QUANTXCER BI-WEEKLY NEWS LETTER

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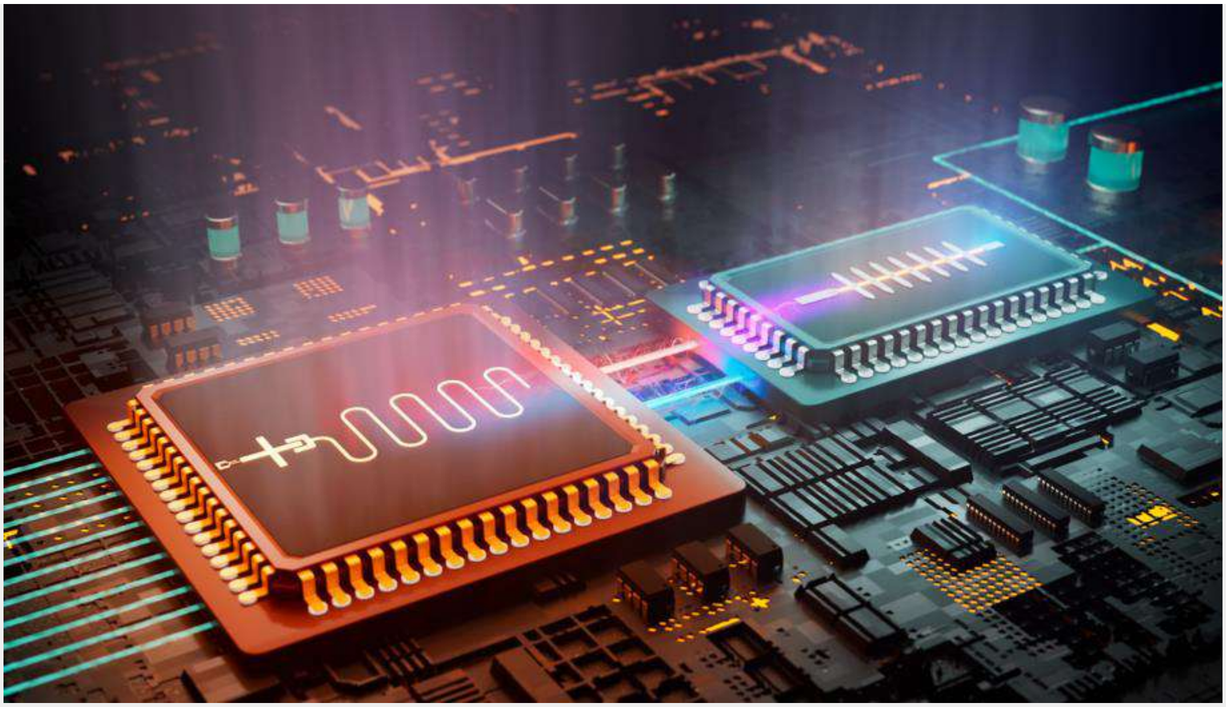
It is a quantum fractal alogorithmic universe

TABLE OF CONTENTS

New Method Of Measuring Qubits Promises Ease Of Scalability In A Microscopic Package

Chasing ever-higher qubit counts in near-term quantum computers constantly demands new feats of engineering.



An artistic illustration shows how microscopic bolometers (depicted on the right) can be used to sense very weak radiation emitted from qubits (depicted on the left). Image credit: Aleksandr Käkinen/Aalto University

Among the troublesome hurdles of this scaling-up race is refining how qubits are measured. Devices called parametric amplifiers are traditionally used to do these measurements. But as the name suggests, the device amplifies weak signals picked up from the qubits to conduct the readout, which causes unwanted noise and can lead to decoherence of the qubits if not protected by additional large components. More importantly, the bulky size of the amplification chain becomes technically challenging to work around as qubit counts increase in size-limited refrigerators.

Cue the Aalto University research group Quantum Computing and Devices (QCD). They have a hefty track record of showing how thermal bolometers can be used as ultrasensitive detectors, and they just demonstrated in an April 10 Nature Electronics paper that bolometer measurements can be accurate enough for single-shot qubit readout.

