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Exploring quantum computing use cases for electronics

New horizons in discovery, design, and manufacturing

IBM

Foreword

Quantum computing doesn't simply sound complex. It is.

But in electronics, we are no strangers to technical complexity, from design to delivery and now decommissioning as we look toward a more sustainable world. From the smallest semiconductor to satellites orbiting the earth, electronics components are essential building blocks of technology.

While we've seen unprecedented advancements in devices and machines, the complexity facing electronics manufacturers is not diminishing—it's growing. *We need new approaches to solve the Herculean challenges in electronics design, research, and manufacturing.*

For example, dynamic AI systems are poised to supercharge both our lives and the machines that power our interactions. We will need ever more powerful chips, ones that may contain as many as 100 billion transistors. We need to examine scheduling and supply chain optimization at global scale. And of utmost importance: we must develop new, readily available materials that are earth friendly.

Quantum computing may be a change agent. To explore the possibilities, IBM began offering open access to an online 5-qubit quantum computer back in 2016.[1] Fast forward to 2022 and we're continually accelerating and scaling the growth of quantum computing and exploring applicable use cases. We're bringing together some of the world's leading electronics companies to collaborate on solutions through the IBM Quantum Network. IBM is gratified and humbled to work with industry giants such as Samsung Advanced Institute of Technology, Toshiba, Sony, Hitachi Ltd., LG Corporation, and others.[2]

The future starts now. We look forward to creating it with you.

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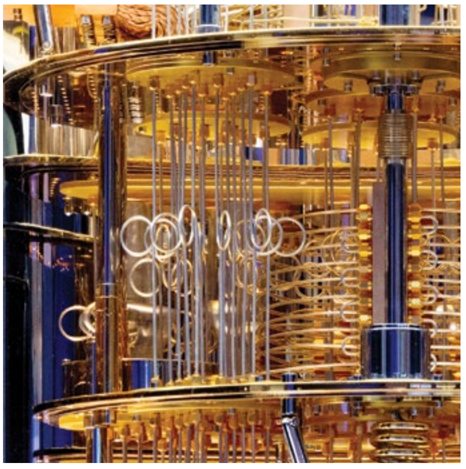


Key takeaways

Quantum computing may help the electronics industry address performance and cost challenges in 3 major areas.

Higher-performance products with advanced materials

It can take decades to develop advanced materials that help achieve new performance levels in electronics products and even entirely new classes of products. Quantum computing may complement classical computing to perform faster, more accurate simulations that may accelerate the commercialization of new materials.

Better designs, faster time to market

Electronic designs have grown so complex that companies face a terrible trade-off: They can either spend more valuable time finding better designs and checking errors while delaying product releases, or they can release products earlier but with potentially less optimal designs and costly bugs. Quantum computers may help companies optimize and verify their designs more rapidly and thoroughly while getting to market faster.

Smarter manufacturing with smarter AI

In electronics manufacturing, quantum machine learning may help distinguish acceptable products from defective products more accurately than classical AI. That may help to lower manufacturing costs and create more reliable products.

A new computing paradigm

The electronics industry faces a number of growing challenges—the cost of the latest generation of semiconductor manufacturing facilities is as much as $25 billion.[3] The design of electronics products grows more complex while expansion in some of the largest traditional markets, such as smartphones, is leveling off.[4]

And as design and manufacturing have become increasingly difficult over the past 50 years, the industry's performance improvements have slowed down.

In brief, the industry's current path is becoming more challenging, risky, and expensive. And this will be felt beyond electronics: as an enabling technology, electronics are used by practically every industry.[5] The electronics industry's responses to its challenges today could impact almost every sector of the global economy.

Quantum computing is a fundamentally new computing paradigm (see "Perspective: The basics" on page 3). It leverages phenomena that simply do not exist in classical physics—which, in turn, can enable computation that hasn't been possible to date. That may offer the electronics industry a powerful tool to help tackle some of its biggest problems.

