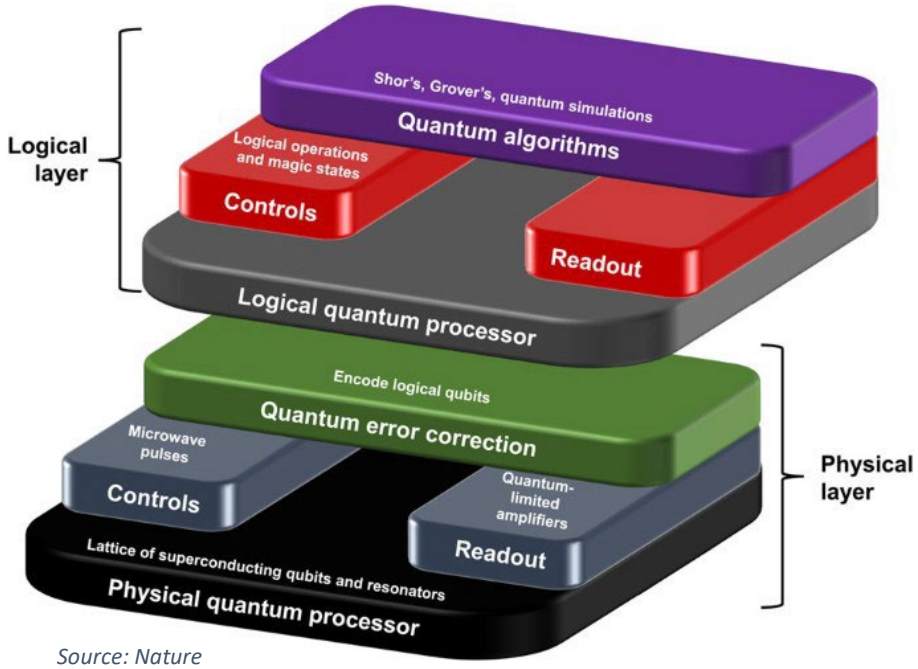
The Quantum Leap
December 12, 2021

The Evolving Quantum Computing Ecosystem

In the past few posts, I have described what a Quantum Computer is and how it can be so powerful and transformative, basic features of qubits and highlights on some of the major players in Quantum Computing ("QC"). But just like the evolution of personal computing, there are many participants in the QC ecosystem beyond just the makers of the actual machines. You likely use a PC today, manufactured by one of several hardware makers. However, your machine's core operating memory is made by a different company, it is built upon an operating system (likely MS-DOS, owned by Microsoft) as well as various software applications. You may also use external data drives, a mouse input device, a screen, a printer, various cables, and other physical devices. You likely also access the internet and some of the cloud services, utilize a virus protection program and other related activities and services. There are likely dozens if not 100's of companies whose technologies you use daily to operate your computing device.