A new method of measuring

To the chagrin of many physicists, the Heisenberg uncertainty principle determines that one cannot simultaneously know a signal's position and momentum, or voltage and current, with accuracy. So it goes with qubit measurements conducted with parametric voltage-current amplifiers. But bolometric energy sensing is a fundamentally different kind of measurement—serving as a means of evading Heisenberg's infamous rule. Since a bolometer measures power, or photon number, it is not bound to add quantum noise stemming from the Heisenberg uncertainty principle in the way that parametric amplifiers are.

Unlike amplifiers, bolometers very subtly sense microwave photons emitted from the qubit via a minimally invasive detection interface. This form factor is roughly 100 times smaller than its amplifier counterpart, making it extremely attractive as a measurement device.

'When thinking of a quantum-supreme future, it is easy to imagine high qubit counts in the thousands or even millions could be commonplace. A careful evaluation of the footprint of each component is absolutely necessary for this massive scale-up. We have shown in the Nature Electronics paper that our nanobolometers could seriously be considered as an alternative to conventional amplifiers. In our very first experiments, we found these bolometers accurate enough for single-shot readout, free of added quantum noise, and they consume 10 000 times less power than the typical amplifiers—all in a tiny bolometer, the temperature-sensitive part of which can fit inside of a single bacterium,' says Aalto University Professor **Mikko Möttönen**, who heads the QCD research group.

Single-shot fidelity is an important metric physicists use to determine how accurately a device can detect a qubit's state in just one measurement as opposed to an average of multiple measurements. In the case of the QCD group's experiments, they were able to obtain a single-shot fidelity of 61.8% with a readout duration of roughly 14 microseconds. When correcting for the qubit's energy relaxation time, the fidelity jumps up to 92.7%.

'With minor modifications, we could expect to see bolometers approaching the desired 99.9% single-shot fidelity in 200 nanoseconds. For example, we can swap the bolometer material from metal to graphene, which has a lower heat capacity and can detect very small changes in its energy quickly. And by removing other unnecessary components between the bolometer and the chip itself, we can not only make even greater improvements on the readout fidelity, but we can achieve a smaller and simpler measurement device that makes scaling-up to higher qubit counts more feasible,' says **András Gunyhó**, the first author on the paper and a doctoral researcher in the QCD group.

Prior to demonstrating the high single-shot readout fidelity of bolometers in their most recent paper, the QCD research group first showed that bolometers can be used for ultrasensitive, real-time microwave measurements in 2019. They then published in 2020 a paper in Nature showing how bolometers made of graphene can shorten readout times to well below a microsecond.

Creating Quantum Sensors – Chemistry Meets Physics

Ben King didn't set out to create a long-sought after material to be used in quantum sensing devices, but life, like quantum science, can be weird. King, a professor in chemistry at the University of Nevada, Reno, had been working on developing two-dimensional materials designed with specific features.

