OSA Industry Development Associates

OIDA QUANTUM PHOTONICS ROADMAP

Every Photon Counts

March 2020

Created in collaboration with CORNING

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EXECUTIVE SUMMARY

Quantum technology is a growing field in physics and engineering focused on harnessing principles of quantum mechanics to enable functions and applications not currently achievable with classical-physics-based technologies. While quantum mechanics has been studied in the research community for a century – and has produced technologies such as lasers, MRI imagers, transistors, etc. – recent progress in controlling individual photons, atoms, electrons, etc. has enabled new advancements.

OIDA developed this roadmap to clarify the market applications and timing for quantum technologies and to specify improvements in optics and photonics components needed to enable advancement.
The ability to create, manipulate, and read out states of individual quantum units is expected to have utility across multiple applications in three primary categories:

- *Sensing and Timing:* The extreme sensitivity of quantum systems to environmental influences can be exploited to measure physical properties with more precision.

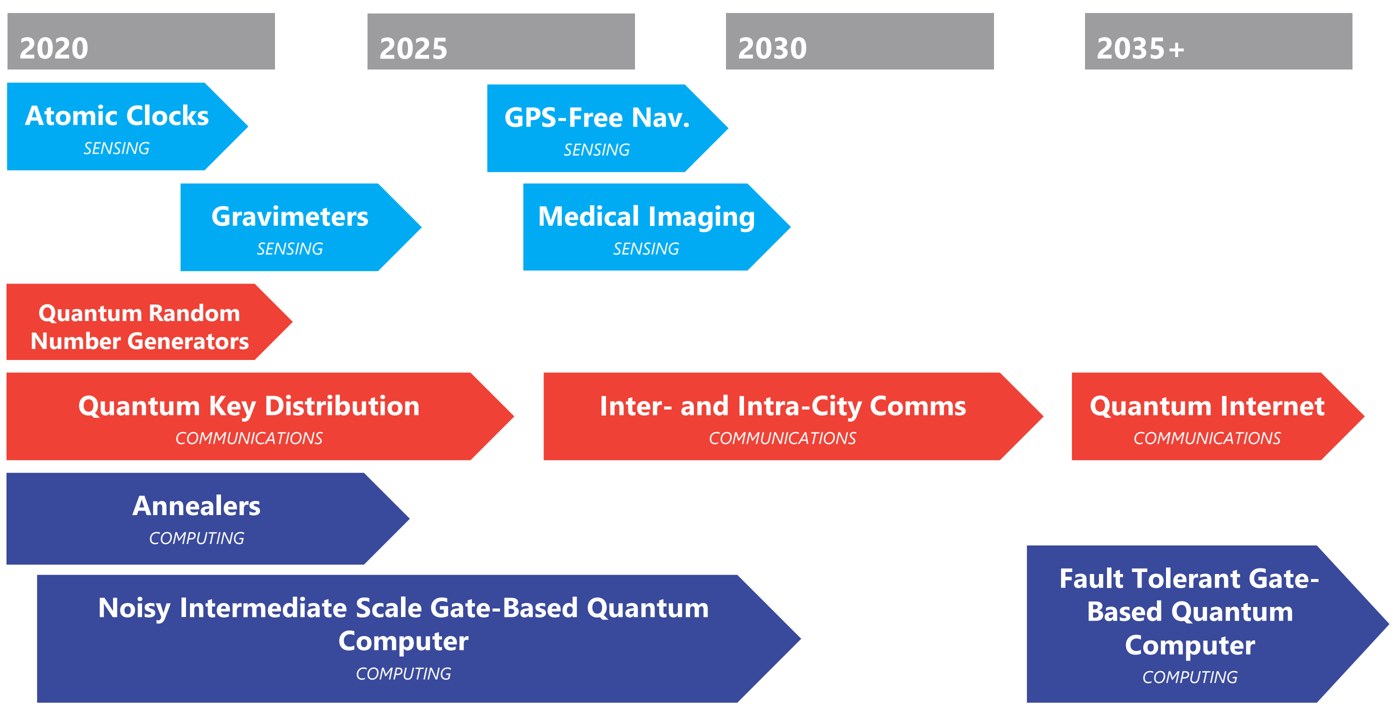
- *Communications:* Attempts to observe a quantum communication channel will irreversibly alter the state of the system in a way that is detectable by the parties exchanging information. A quantum network can distribute entanglement between distant users.

- *Computing:* Using the principles of superposition and entanglement, significant speedup over classical computers is theoretically possible for some problem types.

Early products are being commercialized today, but quantum technology is still a very new frontier. Atomic clocks, quantum key distribution systems, and noisy intermediate-scale quantum computers are available in the near-term, but many other proposed use cases require more advanced hardware and software, and, in some cases, further physics advances.

QUANTUM TECHNOLOGIES TIMELINE

-- Illustrative, Not Exhaustive --



*Chevron placement represents anticipated start date of commercialization
Source: Expert interviews, Newry analysis

EXAMPLE APPLICATIONS FOR QUANTUM TECHNOLOGY

-- Not Exhaustive --

END MARKETS	SENSING & TIMING	COMMUNICATIONS	COMPUTING
Telecom	Clocks for synchronization	Cryptography	Network optimization
Medicine	Improved brain imaging	Protecting patient data long-term	Drug discovery
Oil & Gas	Through-ground imaging	Protecting critical infrastructure	Drilling location analysis; oil distribution logistics
Finance	Clocks for trade timestamping	Secure transactions	Portfolio management
Transportation	GPS-aided navigation; quantum LiDAR	Cryptography for connected vehicles	Battery material simulation; traffic optimization

Quantum computing in particular is attracting significant attention and funding because of its possible security implications. A universal, fault tolerant quantum computer would theoretically be able to factor very large numbers much faster than a classical computer, which could undermine public key cryptography methods such as RSA encryption. While the industry expects it will take more than a decade to develop a quantum computer capable of this kind of computation, there is widespread concern about the potential future vulnerability of highly sensitive information.

This concern is motivating investment in another realm of quantum technology: quantum key distribution (QKD). QKD hardware can create a more secure network in which eavesdroppers trying to steal encryption keys would be detected and could be circumvented.

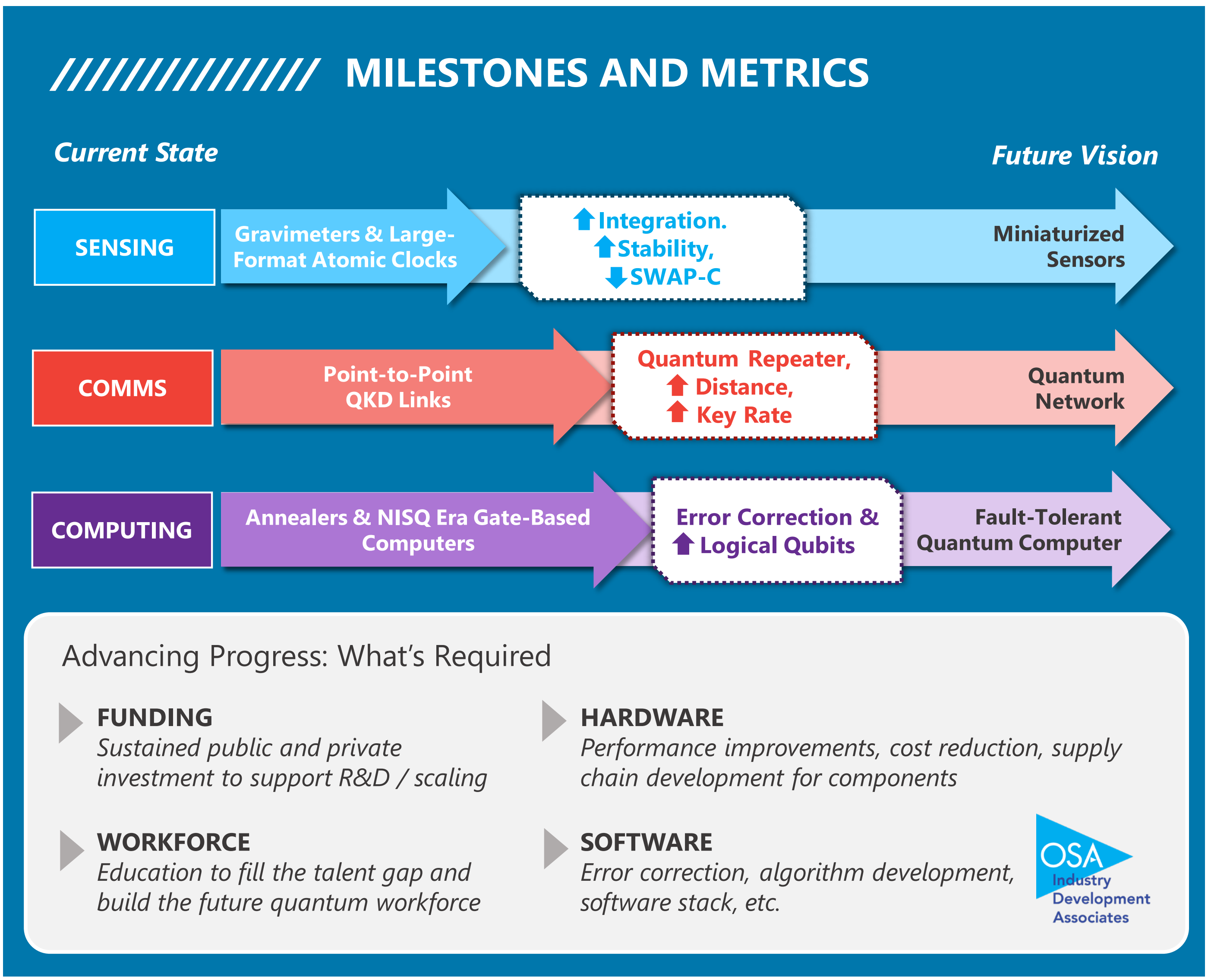
Beyond the cybersecurity implications of quantum technologies, there are many other opportunities for value creation across industries and applications. Quantum sensors are expected to enable higher-performance sensors for GPS-free navigation, through-ground imaging, biomedical imaging, etc. Quantum computers are expected to improve simulation and optimization for drug discovery, material science, financial portfolios, distribution and logistics, etc. Quantum communications infrastructure could network individual quantum computers or sensors together to further enhance performance.

In light of the opportunities and threats created by quantum technologies, significant investments are being made across the public and private sectors. Many governments have large multi-year programs with funding levels that exceed US$1 billion. Thirty-two venture capital deals were executed in 2018, amounting to US$173 million in investment in 2018 alone (Gibney, 2019). In addition to venture-backed startups, many large, established, multi-national corporations that already supply legacy sensing, telecommunications, and computing markets recognize the potential of and are investing in the development and commercialization of quantum technologies.

In addition to proponents, quantum technologies also have their share of skeptics whose opinions are valid. While some applications such as atomic clocks and point-to-point QKD links are commercially available today, current use is modest relative to their addressable market size due to limitations and tradeoffs between technical performance and cost.

Quantum computing has tremendous theoretical potential to disrupt and transform a range of industries; however, we are still many years away from a fault-tolerant quantum computer capable of delivering the performance necessary to enable many applications such as decryption and drug discovery.

For the skeptics who are looking for more evidence of progress, as well as the proponents who wish to make measured investments that balance risk and uncertainty, we recommend monitoring a few metrics and "beacon" milestones that will be indicative of substantial progress. In quantum sensing, progress will be application-specific, as performance and cost advantages need to be demonstrated relative to incumbent sensing approaches. Further integration of these systems (e.g., on-chip) would be a notable advancement to facilitate lower size, weight, power, and cost (SWAP-C) devices. In quantum communications, the development of a quantum repeater and consistent improvements in distance and key rates will indicate advancement. Lastly, implementation of error correction and subsequent scaling in the number of logical qubits will be important improvements on the path to developing a fault-tolerant quantum computer.



Optics and photonics are a core enabling element of quantum technologies, as many of the systems require very precise control of light. To enable many of the applications highlighted above, additional innovation and supply chain development is required. Subsequent chapters further specify necessary components to illustrate the many opportunities available to optics and photonics suppliers, including photon sources, photon detectors, optical fiber, integrated photonics, couplers, modulators, frequency converters, and optical-to-microwave transducers.

In addition to developing the optics and photonics components for individual subsystems (e.g., sensors, computing nodes), interconnects to link subsystems to create a large-scale quantum network or computer are also needed. Quantum interconnects must transfer the quantum states between various physical media (e.g., atoms, photons, microwave fields, semiconductor electronics) with high fidelity, fast rates, and low loss. The community is beginning to recognize the importance of systems thinking and engineering for enabling the full ecosystem of quantum technologies.

SUMMARY: OPTICS AND PHOTONICS COMPONENT REQUIREMENTS

Required | May Use

Category	Technology	Lasers	Single or Entangled Photon Sources	Single Photon Detectors	Heterodyne and Homodyne Photon Detectors	Fiber or Integrated Photonic Waveguides	Modulators	Transducers and Converters	Memories or Repeaters
Sensing	Atomic Clocks							If networked	
	Atom Interferometers							If networked	
	NV Center Sensors							If networked	
	Quantum LiDAR								
Comms.	Continuous Variable QKD								
	Discrete Variable QKD								
	Entanglement-Based QKD								
Computing	Superconducting							If networked	
	Ion Trap							If networked	
	Neutral Atom							If networked	
	Photonic - Discrete Variable							Memory-dependent	
	Photonic - Cont. Variable							Memory-dependent	
	NV Center							If networked	
	Silicon Spin							If networked	
	Topological							TBD	TBD

Source: Expert interviews, Newry analysis

ACKNOWLEDGEMENTS

Many individuals contributed their perspective and expertise to the development of this report. Although the following contributors provided many helpful and constructive comments and suggestions, many were not asked to endorse the conclusions or recommendations of this report and most did not review drafts before its release.

We extend special acknowledgement to our advisory panel, which was instrumental in scoping our effort and reviewing and refining the final document:

- Andrew Lord, British Telecom
- Brandon Rodenburg, MITRE
- Dan Nolan, Corning Incorporated
- Gerd Leuchs, Max Planck Institute
- Hugo Zbinden, Université de Genève
- John Spencer, Photodigm
- Jun Yang, Corning Incorporated
- Michael G. Raymer, University of Oregon
- Richard Murray, ORCA Computing

Dozens of other individuals also graciously contributed hours of their time to share their perspective and expertise. We thank and acknowledge all for their contributions:

- Andrew White, University of Queensland
- Anthony Laing, University of Bristol
- Araceli Venegas-Gomez, QUERCA
- Ben Bloom, Atom Computing
- Brian Smith, University of Oregon
- Carlos Abellan, Quside Technologies
- Chad Hoyt, Honeywell
- Dusan Sarenac, University of Waterloo
- Eleni Diamanti, CNRS
- Eric Fossum, Dartmouth College / Gigagjot Technology
- Fedor Jelezko, Ulm University
- Franck Pereira dos Santos, LNE-SYTRE
- James Gates, University of Southampton
- Jeremy Levy, Pittsburgh Quantum Institute
- John Berg, PsiQuantum
- John Martinis, Google / UCSB
- John Rarity, University of Bristol
- Jonathan Olson, Zapata Computing
- Josh Nunn, ORCA Computing / University of Bath
- Karl Berggren, MIT
- Lijun Ma, NIST
- Maithreyi Gopalakrishnan, Quantum Thought
- Mark Day, Alter Technology TUV Nord UK Ltd
- Mark Saffman, University of Wisconsin Madison / ColdQuanta
- Martin Schell, Fraunhofer HHI
- Michael Fanto, Air Force Research Lab
- Michael Liehr, AIM Photonics
- Mikhail Shalaginov, MIT
- Murray Reed, QLM Technology
- Nan Yu, NASA Jet Propulsion Laboratory
- Nils Trautmann, Zeiss
- Ole Kock, Teledyne
- Oliver Slattery, NIST
- Philippe Bouyer, CNRS / Muquans
- Prem Kumar, Northwestern University
- Ravi Kumar, Atomionics
- Sergey Polyakov, NIST
- Thomas Monz, University of Innsbruck
- Tim Spiller, UK Quantum Communications Hub
- William Munro, NTT
- Yaseera Ismail, University of KwaZulu-Natal
- Zachary Vernon, Xanadu

This work was conducted on an unclassified basis. All assessments of technology-related progress and feasibility are based on one-on-one conversations with experts, a survey, and other public data. Journal articles and websites are cited where relevant, but much of the insight was gathered through expert interviews. The performance targets described in the report are representative of the consensus of a range of expert interviews.

The *OIDA Quantum Photonics Roadmap* was developed in collaboration with Corning Incorporated.

The report was researched and written in collaboration with Newry Corp. Newry is a strategy consulting firm dedicated to fueling growth and enhancing competitive edge for B2B companies in emerging and technology-intensive markets such as optics and photonics and telecommunications. We help our clients accelerate decision-making on critical innovation programs, systematically identify growth areas for new and established products, and anticipate and prepare for future threats and opportunities.

THE QUANTUM 2.0 OPPORTUNITY

How is quantum technology relevant to the optics and photonics community?

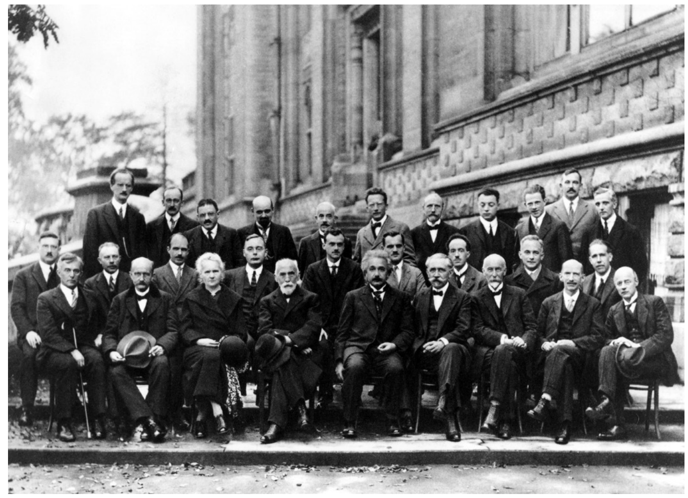
Context and Objectives for OIDA Roadmap

Proponents of quantum technologies argue that quantum systems will transform the way we measure, process, and transmit information, potentially disrupting a wide range of end markets from medical research, to cybersecurity, to telecommunications.

Optics and photonics are key enabling elements of these transformations; however, there are uncertainties about what components and performance levels are specifically required, and the timing and likelihood of adoption by different end markets.

OIDA developed this roadmap to:

- Clarify the market potential for quantum technologies in three technology categories: computing, communications, and sensing
- Specify what improvements are required in optics and photonics components to enable advancement

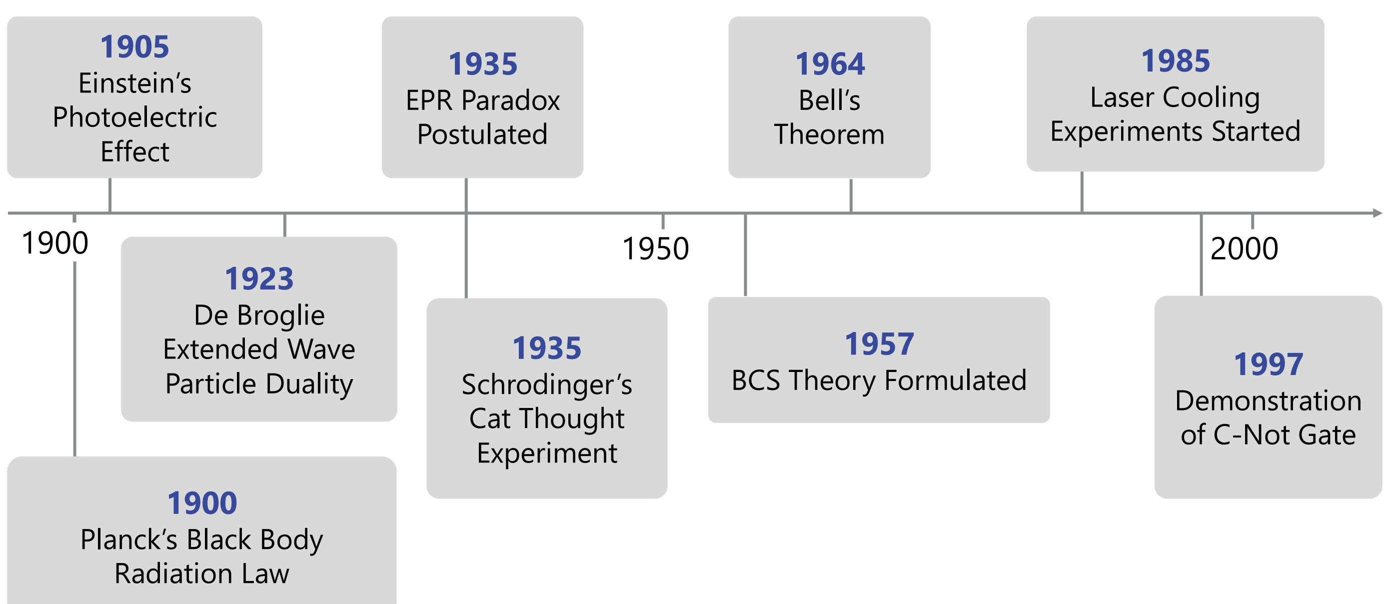


Source: Wikimedia Commons

Quantum Technology Overview

Quantum technology is a growing field in physics and engineering. It is focused on harnessing properties of quantum mechanics to enable functions and applications not currently achievable with classical technology.

