Quantum

Quantum computing promises to solve some of the world's most complex problems. But first, we must learn to control tiny particles' chaotic behaviors.

leap

by Rodika Tollefson

The world's fastest supercomputer, launched by the U.S. Department of Energy in November 2022, can perform more than a quintillion calculations per second.

To achieve this feat, the entire global population would have to crunch the same arithmetical problem for five years. Although the capabilities of this first exascale computer are remarkable, they're not nearly enough to solve some of the world's most pressing problems.

Take fertilizer production, which uses 2–3% of the world's entire energy consumption. As much as 90% of that energy goes to making ammonia through nitrogen fixation. Making this process more energy-efficient would involve simulating such a large number of chemical interactions that it could take classical computers billions of years, and even a supercomputer couldn't achieve it in "reasonable time."

Quantum computing promises to break through the limitations of classical computers—even high-performing ones like supercomputers—to solve these kinds of "unsolvable" problems. They could help achieve anything from understanding the nitrogen fixation process to explaining the mysteries of dark matter. In theory, anyway.

Scientists must first learn to control large numbers of quantum bits—tiny particles such as atoms, electrons or photons that hold quantum information. And these quantum bits, or qubits, are very unruly, behaving in ways that are nothing like the classical computer bits.

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—Raymond Laflamme, Canada research chair, quantum computing, University of Waterloo

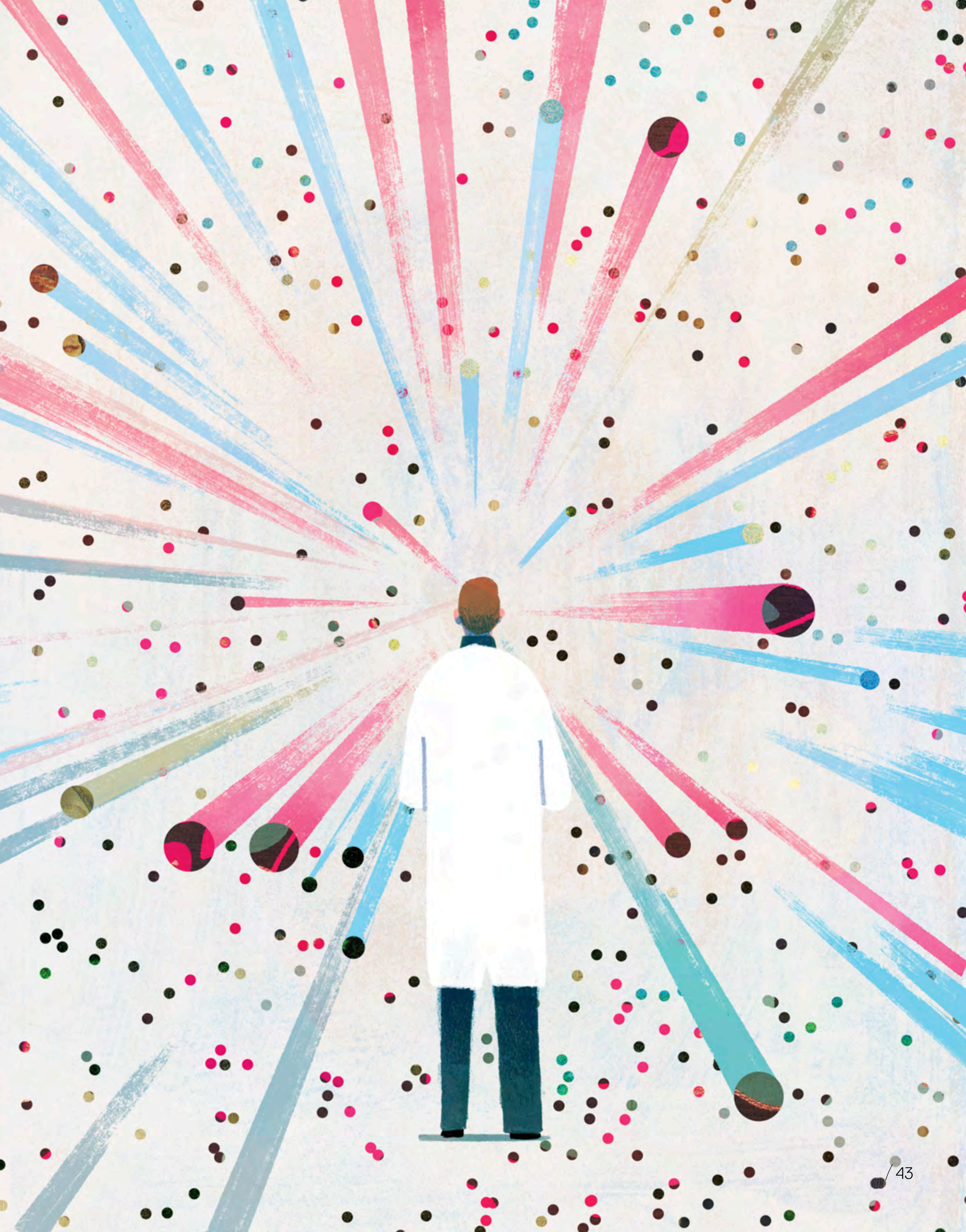
A fundamentally different technology

Raymond Laflamme, Canada research chair in quantum computing at the University of Waterloo in Canada, says there's a fundamental difference between quantum and classical computing.

