Q-NEXT
NEXT GENERATION QUANTUM SCIENCE AND ENGINEERING

A ROADMAP FOR QUANTUM INTERCONNECTS

Q-NEXT

ANL-22/83

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ANL-22/83

A Roadmap for Quantum Interconnects

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Preface

Created by Q-NEXT, a U.S. Department of Energy (DOE) National Quantum Information Science Research Center, this document is a roadmap for quantum interconnects research and its impact for quantum information science and technology. It is the outcome of the collective work of a large team of Q-NEXT members and participants from academia, industry and DOE national laboratories. The roadmap addresses the role of quantum interconnects in three emerging areas of quantum information: computing, communication and sensing. It reviews the materials, components and systems used for these purposes; summarizes relevant scientific questions and issues; and addresses the most pressing research needs. The document then distills these considerations into recommendations for strategic science and technology research imperatives for the next decade. In addition to informing Q-NEXT's internal activities, the roadmap has also been created with a broader objective of developing a guide for key issues and research needed over the next decade for the worldwide scientific and engineering community interested in quantum information.

Acronyms and Abbreviations

1G, 2G, 3G	First, Second, and Third Generation of Quantum Repeaters
API	Application Programming Interface
BSA	Bell State Analyzer
COMP	Full Computational Node
CV	Continuous Variable
DCN	Data Center Network
DOE	U.S. Department of Energy
DOF	Degrees of Freedom
DOS	Denial of Service
DV	Discrete Variable
DWDM	Dense Wavelength Division Multiplexing
EPPS	Entangled Photon Pair Source
GPS	Global Positioning System
HHL	Harrow Hassidim Lloyd algorithm
I/O	Input/Output
ILA	In-Line Am
IR	Infrared
KMS	Key Management System
LAN	Local Area Network
LIGO	Laser Interferometer Gravitational-Wave Observatory
MAN	Metropolitan Area Network
MEAS	Measurement-Only End Node
MEM	Memory-Based End Node
MOB	Mobile Network
NMR	Nuclear Magnetic Resonance
NSA	National Security Agency
NV Center	Nitrogen Vacancy Center in Diamond
OSW	Optical Switch Node

PDL	Polarization Dependent Loss
PMD	Polarization Modal Dispersion
QAOA	Quantum Approximate Optimization Algorithm
QC	Quantum Computing
QCD	Quantum Chromodynamics
QEC	Quantum Error Correction
QKD	Quantum Key Distribution
QND	Quantum Non-Demolition
Q-NEXT	Next-Generation Quantum Science and Engineering
R&D	Research and Development
REP1	Memory-Based Repeater
REP2	QEC-Enabled Repeater
RF	Radio Frequency
RTR	Router (most advanced memory-based repeater)
SAT	Satellite Network
SMF	Single-Mode Fiber
SNSPD	Superconducting Nanowire Single Photon Detector
SNSR	Sensor End Node
SOP	State of Polarization
SPAD	Semiconductor Single Photon Avalanche Photodiode
SQL	Standard Quantum Limit
SQUID	Superconducting Quantum Interference Device
SWaP	Size, Weight, and Power
SWaP-C	Size, Weight, and Power, and Cost
UHV	Ultra-High Vacuum
VLBI	Very Long Baseline Interferometry
WAN	Wide Area Network
XFEL	X-Ray Free-Electron Laser Facility (European)
ZBLAN	53% $\mathbf{Z}rF_4$, 20% $\mathbf{B}aF_2$, 4% $\mathbf{L}aF_3$, 3% $\mathbf{A}lF_3$ and 20% $\mathbf{N}aF$

A. Introduction to the Roadmap

Purpose: Created by the DOE Q-NEXT Quantum Information Science Center, this document seeks to provide a roadmap for the main directions of quantum information science and technology employing quantum interconnects. The roadmap is the outcome of the collective work of a large team of Q-NEXT members and participants. The activities were carried out via a comprehensive set of discussions over several months and a virtual workshop held on May 5, 2021. Participants included members of academia, national laboratories, and industry representatives from the major sectors where quantum information is expected to have an impact (e.g., computing, communications, sensing). The document, in addition to informing Q-NEXT's internal activities, has also been created with a broader objective of developing a guide for key issues and research needed over the next decade for the worldwide scientific and engineering community interested in quantum information.

Why a Roadmap? Roadmaps are an important component of the hardware technology world; their purpose and design have been well described by Robert Galvin.[1] Successful examples of the use of roadmaps may be found, for example, in the semiconductors,[2] batteries,[3] photovoltaics,[4] and aerospace[5] sectors. As quantum information moves from a science-driven field to one that now has pre-competitive and competitive technology elements, it is appropriate to consider a roadmapping process that may expedite the progress from science to technology. The roadmap serves a few important purposes in this regard. It brings together stakeholders with multidisciplinary backgrounds who collectively benefit from the roadmap's integrated view. It acts as a guiding document and informs and aids the strategies and policies of different stakeholders (e.g., academia, national program agencies, industry) with respect to the field. Our roadmap is driven by technology needs, but considering the early stages of the field, a significant focus has been on the needs of enabling science. These scientific directions emerge from the "identification of linkages"[6] and "discontinuities and knowledge voids"[6] (as noted by Galvin) that will be required to build quantum technologies of the future. As examples, "demonstration of homogeneous quantum network at inter-city scale" is a technology imperative and "high-fidelity entanglement swapping" is a science imperative to meet this objective.

What Are Quantum Interconnects and Why Do We Need Them? Quantum interconnects link and distribute coherent quantum information between systems and across different length scales to enable quantum sensing, communications, and computing. Entangling networks of sensors, they may enable the practical measurement of physical properties with sensitivities below classical noise limits. Interconnects will enable the construction of powerful quantum computers to execute quantum algorithms by connecting elements within a quantum subsystem, between quantum processors, and between quantum and classical computers. Quantum interconnects may also allow the movement of quantum information over distances much larger than the systems being interconnected, for a variety of applications. This type of connection is generally known as quantum communication, and a set of interconnected quantum systems with appreciable physical distance between those systems is a quantum network. Across all of these scales and applications, such interconnects may need to connect homogeneous systems (where qubits are of the same kind) and heterogeneous qubit systems. In this document, we focus on the scientific and technical needs for the distribution of such entanglement from the perspectives of computing, sensing, and communications.

Unique Challenges: Unique challenges arise in the development of a roadmap for a high-risk, high-reward, emerging field such as quantum information. The timespan for widespread impact in the public good is likely long; getting there will require the fusion of both science and technology imperatives. Unlike an established technology (such as microelectronics), there is no existing technology substantial enough to use as a clear and definite launch point. And unlike other established engineering roadmaps, there are few evolutionary component; most needs are revolutionary. As a result, our roadmap is deliberately less prescriptive than other engineering roadmaps.

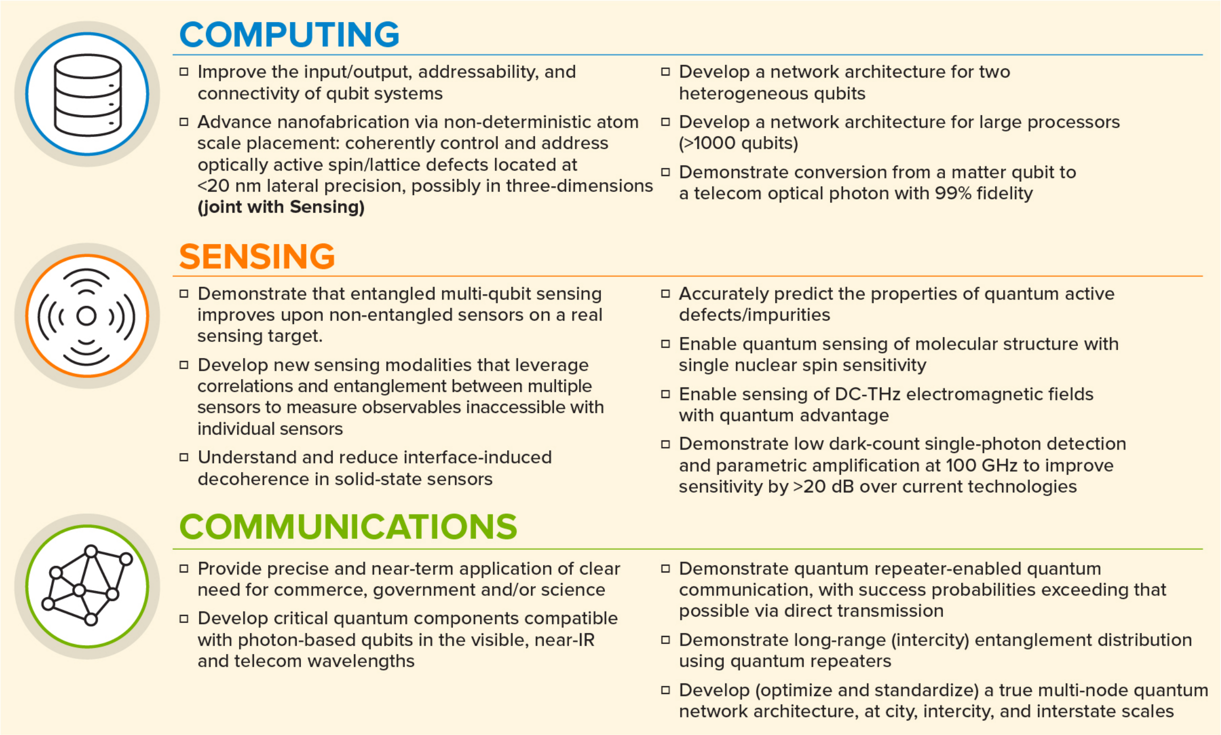
At the current level of our understanding, predictions on even the few-year timescale are challenging, and for that reason, we focus statements of potential impact here on broad categories, avoiding specific, metric-driven predictions (with some exceptions) where uncertainly makes such predictions unreasonable. We are certain to miss important areas, and some of the areas we do list will turn out to be more challenging than expected.

Purpose and Methodology: Our larger objective is to develop a unifying vision for the field of quantum interconnects and inform U.S. Department of Energy (DOE) directions, as well as global quantum science and technology research and development (R&D) in the area of quantum interconnects. It is also the objective of this roadmap to help guide and frame Q-NEXT's specific milestones.

Three teams were created from a group of Q-NEXT team members (identified on p. 1) to explore opportunities and needs associated with quantum interconnects for computing, communications, and sensing. A series of meetings by these teams was followed by a joint workshop during which the findings from each team were used as a basis for discussion and identification of key imperatives and challenges for quantum interconnects over the next 10–15 years. The roadmap team comprised members from academia, industry, and national laboratories. Participants' backgrounds (as well as partner industry focal points) extended across the co-design and application space of quantum science and technology. Specific charges that the teams addressed during development of the roadmap are as follows:

i. What do we expect will be the key impacts in quantum sensing, computing, and communications for the public good in 15 years? These impacts can be both technology and fundamental science.
ii. Identify the range of proposed systems and scientific discoveries that deliver these key impacts. What is your definition of a quantum interconnect in the context of these systems (relevant to the application of your Focus Group)? What are its characteristics?
iii. What are major developments and metrics that need to be achieved for quantum interconnects to achieve the impacts described in (i) for your focus group? Please try to be as quantitative as possible (within reason). Include technology and science milestones.
iv. What are the major specific impediments (e.g., basic knowledge, technology developments, supply-chain-related issues, materials)? What is missing?

Figure 1 summarizes the key research imperatives over the next 10–15 years for quantum interconnect science and technology that will be usable for the public good. Additional details are provided in the three sections into which the roadmap document is divided: one each for quantum computing, communications, and sensing. While there is significant commonality among these three areas, leading to overlap in imperatives and directions, we adopted this approach with the view that these three engineering fields will diverge over time and that readers may be specifically focused on one over the other.



COMPUTING

- Improve the input/output, addressability, and connectivity of qubit systems
- Advance nanofabrication via non-deterministic atom scale placement: coherently control and address optically active spin/lattice defects located at <20 nm lateral precision, possibly in three-dimensions **(joint with Sensing)**
- Develop a network architecture for two heterogeneous qubits
- Develop a network architecture for large processors (>1000 qubits)
- Demonstrate conversion from a matter qubit to a telecom optical photon with 99% fidelity

SENSING

- Demonstrate that entangled multi-qubit sensing improves upon non-entangled sensors on a real sensing target.
- Develop new sensing modalities that leverage correlations and entanglement between multiple sensors to measure observables inaccessible with individual sensors
- Understand and reduce interface-induced decoherence in solid-state sensors
- Accurately predict the properties of quantum active defects/impurities
- Enable quantum sensing of molecular structure with single nuclear spin sensitivity
- Enable sensing of DC-THz electromagnetic fields with quantum advantage
- Demonstrate low dark-count single-photon detection and parametric amplification at 100 GHz to improve sensitivity by >20 dB over current technologies

COMMUNICATIONS

- Provide precise and near-term application of clear need for commerce, government and/or science
- Develop critical quantum components compatible with photon-based qubits in the visible, near-IR and telecom wavelengths
- Demonstrate quantum repeater-enabled quantum communication, with success probabilities exceeding that possible via direct transmission
- Demonstrate long-range (intercity) entanglement distribution using quantum repeaters
- Develop (optimize and standardize) a true multi-node quantum network architecture, at city, intercity, and interstate scales

Figure 1: A summary of key quantum interconnect and related research imperatives required for quantum computing, communications, and sensing over the next 10 years.

B. Roadmap for Quantum Computing

I. Introduction

While quantum computers are currently limited in terms of computational performance, they are rapidly increasing in performance capability. There has been increased investment in building quantum processors with considerable involvement of industry[7–9] and with public announcements of quantum computing goals by companies such as IBM. It is likely that impacts for quantum computers in the coming 10–15 years will be in the following areas:

- Quantum simulation,[10,11] particularly in chemistry, physics, and materials science. Among these, particularly early impacts are expected in:
  - Specific, specialized, "model" Hamiltonians of particular interest in physics, such as Hubbard models.[12–14]
  - Quantum chemistry, with orbital numbers beyond what is possible on classical machines (>100). This area can have significant impacts on computational materials and molecular design,[15] including drug discovery,[16] materials manufacturing, and materials for sustainability.[17]
- Certified random number generators.[18]
- Quantum cryptography. We note here that there are emerging developments, such as lattice-based cryptography, that are resistant to current quantum approaches. Code-breaking applications for quantum computing would be affected by such approaches, if successful.
- Optimization algorithms such as Monte Carlo algorithms and Quantum Approximate Optimization Algorithm (QAOA),[19,20] which can be applied to optimization problems on graphs.
- The deployment of quantum algorithms (for instance, the Harrow Hassidim Lloyd [HHL] algorithm[21]) for efficient computational solutions in linear algebra, with applications in machine learning for data analytics.

