# MechE CONNECTS

Spring 2024

## The breadth of MechE

MechE
CONNECTS
Spring 2024 | meche.mit.edu

## Table of Contents

Six student teams participated in the annual 2.009 (Product Engineering Processes) Build Challenge! The energy was electric as students raced across Killian Court to "return the Mojo to the Tree of Life." Credit: 2.009 Photography Team

MITMECHE

## About MechE

The MIT Department of Mechanical Engineering – MechE – advances the design, fundamental principles, and realization of physical systems with mechanical engineering at their core. Our research and education programs embody MIT's motto "mind and hand", as well as "heart", combining theory and hands-on learning with a commitment to make the world a better place. By uniting the core areas of MechE with emerging frontiers, we discover new knowledge, create innovative technologies, and train future leaders who help address the biggest challenges facing our society.

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**Cover:**
MIT Mechanical Engineering research and teaching spans many collaborative themes. The core principles of mechanical engineering center the work of broadly-trained engineers and interdisciplinary teams.

Credit: Ellen Weinstein

**Have updates or news to share with the MechE community? Have ideas for future issues of MechE Connects?**

**Email us at mecomms@mit.edu**

> **"...Mechanical Engineering has expanded from its traditional areas to encompass many emerging technologies, ideas, and principles. This breadth allows our department to confront multidisciplinary challenges, while embracing the core principles that have always defined MechE."**

Dear MechE Alumni, Students, Faculty, Staff, and Friends,

Over the years, Mechanical Engineering at MIT has expanded from its traditional areas to encompass many emerging technologies, ideas, and principles. This breadth allows our department to confront multidisciplinary challenges, while embracing the core principles that have always defined MechE. This is reflected in the research, education, and impact of work happening in our department.

Since being appointed Department Head in July 2023, I have seen how problem solving and innovation thrive in our classrooms, labs, and beyond. Our students are winning prestigious awards, publishing impactful research, and launching startup companies. Our faculty are teaching classes and conducting research at the frontiers of our field including in bio-inspired robotics, AI for engineering design, and large-scale energy storage. And our alumni are leaders in industry, academia, and the public sector.

Going forward, MechE's combination of "mind and hand" – which is core to MIT's mission – will play a critical role in addressing climate change, embracing the role of AI in physical systems, continuing to advance human health, and much more.

This issue of MechE Connects celebrates the incredible breadth of MIT MechE. For example, you'll learn about research in democratized design approaches (Prof. Faez Ahmed, student Lyle Regenwetter), muscle and tissue regeneration (Prof. Ritu Raman), quantum measurements (Prof. Vivishek Sudhir), machine design (Prof. Alex Slocum), autonomous marine vehicles (Dr. Michael Benjamin), and wearable robotic limbs for astronauts (student Erik Ballesteros). We also describe an AI-informed machine learning approach that responds to prompts with mathematical equations, developed by Prof. Pierre Lermusiaux and Abhinav Gupta PhD '22. And, you'll meet Vijay Vaitheeswaran '90, global energy and climate innovation editor for *The Economist*.

It would be impossible to showcase every facet of our work, or every contributor, but through the stories and highlights in this issue, we invite you to celebrate the breadth of MechE at MIT.

With best regards,

John

John Hart
Professor of Mechanical Engineering
Department Head

# The breadth of MechE

By Anne Wilson

Changes to the technological landscape, and to the needs of industry and society, are rapidly expanding the field of mechanical engineering into new areas, driving increased interdisciplinary collaboration, and even yielding new specializations.

"We are continuously pushing the boundaries of our own fields, and redefining what mechanical engineering is," says Faez Ahmed, ABS career development assistant professor of Mechanical Engineering.

Across MechE, faculty and staff are engaging in cutting-edge research at the frontiers of mechanical engineering, with teaching and exploration at the intersection of engineering and physics, math, electronics, biology, computer science, and many other fields of study. From the nanoscale to the macroscale, across communities, climates, regions, and geographies, and from the ocean floor to the far reaches of space, the incredible breadth of work underway in MechE is transforming ideas and insight into progress.

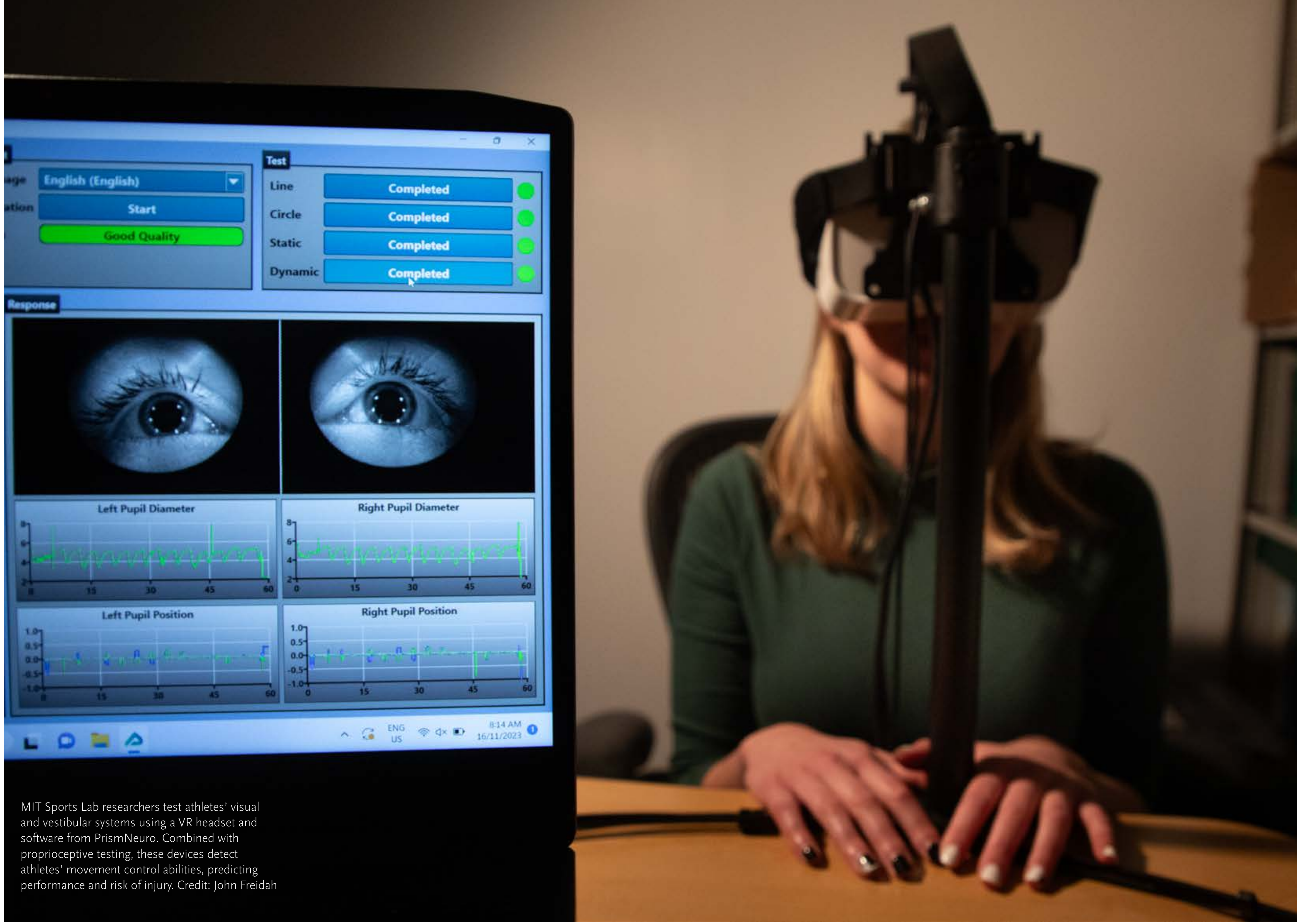
"The classical mechanical engineering department that you're thinking of might have cars, might have steam engines – we have all of those things, but we go so far beyond that," says Peko Hosoi, Pappalardo Professor of Mechanical Engineering.

## Sensory processing in sports

Close your eyes, extend your arms, and bring one finger to touch the tip of your nose. The ability to complete this or similar tasks, aided or unaided by sight, is owed to a sensory concept called proprioception. Proprioception involves a variety of complex sensations that allow you to sense the position and movement of your joints, along with the length of stretch in your muscles. These sensations create awareness of your body's positioning.

"Proprioception, basically, is 'how well do you know where your limbs are,'" explains Anette (Peko) Hosoi, the Pappalardo Professor of Mechanical Engineering and co-founder of the MIT Sports Lab. "If you have poor proprioception, you're more prone to injury and, when you're tired, stressed, or sick, proprioception is one of the first things your brain lets go of."

Hosoi's core research interests bring together fluid dynamics, bio-inspired design, and sports data and technology to tackle problems at the intersection of biomechanics, applied mathematics, and sports. Mixing experimental work, numerical simulation, and theoretical analysis, and combining elements of engineering design and mathematical optimization, her work has been used to guide the engineering design of robotic swimmers, crawlers, burrowers, and other mechanisms.



MIT Sports Lab researchers test athletes' visual and vestibular systems using a VR headset and software from PrismNeuro. Combined with proprioceptive testing, these devices detect athletes' movement control abilities, predicting performance and risk of injury. Credit: John Freidah

Understanding proprioception has applications in robotics, AI, and other mechanical designs, and of course, for keeping athletes healthy and at the top of their game. In a study aimed at understanding whether there are times during the semester when their proprioceptive ability might be lowered, Hosoi and her team are working with MIT varsity athletes to measure proprioceptive abilities.

The measurements are made in collaboration with PrismNeuro, a company focused on advanced human performance and founded by MIT alums. One part of the experiment is eye tracking; the other involves having the athlete place their feet on a tilt plate with a stopper that moves the plate to random positions. The athlete is then asked whether the plate tipped a little or a lot, and the team measures how well they perceive the angle of their foot.

"We measure throughout the semester to understand times when proprioceptive ability is low, which are times when the athletes would be more prone to injury," Hosoi says. "That's information we can give back to the coaches and say 'hey, looks like everyone is really stressed out with midterms right now, maybe go easy on them' – the coaches have been really receptive."

Research in the MIT Sports Lab seeks to improve athletic performance and equipment, advance understanding, and create actionable insights. Other projects underway involve a study to better understand possible differences between men's and women's soccer, a data-informed look at judging in aesthetic sports, like gymnastics, martial arts, or BMX, and studies of the physical performance of professional athletes to determine how good they are at making decisions on the court.

"It's hypothesized, but not known, that women's soccer is different [from men's soccer]," says Hosoi. What is known, she says, is that women suffer from more anterior cruciate ligament (ACL) tears than men, presumably from different stresses. "We can take tools that have been developed for fluid dynamics and turbulence to quantify the differences, then see if that translates to different stresses on the body."

An instrumented balance board is used to gamify the recovery process for lower limb injuries and target the injuries' effects on the body's movement control systems. Credit: John Freidah

Using an accelerometer and gyroscope built into the sole of the cleats of MIT men's and women's soccer, MIT Sports Lab researchers are trying to better understand what is guiding players' motion on the field. "Women's sports equipment is typically designed via 'shrink it and pink it,'" says Hosoi. "Understanding of the mechanics and the flow of the game instead, can translate into better equipment design – and, perhaps, fewer injuries."

Professor Anette (Peko) Hosoi, Pappalardo Professor of Mechanical Engineering. Credit: Tony Pulsone

## DeCoDE-ing product design

Faez Ahmed, assistant professor of mechanical engineering and ABS career development assistant professor of mechanical engineering, envisions a world where anyone with a great product idea can access the tools needed to bring their concept to life.

"There are many people with great ideas, but if a person sitting in a remote part of the world wants to create a new product, right now they have to learn CAD software or simulation software, then maybe they have a chance," he says. "We're looking at how we can democratize design with the help of AI models."

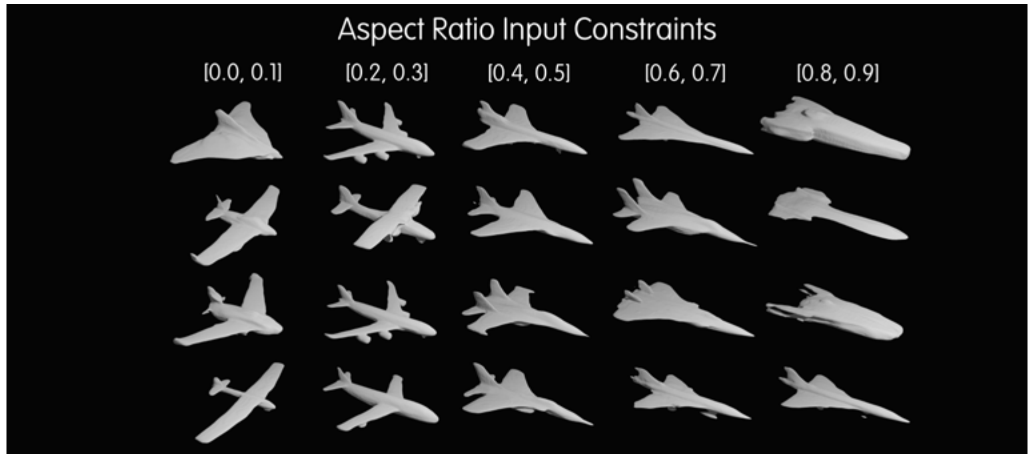
Ahmed leads the Design Computation and Digital Engineering (DeCoDE) lab, where research is focused on developing new machine learning and optimization methods for complex engineering design problems and on making generative AI models more precise and accurate.