Just as IBM has been innovating chip technology for decades,[6] we have also been at the forefront of quantum computing. In 1981, IBM co-hosted the first conference on quantum computing.[7] In 2016, IBM was the first to make quantum computers publicly available.[8] By providing access to quantum computers, IBM has enabled researchers and developers around the world to innovate new quantum algorithms and accelerate advances in quantum computing.

We now have entered the Quantum Decade.[9] With IBM's quantum computing roadmap, organizations can plan for the technology's future capabilities (see Figure 1 on page 4).

Perspective

The basics[10]

Classical computer bits can store information as either a 0 or 1. But as scientists were able to explore subatomic matter, they began to see very different behavior, such as particles that are in 2 locations at the same time, and pairs of particles mysteriously linked no matter how far apart they were. The field of quantum physics emerged to explore and understand these phenomena.

The power of quantum computing leverages several aspects of physics. Two of the most important are superposition and entanglement. The principle of superposition allows a quantum computer to represent and compute upon multiple states simultaneously. Entanglement means the combined state of the quantum bits (qubits) contains more information than the qubits do independently.

Entanglement has no classical analogy and modeling it on a classical computer would require exponential resources. For example, representing the complexity of a 100-qubit fully entangled quantum computer would require more classical bits than there are atoms on the planet Earth.

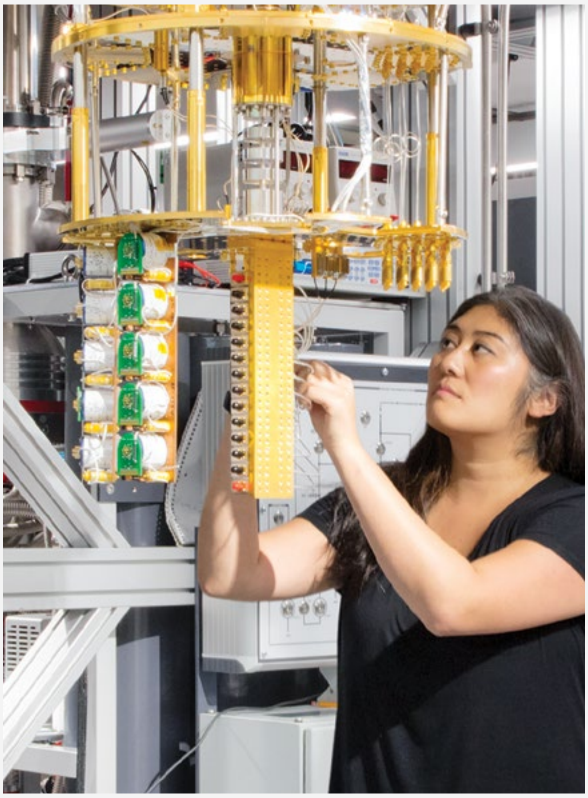
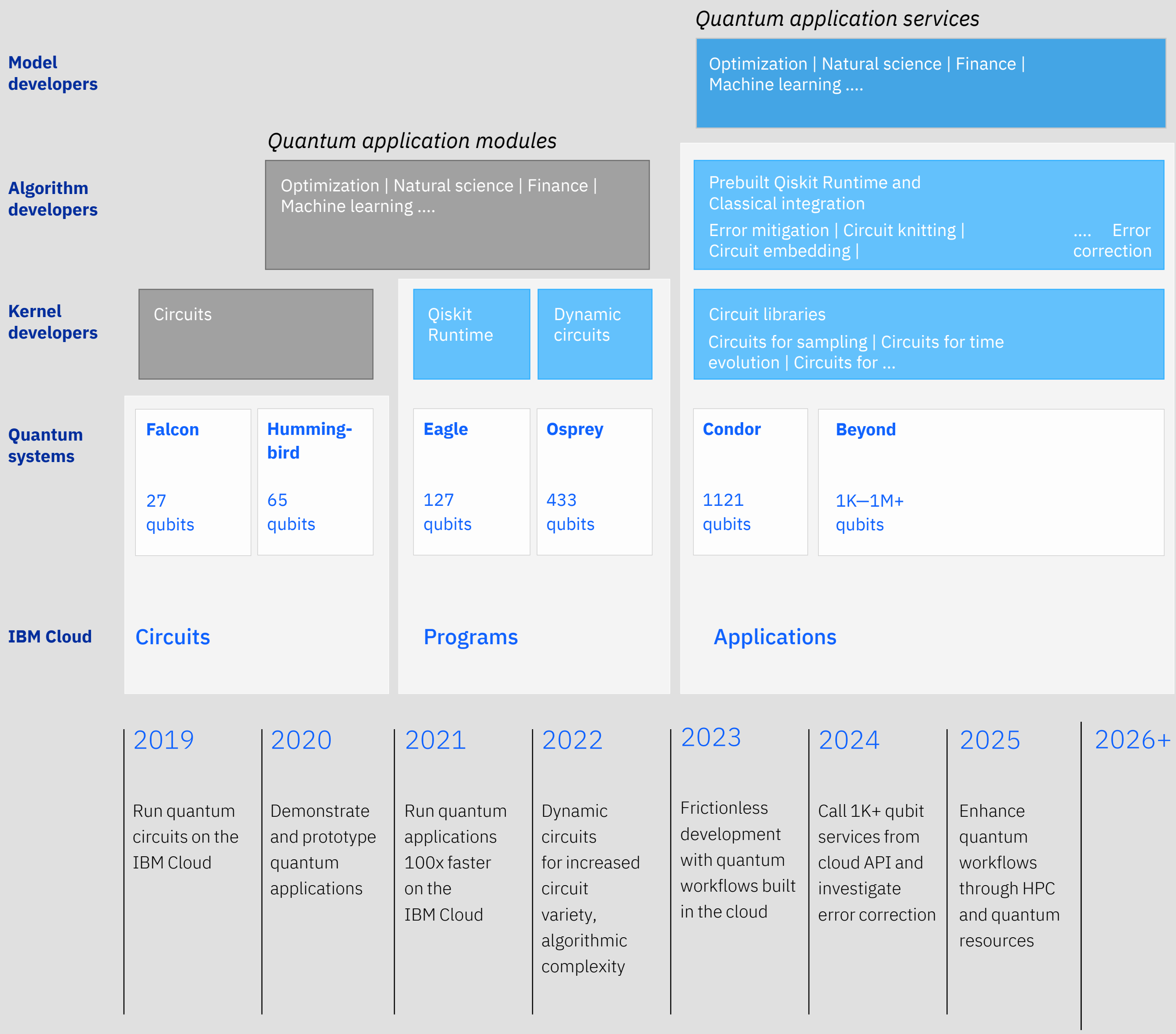