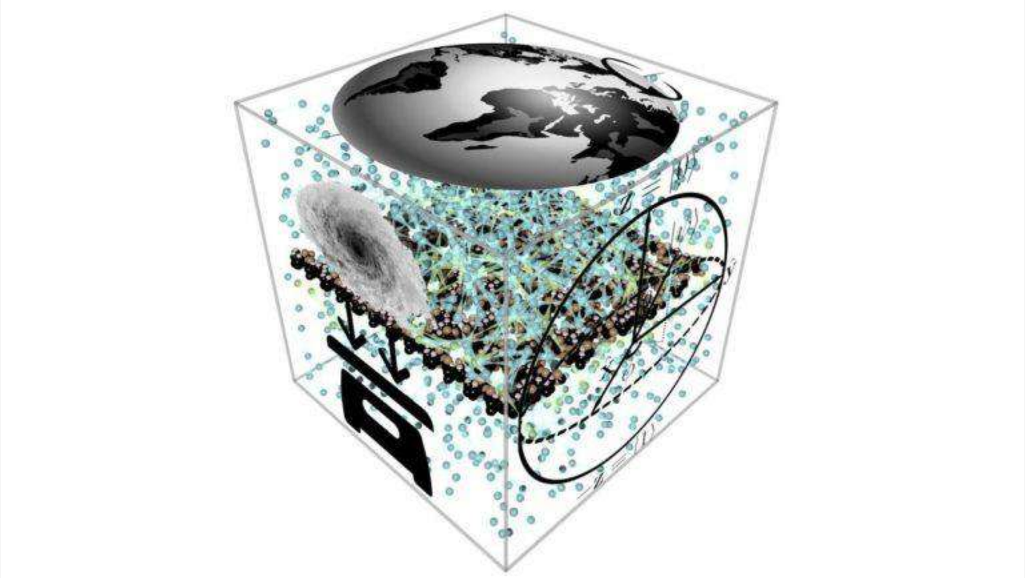


Image credit: UNR

One of the materials he built is a molecular net, a wall with molecule-sized pores that can allow superfluid helium to pass quantum information. The holes in this net are about one nanometer across. For context, a sheet of paper is about 100,000 nanometers thick.

As it happens, physicists have been looking for a material with exactly these features for decades. After King and his colleagues published a paper about the material, he was contacted by Keith Schwab, a physicist at the California Institute of Technology.

"It's kind of funny," King said, "You don't know where research is going to lead you. When we started this program, I had never heard of such devices. When I started trying to make 2D polymers, I knew they were porous. I knew there was nothing else with such small pores out there. So maybe there is something interesting I could do. And then a physicist who had no idea how to make a material like this saw that we could make it."

Using quantum entanglement to detect global changes

The researchers waited for a decade for scientific funding priorities to align with their exciting discovery and were well-rewarded for their patience. King is the principal investigator on a $2 million grant from the National Science Foundation's Quantum Sensing Challenges for Transformational Advances in Quantum Systems program.

The grant provides funding to support the development of a device that uses two reservoirs of superfluid helium separated by the molecular net that King's research group has developed. The net is made up of many smaller pieces, or monomers. The monomers are small molecules that, when the researchers shine a light on them, link to create the 2D polymers. The researchers will use remarkably cold helium, at about 3 Kelvin (-454 F), to achieve the superfluid state.

The device, known as a superfluid helium quantum interference device, or SHe-quid, will use quantum entanglement between the two reservoirs of helium to detect ultra-small changes in the rate of Earth's rotation. These changes can be caused by hurricanes, for example, which have an angular momentum that can speed up or slow down the Earth's rotation.

"One of the more obvious applications for these types of sensors is having really sensitive ways to measure rotational phenomena, like gyroscopic guidance," King said.

Gyroscopic guidance is widely used in navigation and even in the James Webb Space Telescope.

Other applications of SHe-quids can be imagined, including gravitational sensing, which might find exotic applications such as the detection of gravitational waves and fingerprints of dark matter, and there are practical applications.

"Another area that's particularly of interest in Nevada is geodesy and mineral exploration," King said. "There are often small changes in the local gravitational field due to differences in the density of what's below our feet."

Those gravitational changes could provide information about the mineral deposits in a given location.

Interdisciplinary impacts

King's project is one of 18 chosen for funding in this program. King's collaborators on this grant include Adrian Del Maestro, a theorist specializing in the physics of superfluid helium, Erik Henriksen is an experimentalist who will help with fabrication of 2D materials. Keith Schwab will build the device and conduct proof-of-principle measurements.

