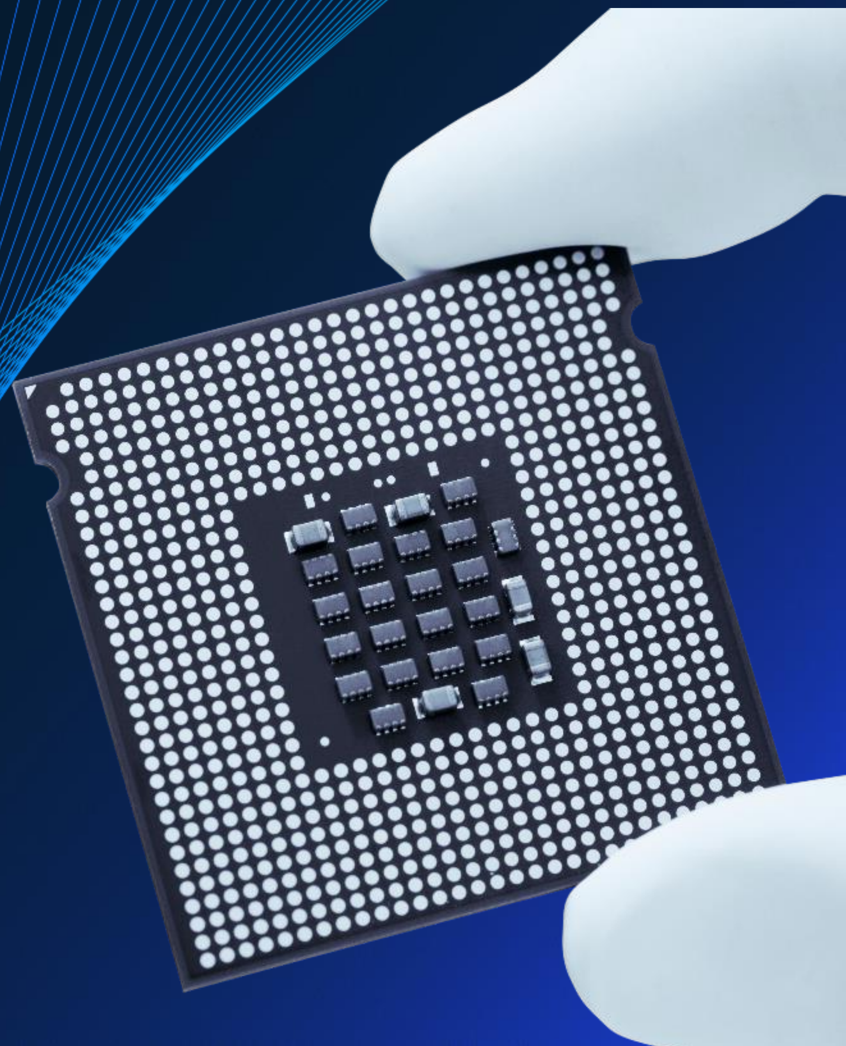
McKinsey & Company

McKinsey Technology Trends Outlook 2022

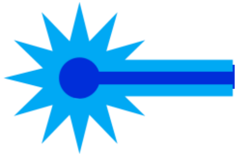
Quantum technologies

August 2022

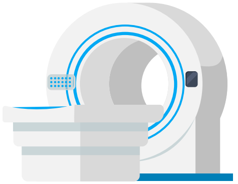


What are the most noteworthy technologies?

Quantum technology has been around for a long time …



Lasers work using the quantum mechanical effect known as *stimulated emission*

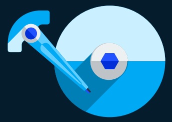


Magnetic resonance imaging uses the quantum phenomenon known as *magnetic resonance*

Source: McKinsey analysis

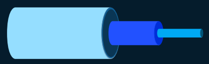
… but a few emerging technologies merit our focus now

These futuristic technologies aspire to change our computational, networking, and sensory infrastructure in the coming decades, unlocking use cases and capabilities previously unimaginable



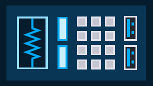
Quantum computing uses quantum properties of particles to process information at a much higher rate than a classical computer can

For some computational problems, quantum technology could make computation exponentially faster than with classical computers



Quantum communication is the transfer of encoded quantum information between distant locations based on an optical fiber network or satellites

A central feature is the quantum-secure connection through quantum encryption



Quantum sensing could provide measurements of various physical quantities at a sensitivity that is orders of magnitude higher than classical sensors can achieve

Applications include radar, microscopy, and magnetometers

Why should leaders pay attention?

