Quantum computing ramps up in private sector

Ridicule has given way to high hopes.

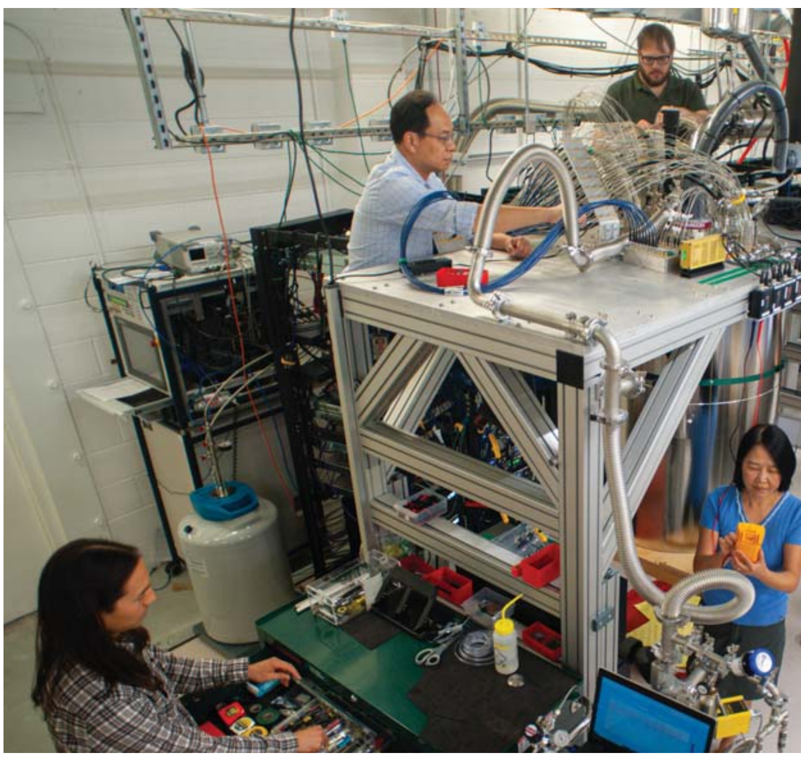
In the early days of quantum computing research, people working in the field routinely encountered skepticism. Twenty years ago eminent physicists told Susan Coppersmith, a theoretical physicist now at the University of New South Wales in Australia, that she was "wasting her time and that quantum computing would never work because of [the difficulties of] error correction." But advances have led to a gradual shift in attitudes.

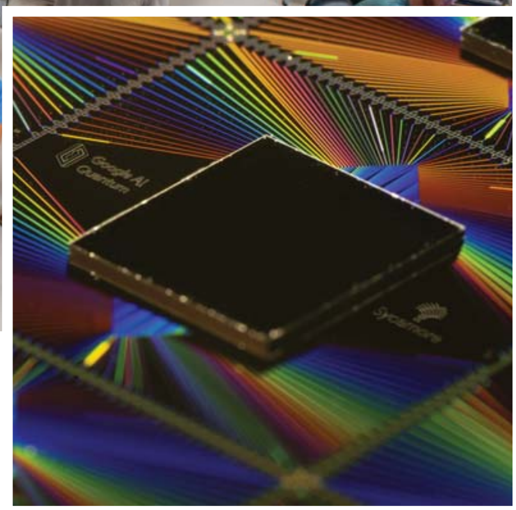
John Preskill of Caltech, a leading theorist in the field, says that over the past couple of years he has observed a shift in expectations about commercialization that is "reflected in a ramping up by tech companies and venture capital." The shift propels progress and creates opportunities for young people, he says. Still, he cautions, "nobody knows when we will have applications running on quantum platforms. I am concerned that the expectations may be inflated as far as time scale." Predictions for achieving a useful quantum computer span from a few years to a few decades; major players IBM and Google both aim for the end of this decade.

