
YQ
YALE QUANTUM INSTITUTE
ANNUAL REPORT
2022

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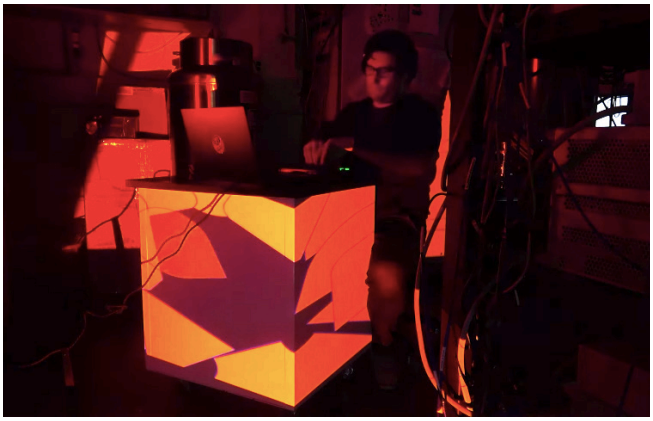

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DIRECTOR'S WORD

ROBERT SCHOELKOPF

Sterling Professor of Applied Physics and Physics

This past year saw a rebirth of activities at YQI, as researchers, students, and staff have adapted to the challenges and stress of working and living through a worldwide pandemic, Yale monitored closely the surge of cases on campus to safely allow us to gather back in person for academic, outreach, and professional development events during the lulls in the surges. The return to more normal campus life has improved the environment for our researchers, who continue to perform cutting edge work: testing new prototypes, developing theories, refining simulations, etc. with the goal of increasing our understanding of quantum science and information.

The University remains committed to the priorities articulated in the strategy for quantum science and engineering, and we are continuing to advance the planning and lay the groundwork for the long-term growth that will meet the University's ambitious goals. The YQI and our members are ready to play a key role in the next phase of growth in this field in research, engineering and teaching activity at Yale.

There have been exciting new developments at YQI in the past year. YQI member, Shruti Puri, Assistant Professor of Applied Physics, will lead Yale's participation in the new Quantum Leap Challenge Institute for Robust Quantum Simulation, a multi-institutional effort supported by the National Science Foundation that is focused on developing quantum simulation devices that can understand, and thereby exploit, the rich behavior of complex quantum systems (page 16). Additionally, we were delighted to welcome newly appointed Assistant Professor of Computer Science Yongshan Ding as our newest YQI Member. His research group focuses on a broad set of problems related to algorithms and computer architecture in quantum computing, and produces impactful research to improve the capability and performance of next-generation quantum computing systems. Yongshan hit the ground running with his membership and has created a new speaker series, the Quantum Computing Colloquium, hosted jointly by YQI and Yale Computer Science Department. that brings together world-leading researchers to interact with the quantum community at Yale for engaging discussions on the latest advances in the field of quantum computing. The series is founded on the idea that researchers across disciplines must work together to unlock the power of quantum computers.

This series will join the large offering of YQI programs (see page 8) organized by Florian Carle, our institute manager, and Racquel Miller, our events coordinator, including our YQI Colloquium Series, Distinguished Lecturer Series, and Professional Development and Networking Series. Science outreach is given a prominent place in this program thanks to our Non-Technical Talk Series in

EXECUTIVE TEAM

collaboration with the Franke Program (page 12) and our Artist-in-Residence Program (page 13).

This year we are launching our biggest and most ambitious program yet: Quantum Week at Yale! From April 8 to 14, YQI has joined forces with 18 partners on the Yale campus to host 23 events celebrating the fascinating world of quantum science! This mini festival (page 14) will consist of a series of talks, workshops, public discussions, exhibitions, and networking opportunities, as well as entertaining events for general audiences, such as: the screening of an indie thriller which uses quantum physics as an integral part of the plot, university-wide public screen displays, a lightshow, and the release of the album "Quantum Sound". Finally, if you are on campus this Spring or Summer, we encourage you to go visit the exhibition "The Quantum Revolution: Handcrafted in New Haven" curated by Florian Carle, and on display at the New Haven Museum. Alumni from Michel Devoret's research group will recognize a familiar "face": Badger! It was one of the first sophisticated quantum processors developed at Yale, and was groundbreaking at the time.

We invite you to learn more about our work and programs through this annual report, and to share our optimism for new scientific and technological advances for the benefit of mankind. We are looking forward to seeing you in person at YQI very soon!