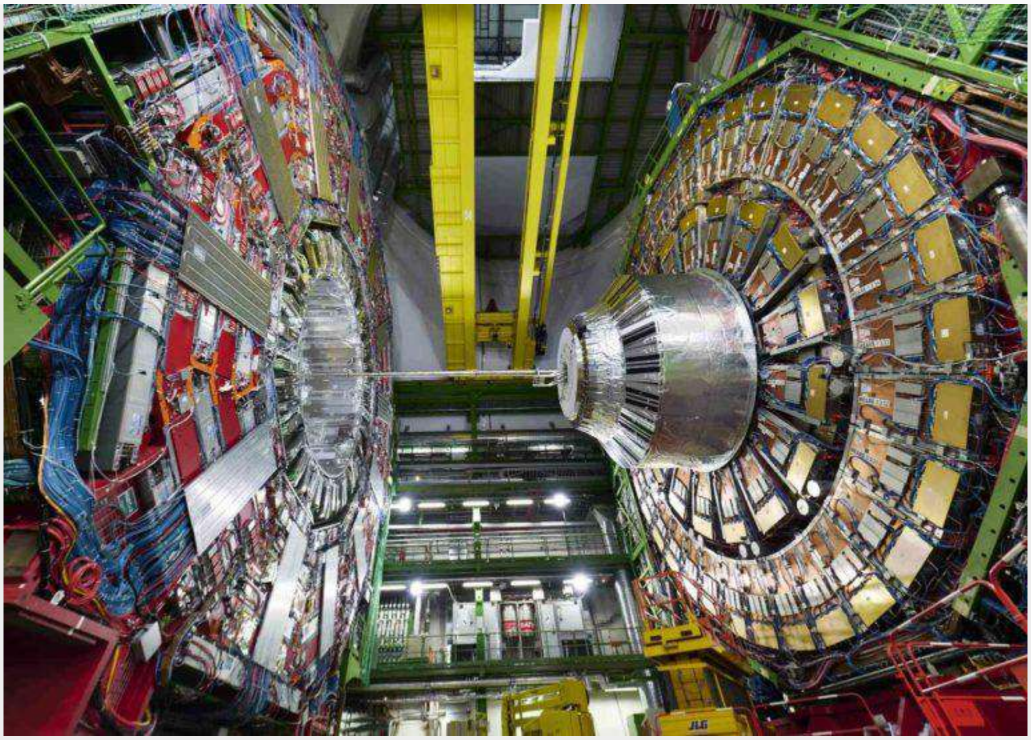
"Being a chemist, I didn't know anything about superfluid helium quantum interference devices," King said. "That's why talking to people, communicating is so important."

King will work with several students in his research lab on the project. Phillip Damke and Seth Freese, undergraduate students, and John Nyogbe, a graduate student, are currently working on building the polymers.

“For decades, scientific exploration at the quantum scale has yielded surprising discoveries about how our universe works — and tantalizing possibilities for quantum-enabled technologies,” NSF Director Sethuraman Panchanathan said in a press release. “We are now taking the next step in quantum research through these projects and others, which combine fundamental research with potential applications that can positively impact our lives, economic prosperity and competitiveness as a nation.”

Physicists Reach Milestone In Understanding The Universe’s Fundamental Forces

Rochester researchers involved with CERN make groundbreaking measurements of the electroweak mixing angle, strengthening an understanding of particle physics.



DISCERNING MINDS: University of Rochester researchers have a long history of work at CERN as part of the Compact Muon Solenoid (CMS) Collaboration, including playing key roles in the 2012 discovery of the Higgs boson. Image credit: Samuel Joseph Hertzog; Julien Marius Ordan / University of Rochester

In the quest to decode the mysteries of the universe, researchers from the University of Rochester have been involved for decades with international collaborations at the European Organization for Nuclear Research, more commonly known as CERN.

Building on their extensive involvement at CERN, particularly within the CMS (Compact Muon Solenoid) Collaboration, the Rochester team—led by Arie Bodek, the George E. Pake Professor of Physics—recently achieved a groundbreaking milestone. Their achievement centers on measuring the electroweak mixing angle, a crucial component of the Standard Model of Particle Physics. This model describes how particles interact and precisely predicts many phenomena in physics and astronomy.

"The recent measurements of the electroweak mixing angle are incredibly precise, calculated from collisions of protons at CERN, and strengthen an understanding of particle physics," Bodek says.

The CMS Collaboration brings together members of the particle physics community from across the globe to better understand the basic laws of the universe. In addition to Bodek, the Rochester cohort to the CMS Collaboration includes principal investigators Regina Demina, a professor of physics, and Aran Garcia-Bellido, an associate professor of physics, along with postdoctoral research associates and graduate and undergraduate students.