20th CENTURY QUANTUM DISCOVERIES



Quantum mechanics has been studied in the research community for nearly a century, resulting in the invention and commercialization of technologies such as laser systems, MRI imagers, transistors, nuclear power generation, and more. These devices and technologies are viewed as the products of the first quantum revolution, or Quantum 1.0.

As our ability to manipulate and control individual quantum objects (e.g., photons, atoms, electrons) increases, we are approaching a second quantum revolution, or Quantum 2.0, which could further enhance performance features such as capacity, sensitivity, speed, and security for numerous end uses.

Performance breakthroughs are possible due to unique quantum properties:

- *Superposition:* A quantum system can exist in two or more basis states at once; its wave function is a linear combination of the contributing basis states with complex coefficients that reflect the relative weight of each basis state.
- *Entanglement:* Two or more quantum objects can be intrinsically linked such that the two states become coupled into an 'entangled' composite state, regardless of how far apart the objects are from one another.
- *Measurement:* Measurement collapses and disrupts a quantum state – i.e., the quantum system's coherent probabilistic superposition state collapses into a discrete state, leaving it fundamentally changed.

Applications and Use Cases

The ability to create, manipulate, and read out states of individual quantum units is expected to have utility across multiple applications in three primary categories:

- *Sensing and Timing:* The extreme sensitivity of quantum systems to environmental disturbances can be exploited to measure physical properties (e.g., gravity, magnetic fields, time, etc.) with more precision.
- *Communications:* Attempts to eavesdrop on a quantum communication channel will irreversibly alter the state of the system, which can be detected by the parties exchanging information and therefore enables more secure communication.
- *Computing:* Using the principles of superposition and entanglement, significant speedup over classical computers is theoretically possible for some problem types (e.g., factoring large numbers and certain optimization problems).

Despite high levels of interest from researchers, the investment community, and the public across all three technology categories, Quantum 2.0 is still a very new frontier. Early products such as atomic clocks, quantum key distribution systems for quantum cryptography, and noisy intermediate-scale quantum computers are being commercialized today, but many of the proposed use cases described on the next page require more advanced hardware and software.

SUPERPOSITION

A quantum object's wave function is a linear combination of multiple states

ENTANGLEMENT

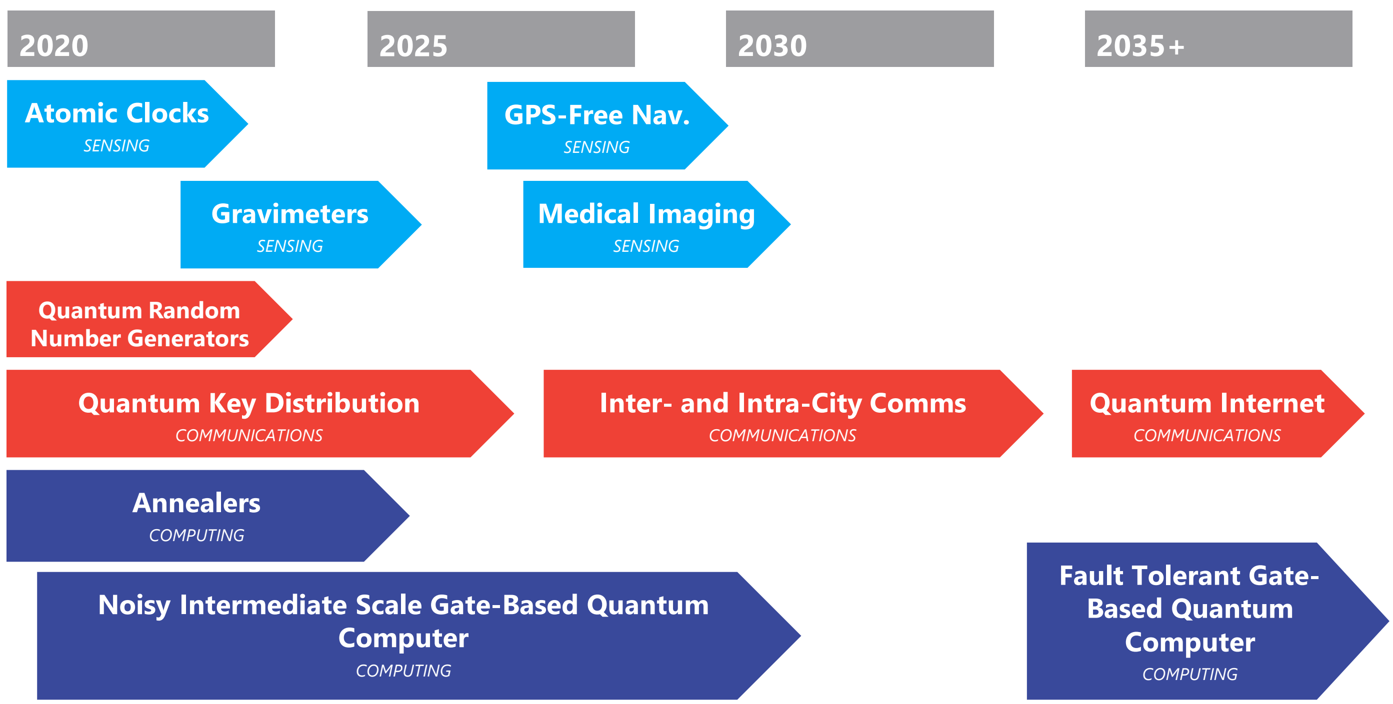
Two or more quantum objects can be intrinsically linked

MEASUREMENT

Measurement collapses the probabilistic information into a discrete classical state

QUANTUM TECHNOLOGIES TIMELINE

-- Illustrative, Not Exhaustive --



*Chevron placement represents anticipated start date of commercialization
Source: Expert interviews, Newry analysis

Significant work is still needed to develop these enabling components and technologies to their full potential; nevertheless, it is clear that quantum systems could potentially have a major impact in many end markets, ranging from telecom, to medicine, to finance, to transportation, and more.

Because we are still in the early stages of quantum technology development, there most likely will be other use cases beyond those mentioned that we have not yet imagined. Many observers draw parallels to the progress that came from the space programs of the 20th century, suggesting that investment in quantum technologies will produce many other enabling component technologies that could have utility in other markets, even applications that we may not be aware of today.

Quantum and Data Security

A quantum computer's theoretical ability to factor very large numbers faster than a classical computer is offered as a major application that is attracting significant attention from governments and the security community. Many public key cryptography methods, such as RSA encryption, rely on the fact that it is exponentially more difficult for a classical computer to factor very large numbers. Quantum computers, on the other hand, can theoretically factor large numbers very quickly using a quantum computer algorithm for integer factorization called Shor's algorithm.

Many banking transactions, online purchases, critical infrastructure, medical records, and other applications use RSA or similar encryption methods, making them susceptible to a quantum computer attack. While we are likely 10+ years away from having a quantum computer capable of running Shor's algorithm, this threat underpins many of the investments being made globally by governments and other actors.

Threats could still occur in advance of a fault-tolerant quantum computer being developed in the form of a "harvest and decrypt" attack. Eavesdroppers may already be tapping fiber networks and storing encrypted data, knowing that they will be able to rapidly decrypt it in the future once a quantum computer is developed. As organizations evaluate the urgency of their data security concerns, they must consider both the "shelf life" of their data (i.e., how long it must remain secure) and the time that it will take to develop, standardize, and migrate to a new security protocol.

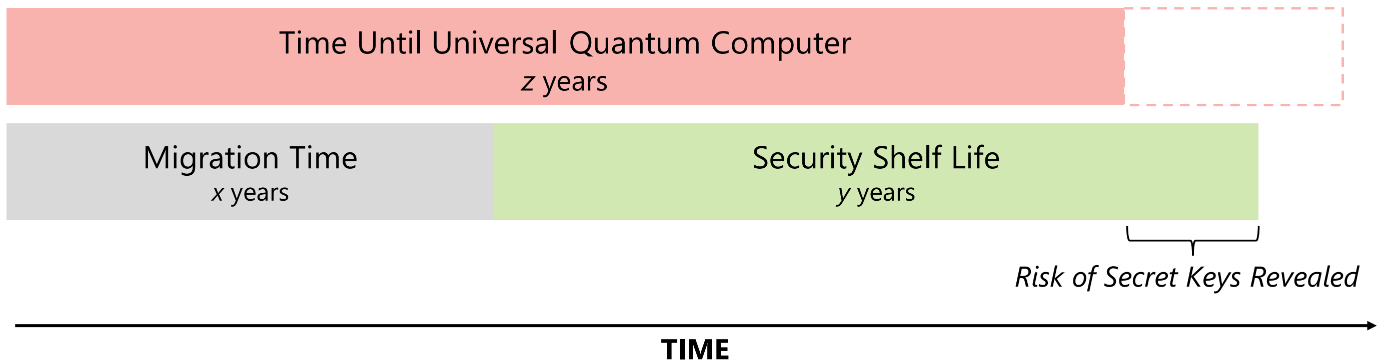
In addition to applications where data needs to remain secure for a long period of time, devices that have long lifecycles and use authenticated over-the-air software updates (e.g., autonomous cars) are also at risk. If a quantum computer is developed, a bad actor could potentially get the manufacturer's key and send a malicious software update to hijack the system.

//////////////// EXAMPLE MARKET APPLICATIONS

TELECOM	Clocks for Synchronization	Cryptography	Network Optimization
MEDICINE	Improved Brain Imaging	Protecting Patient Data Long-Term	Drug Discovery
OIL & GAS	Through-ground Imaging	Protecting Critical Infrastructure	Drilling Location Analysis; Oil Distribution Logistics
FINANCE	Clocks for Trade Timestamping	Secure Transactions	Portfolio Management
TRANSPORT	GPS-Aided or GPS-Free Navigation; Quantum LiDAR	Cryptography for Connected Vehicles	Battery Material Simulation; Traffic Optimization

LEVEL OF RISK DETERMINATION

If x + y > z, worry:



Source: Mosca, M. (2018, September/October). Cybersecurity in an Era with Quantum Computers: Will We Be Ready? *IEEE Security & Privacy*, 16(5), 38-41.

Many groups are already working on developing and evaluating new non-quantum cryptography methods that may not be susceptible to attack by a quantum computer, a field commonly referred to as post-quantum cryptography (PQC). Additionally, the laws of quantum mechanics can be harnessed to provide an additional layer of security using hardware. Quantum key distribution (QKD) is a quantum communications approach that uses principles of quantum measurement to create a more secure network. Additional detail is provided on QKD and PQC in the chapter on Quantum Communications.

While there is a strong sense of urgency around these data security issues, the timeline for developing a fault-tolerant quantum computer capable of running Shor's algorithm is highly uncertain, and leading experts admit that they don't know when – if ever – it will be realized. Many compare the development required to get from today's noisy intermediate-scale quantum computers to a fault-tolerant quantum computer with the development needed to advance from the transistor to the modern-day integrated circuit. Numerous approaches, each with their respective advantages, are being developed, but it is too early to determine which one(s) will win. As one expert put it, "We haven't had our CMOS moment yet."

Global Context: Investments and Activity

In light of the opportunities and threats created by quantum technologies, significant investments are being made worldwide across the public and private sectors. Many governments have large multi-year programs with funding levels that exceed US$1 billion. Examples include:

- *USA:* The National Quantum Initiative Act was signed into public law in late December 2018. The multi-agency plan involving the DOE, NSF, and NIST proposed US$1.2 billion be committed to funding quantum information science over five years (Giles, 2018). In December 2019 the approved federal budget for 2020 included large increases (amounting to approximately US$300 million) in funding for quantum information research support (appropriations specified in Energy and Water Bill and Commerce, Justice, Science Bill).

- *Canada:* Canada has invested over CAN$1 billion in quantum R&D over the last decade according to the National Research Council (Sussman, Corkum, Blais, Cory, & Damascelli, 2019).

- *EU:* The European Union's Quantum Flagship program is budgeted at €1 billion over a ten-year timescale (Cartlidge, 2016).

- *Germany:* The German government will invest €650 million over two years to support the transition of quantum technologies from basic research to market ready applications (IBM, 2019).
- *UK:* The UK's National Quantum Technologies Programme has exceeded £1 billion in cumulative investments since its announcement in late 2013 (UK Research and Innovation, 2019).
- *China:* China is investing heavily in quantum information science. The National Laboratory for Quantum Information Science received 7B RMB in funding to start and additional funding is available through national and provincial initiatives (Kania & Costello, 2018).
- *Japan:* Japan set aside more than 30 billion yen for quantum applications in a 10-year research plan (Quantum Business, 2018).
- *Australia:* Australia's investment is on the order of AU$130M through federal funding alone (Roberson & White, 2019).

EXAMPLE GOVERNMENT PROGRAMS

- US National Quantum Initiative Act proposes US$1.2 billion over 5 years
- Canada invested over CAN$1 billion over the last decade
- EU Quantum Flagship program budgeted at €1.0B over 10 years
- China's National Lab for Quantum Info Science received 7B RMB in funding
- UK program has exceeded £1B in cumulative investments since 2013
- Japan set aside more than 30B yen for quantum in a 10-year research plan

Private sector investment is also increasing worldwide. Many startups are spinning out of academic research across sensing, communications, and computing applications. Additionally, large, established multi-national corporations that already supply legacy markets are recognizing the potential impact of quantum technology and are investing in its development and commercialization. The number and value of venture capital deals, particularly in quantum software and computing startups, is increasing, reaching a total of 32 deals in 2018 at a total value of US$173 million in 2018 (Gibney, 2019).

Given that we are likely many years away from a fault-tolerant quantum computer or a quantum internet, it is possible that the investment community will lose interest if the technology does not advance fast enough to deliver on expectations. Some express concerns that a "Quantum Winter" – i.e., a freeze in venture capital and/or government funding – might be coming.

EXAMPLE COMPANIES INVOLVED IN QUANTUM TECHNOLOGIES

SENSING & TIMING

AO Sense, Atomionics, Bosch, Honeywell, ID Quantique, Lockheed Martin, Microsemi, Muquans, Rydberg Technologies, Teledyne e2v, Thales, Vector Atomic

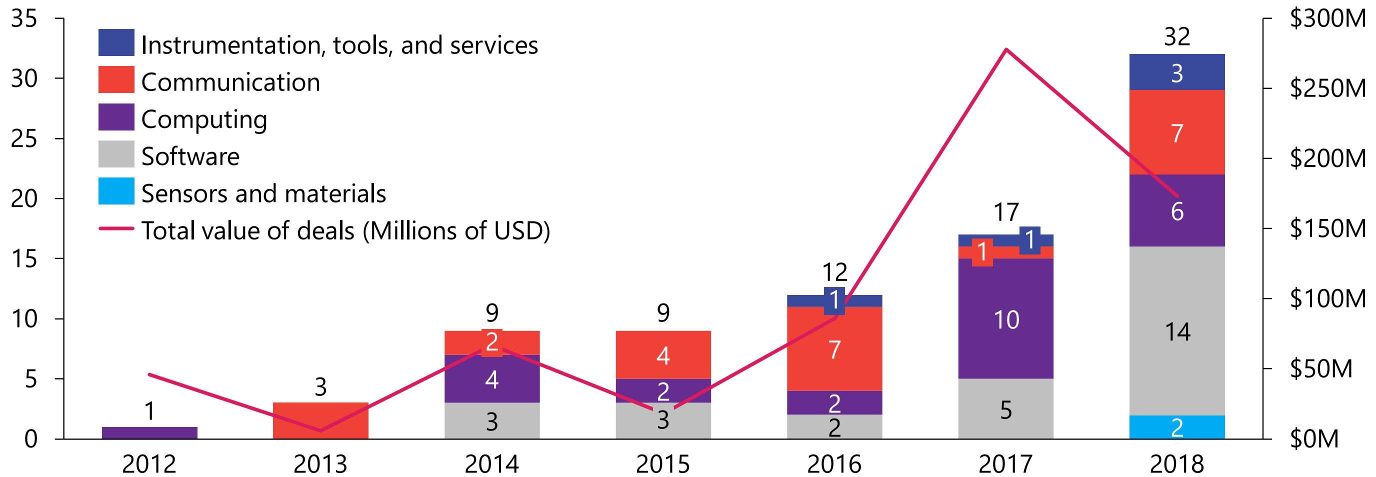
COMMUNICATIONS

ArQit, Fujitsu, Huawei, ID Quantique, Infiniquant, KETS, Mitsubishi, Electric, NEC, NTT, QuantumCTek, Qubitekk, Quintessence Labs

COMPUTING

Atom Computing, ColdQuanta, Google, Honeywell, IBM, Intel, IonQ, Microsoft, ORCA Computing, Psi Quantum, Rigetti, Xanadu

NUMBER OF VC DEALS



Source: Adapted with permission from Springer Nature: Gibney, E. (2019). The quantum gold rush: the private funding pouring into quantum startups. *Nature*, *574*, 22-24.

Some investors are aware of this potential but are hopeful that incremental value created by near-term technologies (e.g., quantum sensors, QKD networks, noisy intermediate-scale quantum computers) will be sufficient to justify the cost of ongoing development efforts. Other investors are hoping that enough progress will be made that a different firm in a later-stage deal will buy them out. A minority are betting that a breakthrough might occur within the next five years to dramatically accelerate the timeline.

Irrespective of the hardware advancements required, significant parallel software and application development is ongoing. Many potential end users such as chemical and energy companies are actively engaging with quantum software development companies to evaluate what problems could be solved by a quantum computer once the hardware is more advanced.

While private funding trends are likely to depend on progress demonstrated in the near term, the large, multi-year government programs are expected to subsidize progress even if private funding levels decline. Given the potential national security implications for quantum technology (e.g., decoding encrypted messages, detection of stealth aircraft with quantum radar, etc.), one expert even asserted that "a quantum arms race is more likely than a quantum winter."

Implications for the Optics and Photonics Community

Optics and photonics are a core enabling element of quantum technologies, as many of the systems require very precise control of light (Awschalom, D., Berggren, K. K., Bernien, et. al., 2019). Quantum technology presents various innovation opportunities for the optics and photonics community, and there is a large ecosystem of component, system, and service players with various requirements for their respective architectures.

Furthermore, system developers have consistently expressed a need for a more robust and developed supply chain. Subsequent chapters further specify necessary components to illustrate the many opportunities available to optics and photonics suppliers to participate in this nascent but growing market.

In addition to opportunities, all entities (not just optics suppliers) should be aware of the potential threats that quantum computers pose to their information security.

INTRODUCTION TO QUANTUM SENSING AND TIMING

While quantum computing receives most of the attention by the mainstream media, most experts believe that quantum sensors and clocks will bring earlier commercial success if they can outperform conventional techniques cost effectively and in a smaller and often portable form factor. In fact, some types of quantum sensors – such as atomic clocks and cold atom interferometers – are already commercially available. Work is ongoing to bring new products to market, while making existing systems smaller and more robust.

