

Examining Varied Quantum Computing Modalities for Large-Scale Computation

A new frontier.

A new frontier in technological advancement is sparking a new arms race between governments and private corporations, and I am not talking about artificial intelligence. While the breakthroughs in machine learning-driven classical algorithms are certain to profoundly change our lives, a new “white whale” technology is already breaching the ocean of human imagination, and every government and major computer hardware manufacturer is eager to be the metaphorical Captain Ahab to spear it first. Like the good captain, we are standing on the deck of the Pequod staring down our greatest potential achievement, a new kind of computer that promises to usher in the age of quantum supremacy.

If you are still trying to wrap your mind around the neural networks and classical computations that enable ChatGPT, you could be forgiven for writing off quantum computers as something that is more science fiction than science fact. However, quantum computers are very real. While there remain immense challenges towards reaching quantum supremacy, the point at which a quantum computer can outperform a classical supercomputer, there are arguably no more breakthroughs in the science needed to achieve it, but rather incremental hurdles that must be overcome.

In this paper, we are going to examine five different modalities of quantum computers currently in development (e.g. superconducting, trapped ions, photonic, neutral atoms [cold atoms], and quantum dots [silicon]). Each unique method of developing quantum computations holds varying advantages and disadvantages, which we will review and assess. Hopefully, by the end of this paper, whether you are being introduced to quantum computers for the first time or are an industry subject matter expert, you will come away with a better understanding of the practical realities of large-scale quantum computation.

The promise of quantum supremacy.

Those who consider themselves subject matter experts in quantum computing and are short on time or patience, are invited to skip this section, which will focus on introducing concepts with which you are likely already familiar. For everyone else, buckle up.

Let me start this story at the end and go straight to selling you on the vision that quantum supremacy promises humanity. If I can sell you on the vision, then perhaps you'll stick around for the gritty details.

Imagine living in a world in which every disease has been cured, and humans travel the solar system in ships made of novel chemical compounds, where communication with people on Mars is instantaneous, and an optimal solution can be found to any problem. Now imagine you see this world with your own eyes, in your lifetime.

Now that I have sold you the dream, let's bring things back to reality and talk about what quantum computers are and why this new technology has the potential to be so ground-breaking. In many ways, quantum computers are like regular computers, both process information. What makes quantum computers unique is that they process this information using specific properties of quantum mechanics; namely superposition, interference, and quantum entanglement.

A classical computer creates computation by manipulating bits of 1's or 0's using electrical pulses and passing these bits through transistors to be computed by a Central Processing Unit (CPU), which, in turn, uses rules of classic logic to execute a program. A quantum computer, on the other hand, creates computation by using entangled qubits whose superpositions are changed by passing them through gates. Quantum interference is used to control the 'phase' of the qubits to manipulate the probability of getting the correct answer and canceling out the wrong ones.

This provides a significant advantage for quantum computers when executing certain tasks, both in their ability to gauge probabilities and their computational scalability. Unlike classical bits, qubits do not have to be a one or zero they can be any probability *between* 1 and 0. This allows quantum computers to throw classical statistics out the window.

In classical statistics, if I flip a coin, the probability of guessing the outcome of the toss correctly is 50%. However, in the world of quantum computers, it is possible to have a greater than 50% chance of guessing the outcome. Have I blown your mind yet? If you're more technically oriented and want more information on this, look into the thought experiment "the quantum coin toss" or research "Quantum Key Distribution (QKD)", which is a real-world application that utilizes these enhanced probabilities for cybersecurity.

For most of us, it's not important to understand how this works, but merely to understand that the math does work. This allows quantum computers to gauge probabilities more accurately than classical computers making them uniquely suited to solving for optimal solutions. However, for those more quantitatively inclined, here's how the math for the "quantum coin toss" is illustrated in Dirac notation:

$$|\psi\rangle = H|0\rangle = \frac{1}{\sqrt{2}}(|0\rangle + |1\rangle)$$

The advantages of quantum computers do not stop at enhanced abilities to gauge probabilities. Quantum computers also have immense scalability advantages over classical computers. Classical computers use electricity to pass bits through transistors, which are processed as lines of code sequentially through a Central Processing Unit (CPU) and an output is generated. The computer's CPU can only process one line of code at a time before moving on to the next line of code.