Discoveries at CERN

Located in Geneva, Switzerland, CERN is the world's largest particle physics laboratory, renowned for its groundbreaking discoveries and cutting-edge experiments.

Rochester researchers have a long history of work at CERN as part of the CMS Collaboration, including key roles in the 2012 discovery of the Higgs boson, an elementary particle that helps explain the origin of mass in the universe.

The collaboration includes collecting and analyzing data from the Compact Muon Solenoid detector at CERN's Large Hadron Collider (LHC), the world's largest and most powerful particle accelerator. The LHC consists of a 17-mile ring of superconducting magnets and accelerating structures built underground, spanning the border between Switzerland and France.

The primary purpose of the LHC is to explore the fundamental building blocks of matter and the forces that govern them. It achieves this by accelerating beams of protons or ions to nearly the speed of light and smashing them into each other at extremely high energies. These collisions recreate conditions similar to those that existed fractions of a second after the Big Bang, allowing scientists to study the behavior of particles under extreme conditions.

Unraveling unified forces

In the 19th century, scientists found that the different forces of electricity and magnetism were linked: a changing electric field produces a magnetic field and vice versa. The discovery formed the basis of electromagnetism, which describes light as a wave and explains many phenomena in optics, along with describing how electric and magnetic fields interact.

Building upon this understanding, physicists in the 1960s discovered that electromagnetism is connected to another force—the weak force. The weak force operates within the nucleus of atoms and is responsible for processes such as radioactive decay and powering the sun's energy production. This revelation led to the development of the electroweak theory, which posits that electromagnetism and the weak force are actually low-energy manifestations of a unified force called the unified electroweak interaction. Key discoveries, such as the Higgs boson, have confirmed this concept.

Exploring electroweak interaction

The CMS Collaboration recently performed one of the most precise measurements to date related to this theory, by analyzing billions of proton-proton collisions at the LHC at CERN. Their focus was measuring the weak mixing angle, a parameter describing how electromagnetism and the weak force blend together to create particles.

Previous measurements of the electroweak mixing angle have sparked debate within the scientific community. However, the latest findings closely align with predictions from the Standard Model of Particle Physics. Rochester graduate student Rhys Taus and postdoctoral research associate Aleko Khukhunaishvili implemented new techniques to minimize systematic uncertainties inherent in this measurement, enhancing its precision.

Understanding the weak mixing angle sheds light on how different forces in the universe work together at the smallest scales, deepening an understanding of the fundamental nature of matter and energy.

“The Rochester team has been developing innovative techniques and measuring these electroweak parameters since 2010 and then implementing them at the Large Hadron Collider,” Bodek says. “These new techniques have heralded a new era of precision tests of the predictions of the Standard Model.”

A Blueprint For Making Quantum Computers Easier To Program

When MIT professor and now Computer Science and Artificial Intelligence Laboratory (CSAIL) member Peter Shor first demonstrated the potential of quantum computers to solve problems faster than classical ones, he inspired scientists to imagine countless possibilities for emerging technology. Thirty years later, though, the quantum edge remains at a peak that has not yet been reached.

