THE QUANTUM EDGE OF TECHNOLOGY

Technology can improve dramatically when quantum phenomena are exploited well. Scientists are learning how to do that.

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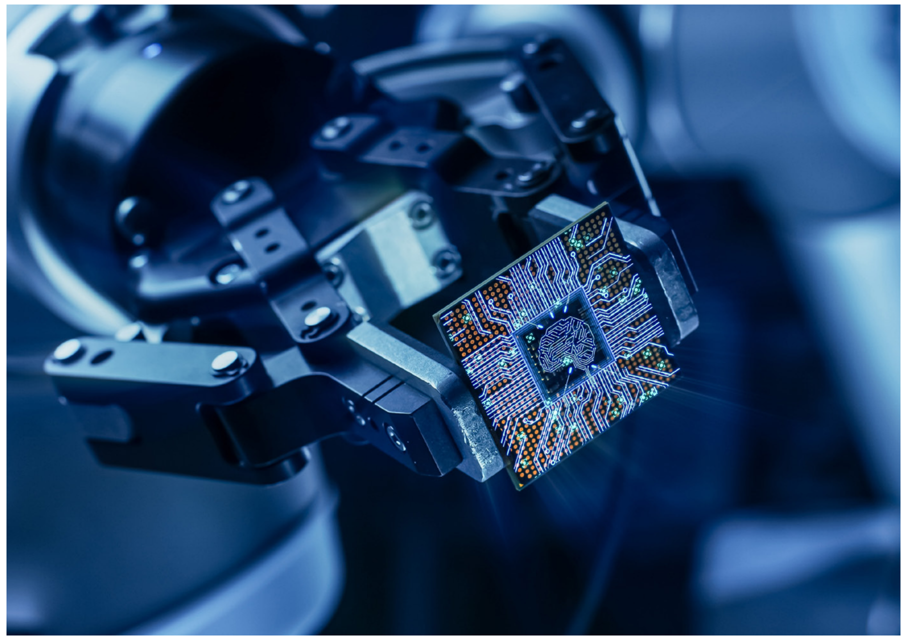
In the early 1990s, when Barry Sanders started work on the applications of quantum theory to develop technology, he was entering a field that was not yet fashionable. Sanders was a theoretical physicist by training, having written a PhD thesis on quantum optics while at Imperial College London. Quantum computing, he had understood, involved more than physics. To be good at it, Sanders had to learn computer science, quantum chemistry and a lot of mathematics, some of which were still to be developed.

"I used to spend more time learning and less time doing than my colleagues," says Sanders, Director of the Institute for Quantum Science and Technology at the University of Calgary in Canada. "I didn't realise it then, but it gave me an early start."

Spending more time learning rather than doing had its consequences: he was publishing less than his colleagues in the field. When he sent his initial papers for publication, he got criticism in response. Scientists then largely believed that quantum computers wouldn't be scalable, and that researchers shouldn't waste time on it. Then, in 1994, Peter Shor, a mathematician from the Massachusetts Institute of Technology, developed a quantum algorithm that could factor numbers much faster than contemporary — or classical — computers. "And then everyone started saying, let us build a quantum computer," says Sanders, who is also a visiting faculty at the Raman Research Institute (RRI) in Bengaluru.

In the last two decades, Sanders has been among researchers identifying and removing hurdles on the path to quantum computers and other quantum-based devices. In the early 2000s, he and his collaborators found a flaw in the way scientists were developing quantum communications, and thus helped improve security. A few years ago, working with post-doctoral fellow Dominic Berry, now at Google, Sanders developed a way to simulate physical phenomena on a quantum computer. Currently, he is developing ideas in quantum communication and computation that will become important when quantum computers become mainstream.