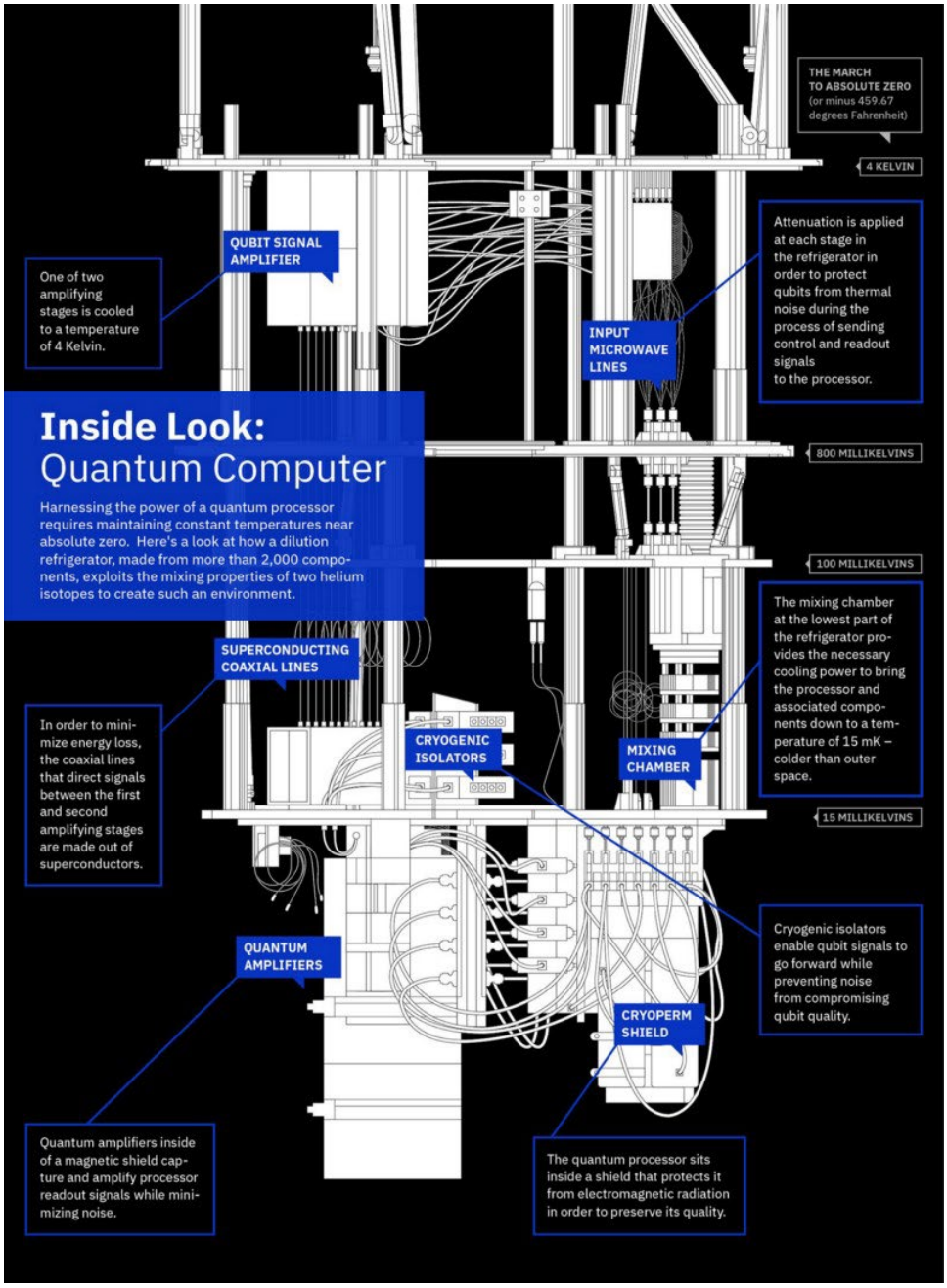
Companies like Oracle ($280 billion market cap; database management), Ingram Micro ($5.8 billion market cap; distributor of technology equipment), Cisco ($250 billion market cap; interconnecting equipment and services), Symantec ($15 billion market cap; antivirus protection), Adobe ($311 billion market cap; document and process software) and Salesforce ($262 billion market cap; productivity platform) have created enormous value despite not actually making any computers. Quantum Computers will likely spur many similar such players in its ecosystem, in fact there are already 100's of players engaged in this space., Some of these participants may also carve out significant market positions and value. To give a sense for the breadth and depth of players needed, you can visualize the basic inner workings of a Quantum Computer as follows:



Source: Nature

As this graphic shows, there are various aspects of the physical creation and manipulation of qubits (the bottom section of the graphic) along with software needed to control the logical layer. Also, covered in a prior post, there are various ways to create qubits, often requiring cryogenic temperatures and/or detailed laser or radio frequency controls.

Here is another graphic to help visualize the complexities of building a quantum computer:



Source: IBM

You'll note the various wiring, amplifying, microwave generation and chilling components all requiring highly specialized design and control. To describe the various QC players, it is helpful to segregate them into some functional categories or buckets as follows:

Hardware: Companies seeking to build a fully functional Quantum Computer. Many are also creating software and integrating access to the cloud. As discussed in a prior post, there are a few competing technologies underlying the creation of a working Quantum Computer including superconducting loops and Quantum Dots (which require cryogenics), or Ion traps and Photonics (which require sophisticated optics/laser controls), among others.

Circuits/Qubits: There are some companies focused on qubits and their interoperability for entanglement rather than attempting to build complete systems.

Cryogenics: Superconducting loops and quantum dots require temperatures that approach "absolute zero" (~negative 460 degrees Fahrenheit). Many of the pictures you may see of Quantum Computers (like the graphic above) generally depict a 7-tiered structure, whereby the temperature is lowered in each of the layers, and there are companies that specialize in temperature control.