Milestones leading to the shift in attitude include the first commercial quantum computers, marketed in 2015 by the Canadian company D-Wave, and the first publicly accessible cloud-based quantum computer, introduced in 2016 by IBM (see "IBM proclaims 'the beginning of the quantum age of computing,'" PHYSICS TODAY online, 4 May 2016). That same year, error rates with some ion-trap systems dipped below 0.1%. And in October 2019, to great fanfare, Google demonstrated quantum supremacy by performing a calculation deemed impractical or impossible for a classical computer: With 53 quantum bits, or qubits, it solved a math problem in 200 seconds that would have taken much longer on a high-performance computer. The actual time a supercomputer would need is debated, with Google claiming thousands of years and IBM saying its Summit supercomputer could do it in 2.5 days.

Still, hurdles remain to achieving useful quantum computers. The number of qubits needs to be scaled up. The qubits are needed not only for computations but also for correcting errors due to decoherence of the fragile quantum state. Engineering infrastructure must be designed and built. Algorithms must be created.

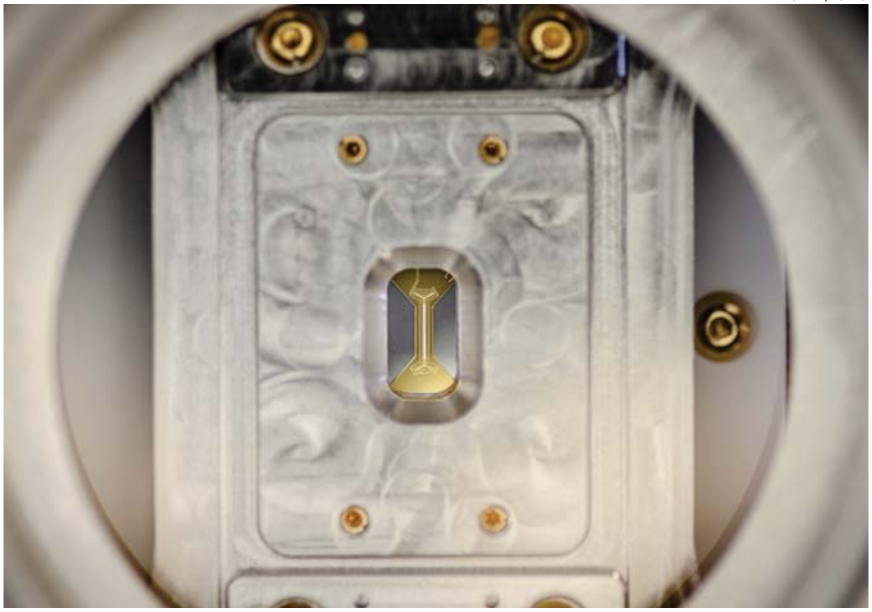
Hartmut Neven, who in 2013 founded Google's Quantum Artificial Intelligence





GOOGLE DEMONSTRATED QUANTUM SUPREMACY in October 2019. Above, scientists and engineers at the company's laboratory in Santa Barbara, California, maintain the dilution refrigerator housing the Sycamore chip (right) that performed the milestone calculation. The chip's 53 superconducting qubits performed in minutes a calculation that would have taken much longer on a classical computer. (Images courtesy of Google AI Quantum.)

KAI HUDEK, IONQ



CHAINS OF YTTERBIUM-171 IONS are loaded into ion traps to serve as qubits at the Maryland-based startup company IonQ. The qubits are controlled with a laser tuned to the frequency difference between the ground state and an excited state of the ions. The thin strip at the center where the ions are trapped measures 1.2 mm by 4 mm.

laboratory, compares the state of quantum computing to the pre-discovery days of the Laser Interferometer Gravitational-Wave Observatory: "It was very difficult to build such a precise instrument, but the bigger concern was, Will there be enough black holes or neutron stars to observe with it?" Sooner or later a reliable quantum computer will be achieved, he continues. "I'm more nervous about the discovery risk: Will we find scientifically and commercially valuable algorithms to make the investments worthwhile?"