FIGURE 1

The IBM quantum computing roadmap

Recent progress and looking ahead



As competitive business advantage looms, quantum computing has been gaining traction. Leaders who aren't learning more about quantum computing—and how it can impact their operations—could find themselves falling behind. While quantum computing quickly evolves, much of the early intellectual property may be proprietary. Quantum computing ranked among the top 5 fastest-growing areas for patent filings among more than 3,300 areas of patent activity from 2017 to 2021.[11] With quantum computing, there can be few fast followers.

Quantum computing may help the electronics industry address its challenges in many ways. In this report, we provide 3 examples, or use cases (see Figure 2), to illustrate quantum computing's potential for the electronics industry in 3 major application areas—chemical simulation, optimization/search, and AI/machine learning. Use cases include:

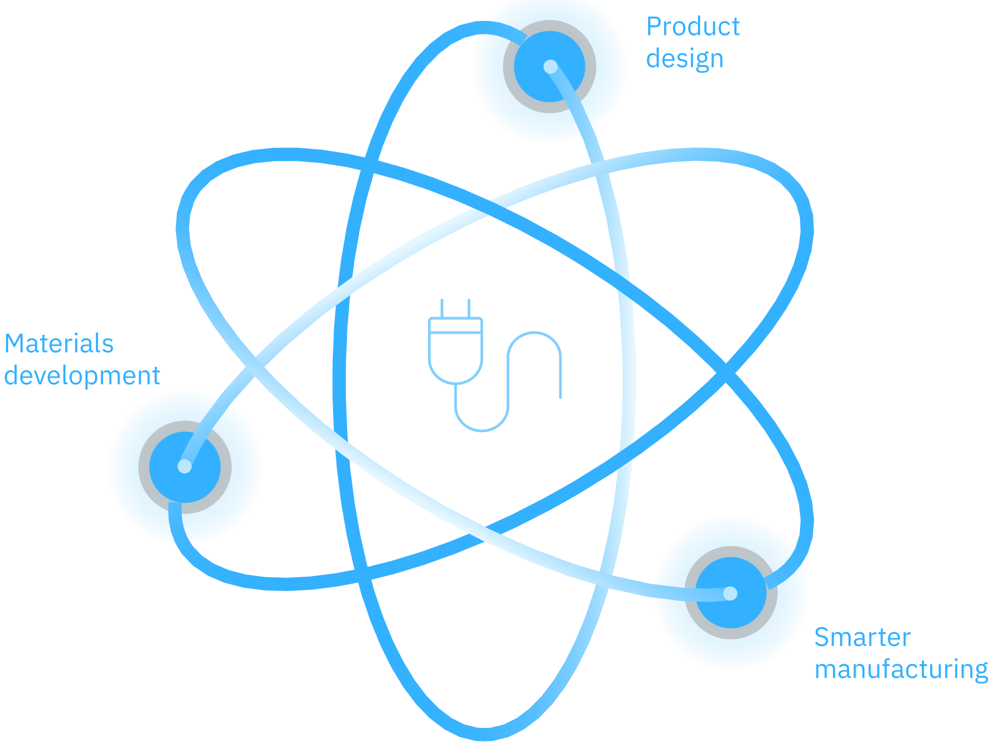
1. *Materials development.* Advancing discovery and commercialization with quantum simulation

2. *Product design.* Accelerating development and verification with quantum search

3. *Smarter manufacturing*. Helping to improve yields and reduce costs, while improving quality with quantum machine learning

FIGURE 2

Quantum computing use cases for electronics



Use case 1

Materials development—Advancing discovery and commercialization with quantum simulation

The design and manufacturing improvements that enabled the electronics revolution over the past 50 years have been slowing down. The world's most powerful supercomputers were able to increase their performance capability 80% every year. Now it's 40%.[12] That's partly because the era of simply shrinking the transistor to improve computer performance is ending.

The electronics industry has sought other ways to boost computational performance, including new materials such as copper interconnects and chemically amplified photoresists, both pioneered by IBM.[13] But classical computers struggle to simulate materials. As a result, materials development has had to rely on time-consuming and costly traditional lab research methods.