The quantum age is just over the horizon …

$300 billion–$700 billion

Conservative estimate of the value at stake of quantum use cases in industries such as automotive, chemicals, finance, and pharmaceuticals

Rapid acceleration in investments

$1.7 billion

Investment in quantum start-ups in 2021, more than double the amount in 2020

Technology approaching maturity

<10 years

Estimated timeline to unlock several of the currently identified use cases as the technology matures and scales

Market expected to grow rapidly

~$10 billion

Projected market size of quantum-computing services in 2027, up from ~$400 million in 2020, growing at 50% per year

However, quantum technology is still very much in its nascent phase, and it would be difficult to predict when or if this technology will mature and scale up

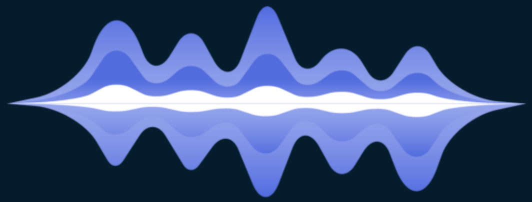
Source: *Worldwide quantum computing forecast*, 2021–25, IDC, Nov 2021; *Quantum computing: An emerging ecosystem and industry use cases*, McKinsey, Dec 2021; Frank Arute et al., “Quantum supremacy using a programmable superconducting processor,” *Nature*, 2019, Volume 574, pp. 505–10 (2019)

Why is quantum computing interesting compared with what already exists?

	Classical computer	Quantum computer
Information storage	Information is stored in *bits,* where each bit can be either 0 or 1 (Bit: 0, 1)	The information is stored in *qubits* (quantum bits), where each qubit represents **any possible combination** of 0 or 1 with each other (Qubit: 0, 1)
Computation	Results can be read **directly from the bit string** of 0s and 1s	Results of the computation are retrieved via **statistical analysis** of repeated quantum measurements
Performance	The performance scales **linearly** with the number of bits	The performance may scale **exponentially** with the number of qubits for certain problems
Pros and cons	+ Good for general-purpose computing + Mature technology with low error rates + Robust and cost-effective − Cannot scale well for certain problems	− Cannot perform general-purpose computing − Nascent technology with high error rates − Currently requires expensive specialized infrastructure + Good at solving certain specific problems

Source: McKinsey analysis

Why is quantum communications interesting compared with what already exists? (continued)



The **ambition** of quantum communications is to offer transfer of encoded quantum information between distant locations through a universal quantum-communication network

Quantum communications enables major applications

Enhanced security based on quantum mechanics

Secure quantum communications guarantees full security of information transfer in the presence of a quantum computer

It will enable the following:

- verified randomness for generating shared keys
- quantum encryption
- tamperproof communications

Enhanced quantum-computing power

Quantum communications enables

- **distributed quantum processing,** where 2 or more quantum computers are connected to enhance computing power
- **blind quantum computing,** where a remote quantum computer is accessed such that it learns nothing about the performed operation

Source: Expert interviews; McKinsey analysis

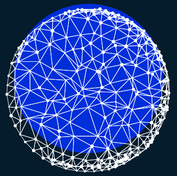
What disruptions could quantum computing enable?

Quantum computing could unleash significant business value across industries, but achieving this will require extensive research and development

Applications

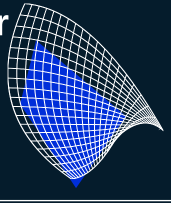
Most known use cases can fit into 4 archetypes:

Quantum simulation



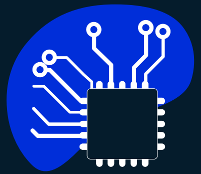
Simulation of quantum-mechanical systems such as molecules, chemical reactions, or electrons to enable use cases such as **lead identification in drug discovery** or **simulation of proteins in pharmaceuticals and agriculture**