Wiring/Controllers: Operating near absolute zero, using lasers to control individual atoms or manipulating and controlling individual photons all require specialized and sophisticated devices and connections. Some players are focused just on these types of challenges.

Error Correction: Due to the current NISQ (noisy intermediate-stage quantum) landscape and the need to have enormous computing "overhead" to correct for the noise in today's qubits, some companies are concentrating on error correction strategies.

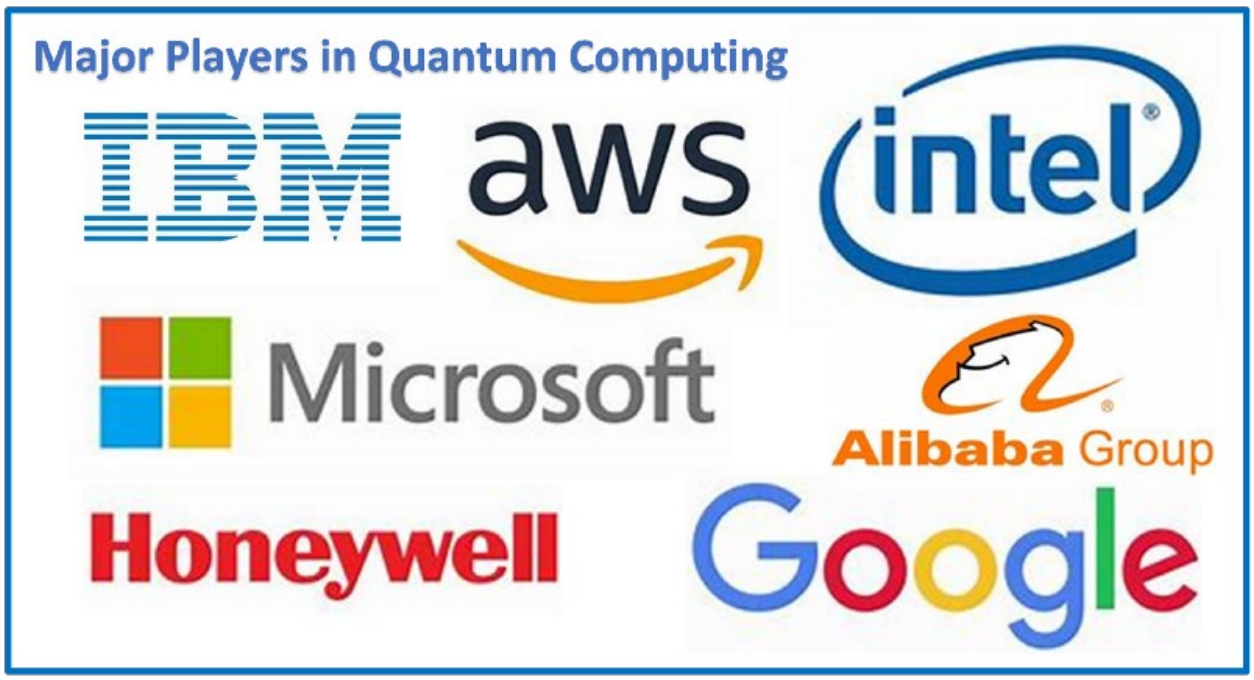
Photonics: Lasers and/or photons are being utilized in various QC constructs and some companies are providing this specialization.

Software: Many of the major companies have developed quantum software to control and manipulate the qubits and the gates formed to perform quantum algorithms. Some of these are creating open-source platforms while others are working on proprietary languages.

Applications: Although this is still a somewhat immature portion of the market, as Quantum Computers continue to become more and more robust, I expect to see many more businesses develop applications and various related consulting services.

I will describe some of the players in this ecosystem, although the list is vast and growing, so this is not meant to be a definitive roster, rather a sampling to highlight the broad set of players and opportunities in Quantum Computing. For a more complete list of players, I encourage you to visit this Quantum Computing Report listing.

In a prior post I noted that some of the largest players in the technology space have already dedicated large departments or divisions to Quantum Computing, as highlighted below:



Each of these firms is making a major push in Quantum Computing, although their "valuation" is more driven by their other activities. In any case, they are worth following and I expect their QC activities will make up an increasing portion of their values.

