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Signals for Strategists

From fantasy to reality

Quantum computing is coming to the marketplace

By David Schatsky and Ramya Kunnath Puliyakodil

Introduction: A new way to solve computationally intensive problems

GRANTED, quantum computing is hard to explain. But that hasn't stopped the fantastical technology from attracting billions of dollars of R&D investment, catching the eye of venture capital firms, and spurring research programs at big tech companies and enterprises. Some companies are getting a head start on applying quantum technology to computationally intensive problems in finance, risk management, cybersecurity, materials science, energy, and logistics.

Signals

- In the last three years, venture capital investors have placed $147 million with quantum computing startups; governments globally have provided $2.2 billion in support to researchers[1]
- Some of the world's leading tech companies have active quantum computing programs
- Financial services, aerospace and defense, and public sector organizations are researching quantum computing applications
- Quantum computer maker D-Wave Systems announced the general availability of its next-

generation computer, along with a first customer for the new system[2]

- VC firm Andreessen Horowitz has signaled its intention to fund quantum computing start-ups[3]
- Standards-setting bodies are seeking a transition to cryptographic systems that can withstand quantum computers[4]

A fantastical form of computing

Inspired by the ideas of a charismatic physicist, quantum computing promises to have an enormous impact on fields ranging from finance to life sciences to manufacturing. It has the potential to create great wealth by making it possible to solve some of the most computationally difficult problems. It could even enable scientists to create entirely new types of matter.

Quantum computers, by harnessing the bizarre properties of subatomic particles, will be able to perform certain kinds of calculations exponentially faster than the fastest computers currently known.[5] Researchers say this power will enable quantum computers to break the encryption systems that currently keep online transactions safe around the world;[6] discover optimal investment portfolios with greater precision and speed than the most sophisticated models in use today;[7] and help design new materials and industrial processes by precisely predicting the behavior of molecules.[8]

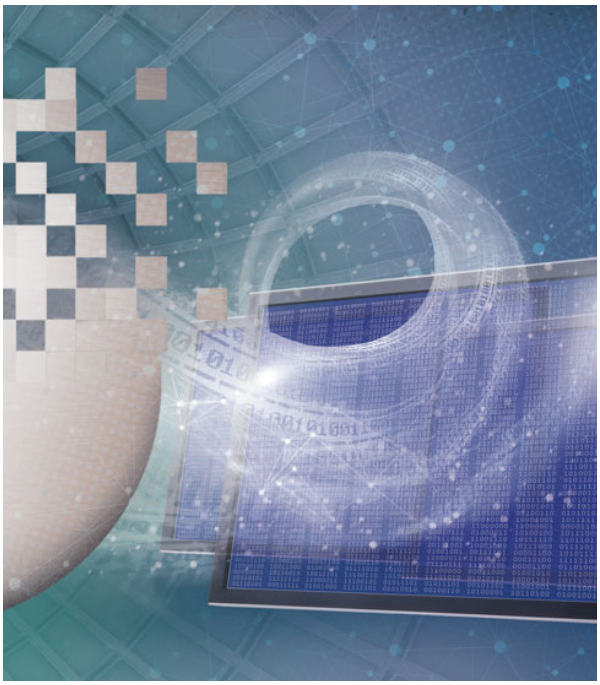
All this may sound like a distant dream, but real money is pouring into quantum computing right now. The field has attracted $147 million in venture capital in the last three years and $2.2 billion in government funding globally. And the pace of investment is increasing.[9] The activity is not confined to academic research labs and start-up companies: A growing number of enterprises are already committing resources to exploring how to apply quantum computing. The stakes appear to be too high to ignore this still-nascent technology.