Initialize, manipulate, measure

The power of quantum computing lies in the quantum nature of qubits. In classical computing, a bit can take the value 0 or 1; a qubit's value can be 0, 1, or a superposition of 0 and 1. With 2 qubits, there are 4 possible states; with 3, there are 8, and with N, there are 2^N. At 50 qubits, computing power exceeds that of a classical supercomputer, says experimental physicist John Martinis of the University of California, Santa Barbara. "By the time you get to 300 qubits, 2^{300} is more than the number of atoms in the universe, so you could never make a classical computer that could do computations comparable to what quantum computers will likely do some day."

Quantum logic gates for implementing the various steps of a computation can operate on individual qubits or pairs. To create quantum algorithms, "you have to learn new rules," says Martinis, who parted ways with Google in the spring and in September joined the Australian startup company Silicon Quantum Computing as an in-house consultant for six months. "It's going from checkers to chess. With qubits, you have an enhanced set of rules, a richer set of gates."

Several approaches are being pursued for realizing physical qubits. Many are based on superconducting tunnel junctions (see PHYSICS TODAY, July 2009, page 14) or on semiconductor quantum dots (see the article by Lieven Vandersypen and Mark Eriksson, PHYSICS TODAY, August 2019, page 38). Such fabricated qubits can be made in quantity, and researchers can adjust their energy levels to tune their behavior. Other implementations use the spins of trapped ions or neutral atoms. (See the PHYSICS TODAY articles by Ignacio Cirac and Peter Zoller, March 2004, page 38, and by David Weiss and Mark Saffman, July 2017, page 44.) In a trapped-ion or neutral-atom system, the qubits are inherently identical and they maintain their coherence longer than superconducting or semiconductor qubits typically do.

"You can find many quantum mechanical two-state systems in nature," says Neven. "If you can initialize, manipulate, and measure them, it's a qubit. You can form an abstract programming language, and the end result will look the same regardless of what's under the hood." What's under the hood, though, can determine what quantum gates and algorithms are suitable.

For now, ion traps and superconducting qubits are widely considered the leading candidates for quantum computers, says Raymond Laflamme, founder and former director of the Institute for Quantum Computing at the University of Waterloo in Ontario, Canada. He studies NMR systems for quantum computation. The approach is interesting for learning about controlling qubits in general, he says, but NMR is not in the running to build large quantum computers.

Isolation versus interaction

The last few years have seen the debut of quantum computers of increasing size and power. "It's getting to the stage where quantum computing is not yet useful," notes Martinis, "but it's useful for research on quantum computing, and that is in itself really interesting." He cites such questions as, What is the physics of a qubit? What are the constraints? Can you solve problems with qubits that you can't solve in any other way? "The difficulty is that quantum computers are hard to build." Typically, the more qubits get linked together, the faster the decoherence. "It's a tradeoff between getting qubits to talk to each other but not talk to the outside world," says Martinis. For Google's quantum supremacy demonstration, he adds, "we were able to solve the problem through chip design."

"The speed at which decoherence occurs can make or break a qubit," says Coppersmith, whose focus is on semiconductor qubits. "Understanding quantum coherence will have huge consequences for quantum computing."

Possible initial applications that many researchers anticipate are in quantum chemistry and materials science. Simulations with quantum computers could lead to more efficient batteries and molecules deployed for cleaning the environment. (See, for example, "Quantum computer models a chemical reaction," PHYSICS TODAY online, 8 September 2020.)

Another class of problems that quantum computing may ace is optimization, such as the well-known "traveling salesman" problem, in which the aim is to find the shortest route to knock on a large

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number of doors. "The hope is that quantum computing can do better by looking at all states at the same time," explains Martinis. Optimization problems—how to route planes, diversify investment portfolios, and so on—are ubiquitous.

How can one know whether the results from a quantum computer are correct? For some tasks, such as factoring numbers, checking the answer is easy. And that's an important task: Implementing Peter Shor's 1994 algorithm for factoring large numbers could help crack encrypted information and encrypt future data. Other simple calculations can be tested too. For more complex, nontestable algorithms, researchers have to make the jump to trusting their quantum computers.

