INNOVATION THEMES & STRATEGY

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The Quantum Landscape: Accelerating Disruption

In This Report

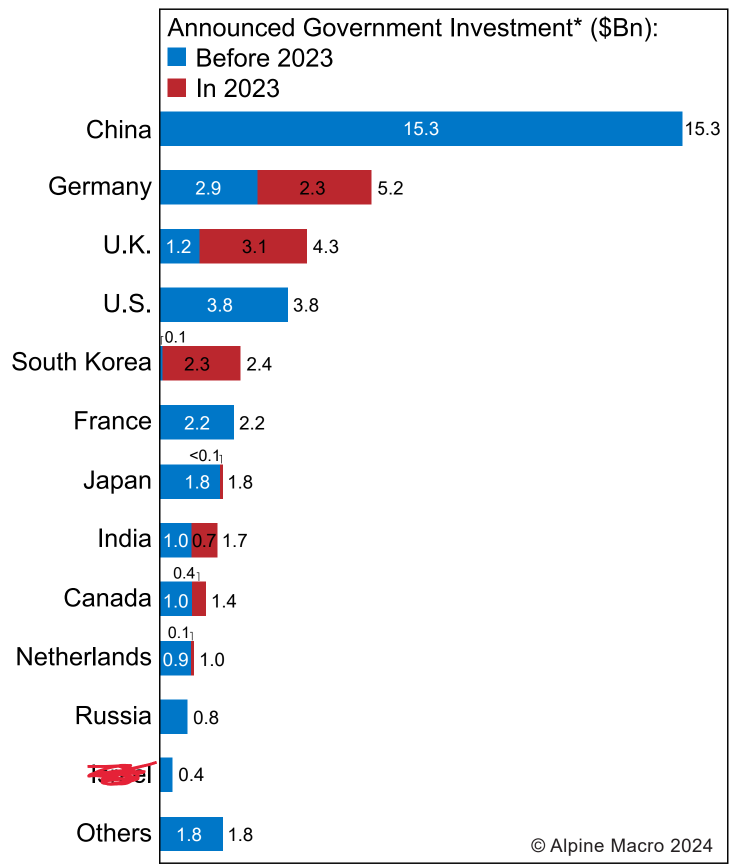
Various quantum technologies are on the precipice of impacting virtually every industry on the planet. While the complexity and slow rollout of quantum technologies has hindered adoption to date, their disruptive potential is finally being showcased. This report will examine the quantum tech ecosystem by exploring key technologies, application areas, and ultimately conclude with investment considerations.

Quantum technology falls under the broader field of Quantum Information Science (QIS), which leverages the principles of quantum physics to process, store, protect, and transmit information in novel and better ways. Importantly, QIS unlocks new possibilities by reaching beyond the limits of classical computing and traditional mathematical constraints.

There are three main pillars of the quantum tech ecosystem: computing, communication, and sensing. Although quantum computing is the sector's posterchild, it ironically remains the most undeveloped pillar. Conversely, quantum sensing and communication technologies have reached a higher level of maturity and are already making an impact. However, the potential of quantum computing should not be dismissed, as researchers continue to make significant progress.