Quantum linear algebra



Algorithms that can provide an exponential speedup over conventional algorithms and be used in tasks such as providing **financial advice, autonomous driving, automated trading,** and **predictive maintenance**

Quantum optimization



Real-time optimization by compressing computation times from hours to seconds, enabling use cases such as **generative design, traffic management,** and **portfolio optimization** in almost every industry; current quantum-optimization approaches yield only a quadratic speedup, which when accounting for the overhead of using quantum versus traditional computing does not yet yield a significant performance improvement

Quantum factorization

The earliest identified application of quantum computing, efficient quantum factorization is readily applicable to **breaking RSA encryption,** the basis of most of today's secure data-transfer protocols; achieving this will require managing many more high-quality qubits than have currently been done

Source: *Quantum computing: An emerging ecosystem and industry use cases*, McKinsey, Dec 2021

What disruptions could quantum communications enable?

Quantum communications enables secure communication of quantum information across distant locations

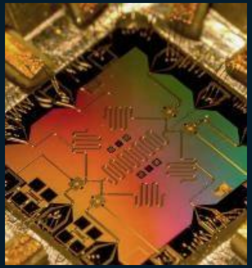
Applications

Quantum-enhanced (classical) cryptography

Quantum random-number generators (QRNG)

Enhanced security of classical cryptography protocols—eg, cryptography, personal identification numbers, lotteries, numerical simulations

Quantum cryptography



Quantum encryption protocols

Secure communication enabled by a quantum-generated confidential key shared between distant partners—eg, quantum key distribution (QKD), BB84

Quantum internet

Quantum communication infrastructure

Quantum-information exchange across continental or global distances to enable:

- long-distance secure communication
- distributed quantum computing

Source: Expert interviews; McKinsey analysis

Who has successfully created impact with quantum technologies?

Recently, many public and private entities have made announcements regarding their early applications of quantum technologies

	Case example
Quantum communi-cations	The **University of Science and Technology of China,** in collaboration with industry partners, has deployed an integrated communication network with QKD spanning more than 4,600 kilometers
	Toshiba and the University of Cambridge have deployed quantum-encryption protocols through existing citywide fibers with high-bandwidth data traffic
Quantum computing	Companies such as **Alibaba, Amazon, Google, and IBM** have already launched commercial quantum-computing cloud services with varying levels of customer adoption and technical maturity
	BMW has used quantum machine learning for autonomous vehicles by using it to train highly accurate models with massive amounts of data and has used quantum computing for car fleet routing optimization
	Pfizer is applying quantum computing to predict the behavior of electrons in a molecule to determine its 3-D structure in order to understand more about new molecules that are potential drug candidates

Source: Company websites; expert interviews; McKinsey analysis

What industries could be most affected by the trend ?

Quantum computing is still in the nascent stage, with few, isolated examples of players adopting it for solving optimization challenges

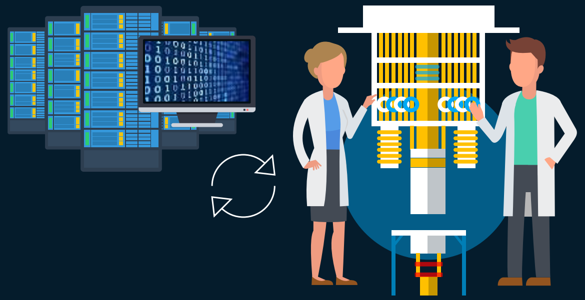
Quantum communications is relatively more mature, with several players globally establishing networks with QKD and reaping the benefits of this technology

Industries affected	Example impact of tech trend
 **Information technology and electronics**	Improving network security through QKD technology; providing capabilities or forming partnerships to offer quantum-computing services
 **Metals and mining; oil and gas**	Increasing the efficiency of companies’ exploration and extraction activities
 **Aerospace and defense**	Using quantum technologies to enable tamperproof communication systems and develop augmented navigation systems
 **Chemicals; pharmaceuticals and medical products**	Leveraging quantum computers for molecular simulations involved in creating new materials and identifying potential drugs

Source: McKinsey analysis

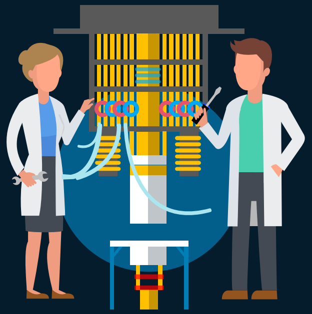
What should leaders consider when engaging with the trend?

