YALE QUANTUM INSTITUTE ANNUAL REPORT

2019

Welcome

THE YALE QUANTUM INSTITUTE, HOME OF EVERYTHING QUANTUM AT YALE

CONTENTS

Covers - Front: *entanglement* (2019), back: *entanglement II (2019)* - Spencer Topel

01

Yale Quantum Institute
This section of the annual report will describe the institute, its mission and its programing.

Director's Word

ROBERT SCHOELKOPF
FOUNDING DIRECTOR

Executive Team

A. DOUGLAS STONE
DEPUTY DIRECTOR

FLORIAN CARLE
INSTITUTE MANAGER

RACQUEL MILLER
ADMINISTRATIVE ASSISTANT

To the next 5 years!

The Yale Quantum Institute turns five years old this year and we are delighted to celebrate with you by publishing this Annual Report.

While Yale's efforts in quantum science and information started in the late 90's, we have seen an acceleration in the field on campus in the last five years, starting with the establishment of the Yale Quantum Institute. YQI is a center and a research forum which brings together faculty and other members of the campus community, from postdoctoral fellows to doctoral and masters students, as well as a significant number of undergraduate researchers. Our mission is to promote progress in quantum science and information and to enhance interdisciplinary research on campus.

> **"WE WANT TO MAKE NEW HAVEN CONNECTICUT THE BIRTH PLACE OF QUANTUM TECHNOLOGY."**

Among the activities of YQI are the hosting of cutting-edge research seminars and symposia in QSTEM by visiting scientists, tutorials on relevant topics in quantum science and information, professional and workforce training, and interdisciplinary Yale team meetings to formulate research questions, to plan research programs to answer these questions, and to write up and disseminate key results. Since 2014, our programing increased to more than 60 events per year, and twice as many private meetings and activities. YQI has been primarily a research hub and has had great success in fostering interdisciplinary collaborations and now plays a major role in everything quantum at Yale. In the last 5 year, YQI members and their groups have published 605 publications which received an annual average of more than 10,000 citations.

In 2016, Yale University undertook a major university-wide strategic planning exercise. Based on the strength of quantum research at Yale and intellectual excitement among students and faculty, the strategic planning committee selected quantum science, engineering and materials as one of the two highest priority areas for Yale in the coming decade. The interest in quantum science and engineering is rapidly expanding all around the globe, as are the sources and levels of research funding. Yale and YQI are playing a role in defining and responding to the US National Quantum Initiative (for example by attending the Quantum Summit at the White House last fall, see p. 11), and we are well positioned to capitalize on Yale's leadership in this space. An important goal will be to broaden the scope of research on campus, especially the opportunities for cross-disciplinary initiatives with engineering and materials science. We look forward to working with administration and the rest of the Yale community to help implement the goals articulated in the Science Strategy Committee's report.

We are particularly proud of our outreach programing (see page 18), especially the Artist in Residence program, curated by our Institute Manager Dr. Florian Carle. His program brought remarkable interest from the public and visibility to the Institute while producing high quality artwork which have been featured two years in a row in the prestigious International Arts & Ideas Festival. It is a mandate of the Institute to bring quantum science to the public in accessible terms for everyone to understand, and mixing quantum science and art is a wonderful way to effectively do it. Since then, YQI programing has inspired other Yale departments and laboratories to mix science and art based on our model.

We will continue our work to develop new quantum technology and models, train students into an efficient quantum work force, and educate the public about the quantum research. We hope you will learn more about our work and programs through the next pages of the annual report.

About the Institute

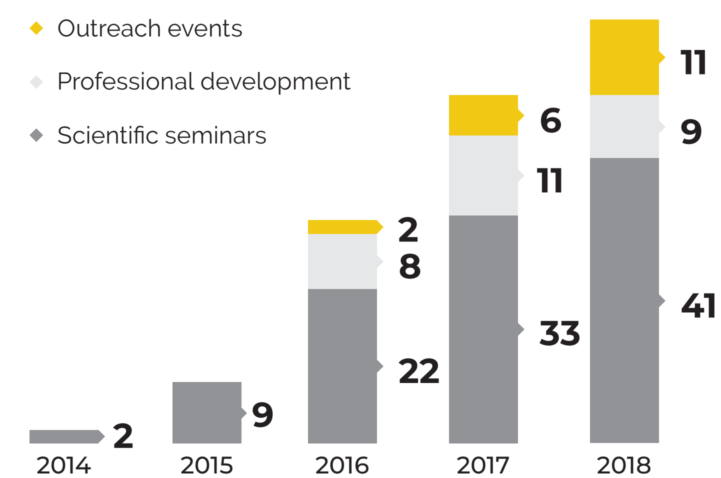
Life as we know it now would not be possible were it not for several profound scientific and technological revolutions over the last century: the Industrial Revolution, the internal combustion engine, the telephone, and most recently the Digital Revolution which ushered in computers, cellular phones, and the Internet. This transformative period was made possible by the understanding of the fundamental laws of the atom and of light embodied in quantum theory, developed in the first half of the 20th century. 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. The goal is to better understand the fundamental quantum laws of 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 probably only be discovered once they are built.

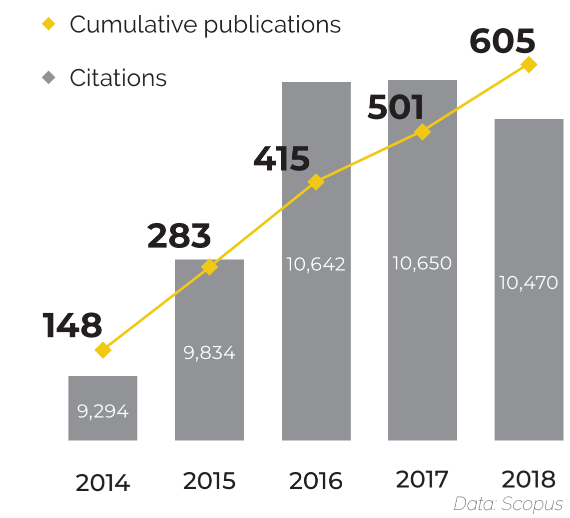
Beginning with pioneering work on macroscopic quantum coherence in the 80's to the realization of today's quantum information processors, Yale professors are renowned for their leadership in the Quantum Revolution. In the past fifteen years, under the leadership of Devoret, Girvin, and Schoelkopf, the Yale superconductive devices team of 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.