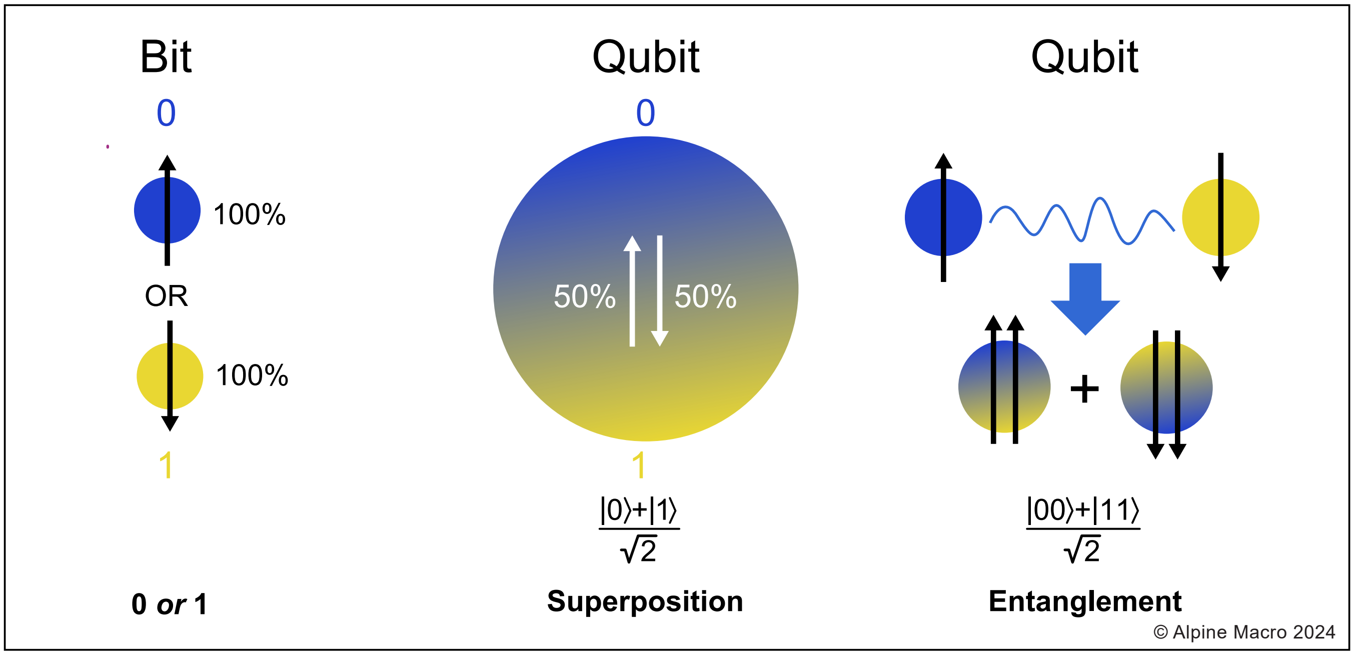
The world is entering a "quantum-empowered" era that will bring significant benefits but also introduce new challenges. For example, capabilities such as un-hackable communication networks, GPS-independent navigation, immense computing power, and novel sensing technologies have the potential to be used for both positive and negative purposes.

Chart 1 Quantum Investment Broadening Out



*Total historic investment.

Chart 2 Qubit Vs Bit



The significance is immense and far reaching. Quantum tech has already become a focal point of the U.S./China technology development race. Earlier this fall, the U.S. announced a fresh batch of export controls on advanced technology including quantum tech. As we outlined in our August cybersecurity report[1], the winner of the quantum race could shift the global balance of technology power.

Quantum Computing Still Advancing, But No Breakthroughs Yet

Although quantum computing likely remains years away from having a revolutionary impact it could be the most disruptive technology ever created. Capital continues to pour into the sector. So far, over $55 billion has been invested globally in quantum technology. It is important to note that while the U.S. and China have historically been leaders in quantum tech investment, there is a broadening out trend (Chart 1). This could accelerate breakthroughs *via* increased collaboration.

Quantum computers function differently from classical computers. While classical systems use bits that represent either 1 or 0, quantum computers use quantum bits, known as qubits. Unlike bits, qubits can exist in multiple states simultaneously due to superposition (Chart 2). This ability enables powerful parallel processing, greatly enhancing their problem-solving capabilities. In contrast to classical computers, whose power increases linearly, quantum computers are exponential in power as adding one qubit doubles the computing power. In fact, traditional computing capabilities have begun to lag Moore's Law, while quantum computers are following Neven's law which states that they are improving at a "doubly exponential" rate.

