



QUANTUM COMPUTING

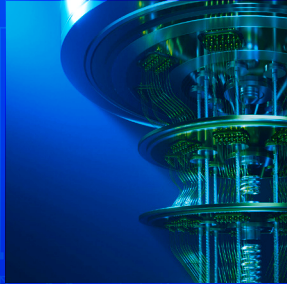
Challenges and Opportunities



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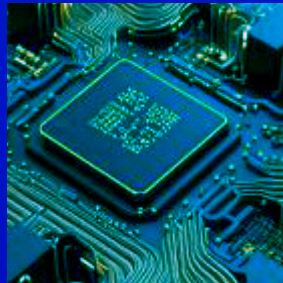
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Introduction

Our world is experiencing an unprecedented era of technological advancement, driven by rapid progress in computing, artificial intelligence, data analytics, and other emerging technologies. Among these innovations, quantum computing has emerged as one of the most significant breakthroughs, serving as a key enabler for technologies that require enormous computational power, such as artificial intelligence and big data analytics.

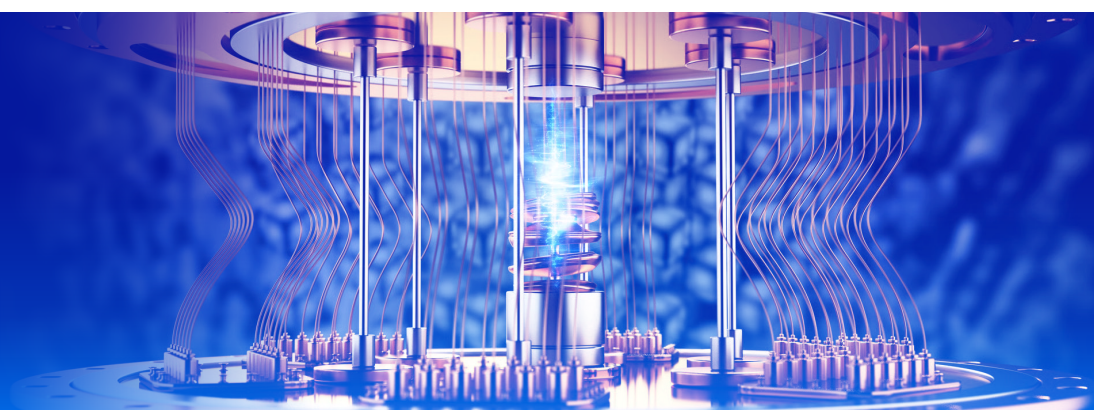
Quantum computing is a revolutionary technology capable of performing computational tasks far beyond the capabilities of classical computers. It is expected to support a wide range of applications and solve complex problems that would otherwise require thousands of years using current computing systems. Consequently, many countries are investing in quantum technologies to achieve their strategic objectives, recognizing their vital role in the digital economy.

Quantum computing has the potential to transform numerous sectors, including chemistry, energy, telecommunications, defense, cybersecurity, and artificial intelligence. It harnesses the principles of quantum physics to perform highly complex computational operations, enabling processing capabilities that significantly exceed those of conventional computing systems.

Despite the enormous opportunities it offers, quantum computing also presents significant challenges. One of the most important concerns is its potential ability to break current encryption methods, threatening cybersecurity and the protection of sensitive information. This could lead to increasingly sophisticated cyberattacks against governments, businesses, and critical infrastructure.

To address these challenges, countries around the world are adopting proactive strategies that include investing in quantum technologies, implementing post-quantum cryptography, developing national expertise, strengthening international collaboration, increasing investment in research and development, and establishing global standards through strategic partnerships. These efforts are intended to ensure that quantum computing becomes a driver of innovation and sustainable development rather than a source of technological risk.

Quantum computing
relies on the laws of
quantum physics
to perform complex
calculations at speeds
significantly faster
than traditional
computers.





Definitions and Terminology

Bit

A bit is the smallest unit of information in classical computing. It can exist in one of two states: 0 or 1, and is used to represent and process digital data.

Qubit

A qubit is the basic unit of quantum information. Unlike a classical bit, it can exist as 0, 1, or a superposition of both states simultaneously.

Quantum Physics

Quantum physics studies the behavior of matter and energy at atomic and subatomic scales. It forms the scientific foundation for technologies such as quantum computing, quantum communication, lasers, semiconductors, and quantum sensing.