HOW QUANTUM COMPUTERS ARE DIFFERENT

Quantum computers work on principles very different from those of classical, electronic computers. They exploit the behavior of subatomic particles as described by quantum mechanics, a subfield of physics that explains the complex and weird behavior of subatomic particles—that is, objects smaller than atoms. For instance, electrons can exist in multiple distinct states at the same time, a phenomenon known as superposition. And it's impossible to know for sure at any given instant what state an electron may be in, because the very act of observing the state changes it. Furthermore, subatomic particles can be "entangled," so that a change to one influences another, even if the two particles are physically distant from each other. To capture these complexities, quantum mechanics describes the state of subatomic particles probabilistically using "complex numbers."[10]

Over 30 years ago, legendary physicist Richard Feynman mused that no computer was powerful enough to perform the calculations needed to simulate the complex behavior of subatomic particles. Yet these particles behave in predictable ways. Their predictable behavior could be seen as a kind of calculation, one that was performed by the particles themselves. Could we harness these particles, he wondered, to perform calculations that are beyond the reach of the fastest known computers?[11] (See sidebar "Much faster—in theory" for a brief account of how it happened.)

Typically, computing has picked up speed when engineers have developed more powerful hardware. But quantum algorithms outpace their classical counterparts not because they run on faster hardware—it's because the quantum mechanical mathematics they



MUCH FASTER—IN THEORY

The idea of a quantum computer remained a curiosity for years. Then came theoretical proof that computing based on quantum mechanics could be much more efficient than classical computing. In 1994, a researcher at AT&T's Bell Labs named Peter Shor showed that a quantum computer could in theory solve a certain type of problem—finding the prime factors of an integer—much faster than classical computing methods.[12] This happens to be a result of great importance, since the encryption systems used around the world rely on the fact that classical computers cannot factor large numbers in a practical amount of time. A quantum computer might someday render these encryption systems obsolete.

Two years later, another researcher at Bell Labs, Lov Grover, proved that a quantum computer could excel at solving other types of problems as well. The *phonebook problem* is the name for the task of finding something in an unsorted list—like looking up someone in the phonebook by her phone number rather than her name. In classical computing, the standard algorithm is to inspect each entry until the matching phone number is found, requiring as many inspection steps are there are entries in the phone book. Grover demonstrated that a quantum computer could solve this problem in far fewer steps—specifically, the number of steps equal to the square root of the number of entries in the phone book. Finding the matching phone number in a list of a billion entries would require just 31,623 operations—the square root of a billion—and, obviously, a small fraction of the time.[13]

use requires fewer steps. (See the sidebar "Building a quantum computer.")

True, superior quantum algorithms probably do not exist for every class of computational problem. In fact, researchers don't yet know all the types of problems at which quantum computing could excel. But the applications are broad. They include optimization problems—finding the best solution to a problem when numerous solutions are feasible—which have applications in many fields; factorization, with immediate applications in cryptography; physics simulation; number theory; and topology.[14]

The engineering challenges involved in building a quantum computer are formidable. The device created by D-Wave Systems, for instance, must operate in an enclosure carefully isolated from the outside environment at a temperature far colder than interstellar space.[15] A typical quantum bit, or qubit, is perishable: It maintains its state for perhaps 50 microseconds before errors creep in.[16] And even reading the value of a qubit is a very exacting process. The difference in energy between a zero and a one is just 10^{-24} joules[17]—one ten-trillionth as much as an X-ray photon.[18]

BUILDING A QUANTUM COMPUTER

The proof of the theoretical superiority of quantum computing methods has spurred research into how engineers might actually build a working quantum computer. Perhaps unsurprisingly, it's a challenge.

As we know, the fundamental unit of information in a classical computer is the bit, short for binary digit. The analogous building block of a quantum computer, which embodies the mysterious and powerful properties of subatomic particles, is known as a quantum bit, or qubit. Classical computers use electrical charge to represent bits. And they perform calculations using circuits that implement Boolean algebra (the logic of *true/false*, *and/or*). Quantum computers, by contrast, take advantage of quantum mechanics rather than electrical conductivity. And to manipulate these properties, they use linear algebra to manipulate matrices of complex numbers rather than Boolean algebra to manipulate bits.