In a quantum computer, calculations are done at the atomic level by each atom acting as its own CPU. This means that, theoretically, a huge amount of entangled atoms (acting as CPUs) are processing information simultaneously without taking up much space since atoms are so small. In other words, a classical computer processes code sequentially through a limited number of large CPUs, whereas quantum computers process code simultaneously through a theoretically enormous number of very small atoms.

We can illustrate these benefits through a simple thought experiment. Imagine a maze. A classical computer is instructed to find the optimal route through the maze. It accomplishes this by trying every possible pathway, in sequence, and then comparing all the results to determine the optimal pathway through the maze. Given the same task, a quantum computer tries every possible pathway through the maze *at the same time*, quickly arriving at the optimal solution.

Another example of how quantum computers excel at optimization is known as the 'traveling salesman problem'. A salesman wants to travel to every city and town in America and wants to know the optimal route to take. There are over 19,000 cities and towns in America. Even if a classical supercomputer could evaluate a trillion routes per second, it would still take longer than the age of the universe to go through all the different permutations of cities due to the high number of factorials. This is the exact type of problem quantum computers promise to be able to address.

Taking advantage of quantum statistics and the enhanced scalability achieved from processing information simultaneously at the atomic level, quantum computers promise to usher in an age of quantum supremacy. Artificial intelligence-driven quantum algorithms can create advanced mathematical optimization models in chemistry, biology, logistics, and natural sciences in mere moments that would take the world's fastest supercomputers hundreds of thousands of years to compute.

The practical challenges with quantum computers.

I said earlier that there are no more breakthroughs needed in the science to make quantum computing a reality, only incremental hurdles that need to be overcome. What are these obstacles, and what are the practical realities of implementing large-scale quantum computers?

Like many things in quantum physics, an oversimplified answer is the best. Keeping matter in a particular quantum state is a delicate exercise, and many things can cause it to fall out of the desired state. The primary issue facing the practical implementation of the technology, therefore, is the need for error correction. There are two primary types of errors: stochastic noise and systemic noise. Stochastic noise is caused by random and unpredictable errors that occur between measurements, such as environmental noise, control errors, and readout errors. Systemic noise is predictable and repeatable and includes such challenges as coherence errors, decoherence (T1 and T2 errors), quantum leakage, and residual couplings.

The challenge for the scientists and engineers who are building quantum computers is how to best identify when an error has occurred and to correct it while continuing to process computations. This process is known as quantum error correction.

The need for error correction isn't a novel problem. Even classical computers require error correction, that said, errors within classical computers are rare in comparison to their quantum counterparts and are, therefore, much more easily managed. For this reason, classical computers present the best opportunity for enabling the practical implementation of the first large-scale quantum computers.

Most current and near-future envisioned quantum computers are hybrid quantum-classical systems, specifically to address the need for quantum error correction. In this hybrid model, quantum algorithms

handle most computations, while classical algorithms serve as a form of quality control analyzing quantum computations for errors and correcting them when necessary.

These hybrid quantum-classical systems can also be used to solve other problems facing large-scale quantum computation, such as memory storage, as quantum matter is not well suited for storing information over long periods. That's another challenge, though, that I will not be diving into in this paper.

Pathways to revolutionizing large-scale computation.

Now that we know what quantum computers are, and we understand the problems with error correction and memory storage currently prohibiting large-scale implementation of quantum computers, it's time to get to the heart of this paper and discuss the different modalities being pursued to generate quantum computation.

Each of these varying modalities comes with different engineering challenges, but also carries unique advantages over competing systems. Assessing the tradeoffs between these systems is important in determining which quantum computer may best service specific practical needs within the marketplace.

To help assess which quantum computers may be superior for a particular field, let's start by discussing specific use cases of problems within the marketplace that quantum computers may be uniquely suited to address.

I started this paper alluding to an "arms race" to reach quantum supremacy and I was not being allegorical. The first and most obvious need within the marketplace is the military application of quantum technologies. In 2023, America, the EU, the UK, and China all funded approximately a billion dollars apiece to fund their quantum research programs.

The technologies at the forefront of the world's military priorities are quantum communication, quantum navigation, quantum clocks, quantum key distribution for cybersecurity, and, of course, AI-powered quantum computers.

It is easy to understand the military appeal. A radio that instantly transmits over any distance, through any medium, and is immune to enemy interception? "Yes, please." Precision navigation for ships without

the need for satellite communication? “Absolutely, for the entire fleet.” A clock so accurate it only loses several milliseconds over the lifespan of the entire universe? “Sounds like a great addition to our missile defense shield.” How about breaking through your enemy’s cybersecurity encryption in mere seconds? You can almost hear the generals screaming “Hercules, Hercules!”

