. In both cases, the animals receiving the treatments lived significantly longer than the ones in the control group.

Ovarian Cancer: The ability of nanoparticles to isolate a specific target and prevent the medicine they're delivering from spreading to other organs in the body has proven valuable in numerous applications. Among them is the potential treatment of ovarian cancer and uterine serous cancer. Working with Alessandro Santin, professor of obstetrics, gynecology, and reproductive sciences, Saltzman developed a particle-based treatment method to battle these two cancers. The research was funded by the Women's Health Resource at Yale and the National Institutes of Health.

Often, patients with high-grade ovarian cancer and uterine serous cancer will initially respond well to a conventional treatment of surgery and chemotherapy. One challenge, though, is that resistance to chemotherapy can lead to recurrence. Further, the tumors of these cancers are prone to spreading into the peritoneal cavity in the abdominal area. To combat this, doctors have administered epothilone B, a drug that's proven effective against these tumors. But it's a highly toxic drug that can have severe side effects.

"With bioadhesive nanoparticles, we can safely entrap a drug and deliver it so that it slowly releases in a high concentration, directly to our target, over a long time," Saltzman said. "By localizing the delivery of the drug, we are decreasing toxicity and increasing effectiveness."

Skin Cancer: Working with Michael Girardi, a professor of dermatology at the Yale School of Medicine, Saltzman's nanoparticles are also tackling skin cancer. Finding a simpler way to treat skin cancers such as basal cell carcinoma and squamous cell carcinoma has long been a holy grail in dermatology. Here, nanoparticles are one part of a two-pronged approach. As a potential alternative to surgery, the polymer-based nanoparticles carrying a chemotherapy agent are injected into the patient. Key to the treatment's success is that the nanoparticles are bioadhesive — that is, they bind to the tumors and remain attached long enough to kill a significant number of the cancer cells.

In many cases, ridding tumors with an injection could eliminate the need for surgery, the researchers said. It may also then avoid potential wound infections and other complications. Additionally, some patients with other medical conditions are poor candidates for surgery.

An injection-based therapy would also mean that patients could have multiple tumors treated in a single visit.

"They accumulate and bind to the tumor matrix, so one single injection lasts for a very long time — the particles stay there and slowly release the compounds," Saltzman says. "You need that to get rid of the lesion."

For comparison, the same drug was injected freely into tumors of control models without the nanoparticles. The researchers found that the tumors were significantly more diminished when the drugs were delivered by nanoparticles.

The researchers have since started the company Stradefy Biosciences based on the technology.

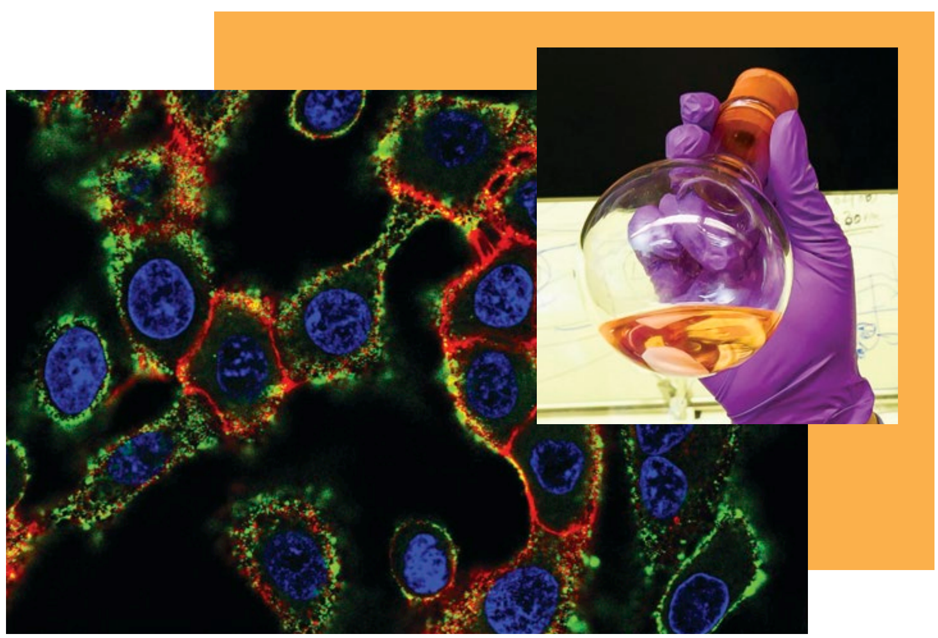
Disease prevention

Vaccines: In addition to treating disease, Saltzman and his team have worked on ways to prevent it as well. As part of that effort, they've developed an inhalable vaccine that successfully protects against the COVID virus.