In the coming years, some of the most significant impacts of quantum computers will be on quantum computation itself:[22]

- Algorithms are likely to evolve and become better optimized once quantum computers with many hundreds, and even thousands, of qubits become available. This evolution will be enabled by a clearer understanding of the architecture, design, and performance modeling of quantum processors with >1,000 qubits.
- An anticipated and essential advance is error-corrected logical qubits with performance superior to that of its component parts. Current work is beginning to demonstrate logical qubits with fidelities that surpass the physical qubits from which they are formed.[23–25]

At a component and device level, the impacts listed above will be enabled by qubits with higher-fidelity one- and especially two-qubit gates and by the availability of those higher-fidelity qubits in increasing numbers. Higher-fidelity qubits will enable algorithms to run with greater gate depth, even with current numbers (on the order of 100) of qubits, opening up important new opportunities to test algorithms.

All of these advances will be enabled by the **creation and processing of entanglement with high fidelity**. The very definition of a high-fidelity, two-qubit gate assumes the entangling of two qubits. If one or more of those qubits are themselves already entangled, a two-qubit gate further distributes that entanglement. Note also that the distribution of entanglement requires the maintenance of coherence across the distributed network; a key challenge, therefore, is the control of coherence in complex and heterogeneous materials systems networked over large length scales. **Unlike classical semiconductor technologies, where a key opportunity is the density scaling of devices, the challenge in quantum processors is the processing of entanglement at scale**.

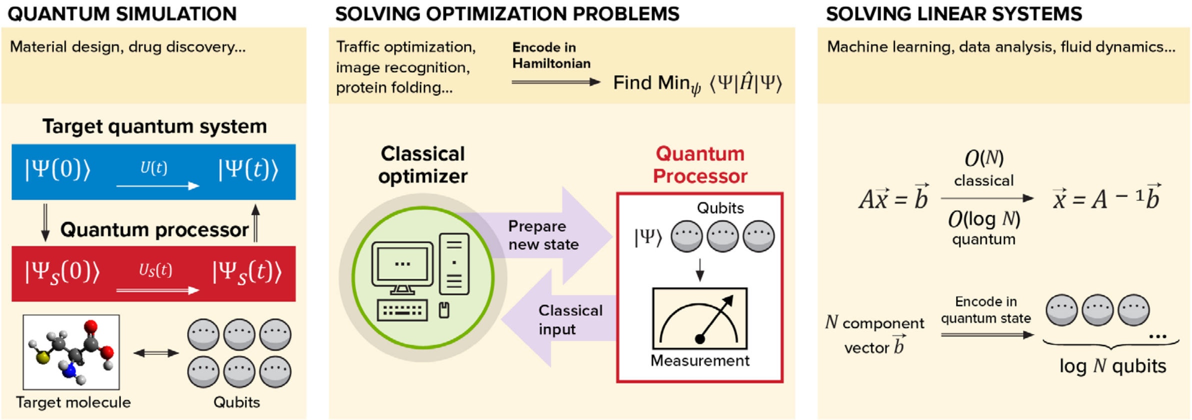


Figure 2: Application of quantum computing. Left (quantum simulation): A target quantum system (blue box) evolves in time according to U(t), while the quantum processor (red box) evolves according to $U_S(t)$. The quantum processor is designed such that there is a mapping between the two systems. Measurements of the quantum processor then yield information about the target quantum system. For example, the difficult electronic structure problem of a target molecule can be mapped onto the qubits of the quantum processor. Center (solving optimization problems): The solution of an optimization problem can be encoded into the ground state of a Hamiltonian, H. This ground state can be found using an iterative, quantum-classical algorithm illustrated at bottom. A state |Ψ> of the quantum processor is prepared. The energy of the state is measured and fed into the classical computer. A classical optimization algorithm then suggests a new quantum state, which is then prepared. The algorithm iterates until the ground state is found. Right (solving linear system): Linear systems of the form Ax=b, where A is an NxN sparse matrix, are ubiquitous in science, engineering, finance, etc. A classical computer can find the solution in O(N) operations, while a quantum computer yields the solution in O(log N) operations, an exponential speedup. This quantum speedup is possible by being able to encode the N component vector b in the state of only log N qubits.

In the context of computing, we conclude that distributing entanglement requires advances across a broad swath of quantum science and technology. Q-NEXT will contribute to many (but not all) of these areas.

II. Science and Technology Imperatives over the Next 10 Years

It is clear that the array of scientific exploration is already quite wide in terms of material systems, device design, and control mechanisms. However, within this diversity, there are common imperatives that we have identified that should be part of a serious effort in quantum interconnects for computing. Each of these imperatives is addressed below.

Improve the input/output, addressability, and connectivity of qubits at low temperatures:

- Connections to and between qubits at cryogenic temperatures is challenging and, at present, restricts progress by requiring qubits to be located on one chip and requiring the use of physically large electronic components like isolators. Establishing the ability to interconnect between quantum chips (e.g., a 2-qubit gate over a cable) and perform qubit readout without bulky components (e.g., microwave isolators) will enable researchers to increase the number of qubits and the size of quantum processors.

Coherently control and address optically active spin/lattice defects located at <20 nm lateral precision, possibly in three-dimensions, using non-deterministic atomic-scale placement and fabrication approaches.

- Optically active spin and lattice defects have superb properties for sensing, communications, and computing. The ability to coherently control these defects, when placed with high spatial resolution, would be transformatative for all such applications, especially computing. These defects may either be native (i.e., crystalline defects such as lattice vacancies) or extrinsic (e.g., dopants).

Develop networked architectures

- Networked architectures for two heterogeneous qubits. It is widely recognized that different qubits have different advantages. The most widely cited example is the tradeoff between qubit operation rate and qubit decoherence rate (e.g., neutral atoms and ions have especially long coherence times, whereas superconducting qubits have faster quantum gate speeds and also shorter coherence times).[26]
- Interconnect architectures for large (>1000 qubit) systems and metrics for benchmarking their performance.

Demonstrate conversion from a matter qubit to a telecom optical photon with 99% fidelity.

- Conversion from matter qubits to optical photons is a relevant, mission-critical goal for quantum communications in the near term, including for networking between distributed processors beyond meter-scale distances. For quantum computing, high-fidelity conversion would enable fiber coupling of qubits housed in different cryostats or different ultra-high vacuum (UHV) chambers. The fidelity requirement for such coupling to be useful is likely set by error correction thresholds. However, it is possible that lower fidelity could still be useful as an entanglement resource, depending on advances in algorithms and architectures to make effective use of such resources.

III. Materials, Components and Systems Used for Quantum Computing

For quantum computing, we anticipate a focus on the following six key qubit systems and the distribution of entanglement related to each:

i. Optically addressable defect center qubits in semiconductors (e.g., diamond,[27] silicon carbide[28,29]). Such defects can be intrinsic (e.g., native defects) or extrinsic (e.g., added dopants).
ii. Superconducting qubits (involving, for example, aluminum, niobium, tantalum).[30]
iii. Neutral atom qubits (optically addressable in atom traps in vacuum).[31]
iv. Electrically addressable spin qubits (e.g., gate-defined quantum dots in silicon [S], germanium [Ge], or their alloys).[32,33]

v. Ion trap qubits (optically addressable in ion traps in vacuum).[34]
vi. Optical qubits for all-photonic quantum processing, both discrete variable and continuous variable approaches.

The following section identifies the critical advances required to interconnect entanglement for quantum computing.

IV. Relevant Questions and Issues for Quantum Computing

Based on the imperatives and the key qubit systems discussed above, we established **three foundational principles** that will guide R&D roadmap needs, helping to ensure that the quantum computing research ecosystem will have impact. These principles coincide with Q-NEXT's objectives.

First, we will roadmap for the interconnection of entanglement in its broadest sense, including all challenges listed above, which range from materials developments to signal control to architectures and, of course, advances in the fundamental operations – the quantum physics – of the qubits themselves. **Second**, we recognize that interconnecting entanglement within a quantum computer means interconnection of coherent and entangled qubits with classical control, logic, and communication.

Third, we will roadmap for activities that are specifically relevant to Q-NEXT, with the understanding that our motivation includes the entire quantum computing ecosystem.

In this context, it is useful to discuss the idea of a quantum interconnect as it applies to quantum computing and quantum processors. As outlined in the introduction, a **quantum interconnect makes use of interactions to transfer information into, out of, and between qubits**. In this respect, two classes of interconnects are important in computation. First, quantum-to-quantum interconnects use interactions to transfer quantum information between qubits. Within quantum-to-quantum interconnects, it is further useful to consider homogenous interconnects – which connect qubits of the same type – and heterogeneous interconnects – which connect qubits of different types. The second class of interconnect essential to quantum computing is quantum-to-classical interconnects, which transfer information between qubits and classical information elements. This information flow can (and must) occur in two directions, from classical control to qubit control and from the qubits to classical readout, including partial classical readout.

The science and technology for both types of quantum interconnects are at an early stage, yet the diversity of possibilities is already large and arises from several key factors described below. First, as noted earlier, we consider six distinct physical qubit implementations, each of which can have further subcategories. For instance, quantum-dot-based qubits can be Si/SiGe gate-defined or metal-oxide-semiconductor gate-defined; defect-based qubits can be embedded in different hosts, such as diamond and silicon carbide; and atom qubits can be based on different elements (e.g., rubidium and holmium).[35] Each of these sub-categories can involve different technical approaches. Furthermore, within each subcategory, a variety of qubit architectures are under active study (e.g., there are at least four spin qubits in gate-defined quantum dots: single-spin qubits, singlet-triplet qubits, exchange-only qubits, and quantum dot hybrid qubits).[33] From a devices design point of view, the native gates for each qubit type (many have more than five) are different, and the classical-to-quantum control signals are different, ranging from optical to microwave to baseband electrical pulses.

QUBIT ARCHITECTURES	STRENGTHS	CHALLENGES
Defect centers in semiconductors	Long coherence times Optical readout	Scalability Placement of defects
Superconducting circuits	Fast gate speeds Tunability of most system parameters	Short coherence times Controlling large scale system
Neutral atoms	All atoms of a given species are identical Large connectivity between qubits	Atom loss and loading Scalability
Gate-defined quantum dots	Long coherence times Leverage microelectronics fabrication industry	Valley degeneracy in Silicon Dot-to-dot variations
Ion traps	All ions of a given species are identical High gate fidelities	Scalability Slow gate speeds
Photonic qubits	No need for transduction in distributed processors	Probabilistic two-qubit gates require large-scale multiplexing and very low loss

Figure 3. Key qubit systems along with some of their strengths and challenges[36] that need to be overcome

Finally, we note here that a focus on “quantum interconnects” in isolation is too narrow; an assessment of its impact and the relevant research tasks often requires consideration of the research required across an entire sub-system. We retain the phrase “quantum interconnect” in all those cases (and only those cases) where it offers value, i.e., where the intuitive sense in the community for what an interconnect is fits the technical challenge to be addressed.

V. Research Needs and Developments Necessary

In light of the issues described above, the following summarize the major and central developments required for quantum computing over the next several years.

(i) Improved fidelity and coherence of qubit gates

The gate fidelity and the qubit coherence time are key metrics for quantum computing. Infidelity limits the depth of gate operations that can be performed in any quantum algorithm. Coherence sets the fidelity for idle gates (waiting). Error correction thresholds set the minimum fidelity beyond which such codes can lead to improvement and that today are at least 99%.[34] Furthermore, details of an implementation are important in this context, and therefore, practical thresholds may be higher.

(ii) Improved classical control of qubits and efficient and scalable driving of gates

Expensive gate control may be tolerable for small and medium numbers of qubits; however, for large numbers of qubits, the scalability and cost of gate control become important and can be prohibitive. Cost and scalability limits arise in several ways.

- *Thermal engineering considerations for low-temperature processor systems*: The heat load for dozens, and even hundreds, of coax cables in a dilution refrigerator is tolerable. The heat load for many thousands is likely not.[37]

- *Integration of optics*: We anticipate growing needs for integrated routing of optical laser pulses on an integrated photonic chip. Such approaches may build on developments in silicon photonics and optical packaging over the past 15 years and may further require the integration of new materials relevant to qubit-based processing.
- *Control signals*: The generation of control signals – optical, microwave, and electrical – likewise involves costs associated with space, heat load, and system/component costs that will become particularly relevant for larger systems. Cryogenic classical control is being explored to help address this problem.[38]

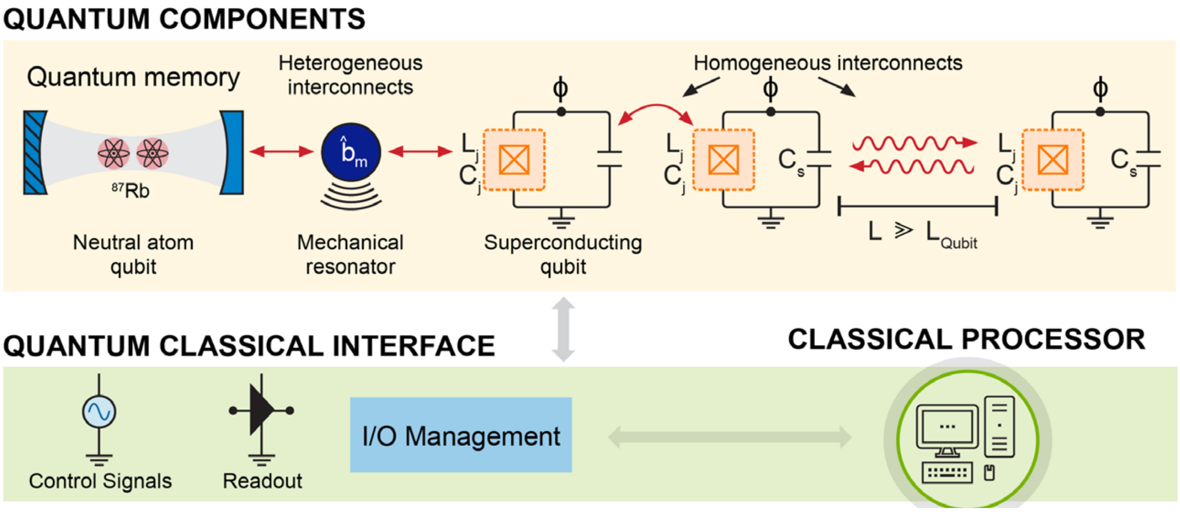


Figure 4. Components of an interconnect. Top: Quantum interconnects have both homogeneous interconnects (information transfer between qubits of the same type) and heterogeneous interconnects (information transfer between qubits of different types). For example, a mechanical resonator can be used to couple superconducting qubits to a cavity harboring neutral atom qubits, which serve as a quantum memory for long-time quantum information storage. Both short- and long-range interconnects are needed. Here, a long-range photon coupling (L >> LQubit, where LQubit is the length scale of a single qubit) between superconducting qubits is shown. Bottom: Information transfer between quantum and classical components occurs through the quantum-classical interface. These components include control signals, readout, input/output (I/O) management, and more. Image of neutral-atom qubit in upper left from S. Welte, et al, "Photon-Mediated Quantum Gate Between Two Neutral Atoms in an Optical Cavity," Phys Rev X 8, 011018 (2018).

