Coming soon to your business – Quantum computing

Five strategies to prepare for the paradigm-shifting technology

IBM Institute for Business Value

In this report

Details about the potentially revolutionary business impact of quantum computing

Why your enterprise may need to act now

A five-step roadmap toward achieving quantum-enabled business advantage

How IBM can help

IBM is building the first universal quantum computers for business and science. IBM Q Experience and Qiskit enable free access to IBM's quantum computers, simulators, educational resources and a collaborative community engaged in exploring quantum computing. Organizations that join the IBM Q Network can collaborate and access more advanced technologies, including larger IBM Q quantum systems via the IBM Cloud. IBM Q Consulting helps clients define their quantum strategies mobilizing consultants, quantum scientists and industry experts to define how high performance and quantum computing can create an advantage. For more information, please visit **ibm.com**/ibmq.

Taking the quantum leap

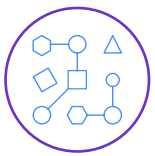
Quantum computing is nearing a phase of commercialization that may change our world. Early adopters of quantum's unique ability to solve certain types of problems may achieve breakthroughs that enable new business models. Visionary organizations are already aligning with the emerging quantum computing ecosystem to become "quantum ready." These forward-thinking enterprises are exploring use cases and associated algorithms that address complex business problems. This report discusses the paradigm shift that quantum computing represents for business, explains why your enterprise may need to act now, and provides five recommendations to advance your organization down the path of quantum-enabled business advantage.

What is quantum computing?

Quantum computing takes advantage of the laws of quantum mechanics found in nature and represents a fundamental change from classical information processing. Two properties of quantum behavior – superposition and entanglement – may allow quantum computers to solve problems intractable for today's conventional, or classical, machines:

- *Superposition.* A classical computer uses binary bits that can only depict either a "1" or a "0." Instead, quantum computers use qubits that can depict a "1", a "0", or any combination (or "superposition") of the qubits' possible states. Therefore, a quantum computer with n qubits can have all 2^n possibilities in superposition with one another. This supplies quantum computers with an exponential set of states they can explore to solve certain types of problems better than classical computers.
- *Entanglement.* In the quantum world, two qubits located even light-years apart can still act in ways that are strongly correlated. Quantum computing takes advantage of this entanglement to encode problems that exploit interdependence between qubits.

The quantum properties of superposition and entanglement help enable quantum computers to rapidly explore an enormous set of possibilities to identify an optimal answer that could drive business value. As future quantum computers can calculate certain answers exponentially faster than today's classical machines (see Figure 1), they will enable tackling business problems that are exponentially more complex. Despite classical computers' limitations, quantum computers are not expected to replace them in the foreseeable future. Instead, hybrid quantum-classical architectures are expected to emerge that "outsource" portions of difficult problems to a quantum computer.



To double the theoretical power of a classical computer, you need to double its number of transistors. To double the theoretical power of a quantum computer, you need to add only one additional qubit for some applications.

A future quantum processor could simulate a caffeine molecule – this would require a gargantuan conventional computer larger than 10 percent of the size of the earth.

Near-term quantum computers may help design new materials that create even more powerful quantum computers in the future.

Figure 1

Quantum computing's potential for significant speedup over classical computers[1]

Type of scaling	Time to solve problem				
Classical algorithm with exponential runtime	10 secs	2 mins	330 years	3300 years	Age of the universe
Quantum algorithm with polynomial runtime	1 min	2 mins	10 mins	11 mins	~24 mins

Quantum computing appears set to potentially transform certain industries. For instance, current computational chemistry methods rely heavily on approximation because the exact equations cannot be solved by classical computers. But, quantum algorithms are expected to deliver accurate simulations of molecules over longer timescales, currently impossible to model precisely. This could enable life-saving drug discoveries and significantly shorten the number of years required to develop pharmaceuticals.

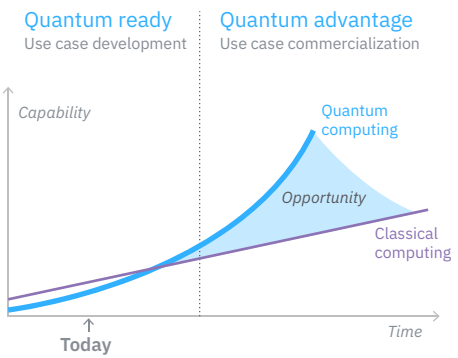
Additionally, quantum computing's anticipated ability to solve today's impossibly complex logistics optimization problems could drive considerable cost savings and carbon footprint reduction. For example, consider improving the global routes of the trillion-dollar shipping industry. If quantum computing could improve container utilization and shipping volumes by even a small fraction, this could save shippers hundreds of millions of dollars. To profit from quantum computing's advantages ahead of competitors, forward-looking businesses are already developing expertise to explore which use cases may benefit their own industries.