5 YEARS IN NUMBERS

EVENTS HOSTED BY YQI

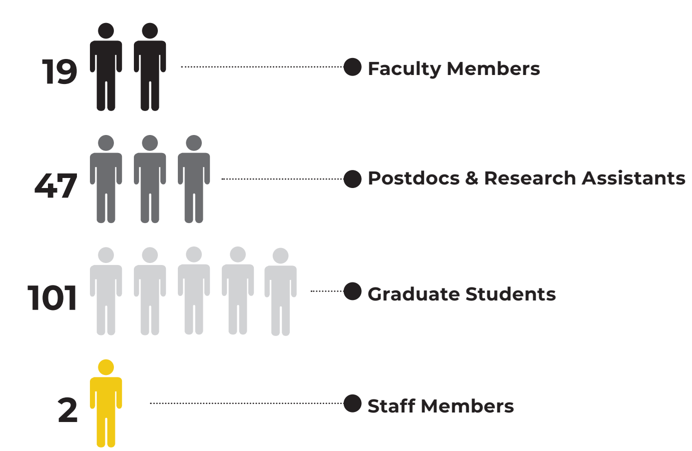


RESEARCH PRODUCTION

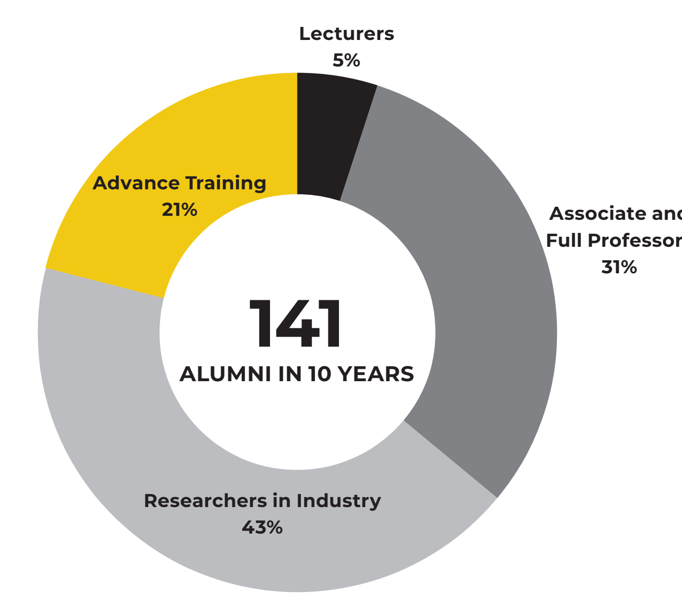


Science	Nature	Nature Group	PRL	PNAS
9	8	28	57	3

INSTITUTE COMPOSITION IN 2019



CURRENT OCCUPATION OF YALE ALUMNI



Mission & Programs

The institute fosters collaboration and welcomes world leaders in the field to foster New Haven's role as an intellectual hub for quantum information science and engineering, and of quantum science more generally.

The Yale Quantum Institute was founded to enhance Yale's leadership in the field of quantum science and technology. It serves as a forum, bringing together experimental and theoretical researchers at Yale in the field 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 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 the practice of quantum science. The properties of superposition and entanglement, once thought of as paradoxical and counterintuitive, are now understood instead as unique resources. Progress in the laboratory now allows unprecedented 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.

Illustration by Zihao Lin for Yale Daily News

COLLOQUIA & SEMINARS SERIES

Every academic year, the institute presents an exciting series of technical seminars and colloquia from experts in the field of quantum information science, quantum control, quantum measurement, and quantum many-body physics. Speakers are proposed by members of the Yale Quantum institute community and approved by a selection committee. The talks are attended by a diverse cross section of the university ranging from undergraduates to emeritus professors.

VENUE FOR QUANTUM INFORMATION EVENTS

The Institute hosts many seminars, presentations, group meetings and other events in the field of quantum information science and engineering. YQI is also the organizer of the annual Yale Science and Engineering Forum. In 2017, we welcomed the workshop *Majorana Fermions & Beyond*, and we will host the symposium *Quantum Mesoscopic Physics and More* in 2019. All interested students, professors and staff from Yale or other academic institutions are welcome to attend our events.

YQI FELLOWSHIP

In keeping with the mission of the institute to facilitate research and teaching of quantum physics, the YQI Fellowship Program provides funding for recent Ph.D. recipients to join each year the group of any of the YQI faculty members for a 2-year period. YQI Fellows are young researchers who have demonstrated excellent research ability in their prior work and exceptional promise for future leadership in their field of quantum science. Meet the YQI Fellows page 23!

NETWORKING AND PROFESSIONAL DEVELOPMENT

We offer a selection of presentations to help students and postdocs with career development, job search and networking. Speakers in this series includes noted scientists, industry leaders, and legal advisors, all of whom are Yale alumni. These experts return to the university to share their career experiences and offer an opportunity for attendees to build a solid career network and to ask questions.

DISTINGUISHED LECTURER SERIES

YQI award the title of Distinguished Lecturer to recognizes a researcher whose work significantly advances quantum science, with emphasis on the areas of mesoscopic physics, nanoscience, quantum information, quantum computing and related theoretical and mathematical topics. Annually, a Distinguished Lecturer will be invited to visit the Yale Quantum Institute to deliver one of more lectures about a valuable research results or a body of important work which has advanced our understanding in one or several sub-fields of quantum science.

VISITORS PROGRAM

The Yale Quantum Institute opens its doors to world leaders in quantum information science for sabbatical visits to Yale. These visiting scientists can focus on their research in close proximity to YQI's professors and students at our 17 Hillhouse Avenue location. This program could be expanded to encourage more long-term collaborations by welcoming visitors on longer periods (month, semester, sabbatical year).

OUTREACH PROGRAMS

The institute outreach programing is detailed in Section 3 of the annual report.

02

Quantum Science
This section of the annual report will concentrate on the scientific activities of the Yale Quantum Institute members, and is constituted of reprints from news articles.

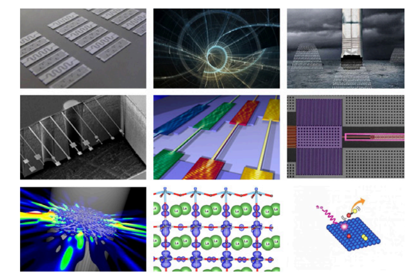
QUANTUM IS TOP PRIORITY FOR YALE

The University Science Strategy Committee released its report featuring quantum science, engineering, and materials as the number 2 ranked priority for the university.

News from the YQI Community

DAN PROBER RECEOVES IEEE AWARD

Dan Prober was awarded the "2018 IEEE Council on Superconductivity" in recognition of his continuing and significant contributions in the field of superconducting electronics .



QUANTUM AT YALE

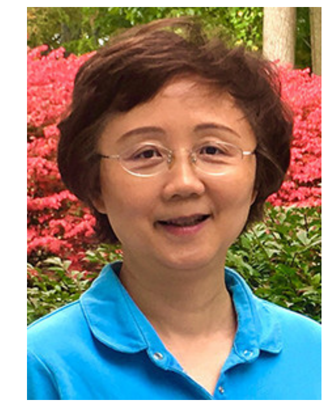
YQI has launched a new hub to learn about all areas of quantum science activity at Yale. The website describes our current research and links to interesting quantum related videos. It also is a portal for students and postdoctoral researchers to apply to Yale programs in quantum science.
quantum.yale.edu

NIR NAVON AWARDED THE SLOAN RESEARCH FELLOWSHIP

Nir Navon, YQI Member and Assistant Professor of Physics, and four other Yale faculty members have been awarded a $70,000 Sloan Research Fellowship to advance their research.