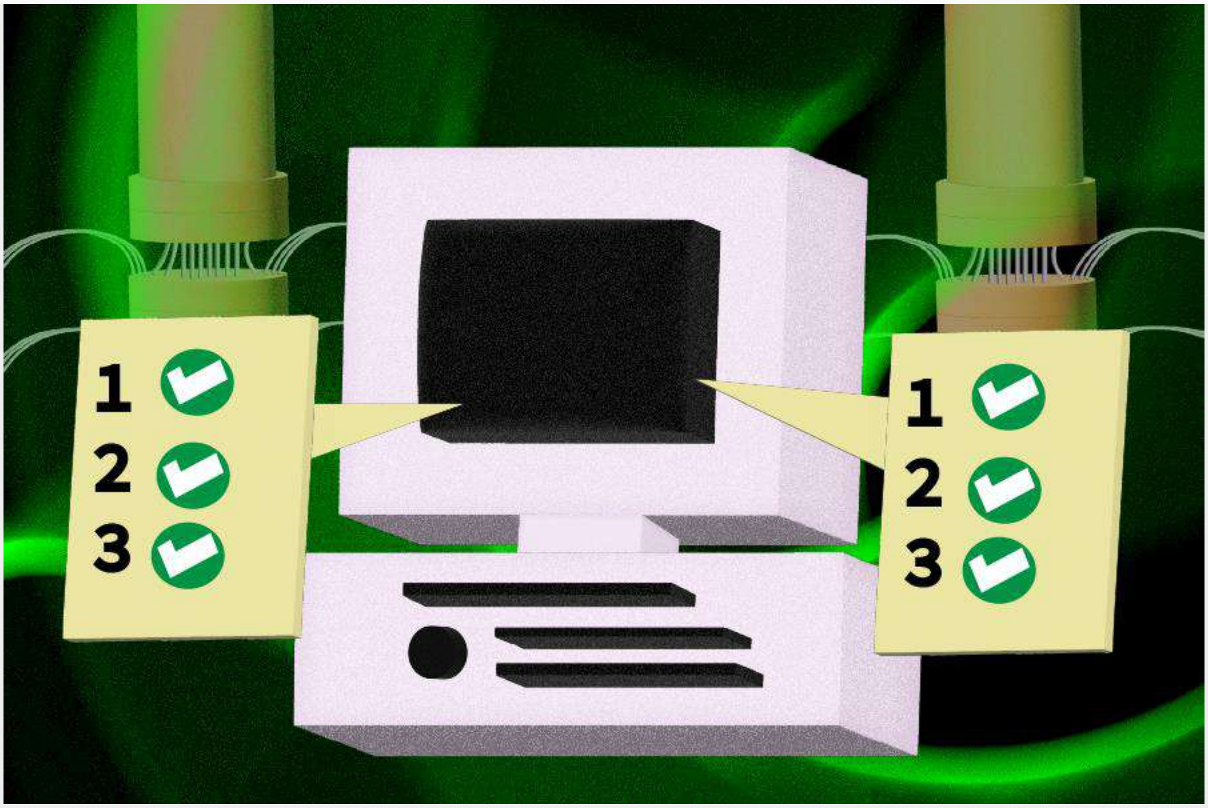


Image credit: MIT CSAIL

Unfortunately, the technology of quantum computing isn't fully operational yet. One major challenge lies in translating quantum algorithms from abstract mathematical concepts into concrete code that can run on a quantum computer. Whereas programmers for regular computers have access to myriad languages such as Python and C++ with constructs that align with standard classical computing abstractions, quantum programmers have no such luxury; few quantum programming languages exist today, and they are comparatively difficult to use because quantum computing abstractions are still in flux. In their recent work, MIT researchers highlight that this disparity exists because quantum computers don’t follow the same rules for how to complete each step of a program in order — an essential process for all computers called control flow — and present a new abstract model for a quantum computer that could be easier to program.

In a paper soon to be presented at the ACM Conference on Object-oriented Programming, Systems, Languages, and Applications, the group outlines a new conceptual model for a quantum computer, called a quantum control machine, that could bring us closer to making programs as easy to write as those for regular classical computers. Such an achievement would help turbocharge tasks that are impossible for regular computers to efficiently complete, like factoring large numbers, retrieving information in databases, and simulating how molecules interact for drug discoveries.

“Our work presents the principles that govern how you can and cannot correctly program a quantum computer,” says lead author and CSAIL PhD student Charles Yuan SM ’22. “One of these laws implies that if you try to program a quantum computer using the same basic instructions as a regular classical computer, you’ll end up turning that quantum computer into a classical computer and lose its performance advantage. These laws explain why quantum programming languages are tricky to design and point us to a way to make them better.”

Old school vs. new school computing

One reason why classical computers are relatively easier to program today is that their control flow is fairly straightforward. The basic ingredients of a classical computer are simple: binary digits or bits, a simple collection of zeros and ones. These ingredients assemble into the instructions and components of the computer’s architecture. One important component is the program counter, which locates the next instruction in a program much like a chef following a recipe, by recalling the next direction from memory. As the algorithm sequentially navigates through the program, a control flow instruction called a conditional jump updates the program counter to make the computer either advance forward to the next instruction or deviate from its current steps.

