Quantum Coast Capital

INTERNATIONAL YEAR OF
Quantum Science
and Technology

A Quantum Technology Framework for Capturing Value

Realizable Innovation Today,
Revolutionary Computing Tomorrow

February 2025

Executive Summary

Quantum technology stands at the cusp of ushering in one of the most profound technological shifts in history. As recognized by the UNESCO *International Year of Quantum Science and Technology (2025)*, this field is poised to reshape industries beyond computing alone. While public discourse often narrows its focus to quantum computing, the reality is far more expansive. For example, quantum sensing is already delivering impactful applications, with technologies like hyperpolarized MRI enhancing medical imaging and frequency combs revolutionizing the detection of methane leaks.

Quantum computing itself is experiencing an unprecedented acceleration, driven by advancements in physical and logical qubit counts. Innovations such as modular architectures and new error correction methods are putting scalable fault tolerant machines in scope plausibly within the next decade. Along the way, intermediate applications, particularly in chemistry and materials science, promise transformative breakthroughs. These developments, may come through a potent integration of quantum with high-performance classical computing and AI.

In addition, much like the space race catalyzed the development of integrated circuits and digital image sensors, quantum innovation is likely to produce spin-off technologies. The opportunities are vast, and as resources from both government and private capital flow into the field, a virtuous cycle of progress is forming.

Putting these short-term, intermediate, and long-term possibilities together, provides investors with a unique “call option” to capture long-term gains while benefiting from near-term opportunities in sensing and other areas.

However, realizing quantum’s full potential requires navigating its complexity, cutting through the surrounding hype, and maintaining tolerance for the volatility and serendipity inherent in scientific discovery. Along with the scientific discipline, a deep understanding of the quantum ecosystem and evolving business models will be essential for success.

Goals and Scope: this document outlines a framework for understanding and capturing the value in quantum technology that is grounded in the current physics and aimed at a general audience. Rather than providing a comprehensive review of this vast field, it uses select concrete examples to illustrate the investment thesis. The examples chosen are illustrative and not meant to diminish the contributions of any researchers, institutions or companies in this dynamic space.

Dmitry Green
Chief Science Officer & General Partner

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A Quantum Technology Framework for Capturing Value

Beyond the Beauty of Physics

I. **Quantum technology is on track to be one of the most profound technological shifts in history, yet public discourse often reduces it to quantum computing alone.** Just to pick two real examples that are already in the quantum sensing market today: hyperpolarized MRI technology is enhancing medical imaging [NV1, 2], while frequency comb technology is revolutionizing methane leak detection in oil fields [LP]. Quantum networking is another large category of emerging applications, e.g., to secure communications. The playground of quantum mechanics is vast [DG21].

II. **Quantum computing itself is experiencing dramatic acceleration.** Two key drivers determine our path to fault-tolerant computing: physical qubit count and logical qubit count. Many innovations have become apparent just in the last couple of years. As an example, scaling via modular quantum architectures [Niu23, Akhtar23, Li24] and remarkable progress on error correction are on the horizon [Wu22, Koottandavida24, Rodriguez24, Cain24]. Assuming that other factors (such as coherence time and speed) also continue to improve, then the possibility of breaking RSA encryption within a decade now appears plausible.

