NSF Engineering Research
Visioning Alliance

Engineering Research to Advance Quantum Technologies

Visioning Event Report

Engineering Research to Advance Quantum Technologies

A visioning report of the Engineering Research Visioning Alliance

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THE UNIVERSITY OF ARIZONA

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The Engineering Research Visioning Alliance (ERVA) is a neutral convener that helps identify and develop bold and transformative new engineering research directions, directly supporting the nation's ability to compete in a rapidly changing global economy. Funded by the National Science Foundation (NSF) Directorate for Engineering, ERVA is an engaged partnership that enables an array of voices to impact national engineering research priorities. The initiative convenes, catalyzes, and empowers the engineering community to identify nascent opportunities and priorities for engineering-led innovative, high-impact, cross-domain research that addresses national, global, and societal needs. Learn more at ervacommunity.org.

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Glossary

AI	Artificial Intelligence
APD	Avalanche Photo Diode
CMOS	Complementary Metal Oxide Semiconductor
DA	Data Assimilation
DNN	Deep Neural Network
EBL	Electron Beam Lithography
FTQC	Fault Tolerant Quantum Computer
HPC	High-Performance Computing
LiDAR	Light Detection and Ranging
LLM	Large Language Model
LNA	Low Noise Amplifier
MIR	Mid Infra-Red
ML	Machine Learning
MRI	Magnetic Resonance Imaging
NISQ	Noisy Intermediate-Scale Quantum
NLP	Natural Language Processing
NLU	Natural Language Understanding
NMR	Nuclear Magnetic Resonance
ONN	Online Neural Network
PDE	Partial Discretization Equation
PET	Positron Emission Tomography
qDA	Quantum Data Assimilation
QEC	Quantum Error Correction
QIST	Quantum Information Science and Technology
QLA	Quantum Logic Array
QML	Quantum Machine Learning
QPU	Quantum Processing Units
qUQ	Quantum Uncertainty Quantification
SPAM	State Preparation and Measurement
SVM	Support Vector Machines
UV	Ultraviolet
VLSI	Very Large-Scale Integration

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ERVA visioning events enable the engineering research community to identify nascent opportunities and priorities for engineering-led, innovative, high-impact research that addresses global and societal needs. Each event relies on the efforts of organizations and individuals who volunteer to lead, guide, and participate in its activities.