Deputy Director

A. DOUGLAS STONE

Carl Morse Professor of Applied Physics and Physics

Institute Manager

FLORIAN CARLE

Benjamin Franklin College Fellow

Events Coordinator

RACQUEL MILLER

ABOUT THE INSTITUTE

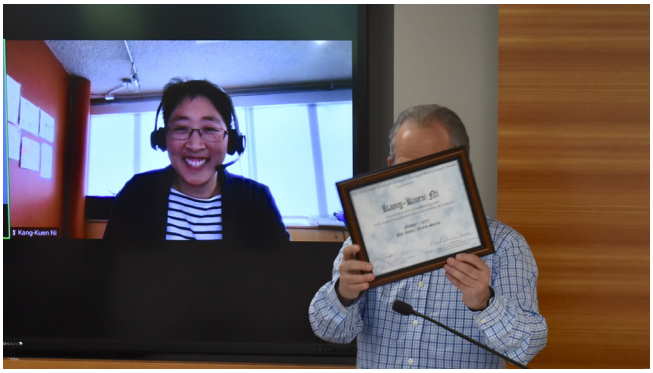
Life as we now know it would not be possible without several profound scientific and technological revolutions over the last century: the Industrial Revolution, the internal combustion engine, the telephone, and, most recently, the Digital Revolution which ushered in computers, cellular phones, and the Internet.

This transformative period was made possible by quantum theory, developed in the first half of the 20th century, which explained the fundamental laws of the atom and of light. At the onset of the 21st century, we are on the brink of a new quantum revolution – and Yale is paving the way. `

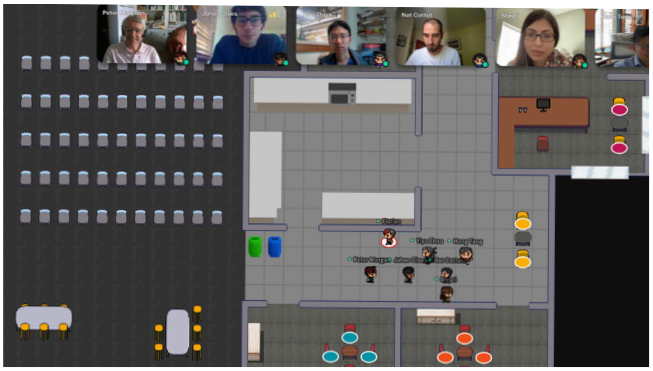
Our faculty members, spanning the departments of Physics, Applied Physics, Computer Science, and Electrical and Mechanical Engineering, are making scientific breakthroughs that would have been unimaginable only a few decades ago. The Yale Quantum Institute was formed in 2015 to advance the progress in fundamental and applied quantum science at Yale and in the broader community of researchers across the globe. Yale has particular expertise in the theoretical and experimental development of new technologies to store and process quantum information. Our goal is to better understand the fundamental quantum laws that govern our universe, and to harness the unique features of quantum mechanics for novel sensors, secure communications, and, eventually, the realization of large-scale quantum computers. We now know that by employing a kind of massive parallel processing, computers based on "quantum bits" can address problems that would otherwise remain forever beyond the reach of our current computers. These problems include basic algorithms underlying secure communication on the internet as well as quantum simulations of new materials, complex optimization problems, and improved machine learning. As with conventional computers, the true scope of their utility will only be discovered once they are built.

Beginning with pioneering work on macroscopic quantum coherence in the 80's, to the realization of today's quantum information processors, Yale professors are renowned for their leadership in the Quantum Revolution. In the past fifteen years, under the leadership of Devoret, Girvin, and Schoelkopf, the Yale superconducting science and technology team, comprising more than fifty researchers, has demonstrated several milestones in quantum computing including the development of the first solid state quantum information processors based on superconducting electronics. Together, the members of YQI are pursuing the collective goal of turning quantum physics into practical technologies and advancing our fundamental understanding of quantum science and engineering. We welcome researchers from around the world to visit and participate in this intellectual adventure.

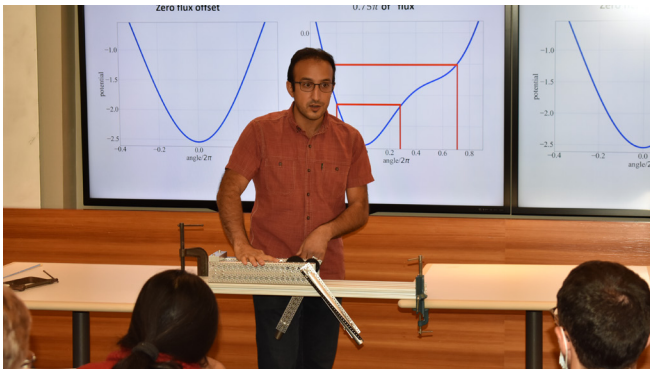
Colloquium & Seminar Series



Distinguished Lecturer Series



YQI Fellowships



Meeting space for research groups

OUR MISSION & PROGRAMING

The Institute acts as an intellectual hub for quantum information science and engineering, and of quantum science more generally, through fostering collaboration and welcoming world leaders in the field.

The Yale Quantum Institute was founded to enhance Yale's leadership in the field of quantum science and technology. It serves as a forum to bring together experimental and theoretical researchers at Yale in the fields of quantum information science and engineering, quantum control, quantum measurement, and quantum many-body physics and chemistry. The Institute also runs an active visitors program to bring in quantum scientists from leading institutions worldwide, and hosts conferences and workshops in sub-fields relating to its core mission.