The dawn of quantum advantage

The time when quantum computers can solve some business problems that classical computers cannot – often called quantum advantage – appears close at hand. For example, "constant-depth" quantum circuits have already been demonstrated to be more powerful than their classical counterparts.[2] Figure 2 illustrates what quantum advantage could look like for a particular business use case. Precisely when quantum advantage will occur for a specific use case is uncertain, causing market forecasts to vary widely over the next five years – from approximately USD 500 million to as much as USD 29 billion.[3]

Development of the quantum computing ecosystem is accelerating, in anticipation of the opportunities the new technology will create. Startups and partnerships between researchers and technology providers are springing up to translate quantum research into capabilities suited to the business world. Technology firms developing quantum computers are already partnering with businesses to identify potential use cases, develop quantum algorithms and test solutions on actual quantum computers. This quickly growing engagement of businesses with quantum technology will hasten the arrival of the first commercial applications.

Figure 2
Commercialization of a quantum use case



Quantum – The smallest amount or unit of something, especially energy.[4]

Selecting the right quantum computer for your business

Not all quantum computers are created equal, nor do they solve the same problems. From the most limited to the most versatile, quantum computers are typically classified into three categories: quantum annealing, noisy intermediate-scale quantum (NISQ) computing,[5] and fault-tolerant universal quantum computing.

The consensus of the scientific community is that quantum annealing will not offer a meaningful speed-up over classical computing.[6] Furthermore, quantum annealers are not on the development path that leads to fault-tolerant universal quantum machines. As a result, quantum annealers cannot be considered true quantum computers.

In the near term, NISQ computers have the best potential to deliver business advantage and many new algorithms are being adapted for them. Moreover, as NISQ computers scale up, they progress toward the ultimate goal of quantum computing – a fault-tolerant universal quantum computer that can handle important classes of business and scientific problems often exponentially faster than a classical machine.

Future shock – Why your organization may need to act now

Why tackle quantum computing now? Technological and competitive forces are ushering in the quantum age sooner than you might expect. Organizations paying attention today could take industry leadership away from those who are not. Here are three reasons why businesses are considering getting quantum ready now:

- Quantum computers have the potential to transform industry value chains, particularly in the areas of chemistry, biology, healthcare, materials science, finance and artificial intelligence (AI).
- Due to quantum computing's steep learning curve, a "fast-follower" approach may only produce laggards that have overspent trying to catch up.
- Building an in-house "Quantum Center of Competency" will take time.

Quantum computers have the potential to transform industry value chains

Quantum computers are expected to transform industries because they have the potential to address exponentially complex problems that classical computers cannot. Future quantum computers could help achieve product breakthroughs in areas such as chemistry, biology, healthcare, finance, AI and materials science, enabling rapid market share gains and greater profitability for the visionary companies that adopt them. In this way, quantum computing's problem-solving capabilities could dramatically redefine competitive advantage, transforming business operating models and value chains that revolutionize entire industries.

"When you change the way you look at things, the things you look at change."

Max Planck, father of quantum physics[7]

For example, the optimization of logistic systems is typically based on a "hub and spoke" network model. The problem of optimally designing individual point-to-point routes satisfying various requirements on a large-scale logistic network is very complex and can quickly become out-of-reach for classical supercomputers. If one were to explore all the possibilities in such an optimization problem, it could take billions of years even with just a few hundred terminals in the network. Quantum computing may be able to explore the space of possibilities much quicker. For example, in the context of airline scheduling optimization, quantum computing may be able to create daily ad hoc flight schedules, specifically tailored for the thousands of passengers flying to hundreds of destinations on a specific day, reducing customer travel time, air traffic congestion and airline fuel costs. If an enterprise were to develop a quantum solution for logistic network design optimization, it could swiftly aim to become a market leader in every industry where logistics are critical to success.

A fast-follower approach may only produce laggards that have overspent

Unlike with more linear or incremental technological advancement, a fast-follower approach is less likely to be effective for adopting quantum computing. This is due to:

- Quantum computing's steep learning curve
- Excessive costs associated with "catching up."