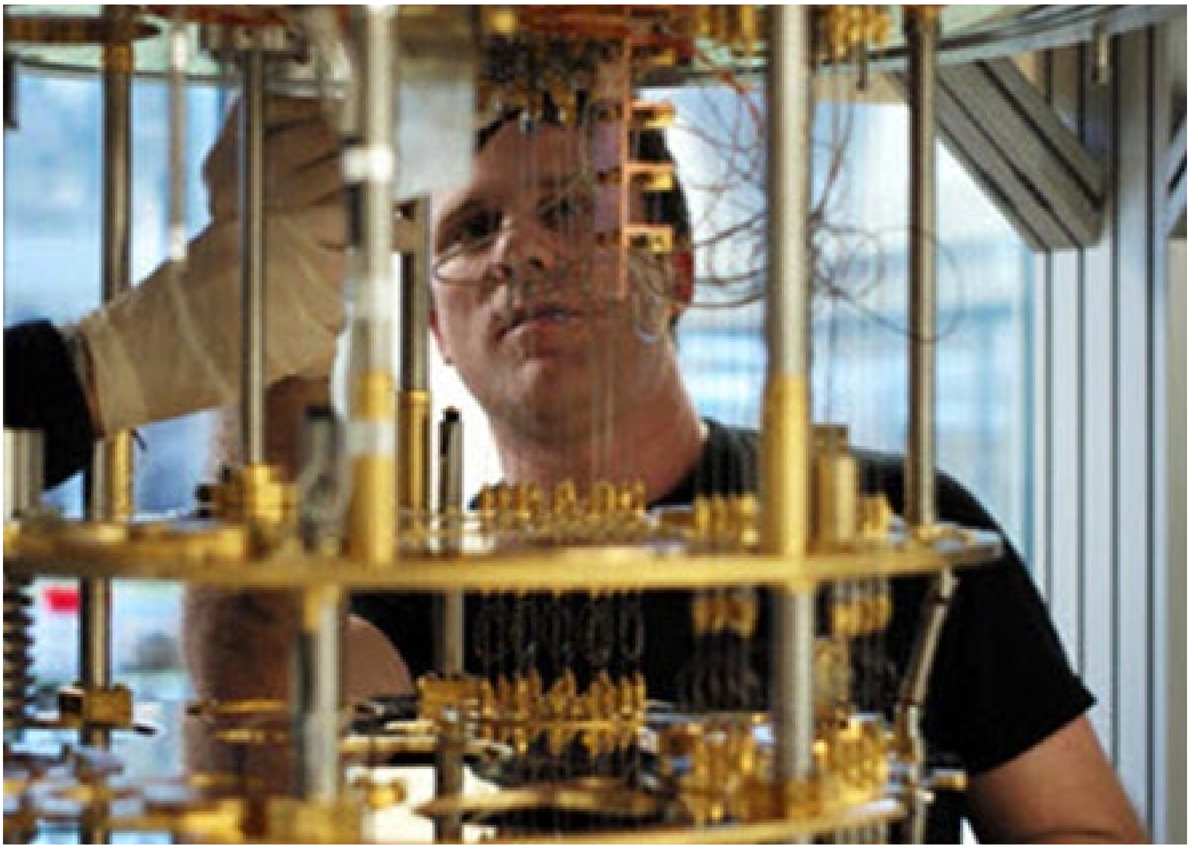
Take this example: Flat-panel displays, the primary interfaces between us and our smartphones, drain power and quickly exhaust batteries. A more efficient display could be possible with a more efficient light emitter. Yet that would require new materials, which take a long time to develop. For organic light-emitting diodes (OLED), now common on smartphones, it was 35 years from the first paper about the technology to the first OLED display.[14]

Let's also consider 2-dimensional transition metal dichalcogenides (TMDs)—atomically thin materials that have attracted significant interest in their potential to increase transistor performance while reducing power consumption. The chemistry and physics of TMDs are best described using quantum mechanics, which is challenging for classical computers—but a natural match for quantum computers.

One reason that materials development is such a long haul: classical computers have difficulty simulating materials. Simply representing a material in a classical computer is challenging. To exactly represent a single molecule from one family of light emitters, a classical computer would need 10^{106} bits. That exceeds the number of atoms in the universe (approximately 10^{84}) many times over. By contrast, a quantum computer could represent the same molecule using just 354 logical qubits. Moreover, a quantum computer can manipulate this compact representation of a light emitter to predict interesting properties, such as its electronic structure and the color it generates.[15]

The quantum capability to model new materials has wide application. IBM is using quantum computers to model more environmentally friendly chemicals for electronics manufacturing.[16] And IBM has worked with Mercedes-Benz Daimler to perform quantum simulation of battery chemistry.[17]

Another case in point: Current light emitters have an internal efficiency of up to 25%. IBM, JSR Corporation, and Mitsubishi teamed together to model OLED light emitters with the potential for 100% internal efficiency.[18] An OLED display made from these emitters could have substantial power efficiency advantages—and valuable market advantages. Just a 1% increase in the OLED display market is worth $320 million per year.[19]



Use case 2

Product design—Accelerating development and verification with quantum search

Design and manufacturing in the electronics industry are areas of intense competition. The goal: products that perpetually perform better, cost less, and are bug free. This takes time, yet the team that gets its product to market first enjoys significant advantages.