The past two decades have seen breakthroughs in both the theory and practice of quantum science. The properties of superposition and entanglement, once thought of as paradoxical and counter intuitive, are understood now as unique resources. Recent progress in the laboratory allows un-

precedented control over individual quantum objects, whether they are naturally occurring microscopic systems like atoms, or macroscopic man-made systems with engineered properties.

These advances may soon enable us to: perform otherwise intractable computations, ensure privacy in communications, better understand and design novel states of matter, and develop new types of sensors and measurement devices. Today, a new discipline is emerging which combines physics, chemistry, electrical engineering, mathematics, and computer science to further the basic understanding of the quantum world, and to develop novel information processing devices and other quantum-enabled measurement and sensing technologies.

CS/YQI Quantum Computing Colloquium Series

Science outreach

Venue for quantum information events

HOME OF EVERYTHING QUANTUM AT YALE

Networking and Professional Development

INSTITUTE MANDATE

Quantum science is seen as a particularly difficult and intimidating subject. At YQI, we work to make it accessible to all.

Excellence in research and outreach go hand in hand

All the programming and outreach activities performed by YQI is only possible thanks to the excellence of the research performed in the quantum laboratories. For more than 20 years, Yale has been at the forefront of quantum research, developing systems, theories, algorithms, tools, and techniques that have been widely adopted by the industry and tech giants, and training graduate students and postdocs who became an invaluable workforce: researchers and leaders in industry and national laboratories, lecturers, and associate and full professors in academia. YQI's programming and outreach activities are made possible by the excellence of quantum research performed at Yale.

Diversity, Equity, and Inclusion

The Yale Quantum Institute is committed to fostering an environment of diversity, equity, and inclusion for every member of our community as we strive for excellence in research, teaching, and mentoring. We have established programs encouraging a welcoming environment that respects groups and their individual members: Physics Open Mic empowers students and postdocs by giving them a platform to voice their ideas; the Women In Quantum Information group promotes an inclusive environment for women in the field; and the speakers for our outreach programs are invited with gender parity and racial diversity in mind to give attendees a correct representation of the field as well as challenge unconscious bias.

A QUANTUM GROUP FOR EVERYONE

Quantum science can be a little intimidating and has developed a reputation as an all-or-nothing kind of commitment. But a new student group is looking to change that. The Yale Undergraduate Quantum Computing (YuQC) group was founded by Shantanu Jha, a math and physics major who graduated in December. Thinking of all the ways that quantum computing can be applied to other fields, Jha said he was inspired to engage a broad spectrum of other students with the emerging field.

"I did a lot of quantum engineering research at Yale, and I had a group of friends who were interested in this stuff—that really kindled my interest in the field," he said. "I wanted to build a community, and I realized that a lot of people are interested in quantum computing who don't come from the traditional background that you might associate with quantum computing."

Since it formed in the fall of 2020, and sponsored by the Yale Quantum Institute, the group has hosted social hours for its members, organized a quantum computing hackathon, and developed its Invited Speaker Series, Key to the group's success is the diversity of the members' backgrounds, said Nikhil Harle '23, a YuQC board member and one of the group's earliest members.

"I think a big misconception about this field is that you have to have the 'right' background or the 'right' degree to be able to contribute something," Harle said. "And through our programming, we've been working to challenge that."

In October, they held a meeting to gauge the level of interest. It turned out that there was a lot. More than 80 people signed up, from about 20 different majors. Some of these majors were the expected ones—physics, computer science, and math—but there were also those from economics, philosophy, psychology, literature, and others. Further, many of these students from non-traditional majors signed up for leadership positions in the group. Besides attracting much more interest—and from a wider range of students—than they had anticipated, the organizers said the event went a long way to advance its goal of opening up quantum computing beyond those in the core fields of research.

"All of this was expressly open to beginners, and we tried to be very clear that you don't have to have any experience to be part of this, and we ended up having a lot of beginners joining," Harle said. "We just wanted to show people that you don't have to be an expert—you can come in and learn. I think we proved that with the hackathon."

YuQC's current co-presidents, Ayelet Kalfus '24 and Allen Mi '22, said one of their goals is to keep building on the group's momentum—including expanding the reach of the Quantum Coalition, and building on QC Hack.

"We're deeply excited about having all of our members on campus this semester," said Kalfus. "Many of our members had never met face to face and we think it will be awesome to continue our projects and talk in person as much as possible."

"Quantum computing is one area that would benefit a lot from interdisciplinary studies," Mi said. "For one thing, it's very new—there hasn't been a specific discipline invented for it. And the other is that it really draws from the best of all kinds of technologies."

This article originally appeared in Yale Engineering magazine.