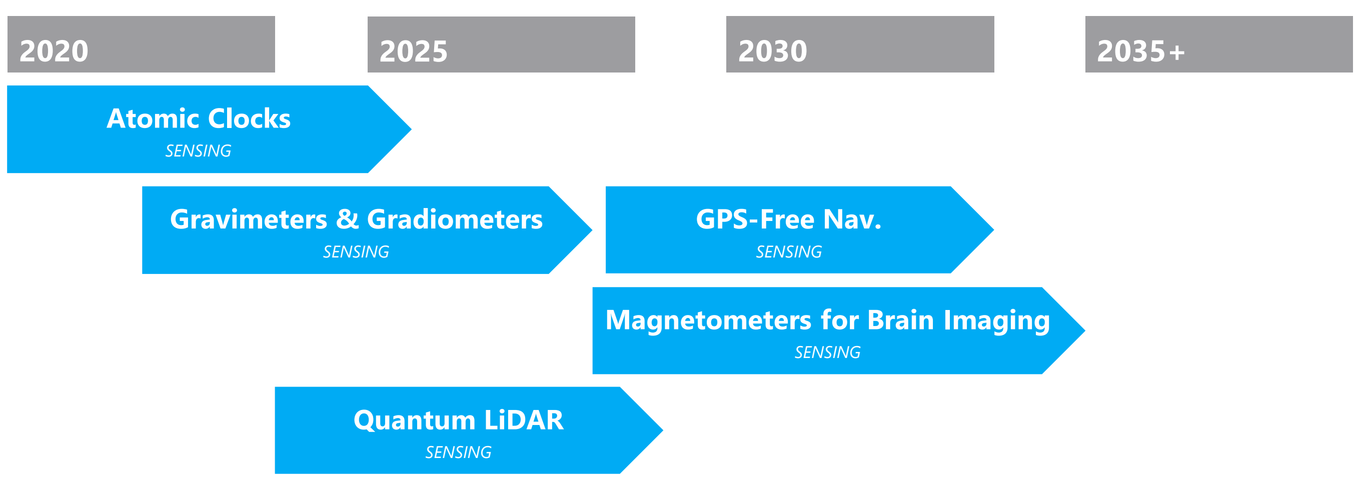
Quantum sensors take advantage of the extraordinary sensitivity of quantum states to their environment to create more sensitive and precise measurement devices to improve navigation (with or without GPS), network synchronization, geological surveying, medical imaging, LiDAR, etc. There are multiple technological approaches to building high-performance quantum sensors, which are outlined below.

Atomic Clocks

Atomic clocks use the hyperfine transitions in atoms as a frequency reference from which they derive a time standard. The high frequency of atomic transitions enables extremely high-resolution timing. Furthermore, while man-made quartz-crystal oscillators used in traditional clocks vary slightly from one to the next, all atoms of a given element and isotope are identical. Thus, as long as the atoms are properly isolated from outside influences, separate atomic clocks based on the same isotope should have nearly constant and identical tick rates and they should experience minimal drift rate over time (uncertainty levels as low as 10^{-18}).

Lasers, heterodyne and homodyne photon detectors, and modulators are common optics and photonics components required for atomic clocks. Optical fiber, integrated photonic waveguides, and transducers and converters may also be used.

QUANTUM SENSOR COMMERCIALIZATION TIMELINE *-- Illustrative, Not Exhaustive --*



*Chevron placement represents anticipated start date of commercialization
Source: Expert interviews, Newry analysis

There are many applications that could benefit from the performance improvements provided by atomic clocks. Examples include:

- *GPS:* Precise time measurement is critical for global positioning systems to ensure accurate determination of the distance between satellites and a ground receiver.

- *Network Synchronization / Time Stamping:* Accurate time coordination and time stamping is essential for synchronizing and sequencing operations or transactions in a network, be it a power grid, telecommunications network, air traffic control, financial systems, etc.

- *Research:* Dark matter research and other fundamental science experiments can benefit from the precision made possible by atomic clocks.

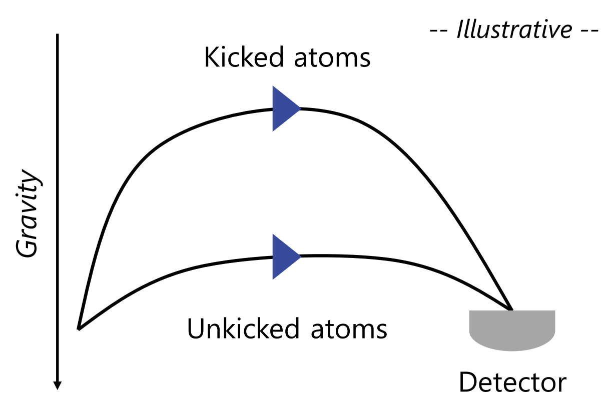
Atomic clocks were commercialized decades ago and multiple companies such as AOSense, Muquans, Vector Atomic, Frequency Electronics, ADVA, Microchip Technology, and Teledyne are developing and commercializing more advanced systems. Current research and engineering efforts are focused on increasing environmental robustness and stability and miniaturizing the systems to be lower size, weight, power, and cost (SWAP-C) to allow for deployment in higher volume, but more cost-sensitive and/or mobile applications.

Atom Interferometers for Gravity, Inertia, and Rotation Sensors

Cold atom interferometers can be applied to create faster and more sensitive devices for measuring gravity, inertia, and rotation. They measure the interference pattern between atomic matter waves traveling along different paths, which allows them to measure a variety of physical signals (e.g., speed, acceleration, etc.). Like atomic clocks, they are also less susceptible to drift than conventional methods.

For example, local gravity will impart a phase shift on an atomic matter wave because it has mass, which modifies the interference pattern in a way that can be detected to create a gravity sensor. Cold-atom systems isolate a cloud of atoms (e.g., Rb) in a vacuum and manipulate the states of these atoms using lasers. A laser can put each atom into a hybrid (superposition) state so that it simultaneously has slightly lower and higher energies. Then, a laser will give the atom cloud a kick so that the higher-energy half of the atom's wavefunction moves up by a few centimeters from the low-energy half.

Next, one more kick moves the two wavefunction halves back together, creating an interference pattern in the presence of a third kick. The gravitational potential energy of the cloud affects the wavefunction, so the interference pattern can be analyzed to determine the strength of the gravitational field. Gradiometers may use the same principle as gravimeters, but with two clouds at different heights to determine the gravitational field gradient.



Kicked and unkicked atoms will follow slightly different paths and create an interference pattern on the detector

Source: Newry

As described, lasers, coherent photon detectors, and modulators are required. Waveguides, transducers, and converters may also be needed depending on the application.

High-precision, drift-free atom interferometers can be used in several applications, such as:

- *Climate Research:* Satellites equipped with a gravimeter may be used to measure gravity across different regions of the earth to inform climate models of polar ice mass, ocean currents, and sea level, which in turn can aid researchers' predictions of natural disasters (e.g., floods, earthquakes, volcano eruptions).

- *Civil Engineering:* More precise quantum gradiometers could better identify pipes, mineshafts, tunnels, and sinkholes in or near work sites, resulting in improved safety for workers and significant cost savings via more accurate digging.

- *Hydrocarbon and Mineral Exploration:* Any object or cavity with a lower density than its surroundings will have a lower local force of gravity. Quantum gravimeters can measure and map these dynamics to guide natural resource investigation.

- *GPS-Free Navigation:* Extremely accurate, precise, and stable quantum accelerometers and gyroscopes based on atom interferometry would not need to rely on GPS satellites, offering a complementary alternative for navigation in environments that do not have access to satellites or in applications that are susceptible to a GPS jamming or spoofing attack. Map matching with gravity or magnetic sensors may also be used for GPS-free navigation.

Magnetometers

Highly sensitive magnetic-field sensors, called magnetometers, have the potential to improve navigation and various imaging applications in arenas such as healthcare and manufacturing. Magnetometers can be developed using one of two approaches:

1. Cold atoms
2. Nitrogen-vacancy (NV) centers in synthetic diamond crystals

Cold atom-based magnetometers isolate a vapor of atoms (e.g., Cs, Rb) in a vacuum chamber. A laser beam is applied to orient the valence electron spins of all atoms in the same direction. Any external magnetic field will cause the spins to wobble in a motion called precession. Precession causes a change in the laser light, which can be measured to determine the strength of the external magnetic field.

Nitrogen-vacancy-based magnetometers rely on the behavior of point defects in synthetic diamond crystals to detect the strength of magnetic fields. NV centers – nitrogen atoms located in vacancies in the diamond lattice – emit red light (637 nm) when excited by green light (532 nm).

Due to spin-dependent decay pathways, the fluorescence intensity of these emissions varies based on the spin state of the NV center, which is affected by the local magnetic field. The strength of that magnetic field can be determined by measuring the variance in fluorescence intensity with microwave and laser pulses. NV centers are also sensitive to other external signals and may be used to measure electric field, strain, and temperature.

Quantum magnetometers are being developed for various end applications:

- *Brain Imaging*: Highly sensitive quantum magnetometers can measure the magnetic fields of electric currents in the brain (often referred to as magnetoencephalography) to study epilepsy, Parkinson's disease, dementia, etc.

- *Heart Imaging*: Measuring magnetic fields from induced electric currents can be used to identify sources of atrial fibrillation (technique called magnetic induction tomography); quantum sensors have the potential to offer lower SWAP-C than incumbent instruments.

- *Metrology*: Magnetometers may be used for defect analysis in nanoelectronic circuits, detection of micro-fissures, etc.

- *Navigation*: Extremely sensitive magnetometers may also be used to measure the direction and strength of magnetic field anomalies. Location can be determined by overlaying the local measurement data on reference maps of the Earth's magnetic field.

Quantum magnetometers, particularly NV center-based magnetometers, are at an earlier stage than the atomic clocks and cold-atom gravimeters described previously. Consistent fabrication of NV centers remains a challenge, and further improvements in sensitivity are needed for many applications.

Academic researchers and startups, including Nvision Imaging Technologies, QuSpin, and Quantum Diamond Technologies, continue to invest in advancing the technology. Large multi-national corporations (e.g., Bosch, Thales, Zeiss, Lockheed Martin) are working on the technology as well, but no product has been commercialized yet. While promising results are being published today, additional engineering and the regulatory approval process is expected to delay commercialization of this technology for medical applications.

Quantum LiDAR/Radar

Quantum LiDAR may use single-photon detectors and in some cases entangled light sources to enable more sensitive LiDAR systems capable of operating in poor visibility environments. Quantum radar has also been theorized and is reportedly being developed. The scheme involves bouncing one half of a series of entangled photon pairs off an object and then comparing the returning photons with the idler photons that were held back. This method could distinguish the radiation of the entangled photons from other sources of noise to spot stealth aircraft, for example. Higher-resolution images are also expected with this approach.

Quantum LiDAR is still being developed but may leverage the single-photon detectors developed for the quantum communications market. Proposed use cases include autonomous vehicles and quantitative imaging for leak detection for methane gas and carbon dioxide. Companies like QLM Technology and ID Quantique are commercializing products for the leak detection application.

Commercialization of quantum LiDAR for gas and leak detection is expected to occur within the next 1-3 years, whereas automotive applications are longer term. In addition to performance improvements and miniaturization, significant cost reductions will be required to make the technology feasible for high-volume, cost-sensitive automotive markets.

There is limited public information about the commercialization status of quantum radar and there is some debate as to whether it is possible at all. There have been announcements that China has developed a quantum radar system, but no data supporting this claim has been shared. Most experts agree the commercialization timeline for quantum radar is longer term than the other sensors described previously.

Imaging

Quantum-enhanced imaging is another field that harnesses the properties of non-classical states of light to enable improved imaging performance (e.g., resolution) (Zeiss, 2018). Examples include ghost imaging (improves signal-to-noise for applications with low intensity), quantum multiphoton microscopy, quantum coherence tomography, quantum interferometry, quantum lithography, etc. Quantum enhanced imaging has relatively less commercial activity compared to other quantum sensing modalities but may likely find use in niche applications in the next several years.

INTRODUCTION TO QUANTUM COMMUNICATIONS

Quantum communications leverages the properties of quantum state preparation and measurement as well as intrinsic quantum phenomena such as entanglement and squeezing to create secure communications networks and to enable a range of longer-term applications including distributed sensing and remote or distributed quantum computing.

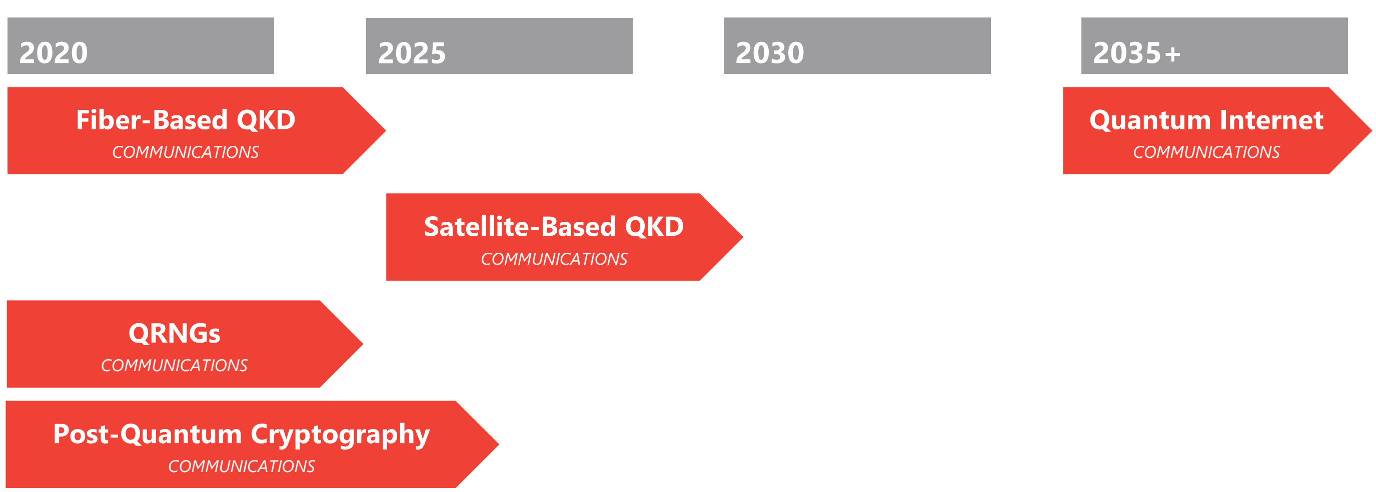
A primary motivation for developing quantum communications networks is to create secure communication networks to protect against the potential data security threat posed by quantum computing. A quantum computer capable of implementing Shor's algorithm could factor large integers exponentially faster than a classical computer, rendering common asymmetric public key encryption protocols such as RSA ineffective (National Academies of Sciences, Engineering, and Medicine, 2019).

RSA is currently used to encrypt and distribute encryption keys, which are then used to encrypt the data that is subsequently transmitted. New key encryption methods that are not susceptible to a quantum computing attack are needed, even in advance of the development of a fault-tolerant quantum computer. Encrypted data that is being exchanged today and needs remain secure long-term is at risk of being stored now and decrypted later once large fault-tolerant quantum computer is developed.

While we are likely a decade or more away from a quantum computer capable of breaking RSA 2048, the industry is actively working on new solutions to resist quantum computing attacks, and some applications and end users are already migrating to quantum-safe solutions today. In the software-based realm of post-quantum cryptography (PQC), quantum-resistant algorithms are being developed. Quantum key distribution (QKD) is a complementary hardware-based approach that is already commercially available and further development is ongoing. While solution selection will likely be application-dependent, most cryptography experts agree that a hybrid approach will be used in the highest security applications for defense in depth.

QUANTUM COMMUNICATIONS COMMERCIALIZATION TIMELINE

-- Illustrative, Not Exhaustive --



*Chevron placement represents anticipated start date of commercialization
Source: Expert interviews, Newry analysis

If encrypted data is stolen, a quantum computer capable of running Shor's algorithm could crack some public key encryption protocols such as RSA much faster than a classical computer, rendering them insecure. New "quantum secure" key exchange solutions are required.

POTENTIAL SOLUTIONS

Post Quantum Cryptography (PQC)
Algorithms that (unlike RSA and ECC) are quantum-resistant – i.e., encryption methods based on math that a quantum computer is not advantaged in computing

Quantum Key Distribution (QKD)
Hardware-based approach that facilitates key exchange by exchanging photons which, by the principles of quantum physics, will be perturbed in a detectable way if an eavesdropper is present

Source: Newry

Post-Quantum Cryptography

Post-quantum cryptography solutions, also described as quantum-proof or quantum-resistant, are cryptography techniques that are expected to be secure against known attacks from a quantum computer. These algorithmic solutions are purely based on new mathematical models and do not incorporate any quantum physical systems; rather, they would be a replacement for RSA to secure key exchange.

Symmetric keys have been proposed as one of many possible solutions and protocols are already available. While a quantum computer running Grover's algorithm could potentially diminish the effective security of symmetric keys, increasing the key length is expected to render them more secure. Many new protocols are being proposed and evaluated, leveraging a multitude of mathematical approaches such as lattice-based, code-based, and multivariate.

Cybersecurity firms such as ISARA Corporation are already providing recommendations to clients about quantum-safe cryptography options. NIST has a large PQC standardization effort underway focused on evaluating alternative approaches for public key encryption and digital signatures. Draft standards are expected to be published around 2022.

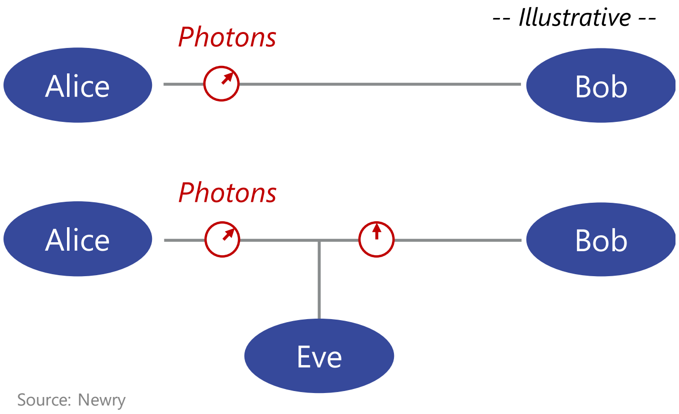
Quantum Key Distribution Approaches

Quantum key distribution is an alternative but complementary hardware-based approach to PQC. It involves exchanging an encryption key between parties over a quantum network, which then enables secure encrypted communication via the classical internet.

QKD systems make use of quantum random number generators (QRNGs) to create truly random keys by leveraging the inherent randomness in quantum systems. In addition to their applicability in cryptography, QRNGs also have utility in applications such as electronic gaming, numerical simulations, and the Internet of Things (IoT). QRNGs are already commercially available through suppliers such as IDQuantique, Quintessence Labs, Quside, etc.

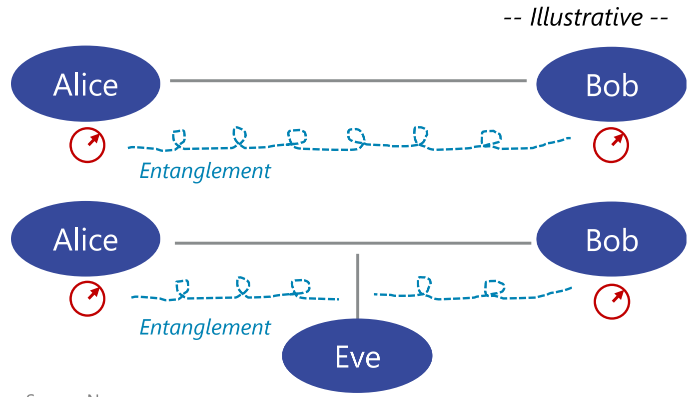
There are multiple protocols and hardware approaches for transmitting these keys, including Prepare and Measure QKD and entanglement-based QKD. Entanglement-based QKD has not been deployed commercially yet.

Prepare and Measure QKD



Source: Newry

Entanglement-Based QKD



Source: Newry

Prepare and Measure QKD protocols take advantage of quantum measurement – i.e., the fact that measuring a qubit collapses its probabilistic wave function into a discrete state.

Consider the case of Alice attempting to transmit a secret encryption key to Bob. Alice, the transmitter prepares photons in certain states in a certain 'state basis' according to randomly generated numbers and sends them over the quantum internet to Bob. Bob measures the photons to determine the prepared state.

If an eavesdropper, Eve, attempts to measure the photons along the transmission path between Eve and Bob, she will alter their state in a detectable way. Thus, Alice and Bob can determine whether the key has been compromised before using it to communicate securely. And, if the disturbance introduced by Eve is below a known threshold, Alice and Bob can use classical error correction and privacy amplification to still obtain a secure key, although reduced in length.

There are two types of Prepare and Measure QKD schemes that leverage different detectors:

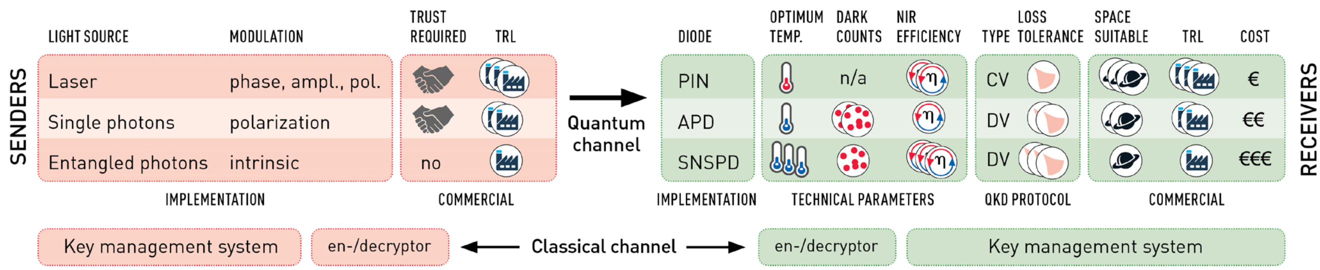
- *Discrete Variable QKD (DV-QKD)*: Uses single-photon detectors.
- *Continuous Variable QKD (CV-QKD)*: Uses homodyne detection / field quadratures.