Consider a use case that a quantum computer could solve exponentially faster than a classical machine – designing a purpose-built material for the electronics or transportation industries that is significantly lighter and stronger than current substances (see Figure 2). The accelerated development of such a revolutionary material would

position a manufacturer to outflank its competitors in short order. Moving up the learning curve, this newly "quantum-enabled" market leader could quickly gain increasing advantage over competitors by fine-tuning its breakthrough material, as well as by expanding into new materials customized for other applications.

While hypothetical, this example illustrates how a steep learning curve could make it extremely difficult even for so-called fast followers to quickly catch up with first-mover businesses, potentially resulting in "winner-take-all" scenarios in certain industries. Even if catching up were possible for a specific use case, it would likely be associated with extortionate costs related to, for example, buying in-house expertise, procuring access to the best infrastructure, funding advantageous partnerships and/or acquiring a company with the necessary capabilities.

Building an in-house Quantum Center of Competency will take time

Although most businesses have heard about quantum computing by now, many do not have the talent or expertise required to take advantage of its impending business transformation – and acquiring it won't be easy. The supply of quantum computing talent is limited, with fierce competition for skilled resources.

Once the right people are on board, it will likely take years to develop a deep understanding of quantum computing's potential impact on a given business. Recent technological shifts, such as the almost decade-long migration to graphics processing units (GPUs) to accelerate big data workloads, underscore the time it takes to build competency when adopting a new technology.

Given quantum's potential for radical industry transformation, exponential problem-solving capabilities and the difficulty to obtain quantum-skilled resources, leading enterprises should consider acting now.

"Any significantly advanced technology is indistinguishable from magic."

Arthur C. Clarke, futurist and writer[8]

Seizing quantum advantage for your business

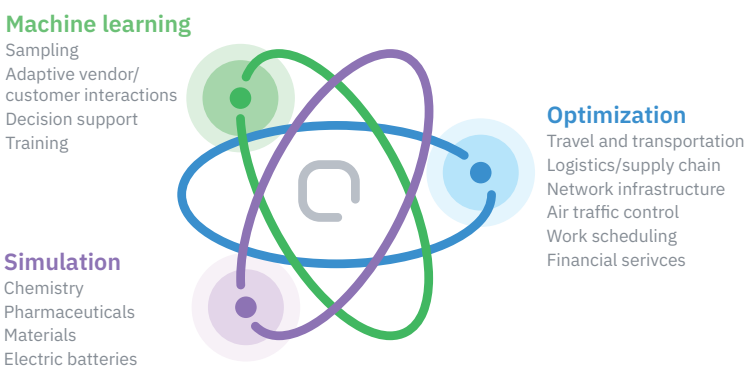
What could the commercialization of quantum computing mean for your business? In the near-to-medium term, quantum computing could confer business benefits in three areas: quantum simulation, quantum optimization and quantum-assisted machine learning (see Figure 3).

Quantum simulation

Because quantum mechanics describes how nature works at a fundamental level, quantum computing is well suited to model processes and systems that occur in nature (see IBM case study on page 9). This potent capability could open the door to electric carmakers developing longer-life batteries. Biotech startups could rapidly develop drugs tailored to an individual patient. The costs of electric power transmission could be reduced. Fertilizer could be manufactured more efficiently, with exciting implications for growing the world's food.

Figure 3

The anticipated uses of NISQ quantum computing



Quantum optimization

The art of solving optimization problems involves finding the best or "optimal" solution in a situation where many possible answers exist. Take the example of building a package delivery schedule. Mathematically, more than 3.6 million possible combinations exist for scheduling ten deliveries in adjacent time slots.[9] But which schedule represents the optimal solution given variables such as timing requirements of the recipients, potential delays and the shelf life of transported goods? Even when applying approximation techniques, the number of possibilities is still far too large for a classical computer to explore.

As a result, classical computers today take extensive shortcuts to solve optimization problems of significant size. Unfortunately, their solutions are often likely suboptimal. Businesses that could benefit from quantum optimization include:

- Telecommunications companies upgrading their network infrastructure
- Healthcare providers optimizing patient treatments
- Governments improving air traffic control
- Consumer products and retail companies tailoring marketing offers
- Financial services firms enhancing their risk optimization
- Organizations developing employee work schedules
- Universities scheduling classes.