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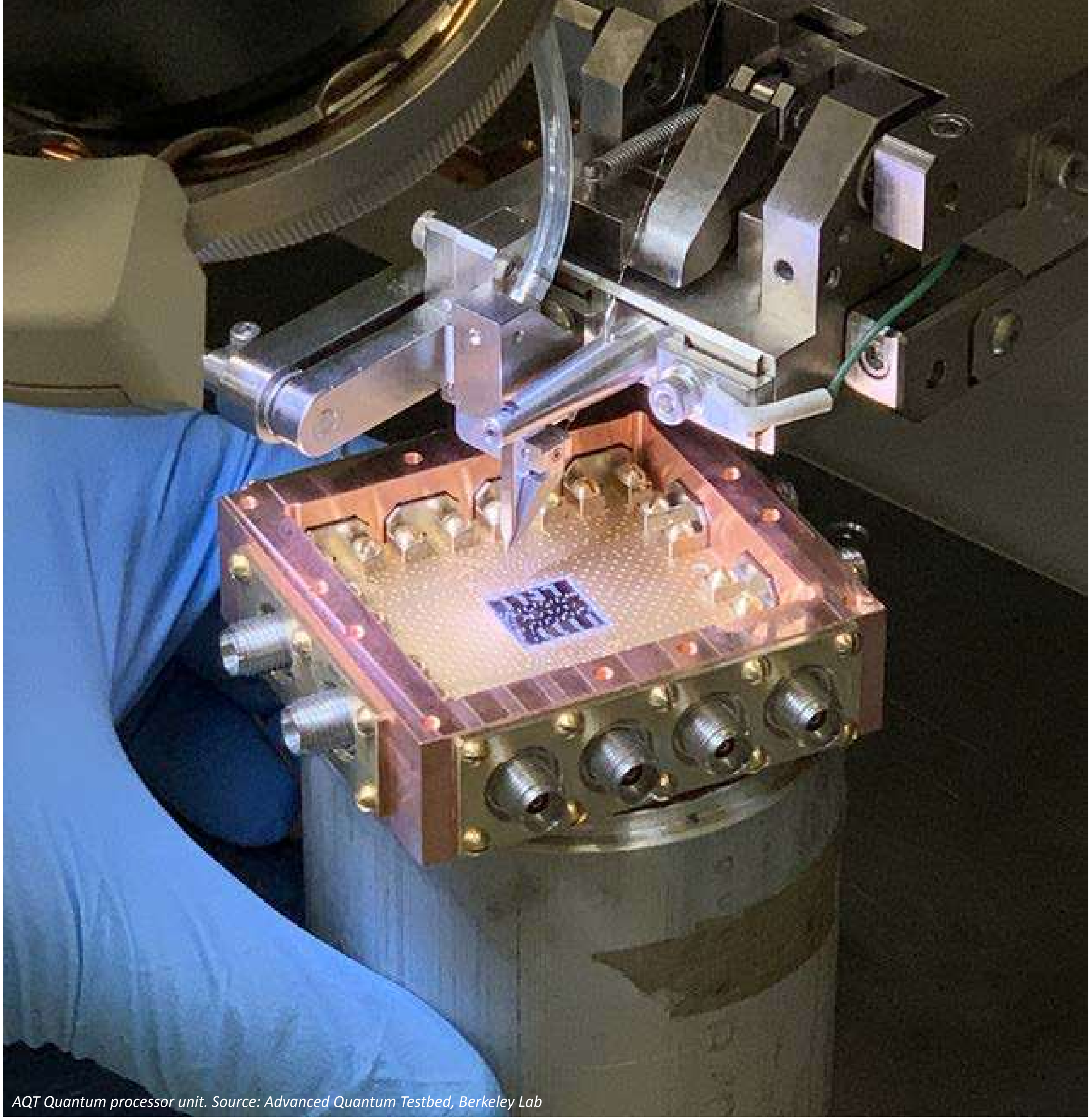
Rebecca Silveston, ERVA executive director, led the event planning, program development, and execution.
The event and report development were executed under the guidance of ERVA Principal Investigator Dorota Grejner-Brzezinska, University of Wisconsin-Madison, and ERVA co-principal investigators Anthony Boccanfuso, UIDP; Charles Johnson-Bey, Booz Allen Hamilton; Pramod Khargonekar, University of California, Irvine; and Edl Schamiloglu, University of New Mexico. Development of the visioning session theme was informed by input from the ERVA Standing Council, Advisory Board, and NSF Directorate for Engineering collaborators.



AQT Quantum processor unit. Source: Advanced Quantum Testbed, Berkeley Lab

Executive Summary

The United States has long been a leader in quantum research, but it faces increasing competition from other countries, particularly China and members of the European Union, as global interest in quantum information science and technology (QIST) and other quantum technologies intensifies. While the United States remains a dominant force in QIST research, with major universities, national laboratories, and technology companies making significant contributions, these efforts are not always as coordinated as those in China or Europe, where government funding and policy initiatives are more centrally planned. In recent years, China has made substantial investments in quantum technology, with the Chinese government prioritizing it as a key area of national development. The European Union has also made significant strides in quantum research through initiatives such as the European Quantum Flagship, which was launched in 2018 to boost Europe's leadership in quantum technologies.

To counteract U.S. fragmentation, the National Institute of Standards and Technology established the Quantum Economic Development Consortium (QED-C) in 2018. The QED-C's mission is "to enable and grow the quantum industry and its surrounding ecosystem," a challenge that has taken longer than the initial five-year timeline, in part due to difficulties in strengthening collaboration between academia, industry, and government initiatives.[1] Remaining challenges include overcoming technical problems, ensuring sustained funding, and competing globally for talent and resources. To enable the United States to maintain its leadership in quantum technologies, substantial investments must be made in the core research and engineering challenges that must be met to unlock quantum's full potential.