QUANTUM SUMMIT AT THE WHITE HOUSE

YQI Director, Robert Schoelkopf, and member Steven Girvin, as well as Yale President Salovey were invited to attend and participate to the White House Quantum Summit in October.



HUI CAO NAMED MALONE PROFESSOR

Hui Cao, who focuses her research on mesoscopic physics and nanophotonics, was newly named as the John C. Malone Professor of Applied Physics and of Physics. She has been a YQI member since 2017.

NIELS BOHR LECTURE BY PROFESSOR RAMAMURTI SHANKAR

YQI member Ramamurti Shankar was invited to give the prestigious Neils Bohr Lecture last May; his talk was titled: "The Royal Road to Landau's Fermi liquid".

Yale quantum computing startup Quantum Circuits Inc. opens lab in New Haven

Excerpted from Yale News

The Jan. 24, 2019 ribbon cutting ceremony. Left to right: Daniel T. Ciporin, general partner at Canaan; Robert Schoelkopf; Gov. Ned Lamont; and Yale Vice Provost for Research Peter Schiffer.
Photo credit: Laura St John

The potential of Yale's research to drive economic growth and produce jobs took center stage on Jan. 24, as Yale startup company Quantum Circuits Inc. (QCI) opened its New Haven development and testing facility for quantum computing.

The facility includes 6,000 square feet of state-of-the-art laboratories and in-house manufacturing. It will house more than 20 scientists and engineers. Company officials said QCI plans to grow significantly over the next several years, increasing both the size of the facilities and the number of highly-skilled employees in New Haven.

The ribbon-cutting ceremony included participation from Connecticut Governor Ned Lamont, Yale Vice Provost for Research Peter Schiffer, and QCI co-founder and chief scientist Robert Schoelkopf, who is Sterling Professor of Applied Physics and Physics at Yale.

QCI is developing the first practical quantum computers. Quantum computing has the potential to enable calculations that are orders of magnitudes faster and more powerful than today's supercomputers for certain types of problems. Applications will include drug design for biotech, materials science, improved processes for industrial chemicals, fintech, logistics, machine learning, and energy.

"We have already seen the power of combining fundamental scientific understanding with the multidisciplinary engineering team that we are building at QCI," Schoelkopf said. "These new facilities will enable us to accelerate our development efforts and ensure that New Haven is at the forefront of the new wave of quantum information processing."

QCI's founding team — Michel Devoret, Yale's F.W. Beinecke Professor of Applied Physics and Physics; Luigi Frunzio, a senior research scientist in applied physics; and Schoelkopf — pioneered the field of quantum computing with superconducting circuits. Their lab was the first to perform quantum algorithms and quantum error correction in integrated circuits.

Yale's longstanding commitment to the field of quantum computing helped cultivate the work, as well as many years of government and philanthropic support, officials noted. Yale recently named quantum science as one of the university's top priority investment areas.

"The story of QCI illustrates the potential to leverage university research to create jobs and to drive a competitive, high-tech economy. Yale is grateful for the generous federal investment in quantum science, the support of Connecticut Innovations and other state agencies, and of course the commitment by Canaan, Sequoia, and others in the private sector," Schiffer said. "Yale is proud of all of the startups based on Yale inventions, and we look forward to working with the private sector and the state to build more companies in New Haven."

Officials at the event cited QCI's roots in New Haven, saying the company is an example of Connecticut as a home for new and innovative technology, often with academic work at Yale contributing to the momentum.

A fault-tolerant system for stopping 'leaks' in quantum computers

Jim Shelton - Excerpted from Yale News

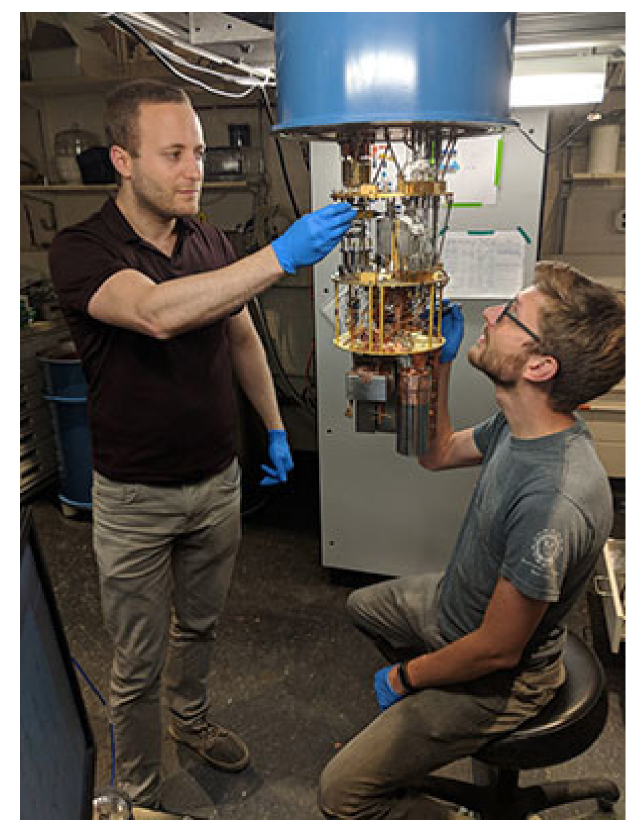
Yale researchers have designed a new system to keep tomorrow's quantum computers from "leaking."

Large-scale quantum computers are still years away, but it is well known that they will need error correction. All of the components in a quantum computer are connected in a fragile, entangled state that allows a quantum computer to solve problems that would be impossible on a classical computer. Because of this entanglement, an error in just one bit of quantum information, called a qubit — or even the act of measuring a qubit — can collapse the entire enterprise.

Unfortunately, researchers say, the process of correcting errors is itself faulty and can further corrupt the information contained in qubits.

"The only way a quantum computer can work is if its 'logical' qubits are constantly monitored by 'ancillary' qubits, which ensure logical errors are detected and corrected before they can affect the computation," said Yale postdoctoral associate Serge Rosenblum, co-lead author of a new study published in the journal Science.

Ancillary qubits have already been shown to correct logical errors, but their use so far has been limited because errors in the ancillary qubits can "leak" to the logical qubits, thereby introducing more errors than they're able to fix. The Yale team solves this problem by making its system fault tolerant — meaning that errors in the ancillary qubits aren't able to leak over to the logical qubits. Fault tolerance prevents faulty ancillary qubits from collapsing the logical quantum state.



Serge Rosenblum (left) and Philip Reinhold, co-lead authors of a new study on a fault-tolerant quantum error correction system.