Besides being more convenient for some people (it can be self-administered, and wouldn't upset those who don't like needles), it delivers the vaccine directly to the lungs, where the virus is likely to cause some of the biggest problems.

Saltzman previously worked with the lab of Akiko Iwasaki, Sterling Professor of Immunology, on what Iwasaki calls a "prime and spike" COVID vaccine delivery system. The "prime" half of the system involves injections of the messenger RNA (mRNA) vaccine into a muscle — the shot that millions of people have already received. These vacci-

Below: *Saltzman's lab utilizes nanoparticles in medicine to improve treatments for various diseases, with innovations in cancer treatment, vaccine delivery, sunscreen development, gene therapy, and more.*



nations were followed up with familiar spike proteins or spike mRNA that are derived from the coronavirus and are sprayed directly into the nose.

In their latest study, the researchers showed that the shot isn't necessary to provide protection.

"We just gave two doses, a prime and a boost, intranasally, and we got a highly protective immune response," Saltzman says.

It also opens the door to delivering other mRNA therapeutics for gene editing and gene replacement therapy in diseases like cystic fibrosis.

It's a significant advance, since scientists have had trouble creating lung-targeted mRNA therapies. Typically, these therapies have had poor transfection efficiency — that is, only a fraction of administered nucleic acids make it into cells that lead to expression of the encoded protein. Also, in the past, the nanoparticles that deliver the mRNA have caused inflammation and other problems. The Saltzman group got around this hurdle in part by using a nanoparticle made from poly(amine-co-ester) polyplexes, or PACE, a biocompatible and highly customizable polymer.

Saltzman and Iwasaki co-founded the start-up Xanadu Bio to develop this vaccine technology and potentially other applications.

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Sunscreens: In another effort to ward off disease, Saltzman's lab has developed an improved sunscreen to prevent skin cancer. Most commercial sunscreens are effective at preventing sunburn. The problem, though, is that the products' chemicals often seep into the skin and then the bloodstream. Besides hormonal side effects, this can lead to the kinds of DNA damage in the skin that these sunscreens are designed to prevent. Working again with Michael Girardi, Saltzman's lab developed a new sunscreen that stays on the skin's surface. The key is bioadhesive nanoparticles that carry the active ingredient.

"We found that if we apply them to the skin, they don't come off, and more importantly, they don't penetrate any further into the skin," Saltzman said.

This new sunscreen proved equally well at protecting against sunburn — the direct effect of ultraviolet (UV) rays — as commercial brands. The biggest difference is in the indirect — and much less studied — effects of UV. When the active ingredients of sunscreen absorb UV light, a chemical change triggers the generation of oxygen-carrying molecules known as reactive oxygen species (ROS). If a sunscreen's agents penetrate the skin, this chemical change could cause cellular damage, and subsequently, skin cancer. Studies on users of commercial sunscreens have also found traces of the products' chemicals in breast milk and urine.

To test penetration levels, the researchers applied strips of adhesive tape to pig skin covered with sunscreen. After six hours, the tape was removed, along with a layer of skin. Traces of commercial sunscreen were found on the 20th tape strip — meaning it had soaked into the skin 20 layers deep. The Yale team's sunblock, though, came off entirely after the first tape strip.

Tests also showed that a substantial amount of the Yale team's sunscreen remained on skin's surface for hours, even after being in the water. When wiped with a towel, the solution was easily removed.

Gene Therapy

Gene therapy, in which a patient's genes are modified in a specific way, has shown great promise in treating numerous diseases. Saltzman's nanoparticles could advance the field even further.

Working with professors Peter Glazer and Marie Egan at the Yale School of Medicine, Saltzman developed a novel chemistry to synthesize a new family of polymers to create a particle that is non-viral, but mimics a virus by introducing a specific gene into diseased cells. This approach allows the researchers to alter the DNA without removing any cells from an organism. Potential applications include treatments for Huntington's Disease and sickle cell disease.

More conventional gene-editing approaches typically involve removing the cells from the patient. Once the genes have been edited, they're transplanted back into the patient. The Yale team's system, though, can make these gene alterations *in vivo*. Saltzman noted that their method could be especially valuable for diseases such as cystic fibrosis that affect the lungs and digestive systems, Saltzman noted, since doctors can't remove those organs to edit genes outside the body.

Saltzman and Glazer first worked on gene-editing methods about 15 years ago, initially working with molecules synthesized in Glazer's lab. Glazer reached out to Saltzman, as their molecules proved too large to penetrate the cells needed to manipulate the genetic repair system, and then Saltzman developed the nanoparticles to carry the novel agents into cells.