(iii) *Research and demonstration of full-stack quantum computation for larger systems*

As quantum computers scale, the topics of software automation, scaling of machine architectures, and system integration become increasingly important. Low-level control signals cannot be generated by hand beyond very small numbers of qubits. Consequently, compilers, firmware, abstraction of the physical platform, and automation are critical. Importantly, the architecture for large (>1000 qubit) systems (including their interconnect architecture) and the metrics for benchmarking their performance today are largely unknown. Research in this direction is crucial to allow development and construction of large and useful systems. Such research will be aimed at determining to what extent progress can be made on systems integration in ways that are consistent with all (or at least more than one) of the six physical qubit platforms considered here.

(iv) Interconversion of quantum information between physical qubits

If high-fidelity interconversion can be achieved, there would be speed advantages in moving from long-lived (but slow) qubits to shorter lived (but faster) qubits. The faster qubits must themselves have high-fidelity operations. The interconversion presumably needs to be performed twice: once to enter the fast domain and again to return to the slower, but more coherent, domain. Algorithms and architectures will need to be designed to adapt to such a hybrid processor.[26,39] Converting matter-based qubits into photon 'data bus' qubits may facilitate more efficient architectures, e.g., approaching all-to-all coupling instead of the nearest-neighbor coupling constraint of many qubit platforms.

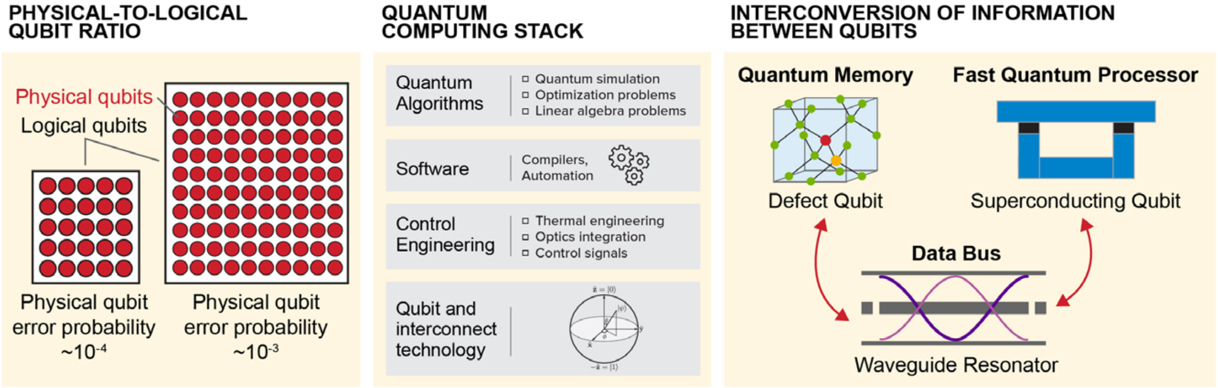


Figure 5. Center: The quantum computing stack involves multiple levels, including qubit and interconnect technology, control engineering, software, and finally quantum algorithms. Two aspects of qubit and interconnect technology are illustrated in the left and right panels. Left (physical-to-logical qubit ratio): Many physical qubits (red circles) make up a single logical qubit (outlined by black blocks). These two logical qubits are composed of physical qubits with different error probabilities for every gate operation, 10-3 and 10-4, respectively. The logical qubit composed of fewer physical qubits performs equally well compared with the logical qubit with more physical qubits because of the different error probabilities. Right (interconversion of information between qubits): Information in a fast quantum processor (e.g., superconducting qubits) is transferred to a quantum memory (e.g., defect qubits) for long-time quantum information storage. The two qubit types are coupled through a data bus (e.g., a waveguide resonator).

C. Roadmap for Quantum Communication

I. Introduction

Quantum communication refers to the interchange of single and entangled photons through a network of devices (a quantum network), in which information is encoded on and measured from those photons. Such an interchange enables a range of potential applications in distributed quantum computing, distributed quantum sensing, and quantum-secured communication. A quantum network's optimal construction will depend on its application. Building a point-to-point quantum cryptography system, for example, using fiber and commercial high-speed optical modulation and multiplexing electronics, would be a very different task than building a long-distance internet of quantum computers using memory-enabled quantum repeaters based on fiber-connected, rare-earth crystals. Complicating the road toward optimizing a design is the present reality that both target applications and architectures for implementation of quantum networks remain at an early stage of technological maturity. A highly concrete roadmap to construction would therefore be premature. But developing aspects of a roadmap is not only possible but valuable because there are identifiable commonalities in imperatives and critical components across many applications and implementations. This document attempts to identify these imperatives and critical components, but not to downselect either an application or a particular set of hardware components. As such, our roadmap includes considerable uncertainty.

A roadmap's destination is in applications, and we identified a number of applications of quantum communication systems (referred to in this document as quantum networks) with likely technological impact over the next 10–15 years. These are listed with descriptions below.

Quantum Key Distribution (QKD)

QKD remains the most well-studied application of quantum communication. Government impact is considered low because of the published statements of the National Security Agency (NSA) indicating key gaps in QKD utility in its present form (in particular, vulnerability to denial-of-service [DOS] attacks and potential irrelevance in light of "post-quantum" security protocols). QKD's impact in private commerce may be stronger than in government, however, with enterprise/carrier-level network components offering additional protection against DOS attacks. Point-to-point short-haul (<200 km) QKD maturity is high, while repeater-enabled approaches that extend the "quantum-secure" distance are in their infancy.

Quantum-Enhanced Classical Communication

Researchers are aware that sharing of entanglement can enhance the transmission rates in many communication tasks such as channel simulation,[40] point-to-point zero-error communication,[41] and multi-user communication.[42] Future classical-quantum hybrid networks might take advantage of the nonlocal coordination provided by the sharing of entanglement for sending and processing classical messages. High-fidelity interconnects between classical and quantum hardware will be crucial for realizing this advantage.

Authentication and Security beyond QKD

Protocols related to QKD have spurred the development of reliable processes for authentication, which may address problems of eavesdroppers storing cyphertext and decrypting later. The presence of adversaries may be more readily detectable using QKD-like methods than classical methods through channel tomography techniques and device-independent processing.[43] A large variety of cryptographic concepts and quantum secret-sharing approaches (for a review, see Broadbent and Schaffner[44]) may offer value if implemented in a quantum network, ranging from private database queries[45] to Quantum Digital Signatures, a verifiable randomness beacon, and Quantum Byzantine authentication protocols.[46] Quantum Secure Voting[47] could have a major impact on government/public voting, as well as on bidding in commercial contexts. This area is ready for early-stage pilots. All of these applications will greatly benefit from the development of a usable quantum memory and high-rate, high-fidelity entanglement distribution capability.

Repeater-Enabled Fundamental Science

Long-distance entanglement distribution provides a setting to study fundamental questions of nature such as nonlocality, decoherence, and quantum gravity. For example, the closing of loopholes in Bell inequality experiments has been a key scientific endeavor for validating the foundations of quantum mechanics, and similar tests may be imagined (e.g., teleporting complex quantum states between matter-based systems) if repeaters extend the distance and speed of entanglement generation. We do not expect "surprises" in the development of faster and longer-distance entangled states as quantum communication systems scale, but if surprises do occur, perhaps because of unknown interactions with gravity or other corrections to standard descriptions of quantum mechanics, such an event would herald significant new advancements in fundamental science.

Quantum Sensing Aided by Repeater-Enabled Quantum Networks

To coordinate with other roadmapping efforts, we refrain from entering details of "entangled sensors"; this topic includes magnetometers, gravimeters, and sensors. Two potential connections for which sensing is integral to a communication task are as follows:

- *Improvements in secure clock synchronization*[48] may have great potential in applications such as transportation networks and global positioning systems (GPS), as well as science applications such as in assisting gravitational experiments.
- *Quantum position verification* offers a scheme for securely confirming the location of users in a network. The demands for classical and quantum time synchronization are high.

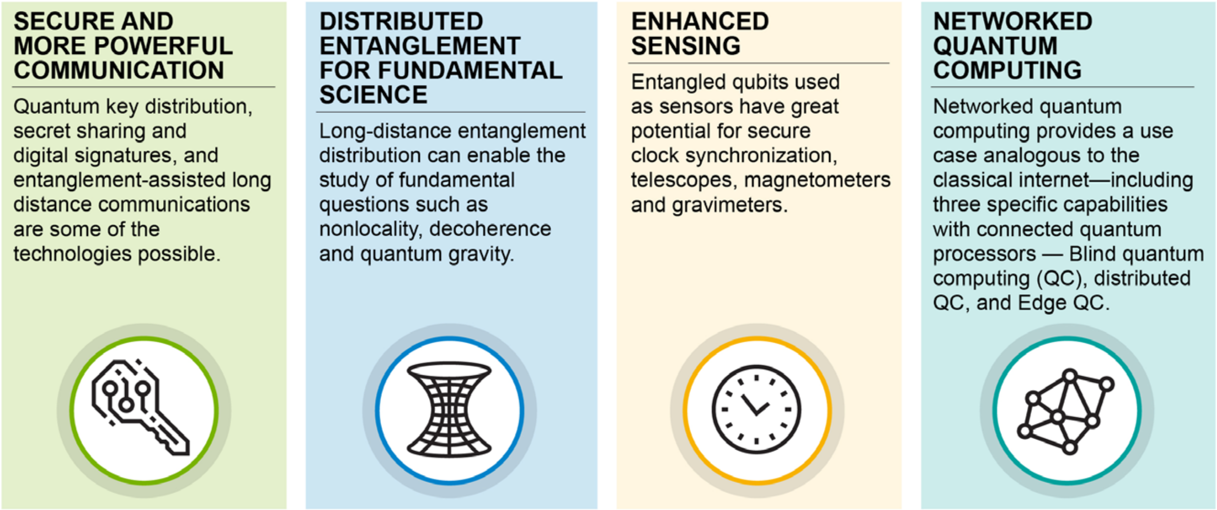
Networked Quantum Computing

If not for the complication of the low maturity of quantum computers themselves, this application would offer the clearest advantage. Quantum networks, unlike classical alternatives, may enable computing capability that is provably impossible for even very large networks of very large classical computers. This application can therefore provide (to the network carrier) the ultimate use case analogous to the classical Internet. Quantum networking across scales ranging from meters to kilometers needs extensive development for implementation over the next 15 years, including the need for efficient quantum transduction and for quantum repeaters. The enumeration of the many applications of quantum computers is provided elsewhere in this document, but we do highlight three applications that emerge specifically when long-distance communication is added to their functionality:

- In *Blind Quantum Computing,* a secure cloud quantum computing platform is possible with clients having only prepare-and-measure technology and the ability to hide computations and data from the server; realistic benchmarks are presently unknown, however.

- In *Distributed Quantum Computing,* multiple quantum processors are connected coherently so that they behave as a single larger quantum computer. Assuming that sufficient levels/rates of connectivity can be maintained, such a system is exponentially more powerful than the individual quantum processors acting independently.
- *Edge Quantum Computing* merges with quantum sensing and refers to the use of entangled resources to compute data from sensors or data streams. Entangled sensing is discussed in the quantum sensing section; networking adds performance scaling unattainable using classical computers.

The impact on society of these identified applications is unclear because they all depend on an adjunct technology: compromises to existing cryptosystems are needed to give QKD significant impact, effective entanglement-driven sensors are needed to impact sensor networks, and better quantum computers are needed to warrant networks of quantum computers. However, the impact of these future technology advances will be amplified by the technology readiness of the accompanying quantum network system.



SECURE AND MORE POWERFUL COMMUNICATION

Quantum key distribution, secret sharing and digital signatures, and entanglement-assisted long distance communications are some of the technologies possible.

DISTRIBUTED ENTANGLEMENT FOR FUNDAMENTAL SCIENCE

Long-distance entanglement distribution can enable the study of fundamental questions such as nonlocality, decoherence and quantum gravity.

ENHANCED SENSING

Entangled qubits used as sensors have great potential for secure clock synchronization, telescopes, magnetometers and gravimeters.

NETWORKED QUANTUM COMPUTING

Networked quantum computing provides a use case analogous to the classical internet—including three specific capabilities with connected quantum processors — Blind quantum computing (QC), distributed QC, and Edge QC.

Figure 6. Quantum communication networks are expected to disrupt applications in the areas of secure communication, entanglement distribution, sensing and distributed quantum computing.

II. Science and Technology Imperatives over the Next 10 Years

What are the key imperatives to drive quantum networking technology toward the applications addressed in the previous section? Here we identify seven, which we will elaborate on in later sections, listed in approximate order of chronological importance; however, parallel pursuit would be required to drive impact on a 10-year timescale.

1. Provide precise and near-term application of clear need for *commerce, government,* and/or *science*

The applications listed in the previous section depend on adjunct technologies whose immaturity may limit relevance for quantum communication on a 10-year timescale. Parallel development of quantum networks therefore needs a clearer purpose to maintain commercial and/or government interest in the <10-year timescale. Using existing technology, the cost of a scaled quantum network is not justified for any of the applications listed because there are classical alternatives for all applications; if a clearer application space with <10-year impact is identified, more industrial investment will drive the technology advancement to allow practical implementation of the presently known, longer-term applications.