If Alice and Bob establish an entangled photon pair, it can be used as the qubit to hold the quantum information necessary to generate a secrete key later on. Alice and Bob may measure directly on the photons carrying the entanglement. The information about the measurements can then be shared via the classical internet to negotiate a secret shared key.

As with other QKD approaches, this scheme is secure because if Eve tries to eavesdrop, it will cause a detectable change in the system, enabling Alice and Bob to determine whether the exchanged key is compromised before using it.

This scheme is also device independent, meaning that it is secure even if the devices used to distribute the keys between Alice and Bob have been maliciously prepared by Eve.

Building a QKD system



TRL= Technology Readiness Level. NIR= near infrared. A larger number of symbols indicates a higher value for the discussed parameter.

Source: Khan, I., Heim, B., Neuzner, A., & Marquardt, C. (2018, February). Satellite-Based QKD. *Optics & Photonics News,* 26-33.

Quantum Key Distribution Hardware

Each of the described approaches uses different components.

Photon Sources

Modulated weak (low-power) lasers, single-photon sources, or entangled photon sources are needed for QKD. Polarization-modulated single photons are an intuitive choice for a qubit but are challenging to implement in practice due to current performance levels of single-photon sources. As an alternative, many protocols may use weak laser pulses, which are already commercially available, that may be modulated in phase, amplitude, or polarization.

Both single-photon and laser-based schemes assume that the receiver trusts the sender; the sender would have a memory where the key is stored. Entangled photon sources, while the least developed, are the only sources that don't necessitate that intrinsic trust.

Photon Detectors

Single-photon detectors (avalanche photodiodes [APDs] or superconducting nanowire single-photon detectors [SNSPDs]) or, in the case of continuous variables, homodyne detectors (PIN diode-based) may be used to receive the transmitted photons. Different protocols (e.g., discrete vs. continuous variable) and applications will use different detectors to optimize for tradeoffs such as efficiency, dark count rate, and cooling requirements. There are also major tradeoffs between performance and cost for single photon detectors. While SNSPDs are highest performance, they require cryogenic cooling, which makes them cost prohibitive for some applications.

Fiber-Based vs. Satellite-Based QKD

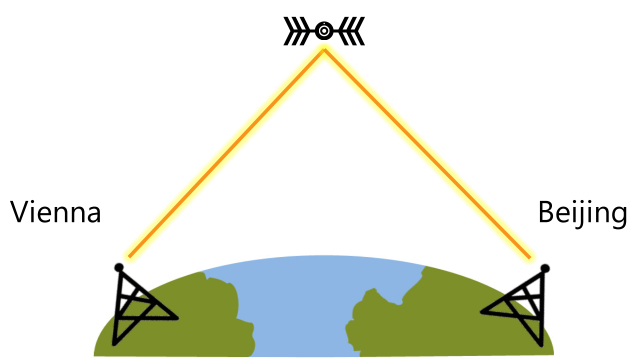
Implementation of these protocols can use either fiber-optic or free-space (satellite-based) links. QKD has already been installed in existing fiber optic communication networks but is limited in its transmission distance as well as its rate. QKD networks cannot use traditional, classical repeaters because amplification would alter the quantum state of the transmitted photons. Current installations are limited to distances of less than a few hundreds of kilometers because of this constraint.

To overcome this distance limitation, many possible solutions are being worked on:

- *Development of quantum repeaters*: Many research groups are working to develop quantum repeaters that would be able to store, manipulate, and re-send qubits without disrupting their quantum state; however, it will likely be several years before a quantum repeater is commercially realized.

- *Using trusted nodes*: Some installations are using classical nodes to refresh the signal, piecing together multiple independent, shorter QKD links. Keys are established separately for each section. These nodes are typically called trusted nodes because they require security at each link to ensure the information is not compromised. Some argue this is only a short-term solution because there is still potential for compromised security while others believe it could be a practical approach for some applications if the costs of the QKD transmitter/receiver boxes fall. Nevertheless, trusted-node quantum networks have already been demonstrated. China, for example, has a 2000 km network connecting Beijing and Shanghai with 32 trusted nodes (Courtland, 2016).

- *Using satellites and free-space optical links*: Propagation losses scale exponentially with distance in fiber, but only quadratically in free space, making space-based QKD an attractive alternative to fiber-based QKD (Khan, Heim, Neuzner, & Marquardt, 2018). Free-space optical communication can also operate over a larger range of wavelengths relative to fiber-based systems, which must operate in the telecommunications band (Awschalom, D., Berggren, K. K., Bernien, et. al., 2019). This method would use low-earth orbit satellites to distribute secure keys to ground stations via free-space optical links.



The principle has already been demonstrated: China famously launched the first publicly known QKD satellite, Micius, in 2016, creating an encrypted intercontinental video link to another research group in Vienna (Khan, Heim, Neuzner, & Marquardt, 2018). The technology is currently limited to low transmission rates and night-time operation, but development is ongoing. ArQit, a London-based startup, is working to build the first commercial satellite-based QKD system. There is also an EU-based QUARTZ Satellite Cybersecurity Consortium. This approach will present additional requirements for optics and photonics components, as they will need to be rugged enough for use in space.

QKD hardware is already commercially available from suppliers such as ID Quantique and Quintessence Labs and has been installed in various networks. Many other large corporations have active research groups as well, including Toshiba, NTT, NEC, Fujitsu, Mitsubishi Electric, etc.

Networks and trials are already installed for various applications. For example:

- *Financial Networks*: In Fall 2018, several major banks and financial institutions began testing a QKD network between Manhattan and northern New Jersey via the Holland Tunnel (Kahn, 2019).

- *Telecom*: SK Telecom announced they plan to install QKD technology on the Seoul-Daejeon section of its LTE and 5G networks (SK Telecom, 2019).

- *Government*: In 2007, QKD was trialed to protect the Geneva state elections in Switzerland (ID Quantique, 2017).

Other applications that are also expected to adopt include corporate networks, healthcare, defense, etc.; however, additional improvements are needed, including increased range, improved key rates, and lower costs / miniaturized hardware. Quantum memories and repeaters will be vital for increasing the reach of fiber-based QKD networks. Active stabilization and synchronization of components at the transmitters and receivers (such as laser frequency, polarization, phase of two optical interferometers) is also critical for long-term operation. Standards also need to be developed and are underway through initiatives at the ITU and ETSI.

From a system engineering perspective, further integration and compatibility with existing infrastructure, networks, and value chain players is another major hurdle. While protocols have been developed, additional experimentation and test beds are required to prove their effectiveness, which will take time. These testbeds are being developed; for example, Europe's OPENQKD network project is being used to demonstrate integration of QKD-enabled technologies to help advanced standardization and certification efforts.

Beyond QKD: Quantum Network/Internet

While QKD is expected to be the first application for quantum communications, a quantum internet with more functionality is expected to be developed longer term, which would enable distributed networks of quantum sensors and quantum computers. While QKD can enable more secure communication, a quantum internet could enable other applications such as:

- Distributed network of quantum sensors to increase performance
- Secure quantum computing in the cloud (i.e., blind quantum computing)
- Quantum computing clusters – distributed quantum computing

Additional development is required to realize these applications. For example, quantum memories are required to enable cloud quantum computing so that two users can obtain and store entangled qubits and use them to teleport quantum information to one another. End nodes for preparing, measuring, storing, and manipulating qubits will also be required for distributed quantum computing and quantum sensing networks. These end nodes may consist of simple photonic devices or small quantum computers.

In addition to hardware, software stacks, network stacks, and control planes need to be developed to enable the quantum internet. Key milestones to monitor progress toward a functioning quantum internet are outlined in a subsequent chapter. Incremental progress is being made today, but many experts expect it will take at least another decade to develop a long-distance, entanglement-based network.

INTRODUCTION TO QUANTUM COMPUTING

By harnessing superposition and entanglement, quantum computers have the potential to solve certain types of problems exponentially faster than classical computers. Where classical computers carry out logical operations on binary bits which can be 0 or 1, quantum computers' bits, called qubits, can be in a superposition state of 0 and 1, allowing for a much larger computational space.

Quantum computers will work in a hybrid architecture with classical computing in most cases. Research is still ongoing to identify the range of problems for which quantum computing can truly provide an advantage and it is very unlikely that quantum computers will completely replace classical computers in the foreseeable future. Most believe that quantum computers are more likely to be specialized machines applied to specific types of problems they are uniquely suited to solve.

COMPARING QUANTUM VS. CLASSICAL

Quantum Advantage	Demonstrating that a quantum computer can solve a problem (irrespective of the usefulness of the problem) faster or lower cost than a classical computer
Quantum Supremacy	Demonstrating that a quantum computer can solve a problem, again irrespective of the usefulness of the problem, that a classical computer cannot solve in a practical length of time
Quantum Value	Demonstrating quantum advantage or supremacy for a problem that has real commercial relevance where value (e.g., a better solution, shorter run time) is created

Source: Newry

Quantum Computing Applications

Quantum computing could have broad applicability, although experts in the community are wary of over-hyping the technology. They caution that for each proposed application, it is critical to understand:

- What algorithm will be used?
- What is the scale of the advantage realized with a quantum computer compared to a classical computer?

In several applications where quantum computers are expected to have an advantage, some algorithms have already been developed, and work is ongoing across many end markets to test the utility of early machines on real-world problems. In other cases, additional algorithms need to be developed and simultaneous improvements in the hardware (e.g., more qubits, lower error rates, etc.) will be required to implement them. Some firms are even developing software in advance of the hardware being available. Quantum computing is expected to be particularly well-suited for the problem types outlined in more detail below.

Large Number Factoring

As described in the Quantum Communications chapter, quantum computers are theoretically capable of leveraging Shor's algorithm to crack common public-key cryptography methods. First devised in 1994, roughly a decade after quantum computers were initially proposed, Shor's algorithm revealed a new approach to factoring large numbers and reignited interest in developing a quantum computer.

Simulation

The automotive and pharmaceutical industries are already exploring the advantages of quantum computers for chemical simulation for molecular design of new materials and drugs. For example, VW is trialing early quantum computing machines to simulate various material options for electric vehicle batteries (Volkswagen, 2018). Pharmaceutical companies, such as Biogen, are evaluating the utility of quantum computers for their drug discovery process (Accenture, 2020).

Quantum computers could also provide an advantage for scenario simulation in end markets spanning distribution and logistics (e.g., scheduling), financial services, and healthcare and life sciences by simulating multiple potential scenarios and their associated outcomes. The increased computing power could improve assessments of risk, pricing, and other market dynamics. Quantum amplitude estimator algorithms may be applied for this purpose.

Machine Leaning and Artificial Intelligence

Quantum computing has been proposed to improve artificial intelligence and machine learning applications by finding relationships and patterns in data (Carleo, et al., 2019). For example, MIT and IBM have collaborated to assess the advantage of using quantum computers for classification, especially feature mapping (Temme & Gambetta, 2019).

More precise classification of data according to different features is expected to improve the performance of artificial intelligence systems. Multiple algorithms may be applied to solve these problems more effectively, including quantum amplitude estimator, quantum support vector machines, and Harrow, Hassidim, and Lloyd's algorithms.

Optimization

Quantum computers can be applied to evaluate many potential solutions extremely quickly, which could apply to vehicle routing for distribution, manufacturing process planning and supply chain optimization, financial portfolio management, network optimization, etc. End users already trialing these examples include Airbus (evaluating the most fuel-efficient ascent paths), VW (traffic flow routing), and British Telecom (cell network optimization) (D-Wave Systems Inc., 2019).

Database Searching

Grover's algorithm is another famous quantum algorithm that can be applied to search large, unsorted databases. It is expected to deliver quadratic speedup, compared to the exponential speedup expected from Shor's algorithm.

IBM ROADMAP: QUANTUM COMPUTING USE CASES

	Chemicals and Petroleum	Distribution and Logistics	Financial Services	Health Care and Life Sciences	Manufacturing
Chemical Simulation	Chemical product design Surfactants, catalysts			Drug discovery Protein structure predictions	Materials discovery Quantum chemistry
Scenario Simulation		Disruption management	Derivatives pricing Investment risk analysis	Disease risk predictions	
Optimization	Feedstock to product Oil shipping / trucking Refining processes	Distribution supply chain Network optimization Vehicle routing	Portfolio management Transaction settlement	Medical / drug supply chain	Fabrication optimization Manufacturing supply chain Process planning
AI / ML	Drilling locations Seismic imaging	Consumer offer recommender Freight forecasting Irregular behaviors (ops)	Finance offer recommender Credit / asset scoring Irregular behaviors (fraud)	Accelerate diagnosis Genomic analysis Clinical trial enhancements	Quality control Structural design and fluid dynamics

Source: IBM, Accessed on https://quantumcomputingreport.com/our-take/a-quantum-computing-application-roadmap-from-ibm/

IBM ROADMAP: QUANTUM COMPUTING ALGORITHMS

Variational Quantum Eigensolver	Uses energy states to calculate the function of the variables to optimize; efficiently calculates complex portion of simulations, but requires many qubits for large problems
Quantum Approximate Optimization	Optimizes combinatorial style problems to find solutions with complex constraints; enables robust optimization in complex scenarios, but need to expand to more classes
Quantum Amplitude Estimator	Creates simulation scenarios by estimating an unknown property; potential to speed up simulations to solve dynamic problems, but high quantum volume needed for efficiency
Quantum Support Vector Machines	Supervised machine learning for dimensional problem sets; allows for better separation of data points to improve accuracy, but runtime can be slowed by data structure
Harrow, Hassidim, and Lloyd	Estimates the measurement of large linear systems; could enable exponential speedup of math calculations, but challenge is it’s hard to satisfy prerequisites

Source: IBM, Accessed on https://quantumcomputingreport.com/our-take/a-quantum-computing-application-roadmap-from-ibm/

Types of Quantum Computing

There are two general classes of quantum computers: analog and gate-based. Analog systems include simulated annealers, adiabatic computers, and more general-purpose quantum simulators, all of which directly manipulate interactions between physical qubits rather than breaking actions into more abstract gate operations. Analog machines involve a system with qubits prepared in an initial quantum state; then, the Hamiltonian is adiabatically changed to the final Hamiltonian such that the problem solution (answer) corresponds to the final state of a modified Hamiltonian. Because the value of the qubits are analog, it is accordingly difficult to implement error correction because the set of quantum operators are nondiscrete.

In contrast, gate-based quantum computers, sometimes referred to as universal quantum computers, use logical gate operations (AND, OR, etc.) on physical qubits, as their name suggests. Each gate operation is performed by allowing qubit evolution for a certain duration driven by a Hamiltonian that can instigate the desired transformation of qubits. Quantum error correction is possible as long as there are a sufficient number of qubits available to provide redundancy.

Quantum annealers and simulators use a different approach to quantum research than gate-model machines and are well-suited for optimization and simulation problems. There are questions about whether annealing machines will be able to run Shor's algorithm directly. D-Wave has already developed commercialized annealers that are being used by a range of customers, including Los Alamos National Laboratories, Volkswagen and OTI. These customers have either installed systems or have access to D-Wave's cloud platform, Leap. Many applications are being tested, and development efforts are ongoing to further scale these systems.

Gate-based quantum computers are currently at an earlier stage. While early systems have been developed and cloud access is even possible for some, they are still relatively small-scale and error prone. One key challenge for all quantum computers is that qubits tend to lose their superposition or coherence when they interact with the environment – a phenomenon called decoherence. Environmental noise (e.g., vibrations, temperature changes) can collapse the qubit into the ground (or a thermally excited state) quantum state before the calculation is finished, which is why many of these systems require vacuum and cryogenic systems to isolate the qubits.

EXAMPLE D-WAVE CUSTOMERS AND APPLICATION CATEGORIES

Los Alamos National Lab	Optimization, machine learning, simulating quantum systems
Volkswagen	Traffic flow optimization, battery simulation, acoustic shape optimization
DLR	Air traffic route optimization, airport gate scheduling
Denso	Traffic flow optimization, manufacturing process optimization
OTI	Materials science
British Telecom	Cell phone network optimization
Qx Branch	Machine learning for election modeling
Nomura	Financial portfolio optimization

Source: Media courtesy of D-Wave Systems

GATE-BASED QUANTUM COMPUTING APPROACHES

Superconducting	Spin	Topological	Ion Trap	Neutral Atom	Photonic
Superpositions of currents flowing in opposite directions around a superconductor at the same time	Uses the spin state of electrons confined in quantum dots on silicon wafers	Maintain quantum states in large clouds of electrons rather than localized, individual electrons (Majorana particles)	Ions trapped in electric fields in vacuum chambers – uses lasers to manipulate quantum states	Atoms trapped in magnetic or optical fields in vacuum chambers – uses lasers to manipulate quantum states	Qubits encoded in the quantum states of photons traveling in waveguides / fiber
Example Players					
IBM Rigetti Google Alibaba	Intel	Microsoft	IonQ Honeywell AQT	ColdQuanta Atom Computing	Psi Quantum Xanadu ORCA Computing

Researchers are working to alleviate these challenges by ensuring calculations can happen fast enough before decoherence occurs and by implementing error correction, which leverage other supporting qubits to rectify the mistakes occurring on the qubits that are being used to perform the calculations. Larger machines with more qubits are required to build in redundancy and implement these codes. Additional improvements are needed from both hardware and software to reduce these errors and to increase the interconnection of qubits as well.

Current systems are limited to tens of physical qubits, and no error correction is applied, meaning that there are no ideal logical qubits. Logical qubits are an abstraction that describes a collection of error-corrected imperfect physical qubits that effectively create one qubit capable of carrying out a fault-tolerant qubit operation. There is wide variation in qubit quality, which is why many refer to these machines as belonging to the NISQ Era – i.e., Noisy Intermediate-Scale Quantum (Preskill, 2018).

While many in the investment community are hopeful that value can be created from these NISQ machines in the near term, the ultimate goal is a large, fault-tolerant quantum computer with error correction implemented. To get there, the National Academy of Sciences, Engineering, and Medicine estimates that systems will need to be about five orders of magnitude larger than current machines with approximately two orders of magnitude lower error rates (National Academies of Sciences, Engineering, and Medicine, 2019).

There are multiple ways to physically make gate-based quantum computers and many large corporations and startups are working hard to scale various approaches. Superconducting and trapped ion approaches are furthest along so far; however, it is too early to speculate which specific architecture will dominate, if any at all. Some believe that multiple approaches will coexist as specialty solutions because the associated tradeoffs may make different types of quantum computers better suited to solve specific types of problems.

We've profiled some of the most prominent approaches for building quantum computers below, but any approach should generally satisfy the guidelines defined by David DiVincenzo in 1996 during his time at IBM, commonly referred to as the DiVincenzo criteria, which require (National Academies of Sciences, Engineering, and Medicine, 2019):

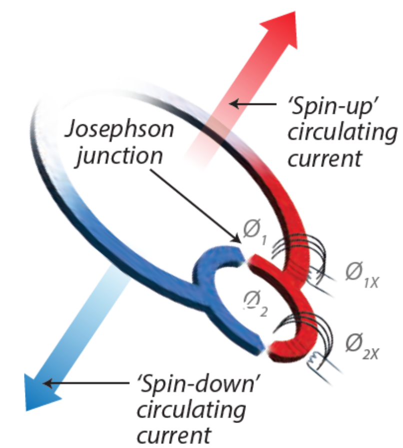
- Well-characterized two-level systems that can be employed as qubits
- An ability to prepare the qubits into a simple |000…> state
- Decoherence times long enough to carry out the computation or error correction
- A universal set of quantum operations (gates)
- An ability to measure qubits one-by-one without disturbing the others

Physical Platforms

There are a number of physical systems that can create platforms for quantum computing. Because superconductors and trapped ions are presently the most advanced implementations, they are discussed first.

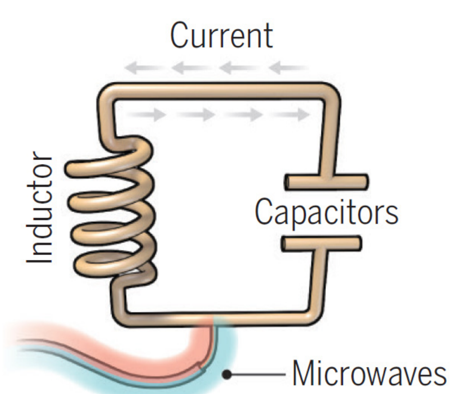
Superconducting

Superconducting quantum computers are based on resistance-free current flowing in opposite directions around a superconducting circuit containing Josephson junctions. The qubit states are controlled using microwave and low-frequency electrical signals. The duration of the microwave pulses determines which quantum operations are performed.