Quantum Superposition

Quantum superposition allows a quantum system to exist in multiple possible states simultaneously until measured. In quantum computing, it enables a qubit to represent 0 and 1 at the same time.

Quantum Communication

Quantum communication uses quantum states, typically photons, to transmit information securely. Any attempt to measure the quantum information disturbs its state, making eavesdropping detectable.

Quantum Key Distribution (QKD)

QKD uses quantum mechanics to securely generate and distribute encryption keys. Any interception attempt alters the quantum state and can be detected, providing a high level of communication security.

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About This Guide

With the rapid advancement of computing technologies, quantum computing has emerged as one of the most significant innovations, with the potential to revolutionize fields such as cybersecurity, artificial intelligence, and data analytics. Given the complexity of this technology, there is an increasing need for a practical guide that explains its fundamental concepts, applications, and potential risks in a clear and accessible manner.

This guide provides a simplified introduction to quantum computing and aims to:



Explain the fundamental concepts of quantum computing through a simplified overview of its principles, applications, and potential risks.



Raise awareness within the technical community about the importance of quantum computing, its opportunities, and its challenges, while encouraging organizations to begin preparing for its adoption.



Encourage universities and research institutions to conduct research and develop innovative solutions based on quantum computing technologies.



Support national policies on advanced technologies by aligning the content of this guide with global trends and strategic investments, while providing policymakers with a reliable reference for decision-making.

This guide is intended for a wide range of readers, including:



Beginners

Individuals with no prior background in quantum physics or computer science who wish to understand the fundamentals of quantum computing.



General Public

Anyone interested in keeping up with scientific and technological developments and understanding their future impact.



Business Leaders and Investors

Professionals seeking to understand the commercial potential, investment opportunities, and future applications of quantum technologies.



Students

High school students and undergraduate students who are beginning to explore modern and emerging technologies.

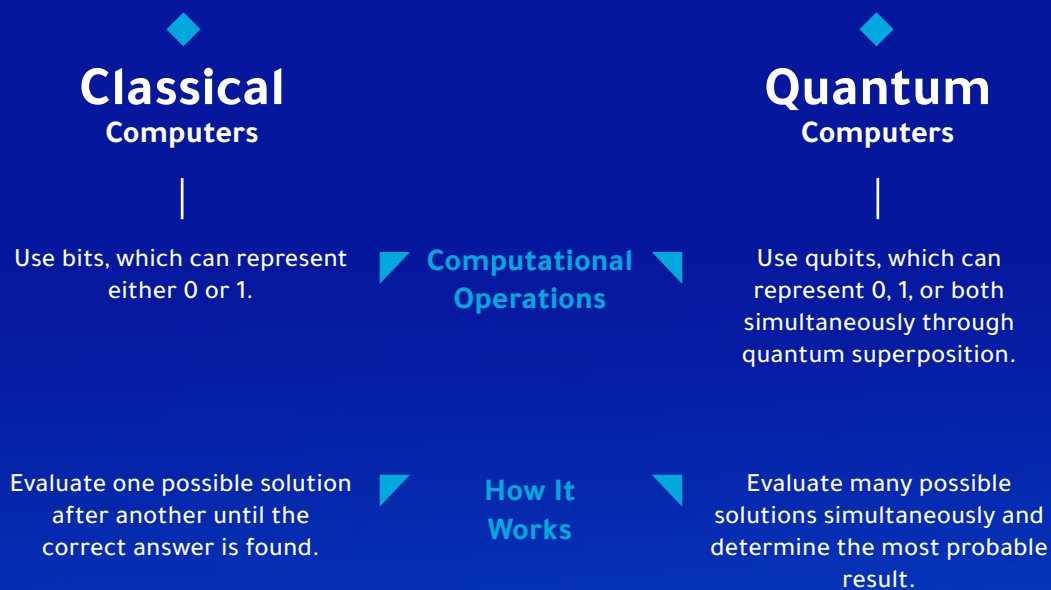


Policymakers

Decision-makers working in government, regulatory authorities, and the private sector who are responsible for technology strategies and digital transformation initiatives.

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The Difference Between Classical and Quantum Computers



Unlike classical computers, which rely on the binary system (0 and 1), quantum computers use qubits, which exploit the unique properties of subatomic particles such as electrons, photons, and ions.