2. Develop *critical quantum components* that are compatible with photon-based qubits in the visible, near-infrared (IR), and telecom wavelengths

This imperative refers to components that require >10x improvement in key metrics. The most prominent example is the quantum memory, which requires order-of-magnitudes improvement in coherent storage time and/or optical coupling fidelity or rate, depending on type (see Section IV). Other examples include quantum light sources and quantum transducers, also discussed in Section IV, and quantum-compatible multiplexing and routing capabilities. Many other telecommunication components (e.g., couplers) are nearly mature but still need engineering improvement for use in the quantum communication context.

3. Demonstrate quantum repeater-enabled quantum communication, with success probabilities exceeding that possible via direct transmission

The essential promise of quantum repeaters[*] is that entanglement may be distributed at rates exceeding the rate when using direct transmission. One critical aspect is that the success probability should be higher when the repeater is used. This "proof-of-principle" demonstration has not yet occurred, although preliminary results with quantum memories are encouraging,[49] and a working prototype would be highly informative because it requires the combination of multiple interworking components that have not been made to work before.

4. Demonstrate long-range (intercity) entanglement distribution using repeaters

The benefit of higher success probability is lost if the attempt rates must be reduced due to component limitations (e.g., if the memories or processing nodes introduce long latencies). Thus, a key milestone is to demonstrate long-distance entanglement distribution at *rates* that exceed those possible without the inclusion of repeaters. For example, in the recent experiments from T.U. Delft,[50] the quantum communication rates were actually much lower than would be possible using repeaterless methods (which could use shorter photon wavepackets and therefore higher repetition rates); the actual traversal of physical distance at speeds indicating the practical advantage of repeaters remains an outstanding goal to prove the quantum repeater-enabled network concept. Achieving a true advantage in the *rate* of entanglement distribution (and not just the efficiency per attempt) will require large amounts of multiplexing on the source, repeater, and detector side.

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[*] QRs can be classified into three generations: 1G and 2G QRs both rely on heralded entanglement generation between neighboring repeater stations to overcome loss errors. 1G QRs use entanglement purification between neighboring and remote repeater stations to correct operation errors; the two-way classical communication needed between remote stations slows down the key generation rates and requires long-lived quantum memories at repeater stations. 2G QRs use quantum error correction to overcome operation errors; this needs two-way classical communication only between neighboring stations, which can be achieved in parallel. Using a completely one-way protocol (analogous to classical repeaters), 3G QRs use only quantum error correction to overcome both loss and operation errors, so their communication rate depends solely on the time to perform local operations, with the potential of reaching ultrafast communication rates; however, the maximum tolerable channel loss between nodes is 50%.

5. Develop (optimize and standardize) a true multi-node quantum network *architecture*

Metrics for components are unclear without an actual architecture. Resource requirements are needed for effective planning, targets are needed by which to benchmark competing component technologies, and standards must be established with future scaling in mind. While protocols and hardware design continue to mature, architecture-in-earnest is conceptual at best. Success in developing an architecture is multi-tiered, as architectures at different scales are inherently different; in fact, for imperatives 6 and 7, we would need multiple network architectures **and** a "single" internetwork architecture.

6. Demonstrate homogeneous multi-node quantum network at intercity scale

This imperative is similar to the DOE Quantum Internet Milestone 3: "Intercity Quantum Communication Using Entanglement Swapping." Reaching the intercity scale for a quantum network requires meaningfully extending distance with full system links, thereby demonstrating the potential for a "Quantum Internet." "Intercity scale" is a label, but not the key characteristic, for this imperative; its key characteristic is network complexity. The network could be a metropolitan network or single city-to-city link with multiple repeaters; the critical characteristic is that it should prove the principle of entanglement-enabled, repeater-based communication for many nodes across a significant distance/area.

7. Demonstrate inhomogeneous quantum internetwork at interstate scale

This final imperative is similar to the DOE Quantum Internet Milestone 4: "Interstate Quantum Communication using Entanglement Swapping." We cannot expect a future quantum internet to be "homogenous" at interstate scales because different institutions will build different components for different purposes, likely with commercial competition. When reaching a state-to-state scale, a quantum network system will certainly require working repeaters, an inhomogeneity-tolerant scalable architecture, standards, and national infrastructure. Such an "internetwork" may also include the use of satellites (while imperative 5 might not.) A true "system" demo, like the Internet, would include a "network of networks."

III. Materials, Components and Systems used for Quantum Communication

The high-level imperatives of the previous section are significant undertakings, and all of them hinge on improvements in the systems to be developed and their components; a roadmap to such high-level destinations must include sub-roadmaps of relevant systems and of the components within each system. To assist, we identify and classify the different types of subsystems that must be architected and engineered to reach those imperatives.

Types of Networks

A "quantum network" may have different architecture and different requirements at different scales or applications. To be more precise, we describe the key types of networks relevant to quantum communication below.

Modular interconnects[51] (also known as *system area networks*[52,53]) address the connectivity within a single laboratory or machine room, with inter-node distances of centimeters to tens of meters. Such a network is a single technology, and the traffic patterns tend to be regular and may be tightly coordinated. Networked quantum computers are likely to employ a modular interconnect system.

Data Center Networks (DCNs) involve connectivity within a large machine room with inter-node distances of up to 100 meters. Generally, DCNs provide outward-facing computing services demanding scalability, flexibility in resource allocation, and connectivity for specialized devices. Point-to-point QKD applications are often envisioned to integrate with DCNs.

Local Area Networks (LANs) are campus-size networks with inter-node distances of up to several hundred meters and with homogeneous technology. LANs will provide access to local quantum computers and a gateway to wide-area networks (WANs). Applications such as coherent sensor data from an entangled sensor network may employ a LAN for quantum resource access.

Metropolitan Area Networks (MANs) will have inter-node distances of tens of kilometers and network diameters of ∼100 kilometers. A MAN, primarily a single technology administered by a single company/carrier, is the scale at which repeater-less quantum communication is expected to have the highest impact.

Mobile Networks (MOBs) are wireless quantum communication channels for connecting to ships, aircraft, or other mobile platforms or distributed quantum sensors. MOBs may also include wireless free-space links between stationary nodes (e.g., buildings) where dedicated fiber links are impractical or undesirable (e.g., because of physical or financial considerations).

Transcontinental Network (or *WANs)* encompass inter-node distances of thousands of kilometers linking cities, national laboratories, etc. A WAN could be a single administrative domain and homogeneous technology, but such networks are expected to bridge to other networks, implying heterogeneity across technology. Its purpose is the sharing of national resources, similar to the original ARPANET and NSFNET vision for classical computing. Quantum-protected e-commerce and communication will have the highest impact on a WAN scale.

Transoceanic Networks (e.g., *Satellite Network [SAT])* have inter-node distances of thousands of kilometers, similar to WANs. Their purpose includes global-scale science projects, quantum protected e-commerce and communication, and distributed quantum processing and sensing.

Classification of Node Hardware

A network is composed of nodes performing different functions. Nodes may be constructed of different hardware components. Network nodes may be one of ten types, roughly grouped into end nodes (the first four types), repeaters (the next three), and support (the last three).[54]

Full computational nodes (COMPs): The long-term vision for the Quantum Internet involves universal quantum computers as end nodes, analogous to today's classical Internet.

Memory-based end nodes (MEMs): Along the road to development of full computational end nodes, MEMs are single-interface repeaters usable for many of the applications under consideration.

Sensor end nodes (SNSRs): May involve specialized hardware (e.g., additional high-precision clocks or multi-mode quantum memories).

Measurement-only end nodes (MEASs): QKD and blind computation can be achieved using MEASs that dynamically select a measurement basis when receiving individual photons.

Memory-based repeaters (REP1s): The “standard” two-interface repeater node for networks employing two-way state and information transfer (classified as 1G networks[55]; see footnote on page 18). REP1s support limited error mitigation protocols such as entanglement purification.

QEC-enabled repeaters (REP2s): Networks employing quantum error correction (QEC), classified as 2G or 3G networks.[55]

Routers (RTRs): The most advanced form of memory-based repeater, able to interface with three or more optical channels, including synchronization. Routers may be used in all generations of error management.

Bell State Analyzers (BSAs) consist of two or more detectors and are used for entanglement swapping to generate entangled links between nodes.

Entangled photon pair sources (EPPSs): Based on nonlinear optical processes or direct emission from quantum sources, including quantum dots or atomic cascades. Other sources may be generation of single photons entangled to a memory, a form of memory node already discussed. Finally, some applications benefit from higher-dimensional encoding and hyperentanglement in multiple degrees of freedom simultaneously.[56]

Optical switch nodes (OSW): All implementations of quantum networks require routing, which requires switching for single photons (as well as “classical” electrical or optical signals). Single-photon switching is particularly critical because highly lossy switches for quantum signals cannot be compensated for with re-amplification, as often happens in classical systems. Switches may be considered part of other types of the nodes described above, as stand-alone nodes in a reroutable network (optical switch nodes), or both, as will most likely be the case in a realistic network implementation.

Assuming ready availability of hardware, the different node types may be either common (C) or rare (R) in different types of networks, as listed in Table 1. For more details on the relationship between applications and end-node capabilities, see Wehner et al.[57]

Classification of Components

Each network node is constructed from a set of hardware components. Equipment vendors will use these components to build the boxes the network operators will buy. While many common components (e.g., waveguides, couplers, switches, lasers) are mature and already deployed in classical telecommunication networks, many of these still require significant improvements for quantum applications (e.g., reducing photonic integrated circuit insertion loss). Other components (e.g., quantum memories, photon sources and detectors, qubit processors) remain under active R&D. Tables 2 and 3 attempt to summarize components for building a variety of quantum communication systems. We assess which node type each component may be used in, referring to Table 1.

Table 1: Networks and Node Types (R: rare; C: common)

NODE	MI	DCN	LAN	MOB	MAN	WAN	SAT
Full computational end (COMP)	C	C	C	R	C	C	C
Memory end (MEM)	R	R	C	C	C	C	C
Sensor end (SNSR)	R	R	R	C	R	R	R
Measurement end (MEAS)	R	R	C	C	C	C	C
Repeater 1G (REP 1)	R	R	R	C	C	C	R
Repeater 2/3G (REP 2)	R	R	R	C	C	C	R
Router (RTR)	R	C	C	C	C	C	R
Bell state analyzer (BSA)	C	C	C	C	C	C	R
Entangled photon pair source (EPPS)	R	R	C	C	C	C	C
Optical switch (OSW)	C	C	C	C	C	R	R

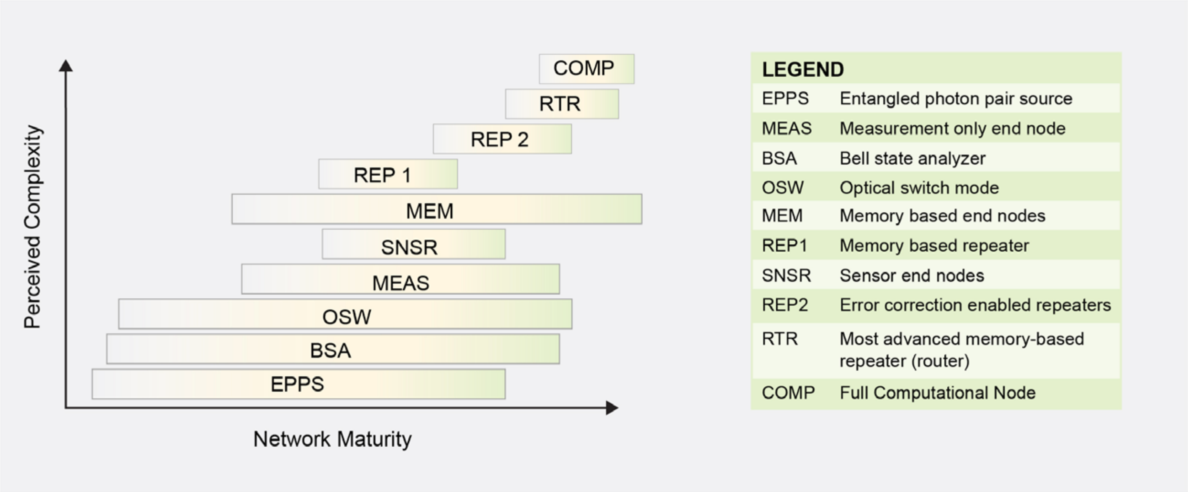


Figure 7. The components that make up a quantum network are at different levels of perceived complexity. As more components see improved performance (represented by the color gradient), the capabilities and maturity of the network also grows.

Classification of Architecture, Protocols, and Software

Protocols and architecture can take years to get “right.” Thus, work on these intangibles must proceed in parallel with hardware development.

The connection architecture is defined by the choice of service (for instance, via end-to-end Bell pairs, qubit transport, or multi-party states).[58] This choice of service then interacts with the generations of repeater technology (1G, 2G, 3G) used and their interoperability.[55] In addition, the Internetworking architecture – which defines how operations proceed across boundaries between separate networks – is key, and negotiation of fidelity management will be critical here. To achieve a true global Quantum Internet, a single internetwork architecture will have to be chosen.