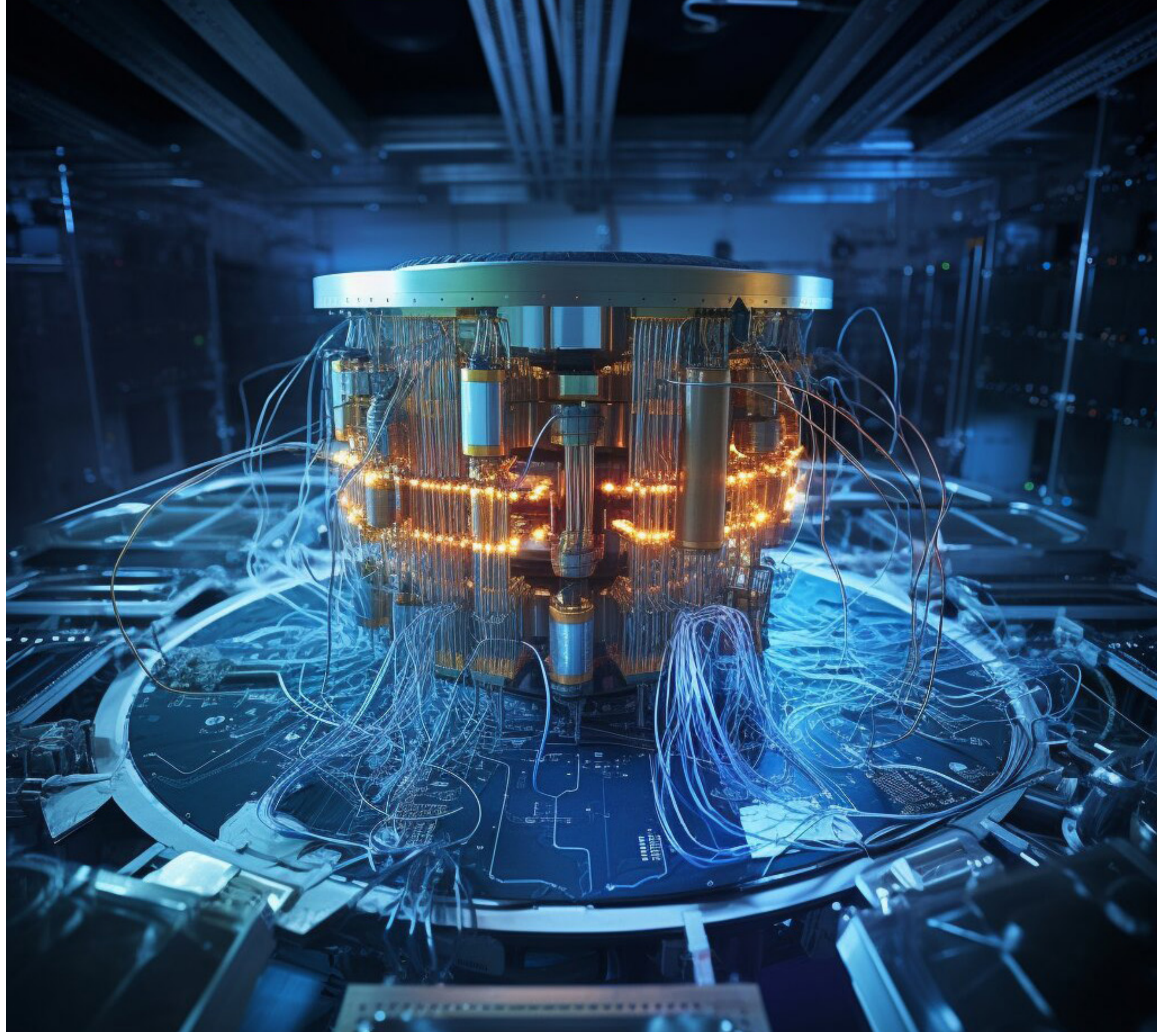
In just over two decades, scientists such as Sanders have created technologies that would be used in a world based on quantum computing. However, they still have some way to go before it is ready for commercialisation. For example, scientists have built small versions of quantum computers that can perform useful work, but they don't perform consistently well like current classical computers. Scientists call these computers noisy. Caltech physicist John Preskill coined the term Noisy Intermediate-Scale Quantum (NISQ) era to describe the present state of quantum computing.



In the future, the first generation of commercial quantum computers will likely be used to solve humanity's pressing problems.

Quantum computers of the NISQ era are not fault-tolerant and are yet to show a clear advantage over classical computers. However, even these noisy quantum computers can be put to work for tasks that are difficult for classical computers. The tasks include simulating molecular interactions for developing new batteries, building quantum refrigerators that can keep molecular clusters cool at the lowest possible temperatures, or developing sensors that can detect a single photon (the particle of light). Noisy quantum computers are being groomed towards developing solutions in drug discovery and in optimisation problems, such as the distribution of vaccines.

Quantum technologies, however, go beyond mainstream computing — into devices used in day-to-day life and research. Atomic clocks, whose prototypes are being developed now for space missions, do not lose more than a second over 13.8 billion years, the entire life of the universe. Quantum radars, whose technology has been demonstrated, will one day image proteins without affecting their structure. In the future, the first generation of commercial quantum computers is expected to be used for solving the pressing problems



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of humanity: to capture carbon dioxide from the air, to develop fertilisers with low energy inputs, to figure out the mechanism that drives photosynthesis, and so on.