A qubit can exist in multiple states simultaneously, a phenomenon known as quantum superposition. This allows quantum computers to perform many calculations in parallel rather than sequentially.

Another fundamental property is quantum entanglement, in which two or more qubits become strongly correlated. When qubits are entangled, they operate as a single interconnected system, regardless of the physical distance between them. This capability enables quantum computers to process information far more efficiently than classical systems.

For example, when two qubits are entangled, they can represent and process multiple computational states simultaneously. As the number of entangled qubits increases, the number of parallel computations grows exponentially, resulting in an unprecedented increase in computational power.

These properties significantly accelerate computational processes and enable quantum computing to solve problems that are difficult for classical computing to address.



For example, quantum computing can perform integer factorization, which is a fundamental component of many modern encryption systems, at speeds billions of times faster than classical computing. This demonstrates the ability of quantum computing to solve complex computational challenges with an efficiency far beyond what classical computers can achieve.

There are **four fundamental principles of quantum mechanics: superposition, entanglement, interference, and decoherence.** These four principles work together in complex ways to enable quantum computers to solve complex problems at speeds that classical computers cannot achieve.

These properties contribute to



Significantly accelerating computational processes.



Solving problems that classical computing struggles to address.

Quantum Entanglement



Quantum entanglement occurs when two or more qubits become strongly linked, causing their states to remain correlated regardless of the distance between them. This enables more coordinated and efficient quantum computations.

Quantum Superposition



A qubit can exist in multiple states simultaneously, rather than being limited to either 0 or 1. This allows quantum computers to evaluate many possible solutions in parallel, increasing computational efficiency.

Quantum Decoherence



Quantum decoherence occurs when qubits interact with their surrounding environment and begin to lose their quantum properties, such as superposition and entanglement. Reducing decoherence is one of the major challenges in developing reliable quantum computers.

Quantum Interference



Quantum interference occurs when quantum states behave like waves that can reinforce or cancel each other. Quantum algorithms use this effect to amplify correct answers and suppress incorrect ones, helping reach solutions more efficiently.

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Selected Global Applications of Quantum Computing

Given that real-world applications of quantum computing are still in the early stages of research and experimentation, this guide focuses on a simple and accessible set of examples. The aim is to provide a clear initial understanding of the promising potential of this technology and its possible future impact on people's lives and society.

1. Cybersecurity and Encryption



Quantum computing is considered one of the most prominent technological developments expected to revolutionize the field of cybersecurity and encryption. Quantum computers have the ability to break traditional encryption systems at extremely high speed, thanks to their ability to perform complex computational operations in a very short time, which poses a major challenge to current security systems.

In contrast, new quantum encryption technologies known as quantum cryptography are being developed. These technologies are based on the laws of quantum mechanics to provide secure means of communication that cannot be breached. These technologies are already being used in a number of projects around the world, particularly in banks, government entities, and sensitive communication networks.

2. Quantum Communication



Quantum communication represents a revolution in the field of data transmission, as it relies on the principles of quantum mechanics, such as superposition and entanglement, to transmit information through qubits instead of traditional bits. This technology is distinguished by its exceptional ability to detect any attempt at eavesdropping. As soon as a third party attempts to monitor quantum data, its physical state collapses and its content changes, making it a physically secure means of communication that cannot be breached by conventional methods or even by future quantum computers.



3. Quantum Key Distribution (QKD)



Quantum Key Distribution (QKD) is considered the most mature application of quantum cryptography. It provides a highly secure method for exchanging secret encryption keys between two parties. The technology works by transmitting individual photons that carry encryption keys. Based on Heisenberg's Uncertainty Principle, any attempt to measure or intercept these keys alters their quantum state, revealing the presence of an eavesdropper.

QKD is currently used to secure major financial transactions and highly confidential government data, helping protect sensitive information even in the era of quantum computing.

4. Artificial Intelligence and Machine Learning



Quantum computing is a promising technology expected to transform Artificial Intelligence (AI), particularly in solving problems that require enormous computational power. Potential applications include pharmaceuticals and chemistry, where quantum computing can accelerate drug discovery, design new molecules, analyze complex chemical interactions, and support the development of innovative materials.

Global companies have already begun exploring these applications to accelerate research and development in the biotechnology and chemical industries.