The United Nations proclaimed 2025 as the International Year of Quantum Science and Technology (IYQ), both to commemorate the centennial of the initial development of quantum mechanics and to increase public awareness of the importance of applications of quantum science.[2] The IYQ could advance the United States' quantum research agenda in meaningful ways, but its success will depend on alignment with the nation's goals. Increased attention to quantum computing could foster collaboration within and beyond the United States, motivate greater investment in research, and encourage talent development. Such results could increase interest in quantum, which currently lacks the engineering research resources required to enable scalable, practical, field-deployable quantum systems to achieve positive impact on society.

To address the complexities underlying the advancement of quantum research, the Engineering Research Visioning Alliance, an initiative funded by the U.S. National Science Foundation's Directorate for Engineering, convened an event at the University of Arizona on March 19-20, 2024. The Engineering Research to Advance Quantum Technologies event sought to create roadmaps for near- and long-term engineering research opportunities with the highest potential for positive societal impact.

The ERVA event focused on four thematic areas of intersection with QIST – materials, biology, computing, and artificial intelligence (AI) – bringing together transdisciplinary experts from areas including quantum information science, quantum computing, and technology-specific engineering communities, such as bioengineering, space science, photonics, quantum computing, and analog very large-scale integration. These four thematic areas emerged during the deliberations of the Thematic Task Force in advance of the ERVA event.

Strategic Engineering Research Priorities

For each of the four thematic areas, the workshop participants considered strategic engineering research priorities in three sub-areas. This report summarizes the discussions and the key engineering research priorities in each area.

Quantum and Materials

1. Materials engineering for quantum information processing
2. Materials engineering for quantum signal transduction
3. Materials engineering for optical and microwave photon generation and detection

Quantum and Biology

4. Quantum sensing and biology
5. Quantum for medical sensing and imaging
6. Quantum inspired by nature

Quantum and Computing

7. Qubit and processor development
8. Interconnects and components
9. Scalable cryogenic systems

Quantum and AI

10. Algorithms for noisy intermediate-scale quantum (NISQ) processors
11. Classical AI for quantum
12. Quantum intelligent sensors and networks

Building the Quantum Workforce

If the “quantum industry” is to become fully realized, it will require a quantum-literate and quantum-expert workforce. Maintaining U.S. leadership in quantum hinges on this critical factor.

The 2022 QIST Workforce Development Plan[3] outlines a national strategy to create just such a workforce. The report identifies four key actions.

- Develop and maintain an understanding of the workforce needs in the QIST ecosystem, with both short-term and long-term perspectives;
- Introduce broader audiences to QIST through public outreach and education materials;
- Address QIST-specific gaps in professional education and training opportunities; and
- Make careers in QIST and related fields more accessible and equitable.

Overcoming the current talent shortage will require developing deep technical expertise, but also equipping a broader range of professionals with a basic familiarity with quantum technologies—preparing them to build on current skills and transition into quantum roles as needed.

This plan reinforces the findings of the 2021 QED-C Workforce Technical Advisory Committee, which suggest that the types of job roles in the quantum industry are expected to remain stable over the next few years. This stability, combined with diversity in skill requirements, also mandates an approach that involves developing specialized quantum programs for those pursuing deep expertise as well as integrating broader quantum-related courses into conventional STEM and business curricula to capture a wider audience.
To realize the potential of the quantum revolution, the nation must invest in educating a new generation that is both quantum-aware and equipped with versatile, high-demand skills such as programming, basic research, and equipment manufacturing.[4]

Without immediate investment in education, workforce shortages could slow quantum innovation, economic growth, and national security advancements. The United States must build a cohesive strategy so it can cultivate an expert quantum workforce, particularly in quantum engineering—one that drives discovery, strengthens industries, and ensures global leadership in this critical field.