"Using this method, the chance of catastrophic failure during error detection has been reduced by a factor of five," Rosenblum said.

Co-lead author Philip Reinhold, a graduate student, said fault tolerance "essentially amounts to making a robust system out of faulty parts. It opens the way for error correction that increases the fidelity of quantum computation."

Rosenblum and Reinhold work in the Yale lab of Robert Schoelkopf, the study's principal investigator.

Additional authors of the study are Liang Jiang and Luigi Frunzio from Yale and Mazyar Mirrahimi from the French Institute for Research in Computer Science and Automation.

Yale researchers are at the forefront of efforts to develop the first fully useful quantum computers, which have the potential to solve certain problems orders of magnitude faster than today's supercomputers. Yale's quantum computing research includes pioneering work using superconducting circuits.

Yale Quantum Engineering Gets a Boost From DOE Grant

Excerpted from Yale SEAS

A team of researchers from Yale Engineering and Yale's Quantum Institute has been selected by the U.S. Department of Energy (DOE) to develop the core quantum computing and networking components that would make the uncanny world of quantum physics realistic for computing.

The project, led by Hong Tang, the Llewellyn West Jones, Jr. Professor of Electrical Engineering, is among 28 universities and national laboratories being awarded by the basic energy sciences division of DOE, which is awarding a total of $218 million for the emerging field of quantum information science (QIS). Yale's three-year grant is for $3.6 million. The awards were made in conjunction with the White House Summit on Advancing American Leadership in QIS.

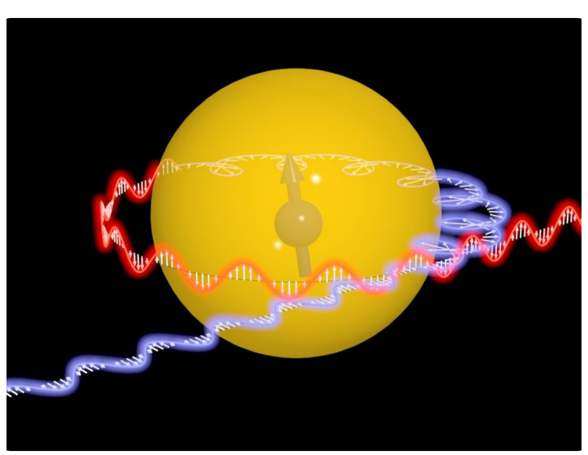
In addition to Tang, the research team includes Liang Jiang and Peter Rakich, both assistant professors in applied physics; Steven Girvin, the Eugene Higgins Professor of Physics; and Robert Schoelkopf, Sterling Professor of Applied Physics. Charles Thiel and Rufus Cone, professors of physics from Montana State University, are also part of the team.

The project focuses on finding new materials for the hardware of quantum computing. In classical computers, the transistor talks to a memory cell, which stores the information. In quantum computers, though, some of the quantum bits of information - known as qubits - excel at computing tasks but have a short lifetime. Others have extended lifetimes but are less capable of logic operation. Plus, the two types of qubits are often hosted in different materials. Yale researchers have previously perfected the qubits made from superconductors for quantum computing tasks. The memory qubits, however, remain elusive. Finding the right kind of memory material is critical. To that end, the team has identified rare earth ions as quantum memories, which are the expertise of the Montana collaborators.

"The wiring between the qubits and the memory is not as simple as it is in a regular computer, so we need to develop some connection mechanism to allow the operation qubits to talk to the memory qubits," Tang said. "We need to get better materials to improve quantum information science - material that has less noise and a high coherence." While Tang, Rakich and Schoekopf will work on the hardware components of the project, Girvin and Jiang will focus on the theoretical side.

"We need a significant theory support because each individual system is still not well understood," Tang said. "Even for the common materials, there are many things we don't understand about the interface, such as defects and noise process. Our goal is to understand this noise process and to make the lifetime of these qubits longer."

Girvin said he and Jiang will work on the question of how material environments cause the rare earth ions to lose the memory of their quantum state, a phenomenon known as decoherence. The researchers noted that the project would be impossible without both the theoretical and engineering sides working on it.



"This is a complex project requiring multiple people with deep expertise in materials science, optics, microwaves and cryogenics, as well as quantum experiment and theory," Girvin said. "We are trying to create a new discipline of 'quantum engineering' that connects the implausibly strange world of quantum physics with practical device and systems engineering. This simply cannot be done without an interdisciplinary team."

Yale plays quantum catch in new research

Jim Shelton - Excerpted from Yale News

Yale's latest work expanding the reach of quantum information science is actually a game of quantum pitch and catch.

In a new study published April 23 in the journal Nature Physics, Yale researchers "pitch" a qubit — a tiny bit of quantum data — from one physical point in a microwave cavity to a separate point in a different cavity. It is the first time an end-to-end quantum transmission has been done on demand and represents the first of two Yale experiments involving "pitch-and-catch" technologies that will be published this year. Quantum computing offers the possibility of computation speeds that are orders of magnitude faster than today's supercomputers. Yale researchers are at the forefront of efforts to develop the first fully useful quantum computers, and have done pioneering work in quantum computing with superconducting circuits.

But in order for a quantum computer to run more complex algorithms, it will need more processing power, just as a classical computer does. To do that, qubits must be interfaced with each other — which is why a "pitch and catch" capability would come in handy. "Our approach is to use a quantum network to connect many qubits together in independent modules," said Christopher Axline, a Yale graduate student and co-lead author of the new study. "The strategy is similar to clustering computers together on a local area network."

Axline works in the Yale lab of Robert Schoelkopf, the study's principal investigator. The other co-lead authors of the study are Yale graduate student Luke Burkhart and former Yale postdoctoral associate Wolfgang Pfaff, who is now at Microsoft. Previous work by the researchers enabled them to pitch a qubit, while preserving its information. Now they're able to catch the information, as well.

"You might think catching our flying qubit would be a straightforward extension of our other work, but it actually requires some careful treatment," Burkhart said. "It meant varying how quickly, and at what frequency, the information is released. If we open the floodgates and let energy flow out as quickly as possible, it will overwhelm the catcher." Instead, the researchers carefully shape their pitch-and-catch over time, so that both ends of the transaction are in sync.