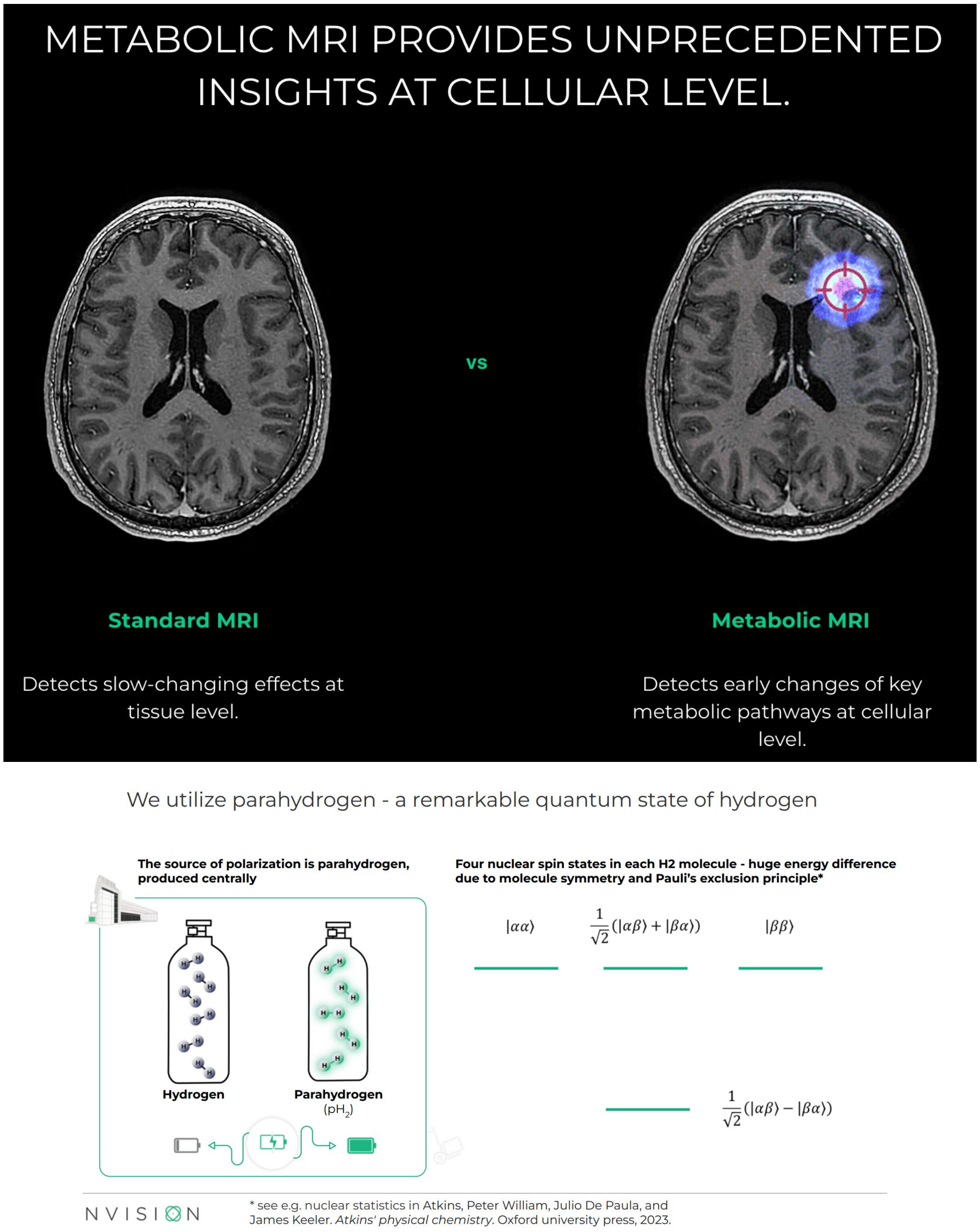
III. **Additionally, two types of practical applications may emerge along the way to fully fault-tolerant machines.** First, the ability to solve some chemistry problems that are not accessible to classical computers using “beyond noisy intermediate scale quantum” machines [Preskill24]. Solving chemistry problems could be transformative to many industries, e.g., life sciences and manufacturing. In fact, one possible path forward is an exciting combination of high performance classical computing, AI and quantum computing all working in tandem [MSFT24]. Second, there will be spin-out technologies. Looking back at the space race, it catalyzed the development and evolution of the now ubiquitous integrated circuits and digital image sensors. History may rhyme again.

IV. **As a result, investors can construct a “quantum call option” where one is effectively paid-to-wait on quantum supremacy because other quantum technologies, such as sensing, will be profitable along the way.** In my view quantum technology has reached critical mass as the opportunities will attract more capital, both government and private. This will feed a virtuous circle as more resources breed more progress and the call option will become more valuable. The call option is not free, however; success will depend on a deep understanding of quantum complexity and ecosystem, cutting through hype, and tolerance of the inherent volatility and serendipity of scientific discovery.