IBM researchers simulate the largest molecule ever on a quantum computer

Earning the cover of the September 14, 2017 edition of *Nature*, IBM scientists simulated beryllium hydride (BeH_2), the largest molecule ever simulated on a quantum computer.[10] Using 6 qubits of a 7-qubit IBM Q system, a NISQ computer, researchers were able to measure BeH_2's lowest energy state, a key measurement for understanding chemical reactions. While this model of BeH_2 can be simulated on a classical computer (verifying the quantum computer's results), this achievement is a next step on the path forward for near-term quantum systems to model more complicated chemical reactions. As more powerful quantum systems are built and concomitant tools and techniques are developed, chemistry and the life sciences are expected to experience groundbreaking applications.

JP Morgan Chase explores quantum advantage

Given the abundance of investment vehicles, portfolio combinations and potential financial scenarios, today's financial advisors cannot build and manage a tailored financial portfolio that has evaluated virtually all possible options.

But quantum computers could investigate the universe of investment options, running valuation and risk scenarios tailored to each client's specific performance criteria.

JP Morgan Chase, in collaboration with IBM, is already experimenting with quantum computing in search of quantum advantage in areas including trading strategies, portfolio optimization, asset pricing and risk analysis.[11] The stakes are high. If a financial institution could gain competitive advantage using quantum computing, it could amass billions for both clients and shareholders before the competition is able to catch up.

While no one has yet delivered a mathematical proof confirming that quantum computing will confer an exponential speedup for optimization problems, researchers are working on demonstrating this heuristically. Forward-thinking companies are already exploring solving optimization problems using quantum computing in their quest to leap ahead of competitors. Their foresight may turn to advantage after the first demonstrations of quantum advantage in optimization are confirmed (see JP Morgan Chase case study).

Quantum-enhanced AI

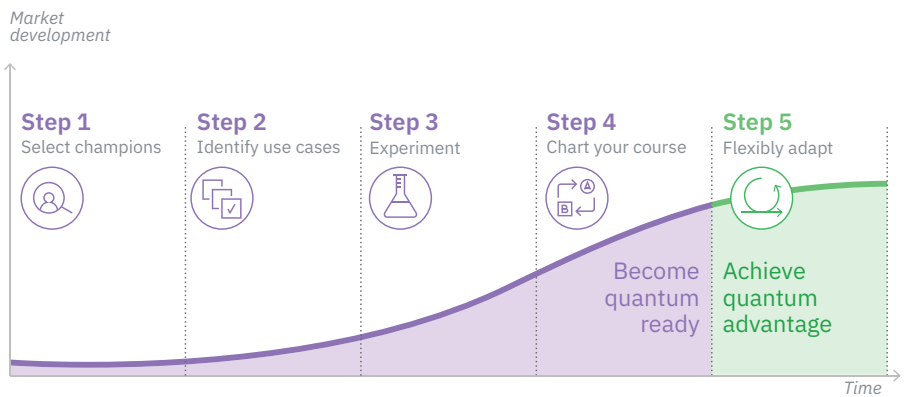
Given its ability to explore a large set of possibilities that a classical computer cannot process, quantum computing could expand the adeptness of AI. In fact, a symbiosis between AI and quantum computing is beginning to spawn a virtuous cycle of advancement in both fields. For example, quantum algorithms can enhance machine learning in the area of data clustering,[12] while machine learning can be used to better understand quantum systems.[13]

Quantum-enabled cognitive computers could eventually pervade virtually all industries, providing professionals with advanced, proactive decision support; employees with targeted, responsive training; and customers with uniquely tailored, adaptive vendor relationships.

Step into your quantum future with these five strategies

Businesses that adopt NISQ early could outflank their peers by dramatically innovating operating models and creating first-of-a-kind products. If you want to be in the vanguard, now is the time for your business to become quantum ready (see Figure 4).

Figure 4
The path to your quantum future



"Nature isn't classical ... and if you want to make a simulation of Nature, you'd better make it quantum mechanical ..."

Richard Feynman, American physicist, 1981[14]

Jumpstart your organization's roadmap to quantum computing

To help your business chart a course to quantum computing adoption, you need to:

- Understand what quantum computing is and how it may impact your industry.
- Identify business challenges where quantum computing may offer competitive advantage.
- Evaluate the potential business value your organization may derive from the application of NISQ computing technology to your business challenges.
- Develop a quantum computing roadmap including next steps that align with your strategic intent.

IBM Q Consulting runs interactive workshops mobilizing consultants, quantum scientists and industry experts to help your organization understand how quantum computing could fit into your business strategy and future growth.[15]

1. Select your quantum champions

Chances are your organization needs to learn more about the prospective benefits of quantum computing. Here's how to get started:

- Designate some of your leading professionals as "quantum champions."
- Charge your quantum champions with understanding quantum computing, its potential impact on your industry, how your competitors are responding, and how your business might benefit (see sidebar).
- Have your quantum champions report periodically to senior management to educate the organization and align progress to strategic objectives.