Despite the promise of the field, physicists have been calling the current era 'the quantum winter', to indicate that two decades of active development — spring and summer — have slowed down. Most researchers, however, look at it as a beginning. "I would say that winter is the first season of the quantum calendar year," Urbasi Sinha, Professor at RRI, says. "Three more seasons are to come and a lot to look forward to."

Two areas of active research demonstrate the power of quantum technologies and the challenges to be solved over the current decade. One of them is the battery, which is being both improved and reimagined by researchers in the field. The other is the sensor, a ubiquitous device being built to exceptional sensitivities using quantum mechanics principles.

Big impact research

The lithium-ion battery is now the most efficient and convenient means of energy storage for contemporary electronic devices. Lithium is the third lightest element after hydrogen and helium. It is also the lightest solid. It has the highest electrochemical potential among elements, which means that it can provide high voltage while occupying low volume and weight. However, the lithium-ion battery uses liquid electrolytes that can overheat and explode. In any case, the lithium-ion battery doesn't use the full possibilities of this magic element.

So, scientists are looking at other ways of using lithium in batteries. Examples are lithium-sulphur and lithium-air batteries. Both can use solid electrolytes and provide extraordinary charge density, at levels where batteries may become viable even for powering planes. Some lithium-sulphur and lithium-air batteries under development also use liquid electrolytes and suffer from poor stability and short life cycles.

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Chaitanya Sharma Yamijala, a computational chemist and Assistant Professor at the Indian Institute of Technology (IIT) Madras, got interested in battery energetics when he read a paper by Qi Gao of the Mitsubishi Chemical Corporation. Qi, who works at Mitsubishi's Science & Innovation Center at Yokohama in Japan, had used a noisy quantum simulator to calculate the behaviour of a lithium superoxide dimer, which is an intermediate state in a crucial reaction in lithium-air batteries. Such calculations are difficult for classical computers in use now, but they are essential in understanding how to store and then coax the maximum energy out of the electrons in an atom.

A simulator is a special-purpose machine used to carry out a specific task, unlike a computer which can be used for any kind of computation. Yamijala worked on the algorithm used by Qi to calculate the energy states of molecules such as hydrogen, water, carbon dioxide, lithium hydride, and beryllium hydride. The simulations used complex hardware made with an IBM package. "Even for a small molecule like lithium hydride, with just two atoms and four electrons, the circuits needed are deep, consisting of hundreds of gates," says Yamijala, who is trying to extend this understanding of lithium-air batteries to study lithium-sulphur batteries.

A lithium-sulphur battery, if made with reliability in the future, can become a game-changer because of its high energy density, which can be twice as much as that of current lithium-ion batteries. A quantum computer will be used to develop it, but a lithium-air battery is still a classical battery that operates on classical physical principles of batteries, using the principles of electrochemistry. New advances in quantum mechanics, especially in combination with thermodynamics, can be used to design quantum batteries. This energy device will use the seemingly bizarre — for human senses, that is — properties of quantum mechanics.

A quantum system is a set of particles that obeys the laws of quantum mechanics, of which the two most common phenomena are superposition and entanglement.

Superposition is the ability of a quantum system to be in more than one state at once, a feature that is exploited by quantum computers to represent — through qubits — zero, one or a weighted combination of both at the same time. In the macroworld, it is somewhat like a flipped coin landing on both head and tail, but phenomena of the atomic world do not have strict analogues in the realm of human senses.

Entanglement is the phenomenon through which particles become so interwoven that they act as one, no matter how separated they are in physical space, as if they know what the other is doing instantly from a distance; spooky action at a distance, Albert Einstein had called it distrustfully.

The phenomena work in practice, however, and quantum batteries are being explored to exploit this property of particles.

Sai Vinjanampathy, at IIT Bombay, became interested in quantum batteries as an extension of his work on open quantum systems, where the particle's environment is also a quantum system. Quantum batteries are small quantum systems that can store energy and release it later without a chemical reaction. They have particles with at least two states, one representing low energy and the other higher energy. Charging the battery gets the particle — a photon, an electron, an atom or a qubit — into a higher energy state, from which it returns to a low energy configuration by releasing energy. The charging can happen in different ways, depending on the type of qubit being used.