Key Engineering Research Priorities

Quantum and Materials

01 Materials Engineering for Quantum Information Processing

- Speeding up coherent processes and slowing down decoherence processes
- Improved control of surfaces, interfaces, and vacancies
- New paradigms for nanomanufacturing of quantum materials and devices
- Improved metrology for quantum materials and devices
- Identification of tractable research problems for materials platforms

02 Materials Engineering for Quantum Signal Transduction

- Bandwidth engineering and pulse shaping
- Development of computational software tools for quantum
- Novel systems for parametric nonlinear optical processes for microwave-to-optical conversion
- Novel materials for true topological photonic materials
- Development of agnostic transducers

03 Materials Engineering for Optical and Microwave Photon Generation and Detection

- Development of next-generation quantum materials and devices
- Materials characterization
- Transformational research in quantum materials
- Extending materials engineering for microwave photons to microwave phonons and magnons
- Cryogenic packaging of photonics
- Engineering a materials integration platform
- Exploring the strong interactions of phonons with other quantum systems
- Engineering for the maturation of quantum materials

Quantum and Biology

04 Quantum Sensing and Biology

- New materials for quantum sensing
- Use of AI and machine learning (ML) techniques
- Interaction of magnetic fields with biomacromolecules
- Control of chemical reactions
- Networked sensing for biological systems
- Detectors for ultra-high sensitivity measurements

05 Quantum for Medical Sensing and Imaging

- Quantum-enhanced diagnostics and therapeutics
- Bioimaging using quantum techniques
- Deep tissue imaging

06 Quantum Inspired by Nature

- Bio-inspired quantum applications
- Bio quantum tools
- Computational quantum models for biological systems

Quantum and Computing

07 Qubit and Processor Development

- System design approach and test bed for hardware and software frameworks
- Scalable manufacturing technology
- Benchmarking strategies consistent with practical use cases

08 Interconnects and Components

- Deterministic entanglement distribution and mode engineering
- Networked quantum processors
- Quantum computing architecture: algorithms, software, quantum error correction (QEC)

09 Scalable Cryogenic Systems

- Vacuum conditions for large-scale quantum processors
- Maintenance in a cryogenic environment
- Scalable qubit modalities and cryogenic packaging
- Digital twins for cryogenic systems

Quantum and AI

10 Algorithms for NISQ Processors

- Quantum data assimilation
- Quantum AI/ML algorithms with quantum versus classical data
- Quantum NISQ architecture, co-design, and software tools
- Suppressing and mitigating errors in quantum computing

11 Classical AI for Quantum

- Hybridizing ML algorithms for augmenting quantum-computing partial discretization equations
- AI-aided design of high-performance quantum computers
- Circuit synthesis and parameter optimization
- QEC and mitigation techniques

12 Quantum Intelligent Sensors and Networks

- Solution-adaptive methods for quantum real-time ML algorithms
- Algorithms for intelligent quantum sensor networks
- Sensor applications for networking
- Novel quantum ML compilations pursuant to native sensor information domain

The United States is well positioned to become a leader in QIST through international partnerships, but significant investments are needed to attain this leadership as we take technologies from the labs to the fabs to deliver quantum systems capable of solving the hardest problems we know today. With the right focus and investment, the nation can become the leader in the emerging quantum industry.

IBM Quantum Lab. Source: Connie Zhou for IBM

Taking Action

The United States is at a critical juncture in scaling quantum technologies, with a significant increase in current investment levels required to take technologies from the lab to the fab. For perspective, it is helpful to examine the lessons learned from scaling semiconductor technologies and infrastructure for insight into the appropriate level of commitment and investment needed to similarly scale quantum computing infrastructure. Decades ago, the United States had clear leadership in semiconductor technologies, but systemic under-investments in domestic fabrication and manufacturing resulted in significant vulnerability and lost ground to Asian competitors. Today's quantum technologies are where the semiconductor technologies were a few decades ago. Now is the time to make bold investments in taking quantum technologies to the marketplace. Success in moving from lab to fab will require a national strategy as well as strong relationships between academia, industry, national labs, and venture capital.