DeCoDE research aims to assist human designers in creating better products and improving the design of complex mechanical systems – including innovative designs for faster cars and better aircrafts, bicycles, ships, and more – and to create a world where humans and AI can design together to solve global challenges.

Humans understand and present the initial parameters, then "AI can look at thousands of related designs and options and quickly present drawings and options that humans may not have thought about to come up with designs that are either better or more innovative."

The DeCoDE team approaches design challenges by fundamentally understanding them as mathematical problems, formulating them into generalized machine learning and optimization problems, to develop methods that are applicable to a wide variety of engineering problems at different scales. One of Ahmed's favorite challenges the team has tackled is the linkage mechanism problem.

Machines depend on mechanical linkages, an assembly of connected systems to manage forces and movement, but creating these assemblies grows more complex as more components are added. "In mechanical engineering, one of the fundamental things we study is how machines are designed – four bar or six bar mechanisms are a fundamental concept – but when the number of linkages starts increasing, it becomes an impossible problem for humans to solve."



Aircraft models created by a generative adversarial network (GAN) are engineered with precision to meet specific design constraints on fuselage length and wing span. Credit: Courtesy of the Researchers

Demonstratively, tracing just the letter M as a linkage mechanism equation entails hundreds of pages of complex explanation. Most current databases include tens of thousands of mechanisms. Ahmed's team created datasets with 100M mechanisms, and then trained their model with the data. With the design output, they've successfully manufactured products – in one case, a single-motor design that's capable of writing out "M-I-T."

Assistant Professor Faez Ahmed, Brit (1961) and Alex (1949) d'Arbeloff Career Development Professor in Engineering Design. Credit: Tony Pulsone

"What we're really solving is a mapping from design space to functional performance space and, given some functional requirements, we can go back to the design space and find the design. This is exciting because it applies to so many other domains – from molecule design to transportation systems – and no other method can solve it."

DeCoDE's datasets are publicly available on the lab's website, a concerted effort to help jumpstart research for the community. "One of the biggest gaps in engineering is a lack of datasets. People focus too much on data-driven method development, but really the methods can't do much without having data out there," says Ahmed, pointing to similar trends in computer science in the early 2000s.

"While there was substantial progress initially, the field saw monumental advancements following the creation of Stanford's ImageNet dataset. There was a cultural change. Today, our focus extends beyond individual contributions from a group; it's about the synergistic progress of the entire domain and requires community effort."

## Open-source underwater autonomy

Early investments in marine vehicle technology focused on "dull, dirty and dangerous" tasks, with control software that guided fairly straightforward point-to-point movement. Today, Autonomous Underwater Vehicles (AUVs) are used for a wide range of civilian, commercial, and military applications – including seafloor mapping, construction, security and defense, climate monitoring, oceanography, and marine research. Traveling unmanned through the ocean for long durations, AUVs need to be able to communicate, avoid collisions, and manage a host of other navigation and environmental challenges without human intervention or access to GPS.

"There's a difference between autonomy and control – control is deciding how to get from point A to point B, where autonomy is deciding what point B should be," says Michael Benjamin, principal research scientist in MechE's Center for Ocean Engineering. "As vehicles have become more capable in sensing and communicating, deciding where to go is no longer just a scripted set of points – it's being left up to the robots."

Custom tasks and modern applications require custom software, which is expensive and resource intensive to create. Benjamin, who leads the Marine Autonomy Lab, designs algorithms and software for autonomous marine vehicles, with a focus on making marine autonomy an accessible commodity.

Principal Research Scientist Mike Benjamin, left, with MIT/WHOI Joint Program PhD student Tyler Paine, prepare the MIT autonomous sailboat for operations on the Charles River. The sailboat is manufactured by Marine Robotics, LLC, with MIT providing the autonomy software. Credit: John Freidah

"If autonomy is a commodity, scientists who are using the software can focus on their area of expertise – which may be ocean sensing, or acoustics, or any number of areas – the autonomy of the robot, then, is just a means to do something," he says. "If the vehicle and autonomy are technologies you can use, the group of people who can explore the ocean with robots becomes a much bigger group."

Benjamin came to MIT as a post-doc in 2002, while also working as a civilian in a U.S. Navy research lab. He joined MIT as a research scientist in 2011. In both environments, he says, it was common for code to be discarded at the conclusion of a project. Students could spend years developing new code instead of building on what was previously created, which Benjamin found frustrating. Working with his then lab-mate, Dr. Paul Newman, who is now a professor at Oxford University, he set out to create an open-source codebase that can outlive any one vehicle, or any one researcher.

Mission Oriented Operating Suite - Interval Programming (MOOS-IvP) is a set of open-source C++ modules for providing autonomy on robotic platforms, in particular autonomous marine vehicles. Some 40 work-years of coding have now gone into developing the codebase, which is used at MIT and beyond. Instead of writing code and creating software from scratch, researchers can innovate using what's already available, making it possible to begin other research aspects sooner.

In Benjamin's group – where there's "a large emphasis on field experimentation, fixing, and improving"– recent projects include autonomous vehicles for aquaculture applications and software for companies working on hybrid, land-to-sea robots. As students work on projects and create particular autonomy capabilities, they contribute to the codebase. As a byproduct, he says, the team is improving the infrastructure behind the scenes and making it more powerful so each new project can start from a better position.

Principal Research Scientist Michael Richard Benjamin. Credit: John Freidah

"If everyone who wanted to explore the ocean had to start by writing a simulator and a control algorithm, it would be very difficult to accomplish anything," he says. "We've increased the number of seats at the table – which means the various minds you're bringing to the work increases, too."

### Cells as building blocks

Ritu Raman, assistant professor of mechanical engineering and d'Arbeloff Career Development Professor of Engineering Design, conducts research in biofabrication, a field where living cells are used as a building material, in the way other engineers might build with synthetic materials.

"As a mechanical engineer, I've long pushed back against the idea that people in my field only build with metals, polymers, or ceramics," she says. "I'm interested in building with biology."

Current research in Raman's lab is focused on building motor control systems (skeletal muscle and the nerves that control its movement) from scratch by patterning cells and proteins in precise 3D architectures. She aims to use these tissues to restore mobility in patients with motor disorders caused by traumatic injury or illness. Her team is also interested in using engineered muscle as an actuator to power soft and adaptable "living" robots.

"Engineering functional muscle tissue is important for a range of applications in medicine and robotics," she says. "Using living materials helps us make implants or machines that can dynamically sense and respond to their surroundings in a way that more traditional building materials (like metals and polymers) cannot."

Assistant Professor Ritu Raman, Brit (1961) and Alex (1949) d'Arbeloff Career Development Professor in Engineering Design. Credit: Tony Pulsone

Raman's team recently introduced Magnetic Matrix Actuation (MagMA), a vibrating gelatinous mat that can used for growing muscle tissue. The vibrating mat is composed of magnetic microparticles embedded within a soft hydrated gel that allows the researchers to impose forces on cells while they are growing and maturing. They found that muscle grown on MagMA gels could be programmed to grow highly aligned muscle fibers, generating strong and coordinated contractions.

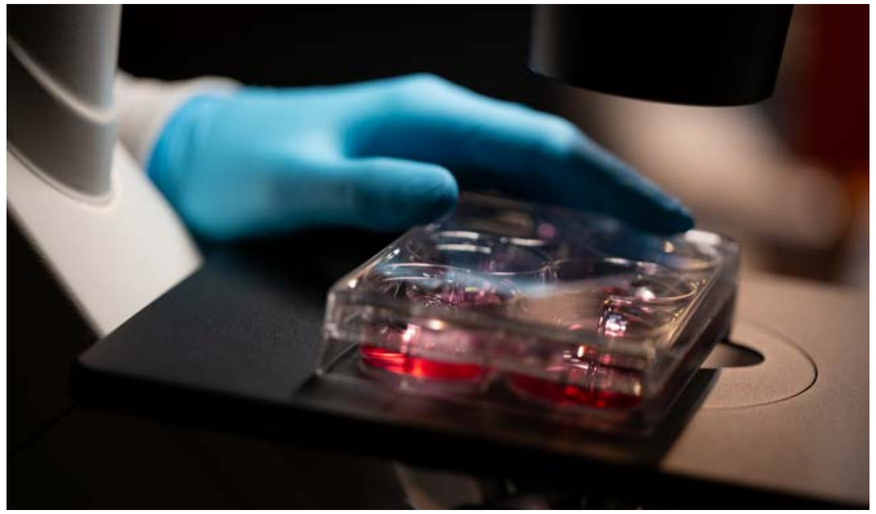
"There's evidence from biology to suggest that a lot of types of cells are responsive to mechanical stimulation," Raman says. "Mechanical forces play a really important role in our bodies and lived environment. And now we have a tool to study that, not only in muscle but in other cell types as well."

Raman says the gel can serve as a quick and noninvasive way to shape muscle fibers and study how they respond to exercise. Her lab plans to grow other cell types on the gel in order to study how mechanical forces, particularly those generated by exercise, control a wide range of biological processes within our body.

In a separate related study, the team found that exercising muscle grafts after they had been implanted in a mouse with a traumatic injury could accelerate recovery and completely restore mobility to the animals within 2 weeks.

"We found that exercising muscle grafts after they've implanted does more than just make muscle stronger, it also appears to affect how muscle communicates with other tissue, like blood vessels and nerves," says Raman. "By actively communicating with the implant and exercising the muscle graft, you can actually improve and accelerate recovery timelines."

Raman's long-term goal is to teach the next generation of engineers how to build with biological materials so that they can build "biohybrid" solutions to real-world challenges.



The Raman Lab develops new ways to build tissues containing muscles and motor neurons that mimic native tissues that control voluntary mobility in humans and other mammals. Their work encompasses a variety of culture formats, from 2D layers on extracellular matrix gels (seen here) to 3D tissues, with potential applications in medicine and robotics. Credit: John Freidah

## Quantum and precision measurements

If you hear the words ‘quantum’ and ‘large’ in the same sentence, the discussion would usually be about something hypothetical or perhaps not experimentally viable, explains Vivishek Sudhir, assistant professor of mechanical engineering and Class of 1957 Career Development Professor.