Initially, incremental value from quantum technologies will be created through hybrid solutions with high-performance computing



Before 'impossible tasks' become solvable, we expect incremental value creation through hybrid solutions with conventional supercomputers:

- Solving business-relevant optimization problems in certain niches would be **10% faster** than previously possible
- Simulating the properties of small molecules with **5% higher accuracy** can enable the creation of new products, such as simulating surfactants to develop a better carpet cleaner
- Better data sampling to train AI may take longer, but the trained algorithm gives **20% better answers**



Meanwhile, researchers work on improving quantum computers with 2 major goals:

- **Improved processors:** Create stand-alone, fully capable quantum processors with a high count of quality qubits in order to achieve "quantum advantage" over classical computers
- **Market-ready tech stack:** Overcome engineering challenges and build a technology stack of hardware and software in order to make state-of-the-art quantum computers market ready

Source: Expert interviews, McKinsey analysis

What should leaders consider when engaging with the trend? (continued)

Advantages

Early-mover advantage: Organizations can begin investing in talent and infrastructure, establish or join quantum-technology ecosystems early, and prepare for upcoming disruption by identifying relevant use cases for their businesses while the technology matures through fundamental scientific research

Short-term applications: Many industries stand to gain from the benefits of quantum computing in the very short term, even if it needs to be paired with traditional high-power computation

Uncertainties and risks

Technical challenges: This includes the ability to manage a sufficient quantity and quality of qubits over enough time to derive meaningful computational results

Cost-effectiveness: Most calculations performed by enterprise quantum computers can be performed reasonably well by traditional supercomputers and at a much lower cost; this is expected to change once quantum advantage is achieved and general-purpose quantum computers take center stage

Uncertain road map: Current advancements in quantum technologies paint a promising future, but there may be potential barriers to adoption (eg, regulatory, technological, financial) that are not yet apparent

Nascent ecosystem: Only a handful of proven hardware platforms are commercially available, and talent skilled in quantum computing is exceedingly rare; this may change as the technology matures and adoption increases

Source: McKinsey analysis

What are some topics of debate related to the trend?

Quantum technologies are nascent, with many unanswered questions; despite generally optimistic outlooks, these technologies still face an uncertain future

1 Technology readiness

Will quantum tech be ready in the next 10 years?

- Many organizations have claimed that their quantum computers are outperforming classical supercomputers, hinting at **mature products within a decade**
- However, **research is often disputed,** and experts have refuted claims of quantum supremacy in the past
- Moreover, quantum computers **have not yet replaced classical computers** in any specific niche despite claims of supremacy, indicating that technologies have yet to mature

2 Impact and disruption

Will quantum tech be as disruptive as projected?

- Organizations from nearly every industry are already **experimenting with or showing interest** in quantum computing, while **quantum communications is already being piloted** by customers in many parts of the world
- Despite years of research, quantum computers **are still not consistently better than classical computers at solving any major business problem**
- Currently, the best quantum approaches to optimization yield only a quadratic speedup, which is not clearly superior to traditional computing when the additional overhead associated with quantum computing (such as error correction) is accounted for
- Quantum computing is **not expected to affect most computational work** and will be useful only for niche tasks

3 Organizational preparedness

How should companies prepare for quantum tech?

- **Talent acquisition** will be a major challenge for organizations in the near term, as companies rush to hire the few experts in the field
- **Identifying effective use cases** before quantum technologies mature will give an upper hand to forward-thinking organizations
- Current **quantum computers require massive investments** to operate, yet they provide computational power similar to that of less costly traditional computers
- Since the quantum-technology stack has yet to mature, companies may find it **difficult to predict which hardware paradigm** for quantum computers will dominate in the next 10 to 15 years

Source: Expert interviews; McKinsey analysis

Additional resources

Knowledge center

The Rise of Quantum Computing

Related reading

Quantum computing use cases are getting real—what you need to know

A game plan for quantum computing

The growing potential of quantum computing

Shaping the long race in quantum communication and quantum sensing