1 Alpine Macro *Innovation Themes & Strategy* "Cybersecurity: Vulnerablilities" (August 7, 2024).

Table 1 **Quantum Computing's Disruptive Potential**

Quantum Computing to Create Up to $850Bn in Economic Value by 2040

Machine Learning	Optimization	Simulation	Cryptography
Automotive: AV AI Algorithms **$1Bn-$10Bn**	Logistics: Network Optimization **$50Bn-$100Bn**	Pharma: Drug Discovery **$40Bn-$80Bn** Aerospace: CFD **$10Bn-$20Bn**	Government: Encryption, Decryption (cybersecurity) **$20Bn-$40Bn**
Finance: AML and Anti-Fraud **$20Bn-$30Bn**	Insurance: Risk Management **$10B-$20Bn**	Chemistry: Catalyst Design **$20Bn-$50Bn**	
Tech: Search/Ads Optimization **$50Bn-$100Bn**	Finance: Portfolio Optimization **$20Bn-$50Bn**	Energy: Solar Conversion **$10Bn-$30Bn** Finance: Market Simulation **$20Bn-$35Bn**	Corporate: Encryption (cybersecurity) **$20Bn-$40Bn**
Other Use Cases **$25Bn-$110Bn**	Aerospace: Route Optimization **$20Bn-$50Bn**	Other Use Cases **$75Bn-$115Bn**	
Machine learning applications to impact most, if not all, industries			

Source: BCG

Although the number of qubits in quantum computers are scaling at roughly 2x the exponential rate[2], obstacles remain. The largest hurdle is error correction, as quantum computers are highly sensitive to even minute disturbances in their surroundings, which can impact qubit stability. However, Microsoft and Quantinuum have recently achieved a record qubit accuracy of 99.9% by combining new error-correction schemes with groundbreaking qubit architectures.

Although somewhat disputed, "quantum supremacy" (when a quantum computer can solve a problem that would be impossible for a classical computer) has not yet been achieved. However, current quantum computing capabilities are already highly valuable and millions of times more powerful than traditional computers. As a result, use cases are rapidly expanding greatly aided by the rise of remote access to a quantum computer through cloud providers. Compelling use cases showcasing the benefits (Table 1) of quantum computing regardless of the sector still chasing "quantum supremacy" include:

- Moderna is leveraging IBM's quantum computing capabilities to accelerate mRNA therapy development. A quantum computer only requires around 50 qubits to perform molecular simulations almost instantly.

- In a major milestone toward achieving quantum advantage in financial applications, researchers from Goldman Sachs and QC Ware have developed

2 IBM has released a 1,180-qubit quantum processor that is more than 2x as powerful as its 2022 433-qubit machine.

Table 2 Quantum Sensing Capabilities

Technology	Implementation Type	System Description	Measured Properties
Solid-State Spins	NV* center in diamonds	Spin of one electron localized in an insulator defect	Magnetic field, electric field, temperature, pressure, rotation
Neutral Atoms	Atomic vapor	Atoms in the vapor cell sense changes in the environment	Magnetic field, rotation, temperature, electric field, frequency, acceleration, rotation
	Cold cloud	Laser-cooled atoms sense changes in the environment	
Superconducting Circuits	SQUIDs**	Difference in Cooper pairs between two islands of a Josephson tunnel junction	Magnetic field, electric field
Trapped Ions***	Single atoms	Mapping of motional amplitude to spin as sensor for electromagnetic fields	Magnetic field, electric field

Note: Other technologies, including photonics, may be used for sensing applications, but there are a few existing application for which photonics are a suitable platform.
*Nitrogen vacancy.
**Superconducting quantum interference devices.
***Trapped ions are currently in the early stages of research and are thus not ready for application in use cases.
Source: Neil Savage, "Quantum diamond sensors," Nature, March 2021, Volume 591

advanced quantum algorithms that surpass the performance of leading classical algorithms in Monte Carlo simulations.

- Automaker's including Volkswagen are utilizing quantum computing to discover new materials, optimize battery cell design, and improve cathode efficiency.
- Quantum computing is emerging as a tool to accelerate AI development. The emerging field of quantum AI unlocks faster processing of large datasets and could supercharge AI capabilities. This is proving critical in the development niche models for specialized functions. Researchers have already accelerated AI reinforcement-learning by over 60% by using a hybrid training approach that uses both quantum and classical computing.