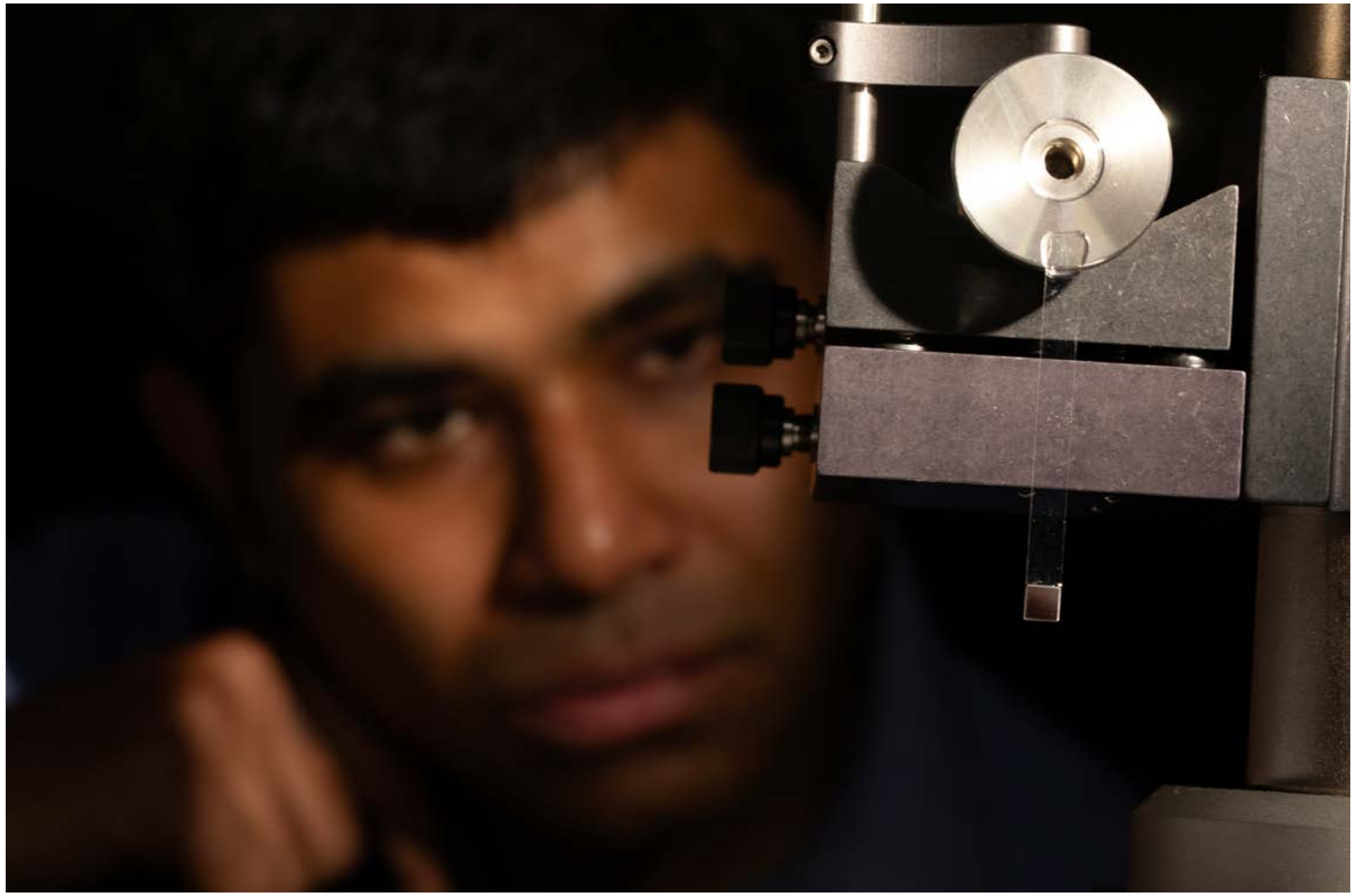
Historically, when researchers have been able to put mechanical objects into quantum states, it’s been single atoms – but not Sudhir’s group. His team has pioneered several techniques to realize large mechanical objects in quantum states of motion.

“We’ve demonstrated how to prepare kilogram-scale objects in quantum states, opening the door to experimental study of how gravity might affect quantum objects,” he says. This understanding is useful for enhancing the precision of measurements in mechanical objects, and in answering the foundational question of what the true nature of gravity is.

In the modern world, almost every conceivable enterprise – from computing, to GPS, to clocks, to economic systems – depends on precise atomic measurements.

Sudhir’s Quantum and Precision Measurements Group makes some of the most precise measurements of motion, borrowing and developing techniques for quantum measurements and control. His team’s current interest is in making measurements that would shed light on the nature of gravity. Theorists have been trying to build a quantum theory of gravity for at least 100 years, but how to combine physics and gravity remains a puzzle. Sudhir says there are a lot of good reasons to assume gravity is quantum.

“One might ask ‘why is this in MechE and not in Physics?’ I think the answer is that it could be either place, and that’s the beauty of MIT,” Sudhir says. “You don’t need to be in one place, you can be in two places at the same time – which is also a pun for the kind of quantum mechanics we’re interested in doing.”



Vivishek Sudhir uses a milligram-mass torsional oscillator, made of fused silica, to measure angular motion as small as 1e-12 rad in 1 s of averaging, such that the noise is only limited by quantum fluctuations of the photons used to make the measurement. Credit: John Freidah

Assistant Professor Vivishek Sudhir, Class of 1957 Career Development Professor. Credit: Tony Pulsone

Working with students in his lab and in the Laser Interferometer Gravitational-wave Observatory (LIGO) Laboratory at MIT, his team is scaling up quantum metrology techniques to gram-scale oscillators, refining quantum technologies based on mechanically compliant interferometers, and developing mechanical systems that allow for probes of basic physics of motion.

“My undergraduate education was in electrical engineering, my PhD is in physics, now I’m teaching mechanical engineering. I draw freely from all of these areas,” Sudhir says. “It is key for my students to be able to do something similar. One day they may be working on making an oscillator, another they’re building a laser to make an optical measurement.”

He says there’s no scope for anyone in his group to remain siloed in any one area, adding that the first thing he asks his mechanical engineering students to do is to go take the graduate quantum physics course over in Physics.

“At the end of the day, a student at MIT should not just be a technician. They need to be able to form their own ideas, to be able to zoom into the details but also to zoom out to see the big picture.”

## Fundamental robustness

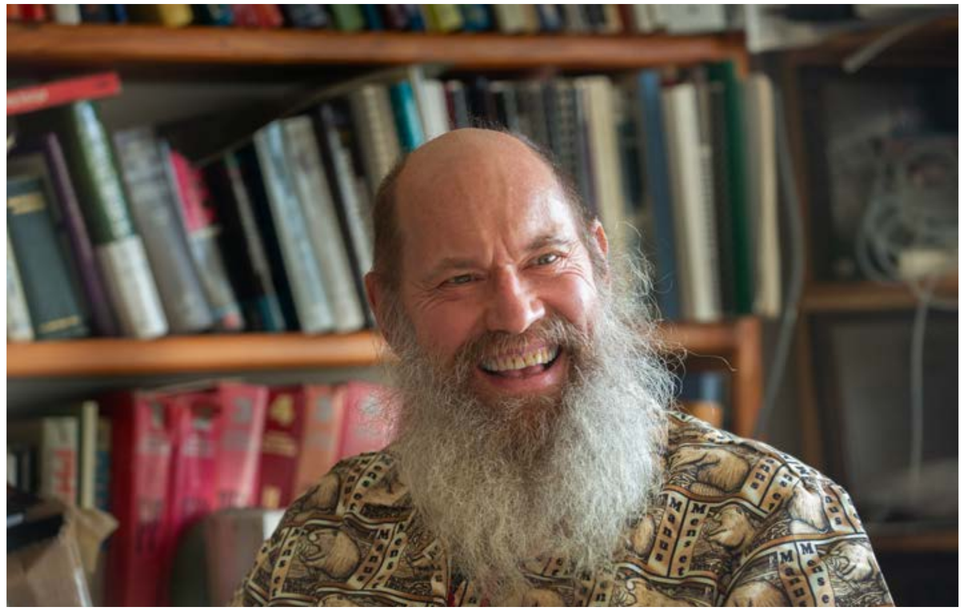
Walking into Professor Alex Slocum’s office, one of the first things you may notice is the collection of objects strewn across his granite surface plate table in the center of the room. Each of the items – from precision machined parts, to catalog components, to Lego pieces, to hand tools, including a pair of toenail clippers – “has a purpose in teaching and research,” he says.

Not only can each object be used to demonstrate some engineering concept or catalyze creation of new ideas – the toenail clippers, for example, can offer a lesson in linkages – the way people choose to interact with the items reveals a lot about the way they think, and that’s important. It’s curiosity he’s looking for in collaborators interested in joining his Precision Engineering Research Group (PERG).

His goal is to inspire students to think differently. “If you think like everyone else, or just like an AI system, the human race may never realize the innovations needed to save the species,” he says.

Slocum, the Walter M. May (1939) and A. Hazel May Chair in Emerging Technologies, designs all sorts of machines for all sorts of applications. A common theme is deterministic design, which means relying on mechanics, not hope, to achieve precision – an example is machines that use kinematic couplings (six points of unique very stiff contact to establish the position and orientation between objects) or elastic averaging interfaces (many compliant points of contact between objects where errors are averaged over a large number of contacting elements). His team is working to improve energy machines, making them ever more precise, for longer useful life, and to lower the cost to make, operate, and dispose of or repurpose at the end of their life, “for example, what we did for oil and gas drilling needs to now be done for geothermal energy systems,” he says.

In his 40 years in academia at MIT, Slocum has seen a lot of trends in mechanical engineering come and go. The thing that hasn’t changed and that will always be true, he says, is that mechanical



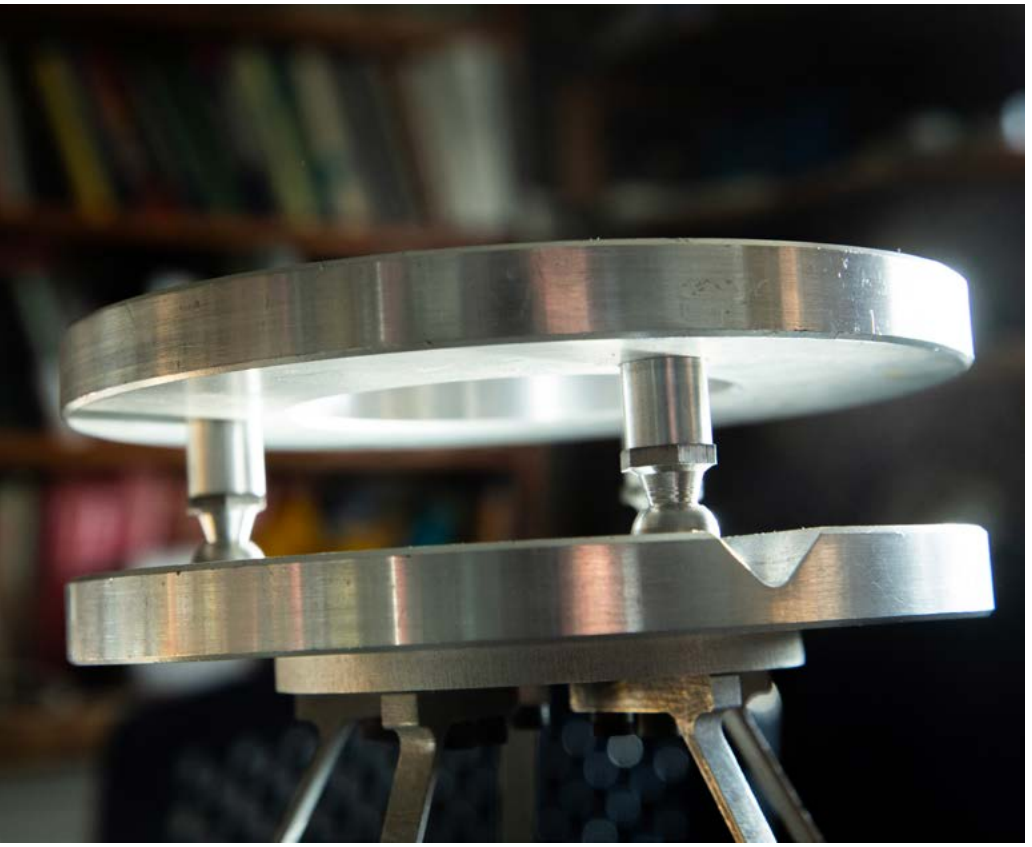
Professor Alex Slocum, the Walter M. May (1939) and A. Hazel May Chair in Emerging Technologies. Credit: John Freidah engineering is ultimately about bringing ideas into physical reality, and the need for these physical realities will always be present.

"Whatever course you're studying in, whatever work you do, ultimately there will be a physical reality that's directly part of it," he says. "If you're a mathematician, you'll need 'things' – a pencil, an iPad – and those 'things' are designed, manufactured, delivered, and must have an end-of-life plan."

These physical needs for things evolve across time and with every new innovation in the many areas across MIT. Current realities mean constructing more efficient machines to make the hardware for data centers, or making power mechanisms more efficient so "all things Internet" can operate. This means there's an ongoing need for mechanical engineers capable of doing the design, manufacturing, and operation engineering, Slocum says, and these engineers must be highly skilled at hands-on problem-solving often in the field when unforeseen issues arise and rapid fixes are required.

"A Mechanical Engineering renascence includes our students and faculty understanding and embracing the fact that nature does not care and physics cannot be fooled," says Slocum. "The fundamentals are not only as important as they ever were, they are critical for our students to passionately embrace and master."

He goes on to opine "As AI gets better and better, and as we ME professors partner with our AI colleagues to encode our knowledge, the bar for our students to master the core mechanics of ME and the "FUNdaMENTALs of design will only rise." And he is optimistic, "Perhaps MechE might also be thought of as MechExciting!"



From Professor Alex Slocum's lab, a kinematic coupling uses six points of unique, very stiff contact to establish the position and orientation between objects. Credit: John Freidah

## AI, robotics, and solar technology – accelerated

Tonio Buonassisi, professor of mechanical engineering, tells a story about a solar-to-fuel problem that existed in the 2010s, a time when the field was driven mostly by chemists. Devices that convert sunlight into fuels using commercial silicon solar cells were only getting a fraction of the expected efficiency. Chemists blamed the catalyst, but the engineers brought in to collaborate viewed the problem differently. They opted to build equivalent-circuit models and, by reviewing various stages in the process, found that a series resistance term was dragging everything down. By redesigning the system, the team was able to improve the system's sunlight-to-fuel conversion efficiency from a fraction of a percent to 10 percent.