Credit: Phil Saunders Graphics/from *Optics & Photonics News*, October 2016.

Several large players are working on superconducting quantum computers, including IBM, Google, Alibaba, Rigetti, and D-Wave. The advantages of this approach are the relatively short gate operation times compared to trapped ion systems, and the opportunity to build on the existing knowledge and manufacturing base from the semiconductor industry to help scale to larger numbers of qubits.



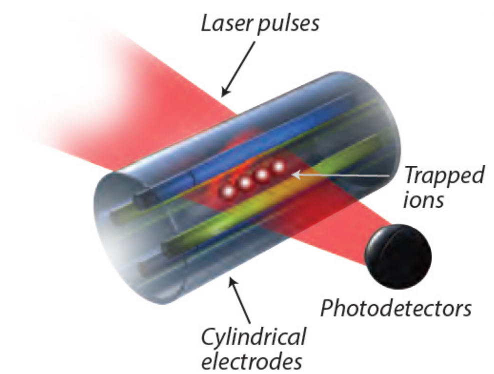
From *Science* News Feature, "Scientists are close to building a quantum computer that can beat a conventional one" by Gabriel Popkin, Illustration by Chris Bickel/Science. Reprinted with permission from AAAS.

Some challenges are that these systems require dilution refrigerators to keep temperatures very cold and the quantum state can collapse easily (i.e., these systems have relatively short coherence times). Coherence times are typically compromised further when scaling to more qubits due to variation in fabrication methods. Furthermore, in current superconducting implementations, the set of qubits is not fully connected (which would allow gate operations between any pair of qubits), restricting the kinds of algorithms that can be performed.

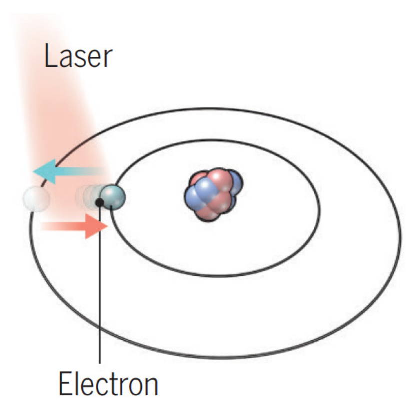
Current superconducting quantum computers do not require optics; however, some believe that fiber optics may be needed to support larger systems. The National Academy of Sciences, Engineering, and Medicine estimates that current dilution refrigerator technology can handle up to ~1,000 qubits; as superconducting systems scale beyond that limit, qubits may need to be stored in separate dilution refrigerators connected by optical fiber (National Academies of Sciences, Engineering, and Medicine, 2019). Microwave-to-optical transducers would be required to temporarily convert the microwave qubits to "flying" photonic qubits.

Trapped Ions

The trapped-ion approach to quantum computing involves suspending ions (ionized atoms) in electric fields in vacuum chambers, then using lasers to cool and prepare the ions (putting them into well-defined initial states). To perform operations, resonant optical or microwave fields are applied to drive qubits into a different state or to generate entanglement between ions. After computation, states are measured by detecting state-dependent fluorescence.



Credit: Phil Saunders Graphics/from *Optics & Photonics News*, October 2016.



From *Science* News Feature, "Scientists are close to building a quantum computer that can beat a conventional one" by Gabriel Popkin, Illustration by Chris Bickel/Science. Reprinted with permission from AAAS.

IonQ and Honeywell are the leading companies working to commercialize ion-trap quantum computers. One advantage of using atoms over synthetic systems is that they are fundamentally identical and therefore not susceptible to errors from manufacturing defects. This approach enables high-fidelity qubit operations and long qubit lifetimes. A big advantage of using trapped ions as qubits is that the set of qubits with an ion chain is fully connected (which allows gate operations between any pair of qubits), enabling a wide range of algorithms that can be performed.

The primary challenge for trapped ion approaches is scaling to larger systems, which will require integration of many lasers, vacuum systems, etc. More complex architectures are needed to scale to larger systems beyond tens of ions lined up in a single chain. The gate operation times are also relatively long compared to other systems.

Multiple photonic components are required for ion-trap quantum computers, including:

- Lasers for modulating the quantum state
- Lasers for cooling the ions, performing gates, and measurement
- Collection and imaging optics to collect the photons scattered from the ions
- Photodetectors to measure the state of ions by detecting the photons they scatter (i.e., measuring the state-dependent fluorescence)

Neutral Atoms

Quantum computers based on neutral atoms are a newer technology, but the operating principle has many similarities to trapped-ion quantum computers. Instead of using ions, neutral atoms are trapped in magnetic or optical fields (arrays of laser light beams) in vacuum chambers. Optical and microwave pulses are again used to manipulate the quantum states of the qubits. Lasers are used to cool the atoms, which reduces computational noise.

Atom-based approaches were developed to address some of the challenges associated with ion trap approaches. Ions, due to their charge, interact strongly with magnetic fields and each other, which can be advantageous for computation, but also makes scaling to larger systems difficult because undesired interactions may occur, resulting in noise.

In contrast, neutral atoms are less prone to cross talk and noise and are easier to scale; however, it is more difficult to get them to interact as required for computation. One other differentiating feature of neutral atom systems is their capacity to support multidimensional arrays of atoms, which is more difficult with trapped ions due to their strong interactions.

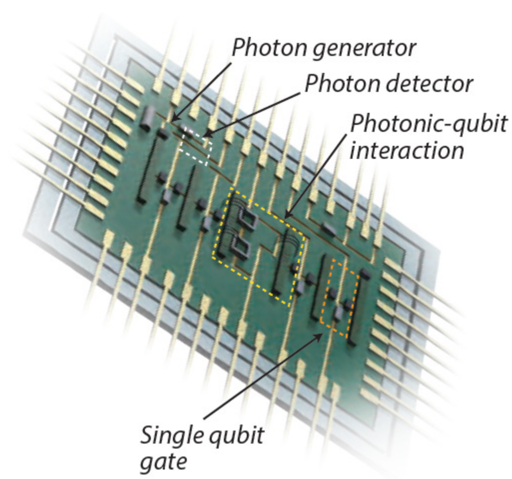
ColdQuanta and Atom Computing are two startups working on neutral atom approaches. Their systems benefit from using inherently identical atoms as their building block and have long qubit lifetimes. They have similar scaling issues to trapped ions because many lasers and vacuum systems need to be engineered into the complete system.

The general requirements for optics and photonics for neutral atom systems are similar to trapped-ion computers; however, different wavelengths of light will be required to match with the atom / ion transition. As in the ion trap approach, photodetectors and collection optics are needed.

Photons

Photonic quantum computers, sometimes referred to as linear-optical quantum computers, encode qubits in light traveling in planar waveguides or optical fiber. Different groups are implementing slightly different approaches using either single photons (so-called discrete states) or squeezed light states (called continuous states).

One key advantage of photonic approaches is that photons generally interact weakly with their environment and with each other, which increases their resistance to interference. Two-photon quantum interference or extremely high nonlinear optical interactions are needed to get the photons to interact for implementing multi-qubit gates.



Credit: Phil Saunders Graphics/from *Optics & Photonics News*, October 2016.

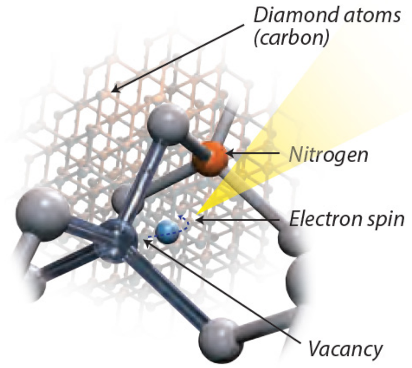
Psi Quantum, Xanadu, and ORCA Computing are each developing their own photonic-based quantum computing architectures. These approaches can operate at room temperature and offer the potential for long qubit lifetimes, fast gate operation times, and high single-qubit gate fidelity. They are also easily networked with fiber optic communications.

Unlike other systems with stationary qubits, there are unique challenges associated with scaling to larger systems because the photons are always moving if not stored in a quantum memory that consists of a collection of absorbing atoms. Many qubits need to be routed along chips or fiber, which could impact the final system size.

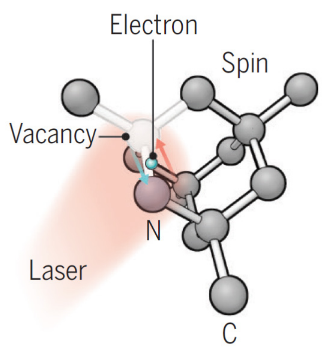
As the name suggests, photonic quantum computing approaches rely heavily on optics and photonics. Additional improvements in components, especially single-photon sources and high-speed, low loss switches, are critical for advancing the performance of these systems. Additional component needs include single-photon detectors, waveguides, modulators, couplers, and filters.

Color (Vacancy) Centers

A nitrogen atom placed next to a carbon atom vacancy can add an electron to a diamond lattice to create what's commonly referred to as a nitrogen-vacancy (NV) center. The spin state of the electron and nearby carbon nuclei can be controlled with light and optically detected. The isolated spins can be very stable and therefore used as qubits. Other color centers, such as the silicon-vacancy (Si-V) center in diamond, offer alternatives with advantages compared to the NV center.



Credit: Phil Saunders Graphics/from *Optics & Photonics News*, October 2016.



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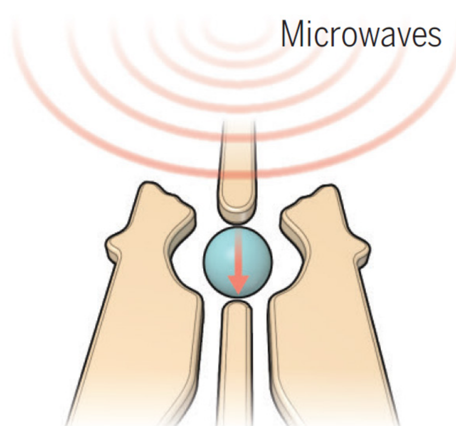
We are not aware of any commercial entities that are developing quantum computers based on NV centers, although there are some academic labs exploring this approach. NV centers are also being explored for quantum memories. One advantage is that these systems could theoretically operate at room temperature; so far, however, establishing entanglement and reliable production of identical vacancies has been challenging. Like other systems, NV-center-based quantum computers would require lasers and photon detectors if commercialized.

Silicon Spins

Silicon-spin quantum computers manipulate the spin state of electrons confined in fabricated quantum dots on silicon wafers.

Intel is the largest player working on this approach in collaboration with some universities. If developed successfully, silicon spin approaches would benefit from existing semiconductor manufacturing expertise that could allow for rapid scaling. Other potential advantages include fast gate operation times and small size; however, like superconducting quantum computers, cryogenic temperatures are required to protect the quantum state.

Challenges include poor qubit uniformity and background disorder, which is currently compensated for through careful tuning of gate voltages. The spin states are also highly sensitive to magnetic noise



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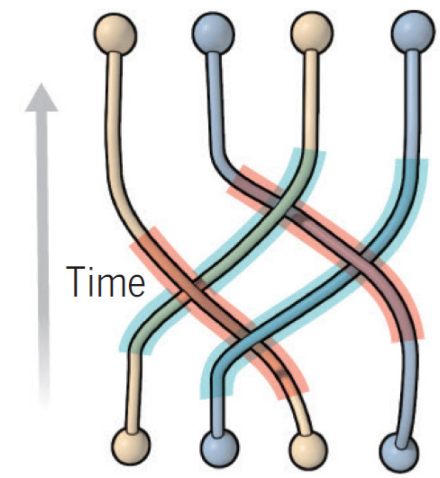
from surrounding atoms on silicon chips; noise needs to be reduced to improve gate fidelity. Furthermore, development of the appropriate geometry to scale to 2D arrays is needed. Aside from the optics required for networking, silicon spin approaches are unlikely to require optics or photonics components.

Topological Qubits

Topological quantum computers maintain quantum states in large clouds of electrons rather than localized, individual electrons. Quasiparticles (e.g., Majorana particles) may be created by channeling electrons through nanowires. Quantum states are encoded by different 'braiding' paths that the particles follow in time. The shapes of the braided paths lead to superpositions and they are topologically protected from collapse.



From *Science* News Feature, "Scientists are close to building a quantum computer that can beat a conventional one" by Gabriel Popkin, Illustration by Chris Bickel/Science. Reprinted with permission from AAAS.

Microsoft is the largest player developing topological quantum computers based on Majorana particles. Since the qubits are protected by the topological symmetry implemented at the microscopic level, these computers are less error-prone. There is potential for very high fidelity and long qubit lifetimes; however, the technology has not yet been demonstrated. While the technology is still very early stage, it has the potential to scale readily once demonstrated and would ideally not require error correction. It is unlikely that topological quantum computers would require optics and photonics components.

OPTICS AND PHOTONICS COMPONENTS NEEDS

What are the opportunities for component suppliers?

Many optics and photonics components are required to enable quantum sensors, computers, and communications networks (Awschalom, D., Berggren, K. K., Bernien, et. al., 2019). This chapter outlines the outstanding needs required for photon sources (lasers and single-photon or entangled photon sources), photon detectors, fiber and waveguides, modulators, interconnects (transducers and converters), memories and repeaters, nonlinear-optical materials, and integrated photonics.

SUMMARY: OPTICS AND PHOTONICS COMPONENT REQUIREMENTS

Required May Use

Category	Technology	Lasers	Single or Entangled Photon Sources	Single Photon Detectors	Heterodyne and Homodyne Photon Detectors	Fiber or Integrated Photonic Waveguides	Modulators	Transducers and Converters	Memories or Repeaters	Operating Wavelength
Sensing	Atomic Clocks							If networked		Non-Telecom
	Atom Interferometers							If networked		Non-Telecom
	NV Center Sensors							If networked		Non-Telecom
	Quantum LiDAR									Non-Telecom
Comms.	Continuous Variable QKD									Telecom
	Discrete Variable QKD									Telecom
	Entanglement-Based QKD									Telecom
Computing	Superconducting							If networked		--
	Ion Trap							If networked		Non-Telecom
	Neutral Atom							If networked		Non-Telecom
	Photonic - Discrete Variable							Memory-dependent		Telecom
	Photonic - Cont. Variable							Memory-dependent		Telecom
	NV Center							If networked		Non-Telecom
	Silicon Spin							If networked		--
	Topological							TBD	TBD	--

Source: Expert interviews, Newry analysis

Photon Sources

Many types of photon sources are required to enable quantum technologies. While the specific performance requirements (e.g., wavelength, power, linewidth, noise, single vs. entangled photons, etc.) vary widely by system, some of the most common unmet needs that exist across multiple applications are outlined below.

Lasers for Atom- and Ion-Based Quantum Computers and Sensors

Atom- and ion-based quantum computers and sensors (e.g., ion trap computers, neutral atom computers, atomic clocks, atom interferometers) require lasers at wavelengths specifically tuned to be resonant with their respective atom or ion transition. Lasers are used to prepare atoms, to initiate quantum states, and to read quantum information. In some cases, these transitions are in the near-UV and blue-violet spectral frequency ranges. Commercial lasers at these wavelengths (if available at all) are often relatively less optimized than lasers developed for telecom applications at infrared wavelengths. Higher-performance and more stable lasers in the near-UV and blue-violet spectrum are desired to ensure precise qubit preparation and manipulation.

EXAMPLE WAVELENGTH REQUIREMENTS

Ions – Yb^+, Sr^+, Ba^+, Ca^+	369, 393, 397, 408, 422, 435, 455, 493 nm
Atoms – Rb, Cs, K	767, 770, 780, 795, 852, 895 nm

Specific requirements include:

- *Narrow linewidth*: Narrow linewidth and low phase noise are common requirements for lasers used in cold atom systems for quantum sensing and computing. For applications such as probing and measurement, linewidths may need to be as low as tens of kHz or even tens of Hz or less; requirements are most stringent for optical-frequency atomic clocks. The lasers used for atom or ion cooling have less demanding parameters, but still require relatively narrow linewidths on the order of one to tens of MHz.

- *Stable output*: Lasers must be mode-hop-free (i.e., must maintain a consistent frequency) and provide stable power output to ensure consistent performance for precise qubit manipulation.

- *High power*: Lasers used for cooling ions / atoms or trapping atoms in optical lattices can require power levels from hundreds of milliwatts up to ten watts. Lasers used for other purposes (e.g., probing) may only require tens of milliwatts or less.

- *High repetition rate*: High repetition rate (on the order of hundreds of megahertz) pulsed lasers are desirable for increasing sensor sampling rates and accelerating gate operation speeds.

- *Compact and rugged*: Smaller scale lasers will be critical for reducing the size and weight of cold atom sensors and clocks to enable broad deployment of systems in the field. Chip-integrated form factors would be desirable. Lasers that are stable in a variety of environmental conditions – e.g., vibration, moisture, temperatures ranging from 0 to 80°C, etc. – are also needed.

There are multiple laser technologies that may be considered to meet these requirements, including:

- External cavity diode lasers (ECDLs)

- Diode-pumped solid-state (DPSS) lasers

- Distributed Bragg reflector (DBR) or distributed feedback (DFB) lasers

- Vertical-cavity surface-emitting lasers (VCSELs)

- Volume-holographic-grating (VHG) lasers

Various suppliers such as M-Squared, Toptica, Photodigm, NKT Photonics, Sacher Lasertechnik, Kelvin Nanotechnology, and UniKLasers have already invested in developing lasers to meet the needs of quantum technology applications. Many quantum computing and sensing customers even claim that recent developments have addressed the majority of their performance needs; however, reductions in cost (3-10x) and size are still desired. Ruggedization will also be required to use these systems in space. Multiple experts said that integrated, on-chip lasers would be the "Holy Grail," particularly for quantum sensors, though they acknowledged that it will be some time before such systems are developed.

Stability of the supply chain is also a concern. For example, the development of ECDLs depends on the availability of laser diode components at the required wavelengths, but the volumes from quantum applications are often too low to motivate suppliers. Until demand increases, many system designers may be limited to selecting atoms / ions with transitions that match other commercially relevant wavelengths (e.g., 780 nm lasers that were developed for CD drives align with the transitions in Rb-based systems). While there are similar wavelength requirements between these applications, many other performance specifications need to be met to make these lasers feasible for quantum technologies.

Single-Photon and Entangled-Photon Sources

Single-photon sources are critical components for discrete-variable quantum key distribution and some types of photonic quantum computing. Some of the approaches used to create single photons may also be used to create pairs of entangled photons, which are needed for quantum LiDAR and entanglement-based quantum key distribution, as well as emerging techniques in quantum-enhanced microscopy and spectroscopy.

An ideal single-photon source would have the following properties:

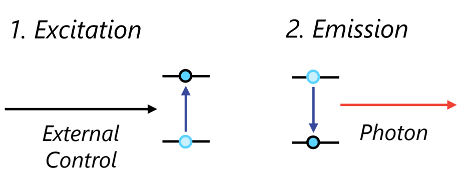
- *Deterministic*: Consistently emit a photon in a controlled manner "on demand" at a time arbitrarily chosen by the user (unlike probabilistic sources, which emit randomly and may not emit any photons for the majority of trials). A truly deterministic single-photon source would enable significant advancements in photonic quantum computing.
- *Indistinguishable*: Each emitted photon is high-purity and indistinguishable from the others; the frequency is the same and there are well-defined states in spatial, temporal, and spectral modes.
- *Low probability of multi-photon emission*: The probability of emitting a discrete single photon would ideally be 100%, with 0% probability of multi-photon emission.
- *High repetition rate / brightness*: Emission rates are very fast – i.e., many single photons can be produced per unit time.
- *Ability to generate entangled pairs*: Some applications (e.g., entanglement-based QKD) require the production of entangled photons.
- *Integrated*: If possible, on-chip integration of single photon sources would be highly desirable for integrated photonics.