Quantum optimization may help product development teams develop higher-performing designs more quickly. In electronics, this has a multitude of applications. Imagine finding the fastest route for moving packets of data around a network. Or calculating the most profitable product mix and production schedule for an electronics manufacturing plant. Or identifying the shortest wiring route for 10 billion transistors on a chip.

Solving these sorts of optimization problems has long challenged classical computers. But finding the optimal solution has the potential to result in huge market advantages. A microprocessor with shorter wire lengths can simultaneously result in both lower power consumption and greater compute performance. In the smartphone application processor market, a particularly power-sensitive market, a 1% increase in market share would translate into an additional $290 million per year.[20]

One challenge these optimization problems pose to classical computers: there are far too many possible solutions. For example, finding the shortest path between just 10 points requires finding the best solution among over 3 million feasible paths. However, quantum computers have the potential to complement classical techniques by finding the solution to these optimization problems more efficiently. This may help product design teams find higher-performing designs more quickly and get a better product to market faster.

Another example of this capability is design verification. Imagine spending 2 days of each week doing your work and the other 3 days checking your work. That's more time verifying than executing—a slow and inefficient process.

And yet, too often that's precisely what happens with electronic design. Microchips, for example, have grown so complex that more of the product cycle time (60%) is spent verifying chips than actually designing them.[21] Unfortunately, a chip released with an undiscovered bug can deliver a huge blow to a company's bottom line.[22] Software is now part of nearly every product. And like microchips, software has become so complex that complete verification isn't possible. For some products, like a music player, a software bug might simply be a nuisance. But for other products, such as biomedical devices, undiscovered software bugs have the potential to literally be a matter of life and death. One study shows that 64% of biomedical device recalls are due to software faults—the top cause of biomedical device recalls.[23]

A powerful design verification method employs Boolean satisfiability solvers, also known as SAT solvers. Like many optimization problems, SAT solving can be challenging for classical computers. Quantum methods to SAT solving are being explored to search large, complex design spaces and increase the probability of finding unknown bugs.[24] The aim is to help design teams more quickly verify designs, develop a more reliable product, and get it to the finish line faster.

Use case 3

Smarter manufacturing—Helping to improve yields and reduce costs with quantum machine learning

Smart factory initiatives and digital transformation are increasingly priorities for manufacturing operations, driving competitiveness and resiliency into the 2020s.[25] AI can play a central role in this transformation, but classical AI is hitting its limits.

One example: to keep costs low and yields high, electronics manufacturing facilities must quickly and accurately identify defective products. Classical AI has been employed for product inspection and brings benefits such as speed and consistency to the process. But its accuracy is still far from ideal. Inspection AI has a high false-positive rate, meaning it too often flags products as bad when they're actually good. There's little point in having a superfast machine if it's often wrong.

For silicon wafers, automated optical inspection has false-positive detection rates ranging from 10% to 15%—which are far too high.[26] A 10% loss of wafers at a 5-nanometer facility would be a loss equivalent to $8 billion per year.[27]

Classical AI's ability to distinguish good products from bad has some fundamental limits. In one analysis, the best error rate for image classification on the ImageNet dataset was 11% at a cost of $1 million.[28] To achieve fully automated AI product inspection, the error rate must be brought to below 1%. But, if we extrapolate current trends in classical AI, getting an 11% error rate down to 1% would cost *$100 billion billion*. (That's not a typo: $100 billion billion.) What's more, that process would produce 1 million times more carbon dioxide than the entire planet emits.[29]

But we can now see beyond classical computing. We can glimpse quantum computing's potential to create smarter AI.