For the balance of this post, I want to focus more on the players who are dedicated to QC or who have major operating divisions participating in the space, segregated by the categories described above:

Xanadu: Operator of a quantum photonic platform which will combine with advanced artificial intelligence to integrate quantum silicon photonic chips into existing hardware to create full-stack quantum computers.

IonQ: IonQ is a quantum computing hardware and software company developing a general-purpose trapped ion quantum computer and software to generate, optimize, and execute quantum circuits. It is the only company with its quantum systems available through the cloud on Amazon Braket, Microsoft Azure, and Google Cloud, as well as through direct API access and was the first pure-play public QC company.

Atom Computing: Developer of quantum computers built using individually controlled atoms, creating nuclear-spin qubits made from neutral atoms that can be controlled, scaled, and stabilized optically.

PsiQuantum: PsiQuantum was founded on the premise that if you want a useful quantum computer, you need fault tolerance and error correction, and therefore ~1,000,000 physical qubits– to address commercially useful quantum computing applications.

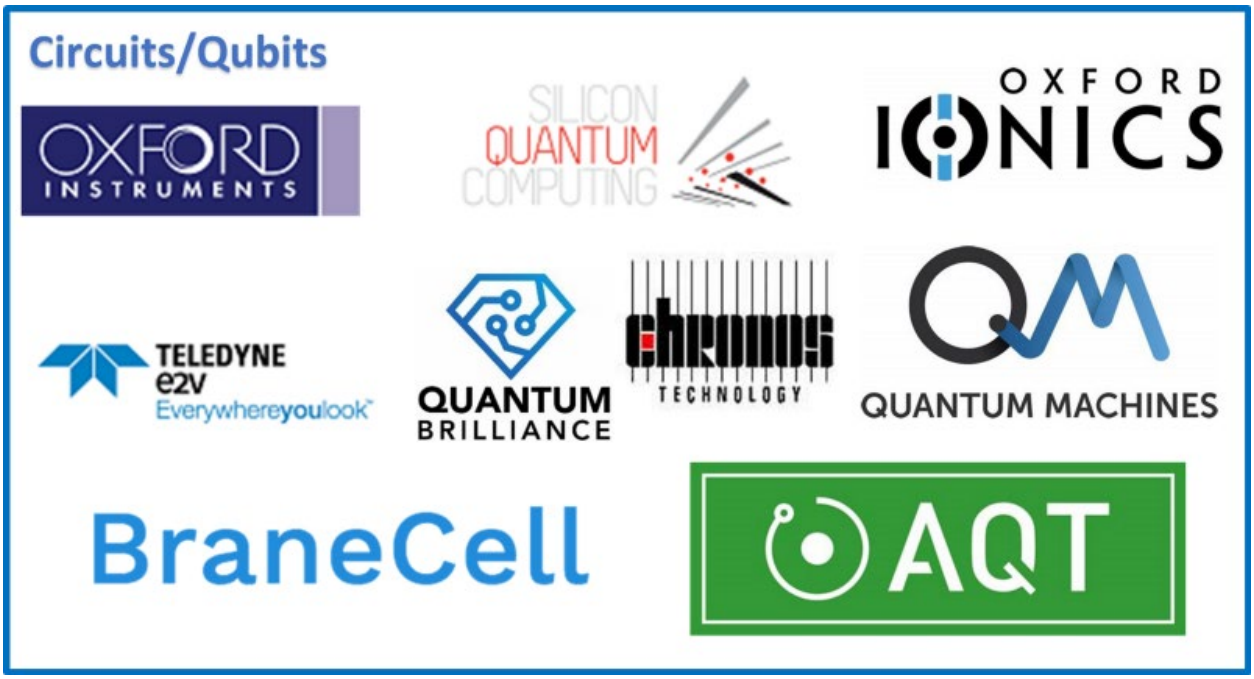
Rigetti: Developer of quantum computing integrated circuits packaged and deployed in cryogenic environments and integrated into cloud infrastructure using pre-configured software. The company also develops a cloud platform called Forest that enables programmers to write quantum algorithms.

EeroQ: Developer of quantum cloud platform using trapping and control of individual electrons floating in a vacuum above superfluid helium, which form the qubits, and the purity of the superfluid protects the intrinsic quantum properties of each electron, allowing users to get seamless delivery of computing power.