Of course, the benefits promised by quantum computing exceed far beyond its military applications. In the biotech industry, the optimization benefits of quantum computation in virus modeling, gene mapping, and many other applications promise to produce new medicines at record speeds.

Financial institutions, like HSBC, that make their living on securing assets are already investing in new, quantum-proof encryption protocols to thwart the quantum hackers of tomorrow. Blockchains, such as Algorand, have already pioneered new consensus protocols to ensure their networks remain secure from quantum attacks.

Chemistry companies will utilize the technology to model new chemical compounds, creating novel materials from elemental mixtures that humans haven’t yet even conceived, and shipping companies will utilize them to optimize their logistics infrastructure.

There are far too many potential applications on which to speculate, much less to list them all, but the larger the data set and the higher the complexity of the problem, the more likely it is that quantum computation will play the key role in creating the solutions.

Superconducting quantum computation.

The first modality we are going to discuss is also the most prevalent, and one with which most people reading this are likely familiar. Superconducting quantum computers are currently being built by some of the world’s largest technology companies and biggest names in the industry. IBM, Google, D-Wave Systems, Rigetti Computing, Intel, and Quantum Circuits, inc. (QCI) are all pursuing superconducting quantum computers.

Superconducting quantum computers have seen some of the highest investment across the industry and are some of the most reliable and powerful forms of quantum computation today. This modality boasts a significant market share for a reason. Superconducting qubits have

been studied for many years, and there is a strong network of subject-matter experts who can support development.

The maturity of this technology has led to advanced techniques for manipulating and measuring the state of superconducting qubits, which helps with their practical usability. These qubits process information at incredibly high speeds, enabling rapid gate operations. This speed enables complex computations to occur within the coherence time of the qubits, minimizing systemic noise.

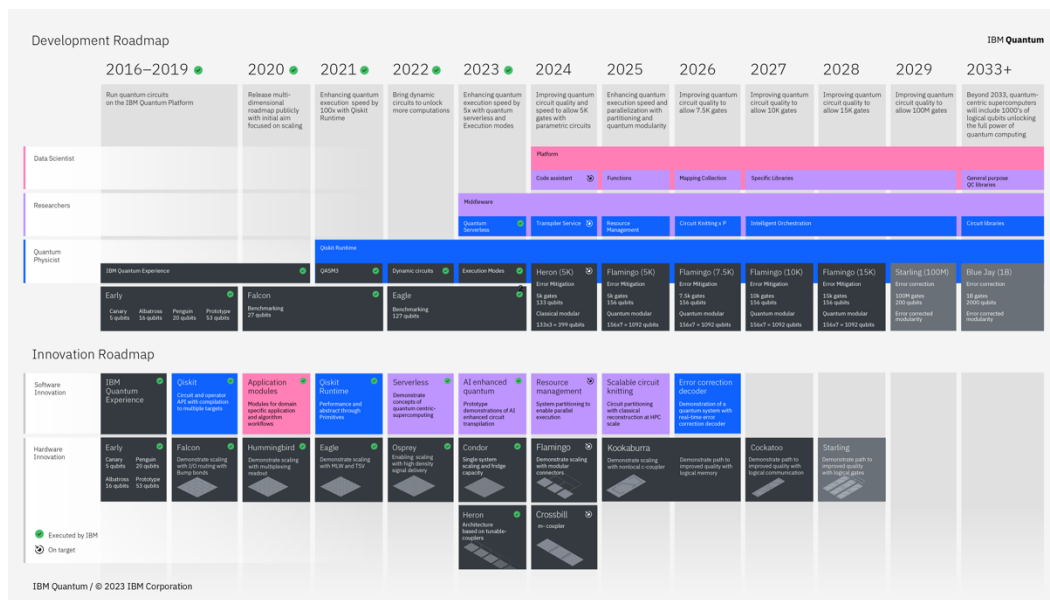
This modality also offers significant benefits in scalability, as superconducting qubits utilize techniques like those in semiconductor manufacturing. This provides time-tested expertise in advanced manufacturing that superconducting quantum computers can feasibly benefit from. It also has the added advantage of aligning well with classical electronics technologies, which may play a significant role in developing hybrid quantum-classical computers in the future.

Superconducting quantum computation is not without its disadvantages. Superconducting qubits operate at extremely low temperatures, some of the coldest temperatures in the known universe. This requires large, expensive dilution refrigerators, and complex maintenance operations.