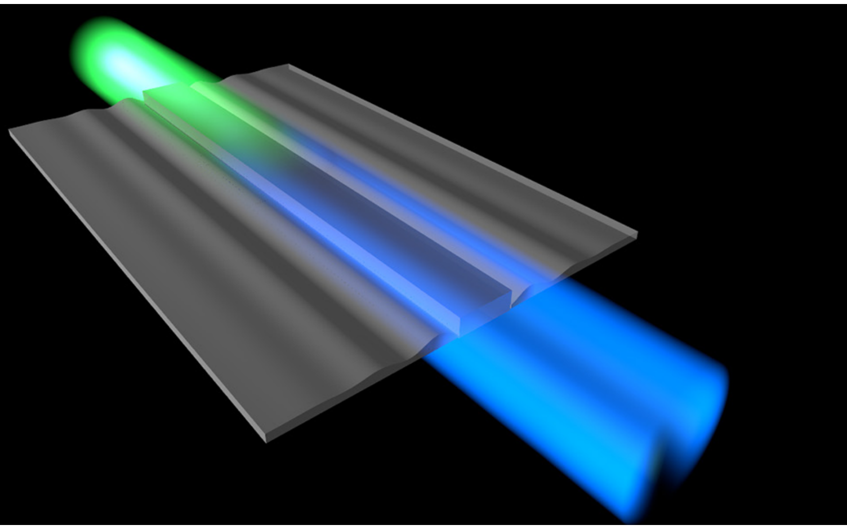
Another first for the experiment is the use of the cavities — in addition to the qubit itself — as the memory for the system. "Much of the research in our lab and at the Yale Quantum Institute focuses on how to take advantage of cavity modes for quantum information processing," Axline said. "Superconducting cavities are the most secure places we can store quantum information, and even more important, cavities are flexible as to the form of the stored information."

This quantum game of pitch and catch also includes quantum entanglement, a key concept in quantum physics and a requirement in any quantum algorithm. In this instance, it means the pitcher is pitching and not pitching, simultaneously.

"We entangle the states between the pitcher and the catcher," Burkhart said. "This remote entanglement will be crucial in quantum networks."

Making sound ‘chill out’

Jim Shelton - Excerpted from Yale News



Cooling sound waves with light involves converting sound energy into light energy, which changes the color of the light.
Image credit: Eric Kittlaus and Nils Otterstrom

Yale scientists have discovered that laser light can be used to cool traveling sound waves in a silicon chip.

In the last several decades, the ability to cool clouds of atoms using laser light has revolutionized atomic physics, leading to the discovery of new states of matter and better atomic clocks. Laser cooling relies on the fact that photons, or light particles, carry momentum and can exert a force on other objects.

These techniques have recently been adapted to slow down, or cool, mechanical oscillators comprised of billions of atoms. This type of cooling has become an enabling technique for exploring the quantum properties of mechanical objects and reducing forms of noise that would otherwise corrupt precision measurement.

Yale researchers have extended these phenomena by showing how light can be used to cool sound waves traveling within solid materials. To do this, the researchers developed a special type of nano-scale silicon structure that allows propagating light and sound waves to interact.

“By tailoring the optical and acoustic properties of these waveguides, we’ve been able to enhance and shape the interaction between light and sound,” said Peter Rakich, an associate professor of applied physics at Yale who led the research. “This is the key that allows us to reduce the energy carried by thermally excited sound waves.”

When a photon interacts with sound waves propagating in a solid, it scatters to different colors of light. When the photon becomes red-shifted, it loses a portion of its energy, imparting it to the sound wave. Simultaneously, the light absorbs the acoustic energy and carries it away as a blue-shifted photon. This second process slows the motion of the sound wave, bringing it to a lower effective temperature.

Normally these two opposing processes would counteract and balance out. However, Yale researchers designed a waveguide in which a certain group of sound waves only experience the cooling process. “We call this symmetry breaking, and it’s the essential ingredient for the cooling process to dominate,” said Eric Kittlaus, a Yale Ph.D. student and co-author of the study.

First author Nils Otterstrom, a Yale Ph.D. student, noted that the researchers were surprised by the strength of the cooling effect. He said it led the team to develop a rigorous theoretical framework for understanding the phenomena, as well as coming up with systematic experimental studies.

“We now have a knob that allows us to control processes that are at the heart of emerging chip-scale technology, including new types of lasers, gyroscopves, and signal processing systems,” Otterstrom said.

Added Rakich, “We are really excited about where this work may lead. We now have the ability to tame and control noise in a large range of systems that are crucial to communication, information processing, and measurement in a way that we never had before.”

Yale quantum researchers harness teleportation

Matt Kristoffersen - Excerpted from Yale Daily News

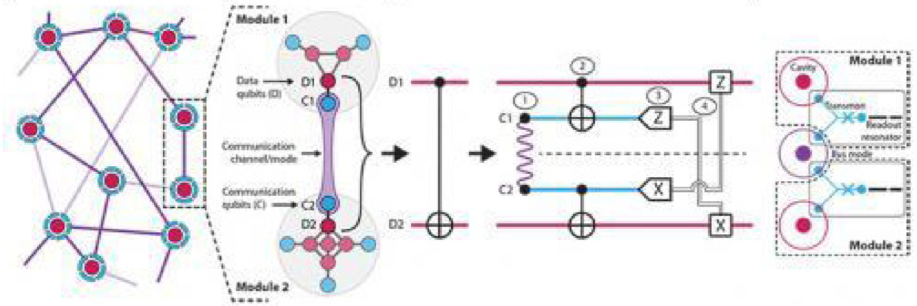
Teleportation and quantum entanglement may sound like aspects of a sci-fi novel, but researchers from the Yale Quantum Institute are exploring these very real phenomena in order to refine the tools that will lead to a more stable quantum computer. The study detailed the researchers’ use of modularity, the use of many simple components as building blocks for a larger entity, as a technique to decrease failure rates in quantum processors and teleportation — instantaneous information movement — to improve the state of quantum computing, a faster form of information processing than classical computers. These subatomic particles behave in odd ways that are not always predictable, study first author Kevin Chou said. “Qubits, in contrast to classical bits, are very fragile. They forget their state pretty easily. If all of your qubits forget what state they are, you can’t perform a computation. They are also very sensitive to noise.” If a bit is on, then it will stay on independently of what happens around it; if a qubit is in a certain position, then it can influence the states of qubits many miles apart in a process called quantum entanglement.

To explain modularity, Chou compared ideal quantum computers to rockets. “[Rockets] don’t just have one big engine. If that engine fails, well, you only have one engine. Your rocket’s not going to fly. So instead, you have a network of many, many smaller rockets, networked in a way that if one fails, there’s redundancy to pick up the slack.” Modularity is not a novel concept, Chou says, but combined with other parts of the team’s study, this represents a large development in tackling the obstacles to a quantum reality. Specifically, the technique allows for redundancy, which can in turn prevent small errors from ruining an entire computation.

“Modularity is the opposite of integration,” said Michel Devoret. Modern computers and cell phones have integrated circuits with billions of transistors on them that either all work or do not, Devoret said. Just as “television sets in the 1960s had many different circuits that [factories] could test individually before wiring it all together,” he said, modularity in a quantum setting is the first step toward having a reliable means of manufacturing quantum computers.

The study also explored another science fiction trope: teleportation. “Teleportation evokes some sort of science fiction imagery, but I should say we’re not doing any sort of human and matter teleportation that leads to instantaneous travel or anything like that,” Chou said. “The way that quantum teleportation works is that it uses entanglement to be able to transport information from one part of the quantum computer to another part.”