ColdQuanta: Developer of quantum sensing technologies with a focus on improving the positioning and navigation systems as well as providing cold atom experimentation, quantum simulation, quantum information processing, atomic clocks, and inertial sensing products, enabling users to explore their own quantum matter innovations for sensing and other applications.

Quantum Circuits: The company's computers are superconducting devices that include a quantum circuit model for quantum computation with an error correction system, enabling clients to make error-free computation through solid-state quantum bits.

D-Wave: Developer of quantum computing technologies offering annealing algorithms to solve optimization problems for commercial use in logistics, bioinformatics, life, and physical sciences, quantitative finance, and electronic design automation.



Oxford Instruments: Designs and manufactures tools and systems for industry and research. Their Quantum Technologies division helps companies with cryogenics, sensing photons and fabricating novel quantum materials.

Silicon Quantum Computing: SQC is currently developing a 10-qubit quantum integrated circuit in silicon to be delivered in 2023 and has the ultimate goal of delivering useful commercial quantum computing solutions.

Oxford Ionics: Manufacturer of computational electronic systems intended to create the most powerful, accurate, and reliable quantum computers. The company's system is based on noiseless electronic qubits trapped ions control technology to create high-performance quantum computers by combining high quality qubits and trapped ions.

Teledyne e2V: The engineering groups of Teledyne draw on a portfolio of leading-edge technology, unique expertise and decades of experience in sensing, signal generation and processing for the development and commercialization of Quantum technologies.

Quantum Brilliance: Using synthetic diamonds to develop quantum computers that can operate at room temperature, without the cryogenics or complex infrastructure, enabling disruptive quantum computing applications.

Chronos: Chronos Technology specializes in time, timing, phase, and monitoring solutions and services including highly accurate atomic clocks and clock synchronization.

BraneCell: Developer of a new quantum processing unit that can function at ambient temperatures. The company offers decentralized quantum computing hardware.

Quantum Machines: Designing quantum controllers that translate quantum algorithms into pulse sequences, enabling organizations to run complex quantum algorithms and experiments in a smooth, intuitive way.

Alpine Quantum Technologies: Developer of ion trap quantum computer technology where single, charged atoms are trapped inside vacuum chambers. Each qubit is manipulated and measured by precisely timed laser pulses.

Bluefors: Developer of a cryogen-free dilution refrigeration system designed to deliver easy-to-operate refrigerators. The company's system provides custom unit connection components for different specifications including dilution units, control systems and gas handling units.

kiutra: Developer of a cooling technology intended to offer cryogen-free cooling service. The company's technology offers sub-Kelvin temperatures for basic research, material science, quantum technology, high-performance electronics, and detector applications.

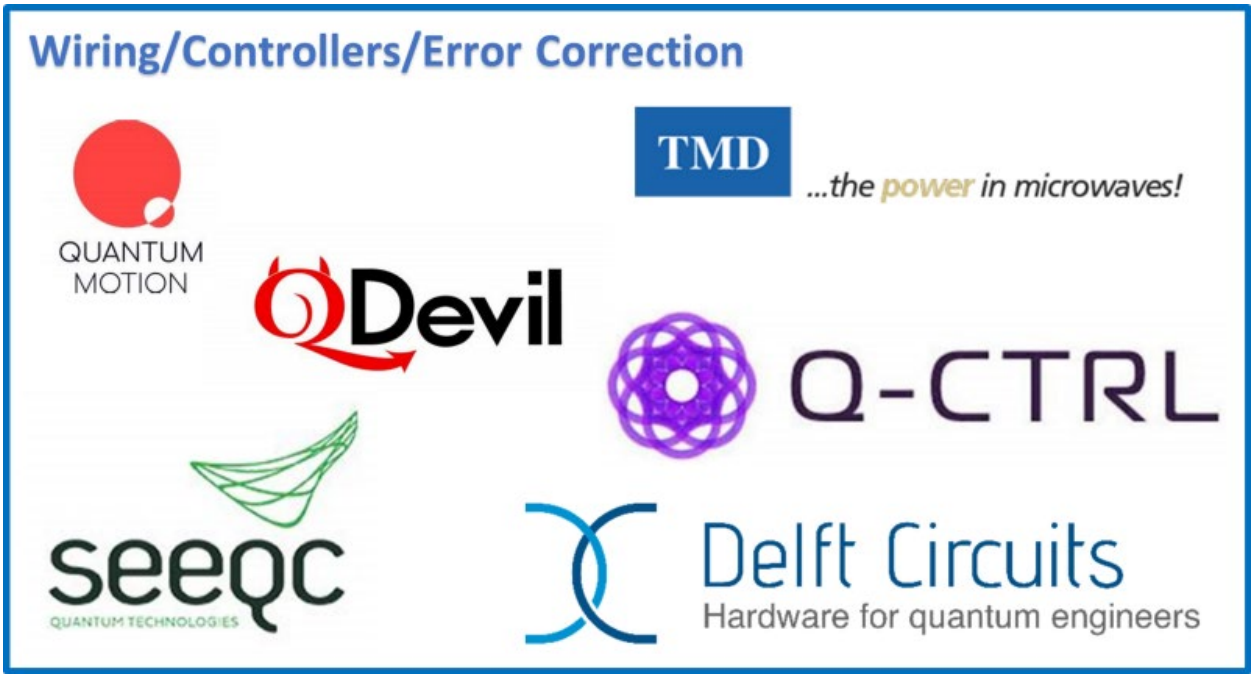
Toptica: Manufacturer of and distributor of high-end laser systems designed for scientific and industrial applications including for qubit control.