Errors and noise

Such trust requires error correction, which in turn means building in redundancy. (See the article by Preskill, Physics Today, June 1999, page 24.) And for many qubit approaches, redundancy can be bulky and costly. The qubit error rate for superconducting systems is currently around 0.5%. For error correction to be effective, Martinis says, "you need to get down to 0.1%." A system can be sampled for errors by checking whether redundant qubits—which together function as a single logical qubit—are in the same state, without disturbing the system by actually reading them out.

In a recent arXiv preprint, University of Maryland experimental physicist Chris Monroe and colleagues report achieving a 0.3% error rate for a logical qubit encoded with 13 physical qubits. The small number of physical qubits—compared with the redundancy employed by other quantum computing approaches—was possible because of the low error rate and dense connectivity in ion-trap systems, says Monroe, cofounder of the Maryland-based startup company IonQ. "This gives trapped ions a clear path to scale up."

In the meantime, many researchers are looking for possible applications with current systems. In the noisy intermediate-scale quantum (NISQ) computing regime, the idea is to write algorithms with few gate operations so they can run before the system is overwhelmed by decoherence. "NISQ is what we do before we can do error correction," says Duke University physicist and IonQ cofounder Jungsang Kim. (See the article by Anne Matsuura, Sonika Johri, and Justin Hogaboam, Physics Today, March 2019, page 40.)

"We have to find out what NISQ is useful for and then generate value so that people reinvest," says Kim. "That will trigger economic development." Preskill, who coined the terms "quantum supremacy" and "NISQ," agrees: "We need practical applications to ignite a virtuous cycle." This past summer Amazon tapped Preskill for the company's quantum computing initiative.

A possible dark horse in the race to useful quantum computers is the five-year-old Palo Alto–based PsiQuantum, which takes a photonics approach to qubits. The company is leapfrogging NISQ and aiming directly for error correction. "The magic is how to come up with architecture that is compatible with the semiconductor industry," says Jeremy O'Brien, company cofounder and a former professor of physics and electrical engineering. The company patterns silicon wafers into thousands of photonic components containing waveguides for carrying the single photons that encode the qubits. "We are going for 10 000 physical qubits to distill into one logical qubit," he says. "It's expensive, but a price well worth paying."

O'Brien predicts that PsiQuantum will have a useful quantum computer with a million logical qubits in just a handful of years—faster than people working with other qubit types are committing to. This past spring the company reached the quarter-billion-dollar mark in venture-capital investments. "I no longer have to convince people it's interesting," O'Brien says. "I have to fend them off with a stick."

The question about which approach to qubits succeeds comes down to who manages to put all the necessary parts together to make the quantum computers do what computer scientists want them to do, says David DiVincenzo. The theoretical physicist is based at Germany's Jülich Research Center, the hub of a consortium working toward a quantum computer as part of the European Union (EU) Quantum Flagship initiative.

Multisector effort

Companies, university researchers, and governments are entering the quantum computing arena. China, Japan, and other countries are investing in quantum computing. In December 2018 President Trump signed into law the National Quantum Initiative, which, among other things, set a 10-year plan for the field. As part of the initiative, in August the US announced awards for new artificial intelligence and quantum information science research institutes. Both the initiative and the EU flagship, launched in 2018, are roughly $1 billion bets on the future commercial potential of quantum information science.

"The community is growing rapidly, and companies can pull off meaningful engineering that is hard to do at universities," says Frank Wilhelm-Mauch, Jülich-based coordinator of the EU quantum computer effort. Companies can also bring large interdisciplinary teams together. "That is extremely hard to do in academia and on academic time scales," he says. Some large companies are investing huge sums, and they can do so more nimbly than governments or academic researchers.