While manufacturing semiconductors capable of storing and manipulating bits is well established, making qubits and quantum gates is very much a work in progress, though firms such as IBM, Google, and Microsoft are exploring[19] a variety of methods, including using superconducting loops, trapped ions, silicon quantum dots, topological qubits, and microscopic diamonds.[20]

Researchers around the world are regularly announcing progress in tackling the engineering challenges of quantum computing.[21] But mass production of quantum computing is widely regarded as years away.[22]

Enterprises are already seeking applications

Despite the nascent state of quantum computing, dozens of public and private sector organizations are already researching applications of great potential value. Financial services firms are notably active. For instance, Barclays,[23] Goldman Sachs,[24] and other financial institutions are investigating the potential use of quantum computing in areas such as portfolio optimization, asset pricing, capital project budgeting, and data security. In aerospace, Airbus is exploring applications in communications and cryptography,[25] while Lockheed Martin is investigating applications in verification and validation of complex systems and accelerating the development of machine learning algorithms.[26] The US Navy is paying for training in quantum computing and plans to develop algorithms for optimization problems such as data storage and energy-efficient data retrieval with underwater autonomous robots,[27] and NASA is exploring applications in communications, distributed navigation, and system diagnostics.[28] Information technology players such as Alibaba,[29] Google,[30] and IBM[31] are working on applications such as hack-resistant cryptography, software debugging, and machine learning. Life sciences firms are seeking applications of quantum computing in personalized medicine and drug discovery.[32]

Other organizations are eyeing applications in logistics, industrial chemistry, and energy that could be extremely valuable. For instance, the standard process for manufacturing fertilizer uses some 2 to 5 percent of global natural gas production each year; quantum simulation could lead to the discovery of a more efficient process that could save billions of dollars and trillions of cubic feet of natural gas annually. Another intriguing application is using quantum computation to discover new, high-density designs that could dramatically expand the capacity of batteries used in everything from portable electronics to electric vehicles. Improvements in battery density have been running at just 5 to 8 percent annually—painfully slow compared to the familiar exponential Moore's Law pace.[33]

WHEN DATA AND TRANSACTIONS ARE NO LONGER SECURE

One area in which quantum computing is already having an impact is encryption. The most widely used techniques for encrypting and protecting transactions depend on the impossibility of swiftly finding the prime factors of large numbers. For example, it would take a classical computer 10.79 quintillion years to break the 128-bit AES encryption standard, while a quantum computer could conceivably break this type of encryption in approximately six months.[34] This has led to a search for encryption methods that would be resistant to attacks from quantum computers—to make information systems "quantum resistant."

In 2015, the National Security Agency's Information Assurance Directorate announced that it will begin guiding agencies and the private contractors who cater to them on transitioning to quantum-resistant algorithms. Public and private sector entities have already begun making plans to transition to encryption systems—so-called post-quantum cryptography—that would withstand attacks by a future quantum computing system.[35] Enterprises are already thinking about risks to their encrypted data even before quantum encryption attacks become a reality. They are restricting access to or completely deleting sensitive data, even in encrypted formats, to prevent hostiles from capturing that scrambled data with the hope of decrypting it with quantum computers in the future.

It's not just the hardware

Fulfilling the potential of quantum computing depends on more than just building new hardware. New software will be crucial as well: Because quantum computing takes an entirely different approach to problem solving, entirely new algorithms that take advantage of this approach will be needed to achieve a quantum speedup in performance. New software development tools will also be required. A quantum computing technology ecosystem—consisting of start-up companies, incumbent tech firms, and research institutions—that aims to provide the needed software is now emerging.

GROWING INVESTMENT IS SUPPORTING A NASCENT TECHNOLOGY ECOSYSTEM

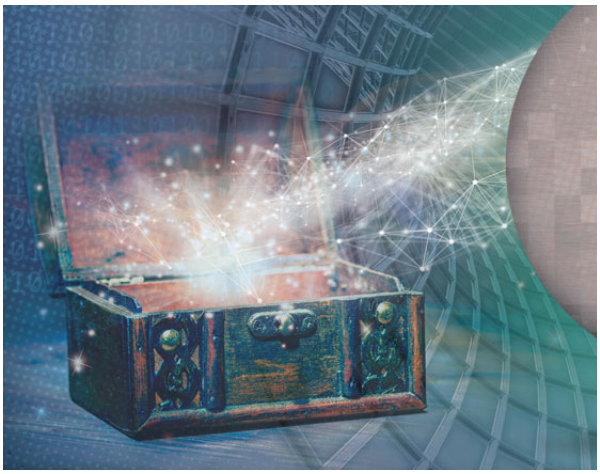
Some incumbent IT providers have active quantum computing research programs that may eventually lead to commercial products. These include Google,[36] IBM,[37] Intel,[38] Hewlett Packard Enterprise,[39] Microsoft,[40] Nokia Bell Labs,[41] and Raytheon.[42] They are exploring various areas, including building components such as qubits and quantum gates (basic circuits) and exploring quantum algorithms, software and tools, and encryption techniques.