M-Squared: Developer of photonics and quantum technology used specifically for quantum research, bio-photonics and chemical sensing application. The company's laser-based systems offer lasers and photonic optical instruments for applications in remote sensing, frontier science, bio-photonics, defense, microscopy, spectroscopy, and metrology.

Montana Instruments: Delivers best-in-class cryostats that are simple to set up, use, and grow with our partners in your journeys over time. Since 2009, Montana Instruments has worked with hundreds of category pioneers to build cryostats with purposeful modularity.

Single Quantum: Developer of single-photon detectors designed to detect particles of light. The company's detectors are based on superconducting nanotechnology.

Sparrow Quantum: Spun out of the Niels Bohr Institute, a developer of a photonic quantum technology based on self-assembled quantum dots coupled to a slow-light photonic-crystal waveguide, enabling nanophononics researchers to increase light-matter interaction and enhance chip out-coupling.



Quantum Motion: Developer of quantum computer architectures designed to solve the problem of fault tolerance. The company's architectures leverage CMOS processing to achieve high-

density qubits which can scale up to large numbers and tackle practical quantum computing problems, enabling users to help reduce errors and thereby improve quality.

QDevil: Developer of electronics and specialized components for quantum electronics research. The QFilter is a cryogenic filter for reducing electron temperatures below 100 mK. The product portfolio also includes the QDAC, a 24-channel ultra-stable low noise Digital-Analogue-Converter, the QBoard, a fast-exchange chip carrier system, and the QBox, a 24-channel breakout box.

SeeQC: The company's technologies are developed and commercialized for quantum information processing applications including scalable fault-tolerant quantum computers and simulators, quantum communications, and quantum sensors, enabling businesses to get access to a full suite of electronic circuit design tools for integrated circuit design including PSCAN2, XIC, WR Spice and InductEx.

Delft Circuits: Manufacturer of cryogenic circuit technologies intended to perform scientific instrumentation, quantum computing, and astronomy. The company's technology offers custom-engineered superconducting circuits and cryogenic instrumentation which have ultra-low thermal conductance and scalable cryogenic cabling, enabling users to conduct their research with cryogenic circuit packaging as per their need.

Q-CTRL: Developer of quantum control infrastructure software designed to perform quantum calculations to identify the potential for errors. The company's platform uses quantum sensors to visualize noise and decoherence and then deploy controls to defeat the errors, enabling R&D professionals and quantum computing end users to improve the efficiency and performance of standoff detection as well as precision navigation and timing for defense and aerospace.

TMD Technologies: Manufacturer of professional microwave and radio frequency products primarily focused n the defense and communications markets as well as providing compact and precise atomic clocks, new gravimetric and magnetic sensors used in quantum computers.

Terra Quantum: Developer of a hybrid quantum algorithm intended to solve a linear system of equations with exponential speedup that utilizes quantum phase estimation.