By harnessing the power of entanglements, Chou said, qubits can interact with each other without being directly linked. This means that researchers can isolate qubits from noise while also allowing them to communicate remotely, or “teleport” information. The Pony Express carried letters across the continent in several days; quantum teleportation can do the same thing instantaneously.



A network overview of the modular quantum architecture.

But although there is significant financial interest, the quantum computer is still a long way away. Substantial research is required in order to make modularity and teleportation in quantum computing less of a proof-of-concept and more of a reality, Chou said.

Bringing quantum outside of the lab

03

Outreach Activities

The Yale Quantum Institute creates and hosts extensive outreach programs to bring science knowledge to the public.

With the increasing media hype about the race for quantum supremacy, YQI believes it is important to counterbalance sensationalism and and to present to the public content and programs of quality, which invites them to learn and reflect about this exciting new area of science and technology.

NONTECHNICAL TALK SERIES

Working at the intersection of science and the humanities, YQI has organized at the time of this report, eight non-technical talks, attracting 495 attendees, with the aim of engaging the public and calming quantum physics phobia, and, in a more general way, science phobia.

The goal of these talks is to present a new perspective on quantum physics and science using music, art, dance, crochet, board games, or literature as a conduit to learning about quantum physics, and more general topics in science, engineering, or mathematics.

These events are accessible to a wide audience, and have attracted a diverse group, including Yale community members, from undergrads to professors and staff with their children, as well as high school students and other Greater New Haven residents. These talks seek to communicate the excitement of scientific exploration and also educate the audience about role that science plays in our daily life.

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

PUBLIC CONVERSATIONS

Public conversations are our newest outreach program. The format is simple, two or three persons are having a conversation in front of an audience on a defined topic, but general enough to allow the conversation to flow from one idea to another depending on the interest of the participants and of the audience.

We tend to mix on these panels YQI members and non-physicists to keep jargon out of the conversation and make sure any concept brought up during the conversation is explained in layman terms. These public conversations are informal events and the audience is encouraged to take part in the conversation by asking questions or sharing ideas and comments.

Our first two events were a conversation between sound artist Spencer Topel & YQI manager Florian Carle on experimental quantum music, and a conversation between science writer Philip Ball, and YQI members Steve Girvin and Douglas Stone on quantum weirdness and the second quantum revolution.

ARTIST IN RESIDENCE PROGRAM

Central to our outreach efforts is the Artist-in-Residence Program. Each year, the institute welcomes an artist for a year-long residency to produce quantum science-based artwork and visuals, participate in a series of public talks to explain their work, and the science behind it across disciplines, and in particular across the humanities-science divide. The artists are rigorously selected by Florian Carle based on the quality and presentation of their work, and their background and experiences.

In 2018, we welcomed visual artist Martha Lewis who created several quantum inspired art pieces in collaboration with YQI researchers. The artworks were featured in a series of public talks relating the workds to quantum physics, discussing how to better use colors in scientific publications, and how art can offer ways of looking at problems that are wobbly and uncertain, as an alternative to strict scientific guidelines for testing theories about the universe. The highlight of the year was the interactive and immersive installation "I'll be your qubit!" where the visitor was invited to experience the world within a quantum circuit, artistically transposed to the human scale.

In 2019, we continue exploring art as a medium to increase our understanding and discourse of quantum physics by welcoming Spencer Topel; a musician and artist working with sound installations, and performances. We are proposing an ambitious project: a live concert where Spencer, and two graduate students, Kyle Serniak and Luke Burkjart, will "play" sound generated by the operation of quantum computers prototypes coolded to nearly absolute zero, as if they were instruments in an orchestra. This live performance will be the first of its kind, attracting the interest of scientists in the quantum community for the technical challenge, and of the public for the novel soundscrape that will be produced.

Spencer Topel
Working between art & science

In the fall of 2018, Spencer Topel presented his first talk at YQI on his artistic practice, uncertain of where it would lead. After a few minutes discussing waves, signals, frequency, resonance, and noise, the sound artist and the quantum physicists discovered they spoke a similar language...

“Being an artist working with scientists, the greatest satisfaction for me comes from learning state-of-the-art concepts, and then finding ways to translate these concepts into meaningful experiences for audiences and visitors through immersive installations, music, and design.

Since the fall of 2018 I have worked most closely with students in the laboratories of Robert Schoelkopf and Michel Devoret. Our bi-weekly interactions provide unique perspectives on several topics of importance to my practice: translation of signals to the mediums of sound and light, engineering and design, and the translation of fundamental scientific phenomena into immersive installations.

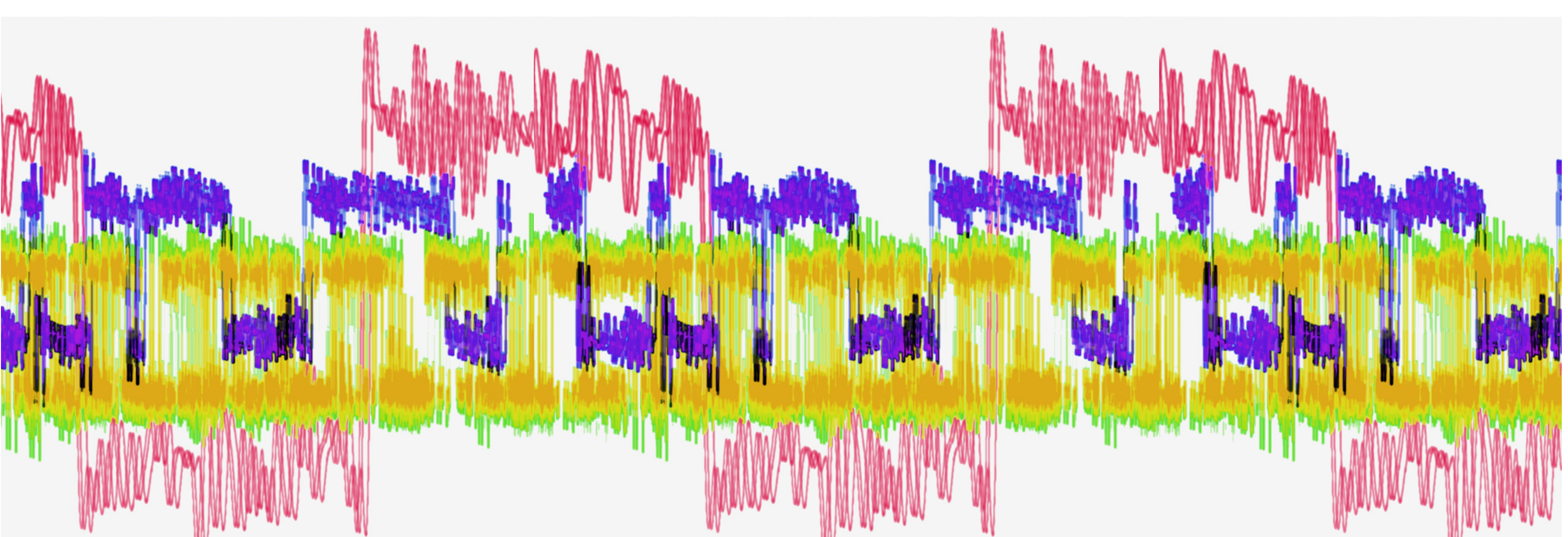
Upon arriving at the Yale Quantum Institute, my first inclination was to assess the artistic potential of various quantum experimental systems. To my surprise the measurements conducted on transmon qubits and other superconducting circuits strongly resemble musical signals generated from canonical sound synthesis techniques. When I and two Yale PhD students, Kyle Serniak and Luke Burkhart, began to experiment with the sonification of these signals directly, the sounds were immediately relatable and musical signals.