Error rates among superconducting qubits are also higher than in other modalities. Fabrication techniques can introduce variability into the physical properties of the qubits. Superconducting qubits are also sensitive to electrical and magnetic fields, which can become problematic the more you try to scale out the technology, decreasing coherence times and increasing the need for error mitigation and correction.

In December of 2023, IBM released its new quantum processor, the 'IBM Quantum Heron,' the highest-performing quantum processor in the world, offering a five-fold improvement in error reduction over its predecessor. This announcement coincided with the release of IBM's new quantum computer, 'IBM Quantum System Two', which features the company's first modular architecture and should boast an industry-leading 399 qubit performance in 2024. This is a significant upgrade over the previous 127 qubit model.

IBM also released its ten-year quantum development roadmap, which provides significant insights into how IBM is planning to develop its superconductor quantum computer. While this roadmap only advocates IBM's position, we can assume it reflects wider industry trends among those pursuing superconducting computation.



IBM Quantum Roadmap

As part of IBM’s ten-year strategic vision, they are planning AI integration with WatsonX, bringing the power of Watson’s formidable generative AI capabilities to quantum processes. IBM will also release Qiskit 1.0 to enable better quantum circuit coding and circuit optimization capabilities, as well as a new developer SDK allowing software developers to utilize traditional classical coding languages to program quantum software.

Error mitigation and correction will remain the primary focus for IBM’s scientific research, and ‘IBM Quantum System Two’ will accommodate future generations of IBM’s quantum processors. Based on this strategic roadmap, we can confidently say IBM sees hybrid quantum-classical computers as the future of quantum supercomputing.

Trapped-ion spin computation.

Another modality seeing significant investment is trapped-ion spin computation. Companies such as IonQ, AQT, Universal Quantum, Oxford Ionics, and Quantinuum (Honeywell) are all pursuing this technology.

Trapped-ion spin computation holds many promising advantages that have made it an attractive area for investment. Trapped-ion qubits have extremely high fidelity in both single-qubit and two-qubit operations.

Having high fidelity is crucial for minimizing error rates in quantum computations.

These qubits also exhibit long coherence times, maintaining their quantum state for relatively long period before decoherence. This allows trapped-ion qubits to perform complex quantum algorithms that require multiple steps. Lasers can be employed to precisely manipulate quantum states, further increasing the likelihood of accurate computations.

Multiple ions can be linked through shared vibrational modes enabling scalability for building larger and more complex quantum computers. The ion traps can be reconfigured to connect qubits into different configurations, allowing for flexibility in how qubits interact with one another. Because each ion can be individually addressed and manipulated without affecting others, unique quantum algorithms can be employed that require manipulation of specific qubits.

Trapped-ion qubits show unique promise in quantum communication technology, as they have a unique property of being able to interact with photons. These photons can potentially be used to carry information over long distances.

This technology does face its own unique disadvantages as well. One of the most prominent challenges facing these computers is their ability to scale while maintaining high gate fidelity. Trapped-ion qubits have relatively slow gates speeds (i.e. high error rates) in relation to other platforms, such as superconducting qubits, which can hinder certain types of computations.

Individual qubit control also serves as a double-edged sword, along with the advantages of enabling unique quantum algorithms, comes the challenge of managing the complex network of laser systems that enable such precise control, but also serve as additional points of potential failures.