A number of start-ups, some backed by venture capital, have entered the market as well. Besides D-Wave Systems, which is developing quantum computers, as many as a dozen companies are developing quantum computing components or quantum computing algorithms, software tools, or applications.[43]

WHAT TO WATCH FOR

Breakthroughs in quantum computing are coming quickly, with some researchers saying that the challenges have progressed from basic science to engineering.[44] Even so, no one knows when quantum computers might become widely commercially available. To stay abreast of progress in quantum computing, here are a few specific areas worth following:

Fundamental hardware engineering. There is a lot of progress still to be made in creating the basic building blocks of quantum computers such as qubits and quantum gates. A recent example of progress: Researchers at the University of New South Wales in Australia recently created a qubit that remains stable 10 times longer than previous technology. In partnership with the Australian government, the researchers are working to develop a prototype quantum silicon chip that could lead to the creation of a practical quantum computer.[45]



Quantum algorithms and software. The design of quantum algorithms requires specialized skills. And designs are specific to the type of quantum computer used. On D-Wave's system, for instance, computational tasks must be expressed as optimization problems. As quantum hardware evolves, the software written for quantum computers will have to evolve too.[46] The level of activity and innovation in quantum software tools, operating systems, and algorithms—as well as in foundational engineering—will help indicate progress toward practical quantum computing.

Quantum supremacy. A symbolic milestone to watch for is the achievement of "quantum supremacy"—the creation of a general-purpose quantum computer that can perform a task no classical computer can. Google, which has already announced a 9-qubit quantum computer, has published a paper suggesting its researchers believe that a planned 50-qubit computer could achieve that goal in the next couple of years.[47]

Implications for enterprises

While mainstream commercial applications of quantum computing are likely years away, executives can do a number of things to begin to prepare their enterprises for the era of quantum computing.

Reimagine analytic workloads. Many companies regularly run large-scale computations for risk management, forecasting, planning, and optimization. Quantum computing could do more than just accelerate these computations—it could enable organizations to rethink how they operate, and to tackle entirely new challenges. Executives should ask themselves, "What would happen if we could do these computations a million times faster?" The answer could lead to new insights about operations and strategy.

Companies may be able to reap some benefits from quantum computing even before the machines themselves are commercially available. Quantum computing researchers have discovered improved ways of solving problems using conventional computers, for example. Some researchers are seeking to bring "quantum

thinking" to classical problems.[48] Kyndi, a start-up that offers quantum-inspired computing technology for machine intelligence, claims to be seeing increases in computational speed using this approach.[49]

Update high-performance computing architectures. Enterprises in industries such as aerospace and defense, oil and gas, life sciences, manufacturing, and financial services that have already invested in high-performance computing (HPC) should familiarize themselves with the impact that quantum computing may have on the architecture of HPC systems. Hybrid architectures that link conventional HPC systems with quantum computers may become common. D-Wave has described an HPC-quantum hybrid for the simulation and design of a water distribution system, for instance; it uses quantum computing to narrow down the set of design choices that need to be simulated on the conventional system, with the potential to significantly reduce total computation time.[50]

Explore academic R&D partnerships. It may be worth considering allocating R&D dollars to collaborations with an academic research institution working in this area, as Commonwealth Bank of Australia is doing.[51] An academic research partnership could be an effective way of getting an early start on building knowledge and exploring applications of quantum computing for your organization. Research institutions currently active in quantum computing include the University of Southern California, Delft University of Technology, University of Waterloo, University of New South Wales, University of Maryland, and Yale Quantum Institute.