SINGLE-PHOTON SOURCE TYPES

Deterministic

Multiple approaches exist but all rely on a similar principle:

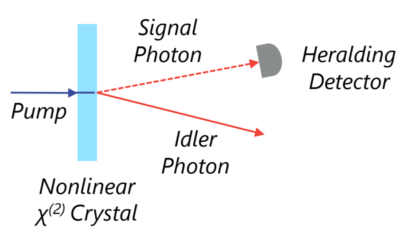
- An external control puts the system into an excited state
- A single photon is emitted upon relaxation to the lower energy state



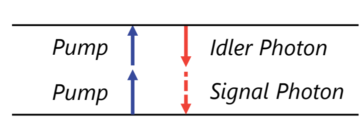
Probabilistic

Generate heralded pair of single photons, and the detection of one "heralding" photon indicates the existence of another photon. Usually involves laser excitation of nonlinear optical materials, but there are two approaches:

Parametric Down-Conversion
Convert one photon of higher energy into a pair of photons



Four-Wave Mixing
Two pump photons convert into two photons in the presence of a third-order nonlinear material



Source: Newry

COMPARISON OF HIGHEST PERFORMANCE LEVELS ACHIEVED BY DIFFERENT SINGLE-PHOTON SOURCE TYPES*

	Spontaneous Down Conversion	Four-Wave Mixing	Atoms and Ions	Quantum Dots	NV Centers	"Ideal" Single-Photon Source
Entanglement fidelity	0.9959	0.997	0.93	0.978	---	Approx. 1
Probabilistic / deterministic	Probabilistic	Probabilistic	Probabilistic, Deterministic	Deterministic	Deterministic	Deterministic
Emission range	600-1700 nm	600-1550 nm	Transition lines	IR, telecom	600-800 nm	Varies – many apps require telecom
Brightness	2.01 MHz	855 kHz	55 kHz	28.3 MHz	850 kHz	High
Best *g* (Purity)	0.004	0.007	0.0003	0.000075	0.07	Approx. 0
HOM visibility (Indistinguishability)	0.99	0.97	0.93	0.9956	0.66	Approx. 1
Operating temp.	273-473 K	Room temp.	Room temp., mK (in cavity)	Room temp., cryogenic	300-500 K	Room temp.
Efficiency max. (Deterministic)	0.84	0.26	0.88	0.97	0.35	Approx. 1
Likely quantum apps	Metrology, information, comms, foundations	Integrated photonics	Foundations	Comms, foundations	Comms, networks	--

*Note: values represent the highest performance level achieved in a single demonstration – i.e., a column is not representative of a singular system and in reality, tradeoffs exist when optimizing versus the various requirements.
Source: OPN September 2019 Issue: Single Photon Sources, U. Sinha, S. Sahoo, A. Singh, K. Joarder, R. Chatterjee, S. Chakraborti
Links to original sources can be found at: http://www.rri.res.in/quic/resources/opn2019

There are five main technological approaches that may be used to generate single and / or entangled photons; however, each has its tradeoffs:

- *Spontaneous Parametric Down-Conversion (SPDC)*: SPDC in a crystalline (second-order) nonlinear optical material is one of the most popular approaches for generating single photons. It generates photons at a fast repetition rate (~2 MHz), often defined as brightness, and provides high entanglement fidelity (>99.5%); however, it is not deterministic and there is some probability that multi-photon emission can occur (Sinha, et al., 2019). Coupling into optical fiber can also be a challenge.

- *Four-Wave Mixing*: Four-wave mixing in a glassy (third-order) nonlinear optical material is a waveguide-based approach that is often used in integrated photonic platforms. It offers high entanglement fidelity but is not deterministic.

- *Atoms and Ions*: Atom and ion sources can be used to create deterministic photon sources with highly indistinguishable output, narrow emission linewidths, and high purity. Because atoms emit isotropically, very high-quality optical cavities are needed to make these sources truly or nearly deterministic. This approach is not considered the optimal choice for many commercial applications due to the complexity of the atom/

ion trap system and the high-quality cavity that is required but may be used in experimental research.

- *Quantum Dots*: Quantum dot-based single-photon sources offer the highest brightness (single photon emission rates of 28+ MHz) and have the potential to be deterministic (Sinha, et al., 2019). They also have relatively high entanglement fidelities (97.8%) and purity, but may require cryogenic temperatures to operate optimally (Sinha, et al., 2019). Many believe this is a promising approach for deterministic generation of indistinguishable single photons, although generating identical quantum dots remains a challenge and most commercial sources are still probabilistic. If two quantum dots have significant structural differences, the photons emitted from each will be distinguishable. Coupling into optical fiber can also be a challenge. Multiple startups (e.g., Quandela, Sparrow Quantum) are actively commercializing the technology.

- *Nitrogen-Vacancy (NV) Centers*: Color centers in diamond, most commonly known as NV centers, are a newer approach to single-photon generation. They are in principle deterministic sources and the emission rate increases with temperature, which makes them potential candidates for room-temperature sources. Consistent manufacturing of NV centers remains a barrier.

Given the tradeoffs described above, different approaches may be preferred for different applications based on the varying requirements.

For example, discrete-variable QKD protocols require bright and high-purity sources to increase key exchange rates and maintain security, respectively. Room temperature operation is also preferred to minimize costs. The preferred emission wavelength is ~1550 nm for fiber-based systems and other spectral ranges may be considered for free-space, satellite-based networks to minimize scattering and maximize transmission.

Discrete-variable photonic quantum computing approaches (e.g., PsiQuantum) require deterministic single-photon sources that have high single-photon purity, high photon indistinguishability, and high brightness. The source should also be compatible with integration into CMOS fabs. Other photonic quantum computing approaches (e.g., Xanadu) may alternatively use squeezed light sources based on nonlinear optics.

Entangled photon sources are required for entanglement-based QKD protocols and specialized applications in metrology and imaging.

Photon Detectors

Photon detectors are also widely used for many quantum technologies, ranging from measurement of state-dependent fluorescence in trapped-ion quantum computers to detection of single photons transmitted in QKD and photonic quantum computers. Two general photodetector categories are outlined in more detail below: single photon detectors and heterodyne / homodyne detectors.

Single-Photon Detectors

Single-photon detectors are required for discrete-variable QKD and photonic quantum computing, some types of quantum imaging, and quantum LiDAR. In addition to quantum technologies, other applications (e.g., ultra-low light sensing and surveillance, medical imaging, astronomy) may benefit from their development.

An ideal single-photon detector would have the following performance specifications:

- *High detection efficiency*: There is high (close to 100%) probability that a photon incident upon the detector is successfully detected – i.e., no false negatives.
- *Low dead time*: The time after a photon-detection event during which the detector cannot detect a photon is negligible (near-zero).
- *Low timing jitter*: There is minimal or no variation from event-to-event in the delay between the input/output signals.
- *Low dark count rate*: There would ideally be no detector output pulses in the absence of incident photons – i.e., no false positives.
- *Photon number resolving*: Some applications require a detector that can distinguish the number of photons in an incident pulse rather than just providing a "0" or "≥1" reading.

There are several technological approaches to meet these requirements. Superconducting single-photon detectors (SSPDs) are a newer technology that is gaining commercial traction. SSPDs offer high efficiency, low dead time, low timing jitter, and low dark count rates; however, they require cryogenic cooling, which can be cost-prohibitive for some applications. Avalanche photodiodes (APDs) operating in Geiger-mode are a more mature technology that is used in applications such as QKD and does not require cryogenic operation. Lastly, photomultiplier tubes (PMTs) are another very mature technology, but their use in quantum applications is relatively limited.

SSPDs, APDs, and PMTs are not intrinsically photon-number resolving; however, superconducting transition edge sensors (TES) and CMOS image sensors that provide this capability are in development. Bolometric TES require cryogenic temperatures but can offer photon-number-resolving capability, high efficiency, and low dark count rates. CMOS image sensors could operate at room temperature and have low dead times, high efficiencies, and low dark count rates; however, the long readout time may be limiting, and current silicon-based imagers are not compatible with telecom wavelengths.

Geiger-mode avalanche single-photon detectors are commercially available from players such as ID Quantique, Aurea Technology, Micro Photon Devices, and PicoQuant. Wooriro is a key supplier of InGaAs/InP avalanche photodiodes. Superconducting single-photon detectors, a newer technology, are also already being supplied by several companies, including Quantum Opus, Single Quantum, and Photon Spot. Research is ongoing to further improve performance, integrate on-chip, and reduce size / cost.

OVERVIEW: SINGLE-PHOTON DETECTOR TECHNOLOGIES

Type	Status	Cost	Advantages	Drawbacks
Photomultiplier Tubes (PMTs)	Very Mature	$	• Room temperature • Mature, low-cost technology	• Low detection efficiency • High timing jitter • High dark count rate • Not photon number resolving
Avalanche Photodiodes (APDs)	Mature	$	• Room temperature • Lower size, weight, and power vs. SSPDs • Moderate timing jitter (high time resolution) • High count rates and room temperature operation can be achieved in fast gating mode	• Incompatible with IR (Si is transparent); InGaAs may be used, but lower efficiency and higher dark count rates • Not photon number resolving, unless multiplexed • High dark count rates and/or after-pulses, especially in NIR; lower dark count rates possible with coolers • Lower efficiency vs. SSPDs • Longer dead times
Superconducting Single Photon Detectors (SSPDs)	Small Volume	$$$	• Low timing jitter • High detection efficiency • Low dead time • Low dark count rate • No after-pulsing • High photon detection rate	• Requires cryogenic cooling (<4K) • Not photon number resolving, unless parallel configuration • Susceptible to picking up background thermal radiation from input fiber
Transition Edge Sensors (TES)	Early Stage	$$$	• High detection efficiency • Photon number resolving • Low dark count rates	• Requires ultra-low-temperature operation (tens of mK) • High timing jitter • Longer dead times
CMOS Image Sensors	Early Stage	$	• Room temperature • Photon number resolving • Low dead time • High detection efficiency • Low dark count rate	• Incompatible with IR (Si is transparent), lower efficiency in blue/UV • Long readout time (microseconds)

Heterodyne and Homodyne Photon Detectors

Other applications that do not use single photons, such as continuous-variable QKD and atom-based computing and sensing systems may use coherent heterodyne or homodyne detectors. In general, our interviews revealed that there are relatively fewer unsolved problems / pain points associated with current heterodyne and homodyne detectors compared to single-photon detectors. This could be because some of these detectors are already used in non-quantum (classical) communications today. Lower noise and higher bandwidth detectors would be a valuable advancement.

COMPARISON OF COMMON COMMERCIALLY AVAILABLE INFRARED SINGLE-PHOTON DETECTORS

	Avalanche Photodiode *InGaAs / InP, Geiger-Mode*	**Superconducting Nanowire SPD**	**"Ideal" SPD**
Example Product	ID Quantique ID230	Single Quantum Eos	--
Detector Efficiency at 1550 nm	10 - 25%	≥ 85%	100%
Reset Time	2 - 25 µs	≤ 30 ns	Approx. 0+
Jitter Time	150 ps	≤ 25 - 50 ps	0.0 ps
Dark Count Rate	<50 – 200 Hz	≤ 300 Hz	0.0 Hz
Operating Temperature	Non-Cryogenic (183 - 223K)	Cryogenic (~2.5K)	Room Temp. (~293K)
Relative Cost	Low	High	--
Intrinsically Photon Number Resolving	No	No	Yes

Sources: Data sheets from Single Quantum, IDQuantique

Components for Transmission and Light Manipulation

Many additional optics and photonics components are required to manipulate and transmit the light between the photon source and detector. Specific needs by component type are profiled in more detail below. One common requirement across most components and applications is the need for ultra-low-loss components; given that many quantum systems are based on manipulating single photons, truly every photon counts.

Fiber / Waveguides

Lower-loss fiber and waveguides would improve the performance of quantum communications networks, photonic quantum computers, and chip-based sensors. Fiber may also be used to network between dilution refrigerators and ion traps in superconducting and trapped ion quantum computers, respectively. Quantum communications and photonic quantum computing approaches may operate at telecom (infrared) wavelengths, while atom- and ion-based sensors may require a different spectral frequency range (commonly blue or UV) and therefore potentially different materials.

In existing ultra-low-loss commercial fiber, losses are ~0.17 dB/km, but quantum communications applications would benefit from additional reduction. For integrated photonic approaches, losses are currently on the order of 0.25 dB/cm in Si and 0.1 dB/cm in SiN, but even lower-loss waveguides (down to 0.01 dB/cm if possible) are desired. Multiple approaches are being trialed to further reduce loss, including new materials and development of optical coatings and improved manufacturing processes (e.g., reducing side wall width variance in integrated photonics).

In addition to being lower loss, fiber or waveguides for systems that use photons as the qubit (e.g., photonic quantum computers, QKD) must be polarization-maintaining. The industry also expressed interest in commercial availability of low-loss hollow fibers filled with reactive alkali-vapor atoms for atom-based quantum memories.

Modulators and Switches

Modulators are another enabling technology used across computing, communications, and sensing platforms for switching and to modulate phase, amplitude, polarization, frequency, etc.

Low-loss, high-speed electro-optic modulators are needed to ensure fast switching and routing for photonic quantum computing, which relies on large, multiplexed optical circuits and rapid feedforward. While high-speed modulators are available today, losses are typically too high (~2-3 dB) for quantum applications, which cannot use amplifiers and therefore require losses under a few tenths of dB. One expert described the ideal, even "game changing" modulator as one that is waveguide- or fiber-based, has a speed of a few GHz, and has very high transmission (99%) at telecom wavelengths.

MODULATOR PERFORMANCE TARGETS

Performance Metric	Current	Ideal
Loss	2-3 dB	<0.1-0.5 dB
Speed	A few GHz	A few GHz

Source: Expert interviews

Modulators are also critical components for quantum key distribution, which requires high-bandwidth, low-voltage, and low-loss modulators. These components need to operate at telecom wavelengths and are used to modulate amplitude, phase, and / or polarization of light.

Atom- and ion-based quantum computers and sensors / clocks also use electro-optic phase, amplitude, and polarization modulators for laser cooling, quantum state manipulation, and readout. Unlike photonic computing and QKD, these applications may require operation in blue / UV wavelengths. I/Q (quadrature) modulators are also desired at these wavelengths. Neutral atom quantum computers specifically require higher-bandwidth (up to tens of GHz) spatial light modulators with greater power handling capacity (up to 1 W) for spatial filtering, acousto-optical reflection, etc. Spatial light modulators may also be used for high-dimensional (multi-state) QKD.

Many existing modulators suppliers serve traditional markets (e.g., telecom) and university labs and other companies are actively working to advance performance further for quantum applications. For example, QUBIG GmbH was founded in 2008 by two quantum optics researchers and is now supplying electro optic modulators to multiple quantum projects in Europe. Hyperlight, a startup spun out of Harvard, is commercializing integrated electro optic modulators based on thin-film lithium niobate. Other example suppliers include EO Space, Gooch & Housego, and Harris Corporation.

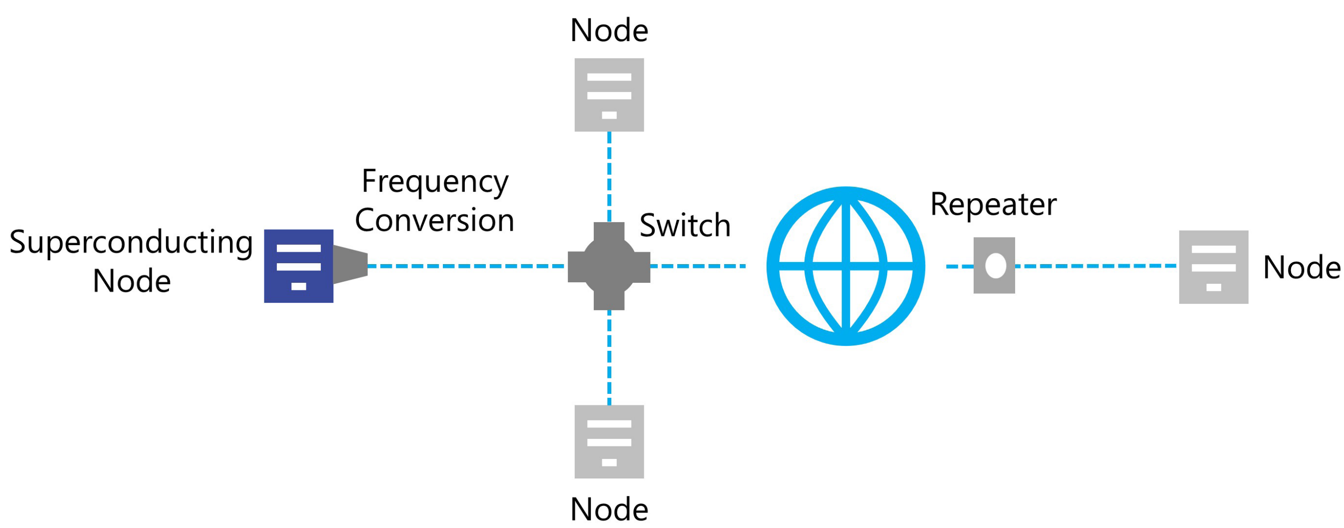
Interconnects: Transducers and Converters

Optical frequency converters and optical-to-microwave transducers will be needed in the future to link disparate systems in a quantum network to create a quantum internet or local network of quantum computers (Awschalom, D., Berggren, K. K., Bernien, et. al., 2019). Quantum interconnects must transfer the quantum states between various physical media (e.g., atoms, photons, microwave fields, semiconductor electronics) with high fidelity, fast rates, and low loss.

Interconnects will be required to link both bosonic-to-atomic and bosonic-to-bosonic systems (Awschalom, D., Berggren, K. K., Bernien, et. al., 2019). Bosonic systems include optical photons, mm waves, microwaves, and acoustic photons. Atomic systems include neutral cold atoms, trapped ions, quantum dots, color centers, superconducting Josephson devices, etc.

Microwave-to-optical transduction will be required to network matter-based quantum computing approaches (e.g., superconducting) with fiber optics because photons are the most practical non-stationary qubits that can be transmitted over long distances. This networking between quantum computing or sensing nodes is likely to occur in the quantum internet.

ILLUSTRATIVE QUANTUM NETWORK



Source: Newry

Optical fiber may also be used to link multiple dilution refrigerators for superconducting quantum computing architectures as they scale to higher-qubit systems. Although these systems operate in the microwave regime, even low-loss microwave cables experience high attenuation (>1 dB/m). By converting between microwave and telecom frequencies, networks of matter-based systems can take advantage of the dramatically lower loss telecom optical fiber (<0.2 db/km).

Requirements for microwave-to-optical transducers include high fidelity, high efficiency (as close to 100% as possible, but must be above 50%), and bandwidth of at least 10 kHz. Transducers also must be able to operate at millikelvin temperatures and have low power dissipation to be compatible with the cryogenically cooled superconducting systems (Lambert, Ruedo, Sedlmeir, & Schwefel, 2020).

A wide range of transducer implementations are being considered, including those that leverage electro-optical, magneto-optical, and optomechanical effects. Systems based on absorption spectra of rare-earth ions and Rydberg systems are also being explored.

Meeting the efficiency targets for microwave-to-optical transduction remains challenging for all implementations. While optomechanical systems have the highest demonstrated efficiencies, they suffer from thermal noise and tend to have low bandwidth. Other systems have seen large improvements over the last decade and may be able to offer competitive efficiencies and wider bandwidths in the future.

Even if non-microwave systems are being used (e.g., trapped ion, NV-center), multi-frequency conversion may be required if the systems operate at different wavelengths (e.g., visible-to-infrared). For example, NV centers, which emit at 637 nm, may be used as network nodes or distributed sensors in the quantum internet; however, conversion to telecom wavelengths (e.g., 1550 nm) is needed to transmit between nodes over traditional fiber optic cable. Quantum memories (described in more detail below) often emit at non-telecom wavelengths as well, so frequency conversion will be required in some memory-based quantum repeaters, once developed.

The quantum state must be maintained during the conversion process, and the converters must be high efficiency (ideally 95-100%), low loss, and low noise. Key research goals include reducing coupling loss and increasing conversion efficiency while preserving the quantum properties of the converted photons.

Multiple approaches are being pursued to meet these performance targets. The most common approaches rely on materials with 2nd order (e.g., lithium niobate) and 3rd order (e.g., silicon nitride) optical non-linearities where laser pumps are used to up- or down-convert the frequency of the signal photon. Bulk crystals may be used for this purpose and near-100% efficiency is possible, but high-power lasers are required, which generate noise via Raman scattering, thereby making it more difficult to isolate the signal photon. Alternatively, waveguides may be used, which enable the use of lower power lasers; however, on- and off-chip coupling losses are a challenge. Additional approaches include ring resonators and electro-optical conversion, which can achieve high efficiency conversion but are limited to smaller frequency shifts.

Quantum Memories and Repeaters

Quantum repeaters are a critical element for enabling quantum communications over longer transmission distances. Due to transmission loss, current fiber-based QKD installations are limited to distances on the order of a few hundred kilometers. While amplifiers are used in classical communications networks to mitigate transmission loss, they cannot be used in quantum networks because they would destroy the quantum state. Accordingly, new quantum repeaters are in development.

There are two main classes of quantum repeaters: memory-based and photonic-based. Memory-based repeaters use a quantum memory to temporarily store quantum states while the system completes some other processing in the network, similar to memories used on classical computers. Once this processing is complete the repeater can pull the quantum state out of its memory and use that qubit in additional processing.