Real-world workforce considerations are also a factor in the nation's future quantum success. Quantum technology scaling requires assembling interdisciplinary teams, which may be drawn from trade schools, colleges, or industrial labs. Importantly, efforts to encourage public-private partnerships can take advantage of synergies between academic research and industry applications, thus increasing access to resources and expertise for innovative projects that align with national interests. The vast majority of the workers required to manufacture quantum systems at scale do not require knowledge of the complicated physics that describes quantum behavior; in terms of preparation, classical engineering training will go a long way. Workforce development programs must focus on bringing interdisciplinary teams together in partnerships that can play an important role in translational research activities, alongside appropriate changes to current funding and regulatory incentives.

The timing is right to encourage potential users of quantum computing to work with hardware manufacturers to innovate in the application space. Although some of the common use cases, like materials discovery and optimization in the financial sector, are commonly cited, there is ample room for innovation in leveraging the immense power of QIST.

Introduction

The United States emerged to become a leader in quantum research in the second half of the 20th century, but it faces increasing competition from other global powers, particularly China and the European Union. For the last century, American research institutions, national laboratories, and technology companies have contributed substantially to the field. Recognizing the strategic importance of quantum, the United States created the National Quantum Initiative Act (NQI) in 2018. In 2020, the U.S. Department of Energy (DOE) launched several programs under the NQI to fund quantum research across the country, particularly targeting the engineering challenges needed to scale quantum technologies. The NQI has spurred a significant increase in federal investment in quantum research, further reinforcing the United States' commitment to quantum.

Although the United States leads in certain areas, particularly in quantum computing and artificial intelligence (AI), other nations are rapidly closing the gap with aggressive investments and strategic priorities. China has invested heavily in quantum research and infrastructure, with a particular focus on quantum communication and quantum cryptography. In 2017, China launched the world's first quantum satellite, Micius, which is capable of transmitting quantum-encrypted communications over long distances, a key step in developing a quantum internet.[5] China's state-backed initiatives and funding have also led to significant progress in quantum computing, where Chinese researchers have demonstrated the ability to perform quantum simulations that outpace classical computers for certain specific tasks.[6] China is now a top contender in terms of quantum publications, patents, and technological breakthroughs, narrowing the gap in areas like quantum entanglement and quantum hardware development, and leading in other areas, such as dilution refrigerator technologies.[7]

Europe is also emerging as a strong competitor. The European Union has accelerated quantum research through its European Quantum Flagship Program, which launched in 2018 and aims to secure Europe's leadership in quantum technology by 2030.[8] The EU is investing approximately €1 billion into quantum technologies, focusing on collaboration between universities, research institutions, and the private sector.[9]

For the United States to be an important player in this increasingly competitive global quantum landscape, particularly in quantum communications and quantum cryptography, where China and the EU have made considerable progress, considerable investment is needed.[10] The United States must continue to prioritize both foundational research and the engineering research needed to make quantum technologies scalable and practical for real-world applications. Quantum information science and engineering touches many fields, as illustrated in Figure 1.

This report offers a roadmap for engineering research priorities in quantum-enabled technologies. It is not intended to be a comprehensive summary of the entire field, but rather a summary of four key research areas that were discussed in depth by the subject matter experts who attended the ERVA visioning event. While the discussion spanned several qubit technologies, the degree of emphasis on each technology reflects how the discussions unfolded. The report's first section, **Quantum and Materials**, brings to light key materials challenges that span several qubit technologies (including control of surfaces and interfaces, metrology, bandwidth engineering, pulse shaping, computational software tools, cryogenic packaging technologies, and engineering for maturation of quantum materials). The **Quantum and Biology** section is agnostic to the qubit technology, as is the last section, **Quantum and AI**. The **Quantum and Computing** section, however, details interconnects and components that are qubit technology specific, while topics covered under scalable systems are broadly applicable to multiple qubit technologies.