> *“What is proved by impossibility proofs is lack of imagination.”*
>
> \- John S. Bell (1982)

I.A. Advancing Medical Imaging with Quantum-Enhanced Metabolic MRI

Hyperpolarized MRI works by artificially enhancing the magnetic signals from specific molecules, similar to sugar, to make them much more detectable in MRI scanning. NVision enables room-temperature hyperpolarization in 3 minutes.* [NV1, NV2]



METABOLIC MRI PROVIDES UNPRECEDENTED INSIGHTS AT CELLULAR LEVEL.

Standard MRI

Detects slow-changing effects at tissue level.

Metabolic MRI

Detects early changes of key metabolic pathways at cellular level.

We utilize parahydrogen - a remarkable quantum state of hydrogen

The source of polarization is parahydrogen, produced centrally

Four nuclear spin states in each H2 molecule - huge energy difference due to molecule symmetry and Pauli's exclusion principle*

$$|\alpha\alpha\rangle \qquad \frac{1}{\sqrt{2}}(|\alpha\beta\rangle + |\beta\alpha\rangle) \qquad |\beta\beta\rangle$$

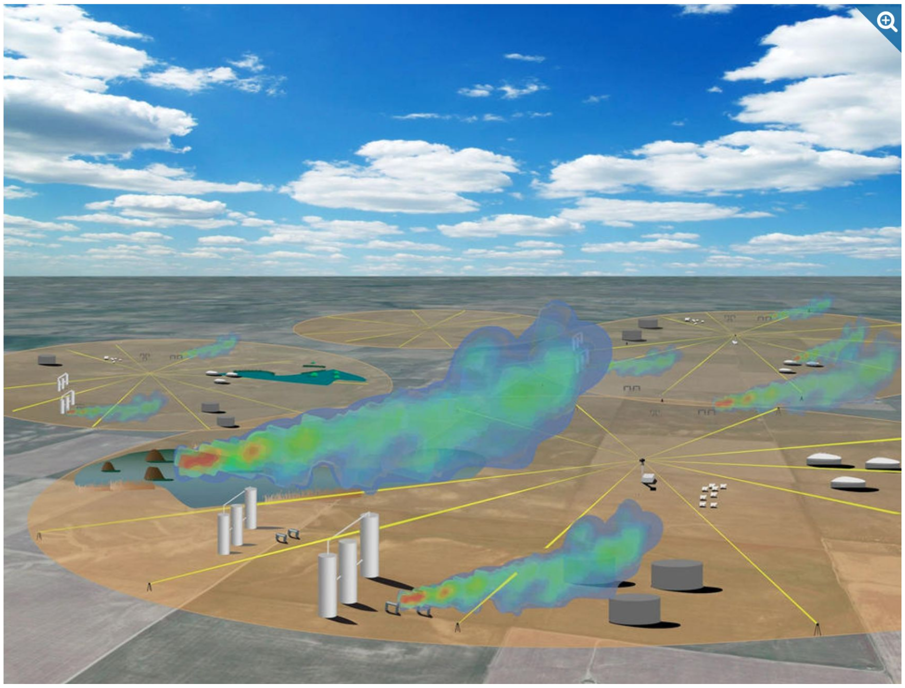
$$\frac{1}{\sqrt{2}}(|\alpha\beta\rangle - |\beta\alpha\rangle)$$

* see e.g. nuclear statistics in Atkins, Peter William, Julio De Paula, and James Keeler. *Atkins' physical chemistry*. Oxford university press, 2023.

I.B. Revolutionizing Environmental Monitoring

with Quantum-Driven Methane Detection

LongPath Technologies uses frequency comb* laser technology to detect methane leaks and other pollutants in the air. Based on a technology invented by John Hall a researcher at CU Boulder and NIST who first demonstrated a laser frequency comb in 1999. Hall received the 2005 Nobel Prize in Physics [LP, NIST].