"I get asked a lot, 'why are you in mechanical engineering, why not chemical engineering or materials science?'" says Buonassisi, noting that he gets similar questions from students about their own path. "For the type of interdisciplinary research we're doing, mechanical engineering brings together the necessary expertise under one roof."

Systems thinking is a way to break down a complex system into its constituents to figure out which things are limiting and how to improve, and it's intrinsic to mechanical engineering. "Design, manufacturing, and systems thinking, among other aspects – our department has these kernels of wisdom embedded, and they're infinitely practical," he says.

Buonassisi leads the Accelerated Materials Lab for Sustainability and ADDEPT, a collaborative research center that merges materials, automation, and computation, specifically in artificial intelligence and solar energy. Today, his lab is working to accelerate new materials development in solar, fusion, and electrochemistry by developing high-throughput experimentation and machine learning tools.

Professor Tonio Buonassisi leads the Accelerated Materials Lab for Sustainability and ADDEPT, a collaborative research center that merges materials, automation, and computation, specifically in artificial intelligence and solar energy. The group is looking to cut the development time of a wide variety of materials. Credit: John Freidah

"Our research takes place in the center of a triangle – the corners are automation and robotics, machine learning and computation, and domain expertise with a deep understanding of solar technology, electrochemistry, and fusion. The interdisciplinary nature of our work means, to do it well, you have to be at the middle of this triangle."

ADDEPT stands for Accelerated Co-Design of Durable, Reproducible, and Efficient Perovskite Tandems. Perovskites – a family of materials with potential for high performance and low production costs in solar cells – are a leading contender to augment silicon-based solar photovoltaics in tandem architectures, but the material has known durability issues. That's something Buonassisi's team is working to solve, and quickly.

"Our vision, as a lab and within our collaborations, is to set up autonomous labs to impact solar, electrochemistry, and fusion. We're developing high-throughput experimentation that is designed to operate more reproducibly and orders of magnitude faster than human hands with closed-loop machine learning."

The closed-loop aspect of the experimentation process is important. In closed-loop learning, continuous feedback mechanisms monitor and adjust operations based on outputs or results. Machine learning is very good at is taking in many variables, quickly, and navigating the high dimensional space. This dramatically speeds up the discovery process.

"In a high-dimensional parameter space, changing just one variable at a time would take forever to find the optimal conditions," he says. "We have a finite time to develop technologies that can mitigate climate change. When you're under that clock, you have to move a lot faster."

A big emphasis of the lab is open science. Creating open software and open hardware is important for reproducibility, Buonassisi says, and it also ensures these tools get into the hands of people who can benefit from them the most.

**Video exclusive:** Hear from more faculty and staff, and learn more about the breadth of MechE at MIT meche.mit.edu/magazine

Student Spotlight

# Engineers of tomorrow

## Grad students explore frontiers of the field

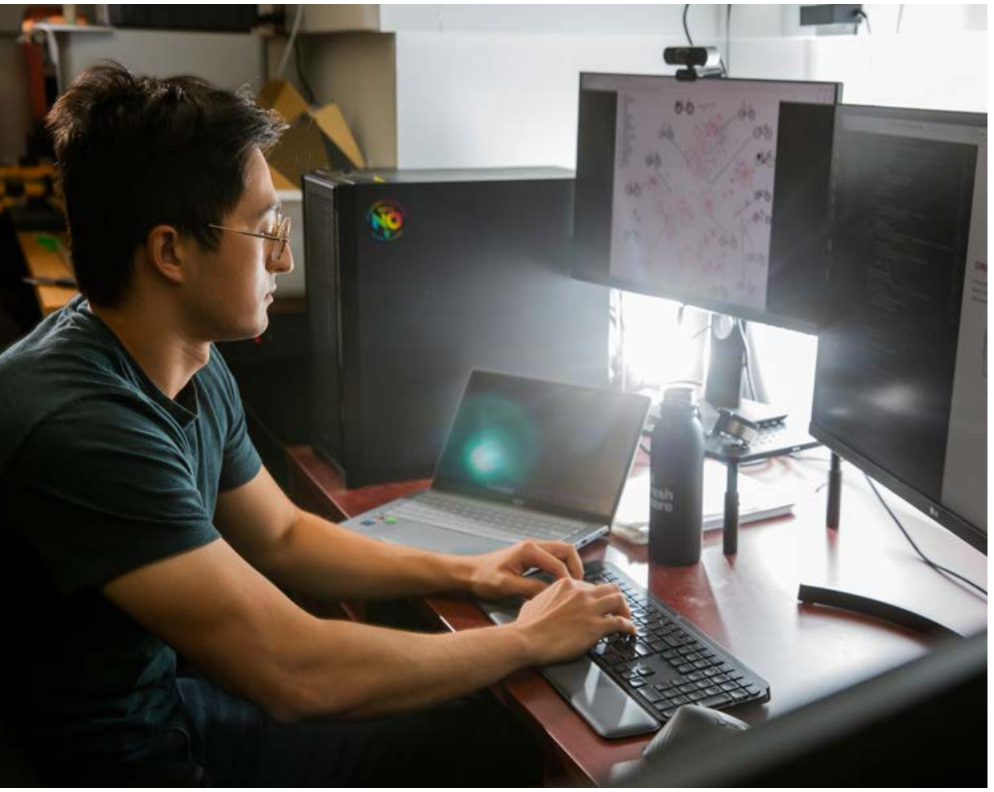
By Kimberly Tecce
Photos by Tony Pulsone

From cutting-edge robotics, design, and bioengineering, to sustainable energy solutions, ocean engineering, nano technology, and innovative materials science, MechE students and their advisors are doing incredibly innovative work. The graduate students highlighted here represent just a snapshot of the great work in progress across our department and demonstrate the ways the future of this field is as limitless as the imaginations of its practitioners.

### Democratizing design through AI

**Lyle Regenwetter**
Hometown: Champaign, Illinois
Advisor: Assistant Professor Faez Ahmed
Interests: Food, climbing, skiing, soccer, tennis, cooking

Lyle Regenwetter finds excitement in the prospect of generative AI to "democratize" design and enable inexperienced designers to tackle complex design problems. His research explores new training methods through which generative AI models can be taught to implicitly obey design constraints and synthesize higher-performing designs. Knowing that prospective designers often have an intimate knowledge of the needs of users, but may otherwise lack the technical training to create solutions, Regenwetter also develops human-AI collaborative tools that allow AI models to interact and support designers in popular CAD software and real design problems.



Lyle Regenwetter works with Professor Faez Ahmed in the DeCoDE (Design Computation and Digital Engineering) Lab.

### Solving a whale of a problem

**Loïcka Baille**
Hometown: L'Escale, France
Advisor: Dr. Daniel Zitterbart
Interests: Being outdoors – scuba-diving, spelunking, or climbing; sailing on the Charles, martial arts classes, and playing volleyball

Loïcka Baille works on ocean tech with her advisor Dr. Daniel Zitterbart and the Woods Hole Oceanographic Institution. Credit: Courtesy of the Researchers

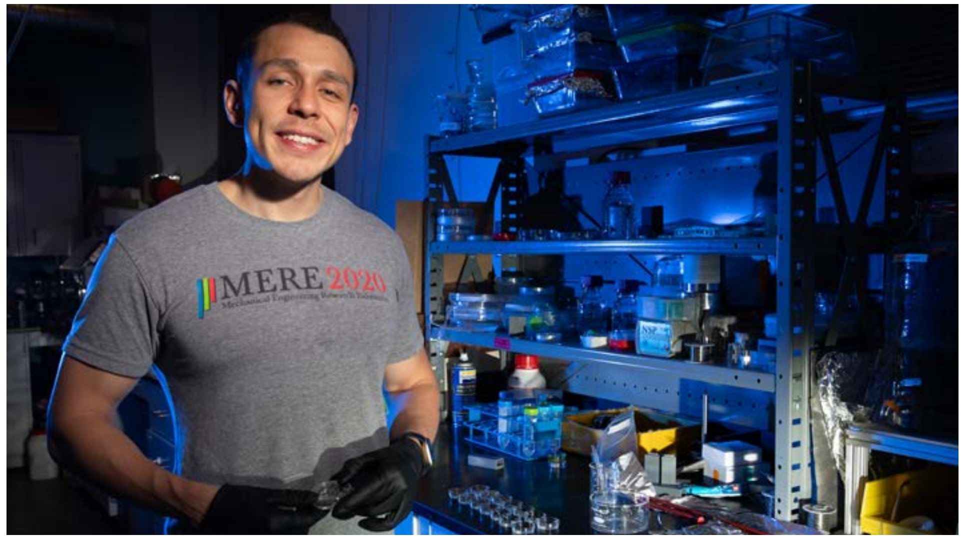
> "In many ways, Antarctica reminds me of MIT. While it can initially appear as an intimidating environment, with patience and tenacity, you will discover the incredible wonders this place has to offer."
>
> – Loïcka Baille

Loïcka Baille's research focuses on developing remote sensing technologies to study and protect marine life. Her main project revolves around improving on-board whale detection technology to prevent vessel strikes, with a special focus on protecting North Atlantic right whales. Baille is also involved in an ongoing study of Emperor penguins. Her team visits Antarctica annually to tag penguins and gather data to enhance their understanding of penguin population dynamics and draw conclusions regarding the overall health of the ecosystem.

### Water, water anywhere

**Carlos Díaz-Marín**
Hometown: San José, Costa Rica
Advisor: Professor Gang Chen
Former Advisor: Professor Evelyn Wang
Interests: New England hiking, biking, and dancing

Carlos Díaz-Marín designs and synthesizes inexpensive salt-polymer materials that can capture large amounts of humidity from the air. He aims to change the way we generate potable water from the air, even in arid conditions. In addition to water generation, these salt-polymer materials can also be used as thermal batteries, capable of storing and reusing heat. Beyond the scientific applications, Díaz-Marín is



Carlos Díaz-Marín previously worked with Professor Evelyn Wang in the Device Research Lab and currently works with Professor Gang Chen in the NanoEngineering Group to address the energy and environmental challenges our society faces today.

excited to continue doing research that can have big social impacts, and that finds and explains new physical phenomena. As a LatinX person, Díaz-Marín is also driven to help increase diversity in STEM.

### Scalable fabrication of nano-architected materials

**Somayajulu Dhulipala**
Hometown: Hyderabad, India
Advisor: Assistant Professor Carlos Portela
Interests: Space exploration, taekwondo, meditation

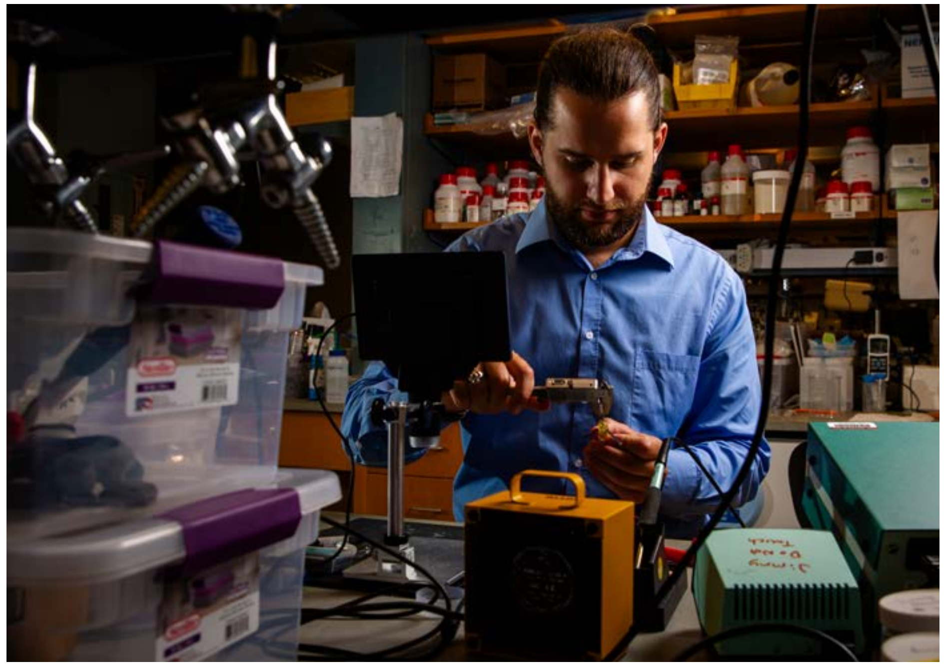
Somayajulu Dhulipala works on developing lightweight materials with tunable mechanical properties. He is currently working on methods for the scalable fabrication of nano-architected materials and predicting their mechanical properties. The ability to fine-tune the mechanical properties of specific materials brings versatility and adaptability, making these materials suitable for a wide range of applications across multiple industries. While the research applications are quite diverse, Dhulipala is passionate about making space habitable for humanity, a crucial step toward becoming a spacefaring civilization.