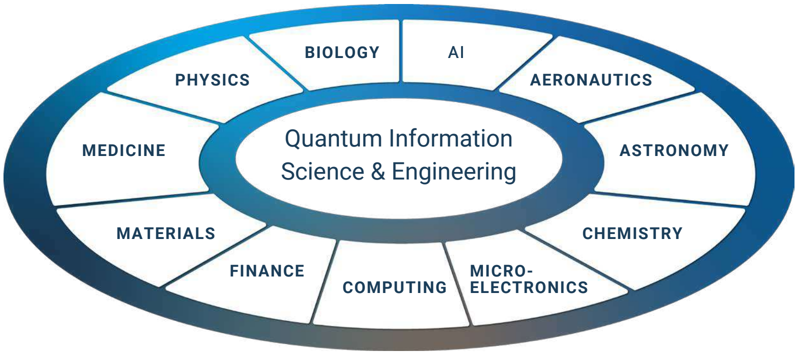


Figure 1: Fields adjacent to quantum information science and engineering.


Source: Vink Fan, Shutterstock

Quantum and Materials

Materials engineering for quantum applications involves designing and synthesizing materials with unique properties to build quantum devices and processors. Discussion at the ERVA event in this domain focused on materials engineering for optical and microwave photon generation and detection, quantum information processing, and quantum signal transduction. Within the larger discussion, the theme "Quantum Photonics for Broad-Range Applications" explored the potential for materials that can simultaneously support a wide array of quantum applications. A breakthrough set of materials could emerge, combining the best characteristics from different approaches. Participants emphasized the need to explore new materials with properties that are today impossible to create, along with efforts to refine and optimize existing platforms by developing prescribed effects in the most promising of those platforms.

This approach must be coupled with high-throughput materials characterization for quantum functionality, followed by additional theory and modeling. A key challenge is identifying the best upstream processes that can be performed to do this characterization in line and as fast as possible to enable more and faster discovery. To augment high-throughput techniques, a new entrant to this space is the use of AI techniques, specifically natural language processing and natural language understanding, to sift through and understand the millions of publications, patents, and materials science databases to offer scientists additional suggestions for synthesizing novel materials. Of course, AI tools and large language models (LLMs) are likely to play a central role in this discovery process, as they are increasingly leveraged to transform fundamental disciplines of engineering science.[11]

Given the complexity of these challenges, even the brainstorming phase requires funding to develop well-thought-out, compelling, and transformative research proposals.

#1 Materials Engineering for Quantum Information Processing

Materials engineering for quantum information processing addresses engineering challenges for matter-based qubit devices that process quantum information. The overarching challenges include:

- Improving the synthesis, characterization, fabrication, and manufacturing of quantum materials for constituent devices;
- Developing scalable ways for reproducing these methods;
- Ensuring the quality of the interfaces with these materials; and
- Enabling the purity and order by which materials are created.

Systems of interest include the materials basis for qubit technologies, such as trapped ions, photonics, semiconductor dots, superconducting transmons, and topological superconductors and insulators. Additionally, materials interfaces for measuring and detecting quantum states in these systems are of interest.

However, the materials must be analyzed systematically with all that surrounds the qubit. Coherence is not just the qubit; it is also the

- Full-state preparation and measurement (SPAM) process, including all control loops and physics, instrumentation, materials and devices, and packaging to do the SPAM in addition to the physical qubit;
- Architecture and the state preparation time (in the case of an ion, the loading, ionization, etc.);
- Lasers and coherence, and the coherence once the readout is attached to the qubit; and
- Noise in the control and probe fields.

Materials engineering for quantum information processing should focus on creating materials that help improve qubits. Better qubits mean more powerful and reliable quantum computing and quantum sensing. If qubits work more effectively, better quantum devices and processors can follow. Specific opportunities for high-impact research are as follows.