5. Optimizing Logistics and Transportation Systems



Quantum computing offers significant potential for analyzing complex data and solving computationally intensive problems. In logistics and transportation, it can help optimize shipping routes by rapidly analyzing variables such as traffic conditions, weather, peak hours, and sudden changes in demand.

Using quantum algorithms, companies could identify faster and more efficient routes, reducing delivery times and fuel costs. DHL and Volkswagen have explored quantum models to improve traffic and transportation flows, while companies such as FedEx and UPS have also explored quantum technologies for optimizing global supply chains (IBM, 2022).

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Potential Risks of Quantum Computing

While quantum computing offers tremendous opportunities, it also introduces significant challenges and risks that governments, organizations, and businesses must prepare for.

1.

Threats to Critical Communications and IT Infrastructure

Quantum computing could bypass current security systems, making critical infrastructure vulnerable to breaches or targeted disruption.

2.

Breaking Encryption

Quantum computers could break today's encryption systems, threatening the confidentiality of sensitive information and data.

3.

Widening the Technology Gap and Global Competition

Advanced nations and companies may gain a major technological advantage, leaving others behind in innovation and technological sovereignty.

4.

Misuse of Quantum Computing

Quantum computing could enable sophisticated cyberattacks that are difficult for traditional systems to detect or counter, posing serious risks to cybersecurity and privacy.



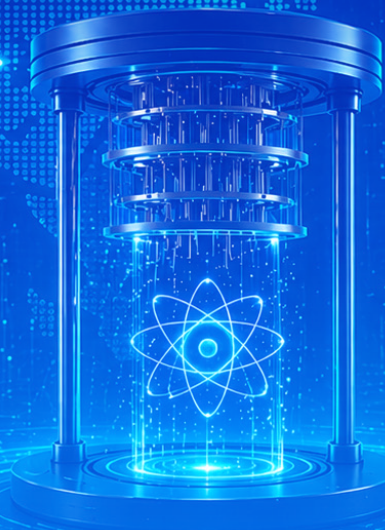
Investment in Quantum Computing

Global Investment in Quantum Computing

As global interest in quantum computing continues to grow, many leading technology companies have made significant investments in developing advanced quantum processors, building powerful systems, and creating practical applications that expand the potential of this technology. The global map below illustrates countries' level of engagement in this field in 2025. Current global investment in quantum technologies exceeds USD 55.7 billion, while the global quantum technology market is projected to reach USD 106 billion by 2040.

In 2025, investment activity in the sector marked a significant shift from experimental models toward large-scale industrial deals, with quantum computing companies' revenues exceeding USD 1 billion for the first time. This growth has been supported not only by private investment but also by major government commitments worldwide. Japan led with an allocation of USD 7.4 billion, followed by strategic investments from Spain, Australia, and Singapore.

As Quantum Error Correction (QEC) technologies continue to mature, the sector is expected to generate between USD 450 billion and USD 850 billion in economic value by 2040, driven by advanced applications in drug discovery, financial modelling, and cybersecurity. This reinforces quantum computing's position as a key pillar of the future global digital economy.



GLOBAL DISTRIBUTION OF INVESTMENTS

in Quantum Computing *



* McKinsey & Company (2025)

Challenges of Investing in Quantum Computing

Investment in quantum computing faces several key challenges that limit its widespread adoption. One of the main challenges is the high cost of infrastructure, as quantum technologies require complex equipment such as ultra-low-temperature cooling systems (Kiutra, 2023) and highly precise operating systems, making them significantly more expensive than classical computing (PatentPC, n.d.). This challenge can be addressed through stronger public-private partnerships and the establishment of joint research centers to reduce financial burdens.

Another major challenge is the shortage of specialized talent. Reports indicate a significant workforce gap, with only one qualified professional for every three available quantum computing jobs (McKinsey & Company, 2024). This gap can be addressed by integrating quantum computing into university curricula and providing practical training programs in collaboration with research institutions.

The Future of Investment in Quantum Computing

Investment in quantum computing is expected to grow rapidly over the next decade, driven by advances in infrastructure and supporting technologies. Global investment is projected to exceed USD 20 billion by 2030, as countries increase their focus on research and development in this strategic field (QURECA, 2025).

Collaboration between the public and private sectors is also expected to expand, with governments partnering with major technology companies to accelerate the development of practical quantum applications (Harrowell & Jamieson, 2023).