In June, to mark the end of my residency, and part of the prestigious Festival of Arts and Ideas of New Haven (see page 22 for more details), we will attempt to perform on two of the circuits running within dilution refrigerators in a live performance, by remotely pulling data, transforming timescales, and sonifying it as a continuous musical experience. Both Kyle and Luke will perform along-side me as fellow musicians to create the first ensemble of quantum superconducting devices. I am also grateful Florian Carle offered me the opportunity to join YQI for an artistic residency and for his work carrying this project forward as producer of the performance at Firehouse 12.

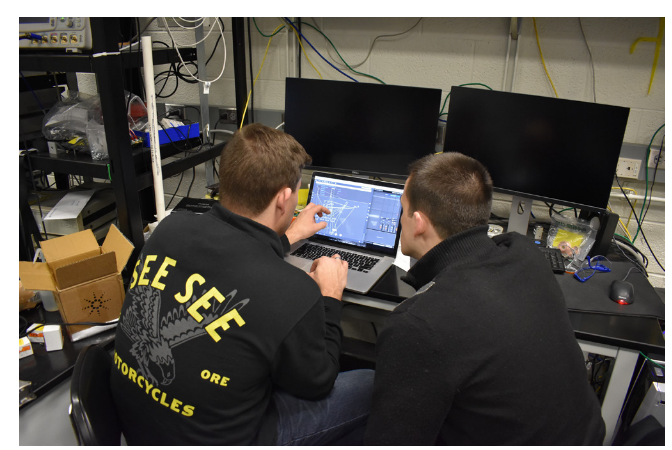
In many respects, these experiences of working with the fundamental technologies being explored inside quamtum systems echo experimentation with new musical processes from more than a century ago, when Leon Theremin invented instruments and transducers exploiting principles of electromagnetism and recently-invented radio proximity sensors. The most famous of these instruments, the ætherphone or theremin, became the first contactless musical instrument and is still fabricated and performed today.

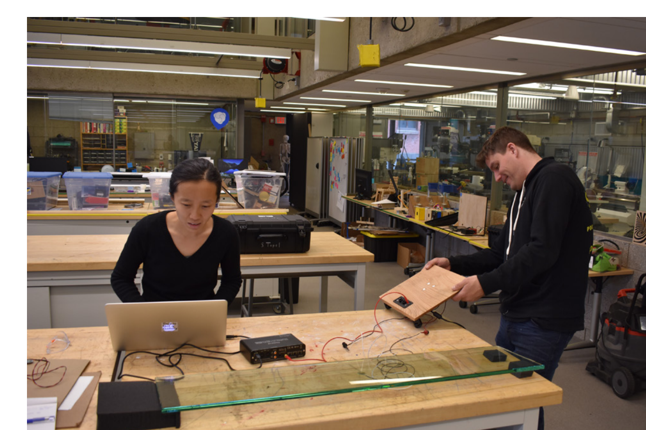
Looking beyond the work accomplished throughout the academic year 18-19, I can say with certainty that my artistic and design practice is significantly enriched by my time developing new sound, music, and art with scientists at YQI. Furthermore, based on our preliminary experimentation this past year, it is clear that we are just beginning to scratch the surface of the fertile and inspiring domain of music and art synthesized through quantum engineering.”

Spencer Topel



Crosstalk (2019) - Spencer Topel





The Arts & Ideas Festival goes quantum… Twice!

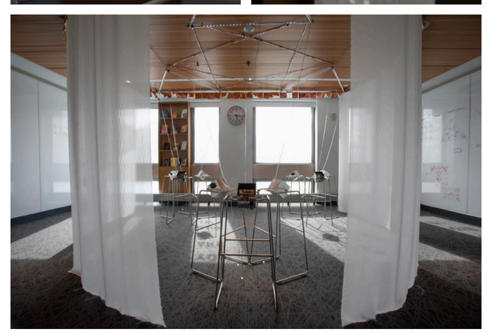
Immediately upon its inception by Florian Carle, the YQI artist-in-residence program became a link to the New Haven arts community and in particular to the prestigious International Festival of Arts and Ideas held yearly in the spring. Martha Willette Lewis, a visual artist, was the first artist welcomed to YQI and she developed in collaboration with quantum physicists several art pieces. Her final piece was featured in the Arts and Ideas Festival in June 2018. Her qubit installation was visited by hundreds of festival attendees, and a panel discussion of quantum science and art at YQI was filled to capacity. Based on the quality of the art created by Martha and the overwhelming positive response of the audience attending the panel and artist-led tours, the organizers of the festival included a performance of quantum sound art, commissioned by YQI, in the 2019 program.

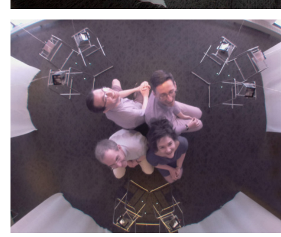
I'LL BE YOUR QUBIT!

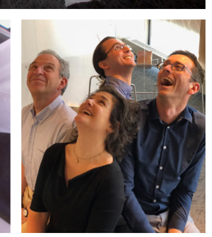
THE ENTANGLEMENT OF QUANTUM PHYSICS AND ART

"I'll be your qubit" is an interactive immersive installation where the visitor experiences the quantum world. Referring to optical toys, early cinema and drawings on her experience at the Institute, Martha W. Lewis has created a particular quantum diagram one can move through, turning the interior space of the institute into a human-scale quantum experiment. The installation features two basic quantum mechanical phenomena, the observer effect and the interference effect. The quantum observer effect corresponds to the act of measurement fundamentally perturbing the system under study. This effect manifests itself as the visitor/observer enters the enclosure of the experiment, modifying by their presence the state of the installation. The quantum interference effect occurs here through the colors of the diagram, in which two incompatible possibilities are realized at once. Around each triangle, there is an even/odd number of red/blue corners. Just as one quantum particle can pass through two slits simultaneously, the color assignments of the diagram evolve as if they satisfy two incompatible patterns.