OUTREACH PROGRAMS

YQI's public programs invite everyone to learn and reflect about this exciting new area of science and technology

Nontechnical talk Series

Franke Program & YQI join forces

YQI organizes non-technical talks to engage the public and try to combat science-phobia, more specifically, quantum physics phobia. These talks seek to communicate the excitement of scientific exploration and educate the audience about the role that science plays in our daily life. At the time of this report, we have organized 12 non-technical talks that attracted 2612 attendees, indicating a great interest and need for this type of programming.

These talks are co-sponsored by The Franke Program in Science and the Humanities.

Public Conversations

Pure Science outreach

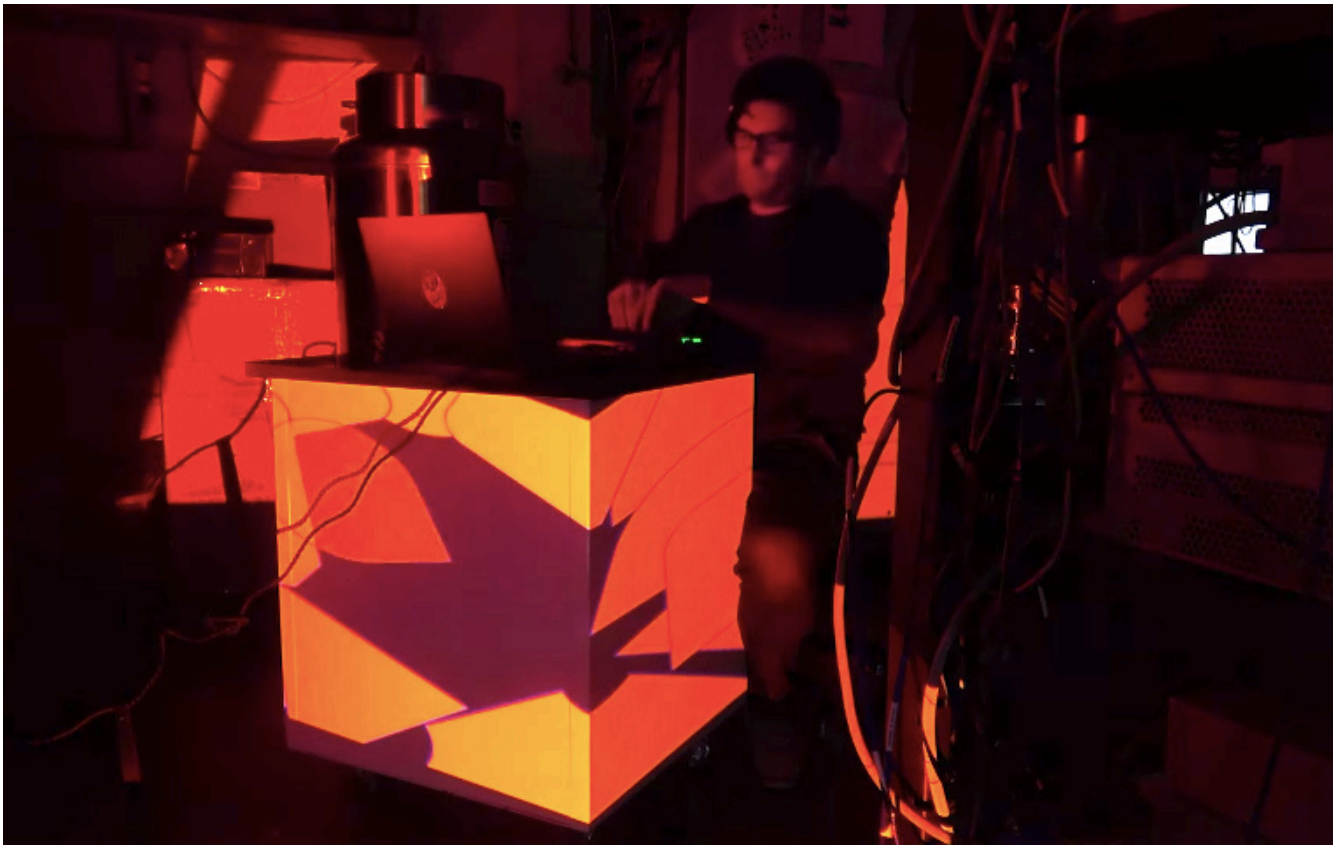
Our newest outreach program is public conversations; two or three people chatting on a somewhat general topic that allows the conversation to flow from one idea to another depending on the interest of the participants and of the audience.

The panels consist of a mix of YQI members and non-physicists to reduce jargon and make sure concepts are explained in layman terms. These public conversations are informal events where the audience is encouraged to take part in the conversation by asking questions or sharing ideas and comments.

COLLECTIVE QUESTIONING ABOUT QUANTUM ETHICS

A small group of quantum researchers, using participative methods, investigate what specialists in the field of quantum computing and simulation can bring to the table about quantum ethics, with a view to coming up with preliminary ways of tackling this complex issue.