By contrast, the basic ingredient of a quantum computer is a qubit, which is a quantum version of a bit. This quantum data exists in a state of zero and one at the same time, known as a superposition. Building on this idea, a quantum algorithm can choose to execute a superposition of two instructions at the same time — a concept called quantum control flow. The problem is that existing designs of quantum computers don’t include an equivalent of the program counter or a conditional jump. In practice, that means programmers typically implement control flow by manually arranging logical gates that describe the computer’s hardware, which is a tedious and error-prone procedure. To provide these features and close the gap with classical computers, Yuan and his coauthors created the quantum control machine — an instruction set for a quantum computer that works like the classical idea of a virtual machine. In their paper, the researchers envision how programmers could use this instruction set to implement quantum algorithms for problems such as factoring numbers and simulating chemical interactions.

As the technical crux of this work, the researchers prove that a quantum computer cannot support the same conditional jump instruction as a classical computer, and show how to modify it to work correctly on a quantum computer. Specifically, the quantum control machine features instructions that are all reversible — they can run both forward and backward in time. A quantum algorithm needs all instructions, including those for control flow, to be reversible so that it can process quantum information without accidentally destroying its superposition and producing a wrong answer.

The hidden simplicity of quantum computers

According to Yuan, you don’t need to be a physicist or mathematician to understand how this futuristic technology works. Quantum computers don’t necessarily have to be arcane machines, he says, that require scary equations to understand. With the quantum control machine, the CSAIL team aims to lower the barrier to entry for people to interact with a quantum computer by raising the unfamiliar concept of quantum control flow to a level that mirrors the familiar concept of control flow in classical computers. By highlighting the dos and don’ts of building and programming quantum computers, they hope to educate people outside of the field about the power of quantum technology and its ultimate limits.

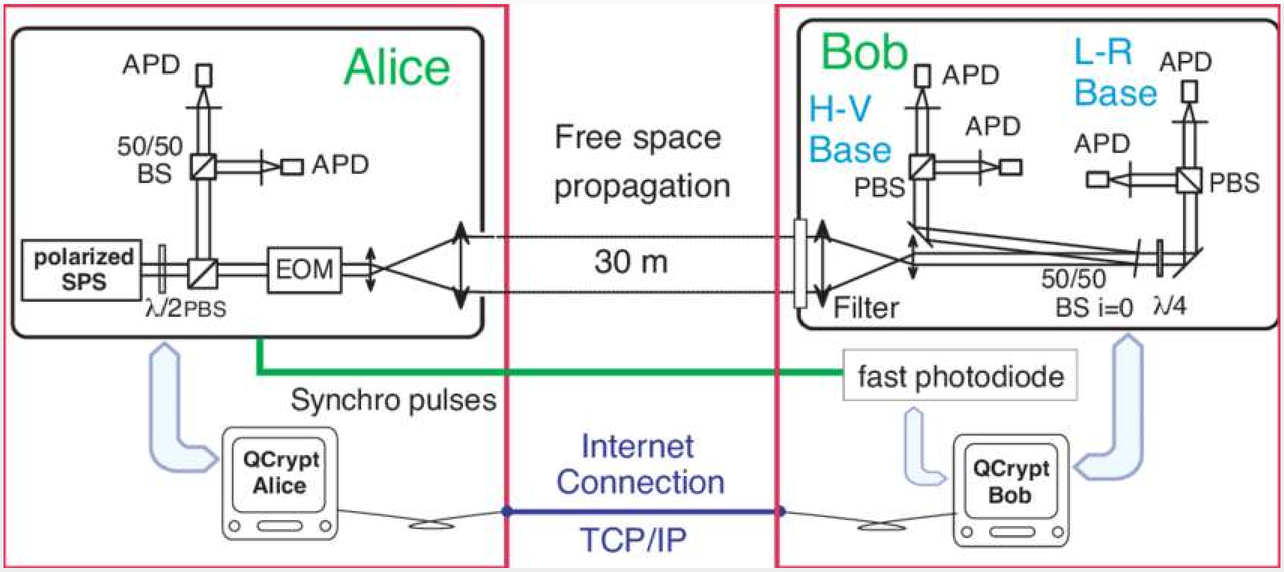
Still, the researchers caution that as is the case for many other designs, it’s not yet possible to directly turn their work into a practical hardware quantum computer due to the limitations of today’s qubit technology. Their goal is to develop ways of implementing more kinds of quantum algorithms as programs that make efficient use of a limited number of qubits and logic gates. Doing so would bring us closer to running these algorithms on the quantum computers that could come online in the near future.