Commercial applications are expected to grow across sectors such as agriculture, energy, and advanced manufacturing, benefiting from quantum computing's ability to analyze complex data and model future scenarios (Johnson, 2025). Ultimately, quantum computing is expected to move beyond laboratory research and become a powerful tool for enhancing global economic competitiveness.



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Frequently Asked Questions (FAQ) About Quantum Computing

What is the difference between quantum computing and classical computing?

Classical computers use bits, which represent either 0 or 1, while quantum computers use qubits, which can represent multiple states simultaneously through superposition. Quantum technologies also use entanglement, enabling more powerful processing for certain complex problems.

Will quantum computers replace classical computers?

Not necessarily. Quantum computers are not expected to completely replace classical computers, but rather complement them in advanced tasks. Classical computers will remain the best choice for everyday activities such as browsing the internet, using office applications, and gaming, while quantum computers are designed to solve highly complex problems that require enormous computational power.

Quantum computers are also still under development and require specialized operating conditions, such as advanced cooling systems. In the future, both technologies are expected to work together, each serving the tasks for which it is best suited.

Is quantum computing environmentally friendly?

Current quantum computers require significant energy, mainly due to advanced cooling systems. Therefore, they are not environmentally friendly. However, ongoing research aims to make future quantum systems more energy-efficient and sustainable.

What is the future of quantum computing?

Quantum computing is expected to transform many fields as quantum hardware and software continue to advance. Its potential applications include drug discovery, cybersecurity, big data analysis, supply chains, transportation, renewable energy, and artificial intelligence.

As governments and major companies continue investing in this technology, quantum computing is expected to become an important pillar of global digital transformation in the coming decades.

What role does quantum computing play in big data analytics?

Quantum computing can process large volumes of data through parallel algorithms, improving the efficiency of search, classification, and prediction. For example, in the healthcare sector, quantum computing can be used to analyze millions of medical records and genetic data in a short period of time to identify hidden patterns that can help diagnose diseases more accurately or determine the most appropriate treatment for each patient based on their genetic data.

How does quantum computing affect cybersecurity?

Quantum computing poses a significant challenge to current cybersecurity systems, as its advanced computational power could eventually make some of today's encryption methods ineffective, potentially exposing sensitive data and digital communications.

At the same time, this challenge is accelerating global efforts to develop quantum-resistant encryption methods. Quantum computing therefore represents both a cybersecurity challenge and an opportunity to build a new generation of stronger digital security.



Quantum Computing Team

Recognizing the importance of quantum technologies and their rapid global development, the Sultanate of Oman established a National Quantum Computing Team, bringing together experts, specialists, and representatives from relevant entities. The team aims to assess the current landscape, explore investment opportunities, and address the challenges associated with adopting quantum computing in Oman.

The team prepared this guide to raise awareness of quantum computing and present its concepts and applications in a clear and accessible manner.

The national team also developed a comprehensive foresight study covering the importance of quantum computing, investment opportunities, potential risks, and leading international strategies. The study also proposed a national roadmap for quantum computing in Oman, with strategic recommendations and implementation programs organized around the following key pillars:

Strategic Pillars for Adopting Quantum Computing

Governance and Legislation



Establish a legal and regulatory framework that keeps pace with technological developments.

Human Capacity Building



Develop qualified human resources to work with quantum technologies.

Competitive Economy



Enable the private sector and encourage investment in quantum technologies.

Infrastructure



Develop the systems and infrastructure needed to support quantum computing.

Research and Development



Promote innovation and scientific research in this field.

Through the implementation of this national roadmap, the Sultanate of Oman aims to keep pace with global technological transformation, maximize the opportunities offered by quantum computing to drive innovation and build a prosperous digital economy, address future challenges by mitigating potential risks, strengthen national capabilities, and reinforce its position among the world's leading advanced economies.

Quantum Computing Roadmap



2024-2026

Short-Term

Establish governance frameworks and assess Oman's quantum ecosystem. Build national awareness and launch strategic partnerships and initiatives.

2027-2029

Medium-Term

Develop national capabilities, specialized organizations, and a skilled quantum workforce. Prepare Oman for the practical adoption of quantum computing.

2030

Long-Term

Position Oman as a regional leader through advanced quantum infrastructure and increased investment. Build an integrated innovation ecosystem for future technologies.

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