Hosted at YQI in November 2021



Artist in Residence

Quantum at the edge of art

Central to our outreach efforts is the Artist-in-Residence Program. Each year, the Institute welcomes an artist for a year-long residency in which they produce quantum science-based artwork and visuals and participate in a series of public talks to explain their work and the science behind it. One of the goals of this program is to bridge the humanities-science divide. The artists are rigorously selected by YQI Institute Manager, Florian Carle, based on the quality and presentation of their work, their background, and experiences.

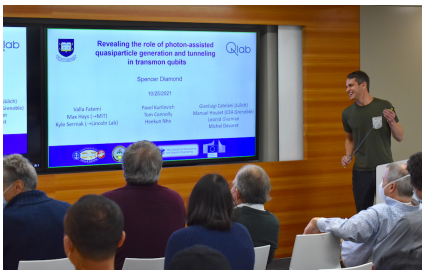
We are always on the lookout for artists interested in our program.

Visit art.quantuminstitute.yale.edu.

"QUANTUM SOUND" LIVE FROM OUR LABS

Sound Artist and Composer Spencer Topel, our 2019 Yale Quantum Institute Artist-in-Residence performed a live set of "Quantum Sound: A Live Performance of Superconductive Devices" in the Quantum Laboratories of Michel Devoret and Robert Schoelkopf for the 1st International Symposium on Quantum Computing and Musical Creativity on November 19, 2021.

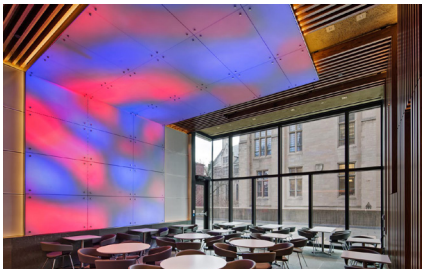
Quantum Sound
Album out now!
Stream or get the vinyl

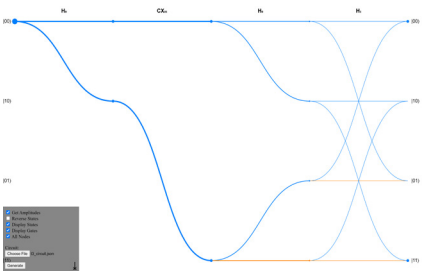


QUANTUM WEEK AT YALE

From April 8 to 14, 2022 YQI partnered with 18 institutes, centers and departments to bring 23 events open to all!

There are a lot of activities around Quantum Sciences and Information at Yale. Yale quantum researchers, leader in the field, performed the world's first demonstration of two-qubit algorithms with a superconducting quantum processor in 2009 and saw their technology widely used in the recent quantum breakthroughs. Quantum science and engineering was identified as one of five top priority areas for the next decade in the University's Science Strategy Report, and Yale is developing a state-of-the-art building that is intended to transform the pursuit of quantum science, engineering, and materials research. However, for most of people on campus, quantum physics stays an obscure topic filled up with dead and alive cats and other spooky actions at a distance. To help people outside the field to enter the fascinating world of quantum science, the YQI is launching Quantum Week at Yale, a full week of events all over campus to celebrate Yale leadership in this field!

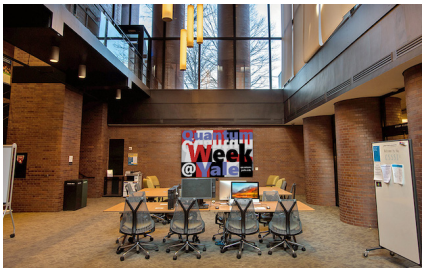


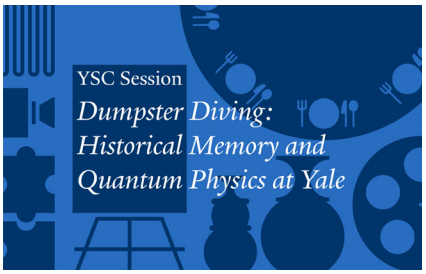


The program is built around four themes to offer various audiences all the information one needs to understand quantum, whether they never heard of quantum or are an expert in the field:

Understanding Quantum

If you are intrigued by quantum science but it seems inaccessible to you, consider attending one or more of these events. Designed especially for





the general public, they do not require any previous knowledge and will teach you key points of quantum science in an accessible way.

Art & Quantum

Strong of its Artist-in-Residence program, YQI uses art as a medium to engage audiences around the topic of quantum physics, and QWAY is no exception. The week features a large number of events mixing art, humanities and quantum, to bridge the gap between Science Hill and the rest of campus.