A growing number of companies are offering quantum computing via the cloud—so far, in addition to IBM, the list includes Microsoft, Honeywell, Alpine Quantum, D-Wave, Rigetti Computing, QuEra, and Atom Computing. Google is planning to host a supremacy-level system soon. In August, IonQ opened an 11-qubit quantum computer to the public via the Amazon Braket cloud platform, and on 1 October it unveiled a 32-qubit version. In putting quantum computers in the cloud, Wilhelm-Mauch notes, companies have sparked interest among computer programmers, venture capitalists, and students who want to explore. "This was a great service, and has pulled the field along faster," he says. The wide access could accelerate the discovery of useful algorithms.

Jan Benhelm leads product management at Zurich Instruments, a company that develops control electronics and software to connect qubits to higher software and applications. Universities are an excellent place to develop new, risky technologies, he says, "for exploring new qubits, new gates, new algorithms." But given academia's emphasis on publishing and the fact that many university researchers don't have permanent positions, he says, "the incentive patterns in universities are not supportive when you want to scale up."

More and more startups and larger companies are populating the quantum computing landscape. One is Quantum Benchmark in Kitchener, Ontario, which provides software diagnostics for qubit designers to test whether their computations are performing as expected. And Tabor Electronics makes arbitrary waveform generators integrated with digitizers to control and read out superconducting qubits.

"The field is making good progress," says Martinis. "It's a mixture of well-placed optimism and a bit of hype." It's still hard to say when quantum computers will become useful, says Wilhelm-Mauch. For now, though, with the range of components available, "It's like during the Gold Rush: The ones benefiting are the shovel makers."

Toni Feder

ARPA–E can't reach the promised land alone

Evaluating the success of an upstart agency that swings for the fences on clean-energy technologies isn't straightforward.

The Advanced Research Projects Agency–Energy (ARPA–E), the 10-year-old Department of Energy program designed to foster high-risk clean-energy technologies, has had limited success in moving them toward commercialization, according to a recently published study. But ARPA–E managers, former program officials, and even the lead author of the study agree that the program is performing as it was intended in advancing potentially game-changing solutions for decarbonizing energy. Additional government programs and market incentives are needed, they say, to attract the investments that will bring those innovations to market.

Anna Goldstein of the University of Massachusetts Amherst and colleagues compared the success of 25 startups, all part of the initial 2010 cohort of 60 ARPA–E awardees, to 1262 other cleantech startups of the same age. The researchers used acquisitions by other companies, initial public offerings, survival through 2019, and the amount of venture capital (VC) raised through 2017 as indicators of successful business outcomes. They found that the ARPA–E startups fared no better than the clean-energy startups that didn't apply for ARPA–E grants. Goldstein and her group published their analysis in *Nature Energy* on 14 September.

The comparison set comprised three groups: startups that had been rejected for ARPA–E grants, ones that had received grants in 2010 from DOE's Office of Energy Efficiency and Renewable Energy (EERE), and startups that didn't apply to ARPA–E or receive EERE funds. The authors said that of those, only the group of rejected ARPA-E applicants had worse business outcomes than the ARPA–E sponsored startups. No significant differences were identified between the success rates of the ARPA–E awardees and those of the EERE awardees. Nor did measures of success differ from those of the "other" group.

The findings "suggest that ARPA–E was not able to fully address the 'valley of death' for cleantech startups within 10–15 years after founding," the paper states. The "valley of death" is a widely used term for the difficulty of obtaining the investment required to move an innovative technology from development to full-scale demonstration and commercialization.

The report concludes, however, that the ARPA–E startups showed a high degree of innovation by obtaining significantly more patents than any of the other groups. "They are patenting at twice the rate after their award, even accounting for other factors that we know influence the patenting rate. That's what I see as the important finding," Goldstein says.

Failure is an option

Patterned after the successful Defense Advanced Research Projects Agency, ARPA–E was created in 2007 legislation to support high-risk technologies that could greatly reduce greenhouse gas emissions. The new agency was initially funded through the American Recovery and Reinvestment Act of 2009, and its first awardees were announced in fiscal