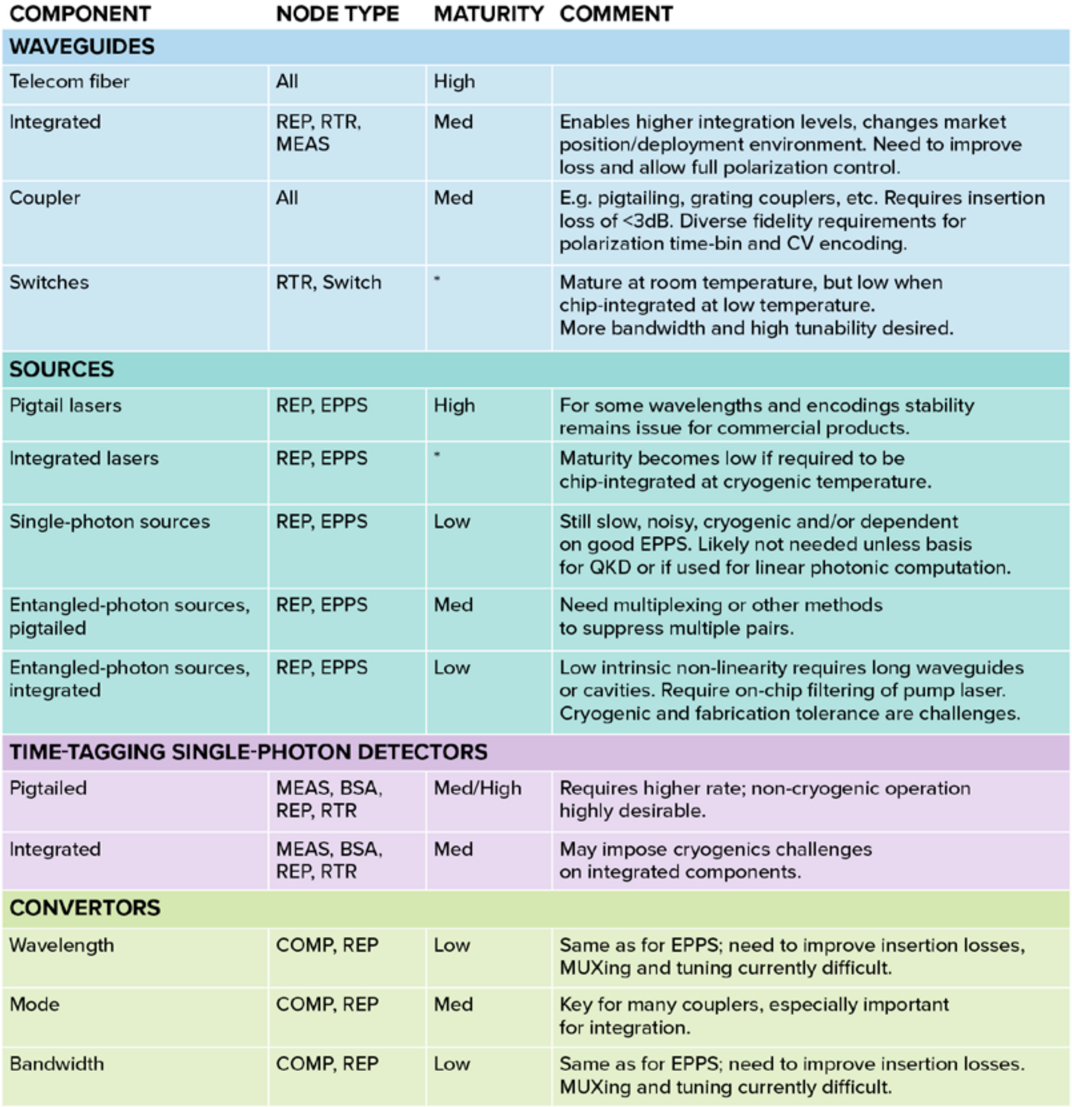
Protocols: One-hop entanglement creation across a link requires exchanging classical messages including the heralding of success or failure. These messages are governed by *link layer protocol*s. *Network-layer protocols* are responsible for delivering the end-to-end service (e.g., achieving multi-hop entanglement for 1G or 2G networks). For 1G networks, for instance, this protocol is responsible for managing purification and entanglement swapping. *Application protocols* couple with Application Programming Interfaces (APIs) and accomplish integration with classical computing services – an area with, to date, no serious work.

Quantum error correction and related techniques: As noted above, purification and quantum error correction can appear in on-the-wire behavior in 1G, 2G, and 3G networks.

Routing and multiplexing:[59] Connections will require some knowledge of how to find partners across a complex network and circuit switching, and “packet” switching (statistical multiplexing) and related concepts will need evaluation and adaptation for quantum information.

Security of network operations: Requires a security architecture, but instantiation will be diffuse, affecting numerous components.

Table 2: Quantum Optical Components



COMPONENT	NODE TYPE	MATURITY	COMMENT
WAVEGUIDES			
Telecom fiber	All	High	
Integrated	REP, RTR, MEAS	Med	Enables higher integration levels, changes market position/deployment environment. Need to improve loss and allow full polarization control.
Coupler	All	Med	E.g. pigtailing, grating couplers, etc. Requires insertion loss of <3dB. Diverse fidelity requirements for polarization time-bin and CV encoding.
Switches	RTR, Switch	*	Mature at room temperature, but low when chip-integrated at low temperature. More bandwidth and high tunability desired.
SOURCES			
Pigtail lasers	REP, EPPS	High	For some wavelengths and encodings stability remains issue for commercial products.
Integrated lasers	REP, EPPS	*	Maturity becomes low if required to be chip-integrated at cryogenic temperature.
Single-photon sources	REP, EPPS	Low	Still slow, noisy, cryogenic and/or dependent on good EPPS. Likely not needed unless basis for QKD or if used for linear photonic computation.
Entangled-photon sources, pigtailed	REP, EPPS	Med	Need multiplexing or other methods to suppress multiple pairs.
Entangled-photon sources, integrated	REP, EPPS	Low	Low intrinsic non-linearity requires long waveguides or cavities. Require on-chip filtering of pump laser. Cryogenic and fabrication tolerance are challenges.
TIME-TAGGING SINGLE-PHOTON DETECTORS			
Pigtailed	MEAS, BSA, REP, RTR	Med/High	Requires higher rate; non-cryogenic operation highly desirable.
Integrated	MEAS, BSA, REP, RTR	Med	May impose cryogenics challenges on integrated components.
CONVERTORS			
Wavelength	COMP, REP	Low	Same as for EPPS; need to improve insertion losses, MUXing and tuning currently difficult.
Mode	COMP, REP	Med	Key for many couplers, especially important for integration.
Bandwidth	COMP, REP	Low	Same as for EPPS; need to improve insertion losses. MUXing and tuning currently difficult.

IV Relevant Questions and Issues for Quantum Communications

Relevant questions and issues for quantum communications revolve around system requirements for networks. It will be most practical to house quantum network systems in the same or similar infrastructure as existing telecommunications systems. This practical systems approach, especially desirable for fiber-based quantum communication systems, raises a number of technological and basic scientific issues. Operations would need to be on existing, commercially deployed, single-mode fiber (e.g., SMF-28). Room-temperature operation systems would largely be preferred, even if some components inside the system incorporate cryogenic requirements. Maintaining these requirements imposes challenging conditions on quantum repeaters likely to be installed in the inline amplifier (ILA) sites/fiber huts because of their harsh environments. Reasonably sized cryogenic systems operable at ranges (4 to 80K) common to widely available commercial cryocompressor technologies (as opposed to milli-Kelvin range temperatures), may be sufficiently practical, but engineering considerations for acceptable footprint and power consumption need to be evaluated for any approach. This requirement depends on the environment. For example, in the case of quantum repeaters, 2 RU footprint on a 19" rack and 100-W power consumption might be needed to satisfy the tight requirements of an ILA station.

Metropolitan, transcontinental, and transoceanic networks will use the vast geospatial optical data networks already deployed by carriers, enterprises, and other entities. Some of the key system-level issues and considerations for these networks are as follows:

- There should be a minimum reach of ~ 100 km for repeater-less operation.
- Quantum channels should ideally be multiplexed on the O-band (1260–1360 nm) and the DWDM (dense wavelength division multiplexing) data channels on the C-band (1530–1565 nm) and L-band (1565–1625 nm). With no special station dedicated to quantum channels, quantum repeaters should be placed in the same ILA stations that house the regular DWDM data channel equipment.
- Resilience against channel degradation factors in scaled systems is an important consideration and includes the effects of polarization modal dispersion (PMD); polarization-dependent loss (PDL); fluctuations in the state of polarization (SOP); and dispersion, Raman scattering, and non-linear optical effects.

The above requirements must be met to make quantum communication systems adaptable to the optical data networks already deployed by carriers, enterprises, and other entities.

Among the first design choices in a network will be the quantum information encoding used in the channels. The encoding may use various degrees of freedom (DOF) (e.g., polarization, time-bin or frequency), including more than one DOF simultaneously ("hyperentanglement"); the latter of these DOFs permit higher dimensional encoding, which may be beneficial in some applications. Some protocols also employ "continuous variable" (CV) encoding (e.g., using modified squeezed states) or hybrids using both CV and discrete variable (DV) encoding.[60] The interaction of CV with end systems that are assumed to work with qubits is an open research area. Simultaneous, correlated success or failure of the arrival of multiple qubits will affect the robustness and efficiency of protocols. Hardware and protocols can be optimized to leverage higher-dimensional encoding schemes, permitting more efficient quantum error correction via cross-layer engineering.[56]

Space-based systems for quantum networks present an attractive alternative to existing fiber networks for a number of reasons, but deployment here will require improvements in synchronization for moving platforms (true teleportation or entanglement swapping has not been demonstrated between moving platforms) and significant reduction in the size, weight, and power (SWaP) of the optical components traditionally employed.

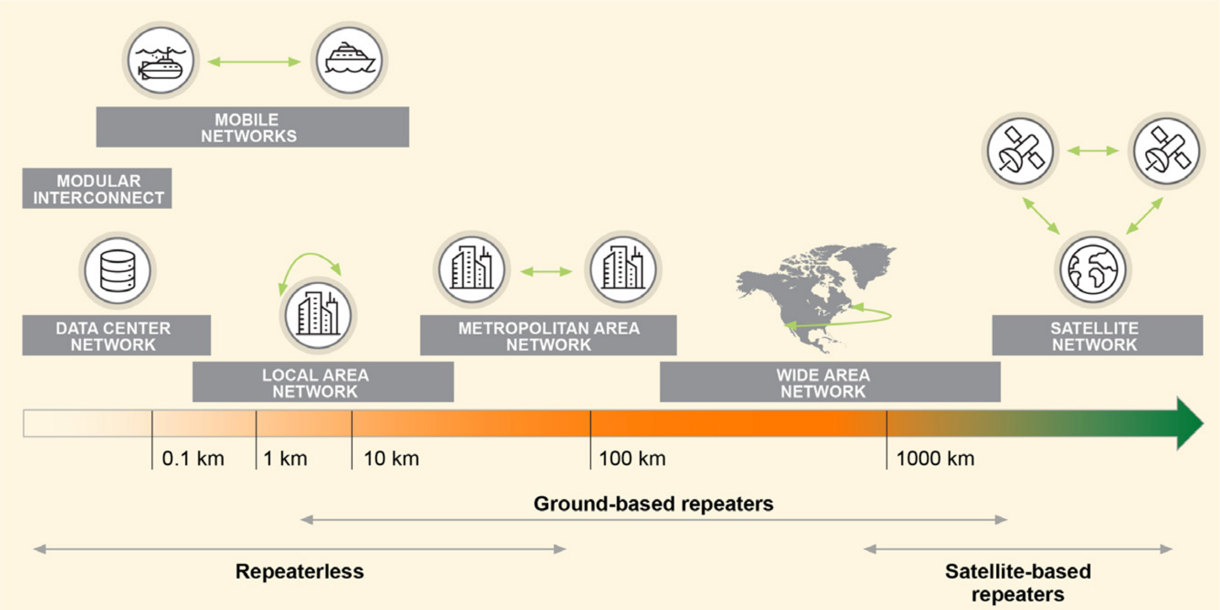


Figure 8. The different types of quantum networks that can be or have been realized. At smaller length scales, these include mobile networks that connect mobile platforms, interconnects that connect single machines, and DCNs that connect many machines. Moving to longer distances brings the LANs, MANs, WANs, and SATs. With repeaterless networking, we only expect to build a network over relatively short distances; ground-based repeaters are needed for longer distances and satellite-based repeaters for even longer ones.

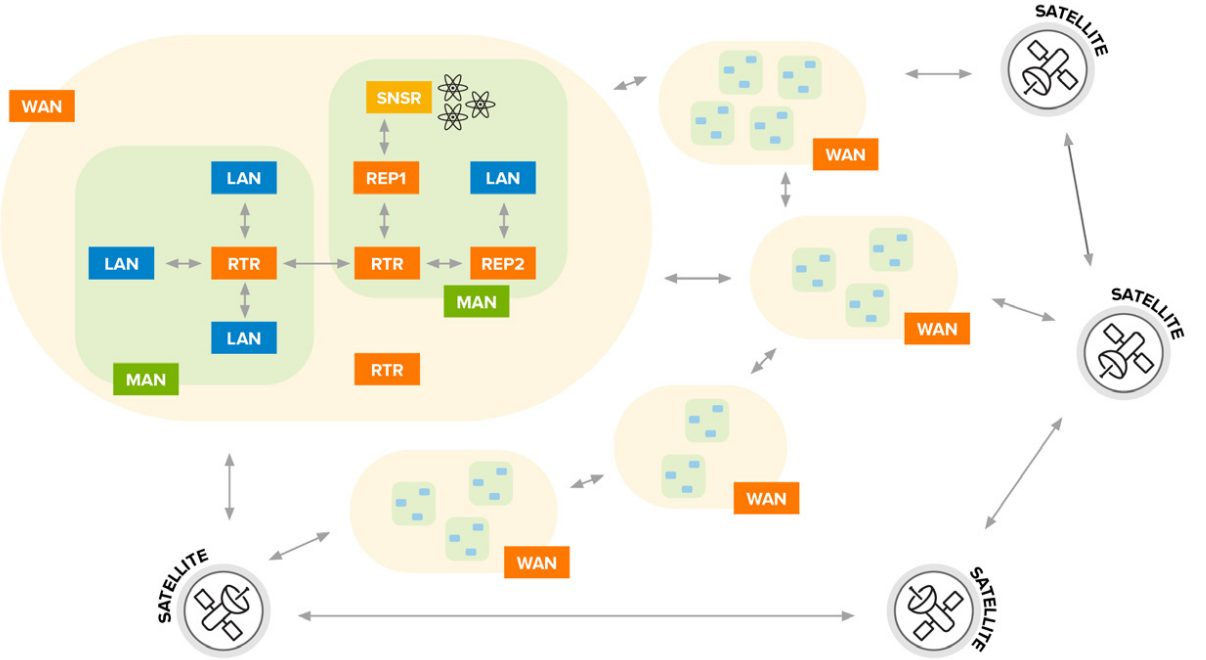


Figure 9: A fully realized quantum network will consist of a network of quantum networks, including SATs, WANs, MANs, and LANs. These will have multiple active components, such as the repeaters with different capabilities (RTR, REP1, REP2) and nodes such as COMP and SNSR.

V. Research Needs and Developments Necessary

With applications, imperatives, and classification of systems identified, we are in a position to look somewhat more closely at components and the research needed to advance them for insertion into architected systems. Below we list some of the critical status points and developments for the elements/components of a quantum network.