2. Begin identifying quantum computing use cases and associated value propositions

Once your quantum champions understand how quantum computing works and how it could address your business challenges and opportunities, have them start identifying specific areas where quantum computing could propel your organization ahead of your competitors.

Evaluate opportunities based on the unique capabilities of quantum systems and their ability to accelerate advantage. Have your quantum champions monitor progress in quantum application development to track which use cases may be commercialized sooner. To help ensure that your quantum exploration links to business results, select your most promising quantum computing applications, such as creating breakthrough products and services or new ways to optimize your supply chain.

3. Experiment with real quantum systems
Demystify quantum computing by trying out a real quantum computer (see sidebar). Have your quantum champions get a sense for how quantum computing may solve your business problems and interface with your existing tools. A quantum solution may not be a fit for every business issue. Your champions need to focus on solutions to your highest-priority use cases that classical computers can't practically solve.

4. Chart your quantum course
Construct a quantum computing roadmap, including viable next steps, with the purpose of pursuing problems that could create formidable competitive barriers and sustainable business advantage. To accelerate your organization's quantum readiness, consider joining an emerging quantum community. This can help you gain better access to technical infrastructure, evolving industry applications, and researchers that can enhance your development of specific quantum applications.

5. Be flexible about your quantum future
Quantum computing is rapidly evolving. Seek out technologies and development toolkits that are becoming the industry standard and around which ecosystems are coalescing. Realize that new breakthroughs may cause you to adjust your approach to your quantum development process, including changing your ecosystem partners. Be aware of how your own quantum computing needs may evolve over time, particularly as you improve your understanding of which business issues can benefit most from quantum computing solutions.

Try out a quantum computer

The IBM Q Experience and Qiskit enable free access to IBM's 16-qubit quantum computers, simulators, educational resources and a collaborative community engaged in exploring quantum computing.[16] Quantum algorithms and experiments are developed using a Python-based, open-source programming framework called Qiskit. Resources available include Jupyter notebook tutorials that solve simulation and optimization problems[17] and over 120 research papers that tackle topics such as discovering new applications for quantum computing and building new functionality, like quantum compilers. Experts in chemistry, AI and optimization, who are unfamiliar with quantum computing, can use Qiskit Aqua, an open-source extensible library of quantum algorithms to research real world applications. To date, more than 100,000 users from enterprises and educational institutions on seven continents (including Antarctica) have run over 6.5 million quantum experiments on the IBM Q Experience via the IBM Cloud.

Join an emerging quantum computing community

Partnerships between technology providers and visionary organizations are expanding. Their aim is nothing short of developing quantum computing use cases and corresponding applications that solve previously intractable real-world problems. The IBM Q Network is a global ecosystem of Fortune 500 companies, leading academic institutions, startups and national research labs, enabled by IBM's quantum computers, scientists, engineers and consultants. Participants collaborate to accelerate advancements in quantum computing that can produce early commercial applications.[18]

Organizations that join the IBM Q Network can experiment with how their high-value problems map to a real quantum computer. Today, they can access a 20-qubit IBM Q quantum processor via the IBM Cloud. In the future, a 50-qubit quantum computer will be available.

Is your organization poised to capture quantum advantage?

There are business problems that classical computers cannot solve – and never will. Now is the time to get quantum ready to position your company for future quantum advantage:

What is the current level of awareness and knowledge regarding quantum in your organization?

How might your industry, and specifically your value chain, be disrupted by quantum computing?

What simulation, optimization or machine learning problems are central to your company's competitive advantage?

Which quantum computing use cases would deliver the highest business and competitive value to your enterprise?

What if your competitors capitalize on quantum solutions before you do?

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Methodology

In addition to a comprehensive review of published research papers and articles, we interviewed IBM executives, scientists, researchers, offering managers and consultants working on IBM Q for this report. We also spoke with subject-matter experts in quantum startups, venture capital firms, universities and quantum technology platform providers.

Related reports

Sutor, Robert and Heather Higgins. "Taking the quantum leap: Why now?" IBM Institute for Business Value. February 2018. ibm.biz/whyquantum

Rjaibi, Walid, Sridhar Muppidi and Mary O'Brien. "Wielding a double-edged sword: Preparing cybersecurity now for a quantum world." IBM Institute for Business Value. July 2018. ibm.biz/quantumsecurity

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Notes and sources

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