Somayajulu Dhulipala works with Professor Carlos Portela and the Portela Research Group on architected mechanics and materials across scales.

### Ingestible healthcare devices

**Jimmy McRae**
Hometown: Woburn, Massachusetts
Advisor: Associate Professor Giovann Traverso
Interests: Anything basketball related: playing, watching, going to games, organizing hometown tournaments

Jimmy McRae aims to drastically improve diagnostic and therapeutic capabilities through non-invasive healthcare technologies. His research focuses on leveraging materials, mechanics, embedded systems, and microfabrication to develop novel ingestible electronic and mechatronic devices. This ranges from ingestible electroceutical capsules that modulate hunger-regulating hormones, to devices capable of continuous ultralong monitoring and remotely triggerable actuations from within the stomach. The principles that guide McRae's work to develop devices that function in extreme environments can be applied far beyond the GI tract, with applications for outer space, the ocean, and more.



Jimmy McRae works closely with Professor Giovanni Traverso, MD, PhD, MBBCH, in the medical device field focusing on gastroenterology.

### Freestyle BMX meets machine learning

**Eva Nates**
Hometown: Narberth, Pennsylvania
Advisor: Professor Peko Hosoi
Interests: Rowing, running, biking, hiking, baking

Eva Nates is working with the Australian Cycling Team to create a tool to classify Bicycle Motocross Freestyle (BMX FS) tricks. She uses a singular value decomposition (SVD) method to conduct a principal component analysis (PCA) of the time dependent point tracking data of an athlete and their bike during a run to classify each trick. The 2024 Olympic team hopes to incorporate this tool into their training workflow, and Nates will work alongside the team at their facilities on the Gold Coast of Australia during MIT's Independent Activities Period in January 2024.

> "This work is blurring the gap between science fiction and reality by working toward revolutionizing how humans and machines interface. With tact, SuperLimbs can greatly impact future human spaceflight."
>
> – Erik Ballesteros

Erik Ballesteros works with Professor Harry Asada in the d'Arbeloff Laboratory to develop the technologies and hardware needed to enable humans and robots to work together.

### Augmenting astronauts with wearable robotic limbs

**Erik Ballesteros**
Hometown: Spring, TX
Advisor: Professor Harry Asada
Interests: Cosplay, Star Wars, Lego bricks

Erik Ballesteros' research seeks to support astronauts who are conducting planetary Extra-Vehicular Activities (EVAs) through the use of Supernumerary Robotic Limbs (SuperLimbs). His work is tailored toward design and control manifestation to assist astronauts with post-fall recovery, human-leader/robot-follower quadruped locomotion, and coordinated manipulation between the SuperLimbs and the astronaut to perform tasks like excavation and sample handling.

Eva Nates works with Professor Peko Hoisoi, co-founder of the MIT Sports Lab, on sports technology.

Alumni Profile

# Vijay Vaitheeswaran ’90: Engineer, economist, editor

By Anne Wilson

“This is a golden age of climate tech innovation,” says Vijay Vaitheeswaran ’90, global energy and climate innovation editor for *The Economist*. “Dealing with climate change and energy needs in a timely fashion, while still allowing the energy use needed for growth, really is the challenge of our lifetime… and there’s a huge contribution to the kind of thinking needed to tackle this that comes from engineering.”

This kind of thinking is something MIT fosters extremely well, Vaitheeswaran says, by encouraging multidisciplinary study and the kind of collaboration that helps to break down traditional silos.

“In my years at MIT and beyond, the people I’ve seen who have had the most impact are the ones who, even as they’re brilliant at their own research, read widely outside of their field. They’re well-traveled and know the context and reality of other parts of the world, different from their daily reality or the world they grew up in. They’re the ones that dabble in adjacencies.”

Hyper-specialization can be attractive, he says, especially in very technical fields, and it can even be necessary for advancing blue-sky research, but the greatest problem solvers need to be “something of a renaissance woman or renaissance man.”

For example, addressing climate issues, he says, requires a broad understanding of the context in which the technology will exist, including factors that drive political consensus, policy, and societal acceptance.

“In the case of climate change, the subsidy policies that have come out of Washington with the inflation reduction act will probably do more to advance the engineering of climate tech solutions than anything that’s happened in a laboratory in the last ten years,” Vaitheeswaran says.

The years Vaitheeswaran attended MIT were some of the first when a big push was taking place for students to enroll in humanities, arts, and social science courses. He studied in Course 2, but was also able to do a UROP in Course 3 (materials science and engineering) and complete a minor in Course 17 (political science).

“We had a lot of opportunities and encouragement to take courses outside of our majors. In my case, I took a lot of courses in political science and economics,” he says. “I was quite inspired. I learned that technology doesn’t just exist in a vacuum. Invention is the beginning of the process, but to connect it to what’s valuable in society is really the process of innovation. I learned an intuitive appreciation for it at MIT.”

After graduation, Vaitheeswaran worked in marketing and was making plans to go to business school when a former roommate suggested he apply for an internship at *The Economist*.

“MIT was a great place to find out who I am, and who I’m not. I clearly didn’t spend my life as a mechanical engineer, as some of my best friends from Course 2 have with start-up companies, or working at national labs, or designing engines for Detroit car companies – that wasn’t where I ended up,” he says. “But the skills I learned at MIT, and, in particular, a certain kind of critical thinking, an engineering mindset around problem solving, and a desire to look for systems solutions, rather than taking facts as they’re presented at face value – those are all things that MIT teaches really well.”

He got the internship, and never left. “I’ve done a lot of thinking and writing and different types of jobs related to how technology connects with policy, with society, and with people’s lives. Figuring out how exactly to do that is where *The Economist* happened to come in.”

Vaitheeswaran joined the publication’s editorial staff in 1992 as its London-based Latin America correspondent, then later opened the magazine’s first regional bureau in Mexico City. He’s covered the politics, economics, business and technology of energy and the environment, and innovation, global health, pharmaceuticals and biotechnology. He’s also written several books addressing sustainability, the future of cars and oil, and global innovation, and he’s served as both US Business Editor and China Business Editor, and as chairman of *The Economist* Innovation Summit.

Today, he covers the energy and utility industries, the clean energy transition, climate innovations and low carbon technologies, along with environmental, social, and governance trends. He picked his area of focus, he says, because it’s the hardest problem he encountered, a trait he said he thinks is shared by many people with MIT connections.

“MIT attracts people who are interested in hard things. They tend to live their lives that way as well. They take on some tough challenges, and not necessarily do the easy thing or the quick thing to make money, but, rather, what’s going to keep your brain engaged, what’s going to make a difference. I think that’s the best of the MIT spirit.”

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# Designing cleaner vehicles

## Graduate student Adi Mehrotra ’22 is developing sustainable solutions in vehicle design

Fueled by curiosity and a love of science, second-year graduate student Adi Mehrotra ’22 is working on sustainable solutions in vehicle design, including the design for a hydrogen-powered motorcycle. The motorcycle, which is designed on an open-source platform, underwent its first full test-track demonstration in October.

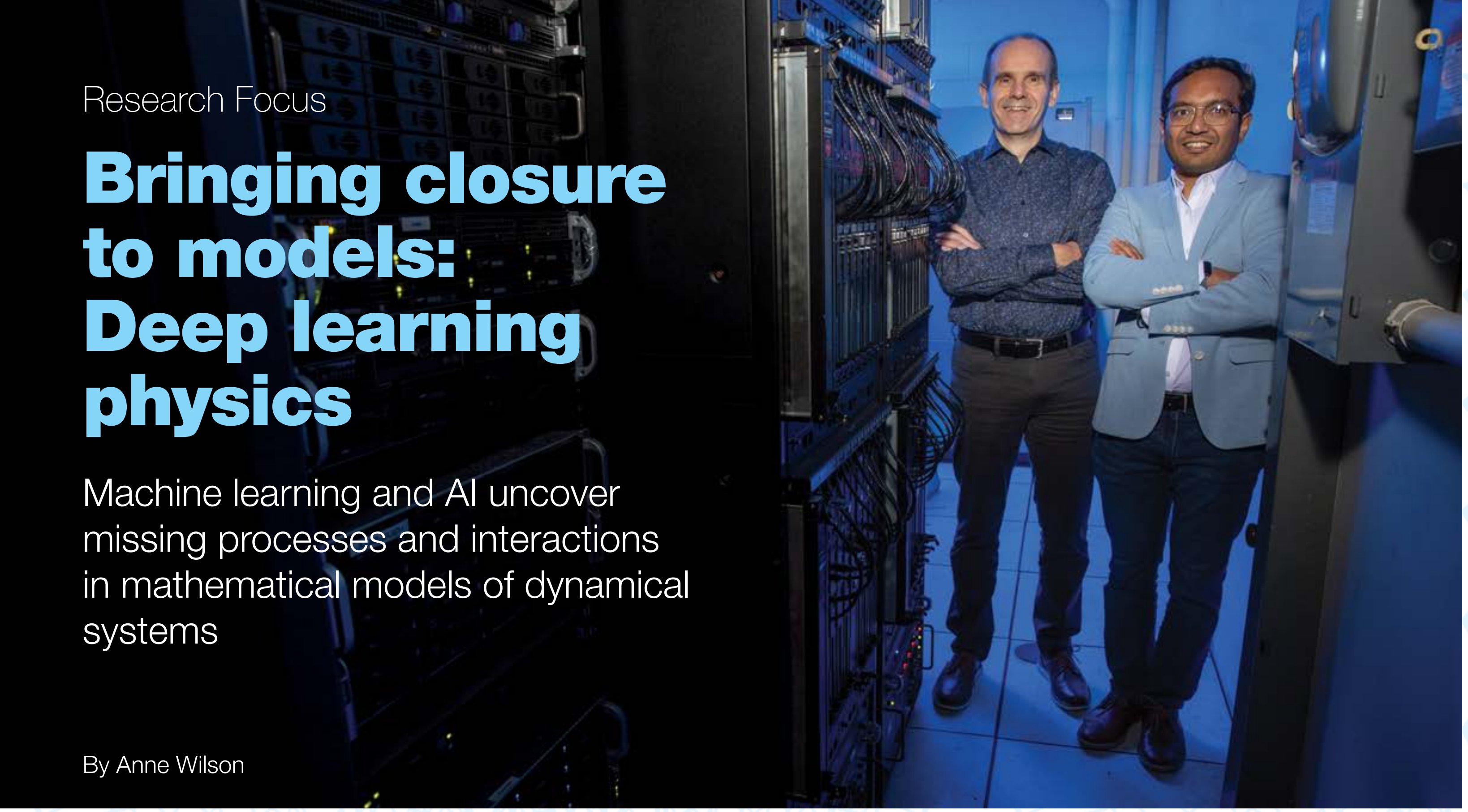
Mehrotra majored in electrical engineering and computer science as an undergraduate, but says he was drawn to mechanical engineering and took as many MechE classes as he could. During his junior year, Mehrotra joined Professor Sangbae Kim’s Biomimetic Robotics lab – a decision that further cemented a passion for mechanical design and sparked an interest in vehicle design. He now heads up a “revamping” of the MIT Electric Vehicle Team (EVT), a student-led research team that is probing the future of transportation.

The EVT, which has a long history of research into renewable energy and electric powered vehicles, has been working on building the hydrogen-powered motorcycle prototype since January 2023. Unlike the team’s past projects, this vehicle will not be entering races or competitions. Instead, it will be taken to conferences with the goal of starting conversations around “small hydrogen” systems and perhaps increase demand or lead to more infrastructure development.

“Initially the goal was to build something cool, but through research for the project we found that sources and knowledge-bases for hydrogen-powered vehicles were limited in scope and much of the details of the technology were proprietary. We concluded that a project that focuses on an open-source hydrogen engine would be important to building a cleaner future.”

With safe and intelligent surrounding vehicle designs, the team believes that hydrogen could be the future of transportation, solving the long charge times of electric vehicles, addressing the power density issues of solar vehicles, and, with super capacitor technology, eliminating the need for heavy and harmful lithium batteries.

Aditya Mehrotra is designing one of the first-ever hydrogen-fuel-cell-powered motorcycles realized in real hardware and tested on the road and racetrack. Mehrotra and his team want to build a truly green vehicle that has the same performance, range, and practicality as a gasoline vehicle with none of the harmful emissions. Credit: Adam Glanzman



Research Focus

# Bringing closure to models: Deep learning physics

## Machine learning and AI uncover missing processes and interactions in mathematical models of dynamical systems

By Anne Wilson

Highly advanced Generative Artificial Intelligence (AI) language models, like ChatGPT, use deep machine learning algorithms to generate human-like, conversational text responses to prompts. The technology is incredibly useful for tasks like writing code, composing emails or essays, or engaging in conversations, but these models have limitations when it comes to more complicated tasks. Imagine, instead, a machine learning technology that can respond to scientific inquiries with clear mathematical expressions, augmenting existing knowledge, understanding, and applicability.