Speeding Up Coherent Processes and Slowing Down Decoherence Processes

A useful metric for closed quantum systems is the number of coherent operations that can occur before decoherence sets in. Addressing the problem of decoherence can follow two complementary strategies: one can increase the coherence time through improved material quality, environmental isolation, or quantum error correction, or alternatively shorten operation times so that they are much shorter than the system's decoherence time T_2.[12] In the latter case, processes become less susceptible to environmental noise simply because they complete faster than decoherence occurs.

One approach to fast optical processes relies on the Purcell effect, which enhances an emitter's spontaneous emission rate by engineering its photonic environment. For example, a bare semiconductor quantum dot typically has a radiative lifetime T_1 of about 1 ns. **By embedding the dot in a high-Q, low-mode-volume cavity, this lifetime can be shortened by one to two orders of magnitude**, reaching 10–20 ps in strongly Purcell-enhanced devices. Such reductions enable 50–100 GHz single-photon emission rates with photons that approach the lifetime-limited (transform-limited) regime, provided T_2 is sufficiently long. More advanced photonic and plasmonic designs have hinted at even faster emission, although pushing into the true THz regime would require unrealistically large Purcell factors and remains beyond current capabilities.

Thus, with Purcell-enhanced lifetimes of 10–20 ps, emitters can generate photons much faster than their typical coherence times (~1 ns), improving photon indistinguishability and making them less affected by dephasing during emission. Enhancements of 100–1,000× are routinely reported, and in extreme plasmonic nanogap structures (e.g., bowtie nanoantennas, nanopatch cavities, or nanoparticle-on-mirror geometries with ~2–15 nm gaps), apparent boosts of up to ~10,000× have been demonstrated, though often at the expense of quantum efficiency or coherence.[13]

The magnitude of this enhancement is described by the Purcell factor, which in its simplest scaling form is $Fp \approx {}^{Q}/_{V}$, where Q is the cavity quality factor and V the effective mode volume (normalized to $(\lambda/n)^3$. The full expression includes prefactors involving wavelength and refractive index, but the Q/V proportionality captures the essential dependence. [14, 15, 16]

This concept applies broadly to other quantum processes, such as photon detection, frequency conversion/transduction, and nonlinear gating—where accelerating system response can suppress decoherence. Although plasmonics often incurs non-radiative losses, advanced designs like dielectric–plasmonic hybrid nanoantennas or optimized nanopatch structures achieve high radiative quantum efficiency, ensuring emitters can radiate faster than they decohere and even faster than plasmon decay. In such setups, emission becomes both less lossy and more coherent.

Improved Control of Surfaces, Interfaces, and Vacancies

Single-atom defects control quantum properties. Control of surfaces, interfaces, and vacancies must be improved so as not to drown out the intended signal. New metrology approaches have chemical sensitivity, spatial resolution, or access to the needed energy range, but never all of these. This gap must be bridged by investing in **tool development specific to quantum interfaces and materials**.

New Paradigms for Nanomanufacturing of Quantum Materials and Devices

All scalable solid-state quantum platforms have their roots in mature nanofabrication techniques optimized for bulk-material processing—pioneered in industries generating roughly $1 trillion per year in revenue.[17] However, transitioning to solid-state quantum information systems shifts the emphasis away from bulk properties toward surfaces and interfaces, which often dominate noise, loss, and decoherence.

In this next era of quantum hardware, atomic-scale control over interfaces—such as metal–oxide, semiconductor–dielectric, or superconductor–substrate boundaries—becomes paramount. Defects, disorder, and contamination at these junctions typically *limit coherence* and gate fidelity in platforms ranging from superconducting qubits to spin-based quantum dots. Miniaturizing devices enhances sensitivity to such interfacial phenomena: now it's surface quality, not just bulk purity, that determines quantum performance. As a result, fabrication techniques like atomic layer deposition, atomic layer etching, and ultra-gentle reactive-ion or wet etching, which can polish and passivate interfaces, are becoming essential steps to improve qubit coherence and ensure scalable, high-fidelity operation.