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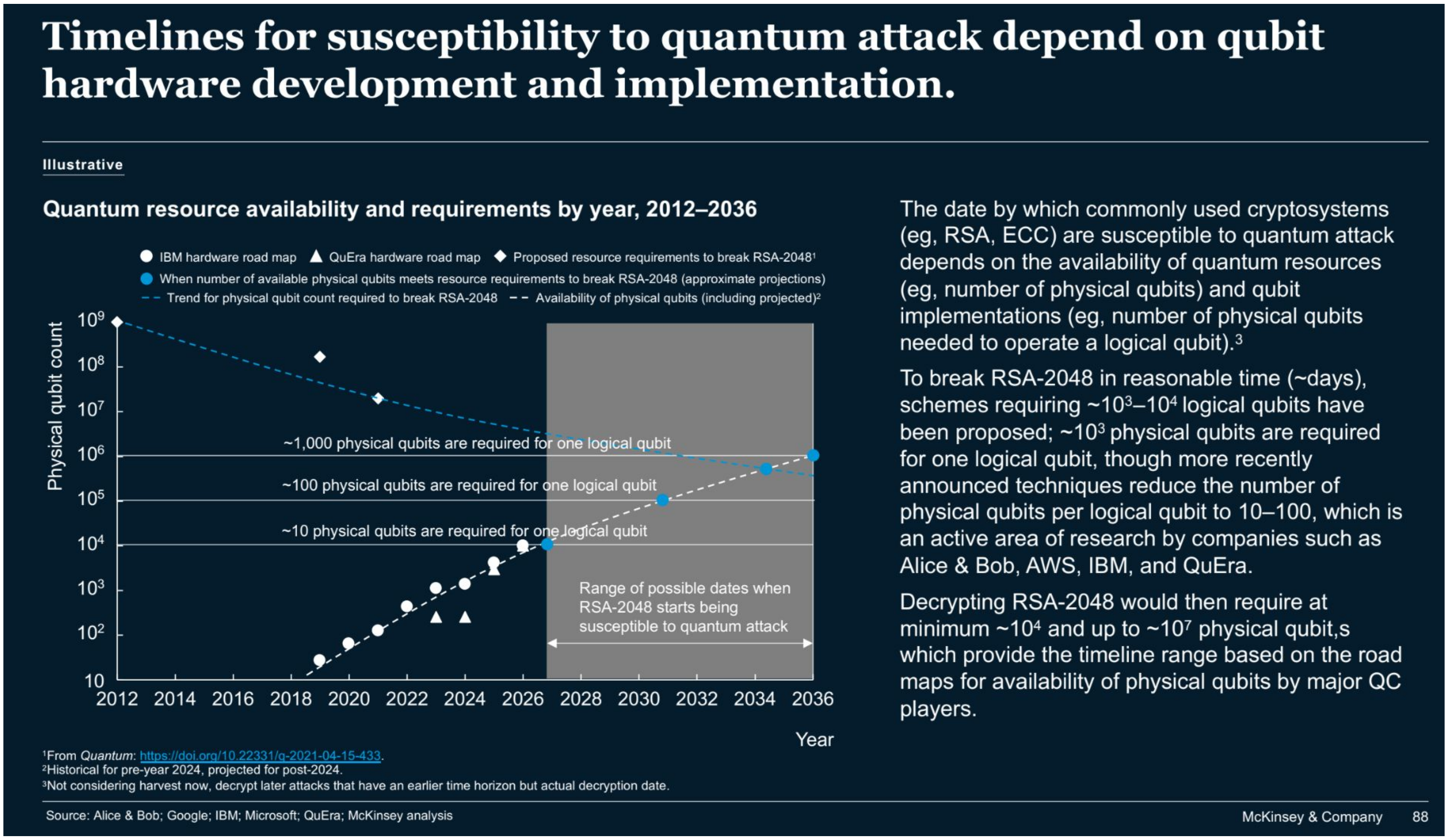
* Frequency combs are lasers that emit multiple frequencies of light with many uses, one of which is to identify specific molecules through their absorption and emission spectra.

II. Achieving Quantum Supremacy:

The Plausibility of Breaking RSA Encryption Within a Decade

Two key drivers of full fault-tolerance—number of physical qubits and number of physical qubits per logical qubit. The intersection of the two trends is within 10 yrs. Enabling innovations include **#1 modular scaling** and **#2 error correction** (examples follow). Assume other factors improve, too, e.g., coherence time, speed and connectivity.