When IBM researchers compared quantum neural networks to classical ones with the same number of degrees of freedom, they demonstrated that—on some datasets—quantum neural networks can be more accurate and learn faster than classical neural networks.[30] Moreover, quantum machine learning models have the potential to achieve lower error rates with less data.[31]

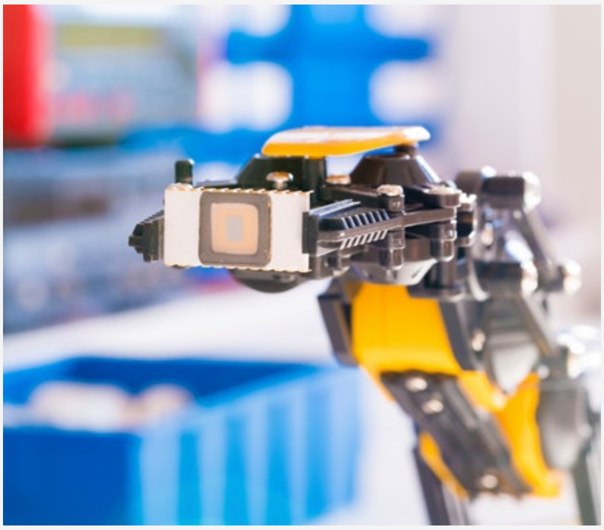
A more accurate AI that can learn faster with less data has many possible applications. In data networks, a more accurate AI can more reliably identify security threats. In biomedical electronics, a more accurate AI could help medical teams more reliably identify tumors in MRI images. In electronic design, an AI that learns faster with less data could identify better designs more quickly, particularly at new process nodes when design data is scarce. And, because electronics companies continuously refresh products, they must also continuously refresh manufacturing. Improvements in time-to-market and data are rare and precious commodities. Quantum AI could help these electronics manufacturers get new products to market faster, with greater yields and at lower costs.[32]

Perspective

Quantum Advantage[33]

Quantum Advantage occurs when a computing task of interest to business or science can be performed more efficiently, more cost effectively, or with better quality using quantum computers. This is the point where quantum computers plus classical systems can do significantly better than classical systems alone. As hardware, software, and algorithmic advancements in quantum computing coalesce, enabling significant performance improvement over classical computing, new opportunities for advantage will emerge across industries. But prioritizing the right use cases—those that can truly transform an organization or an industry—is critical to attaining business value from quantum computing.

Getting to Quantum Advantage will not happen overnight. But while that advantage may progress over months and years, it can still trigger exponential achievements in usage and learning. From exploring the creation of new materials to personalized medical treatments to radical shifts in business models across the economy, change is coming. Organizations that enhance their classical computing capabilities and aggressively explore the potential for industry transformation will be best positioned to seize Quantum Advantage.



Action guide

Quantum computing holds the potential to deeply disrupt today's electronics industry. But let's be clear: Quantum computing isn't intuitive or easy. It takes time and resources to understand and leverage this technology.

Furthermore, it's important to understand that it's not a classical versus quantum proposition. In developing competitive advantage, it is far more strategic to combine the complementary strengths of both computing technologies. This requires mastering not only quantum computing, but also the complex interaction between classical and quantum computing.

Indeed, it can take a few years—or more—from an organization's initial investigation of quantum computing to actual readiness for implementation. In business, a few years can be a lifetime. Taking a wait-and-see approach could mean the difference between being disrupted and being the disruptor.

Here are some ways to enable quantum readiness today:

Develop internal expertise so you can make informed decisions

The learning curve for quantum computing is steep and can take years to master. Quantum computing talent is scarce, so much of the expertise may need to be developed in-house. Identify and upskill both technical and business people inside your organization who can form your quantum computing team. Build capabilities to strategize around this technology in the context of your organization's objectives and constraints.

Identify your most critical and compelling use cases

Highlight the ways your organization could not only benefit from quantum computing but also be threatened by it. With your use cases identified, you can also estimate the time pressure to act.

Translate your use cases into proofs of concept, providing the opportunity to explore quantum computing and learn how it fits into your strategies

Partner with quantum computing experts to develop prototypes. Obtain access to the quantum computing hardware and software platforms you'll need. Experiment with quantum computing code in a scalable fashion, so that when quantum computers are ready, so is your code.

Rethink your core workflows.

Identify the steps in your workflows that can benefit from Quantum Advantage. Understand how quantum and classical workflows and dataflows can intersect. Learn how quantum and classical computing can be combined to leverage each other. And employ design thinking to help you examine your end-to-end processes, so you can make the most of quantum computing's potential.

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