In a paper published in *Physical Review Letters* six years ago (*bit.ly/quantum-efficiency*), Vinjanampathy and his collaborators showed that batteries can use quantum effects to dramatically improve their efficiencies. Moreover, they showed that, under certain conditions, the rate of charging could be higher than that of classical batteries. This is because of entanglement, which creates a bunch of connected particles that go into a higher energy state at the same time. Such quantum features have enormous potential in the wider world of technology.

For example, you could imagine a car driving past a charging station with the battery getting charged wirelessly in microseconds. You could imagine a refrigerator cooling matter down to the lowest possible temperature, very close to absolute zero. "The quantum analogues of many tools used in our daily lives can be transformed by the precision and efficacy of quantum technologies," Vinjanampathy says. The quantum battery is just one of the early ones, and many groups are working on them now.

Jitendra Joshi, a PhD student in the Physics Department of the Indian Institute of Science Education and Research (IISER) in Pune, had just joined the institution when his advisor, T.S. Mahesh, gave him a bunch of papers to read. Among these were those on quantum batteries, some written by Vinjanampathy.

Being experimentalists, Mahesh and Joshi wanted to try the concept in the lab. In the next few years, the duo tested out this hypothesis using their Nuclear Magnetic Resonance (NMR) facility. They built a proof-of-principle quantum battery, with a system of hydrogen atoms arranged in a specific way: a core atom in the middle and a few others surrounding it. The number of hydrogen atoms varied from three to 36. The surrounding hydrogen atoms acted as chargers, and the core atoms as those that got charged. They found that their experiment matched theoretical predictions very well.

The battery system retained charge for up to two minutes, while most quantum systems would have become unstable in seconds. "We are now interested in studying the physics of these systems," Mahesh says. Their paper in *Physical Review A* (*bit.ly/quantum-NMR*) also puts forth the idea of a simple quantum circuit consisting of a charger, battery and load, which they have tested in the lab. Their next job is to build quantum diodes and perhaps a more complex circuit.

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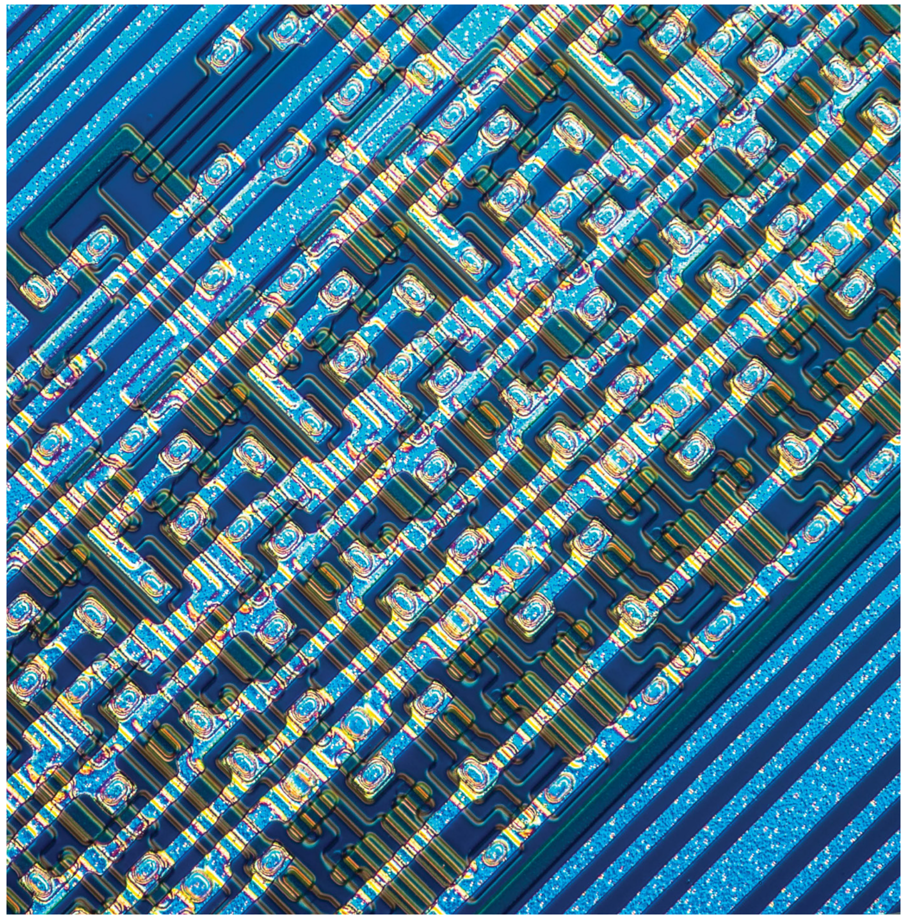
Research has shown that commercial quantum batteries are feasible and will likely be built over time. Hyper-efficient batteries have the power to change the world, but they won't be among the first set of quantum devices to come into people's lives. That honour will most likely go to the sensor.