Create a long-range post-quantum cybersecurity plan. It is not too early to begin planning to fortify cyber defenses against a quantum future. A US government-backed standards-setting body recently assessed the threat of quantum computers and advised organizations to develop "crypto agility"—that is, the ability to swiftly switch out algorithms for newer, more secure ones as they're released.[52] Firms need to pay attention to these developments and have roadmaps in place to follow through on those recommendations. A risk is that adversaries could capture and store encrypted data today for decryption in the future, when quantum computers become available.[53]

THE QUANTUM FUTURE

Most CIOs will not be submitting budgets with line items for quantum computing in the next two years. But that doesn't mean leaders should ignore this field. Because it is advancing rapidly, and because its impact is likely to be large, business and technology strategists should keep an eye on quantum starting now. Large-scale investments will not make sense for most companies for some time. But investments in internal training, R&D partnerships, and strategic planning for a quantum world may pay dividends.

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ENDNOTES

1. Deloitte analysis, based on CB Insights data and press releases.
2. D-Wave Systems Inc., "D-Wave announces D-Wave 2000Q quantum computer and first system order," January 24, 2017, www.dwavesys.com/press-releases/d-wave%C2%A0announces%C2%A0d-wave-2000q-quantum-computer-and-first-system-order.
3. Frank Chen, "Quantum computing: A primer," Andreessen Horowitz, June 26, 2016, http://a16z.com/2016/06/26/quantum-computing-explained/.
4. Brian Robinson, "NIST looks for defense against code-cracking quantum machines," GCN, December 22, 2016, https://gcn.com/articles/2016/12/22/nist-quantum-encryption.aspx; *In Compliance News*, "ETSI launches Quantum Safe Cryptography specification group," April 24, 2015, http://incompliancemag.com/etsi-launches-quantum-safe-cryptography-specification-group/.
5. Davide Castelvecchi, "Quantum computers ready to leap out of the lab in 2017," *Nature*, January 3, 2017, www.nature.com/news/quantum-computers-ready-to-leap-out-of-the-lab-in-2017-1.21239.
6. Nicole Kobie, "The quantum clock is ticking on encryption—and your data is under threat," *Wired*, October 4, 2016, www.wired.co.uk/article/quantum-computers-quantum-security-encryption.
7. Jack Clark and Saijel Kishan, "Quantum computers entice Wall Street vowing higher returns," *Bloomberg Technology*, December 9, 2015, www.bloomberg.com/news/articles/2015-12-09/quantum-supercomputers-entice-wall-street-vowing-higher-returns.
8. Mary-Ann Russon, "Google boasts quantum computing breakthrough with first display of real-world use," *International Business Times*, July 22, 2016, www.ibtimes.co.uk/google-boasts-quantum-computing-breakthrough-first-display-real-world-use-1571823.
9. Deloitte analysis of press releases, government funding announcements, and CB Insights.
10. Ben Deen, "On the road to a quantum computer," *Yale Scientific*, February 26, 2009, www.yalescientific.org/2009/02/on-the-road-to-a-quantum-computer/.
11. Andris Ambainis, "What can we do with a quantum computer?", Institute for Advanced Study, 2014, www.ias.edu/ideas/2014/ambainis-quantum-computing.
12. Jennifer Chu, "The beginning of the end for encryption schemes?", *MIT News*, March 3, 2016, http://news.mit.edu/2016/quantum-computer-end-encryption-schemes-0303.

13. Chen, "Quantum computing: A primer."

14. National Institute of Standards and Technology, "Quantum algorithm zoo," http://math.nist.gov/quantum/zoo/, accessed April 6, 2017.

15. D-Wave Systems Inc., "The D-Wave 2000Q™ system," www.dwavesys.com/d-wave-two-system, accessed April 6, 2017.

16. Chris Lee, "How IBM's new five-qubit universal quantum computer works," *Ars Technica*, May 4, 2016, https://arstechnica.com/science/2016/05/how-ibms-new-five-qubit-universal-quantum-computer-works/.

17. Ibid.

18. Chen, "Quantum computing: A primer"; NASA, "Regions of the electromagnetic spectrum," https://imagine.gsfc.nasa.gov/science/toolbox/spectrum_chart.html, accessed April 6, 2017.