Career and Entrepreneurship

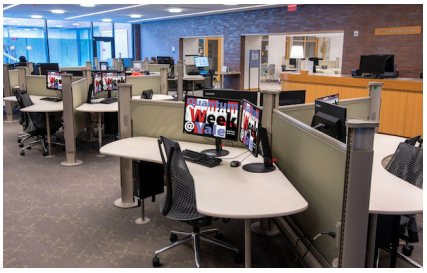
This section of the program is ideal for students interested in pursuing careers in quantum science at Yale or in other institutions, or the industry. Take full advantage of the program to learn more about career path, opportunities, and networking to join a field in full expansion.

For Researchers

IIf you are already in the field, you can also enjoy QWAY with an offering of technical talks especially for quantum researchers.

Full program at quantum.yale.edu

Quantum Week at Yale *is created by Florian Carle for the Yale Quantum Institute, in partnership with the Arts Library, the Bass Library, the Beinecke Library, the Departments of Applied Physics, Computer Science, and Physics, the Jackson Institute for Global Affairs, the Marx library, the New Haven Museum, the Office of Career Strategy, RCUL Jewelry, Studio Topel, Tsai CITY, the Science Librarians at Yale, the Whitney Humanities Center, Wright Lab, the Yale Undergraduate Quantum Computing group, Yale SEAS, and the Yale Schwarzman Center.*



YALE TO PARTNER IN NEW NSF QUANTUM SIMULATION INSTITUTE

This article originally appeared in Yale SEAS News.

Yale University is among the key partners of the new Quantum Leap Challenge Institute for Robust Quantum Simulation, a multi-institutional effort supported by the National Science Foundation (NSF) that is focused on developing quantum simulation devices that can understand, and thereby exploit, the rich behavior of complex quantum systems.

With the University of Maryland serving as the lead institution and funded by a $25 million award from the NSF, the institute brings together computer scientists, engineers, and physicists to develop theoretical concepts, design innovative hardware, and provide education and training for a suite of novel simulation devices that can predict and understand quantum phenomena. In addition to Yale, partners include Duke University, Princeton University, North Carolina State University, and researchers from the National Institute of Standards and Technology.

Quantum simulation is a fundamental step toward realizing a world where general-purpose quantum computers can transform medicine, break encryption, and revolutionize communications. Even the most powerful of today's "classical" computers struggle to represent even relatively small quantum systems, an obstacle that could be overcome by building next-generation quantum simulators.

The researchers believe that by evaluating the best approaches to small-scale quantum simulation, they can provide a detailed blueprint for what could be early practical applications for quantum computers. They have identified three major scientific challenges to focus their efforts on: methods for verifying the correctness of simulations, the interaction of simulators with their environments, and the development of scalable quantum simulators for science and technology applications.

To do this, the researchers plan to explore the theoretical foundations of quantum algorithms and error correction—in conjunction with experimental implementations of reconfigurable quantum simulators—on four leading hardware platforms: trapped ions, arrays of Rydberg atoms, quantum photonics with solid-state defects and superconducting circuits.

They envision tight collaboration between theoretical and experimental approaches to co-design near-term simulation protocols with current and next-generation devices. This includes the joint development of optical and microwave control techniques across different experimental platforms, allowing for rapid advances in system size and controllability. Yale's participation in the institute is led by Shruti Puri, assistant professor of applied physics and a theorist working at the intersection of quantum optics and quantum information processing. Puri will apply her expertise to develop noise-aware protocols for robust quantum simulations.

When designing a quantum simulator, you only want the user to be able to interact with the system. However, in opening the system to the user, it can inadvertently expose it to other objects that the system can interact with in uncontrollable ways.

"You can think of it as an eavesdropper trying to learn something about your quantum system," Puri said. "And in doing so, it disturbs the system and introduces errors in the quantum simulator."

Puri's goal is to find efficient approaches to mitigate or completely suppress such effects.

"The keyword here is efficient, that is, we want to protect our system with as little hardware- or time-overheads as possible," Puri said. "To this end, our aim is to take a bottom-up approach which exploits the features in the underlying quantum hardware to design robust protocols for quantum control. At Yale,

YQI Member Shruti Puri

Yale's participation in the institute is led by Shruti Puri, assistant professor of applied physics and a theorist working at the intersection of quantum optics and quantum information processing.

we combine our expertise in physics of quantum hardware and quantum control protocols to achieve this aim."

The ongoing mission of the NSF Quantum Leap Challenge Institute for Robust Quantum Simulation will also include a strong educational component. Plans call for a new flagship conference on quantum simulation and other outreach and education programs that engage diverse groups of students in quantum science.