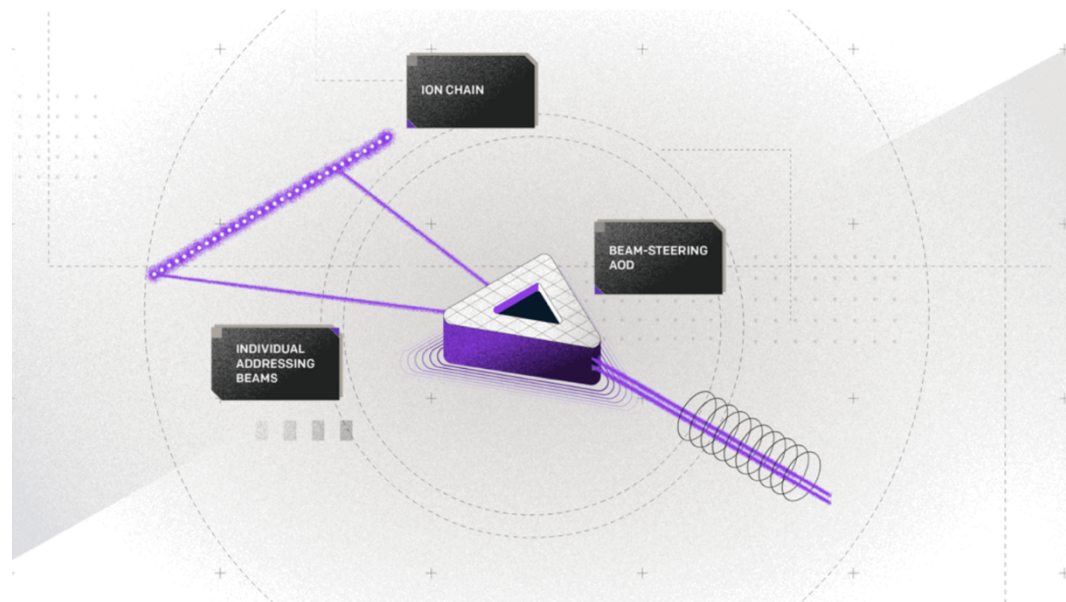
Trapped-ion computers also face unique possibilities of generating systemic noise. In ion trap systems, ions are trapped using oscillating electric fields, which can cause micromotion and ion heating, leading to interference with qubit operations. They are also sensitive to unique possibilities of experiencing stochastic noise, as trapped ions are sensitive to external magnetic fields. Shielding and advanced error correction techniques are required to mitigate these effects.

Ion trap devices are not a natural fit with classical technologies, both in their suitability for hardware interfacing as well as their ability to

integrate with classical software and algorithms. This may lead to unique challenges when developing hybrid quantum-classical platforms as well as difficulty in building out software development kits (SDK's) for developers who are trained on classical systems.

In 2023 IonQ announced its newest commercially available trapped-ion quantum computer, the IonQ Forte. With this new iteration, IonQ has put a heavy focus on qubit and operation fidelities over qubit count, demonstrating IonQ understands how imperative it is to mitigate errors and enhance computational accuracy in tandem with increasing the number of qubits.

IonQ accomplished this by integrating acousto-optic deflectors (AODs) to direct the laser beams at individual qubits. The significance of this new approach is the ability to support more qubits, and an increase in precision and stability to the laser beam to provide higher fidelity by minimizing noise and ion heating, which lead to unintended errors.



An illustration of the AOD architecture in Forte

These upgrades bring IonQ's commercially available trapped ion-spin quantum computer to 29 qubits that can run circuits across roughly 840 gates. While 29 qubits may not seem like a lot, keep in mind that each additional qubit doubles the computational power of the system. In IonQ's previous version which had #AQ25 (IBM's metric for measuring high-fidelity qubits), IonQ could offer customers 33.5 million usable computational states – the possible answers that can be sampled at the

end of a quantum circuit. With Forte and an #AQ29, the number of possible computational states has increased to 536,870,912.

Photonic Computation.

Photonics is a particularly interesting modality due to its potential for integrating into fiber-optic communications networks, giving photonic computation intriguing applications within the telecommunications sectors, and unique capabilities within quantum communications technologies.

PsiQuantum, Xanadu, Bosch, IBM, Google Quantum AI, NTT Research, and Quix are all investing in photonics-based approaches to quantum computation. While IBM and Google are typically known for their research into superconducting quantum computers, they are also developing a photonics-based approach.

Photonic quantum computers use photons (light particles) for quantum computation. They have high speed and low latency and are less prone to decoherence due to stochastic noise making photonic computation more stable and reliable. Since they use light particles, they can be more readily integrated with existing optical fiber networks, which may be beneficial for communication and networking applications.

These computers also have some advantages when it comes to scalability, as they can operate at room temperatures and don't have to be cooled to extremely cool temperatures like other quantum systems. Because they do not require these large cooling systems, they are also more energy efficient.

There are also several theoretical advantages to photonics that are actively being researched. Due to unique properties of photons, this modality may have unique and enhanced potential for quantum error correction. It is suitable for a range of quantum algorithms and applications.

A major drawback to this modality is the lack of longevity of research within the field, as photonic computation is still in its infancy. Specific challenges such as efficiently generating and manipulating single photons are actively under research.

Error correction is more challenging in photonic systems because photons do not interact easily with one another, making the implementation of quantum error correction protocols more difficult.