19. Gabriel Popki, "Scientists are close to building a quantum computer that can beat a conventional one," *Science*, December 1, 2016, www.sciencemag.org/news/2016/12/scientists-are-close-building-quantum-computer-can-beat-conventional-one.

20. Benjamin Skuse, "The trouble with quantum computing," *Engineering & Technology*, November 8, 2016, https://eandt.theiet.org/content/articles/2016/11/the-trouble-with-quantum-computing/; Jacob Aron, "Quantum computing race heats up as trapped ions rival microchips," *New Scientist*, August 3, 2016, www.newscientist.com/article/2099886-quantum-computing-race-heats-up-as-trapped-ions-rival-microchips/; Popki, "Scientists are close to building a quantum computer that can beat a conventional one"; Agam Shah, "Diamonds could be building blocks for quantum computers," *PC World*, November 7, 2016, www.pcworld.com/article/3139445/hardware/diamonds-could-be-building-blocks-for-quantum-computers.html.

21. R. Colin Johnson, "Quantum computing on cusp," *EE Times*, January 7, 2017, www.eetimes.com/document.asp?doc_id=1330680.

22. Edwin Cartlidge, "Quantum computing: How close are we?", *Optics & Photonics News*, October 2016, www.osa-opn.org/home/articles/volume_27/october_2016/features/quantum_computing_how_close_are_we/; Timothy Prickett Morgan, "Is quantum computing set for an investment boom?", *Next Platform*, September 3, 2015, www.nextplatform.com/2015/09/03/is-quantum-computing-set-for-an-investment-boom/.

23. Natasha Lomas, "Post-quantum encryption no longer a laughing matter," *TechCrunch*, June 22, 2015, https://techcrunch.com/2015/06/22/pq-solutions/.

24. Zoe Thomas, "Quantum computing: Game changer or security threat?", *BBC*, April 5, 2016, www.bbc.com/news/business-35886456; Clark and Kishan, "Quantum computers entice Wall Street vowing higher returns."

25. Airbus, "Quantum computing using the power of atoms," www.airbusgroup.com/int/en/news-media/corporate-magazine/Forum-87/quantum-computing.html, accessed April 6, 2017.

26. Lockheed Martin, "Quantum," www.lockheedmartin.co.in/us/what-we-do/emerging/quantum.html, accessed April 6, 2017; D-Wave Systems Inc., "Customers," www.dwavesys.com/our-company/customers, accessed April 6, 2017; George Leopold, "Quantum computing center upgrades to focus on AI," *Defense Systems*, August 12, 2016, https://defensesystems.com/articles/2016/08/12/quantum-center-upgrade-lockheed-usc.aspx.

27. Chris Jennewein, "SPAWAR testing military applications of quantum computing," *Times of San Diego*, April 25, 2016, http://timesofsandiego.com/tech/2016/04/25/spawar-testing-military-applications-of-quantum-computing/.

28. NASA, "Quantum computing," www.nas.nasa.gov/projects/quantum.html, accessed April 6, 2017.

29. Jack Clark, "Alibaba secures data centers with quantum research lab," *Bloomberg Technology*, July 30, 2015, www.bloomberg.com/news/articles/2015-07-30/alibaba-secures-data-centers-with-quantum-research-lab.

30. Nick Statt, "Google is working to safeguard Chrome from quantum computers," *Verge*, July 7, 2016, www.theverge.com/2016/7/7/12120280/google-chrome-canary-quantum-computing-encryption-new-hope; Tom Simonite, "Google's quantum dream machine," *MIT Technology Review*, December 18, 2015, www.technologyreview.com/s/544421/googles-quantum-dream-machine/.

31. Cliff Saran, "IBM develops quantum as a service," *ComputerWeekly*, May 4, 2016, www.computerweekly.com/news/450295510/IBM-develops-quantum-as-a-service.