"There's an exponential gap between quantum computers and classical ones," he says. "The science tells us that these quantum devices, if we're able to build them, will make an incredible difference in a set of very specific problems, and they do this in a really surprising way compared to the computers that we have around today."

These surprising ways—based on the principles of quantum physics—allow quantum computers to process information much faster, especially when performing tasks such as quantum simulations, optimization and large number factorization.

ILLUSTRATIONS BY KEITH NEGLEY



The challenge is that qubits, the building blocks of quantum computers, are very difficult to control. They're highly susceptible to "noise" (interference), which leads to computational errors. One of the most common breeds of quantum computers is described as being noisy intermediate-scale devices. They're prone to error, and the largest has just over 400 qubits, far from the tens of thousands or even millions that it would take to solve the most complex problems.

Scott Buchholz, global quantum computing lead at Deloitte Consulting LLP, says the noise challenge stems from the difficulty of getting particles like atoms or electrons "to sit still and then do useful work." Buchholz compares these particles to 3-year-old toddlers.

"Toddlers want to talk to everybody, and you're trying to get a whole field of them to sit still and only talk to the right ones in the right way," he says. "All it takes is two toddlers to start squirming, and they all degenerate into a mass of chaos." And, as you add more toddlers—or particles—the likelihood of chaos grows exponentially.

"That's analogous to where the quantum space is today, and we need the qubits to grow up and be more mature so we can get them to behave better and work together in the right way," Buchholz says.

Another big challenge researchers face is quantum error correction, according to Laflamme. This technique reduces error rates due to noise by encoding a large number of qubits to provide redundancy.

"Today, technology companies have demonstrated increased control of qubits and ability to scale up, but not enough to do quantum error correction," says Laflamme, who has conducted foundational research on error correction. "To get to quantum error correction, we'll need many tens of thousands of qubits, and what we need to get there is stamina, because

it's not going to happen right away. And when we get near there, that's when the technology that looks like magic to us today will really make progress."

The 'proof of concept' era

The technology has already made significant progress in the past decade. But "we're still in the proof of concept, or pilot, era," says Olivier Ezratty, co-founder of the Quantum Energy Initiative and a Paris-based technology consultant who specializes in quantum technologies. Ezratty and others say quantum computing is today where classical computers were in the 1950s or '60s, when people saw the potential of the machines, but everyday use was decades away.

"We're not yet at a point where quantum computing brings value that exceeds what you can do with a classical computer," he says.

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The quantum computing economy, in the meantime, is growing rapidly. By 2022, the total of public and private investments had reached $35.5 billion globally, according to the World Economic Forum (WEF), although other estimates are more conservative. Research company Market Research Future has been tracking the space since 2016, and Shubham Munde, its senior research analyst for the technology domain, says the worldwide enterprise quantum computing market is growing at a 31.3% compound annual growth rate between 2022 and 2030.

"There are more than a hundred companies in research and development, with the United States leading the market, followed by European companies," Munde says.

A lot of the investment up until recently was in hardware platforms, according to the WEF, but not all companies are pursuing the same path. Currently, at least half a dozen technologies can be used to build the hardware, from superconducting qubits and trapped ions to photonic qubits and neutral atoms.

Each technology has its pros and cons, Buchholz says. For example, superconducting provides faster processing, but the qubits have a higher susceptibility to noise and require refrigeration to control, while ion traps work at room temperature and provide higher quality qubits but have lower connectivity and scalability.

"Each proponent believes their technology is better suited to overcome problems than competitors', but, in reality, that's hard to discern," Buchholz says. "The good news is that there's a fair amount of consistency in terms of how people are thinking about building software on top of these systems."

The vision

Regardless of how far we are from practical implementation, the future impact of quantum computing could be tremendous. The environmental applications range from reducing energy consumption to developing better alternative energy sources.

Munde gives the example of solar panels. "Solar panels don't collect 100% of the power they're capable of collecting," he says. To improve the properties of the solar panel materials and their efficiency would require molecular-level simulations. Classical computers aren't fast enough because they have to approach simulations sequentially, whereas quantum computers can do so simultaneously, he explains.