The optical circuits required to manipulate atoms using photonics become significantly complex the more you scale out the technology, which can lead to difficulties in maintaining coherence due to lack of synchronization across all the components. Accurate timing and synchronization are essential when dealing with entanglement and interference of photons.

Photon loss is a unique issue for photonic systems. Because photons can be lost through absorption and scattering in the optical components, this can cause computational errors that would not occur in other modalities. This loss becomes more problematic the more you scale out the system.

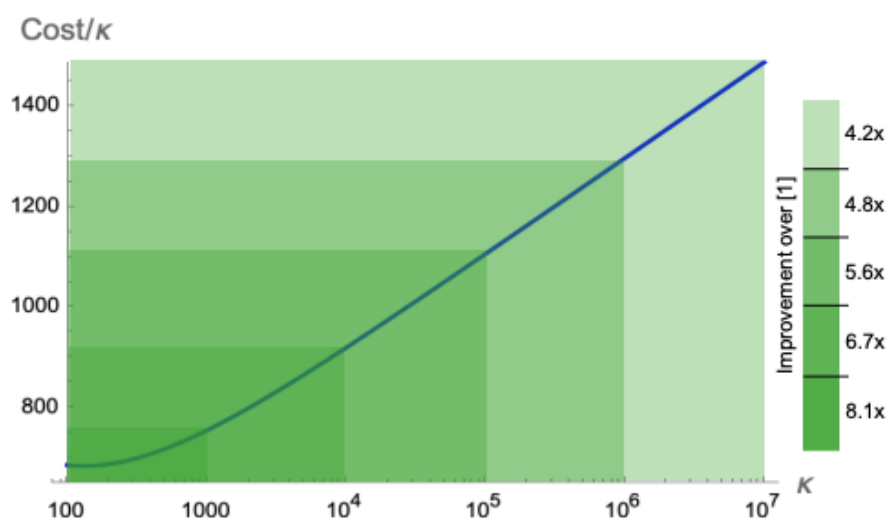
As mentioned earlier, while photonics has significantly fewer cooling requirements than superconducting systems, they still require cryogenic cooling for some components.

PsiQuantum, a leading developer of photonic quantum computation has a vision of developing the first million qubit photonic computer. Recently, PsiQuantum partnered with the United States Department of Energy's (DOE) SLAC National Accelerator Laboratory to leverage its infrastructure and cryogenic engineering expertise.

Their primary focus is scaling a highly fault-tolerant computer at a large scale. All quantum computing systems require cryogenic cooling, PsiQuantum's photonics approach requires much less than other modalities because the qubit itself does not feel heat. Only the single-photon detectors that measure the qubit need to be cooled.

While most other modalities operate at near absolute zero, PsiQuantum's photonic computer can operate at several degrees above absolute zero, which means it can operate at temperatures hundreds of times warmer than superconducting quantum computers.

PsiQuantum has strong ties to the American government, working with the DOE, DARPA, Air Force, and the Los Alamos National Laboratory, the latter of which resulted in a quantum linear solver algorithm that combined ideas from adiabatic quantum computing and quantum signal processing filtering techniques to improve error scaling, as shown in the image below.



Plotted is the query count of the QLSA algorithm in units of κ , for $\alpha=1$ and $\epsilon=10^{-10}$

Neutral [Cold] atom quantum computation.

Our next exciting modality of quantum computation is one of the modalities I am most excited about. Neutral atom computers also utilize photonics, however, qubits are comprised of atoms with no electric charge, such as Rubidium (Rb), Cesium (Cs), Strontium (Sr), and Ytterbium (Yb). The ability to utilize these different elements allows neutral atom computers to take advantage of some of the natural variations in properties of the different elements.

Some companies currently pursuing neutral atom quantum computers are Infleqtion (ColdQuanta), Pasqal, Atom Computing, QuEra Computing, and Rydberg Technologies.

Rubidium atoms are structured well for ease of cooling and trapping using laser light, and therefore well suited for quantum computation. Cesium and Strontium have specific properties well suited for precise timekeeping in atomic clocks. Ytterbium has unique electronic configurations and fermionic and bosonic isotopes, which are advantageous for different quantum technologies.

The desired element is chosen for its unique properties and based on the desired application of the product being developed. These atoms

are then cooled to near absolute zero using laser cooling techniques. At these low temperatures, atoms form a Bose-Einstein condensate state of matter, where atoms become almost motionless and condense together like the droplets on the outside of a cold glass of water. This allows the atoms to be precisely controlled and manipulated using lasers and magnetic fields.