As we have warned in past reports, the greatest risk posed by a quantum computing breakthrough is that an adversary could potentially break RSA encryption. To thwart this threat, the development of quantum-safe encryption is paramount. In August of 2024, the National Institute of Standards and Technology (NIST) released three new algorithms of this standard to serve as blueprints to support adoption of post-quantum cybersecurity solutions.

Novel Sensing Capabilities

Although the quantum sensing ecosystem has been progressing rather quietly behind the scenes, it is considered the most mature quantum technology. Quantum Sensors (QS) negate the need for complex error correction and are beginning to become commercially available. They function by using various particles, including atoms and photons, to detect and measure changes to their states with exceptional precision at a granular level (Table 2). In general, QS' are one to two orders of magnitude more sensitive than conventional sensors, notes McKinsey.

Aside from unrivaled sensitivity, QS can collect data across a multitude of domains including position, velocity, temperature, and magnetic fields. This utility positions QS to proliferate and replace legacy sensing instruments (Table 3). Moreover, the rising global demand for high-precision measurements and critical-application data, especially in AI and next-generation defense technologies, serves as a significant tailwind. QS can produce up to ten tera-bytes of data per second- a treasure-trove for AI.

The initial QS market could top $6 billion while growing at a CAGR between 10-15% according to McKinsey. Yet, we believe the technologies' potential is likely much greater as it replaces vulnerable technologies like GPS and enhances other areas including medical diagnostic equipment, surveillance capabilities, and resource extraction screening. Quantum sensors can be easily integrated into a multitude of devices including advanced weapon systems and function across many domains including air, land, sea, subsoil, and space.[3]

Examples of where quantum sensing is proving highly disruptive include:

- Creating un-jammable worldwide navigation systems. Quantum geophysical sensing is enabling navigation in geographies susceptible to GPS blocking as the technology does not rely on satellites or ground stations. This is highly valuable for both the commercial aviation and defense industries, which are experiencing record high jamming incidents. Quantum startup Sandbox AQ is working with the U.S. Airforce to develop a quantum-navigation technology intended to complement GPS. NATO is also applying the technology to submarine detection. QS will play a key role in many next-generation defense products.

- Revolutionizing medical diagnostic accuracy. The emerging field of non-invasive biomagnetic quantum sensing can detect previously undetectable fluctuations in electrical impulses and magnetic fields across vital organs. For example, highly accurate magnetocardiography devices using quantum sensors are improving physicians' ability to spot abnormalities in an EKG that would have once gone undetected. QS also offer exceptional sensitivity to magnetic fields, enabling high-resolution measurements of brain activity with unprecedented spatial resolution

- Unlocking imaging at the nanoscale. Magnetic resonance imaging can examine materials and molecules at the atomic level. This is facilitating the development of new materials in the field of materials science while also accelerating therapeutic development in healthcare. In drug development specifically, QS spectroscopy devices are enabling drug developers to observe how molecules interact with each other with unrivaled detail. This provides researchers with a clearer understanding of how a drug will interact with the body and other molecules before it even enters clinical trials.

3 Alpine Macro *Innovation Themes & Strategy* "The Intensifying Space Race: Key Insights For Investors" (July 10, 2024).

Table 3 Expected Development Timeline

Development Timeline for Quantum-Sensing Technologies, Non-Exhaustive

- Microelectronics
- Communications and logistics
- Energy and materials
- Life sciences
- Other