Such technology could be a “holy grail for engineers and scientists,” according to Pierre Lermusiaux, the Nam Pyo Suh Professor of Mechanical Engineering and Professor of Ocean Science and Engineering. Applications could include better weather, ocean, earth system, and climate forecasts, improved energy systems, new control and robotics systems, better financial and economic market forecasts, and even new human health models.

An approach called generalized neural closure models (gnCMs), created by Abhinav Gupta PhD ’22 and Lermusiaux, combines machine learning with fundamental physics to discover and improve predictive models. By incorporating neural networks into existing mathematical models, the researchers have achieved better interpretability and generalization across different scenarios – and, unlike general deep learning models, “the mathematical answer is not hidden in the machine learning black box,” Lermusiaux says. “It is laid bare for humans to use and to learn from.”

Using machine learning from scratch works well in situations where existing models aren’t available. Generating images, for example, is something machines can do really well working from big data, but in physics-based systems or biological systems – where governing laws already exist but observations are limited – it doesn’t make much sense to start from scratch.

“Over centuries, people have built models – which are based on physical, biological laws – and they are inherently generalizable,” says Gupta. “The idea of our approach is to leverage the generalizability of the existing models, then piggyback on that to make sure machine learning models that build on top of that are also generalizable in the same sense.”

The field of Scientific Machine Learning has seen the introduction of several innovative methods that combine machine learning with existing scientifically derived differential equation models and computational physics. This is because all models are approximate. In the new application, machine learning is used to learn and represent neglected and unresolved terms to express missing dynamics as functions of modeled state variables and parameters, which is referred to as neural closure modeling.

Take Newton’s second law of motion. “If I drop my watch, it’s going to fall,” says Lermusiaux. “There’s a force, gravity, and mass, so there’s acceleration. If I kick a soccer ball, that’s also F = ma, but the full picture is more complicated because you have to simulate the fluid of the air around the ball, the structure of the ball, and such.”

To really understand and explain the motion of the ball, factors like the drag created by the surrounding air must be considered. Without viscous effects, the ball continues to accelerate; closure models then account for these viscous effects.

The gnCMs framework provides full autonomy for the design of the unknown closure terms, including, for the first time, capturing delays in the system. It learns new closure models for existing known-physics and low-fidelity models – using sparse real, high-fidelity data – to ensure that learned closure models are generalizable and interpretable, and it makes this closure modeling more accessible.

Once a simple soccer ball model exists, the gnCMs approach can augment and interpret the knowledge gained to allow reuse for other applications – a researcher trying to understand and predict curveballs in baseball, for example, could benefit from the understanding of fluid dynamics gained developing the soccer ball model – a task that most machine-learned models traditionally lack.

Closure modeling is necessary for a variety of reasons. It can decrease computational costs and is beneficial in situations where simple models are preferred over complicated models or when scientific understanding of the processes and variables involved is lacking, but overdependence on too simple models can have consequences. In general, it is a significant scientific undertaking to find such closure models even for very simple systems.

Simple or known models (low-fidelity models) may be computationally cheaper or faster to use than high-fidelity models (models drawn from real-world data), but low-fidelity models can quickly accumulate errors due to unaccounted or missing, neglected, or unresolved terms. This can lead to incomplete representations of data or incorrect approximations which, in research on dynamical systems, can have real-world, global-scale impacts.

The gnCMs method builds on learned information for dynamical systems and then successfully discriminates among existing models, discovers missing physics, identifies numerical errors, selects optimal functional forms, identifies generalized models outside of their sparse training data, and compensates for the lack of complexity in simpler models without compromising computational speeds – and the framework works for many dynamical systems.

“We wanted to create a framework which would enable people, in an agnostic fashion, to augment existing models and make them more accurate without sacrificing too much on computational costs,” Gupta says. “Or, if a researcher doesn’t have a model, this approach can help them discover a model from scratch, if needed.”

This is particularly beneficial when attempting to collect data in real, physical systems – and from natural systems in particular – which tends to be difficult and expensive. “For example, collecting data from a system as vast as the ocean is really resource intensive,” says Gupta. “The kind of machine learning models we’ve developed reduces the data requirement.”

For ocean processes, the team has been able to augment existing physical, biogeochemical, and ecosystem models – machines correct missing terms and numerical errors in dynamical models of nonlinear waves and shocks, and discover mathematical formulations that better explain real impacts on ocean acidification and zooplankton mortality.

In one experiment, the researchers started with low-fidelity models used to study and predict essential carbonate chemistry and biological production cycles and their interplay with global warming. They then added high-fidelity data to resolve biological variables, nitrogen, depth, and other more complex parameters like the maximum growth rate of phytoplankton, saturation and light measures, and known data for photosynthetically active radiation at the sea surface.

In another experiment, for the low-fidelity model, the researchers assumed only prior knowledge about the existence of a linear zooplankton mortality term. For the high-fidelity model, however, the true zooplankton mortality contained an additional quadratic dependence. Their framework not only ensured that the learned closure kept errors low throughout the observation period, but also discovered the exact functional form of the zooplankton mortality in the high-fidelity model.

In these and other experiments, they found that training on a limited set of data is sufficient to ensure that the learned closures are generalizable over large ranges of grid resolution and initial and boundary conditions and problem-specific parameters, and to outperform popular closure models.

“Usually, the way science and engineering progress is that you start from what you know and what you’ve built, then you create new thoughts, new ideas, then build new things,” says Lermusiaux. “The machine learning we’ve created fills in more complex knowledge gaps, and reduces the time and expense to help get to the answers you’re seeking.”

*“Generalized neural closure models with interpretability” appeared in the journal* Scientific Reports. *Gupta, A., Lermusiaux, P.F.J. Generalized neural closure models with interpretability.* Sci Rep *13, 10634 (2023).*

# More crop per drop

## Low-cost, solar-powered irrigation tools make precision agriculture more accessible

By Anne Wilson

GEAR Lab researcher Carolyn Sheline troubleshoots a drip irrigation system at a full-scale test farm in the Jordan Valley where the team is piloting a low-cost precision irrigation controller that optimizes system energy and water use. Credit: John Freidah

In agriculture today, a host of technological systems and devices make farms more efficient, resource conscious, and profitable. Use of Precision Agriculture – as these technologies are collectively known – offers significant advantages but, because it can be costly, it remains out of reach for the majority of the world's famers.

"Many of the poor around the world are small, subsistence farmers," says Susan Amrose, research scientist with the MIT Global Engineering and Research (GEAR) Lab. "With intensification of food production needs, worsening soil, water scarcity, and smaller plots these farmers can't continue with their current practices."

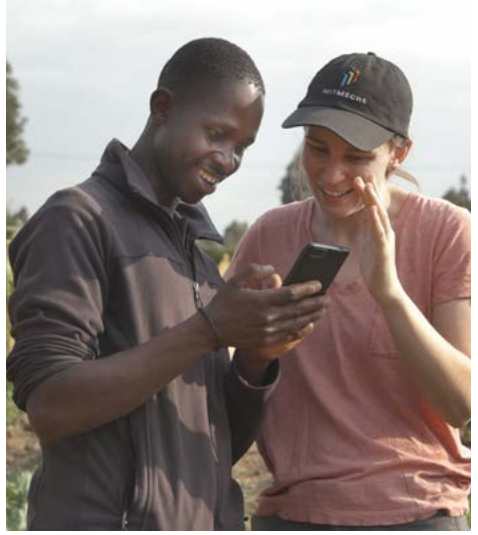
Nearly 80 percent of the world's 570 million farms are smallholder farms, and many of these are located in under-resourced and water-stressed regions. "We're trying to make it much, much more affordable for farmers to utilize solar-powered irrigation, and to have access to tools that, right now, they're priced out of," says Amrose. "More crop per drop, more crop per area, that's our goal."

Drip irrigation systems release water and nutrients in controlled volumes directly to the root zone of the crop through a network of pipes and emitters, and can reduce water consumption by 20 to 60 percent when compared to conventional flood irrigation methods. Carolyn Sheline SM '19, PhD '23, a member of the GEAR Lab's Drip Irrigation team, says, "a lot of irrigation technology is developed for larger farms that can put more money into it – but inexpensive doesn't need to mean 'not technologically advanced.'"

GEAR Lab has created several low-cost drip irrigation technology solutions to date, including a low-pressure drip emitter; a systems-level optimization model; and a low-cost precision irrigation controller that enables farmers to operate their system on an ideal schedule given specific resources, needs, and preferences. To build these new, affordable technologies, the team tapped into a critical knowledge source – the farmers themselves.

"We didn't just create technology in isolation – we also advanced our understanding of how people would interact with and value this technology, and we did that before the technology had come to fruition," says Amos Winter, SM '05, PhD '11, Associate Professor of Mechanical Engineering and MIT GEAR Lab Principal Investigator.

The team held "Farmer Field Days" and conducted interviews with more than 200 farmers, suppliers, and industry professionals in Kenya, Morocco, and Jordan, the regions selected to host field pilot test sites. These sites were selected for a variety of reasons, including solar availability and water scarcity, and because all were great candidate markets for eventual adoption of the technology.



GEAR Lab researcher Georgia Van de Zande demonstrates the smartphone app, which provides an ideal irrigation schedule, to farm manager Ezra Ondimu. Credit: John Freidah

A drip irrigation line is repaired at Puma Springs Farm in Kenya. The farm is a test site for the GEAR Lab's low-cost precision irrigation controller, which optimizes system energy and water use. Credit: John Freidah

"People usually understand their own problems really well, and they're very good at coming up with solutions to them," says Fiona Grant, SB '17, SM '19, a PhD candidate with the GEAR Lab Drip Irrigation team. "As designers, our role really is to provide a different set of expertise and another avenue for them to get the tools or the resources that they need."

The controller, for example, takes in weather information, like relative humidity, temperature, wind speed values and precipitation, then uses AI to calculate and predict the area's solar exposure for the day and exact irrigation needs before sending information to the farmer's smartphone. How much, or how little, automation is used remains up to the farmer.

"The way you're going to operate a system is going to have a big impact on the way you design it," says Grant. "We gained a sense of what farmers would be willing to change, or not, regarding interactions with the system. We found that what we might change, and what would be acceptable to change, were not necessarily the same thing."

GEAR Lab alumna Georgia Van de Zande, SB '15, SM '18, PhD '23, concurs. "It's about more than just delivering a lower cost system, it's also about creating something they're going to want to use and want to trust."

"The most powerful tool a designer can have is perspective," Winter says. "I have one perspective – the math and science and tech innovation side – but I don't know a thing about what it's like to live every day as a farmer in Jordan or Morocco. I don't know what clogs the filters, or who shuts off the water. If you can see the world through the eyes of stakeholders, you're going to spot requirements and constraints that you wouldn't have picked up on otherwise."

In Jordan, researchers at a full-scale test farm are now operating a solar-powered drip system with a prototype of the controller and receiving smartphone commands on when to open and close the manual valves. In Kenya, where Precision Agriculture and smart irrigation haven't yet seen very much adoption, a simpler version of the controller serves to provide educational and training information, along with scheduling and control capabilities.

In Morocco, the controller is operating at a research farm with a fully automated hydraulic system and researchers are monitoring the irrigation and conducting additional agronomic tasks – and in its first season of operation, GEAR Lab technology reduced water consumption by 44 percent and energy by 38 percent when compared to a neighboring farm using traditional drip irrigation practice.

Global Engineering and Research (GEAR) Lab researchers (from left to right) Georgia Van de Zande, Carolyn Sheline, and Fiona Grant. Credit: John Freidah

Watch **"No Drop to Spare"**
a video that follows
team members and
collaborators at the
field test sites
meche.mit.edu/magazine

Class Close-Up

# 2.74: Bio-Inspired Robotics

By Michaela Jarvis

People tend to think of a task's difficulty based on human standards. Actions that most people perform reflexively – like grasping a cup or moving food around in your mouth to chew it – seem easy, but when it comes to programming robots to accomplish similar feats, the problem is actually much more complicated.

Professor Sangbae Kim's class, 2.74 (Bio-Inspired Robotics), invites students to not just explore how we move, but also to understand the ways we don't consciously recognize how all of these movements work. When confronted with how little we know about the subconscious processes that allow humans to interact with their environment, students gain a sense of wonder, he says.

Kim, who also directs the Biomimetic Robotics Laboratory, says researchers need to understand this cognitive bias and tendency toward anthropomorphism in order to even begin developing robots that can help humans with their physical movements.

2.74 is made up of 50 or fewer seniors and graduate students. During the first half of the class students study biology and biomechanics. Graduate student Roberto Bolli says one of the most surprising things he learned has to do with how humans walk.