One of the most significant advantages of this approach is the potential for scalability. Due to the atoms of a given element being naturally identical, large arrays of qubits can be created using optical lattices. This uniformity allows easy manipulation of multiple atoms simultaneously, and theoretically, should make it easier to build larger and more scalable quantum systems. This uniformity has the added benefit of leading to fewer errors in computations.

Neutral atoms have long coherence times compared to other qubit types and offer flexibility in the way qubits interact with one another. Rydberg states allow for the precise control of interactions between each atom, essential for performing quantum gates and algorithms.

One of the most unique and important advantages is that neutral atom setups do not require cryogenics. The atoms are cooled using specific frequencies of laser light, which cools the atoms to near absolute zero, but the system itself can operate at room temperature. The ability to operate at room temperature gives this modality unique capabilities that will certainly be appealing to the militaries of the world.

The neutral atom approach is also suitable for quantum communications, as atoms of these elements interact with photons, which are essential for carrying quantum information over long distances.

These systems can detect states of matter with high precision and are very well-suited for quantum algorithms and error correction.

Neutral atom computing faces a lot of the same challenges as photonics, such as maintaining the ability to manipulate individual qubits at scale and managing technical challenges of optical system complexity as the system scales and has similar challenges integrating with classical systems. This approach also lacks some of the longevity of research enjoyed by other modalities.

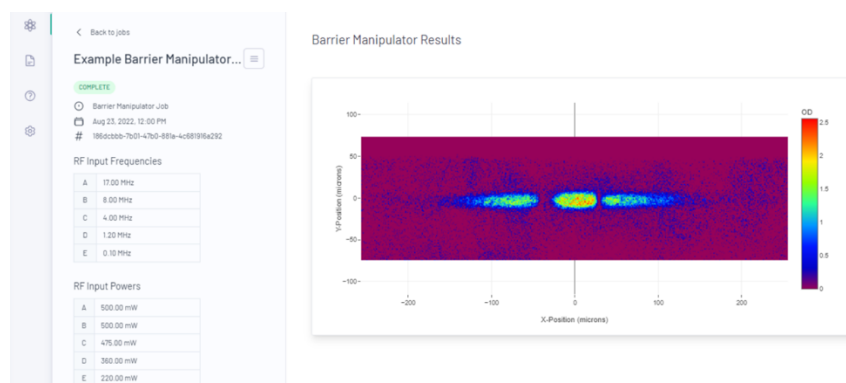
Increasing the speed of quantum gate fidelity is a significant challenge to this approach, as other approaches can achieve faster gate speeds and therefore make faster computations.

Unlike photonics, neutral atom computers are susceptible to environmental factors, such as magnetic and electrical fields, but also temperature fluctuation. This makes this modality more prone to errors due to stochastic noise.

Infleqtion (ColdQuanta) has been a leading pioneer in neutral atom technologies, and has significant ties to the US government, netting hundreds of millions in investment from DARPA as well as being contracted to build the US Military's first atomic clocks. Most recently, they secured a contract to partner with QinetiQ, a leading defense company in the UK, to develop AI and machine learning quantum systems in handling datasets with complex correlations.

Taking full advantage of the unique capabilities of the different elements utilized to form qubits using this method, Infleqtion has developed a product lineup comprised of an atomic clock called 'Tiqker', a cloud-accessible Quantum Matter Service called 'Oqtant'. They manufacture atomic prisms, cold atom source cells, trapped atom vacuum systems, magneto-optical traps, and cold atom cores for other laboratories.

Through a recent acquisition, Infleqtion now boasts a formidable software portfolio called 'Superstaq' that enables developers to write quantum program in any source language (CirQ, OpenAPI, Qiskit, and Build-your-own). The software also has significant test and benchmark capabilities, and Infleqtion offers application libraries and compilers through APIs and Python interfaces.



Infleqtion's cloud-based quantum matter service allows scientists, teachers, and enthusiasts to create their own Bose-Einstein condensate states of matter for novel experiments and is accessible via python API's and a web application.

Quantum dots [silicon] computation.

Representing an emerging and lesser-known system of generating quantum computation, quantum dots are nanoscale particles that exhibit quantum mechanical properties. They are small enough that they confine electrons into three spatial dimensions, which creates atom-like energy levels. This is known as the “quantum confinement effect.” This is a great example of how the miniaturization of materials to the nanoscale can lead to new technologies that are not possible with larger materials.