Cryogenic single-photon detectors: Superconducting nanowire single photon detectors (SNSPDs) already have demonstrated high performance in efficiency and dark counts (current specifications include critical temperatures Tc, ~ 1-4K; critical current, Ic, > 1 μA; < 100 dark counts per second; timing jitter ~ 10 ps). Some photon-number-resolving capability is present in these detectors, which is beneficial for some protocols. Lower detector dead times than presently available would simplify hardware by requiring fewer detectors and less switching. Performance improvements depend on additional nanoscale superconducting materials research. Widespread adoption will be gated by improved and cost-competitive cryogenic engineering.

Semiconductor single photon avalanche photodiodes (SPADs): Demonstrated Si-based SPAD performance efficiencies have exceeded 40–70% (550–800 nm) with timing jitter below 50 ps, dark counts <100 cps, and saturation rates above 150 Mcps, all at room temperature. The challenge (and research needs) for SPADs is in efficient detection in the IR O- and C-band telecom wavelengths, where silicon devices meeting the specifications above are completely ineffective. Maturity of SPADs into telecom could include new materials research, research on electronic drivers to reduce jitter and afterpulsing, as well as research on high-efficiency wavelength transduction. A target of net efficiency t>80% and timing jitter <50 ps is reasonable.

Entangled/hyper-entangled photon pair sources: Entangled photon sources based on nonlinear optical processes are now a commercial product. However, demonstration of highly multiplexed sources is still needed; improved rates (> $10^7 s^{-1}$, with > 95% fidelity/spectral purity and < 5% multi-pair events, or truly non-probabilistic generation) would significantly accelerate adoption. Also, existing sources and memories are largely incompatible because of the different wavelengths and bandwidths, requiring quantum transduction. Needs also include scaling and integrated packaging; these require advances in nonlinear materials and integration of active lasers. Optimized sources of higher-dimensional entanglement or hyperentanglement across multiple degrees of freedom are also needed.

Ultra-low loss optical channel research has been largely static on the fiber side as a result of the success of fused silica fiber at telecom wavelengths (with some exceptions such as the development of ultralow loss fiber [0.142 dB/km][61] and ZBLAN fluoride ultra-low loss fibers for repeater-free communications).[62] In many systems, loss is limited by interconnects and the insertion loss of optical couplers. Significant development would be gated by an affordable, high-yield pathway to lower insertion loss (~ 10x), which would extend repeater spacing requirements.

Space-to-ground connections: Research needs include improvements in low-SWaP robust sources and detectors, as well as improved time-synchronization systems, quantum memories, and free-space adaptive optics methods (to improve success rates of teleportation and entanglement swapping). Needs may also require flight-ready cryogenics (e.g., for superconducting nanowire detectors). A clear indication of practicality will be gated by the success of pilot studies, such as true teleportation/ entanglement swapping between mobile platforms and through space-to-ground channels.

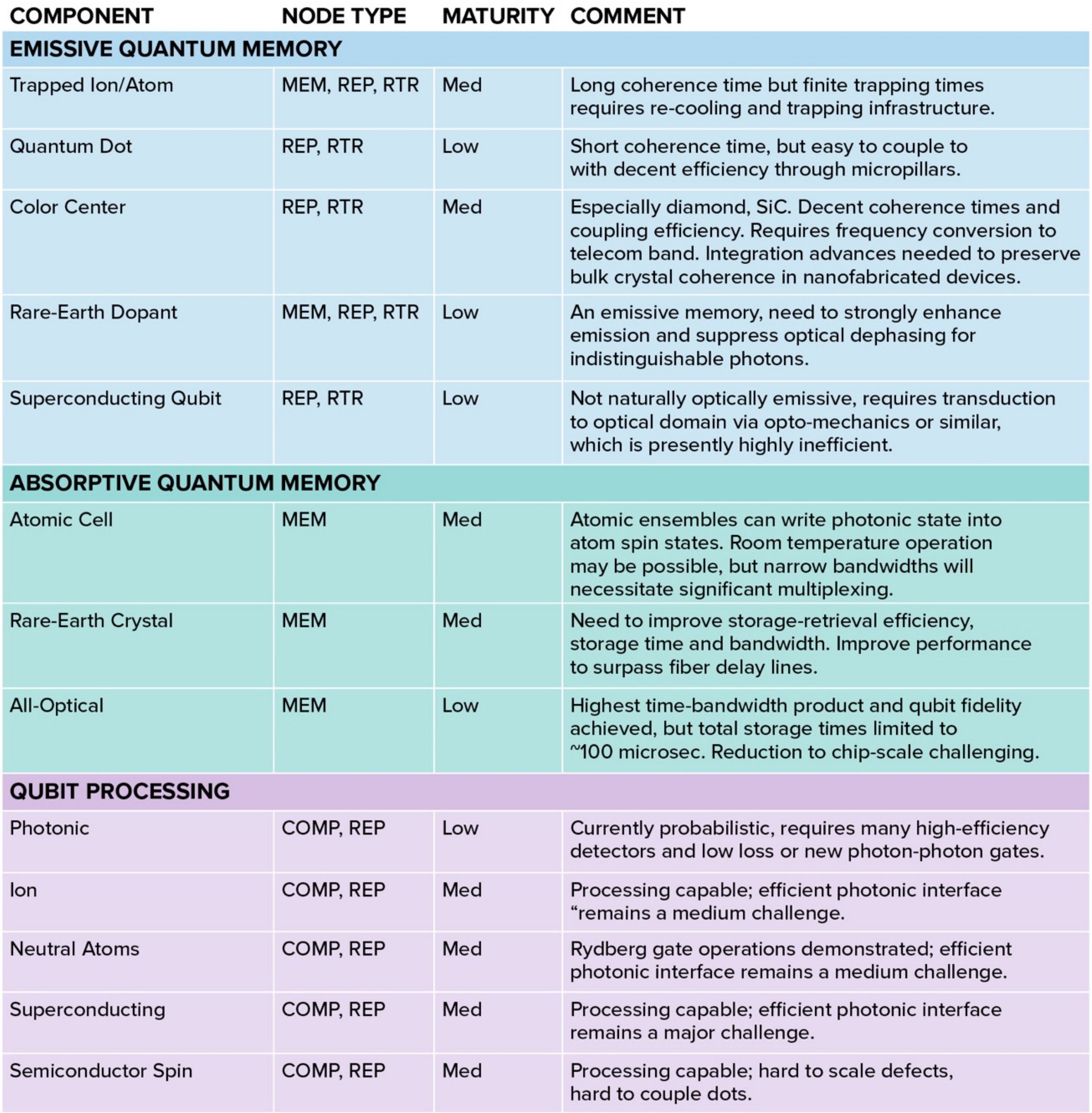
Integration with classical networking, synchronization, and complete cybersecurity protocols: The quantum Internet will be a hybrid network (both classical and quantum channels). Commercial adoption depends on the clear interplay of quantum communication with classical protocols (e.g., routing is likely to be handled over the classical channels). An enterprise or carrier will require that all components of the quantum network meet current norms for manageability (e.g., performance monitoring, alarming, telemetry, fault management).

Transducers: *Optical-to-optical transduction* (wavelength transduction) research is relevant for linking matter qubits to telecom wavelengths. Adoption into a network requires a manufacturable system with decent performance specifications (> 80% efficiency, > 90% fidelity) compatible with wavelength division multiplexing systems. Photon bandwidth conversion, so that sources and memories are compatible, is also likely to be necessary. *Microwave-to-optical telecom wavelength transduction* is important given the relevance of superconducting qubit-based computing. The gateway to significant development requires passing an efficiency threshold to enable transduction of quantum states at >90% fidelity and bandwidth of >1 kHz,[63] while maintaining low noise to permit operation at the single-photon level.

Quantum memories: There is a significant need for quantum memories that are scalable (e.g, on chip). Typical targets are a quantum-memory retention time of >10/100 ms (target/stretch) and memory efficiency of >80/90% (target/stretch) at 3 K, integrated with silicon photonics. Given the importance to quantum computing, quantum science, and quantum communication, many avenues for improved memories for quantum networks are under active research (see Table 3). Research needs include exploring defect- and dopant-based semiconductor and insulator host memories; materials development including growth, processing, etching and polishing; and device integration that includes fiber coupling, on-chip photonics, and packaging.

Further development of key quantum network components, such as high-speed, low-loss quantum switches and multiplexing technologies, will be needed. These components may depend on cryogenic electronics developments for utilizing fast feedback from low-jitter superconducting detectors. Hardware for switching (inside multiplexing units) must be shown to be compatible with single photons (insertion losses < 0.5 dB).

Table 3: Quantum Memory Components



COMPONENT	NODE TYPE	MATURITY	COMMENT
EMISSIVE QUANTUM MEMORY			
Trapped Ion/Atom	MEM, REP, RTR	Med	Long coherence time but finite trapping times requires re-cooling and trapping infrastructure.
Quantum Dot	REP, RTR	Low	Short coherence time, but easy to couple to with decent efficiency through micropillars.
Color Center	REP, RTR	Med	Especially diamond, SiC. Decent coherence times and coupling efficiency. Requires frequency conversion to telecom band. Integration advances needed to preserve bulk crystal coherence in nanofabricated devices.
Rare-Earth Dopant	MEM, REP, RTR	Low	An emissive memory, need to strongly enhance emission and suppress optical dephasing for indistinguishable photons.
Superconducting Qubit	REP, RTR	Low	Not naturally optically emissive, requires transduction to optical domain via opto-mechanics or similar, which is presently highly inefficient.
ABSORPTIVE QUANTUM MEMORY			
Atomic Cell	MEM	Med	Atomic ensembles can write photonic state into atom spin states. Room temperature operation may be possible, but narrow bandwidths will necessitate significant multiplexing.
Rare-Earth Crystal	MEM	Med	Need to improve storage-retrieval efficiency, storage time and bandwidth. Improve performance to surpass fiber delay lines.
All-Optical	MEM	Low	Highest time-bandwidth product and qubit fidelity achieved, but total storage times limited to ~100 microsec. Reduction to chip-scale challenging.
QUBIT PROCESSING			
Photonic	COMP, REP	Low	Currently probabilistic, requires many high-efficiency detectors and low loss or new photon-photon gates.
Ion	COMP, REP	Med	Processing capable; efficient photonic interface "remains a medium challenge.
Neutral Atoms	COMP, REP	Med	Rydberg gate operations demonstrated; efficient photonic interface remains a medium challenge.
Superconducting	COMP, REP	Med	Processing capable; efficient photonic interface remains a major challenge.
Semiconductor Spin	COMP, REP	Med	Processing capable; hard to scale defects, hard to couple dots.

Network protocol optimization is a must in moving from links to networks. Implementing multi-hop networks will require both a means of routing information along selected paths through the network and of incorporating quantum repeaters to compensate for the signal loss in the channel. This requires the evaluation and development of detailed switching/routing protocols.

Network architecture: While connection architectures (1G-3G) have been proposed, there are no true complete network architectures. Proposals to design an architecture provide a key demonstration gateway; however, this step will hinge significantly on emerging theoretical work in *quantum error mitigation techniques*, as well as *reliable models of quantum network components.*

Integration with classical computing and communication services: The services provided by quantum networks and computers are specialized, and architecturally are best viewed as one type of processor within a more complete, more general system. Consequently, programming tools, as well as hardware, will need to incorporate into classical systems as seamless components. As an example, cryptographic services will have to integrate into a classical key management system (KMS) or into a complex e-commerce system.

Error-corrected quantum networking functions: All feasible applications on realistic hardware will depend on error correction. Realistic theoretical error thresholds with performance guarantees gate more significant hardware development. Substantial research has already begun in this area, such as development of models for three generations of repeaters and establishment of thresholds for purification- and QEC-based systems. This topic may be coordinated with the quantum computation effort.

Monitoring and management of links, nodes and networks: Quantum networks will introduce new challenges in network management, as we learn to test and describe the condition of entangling links and other hardware at relevant timescales. This work will require both low-level hardware control and operations at the qubit or entangled state level. Active research in certification of quantum computers focuses on the challenges of scaling as the number of qubits increases, but for networks a bigger challenge may be the large constant factors for statistical accuracy of bipartite entangled states and the need to perform validation (e.g., a Bell inequality violation experiment) continuously for operational purposes, rather than in batch after a long run.

Application programming model and interfaces: Only QKD has been addressed to date. APIs and libraries will require linkage to high-precision clocks and will also have to carry some notion of statistical certainty as part of the programming model for many purposes, including eavesdropper detection. Classical Internet applications use an intermediate-level software structure known as a socket, or higher-level tools for remote data queries or processing requests. Quantum equivalents that support portable, easy-to-write and easy-to-debug code will have to be developed.

To date, all of the above items have received only modest amounts of attention from researchers. In particular, programming APIs and interfacing with classical computing and communication systems, with the exception of QKD, have been the focus of almost no work. Finally, development of software and architectural concepts is best done with the support of simulators.

VI. Outlook

With the networking of quantum computers, a likely target application for a quantum network, the development of a quantum network may be imagined to follow a course significantly similar to the development of the Internet. Some factors may accelerate development — in particular, the lessons learned from the scaling of the classical Internet in the past 50 years — but other factors may render it slower, in particular, the additional technology challenges inherent to single-photon systems and (likely) cryogenic memories. However, if attention is paid early to the overarching system needs, uses, and architectural considerations, the technology of quantum communication is far more likely to reach a stage of genuine impact to society in security, awareness, or computational capability.

D. Roadmap for Quantum Sensing

I. Introduction

Quantum sensors can play an important role within many technologies. For example, quantum sensing principles are already being used in applications such as GPS[64,65] and the Laser Interferometer Gravitational-Wave Observatory (LIGO),[66] impacting everyday technologies and fundamental scientific discovery. In the term "quantum sensors," we include sensing architectures that require entanglement, as well as those that do not need quantum entanglement but make optical use of quantum mechanical principles in their design. Practical quantum sensors will need to possess the properties of high sensitivity (enabled by long quantum coherence and high-fidelity quantum state readout); high spatial resolution (enabled by controlled positioning and proximity);[67] and in many cases, interconnectivity, so that sensors can communicate with each other and with detectors.[68] The sensors will also need to be quantitative and robustly coherent upon deployment in the field. Quantum sensors promise transformative impact spanning fundamental physics, biology, and materials science. Such promise can be realized with focused developments over the next 15 years as described in this section.

A quantum sensing roadmap for the next 15 years features dramatic improvements to the figures of merit for existing quantum sensing technologies, such as precision, accuracy, bandwidth, dynamic range, and spatial and temporal resolution. Such a roadmap will also enable the interconnection of sensors across frequency and space and the discovery of altogether new sensing modalities that harness these interconnects. Provided progress is made in these areas, some of the anticipated key areas of impact and commercial deployment for quantum sensing are noted below.