QxBranch: Developer of algorithms and software intended to provide predictive analytics, forecasting and optimization for quantum and classical computers.

Zapata: Spun out from Harvard in 2017, developer of quantum software and algorithms to compose quantum workflows and orchestrate their execution across classical and quantum technologies. The company's platform provides artificial intelligence, machine learning and quantum autoencoder to deliver an end-to-end, workflow-based toolset for quantum computing that advances computational power.

Cambridge Quantum Computing: Quantum computing software company building tools for commercialization of quantum technologies. The company designs software combining enterprise applications in quantum chemistry, quantum machine learning and augmented cybersecurity in a variety of corporate and government use cases.

RiverLane: Developer of quantum computing software using an ultra-low latency quantum operating system that accelerates quantum-classical hybrid algorithms to facilitate hardware research and development and develops algorithms to make optimal use of the full quantum computing stack, enabling hardware partners to focus on the physics and build better full-stack solutions.

QCWare: Developer of enterprise software designed to perform quantum computing. The company's software simplifies QC programming and provides access to QC machines while improving risk-adjusted returns and monitoring networks, enabling clients to integrate quantum computing power into any existing application and remove performance bottlenecks.

StrangeWorks: Strangeworks QC™ is used by thousands of researchers, developers, and companies around the world to learn, teach, create, and collaborate on quantum computing projects and, enabling clients to overcome the risks of vendor lock-in and architectural uncertainties.

1Qbit: 1QB Information Technologies is a quantum computing software company in hardware partnerships with Microsoft, IBM, Fujitsu, and D-Wave Systems. 1QBit develops general purpose algorithms focused on computational finance, materials science, quantum chemistry, and life sciences.

Quantum Computing Inc.: Quantum Computing Inc is focused on providing software tools and applications for quantum computers. Its products include the Qatalyst, Qatalyst Core, and Quantum Application Accelerator. Qatalyst enables developers to create and execute quantum-ready applications on conventional computers while being ready to run on quantum computers where those systems achieve performance advantage.

Quintessence Labs: Developer of quantum-cybersecurity applications designed to implement robust security strategies to protect data. The company's cybersecurity technologies are used for cryptographic purposes to centralize the management and control of data-security policy and harness quantum science properties, thereby enabling businesses to increase returns on investment from existing assets and reduce data-security complexities.

MagiQ: A research and development company offering quantum cryptography systems. The company's offering includes optical sensing applications for RF interference cancellation, quantum cryptography, and optical surveillance for advanced energy exploration, enabling customers to better communicate, safeguard and secure their worlds.

Quantinuum: A Honeywell spin-out, the company provides an open-access, architecture-independent quantum software stack and a development platform, enabling researchers and developers to work seamlessly across multiple platforms and tackle some of the most intriguing problems in chemistry, material science, finance, and optimization.

Nu Quantum: Developer of cryptography systems designed to be more secure and time efficient. The company's system created a portfolio of patented ground-breaking single-photon components fundamental to the realization of commercially viable photonic technologies by combining novel materials and semiconductor technology, enabling clients to secure exchange of cryptographic keys worldwide for the ultra-sensitive detection of light.

ID Quantique: Provider of quantum-safe crypto services designed to protect data for the long-term future. The company offers quantum-safe network encryption, secure quantum key generation, and quantum key distribution, enabling financial clients, enterprises, and government organizations to solve problems by exploiting the potential of quantum physics.

Some of these companies are now publicly traded or about to go public, others are private but well-funded by preeminent venture firms or other institutions. Many are independent and working hard to establish a strong position in the ecosystem. Stay tuned to this blog for future reports which will showcase some of the individual players and investment opportunities.

References:

Nature, "Building logical qubits in a superconducting quantum computing system," Gambetta, Chow and Steffen, January 13, 20917

AI Multiple, "QC Companies of 2021: Guide based on 4 ecosystem maps" Dilmegani, Cem , January 1, 2021

Fact Based Insight, Accessed December 2021

If you enjoyed this post, please visit my website and enter your email to receive future posts and updates: http://quantumleap.blog

Russ Fein is a venture investor with deep interests in Quantum Computing (QC). For more of his thoughts about QC please visit the link to the left. For more information about his firm, please visit Corporate Fuel. Russ can be reached at russ@quantumleap.blog.