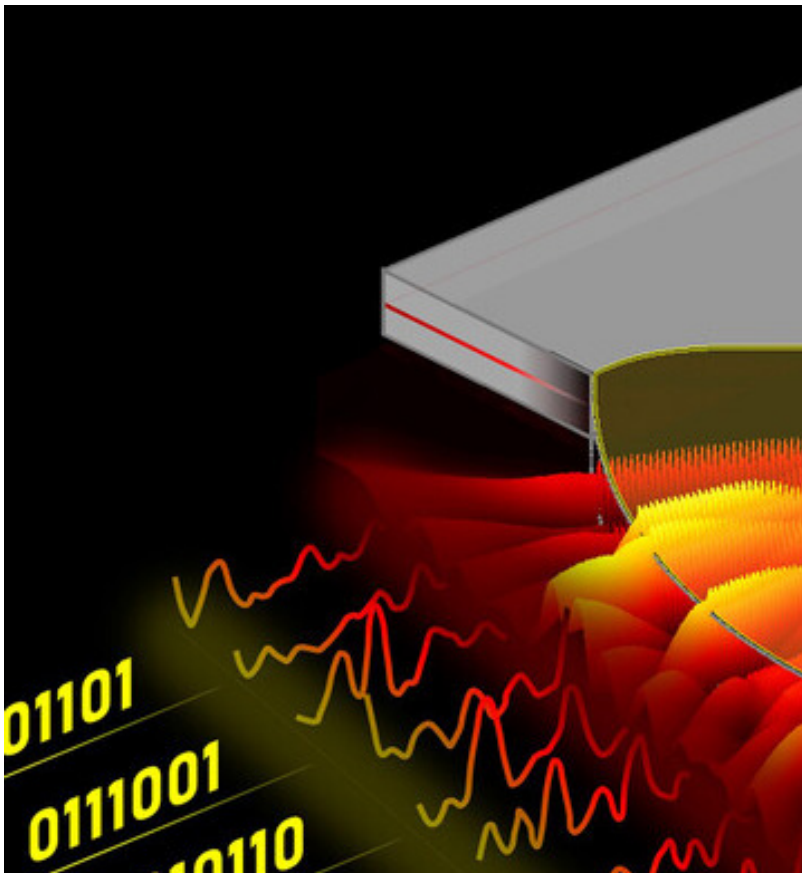
Today's announcement is the latest in a series of federal grants establishing a cohort of Quantum Leap Challenge Institutes nationwide. Three Quantum Leap Challenge Institutes launched last year, with the Quantum Leap Challenge Institute for Robust Quantum Simulation and the Quantum Leap Challenge Institute for Quantum Sensing in Biophysics and Bioengineering—led by the University of Chicago—being funded in 2021.

With science currently undergoing a quantum revolution, NSF is leading the charge through large-scale investments into centers that further the understanding of basic quantum phenomena, fundamental discoveries that will translate into transformative technologies.

"Our Quantum Leap Challenge Institutes program is developing the foundation of quantum information sciences, as well as developing the future students, faculty, startups and industry partners who are engaged in it," said Sean L. Jones, NSF assistant director of mathematical and physical sciences. "These two new institutes are tapping into challenging fields that have the potential to develop the next generation of tools that will establish the United States at the forefront of quantum innovation."

RANDOM NUMBERS: FASTER, AND FROM A LASER

YQI Member Hui Cao, John C. Malone Professor of Applied Physics and professor of physics and of electrical engineering, talks to William Weir for Yale SEAS News about her group's work on a chip that detects laser fluctuations to generate random numbers.