They found that the nanoparticles, carrying a combination of a synthetic peptide nucleic acid (PNA) molecule and a donor strand of DNA, could travel to cells in even remote areas of the body. Once there, the PNA binds to the target gene to create a three-stranded helix. The donor strand of DNA then serves as a template to the faulty DNA, stimulating natural DNA repair mechanisms to repair the malfunctioning gene.

Other methods, such as CRISPR, that use enzymes to sever DNA can often affect other genes that don't need repair. That's significantly less likely to happen with the method devised by Saltzman's team because it leverages the DNA's natural repair mechanisms.

In another recent study in *Science,* Saltzman and collaborators demonstrated that they could use nanoparticles designed to correct certain mutations to mitigate the effects of cystic fibrosis in affected organs.

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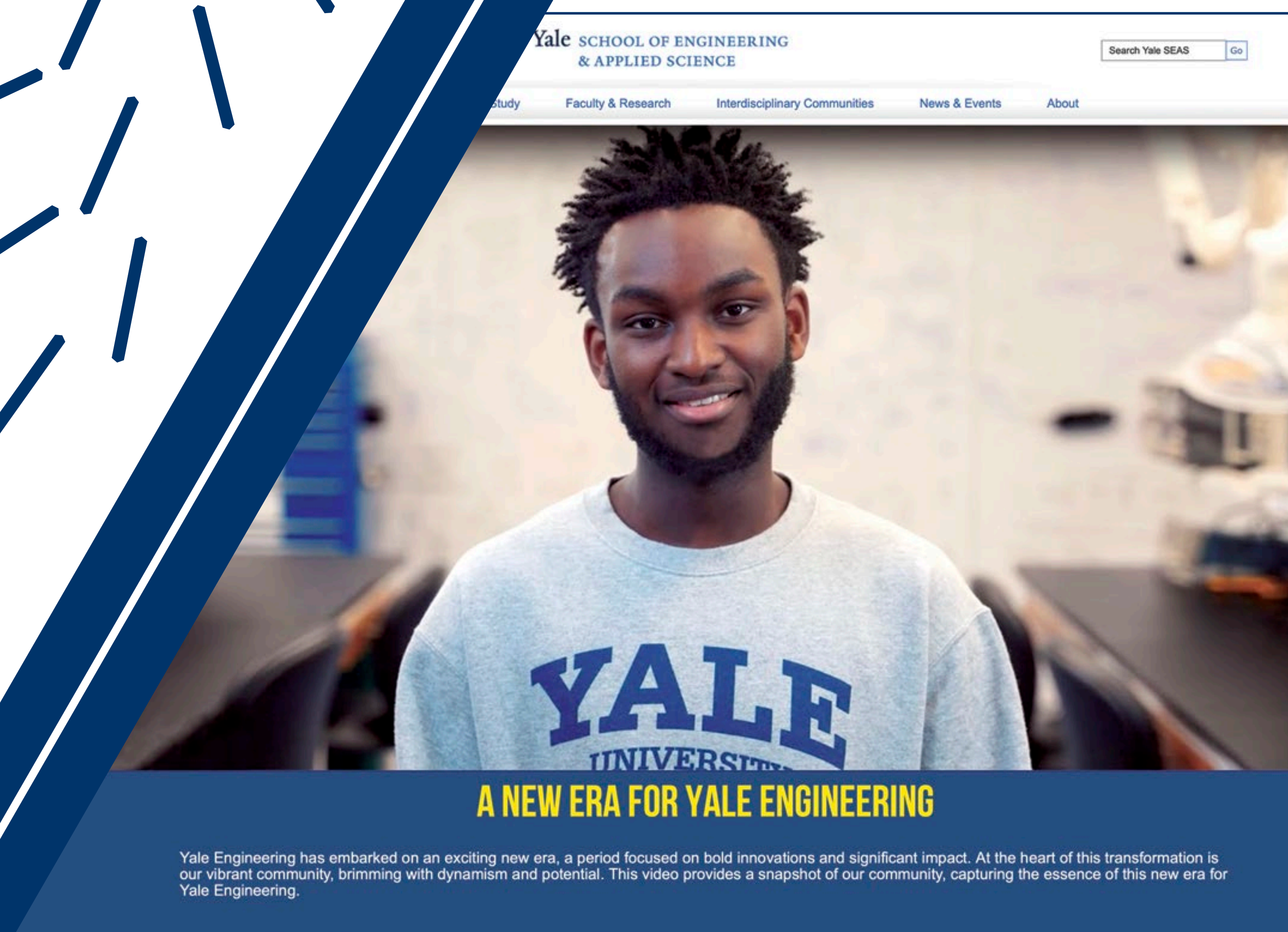

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