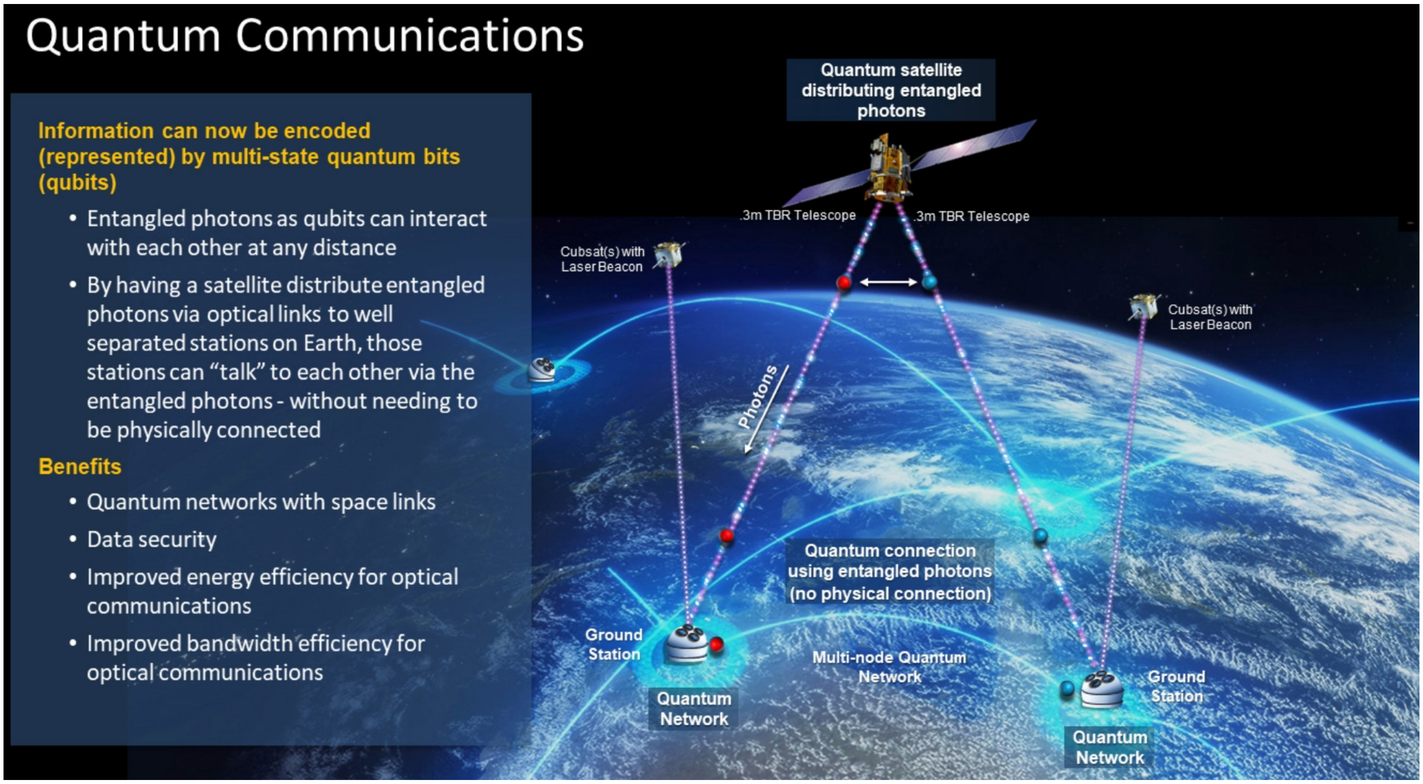
- Solid-state spins
- Superconducting circuits
- Neutral atoms
- Photonics
- Futuristic applications

Now or Existing	Near Term	Medium Term	Long Term
Scanning nanoscale quantum sensors (for research use)	Defect inspection and design improvement of batteries	Flaw detection of microelectronics (e.g. chips, boards)	Efficiency boost for energy conversion in solar cells
Navigation enabled by satellite-based atomic clocks	Navigation based on electromagnetic fields (e.g. airborne, ships, drones)	Quantum sensor-based navigation (when no GPS available)	Identifying objects through camera (e.g. position of a drone)
Monitoring volcano activity	Monitoring corrosion for pipeline integrity	Long wavelength communication with atom acting as antenna	Calibration and inspection of electrical standards beyond 5th generation (5G)
Underground analysis of pipes, structures, and power lines	Cardiac diagnostics with biomagnetics	Single receivers and amplifiers for radar communication	Magnetometer for fusion reactors
Brain injury imaging through MEG*	Temperature measurements in cells and small organisms	Monitoring temperature in transformers and power plants	Determination of protein structure and dynamics under near-physiological conditions
	Bioimaging with enhanced MRI**, PET***	Monitoring stability and integrity of infrastructure (e.g. detection of cavities)	Personalized medicine (checking response to drugs with single-cell sensors, measuring drug degradation)
	Better understanding of disease through spectroscopy at single-biomarker level (e.g. neurological, inflammatory)	Geophysical surveying through gravity or electromagnetic imaging for oil, gas, and mineral detection	Understanding molecular structures and spectroscopy at single-protein level
		Targeted photodynamic therapy for cancer treatment	On-chip monitoring of security and malfunction of chips
		Better disease understanding through spectroscopy at single-cell level	Microscopy for verification of high-value artifacts
		Metabolic measurements in living cells	Mind-machine interface