Photonic quantum repeaters would obviate the need for memory by creating "cluster states," large groups of highly entangled photons, and then performing specific operations and measurements on those qubits. Rudimentary photonic-based quantum repeaters may be able to be implemented at an earlier stage.

Quantum memories can be applied in quantum computing as well as communications. The memory stores the qubits (e.g., single photons) temporarily while other processing occurs and then the quantum state is recreated for subsequent processing. The memory must hold multiple pieces of information in parallel, and the information cannot be observed.

Quantum memories may also be combined with probabilistic single-photon sources (e.g., spontaneous parametric down conversion) to temporarily store single photons, thereby creating an effectively deterministic single photon source as long as the memory is high-efficiency. There are several key parameters that must be met:

- *High efficiency and fidelity*: The ideal quantum memory would have write-in/write-out efficiencies exceeding ~90%, meaning that the more than 90% of the input information is successfully output.
- *Multiplexed:* Storing multiple quantum states in various modes is desired – some experts estimate that the ability to multiplex in excess of hundreds or thousands of modes will be required.
- *High storage lifetime*: The qubit storage lifetimes must be long – on the order of 500 microseconds to 500 milliseconds. Long storage lifetime is particularly critical for quantum communications, which has requirements on the millisecond or second time scale. Photonic quantum computers can tolerate shorter storage times, but other features, such as multi-mode capacity, become more important.

- *Compatible with networks*: Most memories will need to interface with telecom networks; the memory must couple with the infrastructure effectively.

There are multiple physical approaches to creating quantum memories. Most are based on resonant (first order) and Raman (second order) interactions in atoms that may be in crystalline and amorphous solids, molecular gases, metamaterials, etc. Example technologies that are in development include:

- *Rare-Earth Ion-Doped Solids*: Rare-earth ion-doped solids use crystals (e.g., yttrium or lanthanum) or optical fiber doped with rare-earth ions (e.g., Nd, Pr, Eu, and Er). These systems can demonstrate excellent storage lifetimes at cryogenic temperatures – in some cases, on the order of hours – and efficiencies of 70%. They are also compatible with spatial, temporal, and spectral multiplexing. These memories can be used for systems operating at telecom wavelengths, as well as microwave frequencies (e.g., for superconducting qubit systems).

- *Nitrogen-Vacancy Centers:* Nitrogen-vacancy centers, often in diamond crystals, can be used as a quantum memory with a long storage lifetime. Other advantages include the ability to optically prepare and read out states and the potential for implantation in optical micro / nanophotonic devices. In addition to storing optical photon states, nitrogen-vacancy memories are also able to couple to and store microwave photons from superconducting qubit systems.

- *Raman Scattering in Diamond*: The high Raman gain of diamond and its broad transmission window could make it useful as an optical memory; however, the short storage lifetime (picoseconds to a few nanosceconds) would be insufficient for most applications.

- *Atomic Gases*: Clouds of atomic gases, typically alkali elements like Cs and Rb, can be used to store quantum states. These systems can achieve high efficiency (~80%) [the majority of photons that have been stored a re-emitted] due to their large resonant optical depth, have long storage lifetimes, and operate at convenient near-IR transition wavelengths. They can also multiplex over 200 modes. While systems can achieve good storage lifetimes at room temperature, cooling vapors to mK temperatures or confining them in magneto-optical traps (MOTs) can dramatically improve lifetimes, in some cases to tens of seconds. Scaling and efficient in- and out-coupling remains a challenge for atomic gas memories, so integration into optical cavities or hollow core fiber are also being explored.

- *Optical Fiber / Waveguide Memories*: Since photons travel through fiber at a set speed, long lengths of fiber or loops of fiber with a switch can be used to effectively delay photons while other computational tasks are completed. Fiber-based memories are compatible with telecom networks and are multiplexable. The key challenge is transmission loss because long fiber distances are required to achieve the necessary storage times. Even low-loss fiber will only be able to hold a photon for a few hundred microseconds before loss drives the system efficiency below 50% (3dB loss). Switch-based approaches face the same issue.

While there are many research groups actively working on developing quantum memories and repeaters, additional development will be required before a product can be commercialized. Similar to quantum computing, no single approach has emerged as the most promising candidate technology yet. Some form of error correction will likely be required as well. An NSF workshop concluded that there are likely to be three generations of quantum repeaters that will bring incremental performance improvements over the next 3-10 years (Awschalom, D., Berggren, K. K., Bernien, et. al., 2019).

Nonlinear Optics

Many of the technologies discussed above will require advanced development of nonlinear optical materials and devices (Awschalom, D., Berggren,

K. K., Bernien, et. al., 2019). Spontaneous down conversion and four-wave mixing as single-photon sources need to be developed further to provide high efficiency, wavelength tunability, linewidth control, etc. Optical squeezed-state generators are fairly well advanced (and are deployed already in the laser interferometer gravitational-wave observatory [LIGO] systems) but need to be developed on-chip for size and cost considerations. Optical frequency converters (including optical-to-microwave transducers) rely on nonlinear-optical processes and need to be further optimized and commercialized for specific applications.

Other

The components described above represent the needs that were most commonly expressed throughout our interviews. Other system-specific optics and photonics needs were also identified, including:

- On-chip, high-extinction ratio (up to 80-100 dB), low-loss optical filters
- High-collection efficiency optics to couple light into detectors for atom- and ion-based sensors, clocks, or computers
- Lower-loss, smaller isolators (including at non-telecom wavelengths for atom-based sensors)
- Small or chip-scale optical frequency combs (low-power fiber combs)

Integrated Photonics: Linear and Nonlinear

Integrated photonics – linear and nonlinear optical – is commonly cited as another set of enabling technologies that would provide many essential benefits:

- Devices with lower size, weight, power, and cost (SWAP-C)
- Greater scalability
- Improved stability of optical elements
- Greater ability to interface with CMOS electronics
- Potential for enhanced light-matter interaction

Lower SWAP-C is particularly important for mobile applications – e.g., field-deployable quantum sensors and quantum key distribution transceivers. In photonic quantum computers, maintaining amplitude and phase stability are key advantages gained by integrating many components on one chip to reduce the number of parts. In addition to these applications, integrated photonics platforms are also being developed for non-quantum markets such as classical communications (e.g., transceivers), biophotonics (e.g., lab-on-a-chip, optical biosensors), LiDAR, and more.

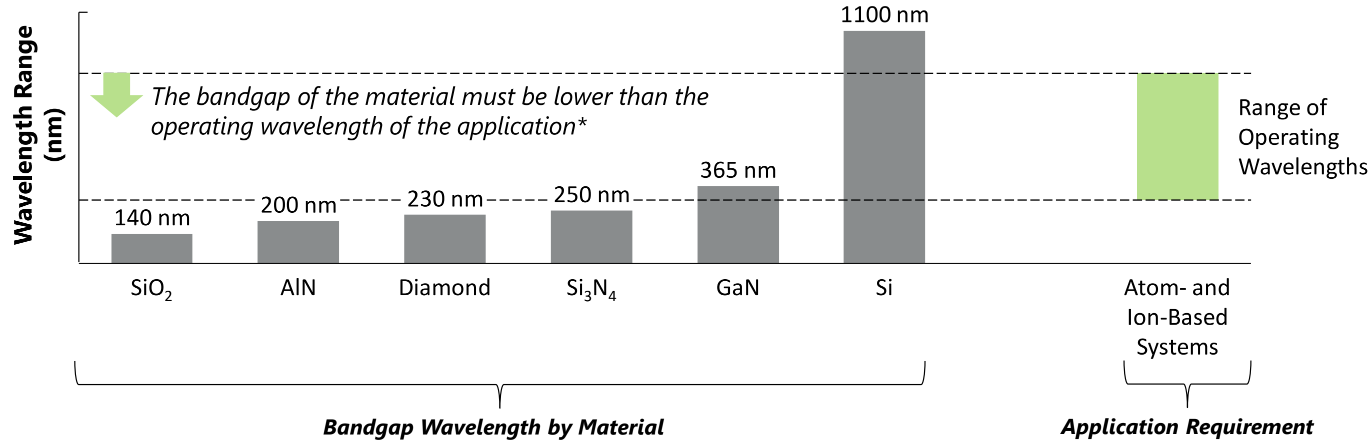
There are many different material platforms (e.g., silica, silicon, silicon nitride, silicon carbide, lithium niobate, indium phosphide, diamond, etc.) being developed for linear and nonlinear integrated photonics and each brings its own advantages and tradeoffs. Silicon-based platforms are preferred by the industry where applicable because they can leverage the existing installed manufacturing and knowledge base; however, different materials may be needed to minimize loss and to integrate certain components. Polarization-maintaining materials and components define another common requirement in some applications.

Transmission loss varies by wavelength in different materials; while QKD and photonic quantum computing chips will likely use telecom wavelengths (1550 nm), many atom-based systems require different materials optimized for the blue- or UV-spectrum. Silicon's bandgap is 1.1 micron, making it unsuitable for chips operating in the UV-visible spectrum, which require a wide bandgap for optical transparency. Alternate materials such as III-V Nitride semiconductors (which are more transparent) and / or other crystalline materials (which have lower optical absorption and autofluorescence) may be preferred, but these materials are relatively less developed.

COMPARISON OF COMMON PHOTONIC INTEGRATED CIRCUIT MATERIAL PLATFORMS

Material	Component Integration	Propagation Loss	Refractive Index Contrast	Thermo-optic Coefficient	Compatible with CMOS
Silicon	Filters, modulators, switches	Relatively High	High	High	Yes
Silica on Silicon	Filters, modulators, switches, splitters	Low	Low	Low	Yes
III-V Semiconductors	Lasers, amplifiers, modulators, detectors	Relatively High	Low	High	No
Ideal Material	Many or all	Low	High	Depends	Yes

EXAMPLE MATERIAL OPTIONS FOR ATOM- AND ION-BASED SYSTEMS



*Applications require materials that are transparent at the operating wavelength. Above the bandgap wavelength, the materials listed start to become transparent and could therefore be considered; however, loss must also be considered

On-chip integration of different components, such as lasers and photodetectors, remains a challenge for different material platforms. For example, on-chip integration of pump lasers has been demonstrated in indium phosphide, but not CMOS-compatible platforms.

Most experts argue that heterogeneous integration of multiple material platforms will be required to integrate all the necessary components on-chip. While many approaches (e.g., flip-chip bonding, full wafer bonding, transfer printing, electron-beam lithography) are being developed to accomplish this goal, other experts argue that the manufacturing complexity (e.g., optimizing alignment, adhesion, thermal budget management) is a challenge that needs to be addressed to do this at-scale and realize this functionality.

Different materials may be advantageous for different device types. For example, integrated photonic chips for quantum frequency conversion would optimally use a material that is low loss, has a wide transparency window, and has a fast switching mechanism.

DEMONSTRATED INTEGRATION OF DIFFERENT QUANTUM PHOTONIC COMPONENTS ON CHIP BY MATERIAL PLATFORM*

	Pump	Single-Photon Source	Correlated Photon Pair Source	Waveguide	Passive Elements	Active Elements	Detector	Fiber Coupler
Silicon-on-Insulator			✓	✓	✓	✓	✓	✓
Silica			✓	✓	✓	✓	✓	✓
Silicon Nitride			✓	✓	✓	✓	✓	✓
Indium Phosphide	✓			✓	✓	✓		
Gallium Arsenide		✓					✓	
Diamond / DOI		✓		✓	✓		✓	✓
Lithium Niobate			✓	✓	✓	✓	✓	✓

*Note: Simplified visual – different approaches and different performance levels were achieved in different materials
Source: Reprinted with permission from © The Optical Society. Opt. Mater. Express 7, 111 (2017)

QUANTUM FREQUENCY CONVERSION: COMPARISON OF INTEGRATED PHOTONICS PLATFORMS

Platform	Transparency Window	Nonlinear Coefficient	Demonstrated Optical Loss	Single Quantum Emitter Integration	Tuning / Switching Mechanism
Silica	>140 nm	Weak chi(3)	Ultra-low	Not native	Thermo-optic
SiN	>350 nm	Moderate chi(3)	Low	Not native	Thermo-optic / MEMS
Silicon-on-Insulator	>1000 nm	Strong chi(3)	Medium	Nascent (Se defects)	Thermo-optic / free-carrier / MEMS
$LiNbO_3$-on-Insulator	>300 nm	Strong chi(2); Moderate chi(3)	Low	Rare earth incorporation	Electro-optic / piezoelectric
AlN	>200 nm	Moderate chi(2); Moderate chi(3)	Low	Not native	Electro-optic / piezoelectric
GaAs-on-Insulator	>750 nm	Strong chi(2); Strong chi(3)	Medium	InAs quantum dots	Piezoelectric
SiC-on-Insulator	>400 nm (4H)	Moderate chi(2); Moderate chi(3)	High	Via electron beam irradiation, ion implantation	Electro-optic / piezoelectric / DC Stark-shift
Diamond-on-Insulator	>250 nm	Moderate chi(3)	Medium	Ion implantation, CVD	Strain
Si or GaAs on Rare-Earth-Doped Oxides	>300 nm	--	Low	Rare earth incorporation	DC Stark-shift / Zeeman shift
Ideal	Wide	Strong chi(2) = electro-optic effect for fast switching	Ultra-low	Integration possible	Electro-optic is fastest

Source: Awschalom, D., Berggren, K. K., Berinien, et. al. (2019). Development of Quantum InterConnects for Next-Generation Information Technologies. *arXiv preprint arXiv:1912.06642.*

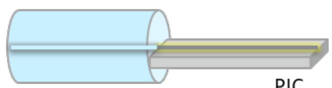
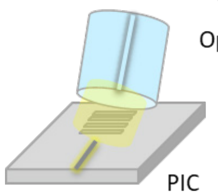
Chip-to-Fiber and Chip-to-Chip Couplers

Chip-to-fiber couplers and chip-to-chip couplers / interposers are also critical, and often overlooked, components for integrated photonic platforms. Significant improvements are needed to reduce coupling loss to make these components viable for quantum technologies. While progress has been made to reduce waveguide losses (e.g., <0.1 dB/cm loss achieved in SiN), coupling losses on the order of 3-5 or more dB still need to be reduced. Matching the size of the device mode to the size of the fiber mode is critical for achieving high coupling efficiency.

There are two general categories of chip-to-fiber couplers: edge couplers and grating couplers. Edge couplers couple light in and out of the lateral side of the waveguide and light propagates in-plane. In contrast, grating couplers use diffraction gratings, as their name suggests, to couple light out-of-plane (i.e., the light is incident from the top surface of the silicon chip).

Both approaches are in development and have their own advantages and tradeoffs. Higher coupling efficiencies and lower polarization dependence are possible with edge couplers, whereas grating couplers are more compatible with high-volume fabrication. Evanescent coupling schemes are also possible, where a small size optical waveguide is coupled to a large waveguide through an intermediate mode size waveguide.

COMPARISON OF FIBER-TO-SILICON PHOTONIC INTEGRATED CHIP COUPLER TYPES

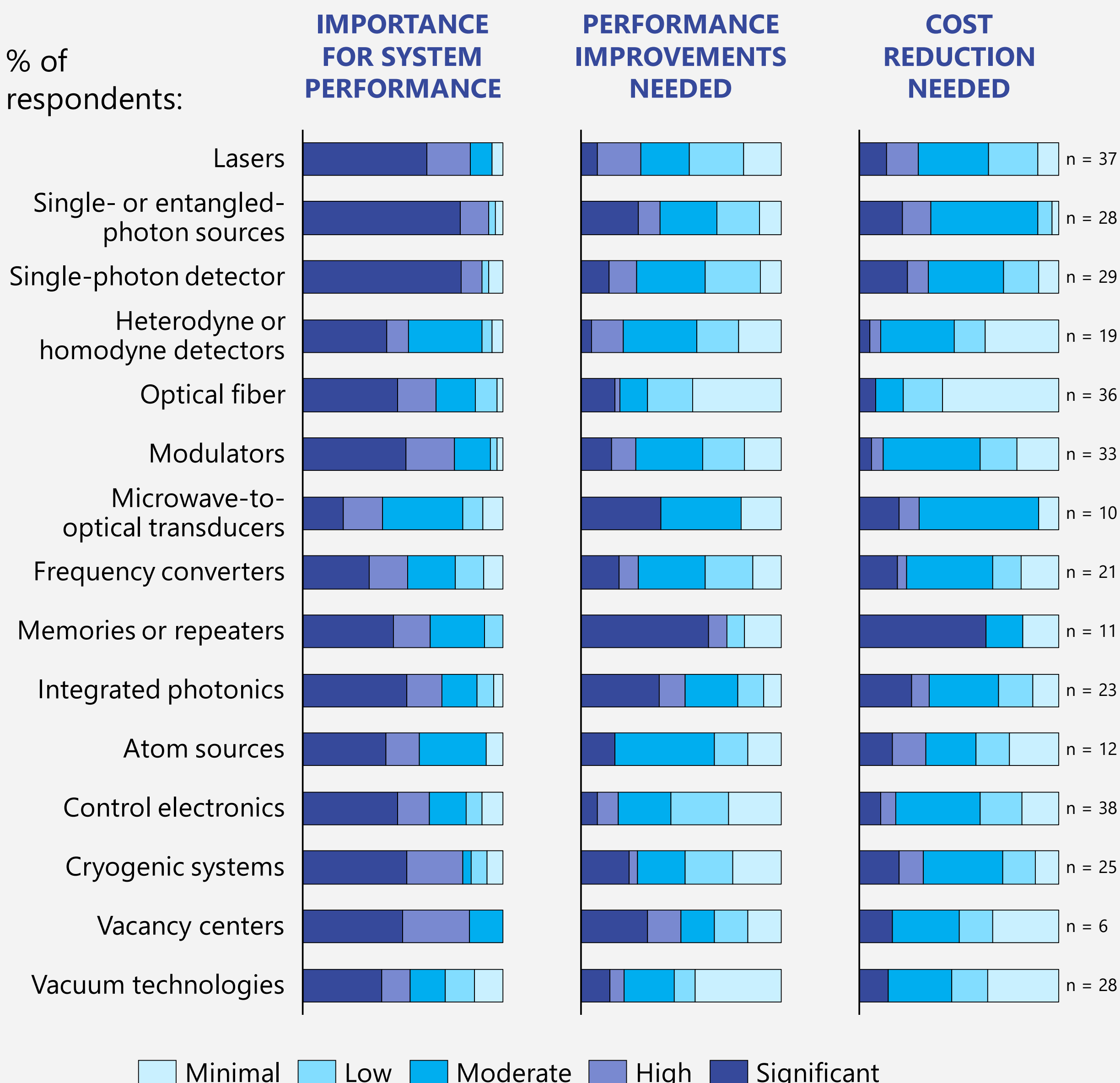
Coupler Type	Advantages	Challenges
Edge (In-Plane) *-- Illustrative --*  	• Relatively high coupling efficiency • Broad coupling bandwidth (wavelength) • Low polarization dependence	Requires relatively complex fabrication and assembly procedures (not always compatible with wafer-scale testing)
Grating (Out-of-Plane) *-- Illustrative --*  	• More compatible with high-volume fabrication – no cleaving, facet-polishing, etc. • Allows for access to any part of optical circuit (important for wafer-level testing) • Higher fiber-positioning tolerances	• Relatively lower efficiency • Relatively narrower bandwidth • Polarization-dependent; requires more complex grating if multiple states of polarization

Source: Newry

OIDA SURVEY: CHARACTERIZING WHAT'S NEEDED

While researching and writing this report, OIDA conducted a survey with academic and industry experts in the fields of quantum sensing, communications, and computing. This data, gathered from 60 individuals who completed the survey, was used to develop many of the conclusions in the roadmap.

Part of the survey was focused on characterizing the criticality and type of improvements that are needed across different components.



Note: Respondents were only asked to evaluate components that they currently specify in the systems they work on
Source: OIDA/Newry Quantum Technology Survey – February 2020

While early products are or are being commercialized today (e.g., atomic clocks, QKD networks, NISQ quantum computers), overall the quantum technology market is nascent. We are many years away from a fault-tolerant, universal quantum computer or a quantum internet. To help the investment community evaluate progress toward these ultimate breakthroughs, we've outlined key technical milestones and metrics to monitor (where possible and appropriate) across each of the technology categories below.

Quantum Sensing

Given the breadth of technological approaches and applications for quantum sensors, it is difficult to isolate metrics that are relevant across all segments. The utility of quantum sensors is dependent on the performance improvements that they are able to deliver relative to the specific incumbent technology used in any given application. Furthermore, different applications will be optimized for different tradeoffs, such as sensor size / weight, resolution, and precision; therefore, no absolute metrics are appropriate. Key market drivers include usability, portability, environmental stability, performance vs. incumbent approaches, and price.