32. DNA SEQ alliance, "About us," www.dna-seqalliance.com/about-us, accessed April 6, 2017.

33. Fred Lambert, "Musk: Tesla Gigafactory will produce cells with 'moderate' battery technology improvement over current products," *Electrek*, December 15, 2015, https://electrek.co/2015/12/15/musk-tesla-gigafactory-will-produce-cells-with-moderate-battery-technology-improvement-over-current-products/.

34. Lamont Wood, "The clock is ticking for encryption," *ComputerWorld*, March 21, 2011, www.computerworld.com/article/2550008/security0/the-clock-is-ticking-for-encryption.html.

35. Dan Goodin, "NSA preps quantum-resistant algorithms to head off crypto-apocalypse," *Ars Technica*, August 21, 2015, http://arstechnica.com/security/2015/08/nsa-preps-quantum-resistant-algorithms-to-head-off-crypto-apocolypse/; Bruce Schneier, "NSA plans for a post-quantum world," Schneier on Security, August 21, 2015, www.schneier.com/blog/archives/2015/08/nsa_plans_for_a.html.

36. Simonite, "Google's quantum dream machine."

37. *Economist*, "Quantum computing," May 5, 2016, www.economist.com/news/science-and-technology/21698234-ibm-making-quantum-computer-available-anyone-play-now-try.

38. Intel, "Intel invests US$50 million to advance quantum computing," September 3, 2015, https://newsroom.intel.com/news-releases/intel-invests-us50-million-to-advance-quantum-computing/.

39. HP, "Areas of interest," www.hpl.hp.com/research/qip/areas.html, accessed April 6, 2017.

40. Microsoft, "Quantum Architectures and Computation Group (QuArC)," www.microsoft.com/en-us/research/group/quantum-architectures-and-computation-group-quarc/, accessed April 6, 2017.

41. Nokia Bell Labs, "Overcoming the physical and computational limits of conventional computing," www.bell-labs.com/our-research/disciplines/quantum-computingcommunications/, accessed April 6, 2017.

42. Raytheon, "Quantum information," www.raytheon.com/capabilities/products/quantum/, accessed April 6, 2017.

43. Examples include Rigetti Computing, Sparrow Quantum, IonQ, Quantum Circuits Inc., Cambridge Quantum Computing, QxBranch, QC Ware, and 1Qbit.

44. Castelvecchi, "Quantum computers ready to leap out of the lab in 2017."

45. Michael Cruickshank, "Australian scientists make quantum computing breakthrough," *Manufacturer*, November 7, 2016, www.themanufacturer.com/articles/australian-scientists-make-quantum-computing-breakthrough/.

46. Nicole Hemsoth, "So, you want to program quantum computers . . .," *Next Platform*, September 14, 2016, www.nextplatform.com/2016/09/14/want-program-quantum-computers/.

47. Jacob Aron, "Revealed: Google's plan for quantum computer supremacy," *New Scientist*, August 31, 2016, www.newscientist.com/article/mg23130894-000-revealed-googles-plan-for-quantum-computer-supremacy/.

48. Natalie Wolchover, "Classical computing embraces quantum ideas," *Quanta Magazine*, December 18, 2012, www.quantamagazine.org/20121218-classical-computing-embraces-quantum-ideas/.

49. Arun Majumdar, "Quantum inspired computing: QuIC," LinkedIn Pulse, April 29, 2015, www.linkedin.com/pulse/quantum-inspired-computing-quic-arun-majumdar.

50. D-Wave Systems Inc., "Applications," www.dwavesys.com/quantum-computing/applications, accessed April 6, 2017.

51. Rohan Pearce, "Behind the Commonwealth Bank's investment in quantum computing," *ComputerWorld*, June 2, 2016, www.computerworld.com.au/article/600879/behind-commonwealth-bank-investment-quantum-computing/.

52. Lily Chen et al., *Report on post-quantum cryptography*, National Institute of Standards and Technology, April 2016, http://nvlpubs.nist.gov/nistpubs/ir/2016/NIST.IR.8105.pdf, p. 7.

53. Tina Amirtha, "Everyday quantum computing is years off—so why are some firms already doing quantum encryption?", ZDNet, June 2, 2016, www.zdnet.com/article/everyday-quantum-computing-is-years-off-so-why-are-some-firms-already-doing-quantum-encryption/.

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