"Walking is essentially continuous falling, where the center of mass of the body falls forward like an inverted pendulum," says Bolli, whose 2.74 team developed a robot named Chicken-Bot 9000. "This means that our maximum walking speed is roughly determined by the length of our legs and gravity, and not by our fitness or overall stamina."

In the second half of the class, students single out very specific biological behaviors to study, then seek to employ the simplest model possible. For example, they might investigate placement of a battery or other payload to determine placement on a jumping robot in order to achieve the highest jump. Students compare what they've learned about biology to robotics, then recreate the information in a robotics context, as they develop and fine-tune hypotheses.

Students Michael Burgess (left), Sharmi Shah (middle), and Maheera Bawa (right) enjoy the fruits of their labor in the form of their hula-hooping robot, Hula Hooper, performing a successful demonstration during the class final project exhibition. Credit: Lauren Futami

MIT students Gillian Roeder, left, and Kate Sanderson view the various robots on display at the final exhibition of the Mechanical Engineering class, Bio-Inspired Robotics, taught by Professor Sangbae Kim. Credit: John Freidah

"If you saw a kangaroo jumping, you might say, 'how can a kangaroo jump so high?'," says Kim. However, the hypothesis can't be tested with the animal, because robots don't have, for example, the same kind of muscle or tendons. "Half the class is about biology and biomechanics so students can really compare muscles versus electric motors, computers versus our brain, computer algorithms versus our motor control."

"Biomimetics isn't just 'let's copy this design we found in nature and see how well it works on a robot,'" Bolli says. "It's about extracting useful principles from natural systems to solve such challenges as manipulation and locomotion in novel and interesting ways."

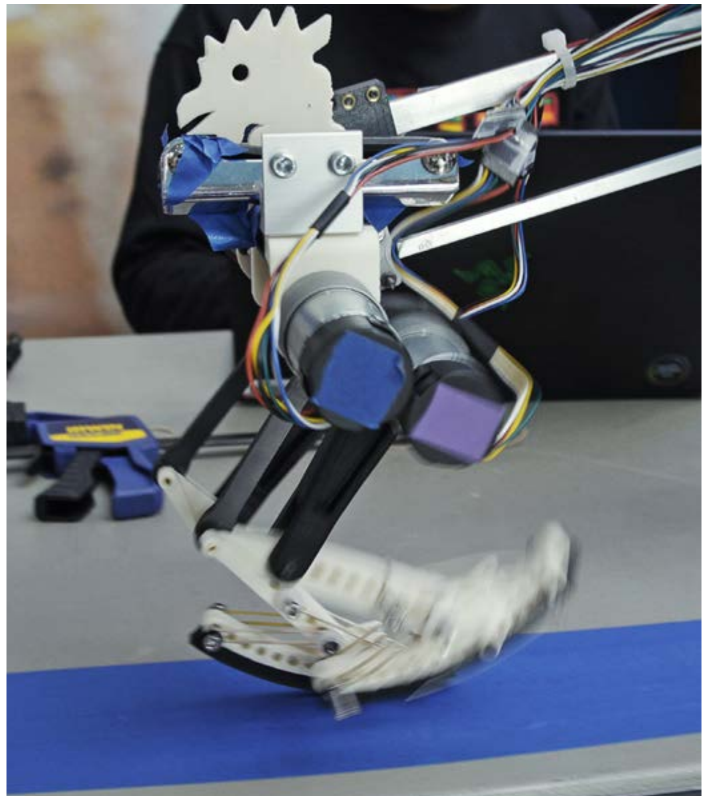
The class also encourages critical thinking about biology and robotics design. This is important because, as Jess Han, a first-year MS-PhD student, says "nature does not always offer the best design."

"Natural selection allows for things that are 'good enough' to survive instead of selecting for the optimal solution," says Han, a member of the 2.74 team that created Suni-Bot, named after Olympian gymnast Suni Lee. "If we copy biology without thinking, we may actually design robots that aren't as effective as they could be or that don't fully utilize the capabilities of the technology that we have."

Kim says about 70 percent of the class is programming. Students study and experiment with both the robot hardware and computer simulations. The data from the dynamic simulation and the hardware results are used to draw a scientific result. He says such findings can enlighten small regions of the huge, unknown expanse of subconscious behaviors behind much of human movement.

The class culminates with teams exhibiting their final projects, which this year included Han's team's Suni-Bot gymnastics robot, a hula-hooping robot, and the "Chicken-bot 9000."

"As a mechanical engineering student," Bolli says, "I think I was much more excited about the 'manus' aspect of 'mens et manus' ['mind and hand,' MIT's motto], so labs that involved building and controlling robot legs, as well as the final project, were definitely the most interesting part of the class."



The Chicken-bot 9000, created by Erik Ballesteros, Roberto Bolli, and Jadal Williams, in a demonstration of its walking gait. Credit: Lauren Futami

# 2.002: Mechanics and Materials II

## Compression-resistant nanoscale material – and possibly the world's smallest trophy

By Michaela Jarvis

Students taking 2.002: Mechanics and Materials II were brought into a lab at MIT.nano, an environment so delicate that all who enter must first cover themselves head to toe to try to keep out even the most minute speck of dust. Credit: John Freidah

The trophy Peter Williams won when he emerged victorious in last year's 2.002 (Mechanics and Materials II) class competition has a height approximately equal to the width of three human hairs. Claiming this minuscule prize, however, was a tall order.

In the design challenge, which represents an innovative new part of the undergraduate class on the mechanical properties of materials, Williams and his classmates were asked to design a nanoscale material able to withstand compression. Their mission: design the most compression-resistant microscopic cube possible using a material that would touch each side of the cube, but fill only 20 percent of the total volume.

In presenting the challenge, Professor Carlos Portela, the d'Arbeloff Career Development Assistant Professor of Mechanical Engineering, wanted to give students a hands-on research experience in an exciting space at the frontier of their field. "The objective was not only to expose students to leading-edge concepts of nanotechnology, nanomechanics, and metamaterials, but particularly for them to be in the 'driver's seat' of this experience," says Portela.

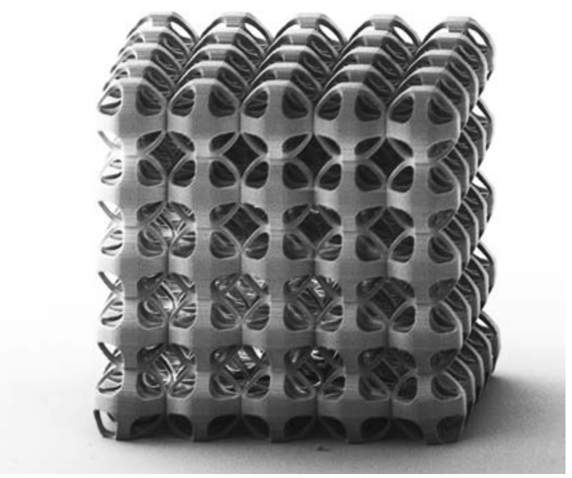
Working in a lab at the world-class MIT.nano facility – an environment so delicate that all who enter must first cover themselves head-to-toe to try to keep out even the most minute speck of dust – the students used materials fabricated using a 3D printer that shines a laser on resin to create precise, high-resolution structures.

"We were able to architect microscale metamaterials [materials designed to have certain mechanical behaviors] and come up with some really interesting designs and findings from that," recalls Williams, adding that he appreciated having the opportunity to work on "the questions that real scientists are asking currently."

For his winning design, Williams relied on a design principle he'd learned earlier in his studies. Calling it a "clear way to win," he arranged his nanomaterial in a two-dimensional profile that looks like vertical walls.

"If you have some kind of truss structure, it's not going to be as good as if the material is directly supported by the material under it. You can't put the same material diagonally and expect it to be as strong," Williams says. "I'm very good at CAD, and this is a very simple design. The more complicated ones didn't work."

A scanning electron microscope image of one of the student groups' designs. Credit: Courtesy of the Researchers



Allison King '23 designed her material using hexagons, which are also known to withstand compression really well. She says she was "on the edge of [her] seat," as her material, made visible with an electron microscope, was shown on a monitor while undergoing compression. King's design came in second. She said she was a bit disappointed that she didn't walk away with the nearly invisible trophy but, like the trophy, the disappointment was small and, ultimately, it was completely overshadowed by the immenseness of the experience.

"You walked in the lab, and it made you realize in that moment that, wow, MIT is a very cool place," King says. "People are literally pushing the bounds of engineering right in front of you and right now."

"I love the design side of mechanical engineering and getting to test hypotheses," she says. "So, being given a whole lot of freedom – like, 'Hey, go design anything you want and see if it works,' – actually put to use the skills and training that we've been learning to see if we can actually build a product."

The design challenge was fun and exciting for the students, but the work also has profound implications, according to Portela.

"Nano-architected materials have the potential to address unsolved societal and engineering challenges, since they achieve combinations of properties that no existing material could ever attain. The ability to produce materials that possess nanostructures in large volumes could have an impact on a variety of fields," he says, adding, "Enabling these properties beyond the nano- or microscale will be game-changing... [even though] a lot of hard work remains to be done to get us to that point."

MechE student Peter Williams '22 holds up his winning trophy from the "Design Challenge," where they are asked to architect a nanoscale material able to withstand the greatest compression.

For Williams, 2.002 and the design challenge may also be personally life-changing. Although he's planning to work in industry after he graduates, the experience is making him consider returning to academia. "As an undergrad taking 2.002, I was able to do very graduate-level research and use very high-level facilities," he says. "It got me excited to potentially go back into research."

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# News & Awards

## Departmental news

**Leadership appointments**

Department Head John Hart appointed Professors John Leonard and Sangbae Kim and Associate Professor Ellen Roche as Associate Department Heads, and Associate Professor Cullen Buie as MechE's new Faculty Diversity, Equity, and Inclusion (DEI) Chair.

**Topping the lists**

QS World University Rankings honored MIT with a number one ranking in the subject area of Mechanical, Aeronautical, and Manufacturing Engineering for 2023, and U.S. News and World Report named MechE the top graduate program and undergraduate program in Mechanical Engineering for 2022–2023.

**Women's Technology Program (WTP-ME)**

The Women's Technology Program (WTP-ME) introduces high school students to mechanical engineering. Returning in-person last summer, the rising high school seniors who attended presented a final poster session and participated in a Rube Goldberg Machine Challenge.

MechE leadership team. Top left: Cullen Buie, John Hart, Sangbae Kim | Bottom left: Joanne Mathias, Ellen Roche, John Leonard. Credit: Tony Pulsone

## Research highlights

**Injectable hydrogels**

A computational framework developed by Professor Ellen Roche and her team could help researchers design granular hydrogels to repair or replace diseased tissues. (Journal: *Nature*)

**Vertical, full-color microscopic LEDs**

Associate Professor Jeehwan Kim and team developed a new way to make sharper, defect-free displays by inventing a way to stack the diodes to create vertical, multicolored pixels. (Journal: *Nature*).

**Implantable ventilator**

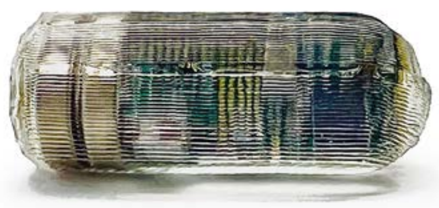
Associate Professor Ellen Roche and colleagues developed a soft, robotic, implantable ventilator designed to augment the diaphragm's natural contractions. (Journal: *Nature*)

**Ingestible sensors could pinpoint GI difficulties**

An ingestible sensor developed by Associate Professor Giovanni Traverso and team could help doctors pinpoint gastrointestinal difficulties. The sensor sends out its location as it moves through the GI tract and reveals where slowdowns in digestion may occur. (Journal: *Nature Electronics*)

**Hydrogel material keeps absorbing moisture, even in rising temps**

A team from Professor Evelyn Wang's Device Research Lab have identified an unusually absorbent material that could be used for passive cooling or water harvesting in warm climates. (Journal: *Advanced Materials*)



An ingestible sensor developed by Associate Professor Giovanni Traverso. Credit: The Researchers

The department hosted the Women's Technology Program, back in person for the first time since 2019. WTP introduces high school students to the basic principles and ideas of mechanical engineering for four weeks throughout the summer. Credit: Barbara Hughey

A soft, robotic, implantable ventilator developed by Ellen Roche and her colleagues. Credit: M. Scott Brauer

**Moving water and earth**

Professor Ken Kamrin and team found a more accurate formula for calculating how much sediment a fluid can push across a granular bed, which could help engineers manage river restoration and coastal erosion. (Journal: *Nature*)

**Optical fibers block pain**

Professor Xuanhe Zhao and team designed a soft hydrogel optical fiber that stimulates peripheral nerves and could help researchers in identifying the origins and treatments for nerve-related pain. (Journal: *Nature Methods*)

**Evaporation without heat**

Professor Gang Chen, Postdoc Yaodong Tu, and team identified a process that could explain various natural phenomena and enable new approaches to desalination. At the interface of water and air, light can bring about evaporation without the need for heat in certain conditions. (Journal: *PNAS*)

## Faculty & research staff promotions

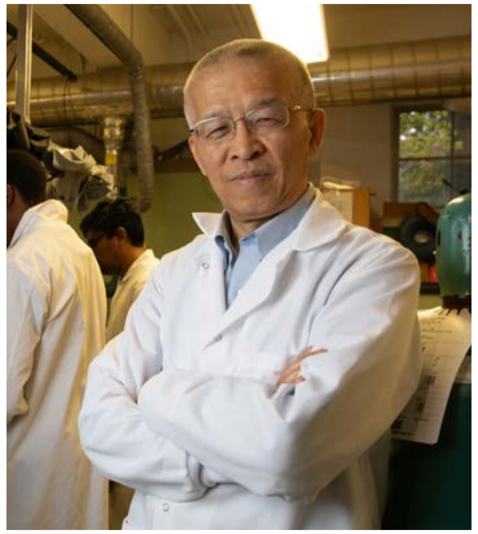
Asegun Henry was promoted to Full Professor. Henry is an internationally recognized leader in two areas within the field of thermal science and engineering.