Despite this fragmentation at the level of specific performance metrics, wafer-scale integration of these systems is a more general technological milestone that would enable progress across multiple applications. Lower SWAP-C devices are needed across multiple sensing categories, and most experts agree that integration of these systems onto photonic chips is a critical path to doing so. While some integration is possible today, more on-chip functionality (e.g., sources, modulators, switches) is needed. For example, integrated lasers with the appropriate performance levels (e.g., mode hop-free, narrow linewidth, temperature stable) would be a significant advancement. Some experts even described this as the "Holy Grail."

Quantum Communications

Transmission distance and key / data rates are the primary metrics to evaluate progress for quantum communications. Current technology is limited to fiber links on the order of a few hundred kilometers in length if thermoelectrically cooled semiconductor detectors are used, or up to ~400 kilometers if cryogenically cooled superconducting detectors are used (Quantum Flagship, 2019). Increasing transmission distance will be critical to expand the utility of QKD to more applications.

Additionally, current QKD rates are limited to several megabits per second. A 2019 NSF workshop set a three-year target of quantum-secured communication rates >1 MB/sec over 100 km distance (Awschalom, D., Berggren, K. K., Bernien, et. al., 2019). Different rates will be required depending on the quantum communications application. QKD can tolerate relatively slower key exchange rates on the order of a few keys per second, whereas distributed quantum computing applications would require much faster data rates. In addition to rate and distance, cost is another metric to monitor, as current QKD system costs are prohibitively high for many applications.

The commercialization of a quantum repeater would be an important technological milestone and may enable revolutionary progress in quantum communications including remote or distributed quantum computing. As described in the previous chapter, various physical approaches are being pursued to develop a quantum repeater; however, it will be several years before a quantum repeater is commercialized.

Satellite-based QKD development is also ongoing as an alternative approach to increasing transmission distance, but data rates need to improve further. Incremental improvements may come from improved components such as lower-loss fiber optics and lower-noise, higher-efficiency, faster detectors.

Quantum Computing

Multiple metrics can be considered to evaluate the progress and performance levels of quantum computers and not all are mutually exclusive. Some of the most common metrics include:

- *Qubit count (physical and logical):* The number of physical qubits in a system – e.g., the number of ions in a trapped-ion quantum computer. Logical qubits are an abstraction that describes a collection of error-corrected imperfect physical qubits that can effectively represent a single ideal mathematical qubit with which to participate in a fault-tolerant qubit operation. Qubit count is a measure of scaling and is an important indicator of achievable operational complexity.

- *Gate fidelity (1- and 2-qubit):* Gate fidelity is the accuracy of a gate operation and is a measurement of the qubit quality and the quantum control used to carry out the gate operation. Gate fidelities need to reach a minimum threshold to implement quantum error correction.

- *Gate set*: Different systems have different gate sets, meaning they are able to implement different elementary 1- and 2-qubit operations.

- *Gate operation time*: Gate operation time is the clock cycle time required to manipulate the physical qubits for the operation.

- *Qubit lifetime (coherence time)*: Qubit lifetime is the time that information can be stored and processed in the qubit, and therefore used for computing, before it decoheres.

- *Inter-qubit connectivity*: Qubit connectivity defines the number of connections between qubits in the array. The higher the connectivity, the easier it is to implement quantum algorithms.

- *Circuit depth*: Circuit depth is the number of operations that can be performed before an uncorrectable error is observed.

- *Quantum volume*: Quantum volume is a figure of merit developed by IBM that approximates how powerful a quantum computer is by accounting for qubit count, gate and measurement errors, device cross talk, device connectivity, and circuit compiler efficiency. IBM has doubled the quantum volume of its quantum computers every year since 2017.

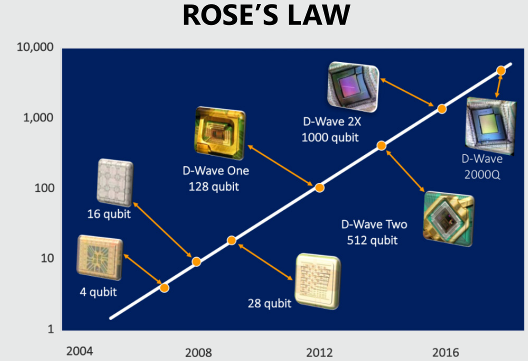
THE MOORE'S LAW(S) OF QUANTUM COMPUTING?

NEVEN'S LAW

At Google's Quantum Spring Symposium in May 2019, Hartmut Neven, Engineering Director, stated that quantum computers are gaining computational power at a "doubly exponential" rate, surpassing Moore's law

Year	Moore's Law	Neven's Law
Year 1	$2^1 = 2$	$2^{2^1} = 2^2 = 4$
Year 2	$2^2 = 4$	$2^{2^2} = 2^4 = 16$
Year 3	$2^3 = 8$	$2^{2^3} = 2^6 = 64$
Year 4	$2^4 = 16$	$2^{2^4} = 2^8 = 256$

ROSE'S LAW



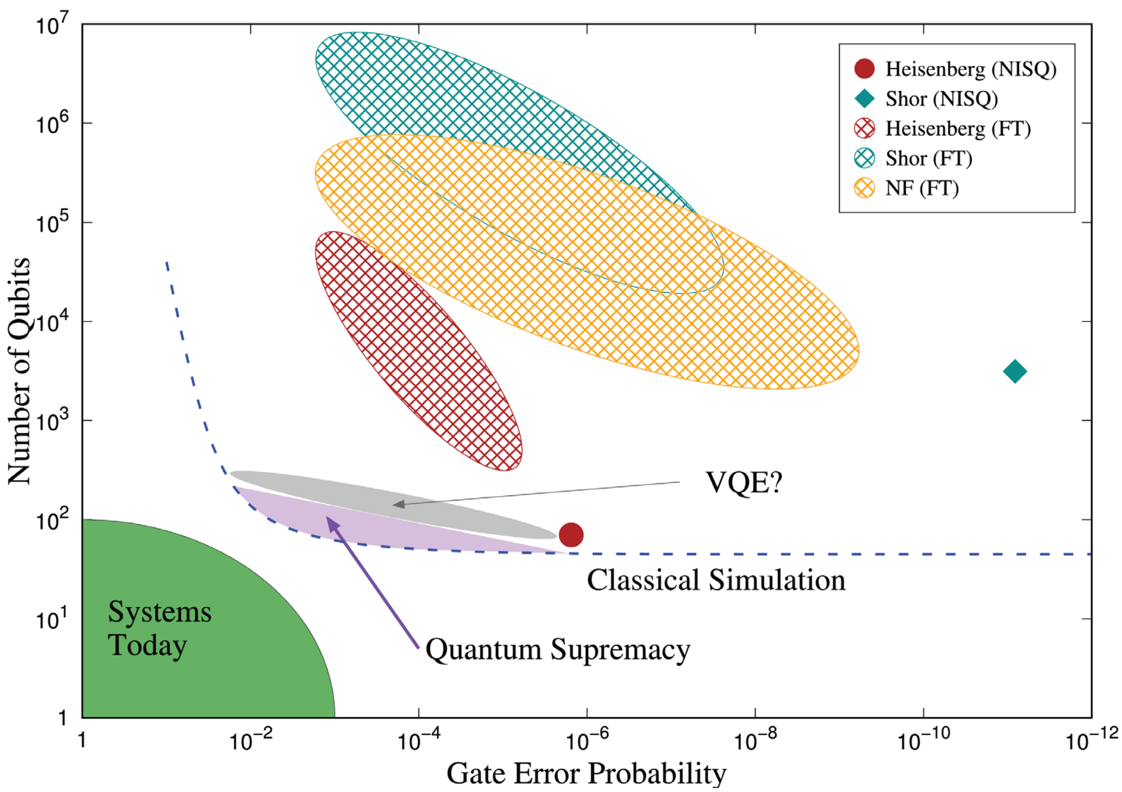
Source: Media courtesy of D-Wave Systems

Rose's law is attributed to Geordie Rose (former CTO, D-Wave), and observes that the number of qubits on D-Wave's processors has doubled every year for the past 10 years, in-line with Moore's law

The number of qubits and the qubit quality both need to be significantly improved to develop a fault-tolerant quantum computer. The National Academy of Sciences, Engineering, and Medicine estimates that systems need to be about five orders of magnitude larger than current machines – current NISQ-era machines have tens of physical qubits (National Academies of Sciences, Engineering, and Medicine, 2019). Furthermore, they estimate that error rates need to be reduced by two orders of magnitude (National Academies of Sciences, Engineering, and Medicine, 2019).

Quantum error correction will play a key role in further reducing error rates; however, it cannot be implemented on current machines because many high-quality physical qubits are required, and many gate operations must be performed. The worst gate in the system needs to have an error rate below the threshold of 10^{-2} or 10^{-3} or better before error correction can be applied (National Academies of Sciences, Engineering, and Medicine, 2019). The timing of when it will be possible to implement error correction is uncertain, but the National Academy of Sciences, Engineering, and Medicine estimates it may occur by the early 2020s, which will be a critical milestone for the industry (National Academies of Sciences, Engineering, and Medicine, 2019).

Because of the error rates of current machines, the number of logical qubits is at present effectively zero; however, once error correction is implemented, effectively creating logical qubits, a collection of such qubits will be able to carry out an indefinitely long series of fault-tolerant qubit operations. Accordingly, to monitor progress in the near-term (before error correction is implemented), the industry can track the scale of systems (number of physical qubits) and the average gate error rates. In the longer term, the number of logical qubits will become non-zero, and will be an appropriate metric to track the achievable operational complexity of the system.



Source: Maslov D, Nam Y, Kim J. An Outlook for Quantum Computing [Point of View]. *Proceedings of the IEEE*. 2019 Jan 1;107(1):5–10.

METRICS FOR MONITORING PROGRESS

Near Term: Monitor number of physical qubits and average gate error rates

Quantum error correction implemented

Long Term: Monitor the number of logical qubits

As systems scale to more logical qubits (and necessarily more physical qubits and lower error rates), new problem types are expected to become addressable. For example, Gartner estimates that organic chemistry and portfolio optimization applications will require systems on the order of a couple hundred logical qubits compared to the two thousand or more required to crack RSA (Brisse, Reynolds, & Horvath, 2019). Other applications, such as route optimization and drug design, will likely come in between.

Research and development are rapidly advancing but we are likely a decade or more away from having a fault-tolerant quantum computer capable of cracking RSA. In addition to the hardware improvements that are required, quantum algorithms and software stacks need to be developed to address applications and improve the efficiency of loading large data inputs into these machines.

Quantum Workforce Development

In addition to the hardware and software supply chain needs described above, education and workforce development are also required to enable progress. Quantum technology is an interdisciplinary field that engages physicists (theoretical, experimental, optical, etc.), computer scientists, mathematicians, chemists, engineers, material scientists, etc. While many university programs have been created to address the needs of the community, further workforce development is needed to commercialize and apply these technologies in real-world applications.

For example, a critical transition needs to be made to progress current lab-scale demonstrations to scalable manufacturing, which will require quantum engineers. While quantum science university programs are established, other programs and strategies to train a future quantum engineering workforce are still emerging.

Standards

Standardization efforts are also being framed and developed to help coordinate and accelerate progress. The development of standards could help establish metrics for inter-device comparison and could encourage supply chain development for an interoperable ecosystem, among other benefits. Multiple groups such as ANSI, ITU, and IEEE are engaging in early standardization efforts.

Software

While this report has focused on the optics and photonics components required to enable quantum technologies, other hardware (e.g., cryogenic coolers, control electronics) and software also needs to be developed to enable the finished systems. There is notable investment in software startups such as Zapata Computing, 1QBit, and Cambridge Quantum Computing, by the venture capital community. Both the software stack and the application-specific algorithms are under development. In fact, significant investments are already being made in software and services, even in advance of a functioning fault-tolerant quantum computer.

Societal Impacts

While it is early to predict specific societal impacts of quantum technology, it is safe to predict there might be potentially large impacts, both positive ones and those with risks or even negative impacts. Some scholars and observers are beginning now to consider such issues (Vermaas, 2017). These potential impacts should be actively considered as the technical ecosystem develops further.

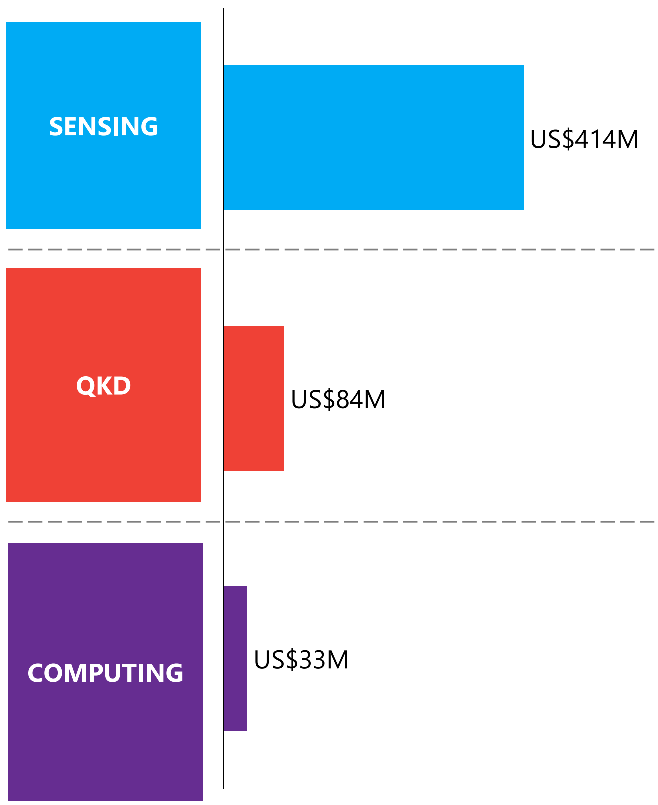
CONCLUSION

The quantum technology market is still very early-stage. Volumes are modest and commercial timing is uncertain. Nevertheless, there are opportunities for the optics and photonics community to participate in this industry and supply the critical enabling components – sometimes compared to the "picks and shovels" of the gold rush – to the well-funded R&D community in the near-term so that progress can continue. Optics and photonics are core enabling technologies across many of the architectures and systems being developed, and a measured investment today could yield future opportunities as the market for quantum devices advances.

Of the three main categories of quantum technology, quantum computing receives the most media attention but is also the most speculative and longer-term. Many large players such as IBM, Google, Intel, Microsoft, Honeywell, etc. are investing in system development. However, the supply chain is still immature – many of the necessary components are supplied by small, specialized players and startups (some of which are sole suppliers). Furthermore, quantum computers are likely to remain highly specialized in the near term, meaning that component volumes will remain low. Quantum sensing and communications are expected to bring much earlier commercial success for OEMs and component suppliers alike.

HOW BIG IS THE MARKET?

2020 Market Size



Expected Growth Potential

- Current sales primarily clocks, gravimeters, and SQUIDs
- Market forecasts vary widely – between US$0.5B (Yole) and >US$2B (INSIDE Quantum) by the end of the decade
- Market penetration depends on ability to demonstrate improvements versus incumbent technology

- Relatively less variation in today's market size estimates
- Divergence between sources in market forecasts ranging from US$785M (Yole) to over US$7B (INSIDE Quantum) by end of decade
- Market uptake dependent on demonstrated tech. advancements

- Current sales largely limited to quantum annealers
- Most agree that the future market size (once a large-scale fault-tolerant computer is developed) will be comparable to the current supercomputer market which is about US$50B
- Market forecasts vary likely due to uncertainty about the pace of expected progress

Source: Yole Développement (2020)

Fortunately, many of the components required for quantum sensors or communications networks could also have utility in some types of quantum computing architectures. While the winning approach to building a quantum computer has yet to emerge, optics and photonics component suppliers can de-risk investment in R&D by prioritizing platform technologies and components that:

- *can be used across multiple quantum application categories*: Some components are applicable to sensing, communications, and computing markets. For example, lasers for atom-based systems are required in specific types of quantum computing (e.g., neutral atom, trapped-ion) and quantum sensors based on cold atom interferometry. Single-photon sources, single-photon detectors, and modulators are used in both discrete variable quantum communications protocols and photonic quantum computing.

- *will be required regardless of which architecture wins*: Regardless of which network architecture (e.g., superconducting versus ion trap) emerges as the preferred solution for quantum computers, interconnects such as microwave-to-optical transducers and frequency converters are likely to be required to connect the various nodes and components in the network, all of which operate at different frequencies.

- *will have value in non-quantum markets*: Some components required for quantum technology will also have utility in other markets that may demand higher volumes. For example, single-photon detectors can be used in low-light imaging for life sciences and metrology applications. Integrated photonic chips and couplers also have broad utility in larger markets, including classical telecom.

As system performance improves and implementation uncertainties are resolved, the community may begin to coalesce around specific devices for specific applications. As this change occurs, the optics and photonics community can scale and refine investment further. We recommend monitoring the following metrics and technological milestones as leading indicators:

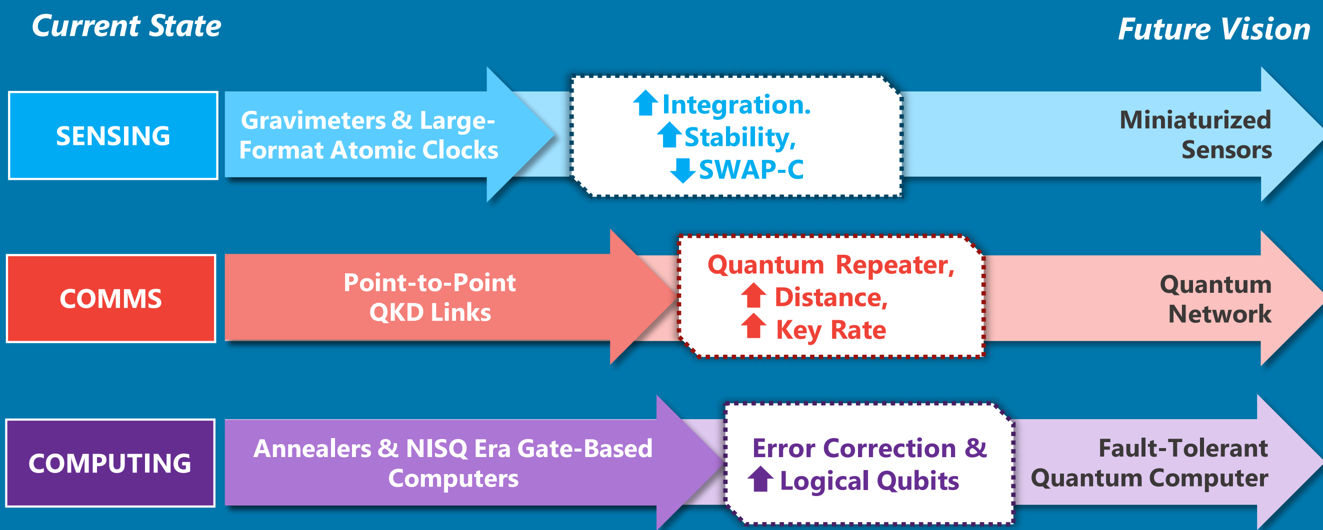
- Commercialization of field-deployable quantum repeaters will be a significant milestone for quantum communications, as it should have a substantial impact on potential transmission distance. Progress can be tracked by monitoring the transmission distance and data rates achieved in new experiments and commercial installations.

- Implementation of error correction on a small quantum computer will be a significant milestone on the path to large-scale fault-tolerant quantum computing. Once error correction is implemented, the number of logical qubits will become non-zero. To monitor progress across the different groups, investors can track the number of logical qubits achieved by different systems. Gartner estimates the first applications (e.g., chemistry, portfolio, and/or route optimization) are likely to be addressable once ~100-500 logical qubits are achieved. Longer term, machines with numbers of logical qubits on the order of 2,000-3,000 may be required for breaking RSA encryption.

- Due to the wide array of different sensing applications, it is difficult to point to a single milestone as a key landmark of progress. Instead, quantum sensors should be compared to classical incumbents based on their performance, cost, and SWAP. Commercialization of quantum sensors for GPS-free navigation would be a notable technological milestone.

While the exact timing of these advancements is not definite, most experts currently project that significant progress will be made in the next 5-10 years. Monitoring the progress toward these goals over the next decade will provide a much clearer picture. Despite the highly uncertain nature of the market for quantum technology today, the scale of ongoing development activity and the potential for future disruption justifies measured investments to understand what opportunities could materialize in the near- and long-term.

MILESTONES AND METRICS



Advancing Progress: What's Required

- **FUNDING**
  Sustained public and private investment to support R&D / scaling
- **HARDWARE**
  Performance improvements, cost reduction, supply chain development for components
- **WORKFORCE**
  Education to fill the talent gap and build the future quantum workforce
- **SOFTWARE**
  Error correction, algorithm development, software stack, etc.

OSA Industry Development Associates

QUESTIONS? CONTACT US!

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