Quantum sense

Nearly a decade ago, Arindam Ghosh was on a tea break with his PhD students when they came up with an idea. Two groups of his students were working with thin layers of graphene and molybdenum disulphide, both of which have unique and distinct properties. The students wanted to combine them and see how they behaved. It was an unlikely combination, not tried by anyone in the world.

Ghosh is a Professor of Physics at the Indian Institute of Science (IISc) in Bengaluru, where he researches phenomena at nanoscales, at dimensions of one-billionth of a metre. His primary interest is in understanding electrical and magnetic properties at such tiny scales and the stability of nanostructures. Specifically, his research group has built expertise in measuring signals at very low levels, a useful skill in developing exceptionally sensitive sensors.

Soon after the meeting, Kallol Roy, one of Ghosh's PhD students, was given the task of joining single layers of graphene and molybdenum disulphide, each layer one molecule thick. "He was very good with hands-on work," Ghosh says. Such single-layer materials had become common in research after the discovery of graphene



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in 2004. The hybrid material resulted in a sensor so sensitive that it could detect single photons. A decade later, it is still among the most sensitive light sensors in the world.

Devices that can sense single photons already exist, but the initial signal due to the detection is feeble. This signal must be amplified — varying from sensor to sensor and material to material — so that the current generated in the detector is strong enough. In the case of the graphene-molybdenum disulphide device, the signal itself is so strong that a significant current is generated without the need for amplification. Using graphene-hybrid bilayers to make photon sensors still holds a unique record, Ghosh says.

The bilayer materials are special in the way they are fabricated. A single layer of graphene is made to lie next to a single layer of molybdenum disulphide. This brings the molecules in a single-layer material very close to a second single-layer material, endowing them with properties that are essentially quantum. In the light sensor, a photon falling on the graphene layer will excite electrons and create an electron-hole pair. Under normal circumstances, when there is only graphene, the electron will fall back into the hole quickly. However, in the hybrid, the electron tunnels into the molybdenum disulphide layer, in the process knocking into other molecules in that layer, exciting more electrons in a cascading fashion until soon there are a billion electrons excited. So, there is no need to amplify the signal, unlike in a silicon detector.

The tunnelling is a uniquely quantum phenomenon, as the electron surmounts a barrier without quite having the energy to do so. Such sensors are the early entrants into the arena of quantum technology, and they will get integrated into quantum devices where single photon detectors are needed.

Ghosh and his students have now carried this work into thermal sensors. Using bilayers of tungsten disulphide and tungsten diselenide, which are materials in the same family, the group has shown that extremely low temperatures — a few degrees above absolute zero — can be measured efficiently and quickly using these materials. "The power comes from being able to join materials at the sub-nanometre thickness," Ghosh says.

Usually, temperature is measured using a thermometer. This is a secondary measurement. First, the heat in the object is absorbed by the thermometer substance, which then expands to show the reading on the meter. In the case of the thermal sensors, called bolometers, which Ghosh's group is developing, the sensor directly responds to the temperature fluctuations in the medium. The response is then immediate. It is called primary thermometry.

The material is so sensitive that it can sense voltage fluctuations in the order of a picovolt — one trillionth of a volt — generated by the random thermal motion of electrons in the conductor. These sensors are invaluable in quantum devices. The light sensors will be used in building single photon detectors that are needed in quantum communication and quantum computing. The temperature sensors can be used to know the state of individual qubits in quantum computers. They are useful in quantum-enabled metrology, where very accurate measurements are needed to establish standards of measurement. They can be used also to study materials when tiny undulations on surfaces need to be measured. Early detection of cancer is another application area.

Most scientists in the domain believe that quantum technology will first deliver sensors and materials. Next will be the field of quantum communication. Quantum computing will follow these two areas. Recent discoveries have set the pace, and it is possible to intuitively understand how far the field can go and how fast. "Physics sets the limits on the hardware, and computational science sets a limit on the software you can develop to run on the hardware," Vinjanampathy says. "Quantum computer science sits at the intersection of these two limits." •