Most quantum dots are made from semiconductor materials like silicon, cadmium selenide, or indium arsenide. Each different material determines varied characteristics of the quantum dot’s properties. The energy levels of quantum dots are tunable, including their optical and electronic properties, which can be manipulated by changing size, shape, and material composition. The smaller a quantum dot the higher the energy level.

Quantum dots also exhibit properties of photoluminescence, meaning they can absorb light in a specific wavelength and emit light at a different wavelength. This makes them very useful in applications like TVs and monitors. For quantum computation, quantum dots can be used to create qubits, which can be manipulated by controlling their electronic properties.

Some of the companies currently pursuing quantum dot computation are Toshiba, Intel, Quantum Motion Technologies, Quecetel, Microsoft, and Delft Circuits.

This unique approach to quantum computation comes with notable benefits, such as theoretically high scalability, as quantum dots are nanoscale in size and can fit a high density of qubits into a small space.

Because quantum dots are fabricated using existing semiconductor techniques, this modality also benefits from being able to leverage the existing manufacturing structures and expertise of the semiconductor industry. This compatibility with semiconductor technology may lead to easier integration with classical electronic systems as well as yield the benefit of lower production costs. Since the quantum states are manipulated using electricity, this modality does not require the use of lasers, possibly reducing the complexity of highly scaled systems.

Quantum dot systems have the potential for high-fidelity gate operations, and the energy levels can be finely tuned using external electric or magnetic fields allowing precise control over quantum states with low error rates.

They can also integrate with photonic systems, as they can both emit and absorb photons, making them suitable for quantum communication and networking.

This modality also faces some unique challenges. While utilizing existing semiconductor manufacturing techniques is an advantage, due to the small size of manufacturing at the nanoscale, it is technically challenging to fabricate quantum dots with uniform size and properties. Any variation in the components can affect computation accuracy.

Quantum dots are sensitive to environmental factors, such as temperature and electromagnetic fields, which can lead to stochastic errors within the computations. It is also hard to measure the states of quantum dots without disturbing the quantum state, which causes readout difficulty.

Controlling individual quantum dots is technically demanding, as electricity used to affect a single qubit may inadvertently affect the states of surrounding qubits. This makes error correction within this modality uniquely challenging, and robust error correction mechanisms and advancements will be needed for reliable computation.

There are environmental concerns as some of the materials used to create qubits, such as cadmium selenide, can be toxic or unstable posing environmental and health risks. Energy costs are also higher due to the need to operate at extremely low temperatures and therefore the need to run cryogenic cooling processes.

Recently, Intel labs introduced 'Tunnel Falls', their most advanced silicon spin qubit chip to date and an iterative step towards building a full-stack commercial quantum computing system. The chip was developed using CMOS transistor technology and represents significant progress towards creating a manufacturable and operationally reliable quantum chip.



Intel's 'Tunnel Falls' silicon spin quantum chip.

Currently, the chip is being offered to scientists and research institutions to utilize for their experiments and eliminate the need for laboratories to manufacture their own devices. Intel is hoping to open a wider range of experimentation to learn more about the fundamentals of qubits and quantum dots, and to develop new techniques for working with multiple qubit devices.

The white whale.

When Herman Melville published “Moby-Dick” in 1851, it became and has remained a classic tale that explores themes such as the elusiveness of truth and meaning, the uncharted territory of the human psyche, and the limitations of knowledge and exploration. In the vast ocean, Captain Ahab is forced to contend with the limitations of human knowledge and exploration, as he pursues an ultimate truth that cannot easily be attained.

In many ways, Melville’s novel is reflective of the scientific pursuits challenging the engineering of today’s quantum computers, as researchers embark on a journey that is not guided by any external map, and indeed brings them to push the limits of humanity’s understanding of the natural world.

Perhaps there is a lesson in this novel for the investors who are pursuing development in this space. When the opportunities are so great

but carry immense challenges and risks, remember Melville's famous quote "I know not all that may be coming, but be it what it will, I'll go to it laughing." As we face the dangers of life at sea, pursuing our white whale, proceed with cheerful stoicism.

There is no current modality that can claim it holds the keys to achieving quantum supremacy, and no development roadmap that paves a certain pathway to the promises this achievement holds. With the direction unclear, investors should press forward with the humility of one seeking treasure without a map. You must be prepared to change direction.

As the industry matures, no doubt certain modalities will rise above others to dominate certain industries, but until the direction becomes clearer, your best chance of catching the white whale is to cast a wide net.