Tuesday, June 12, 2018 - Idea Talk and Artist Lead Tours – YQI Seminar Room
Concept and Realization: Martha W. Lewis
Realization and Electronic Wizardry: Stefan Krastanov
Scientific consultant: Michel Devoret
Producer and Realization: Florian Carle







QUANTUM SOUND

A LIVE PERFORMANCE OF SUPERCONDUCTING INSTRUMENTS

Did you ever wonder what a single electron moving through the universe sounds like? With scientists Kyle Serniak and Luke Burkhart from the Yale Quantum Institute, sound artist and composer Spencer Topel presents the first-ever music created from the measurements of the dynamics inside superconducting quantum devices, the precursors to quantum computers. In the intimate space of New Haven's premiere recording studio Firehouse 12, quantum systems will be played live throughout a one-hour set. Together, they will explore these unique scientific devices as musical instruments in this ground-breaking musical experience.

Friday, June 14, 2019 - Two Musical Performances – Firehouse 12
Composer and Performer: Spencer Topel
Performers: Luke Burkhart, Kyle Serniak
Producer: Florian Carle

The YQI Fellows

The newly launched YQI Fellowship program has already brought four top scientists to join the groups of YQI members to advance quantum research at Yale. Not only will they represent the institute and pursue cutting edge research, and they each are asked to help disseminate scientific knowledge to the larger public. The YQI Fellows can choose and propose outreach activities that are mutually beneficial for them and for the public. Medhi Menazi, a 2018 YQI Fellow, participated in a science communication competition at the Boston Museum of Science to explain quantum physics to K-12 students. Other Fellows will participate in writing scientific popularization blog posts, use YQI social media to show the day to day life of a scientist, give an outreach talks about a quantum related topic, and create a network and improved communication between quantum institutes in the US and in the world.

Become a YQI Fellow by applying online at **quantuminstitute.yale.edu/apply**.

CHRISTA FLÜHMANN, '19

ROBERT SCHOELKOPF GROUP

During my PhD at ETH Zürich I performed experiments with the motion of a trapped ion using it to realize a potentially error correctable quantum bit. Before leaving Switzerland I experienced its landscape by trekking across the Alps.

MEHDI NAMAZI, '18

JACK HARRIS GROUP

Quantum physics lover by day, very bad at pool and karaoke by night! Worked on room-temperature quantum information systems for six years, got traumatized by the noise, moved to cryogenic systems at Yale. Retirement plans, becoming the world's greatest mixologist!

THOMAS LANGIN, '19

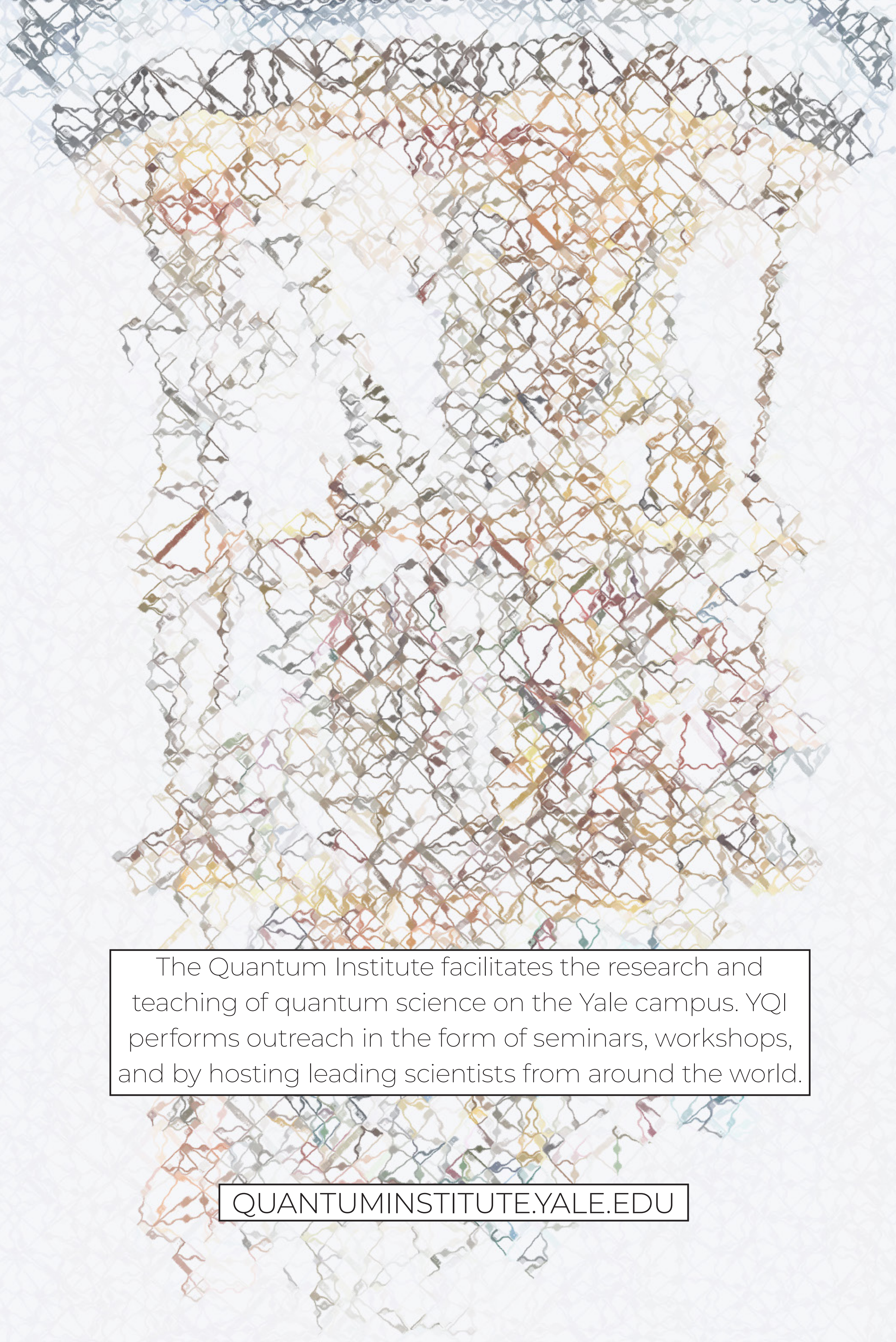
DAVID DEMILLE GROUP

At Yale, I will be studying laser-cooling and trapping of molecules, with the goal of producing a molecular Bose-Einstein condensate. Ultimately, I hope to bring the skills I gain during my YQI fellowship to a career as a professor running my own research lab and teaching a new generation of physicists.

JERE MÄKINEN, '19

NIR NAVON GROUP

Jere recently defended his PhD thesis on quantized vortices at Aalto University and is eager to face new challenges at Yale University as an YQI fellow! He has conducted his experiments in a rotating cryostat shown in the background.



The 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