Many quantum technology investors are also looking at coal alternatives such as liquid nitrogen gas (LNG), according to Munde. "Coal and other conventional sources used for electric generation contribute to around 30–33% of global greenhouse gas emissions," he says. "But to directly substitute LNG, for example, we need to make a lot of discrete decisions, from production to supply chain, and that means we need to solve very difficult, complex problems."

And then there's the elusive nitrogen fixation problem. Understanding that chemical process alone could bring significant impact. "Even if you improve the energy consumption by 10%, 10% of the 3% of the energy we use on Earth is not negligible," says Laflamme.

The challenge is that solving this particular problem would require a computer with about 50 million qubits, according to Ezratty, author of "Understanding Quantum Technologies" and speaker and trainer on the subject for government and private sectors. "Right now,

Quantum computing 101

by Mike Robillard

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Quantum computers operate with a set of rules that are fundamentally different from classical computers. For certain applications, these rules can enable quantum computers to process information faster—potentially solving problems that would take traditional machines millions of years.

Basic quantum computing rules

Qubits Short for quantum bits, qubits are typically small particles (atoms, ions, photons or electrons) that hold information and behave according to the laws of quantum physics.

Superposition A classical bit is either 1 (on) or 0 (off), but a qubit can be in both states simultaneously. Once you measure the qubit's value, it resolves to either 0 or 1. Reading a qubit causes the quantum state to collapse.

Entanglement The phenomenon by which two or more qubits share the same quantum states and are correlated regardless of distance from each other is called entanglement. A change to one of the entangled qubits directly impacts the other's behavior.

Superposition and entanglement enable quantum computers to perform computations simultaneously rather than sequentially or in parallel. This ability is a key difference between classical and quantum machines.

The engineering challenge

Quantum computers are susceptible to noise and this causes them to decohere. Decoherence is the collapse of the quantum state. It is a loss of information and a corruption of the calculations being performed.

Since quantum computers work at the atomic or subatomic level, the control and measurement signals within them are tiny. Because of this, minimizing environmental noise becomes critical.

Qubits in a superconducting quantum computer

Superconducting quantum computers, one type of quantum computer, use the properties of superconducting materials to create a circuit that acts like an artificial atom. These circuits are built using a process similar to that used for manufacturing semiconductors.

The state of these qubits is controlled with microwave radiation and entangled using electronic coupling. As you might imagine, the energy levels in these circuits are very small and require isolation from the external environment. For this type of quantum computer, special cooling technology is used to maintain coherence.

quantum computers only have between 50 and 400 qubits, so we would need to have a six order of magnitude difference in the number of qubits."

From high aspirations to interim applications

While many technology companies are focused on aspirational use cases—working on prototypes for future applications—others are "kicking the tires" and looking for useful functionality today, Buchholz says.

That's exactly what U.S.-based Quantum Computing Inc. (QCI) is doing. The company initially set out to provide agnostic software for quantum computer users but switched gears because "quantum just didn't deliver the benefits yet that people were expecting," company CEO Robert Liscouski says. QCI, now a full-stack quantum hardware and software solution developer, applies photonics-based quantum capabilities to optimization problems.

Liscouski says that since photons (which carry information in light particles) don't require a stable environment, they don't have to be error corrected. QCI has been able to demonstrate quantum capabilities with about 5,000 qubits to "solve big optimization problems." One pilot project focused on optimizing the placement of wind turbines on a parcel to create the highest electricity production with the lowest investment. Although the parcel could accommodate 200 turbines producing 14.75 GWh each, QCI determined through quantum optimization that it was more efficient to place only 69 turbines producing 16.17 GWh each.

"We have the ability to implement a more efficient application of wind turbine energy, saving money on the investment and increasing output while having no environmental impact or even reducing the impact," he says.

Quantum computing also has a side benefit: The technology itself requires less energy use

than a classical computer. That, too, is part of the draw for quantum capabilities for companies, Liscouski says. “When we compare quantum computing to classical computing, it’s not just the ability to get better results; it’s getting better results in less time and with less power consumption,” he says.

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Making the leap

While quantum computers are only on the cusp of what may be possible, business leaders need to start paying attention now. Buchholz notes that quantum computing may be just one research breakthrough away, and it’s hard to predict research breakthroughs. “The industry is changing very quickly, and I would not want to see a business leader wake up one morning and discover that a bright researcher has made the breakthrough,” he says. “Suddenly, the technology is much closer than you thought, and now you have to fight for the experience and resources and start the long journey to get there.”

And business leaders don’t need to understand how quantum physics works. “Most of us don’t reason from first principles,” he says. “I don’t know exactly how transistors work on my phone, but that doesn’t stop me from using the phone.”

In other words, leave it to researchers to figure out the unruly qubits. Instead, ask what business problems those qubits could solve for you today or in the future—and make the leap. ■