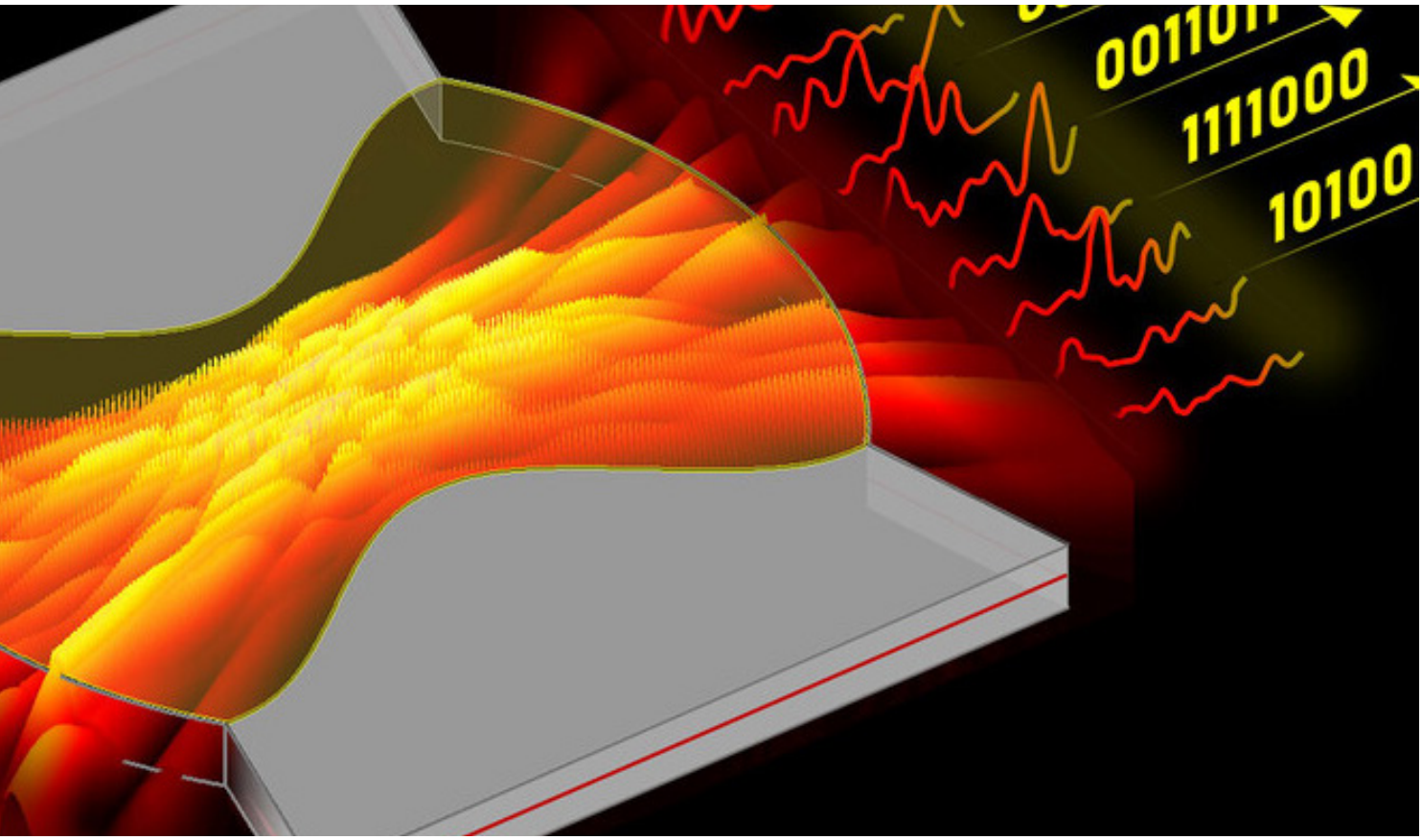
Random numbers are increasingly important to our digitally connected world, with applications that include e-commerce, cryptography, and cloud computing. Producing a large amount of truly random numbers quickly, though, is a challenge.

To speed things up, a team of researchers has developed a compact laser that can produce these random numbers 100 times quicker than the fastest current systems. The results are published February 26 in the journal Science.

To foil would-be hackers, computer systems need to generate sequences of random numbers. Some systems use what's known as pseudo-random numbers, which are actually complex patterns that begin with a particular number, or "seed." They work fine for some applications, but if attackers know the seed or any part of the algorithm, they can get past the encryption. Other systems employ true randomness, often relying on such unpredictable phenomena as an atom's radioactive decay, in which the timing of the decay is measured with a Geiger detector and then converted to random bits. These also have their drawbacks, such as low speed and high cost.

"Usually, those physical random number generators are not very fast — that's one problem," said Yale's Hui Cao, the John C. Malone Professor of Applied Physics and professor of physics and of electrical engineering, who led the study. "Also, they are sequential — that is, they usually just generate one bitstream. They cannot generate many bitstreams simultaneously. And in each stream, the rate is relatively low, so that prevents it from generating a lot of random numbers very quickly."

Cao and the research team designed a special type of semiconductor laser to generate randomness. The unpredictable properties of lasers have been used to generate random numbers before, but those systems relied on the lasers' chaotic temporal dynamics, which



were caused by introducing feedback. However, the frequency of the fluctuations is limited by the response time of the material, which in turn limits the number of random bits those systems can produce.

Cao and her collaborators tailored their laser cavity to amplify many optical modes simultaneously. These modes will interfere with each other to generate rapid intensity fluctuations, which are recorded by a fast camera. The fluctuations at different locations are then digitized to generate many random bit streams in parallel, which translate to random numbers.

Cao compared the hourglass-shaped device to a violin which is formed specifically to amplify sound and resonate with many acoustic frequencies. Similarly, the new laser cavity acts as a resonator for optical waves and amplifies many modes of light

In all of these modes, the spontaneous emissions — caused by quantum fluctuations — make the bitstreams unpredictable, creating a massively parallel, ultrafast random bit generator. The result is a system that can generate about 250 terabits, or 250,000 gigabits, of random bits per second — more than two orders of magnitude higher than the fastest current systems. It's also energy-efficient and can be scaled up significantly.

Having demonstrated that this new physical process can be used for this purpose, Cao noted that there's still much more to study.

"It really opens a new avenue on how to generate random numbers much faster, and we have not reached the limit yet," she said. "As to how far it can go, I think there's still a lot more to explore."

The researchers will next work on making the technology ready for practical use by creating a compact chip that incorporates both the laser and photodetectors. At that point, the random numbers could be fed directly into a computer.


The Yale quantum institute facilitates the research and teaching of quantum science on the Yale campus. YQI performs outreach in the form of seminars, workshops, and by hosting leading scientists from around the world.
QuantumInstitute.yale.edu