Hedge: what if we get to ~100k of physical qubits by ~2030 but without full fault-tolerance? It is very possible that there will be practical applications to chemistry and materials problems* on such machines [Preskill24, Clinton24, MSFT24].



Timelines for susceptibility to quantum attack depend on qubit hardware development and implementation.

Illustrative

Quantum resource availability and requirements by year, 2012–2036

The date by which commonly used cryptosystems (eg, RSA, ECC) are susceptible to quantum attack depends on the availability of quantum resources (eg, number of physical qubits) and qubit implementations (eg, number of physical qubits needed to operate a logical qubit).[3]

To break RSA-2048 in reasonable time (~days), schemes requiring ~10^3–10^4 logical qubits have been proposed; ~10^3 physical qubits are required for one logical qubit, though more recently announced techniques reduce the number of physical qubits per logical qubit to 10–100, which is an active area of research by companies such as Alice & Bob, AWS, IBM, and QuEra.

Decrypting RSA-2048 would then require at minimum ~10^4 and up to ~10^7 physical qubit,s which provide the timeline range based on the road maps for availability of physical qubits by major QC players.

[1] From *Quantum*: https://doi.org/10.22331/q-2021-04-15-433.
[2] Historical for pre-year 2024, projected for post-2024.
[3] Not considering harvest now, decrypt later attacks that have an earlier time horizon but actual decryption date.

Source: Alice & Bob; Google; IBM; Microsoft; QuEra; McKinsey analysis

McKinsey & Company 88

[MCK24]

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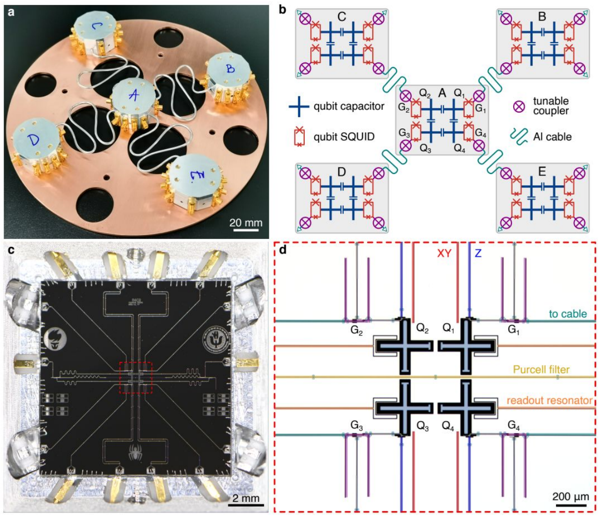
* Chemistry will require fewer qubits/higher circuit depth, while materials will require more qubits/lower circuit depth.

II.A. Why It is Plausible:

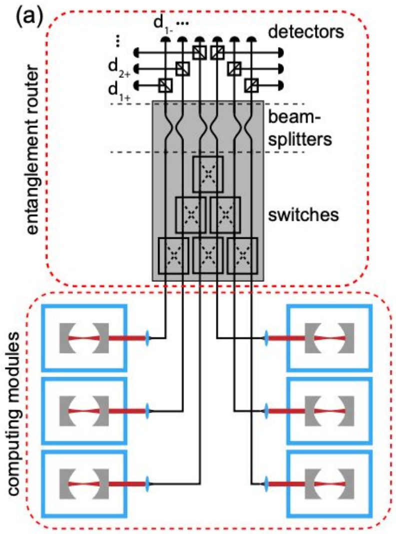
#1 Modular scaling

Architectures for interconnecting qubit modules would enable scaling of the total number of physical qubits.
Examples of recent proofs of concept:

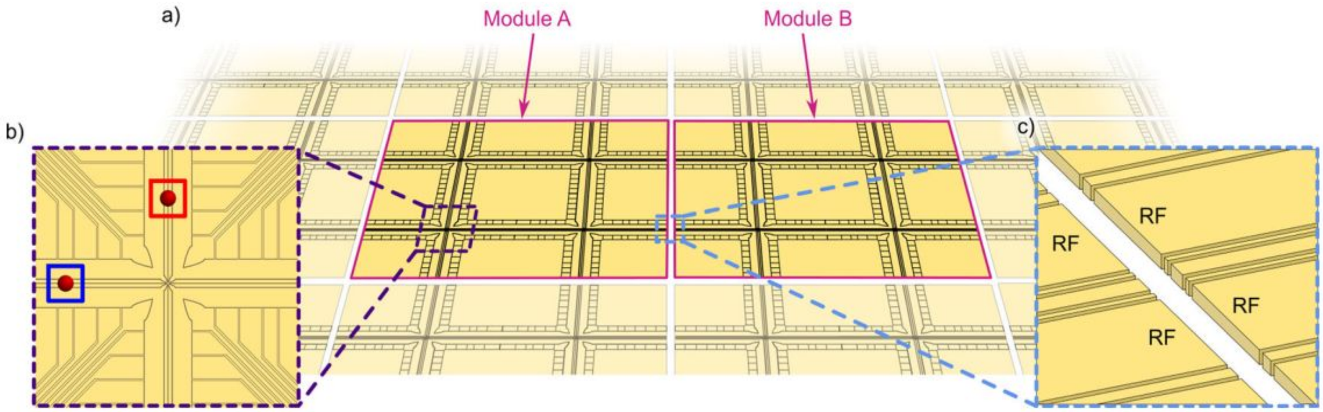
Superconducting quantum processors [Niu23]



Neutral atoms [Li24]



Trapped-Ions [Akhtar23]



II.B. Why It is Plausible:

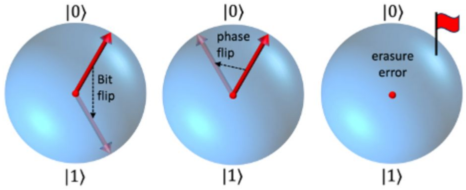
#2 Remarkable progress in error correction

Error correction is crucial for controlling qubit decoherence so as to preserve the fragile quantum information stored in qubits. Below are three examples of recent innovations that promise to reduce the ratio of physical-to-logical qubits dramatically.

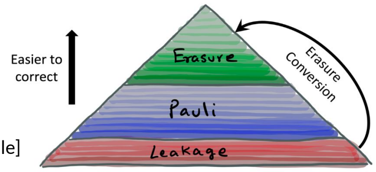
Erasure:

The dominant source of error in some architectures is qubit leakage errors out of the computation space. Raising a flag on leakage errors converts them to erasures, which are easier to correct since we know where they are.

This idea was recently demonstrated with neutral atoms* [Wu22] and quickly spread to other modalities [e.g., Koottandavida24]. This could make errors up to ten times easier to correct [Princeton].



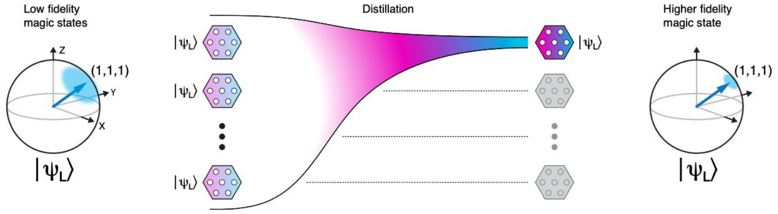
[AWS]



[Yale]

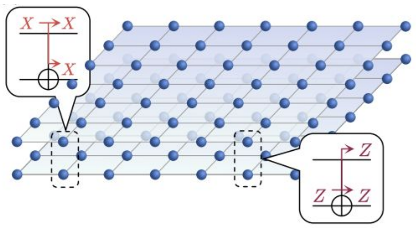
Logical magic state distillation:

Magic states are a key requirement for scalable processing. They complete the set of universal gates but are resource intensive. Such higher fidelity gates were recently demonstrated with neutral atoms. [Rodriguez24]



Correlated decoding:

Errors on one logical qubit can be correlated to errors on other logical qubits, and this information can be utilized within error correcting algorithms to reduce the resource requirements. This methodology was recently proposed. [Cain24]



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* Erasure errors are known to be easier to correct in the context of photonic systems [Knill01]

III. High-Performance Computing + AI + Quantum:

an exciting prospect Chemistry example

Solutions to important chemistry problems are likely to require an integration of classical high-performance computing (HPC), AI and quantum computing. Below is a proof of concept example [MSFT24].