*Magnetoencephalography
**Magnetic resonance imaging
***Position emission tomography
Source: Quantum sensing use cases; prospects and priorities for emerging quantum sensors, Quantum Economic Development Consortium, September 2022

Chart 3 Quantum Communication Network

OMG this is super cool



Source: NASA

Un-Hackable Communications

Although some hurdles remain at long distance and with obstacles like thick clouds, quantum communications networks are beginning to usher in an era of ultra-secure communications (**Chart 3**). The technology is already being leveraged and is becoming a focal point of the U.S./China technology race.

The most developed quantum-communication method is quantum key distribution (QKD). QKD uses photons to generate shared "encryption keys" between two parties. This approach provides guaranteed encryption, as any attempt to crack it is detected by the photons themselves due to their states being altered. Unlike traditional RSA encryption that is based on mathematical complexity, QKD is based on the laws of physics.

China is the global leader in quantum communications including QKD.[4] The nations' quantum communication supremacy is a security concern for the West. Particularly, an un-hackable communications system between China and other BRICS nations could expand beyond defense-related issues and serve as a tool to share secrets across information, technology, and even finance. Just last week, President Xi called for "urgent" reform of the international financial architecture.

The Middle Kingdom has over 30 experimental quantum communications networks and continues to routinely shatter quantum communication distance records. China first showcased a hack-proof land-based quantum-communications network

4 Information Technology and Innovation Foundation.

connecting Beijing and Shanghai in 2017 but has since applied the technology to space communications. Using their quantum-satellite Micius, China has already showcased its ability to create a secure link between space and two ground stations 7,400 kilometers apart – a global record. In late 2023, a communication between China and Russia successfully completed a "full cycle" transmission of two encoded images secured by quantum keys over a distance of 2,360 miles.

The implications are broad and significant. China intends to launch multiple quantum communication satellites in the coming years, with the goal of announcing a global quantum communication service by 2027. Quantum communication milestones are being tallied with increased speed in the East. In contrast, the West woefully lags behind and plans to launch quantum satellites remain in early stages. Without urgent action, the West risks being too late to the quantum communications party and could be at a strategic disadvantage.

Investment Considerations

While a breakthrough in quantum computing that leads to "quantum supremacy" likely remains years away, it is important for investors to understand that quantum technologies, including computing, are already having a profound impact. This remains largely overlooked by market participants, as the adoption of quantum technologies and their potential has been overshadowed by other technological disruptions – most specifically AI. Quantum sensing capabilities specifically are robustly developed and are merely waiting on broad commercialization.

In the short to medium term, we are in the camp that quantum sensing will be the first quantum technology to emerge from the shadows and highlight quantum tech's potential. Specifically, quantum sensors will realize rapid adoption in industries such as healthcare and aerospace while also helping to modernize electric grids.[5] The adoption of any quantum tech is a boon to support an increase in R&D across the entire QIS ecosystem and could accelerate breakthroughs in other quantum verticals.

Due to the nebulous nature of quantum technologies, we advise investors to seek exposure through a variety of equities across the quantum value chain. The ETF QTUM provides broad sector exposure, while Rigetti Computing (RGTI) and IonQ Inc (IONQ) serve as pure-play quantum computing vehicles. SK Telecom (017670 KS), Exail Technologies (EXA FP), and BAE Systems (BAESY) provide exposure to quantum communications and sensing.

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5 Alpine Macro *Innovation Themes & Strategy* "The U.S. Grid: Revamp Time" (July 31, 2024).

A Unique Mind On The Markets