- Biochemical applications
    - Image real-time molecular structure and dynamics on the atomic scale.[69]
    - Probe in-vivo metabolic processes and function on the cellular scale.[70]
- Fundamental physics
    - Detect gravitational waves over a wide frequency range (at low frequencies outside bandwidth of LIGO) and with greater sensitivity and therefore astronomical reach.[71,72]
    - Make possible, for the first time, a search for quantum chromodynamics (QCD) axion dark matter over its full mass range.[73,74]
    - Search for new particles and interactions beyond the Standard Model of physics.[75]
    - Improve the performance of optical very long baseline interferometry (VLBI) for high-resolution astronomical imaging (e.g., of exoplanets).[76,77]
- Navigation/time keeping
    - Keep time at higher levels of precision and accuracy for network synchronization and unit definitions.
    - Enable more precise inertial navigation and dead reckoning in GPS-denied environments.[78]
- Condensed matter physics/materials science/quantum technologies

- Provide a fundamental understanding of exotic phases in condensed matter systems that will enable the control and harnessing of these materials for developing classical and quantum technologies.[79,80]
- Probe decoherence in quantum systems to improve quantum interfaces and interconnects.

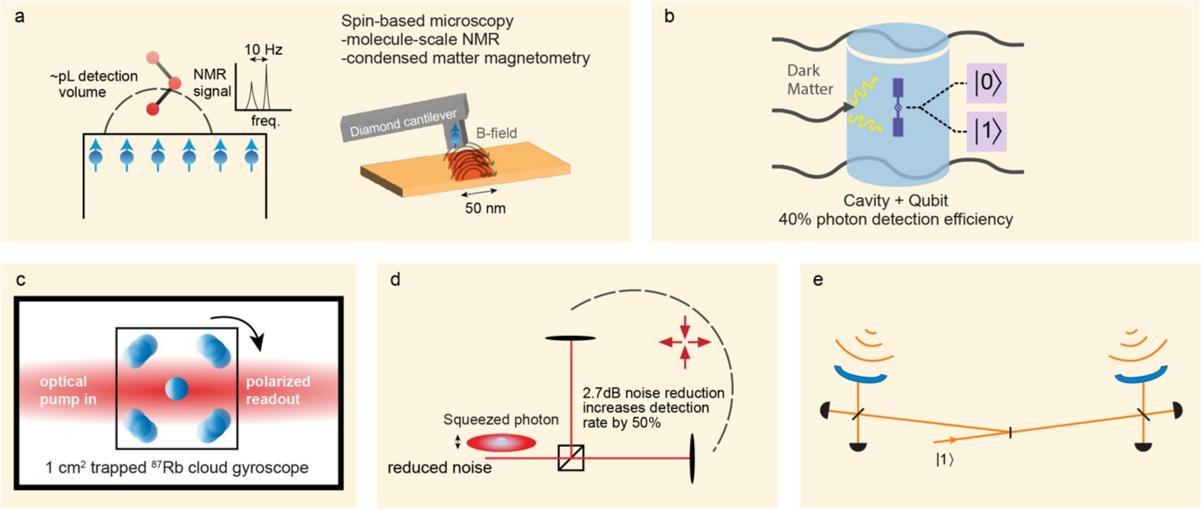


Figure 10: Quantum sensing impact areas. We present examples of current advances in quantum sensing. (a) Left: Spin-based microscopy for chemically sensitive nuclear magnetic resonance (NMR) and scan-probe magnetometry. Ensemble measurements of NV centers at ambient conditions have achieved 10 Hz sensitivity in picoliter volumes.[81] Right: Single nitrogen vacancy (NV) center-containing diamond cantilevers probe sub-diffraction limited magnetic textures.[80] (b) Sensitive detectors of dark-matter/light interactions. Superconducting cavity-qubit systems with 40% photon detection efficiency and 15.7dB advantage over the standard quantum limit (SQL) hold promise for axion detection[82] (figure courtesy of Akash Dixit). (c) Matter wave gyroscope in cSWaP devices. Atom interferometers can be scaled down for integration into practical devices, with 1 cm^2 atom trap areas[83]. (d) Larger-volume gravitational wave detection. Non-classical, squeezed photons reduce noise in km-scale interferometers, increasing detection rate by 50%.[66] (e) Distributed quantum states (via a quantum network) can enable shot-noise-free very long baseline interferometric telescope arrays in the optical spectrum, whose angular resolution varies as the reciprocal separation of the telescopes[84]. Credit for image 4b: A. Dixit/University of Chicago

II. Science and Technology Imperatives over the Next 10 Years

Q-NEXT aims to address the scientific and engineering challenges laid out in this roadmap. Activities, presented below, span theoretical developments to materials scalability, tackling the interconnected roadblocks to developing high-performance quantum sensors.

1. Achieve entangled multi-qubit sensing (over local scales) with a demonstrated improvement over non-entangled sensors on a real sensing target (10 years). Interconnected sensors could improve any of these figures of merit: sensitivity, dynamic range, bandwidth, spatial resolution, access to correlations, and non-invasiveness of the measurement.
2. Develop a rigorous theory of quantum metrology using remote entanglement to identify the kinds of distributed sensing tasks that can benefit from a quantum advantage, assess the scaling

nature of this advantage, and evaluate the performance metrics of the interconnected sensing system needed to accomplish this quantum advantage.

3. Develop new sensing modalities that leverage correlations and entanglement between multiple sensors to measure observables that are inaccessible with individual sensors (10 years). Such modalities would provide access to new physics (e.g., quantum correlations in a material, nonlocal phase transitions).
4. Understand and reduce interface-induced decoherence in solid-state sensors (10 years). Interfaces will be unavoidable in interconnected sensors, and these are known sources of decoherence.
5. Deterministically position addressable active spin/lattice defects/impurities with < 5-nm precision and predict their properties in materials (10 years).This work will enable interconnecting sensors via dipolar interactions.
6. Enable quantum sensing of molecular structure with single nuclear spin sensitivity (10 years) to allow studies of molecular functionality and structures.
7. Enable sensing of DC-THz electromagnetic fields with quantum advantage (10 years), including the following:
    - Back-action-evasion/squeezed states for 100 kHz–100 MHz signals for dark matter and axion searches; and
    - Low dark-count single-photon detection and parametric amplification at 100 GHz to improve sensitivity by >20 dB over current technologies.
8. Achieve photon-number-resolved detection of optical pulses with errors <1%, at rates >1 GHz.

III. Materials, Components and Systems Used for Quantum Sensing

A wide range of materials, excitations, and device architectures have been proposed for quantum sensing. So it is important to identify, pursue, and improve the most suitable sensor platforms for particular applications. The major systems explored to date include the following.

- Defects in the solid state
    - Diamond, SiC, hBN, transition metal dichalcogenides, molecular spins, and other defects still to be discovered/developed[85–88]
- Atomic systems
    - Trapped atoms and atomic vapors[64]
    - Entangled atomic clocks connected with low-phase-noise precision photonic links[89]
    - Rydberg atoms for field sensing and photodetection across frequency scales[90]
- Superconducting systems
    - Superconducting qubits and superconducting quantum interference device (SQUID)-based sensors for electromagnetic measurements[91,92]
    - Superconducting pair-breaking detectors for photon counting[93]
- Non-classical photonic states (optical, microwave, mm-wave)[66]
- Mechanical systems in the quantum regime (including opto- and electro-mechanical systems)[94]

IV. Relevant Questions and Issues for Quantum Sensing

Harnessing these systems for useful sensing applications will be enabled by adopting a multi-pronged approach that aims to interconnect sensors across many frequency and spatial scales, realize altogether new sensing paradigms, and advance the performance of quantum sensors beyond their classical counterparts and beyond the quantum sensors of today. **Achieving these key impacts is not simply an engineering challenge; indeed, significant scientific discovery is a necessary part of a quantum sensing roadmap**. Below is a list of questions and issues that highlight anticipated needs for scientific discovery where we lack clarity. Progress in these areas is essential over the next 15 years to enable viable quantum sensing technologies.

- **Physics of sensing and metrology**
    - How does one harness entanglement for enhancing practical figures of merit including not only absolute sensitivity but also, for example, dynamic range, bandwidth, spatial resolution, access to correlations, and non-invasiveness of the measurement?
    - What types of entangled states are metrologically useful for each specific task and what targets will benefit the most?
    - Can entanglement be created, protected, and accessed in the context of a practical sensing target?
    - How do we use the destruction of entanglement as a quantum sensor?
    - How can entanglement be used to evade (1) measurement backaction and (2) SQLs of measurement in practical applications?
    - Can the typical per-photon advantage of optical quantum sensors be leveraged to overcome the concomitant technical and intrinsic constraints of needing to use only one photon per mode at a time, i.e., when is the quantum solution superior *in practice* to the classical solution employing coherent states with many photons?
- **Materials and architectures**
    - How do we deterministically generate or place defects (native or impurity based) in solids with nanometer- or even Angstrom-level precision to controllably generate entanglement among solid-state sensors?
    - How do we achieve robust and reliable control over surfaces and interfaces that can transmit entanglement while maintaining coherence of constituent sensors?
- **System scale for interconnects**
    - Quantum sensors can be interconnected in a variety of ways, including transferring quantum information between quantum systems, inducing correlations among spins, or generating entanglement that is measurement-induced or deterministic. Initial experimental demonstrations will be based on small-scale entangled systems. These will provide a controllable testbed that will inform the design principles for larger entangled systems that will benefit from the developments in the quantum networking thrust.

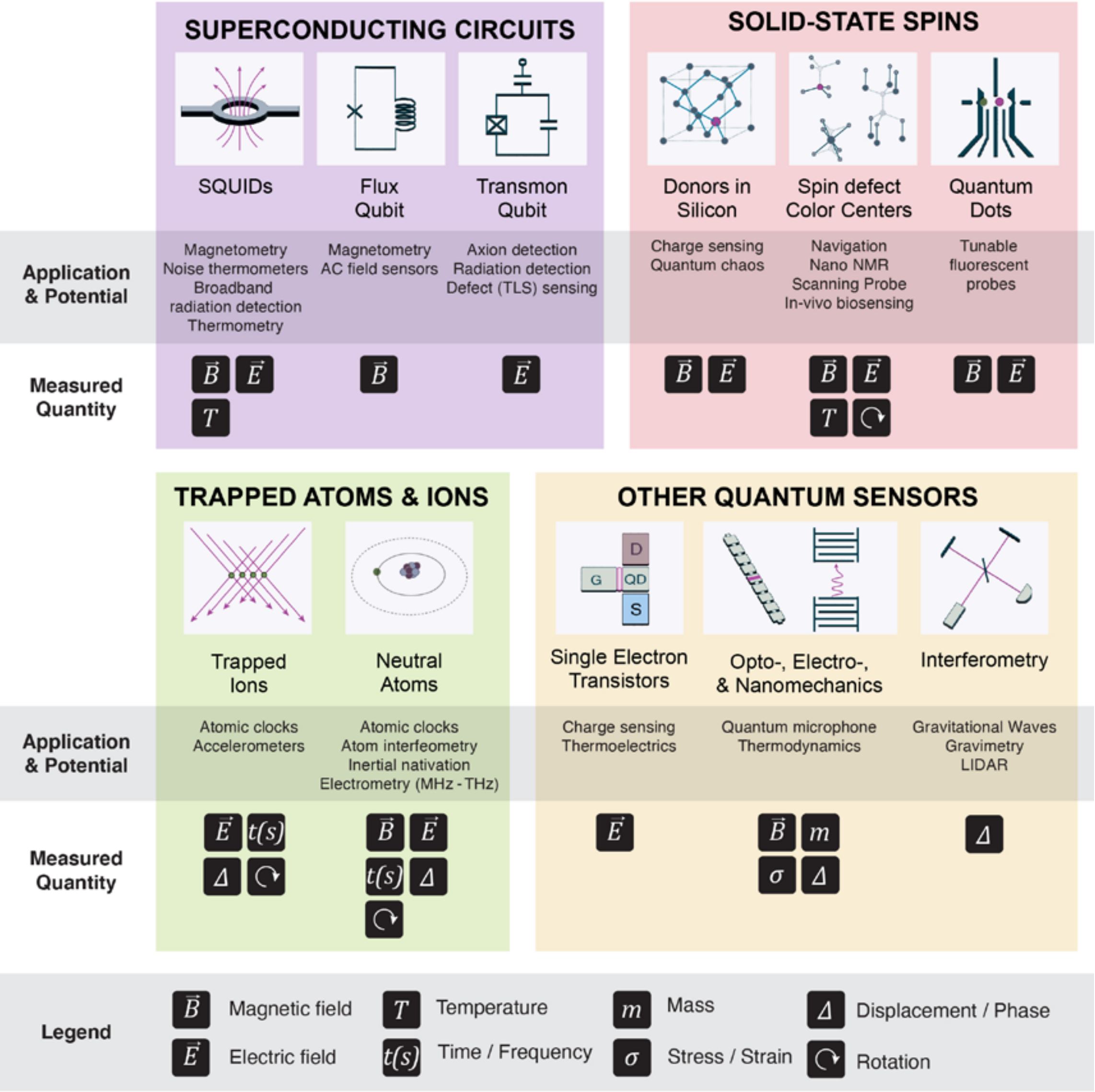


Figure 11. Quantum sensing platforms and applications. All qubit platforms couple to physical quantities. This is a resource for sensing, enabling a wide variety of applications across platforms. This is not an exhaustive list and is intended as a snapshot of current applications and potentials.

V. Research Needs and Developments Necessary

The scientific questions listed above are largely — and deliberately — broader questions that are less targeted to specific materials systems. A sensing roadmap, while using specific material systems to demonstrate concepts and ideas, needs to consider the need for an overall approach, theory, and design methodology. These questions frame the following specific research needs over the next decade, with emphasis on obtaining more clarity around sensing metrics and sensing needs, theory, and the investigation of more complete ranges of systems and excitations.

(i) Control and Determination of Metrics

In order to take advantage of interconnected quantum sensors, the following metrics should be achieved. In some cases, these metrics can be quantified, and in some cases, the research is not yet there and we must focus more on determining specific target metrics. In almost all cases, the interplay between metrics needs a strong analytical foundation.