Such algorithms will continue to improve as the number of qubits increases and we are able to experiment with and develop the algorithms on larger machines. This would mirror the the evolution of AI which required bigger hardware in order for the initial models to become practical.

Recent case study from Microsoft Azure for a practical problem involving a chiral reaction and a catalyst.

Quantum computers enable the solution by targeting just the molecular configurations that are impossible for classical computers to solve, i.e., the strongly correlated configurations where electron entanglement is important.

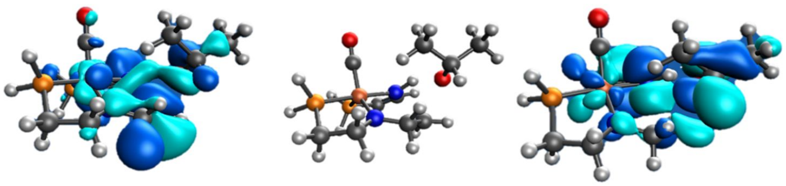
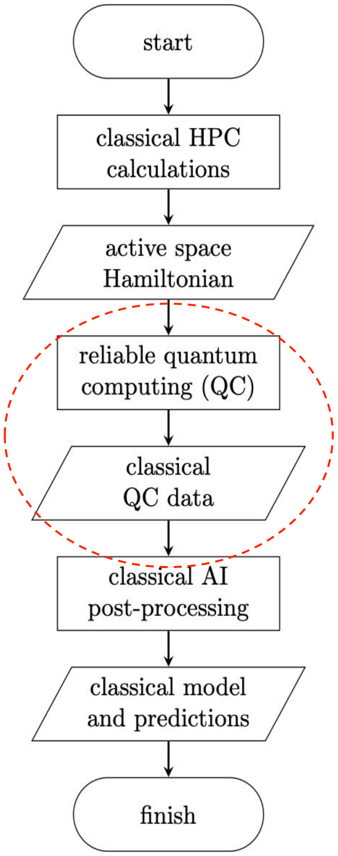


Figure 3: An example of a correlated molecule (middle), and the orbitals containing the entangled electrons (left, right) in the active space.