“The fundamental capabilities of models of quantum computation has been a central discussion in quantum computation theory since its inception,” says MIT-IBM Watson AI Lab researcher Patrick Rall, who was not involved in the paper.

“Among the earliest of these models are quantum Turing machines which are capable of quantum control flow. However, the field has largely moved on to the simpler and more convenient circuit model, for which quantum lacks control flow. Yuan, Villanyi, and Carbin successfully capture the underlying reason for this transition using the perspective of programming languages. While control flow is central to our understanding of classical computation, quantum is completely different! I expect this observation to be critical for the design of modern quantum software frameworks as hardware platforms become more mature.”

Researchers Achieve Quantum Key Distribution For Cybersecurity In Novel Experiment

Researchers at the Department of Energy's Oak Ridge National Laboratory have demonstrated that advanced quantum-based cybersecurity can be realized in a deployed fiber link.



ORNL A demonstration of a quantum key distribution system.

Their results, published in *Physical Review Applied*, validate an earlier proof-of-principle laboratory experiment by ORNL scientists in 2015.
The team transmitted a quantum signal for quantum key distribution — a secure approach to sharing a secret key — using a true local oscillator. A local oscillator quells the effects of noise scattered from other data transmitted in the same fiber-optic network, and the work demonstrated coexistence between the quantum and conventional data signals.

The signal traveled across ORNL's fiber-optic network encoded in continuous variables that described the properties of light particles, or photons, in amplitude and phase. Using continuous variables of photons for encoding allows an almost infinite number of settings for distributing randomness that can be used for cybersecurity and enables compatibility with existing classical communications systems.

The ORNL team's experiment not only broke new ground in information security but leveraged existing fiber-optic infrastructure, which would enable cheaper, easier adoption.

The experiment resolved major roadblocks to implementing quantum key distribution while enhancing security, said Nicholas Peters, head of ORNL’s Quantum Information Science Section and the study’s principal investigator.

“Quantum key distribution is a cryptographic protocol where two parties can generate a secure key that only they know,” Peters said. “In this experiment, this is done by using lasers to generate weak optical pulses between two points, usually referred to as Alice and Bob.”

When the receiving party measures a pulse, measurements can reveal whether an eavesdropper intercepted and corrupted the message. In past experiments without a true local oscillator, this optical pulse was transmitted along with the local oscillator. Previous methods created the potential for vulnerabilities not addressed in current best practices defined by the underlying concept of security. The new method relies on optical signals generated by independent lasers at the transmitting and receiving points.

“Basically, we’re looking at interference,” said Brian Williams, lead author of the study and an ORNL quantum research scientist. “It’s like throwing a rock into a lake and creating ripples. That’s similar to the wavelike nature of a photon that we are looking at. If two rocks are thrown in, they create weird patterns in the water. We’re doing a similar interference-based measurement on that quantum signal, but only the part that matches up with the laser gets detected. This requires a very narrow energy resolution.”

Excess noise erodes the rate of the key that can be distributed. Too much noise, and a fraction of the potential key is consumed to protect confidentiality.

“The goal is to get the best possible signal-to-noise ratio,” Williams said. “By using a narrow energy laser as your local oscillator, it acts as a filter for the background noise and improves the signal-to-noise ratio.”

Future efforts will focus on reproducing the experiment’s results under a wider range of network scenarios.

UT-Battelle manages ORNL for DOE’s Office of Science, the single largest supporter of basic research in the physical sciences in the United States. The Office of Science is working to address some of the most pressing challenges of our time.

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