- The application determines the coherence and the detector efficiencies. Detector efficiencies must be increased with target numbers being application-specific. This process is not always clear; a case study could help with metrics for one target. Coherence must be maintained over the length scales of the interconnected system, which can vary from sub-micron for microscopic imaging systems to a few hundred kilometers for inter-repeater distances for the distribution of entanglement over long-distance fiber optical or space-based networks. Detection targets should be at and below the quantum projection noise limit.
- The sensitivity (noise per root hertz) and bandwidth of sensors are key parameters. Single electron spin sensitivity should be improved beyond the ~10-nm spatial resolutions that have already been reproducibly reached. Typical bandwidths for various sensing applications span a large range, from sub-Hz to THz.[67] The phase noise should typically be less than 1 mrad per node interrogation (rms phase jitter).
- Backaction evasion and/or squeezed-state generation of better than 3 dB at 100 kHz–100 MHz with coherent superconducting systems will have important practical impact for sensing. Eventually, 20 dB is needed for wide-ranging applications.
- Quantum non-demolition (QND) methods have been proposed as a way to count the number of photons within a microwave cavity without destroying the photons, using a technique that involves coupling and then decoupling a superconducting qubit.[82,95] Microwave photon counting targets should be at 10–30 GHz using superconducting qubits with dark counts of less than 0.01 per second.
- Similar QND capability for optical photons would also be desirable, for example, effectively converting any quantum memory into a *heralded* quantum memory (which not only stores a quantum state transmitted on a photon, but also produces a measurable signal that it has done so), a critical resource for quantum repeater architectures.
- For networked sensors, bandwidth of the interconnect (number of entangled pairs transmitted per second) should be 100 kHz (100 GHz) with (without) memories.
- Single-photon detectors with system efficiencies >98%, saturation rates > 10^9 cps, noise < 100 cps, jitter < 10 ps, photon-number resolution (at least to distinguish 1 and >1 photon).

(ii) Materials

There is a severe lack of understanding of materials science issues in quantum information applications in general, and quantum sensing is not an exception. Some of the major materials developments needed are as follows.

- *Deterministic positioning and/or generation of sensing qubits*: Sensing with multiple solid-state defect qubits will require deterministic positioning of those defects to within $\sim$ 5 nm to enable controlled entanglement generation. By "defects," we mean either native defects such as vacancies, self-interstitials, or their complexes or extrinsic defects such as impurity atoms deliberately introduced via doping techniques. Current two-dimensional lithographic techniques are inadequate. Approaches such as ion implantation suffer from uncertainty in the depth of implant because of the statistical nature of the process. For solid-state sensors, this is a significant materials and processing challenge that must be overcome to create entanglement between multiple solid-state defect qubits.

- *Robust and reliable control over interfaces and surfaces*: A comprehensive and quantitative understanding of the role that interfaces and surfaces have on quantum sensors, particularly with respect to noise, is lacking.[96] As a result, clear approaches to control interfaces and surfaces experimentally have been lacking as well, with learning often benefitting from Edisonian successes. Interface- and surface-induced noise examples exist in both solid-state defect-host materials systems, as well as superconducting microwave qubits. Understanding and mitigating interface- and surface-induced noise to approach bulk-like or vacuum-like properties — even at interfaces and over the length scale of the interconnected system — is a key materials target. Such materials design will need to, eventually, control entanglement in the presence of unwanted interactions/entanglement with the environment.
- *Low-loss robust sources of quantum light*
    - On-chip optical squeezing (requiring low-loss strong optical nonlinearity) >10dB.
    - Efficient pure-state single-photon sources, with efficiencies >95% (collection and fraction of single photons). Such sources are important for sub-shot noise quantum metrology (e.g., of material absorption) and quantum-enhanced telescopy.
- *Access to, and development of, advanced characterization methods*: Materials characterization is key to accelerating quantum sensor R&D by establishing local structural, dynamical, and coherence properties of quantum systems.
    - The primary challenge is *sensitivity (or precision)*. Spatial, temporal, and spectral precision at the picometer and femtosecond scale is critical to identify quantum-state behavior and quantify its relationship to intrinsic and extrinsic parameters.
    - The second challenge is *environmental control*, which is required to create quantum-relevant in-situ conditions allowing for the real-world observation of synthesis, defect dynamics, hybridization, and device-level validation.
    - The third challenge is *correlation* to develop a cohesive multi-platform integration of synchrotron, X-Ray Free-Electron Laser Facility (XFEL), electron, optical, and scanning probe techniques necessary for understanding and optimizing quantum structure-function relationships spanning large length and timescales — from the single defect level to the full quantum network level. Frontier materials characterization capabilities span optical, x-ray, electron, and scanning probe microscopies. These can be used to enable imaging at and below the single-defect level, with femtosecond temporal resolution to probe dynamic quantum responses. Such methods provide a micro-to-nanoscopic understanding of defect structure, sources of decoherence and instability, noise sources, and dissipation of information transduction.

(iii) Theoretical Advances

Theoretical advances will also be needed to realize significant advances in quantum sensing over the target 15-year timeframe. Theory needs for a roadmap will include the following.

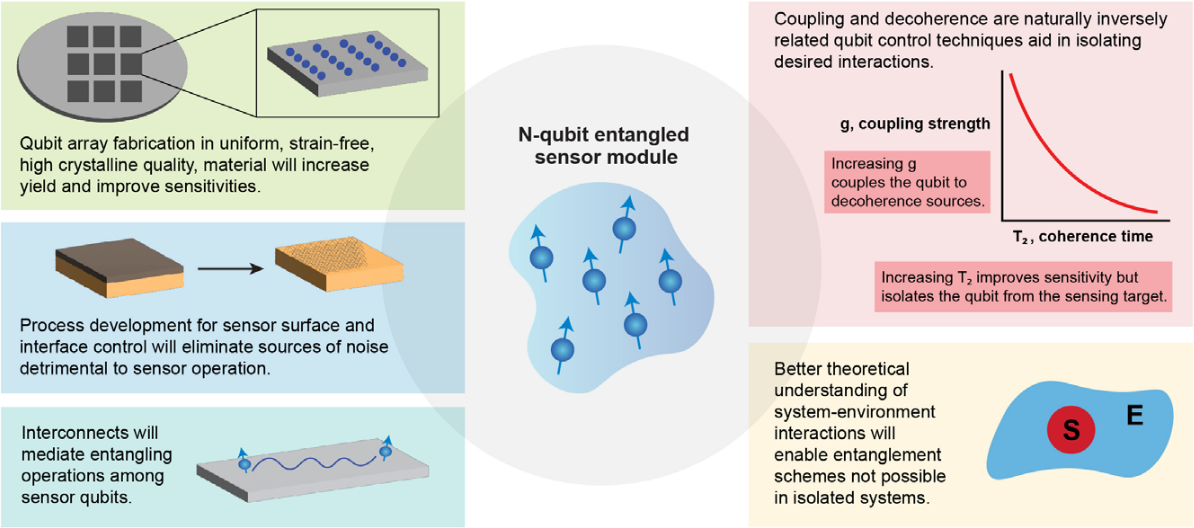
- *A rigorous theory of quantum metrology* using remote quantum states that elucidates the kind of distributed sensing tasks that can benefit from a quantum advantage and the scaling nature of this advantage.
- *Protocols:* There are three major needs here. First, basic knowledge is lacking about how best to exploit entangled states in a realistic noise environment (e.g., in the presence of inevitable dephasing) and under realistic levels of measurement imprecision. New protocols and approaches are needed that allow quantum sensors to benefit from entanglement under such constraints. We need to address this issue via new protocols and approaches (e.g., through the use of error correction and error mitigation strategies). For example, quantum "weak measurements" can be used to suppress the effects of some types of systematic noise[97]. This issue is also related to the second major need: new ways to generate and stabilize metrologically useful quantum states in such realistic, resource-limited experimental platforms. This work needs to be conducted in tandem with experimental improvements in the materials and sensors to mitigate dephasing so that entanglement can be useful. Third, there is a need for new protocols to SQLs of measurement by preparing novel quantum states, using error-correction techniques, and taking advantage of all quantum resources including entanglement. Finally, we note that it is important to benchmark the efficiency of such protocols — an important, but often overlooked, aspect. It is therefore important to determine efficiency specifications as part of protocol development.

(iv) System Scaling and Sensing Platform Maturity

There is still a significant gap between laboratory demonstrations of quantum sensing and deployable platforms in many application spaces. For example, inertial systems based on quantum sensing are not SWaP-C competitive with existing solid-state sensors.[83,98] Building up to large number of sensing nodes (in terms of cost and manufacturability) will be important to leverage the scaling advantages of a quantum network over a classical one, which underlines the need for improving SWaP-C and robustness. Such durability of sensing systems (survivability to shock, operation across temperature) is also important if they are to be deployed in the field for long periods. Understanding materials properties, as well as understanding which system integration schemes will be compatible, will also be critical to sensor performance.

(v) Broadening the Frequency Space

Quantum modalities are only well-developed in specific islands in the frequency space (optical and microwave).[67] These techniques need to be extended to longer wavelengths (radio frequency [RF] and below), and in between to THz and mid-IR wavelengths. These frequency bands are already especially useful in medical imaging, security applications, and chemical fingerprinting. Operating in these new wavebands requires new infrastructure, including improved detectors, improved refrigeration technology, and the development of testing and calibration equipment and techniques.



Qubit array fabrication in uniform, strain-free, high crystalline quality, material will increase yield and improve sensitivities.

Process development for sensor surface and interface control will eliminate sources of noise detrimental to sensor operation.

Interconnects will mediate entangling operations among sensor qubits.

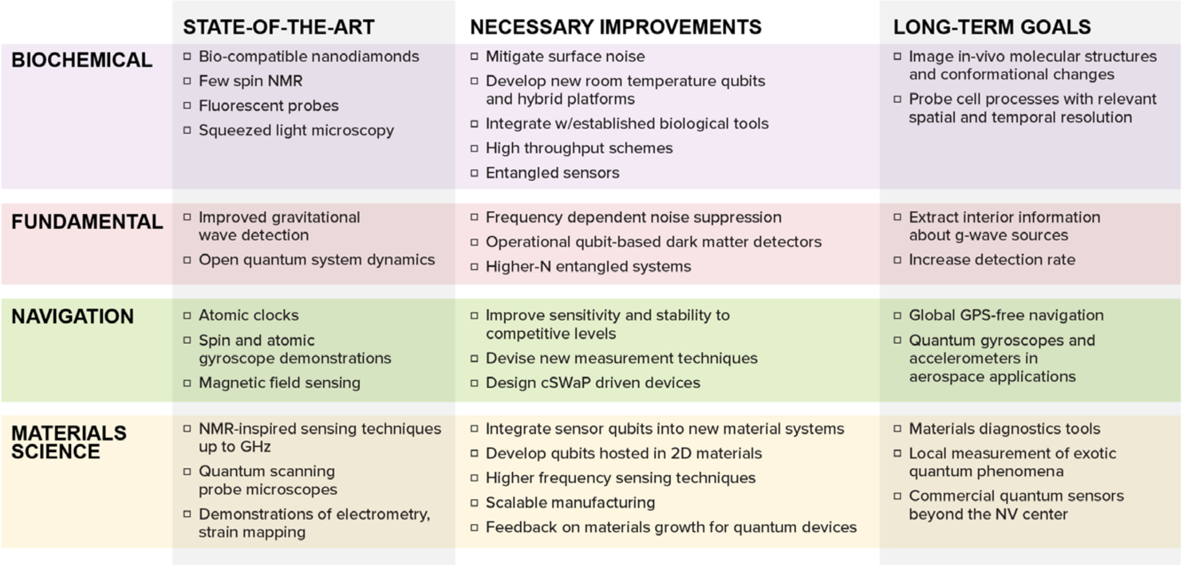
Coupling and decoherence are naturally inversely related qubit control techniques aid in isolating desired interactions.

Increasing g couples the qubit to decoherence sources.

Increasing T_2 improves sensitivity but isolates the qubit from the sensing target.

Better theoretical understanding of system-environment interactions will enable entanglement schemes not possible in isolated systems.

Figure 12: Components of an example practical quantum sensing module. A network of all-to-all entangled qubits will enable sensitivities beyond the SQL. There are multiple, parallel steps needed to accomplish this, spanning a large range of skill sets, and necessitating interdisciplinary efforts. Qubit creation and material quality, as well as mitigation of surface effects, will push materials science to a level not required for classical electronics. On the other hand, new theoretical understandings of quantum control techniques and system-environment interactions will enable more coherent systems and new entanglement protocols. Interconnects that mediate entangling interactions are needed to realize such a sensor.



	STATE-OF-THE-ART	NECESSARY IMPROVEMENTS	LONG-TERM GOALS
BIOCHEMICAL	◻ Bio-compatible nanodiamonds ◻ Few spin NMR ◻ Fluorescent probes ◻ Squeezed light microscopy	◻ Mitigate surface noise ◻ Develop new room temperature qubits and hybrid platforms ◻ Integrate w/established biological tools ◻ High throughput schemes ◻ Entangled sensors	◻ Image in-vivo molecular structures and conformational changes ◻ Probe cell processes with relevant spatial and temporal resolution
FUNDAMENTAL	◻ Improved gravitational wave detection ◻ Open quantum system dynamics	◻ Frequency dependent noise suppression ◻ Operational qubit-based dark matter detectors ◻ Higher-N entangled systems	◻ Extract interior information about g-wave sources ◻ Increase detection rate
NAVIGATION	◻ Atomic clocks ◻ Spin and atomic gyroscope demonstrations ◻ Magnetic field sensing	◻ Improve sensitivity and stability to competitive levels ◻ Devise new measurement techniques ◻ Design cSWaP driven devices	◻ Global GPS-free navigation ◻ Quantum gyroscopes and accelerometers in aerospace applications
MATERIALS SCIENCE	◻ NMR-inspired sensing techniques up to GHz ◻ Quantum scanning probe microscopes ◻ Demonstrations of electrometry, strain mapping	◻ Integrate sensor qubits into new material systems ◻ Develop qubits hosted in 2D materials ◻ Higher frequency sensing techniques ◻ Scalable manufacturing ◻ Feedback on materials growth for quantum devices	◻ Materials diagnostics tools ◻ Local measurement of exotic quantum phenomena ◻ Commercial quantum sensors beyond the NV center

Figure 13: This chart summarizes the necessary advances toward functional quantum sensing technologies. We frame these alongside the state of the art and the 15-year goals discussed in the text to show the progress that these advances will enable.

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