Workflow*

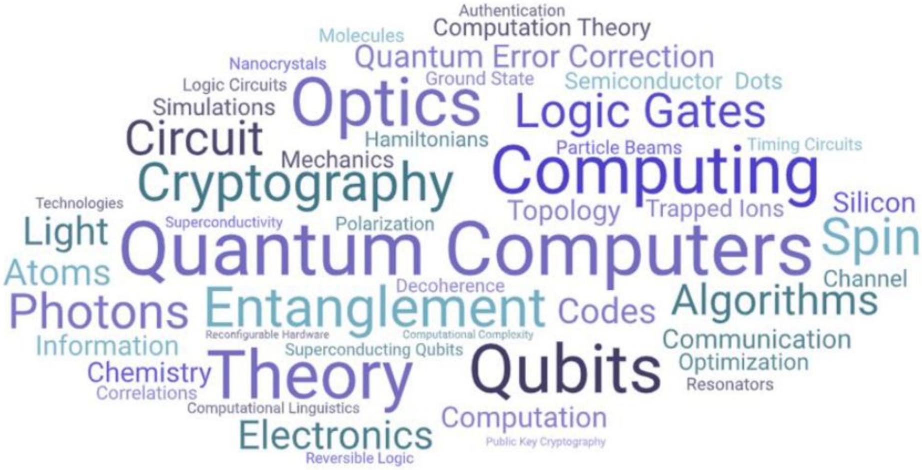


*Dotted circle added by me for emphasis

IV. Capturing value will require cutting through complexity & hype

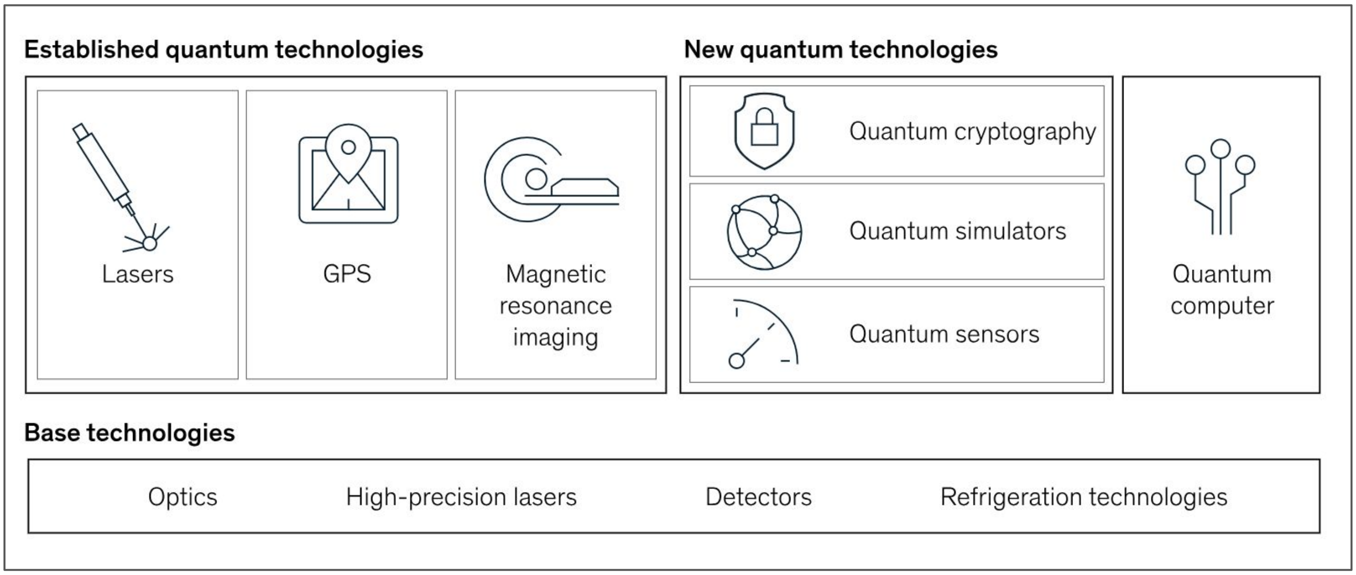
From exotic concepts…

50 most used keywords in quantum technology publications [Kurek20]



… to a structured portfolio of real applications

Illustrative. Many factors, *e.g.*, size and timing must also be considered [MCK21]



> *“I think there is a world market for maybe five computers.”*
>
> - Thomas Watson, chairman of IBM (1943)

Acknowledgments

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Glossary

Fault-Tolerant Quantum Computer:

A quantum computer uses qubits to reliably performs computations despite errors, using quantum error correction to maintain accuracy.

High-Performance Computing (HPC):

A system that combines multiple powerful *classical* computers working together to solve complex problems and process massive amounts of data far faster than standard computers can achieve.

Logical Qubit:

A reliable unit of quantum information in a quantum computer, created by combining multiple physical qubits to correct errors. This makes quantum computations more accurate, ensuring dependable results even when individual physical qubits might be prone to mistakes.

Modular architecture:

A design approach where a quantum computer is built from smaller, interconnected units rather than one large system, allowing better control, error correction, and scalability.

Physical Qubit:

The actual hardware unit in a quantum computer that stores and processes quantum information. It is the quantum equivalent of a classical computer bit. Unlike a classical bit, which can be either 0 or 1, a qubit can exist in a superposition of both states simultaneously, enabling more complex computations.

Quantum Error Correction:

Techniques used to protect quantum information from errors due to decoherence and other quantum noise. Error correction is essential for building practical and reliable quantum computers.

RSA Encryption:

A widely-used security method to protect digital communication, forming the backbone of modern internet security.Encryption systems like RSA rely on the difficulty of factoring large numbers to keep information secure. In principle a fault-tolerant quantum computer could break RSA encryption by efficiently solving the factoring problem.

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