Giovanni Traverso was promoted to Associate Professor with Tenure. Traverso is a rising star who has made groundbreaking contributions combining mechanical device engineering, biomedical engineering, and materials science with pharmaceutical and clinical sciences to address critical needs in human health.

Betar Gallant was promoted to Associate Professor with Tenure. Gallant is a leader in the electrochemistry of materials to address needs in energy storage and carbon capture for a sustainable future.

Ellen Roche was promoted to Associate Professor with Tenure. Roche is a recognized leader in biomechanics and physiology-based engineering of medical devices and soft robotics. She has established new innovative technologies that support or repair impaired organ functions and improve patient outcomes, targeting unmet needs.

The department hired two new 2N (naval) professors this year: Andrew Gillespy (PoP) and Christopher MacLean (APoP).

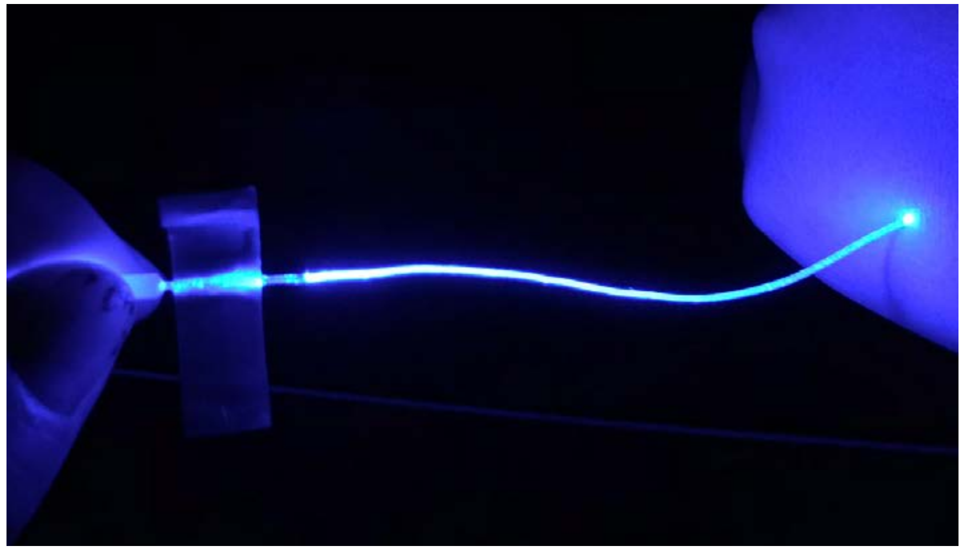


Gang Chen, Carl Richard Soderberg Professor of Power Engineering; Director, Pappalardo Micro and Nano Engineering Laboratories. Credit: Tony Pulsone

## Faculty awards

Gang Chen is one of 120 members and 23 international members elected to the National Academy of Sciences in recognition of his distinguished and continuing achievements in original research. Chen is also a member of the National Academy of Engineering.

Giovanni Traverso was named a 2022 National Academy of Inventors Fellow for demonstration of a highly prolific spirit of innovation in creating outstanding inventions that have made a tangible impact on the quality of life, economic development, and welfare of society.



A soft hydrogel optical fiber (shown illuminated) that stimulates peripheral nerves, designed by Xuanhe Zhao. Credit: The Researchers

Kaitlyn Becker teaching a group of students how to pull a vase in MIT's Glass Lab. Credit: Tony Pulsone

Kaitlyn Becker was named the 2023 Doherty Professor in Ocean Utilization. Becker's research focuses on adaptive soft robots for grasping and manipulation of delicate structures, from the desktop to the deep sea.

Roger Kamm and Markus Buehler were elected into the National Academy of Engineers.

Harry Asada was awarded the 2023 Pioneer in Robotics and Automation Award from the IEEE Robotics and Automation Society for pioneering contributions to robotics and automation in grasp stability and fixturing, direct-drive, skill transfer, and wearable systems.

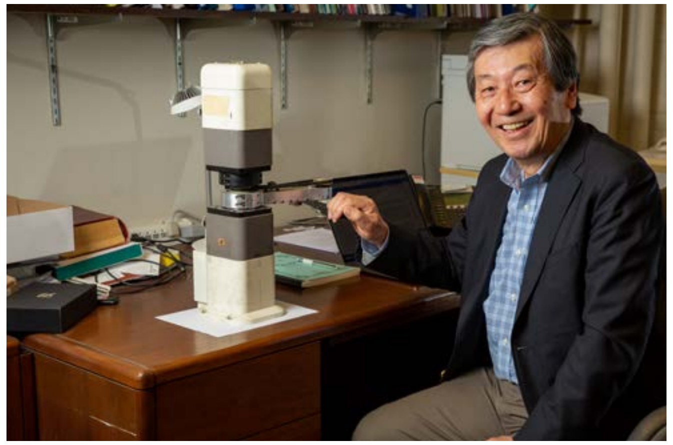
Ellen Roche received MIT's annual Harold E. Edgerton Faculty Achievement Award, which recognizes exceptional distinction in teaching, research, and service.

Evelyn Wang was elected to the American Academy of Arts and Sciences for 2023.

Peko Hosoi received MIT's Earll M. Murman Award for Excellence in Undergraduate Advising. The annual award recognizes one faculty member for excellence, mentorship, and significant impact on undergraduate lives and academic success.

Navid Azizan was selected as the 2023 Outstanding UROP faculty mentor, based on student nominations for research mentors who have demonstrated exceptional guidance and teaching. Azizan was also recognized as an Academic Data Leader in the CDO Magazine Leading Academic Data Leaders 2023 List.

Asegun Henry received The U.S. National Science Foundation's Alan T. Waterman Award. The annual award is the nation's highest honor for early-career scientists and engineers.

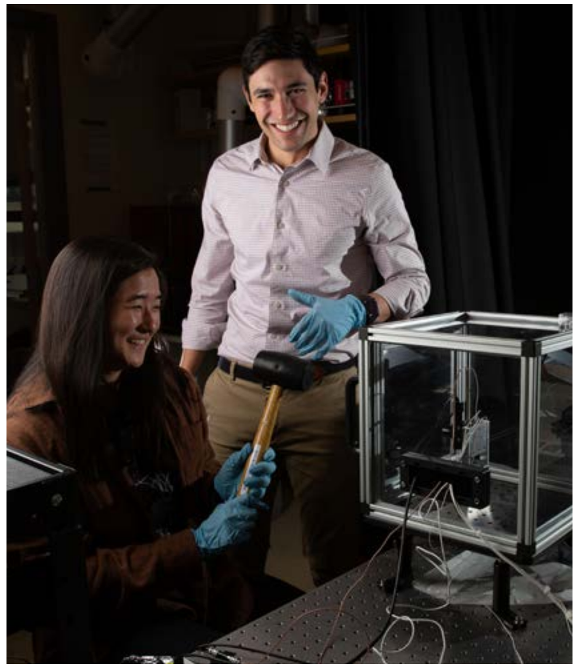


Harry Asada, Ford Professor of Engineering; Director, d'Arbeloff Laboratory for Information Systems and Technology; Head, Control, Instrumentation, and Robotics. Credit: Tony Pulsone

Lydia Bourouiba received the 2023 Paul Gray Award for Public Service for impact in the field of public health, and recognizing her contributions as "invaluable" in mitigating the impact of SARS-CoV-2 on society.

Gareth McKinley was elected as a Corresponding Member of the Australian Academy of Science for outstanding contributions to viscoelastic fluid mechanics, understanding flow instabilities and stretching flows, and rheological analysis techniques.

Carlos Portela received the 2023 Ruth and Joel Spira Award for Excellence in Teaching, which recognizes "the tradition of high-quality engineering education at MIT."



Assistant Professor Carlos Portela in the lab with graduate student Rachel Sun. Credit: Tony Pulsone

## Staff awards

Janice McCarthy, MechE Administrative Assistant 2, received an MIT 2023 Infinite Mile Award. Infinite Mile awards recognize individuals or teams who have made extraordinary contributions within their own organizations to help the Institute carry out its mission.

## Alumni news

Yamilée Toussaint-Beach '08 and Katy Croft Bell '00, along with Assistant Professor Ritu Raman, were featured in the Cambridge Science Festival's pop-up exhibit #IfSheCan, which highlighted the ways a more diverse, more inclusive workforce strengthens the world's shared future. (Cambridge Science Fest/MIT Museum)

Yamilée Toussaint-Beach '08 poses with her statue in the #IfSheCan Exhibit. Credit: Cambridge Science Festival/MIT Museum

Antora Energy, co-founded by David Bierman SM '14, PhD '17, is commercializing a thermal battery that lets manufacturers use renewable energy around the clock.

AJ Perez '13, MNG '14 developed a 3D-printed house foundation using recycled plastic bottles as part of a project exploring the viability of using the material to create affordable housing. Supported by the 2023 Chandler Fellowship, the work will continue with the establishment of a recycled-plastic microfactory research lab at MIT.

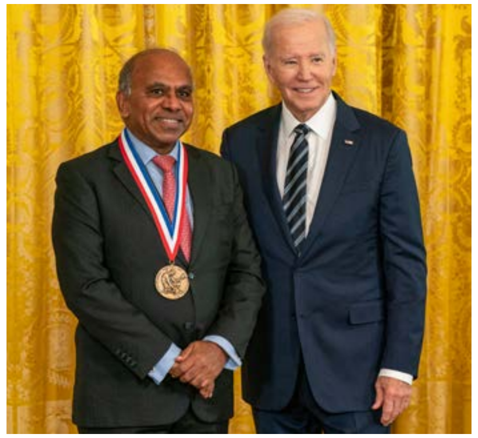
Yirui Zhang SM '19, PhD '22 is one of four researchers with MIT ties to earn a 2023 Schmidt Science Fellowship, which supports early-career scientists and engineers as they pursue interdisciplinary work.

Sreya Vangara '22 is one of three from MIT named Knight-Hennessy Scholars for 2023. The fellowship funds graduate studies at Stanford University.

Stacy Godfrey-Igwe '22 is the first MIT graduate with a major in African and African diaspora studies. The major invites students to explore the riches of culture, innovation, and more.

Vishnu Jayaprakash SM '19, PhD '22 placed first in the graduate category of the National Inventors Hall of Fame Collegiate Inventors Competition for his invention AgZen-Cloak, which helps pesticide stick to crops.

Subra Suresh SCD '81 received the National Medal of Science for his commitment to research, education, and international collaboration that has advanced the study of material science and its applications to other disciplines, and forged cooperation among people and nations.



President Joe Biden awards Subra Suresh, Nanyang Technological University, the National Medal of Science during an awards ceremony in the East Room of the White House, Oct. 24, 2023. Credit: Ryan K. Morris

Boston-based Gradiant, co-founded by Prakash Govindan PD '12, PhD '12 and Anurag Bajpayee SM '08, PD '12, PhD '12, achieved funding valued at $1 billion – making it the first water technology startup to attain the "unicorn" milestone.

Morris Chang '52, SM '53, ME '55, Taiwan Semiconductor Manufacturing Company (TWMC) Founder, visited campus to speak as part of the Manufacturing@MIT Distinguished Speaker Series.

Taiwan Semiconductor Manufacturing Company (TSMC) Founder, Dr. Morris Chang '52, SM '53, ME '55, visited campus to speak at the Manufacturing@MIT Distinguished Speaker Series. Credit: Gretchen Ertl

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