We must seed the creation of a quantum ecosystem that allows for:

- **Creation of new quantum materials** with vastly different properties of interest than those now driving the state-of-the-art in nanoscience;
- **Processing of those materials into geometries that make them functional** in ways that are compatible with preserving their delicate quantum properties;
- **Construction of metrological and in-line characterization tools** that allow for the measurement of those quantum properties; and
- **Scaling versions** of these that can enable them to ultimately be practical for large-scale integration into QIST systems.

Improved Metrology for Quantum Materials and Devices

Most existing metrology tools were developed for bulk semiconductors and must be significantly adapted to probe individual quantum defects. Advancing these tools into scalable metrological systems is essential for conducting foundational studies in quantum materials.

While qubit performance metrics are generally well-characterized, the influence of the broader phase space on key qubit properties remains poorly understood. **Critical questions include the roles of structural defects, surface states, and the complex relationship between atomic-scale structure and device-relevant properties.** The impact of patterned surfaces and nanoscale surface complexity further complicates this picture. Identifying the atomic-scale factors that limit qubit performance—and developing strategies to mitigate them—is a central challenge.

Conventional metrology lacks the sensitivity and resolution necessary for quantum materials research. This limitation spans all focus areas, including quantum light generation, qubit platforms for quantum information science and technology (QIST), and quantum transduction. Bulk point defects typically occur at low concentrations, making them undetectable using standard techniques. In contrast, surface defect densities are often higher, and their effects are not yet well understood. Moreover, the stability and reliability of these materials under extreme operating conditions remain open questions.

Identification of Tractable Research Problems for Materials Platforms

A dedicated effort from the materials science community is required to determine what problems, such as purity and interfaces, are attackable for different materials platforms. This requires conversation with both the device and quantum communities to identify potentially fruitful pathways.

#2 Materials Engineering for Quantum Signal Transduction

Materials engineering for quantum signal transduction focuses on overcoming the material-related challenges involved in converting quantum signals across different domains. This includes both optical-to-optical and microwave-to-optical conversion. **Key objectives include conversion efficiency, preserving the fidelity of the quantum state during transduction, and achieving precise control over the frequencies and waveforms of both input and output modes.**

Topics discussed include the choice of materials or combination of materials that achieve optimal functionality in the different domains; challenges in achieving materials and process compatibility in these domains; noise considerations; and difficulties in co-design/simulation to optimize performance.

Systems of interest include nonlinear optical materials, atomic ensembles, opto-electromechanics, piezo-opto-mechanics, electro-optics, magnons, and quantum dots. This section outlines specific areas for high-impact engineering research on quantum signal transduction.

Bandwidth Engineering and Pulse Shaping

A post-transduction need exists for temporal-spectral mode matching. The challenge is different across the scales. Getting large and low-loss dispersion, especially over narrow bandwidths, requires a dedicated effort to identify or engineer systems of materials that meet these needs. Similarly, pulse shaping requires development, particularly for sufficiently slow pulses, so that time-domain shaping is easy and broad enough that frequency-domain shaping becomes easy. This can be accomplished on the source side or in the transducer by engineering the bandwidth and shape of the emission, but this similarly requires new dispersion engineering. This requirement is crucial to the idea of heterogeneous, interconnected quantum systems.

Development of Computational Software Tools for Quantum

Multiphysics simulation tools are needed for microwave-optical systems design, but a gap exists in the current ecosystem of software for simulations. The United States lacks an infrastructure for funding modeling software development, which increases reliance on proprietary software. A consortium of universities could assist in achieving this goal.

Novel Systems for Parametric Nonlinear Optical Processes for Microwave-to-Optical Conversion

For microwave-to-optical conversion, major issues exist with

- Microwave and optical modal overlap, and
- Small/complex structures with substantial charge and spin noise directly related to quality factors for both microwave and optical.

Parametric nonlinear optical processes for microwave-to-optical conversion have plateaued, presenting opportunities for novel systems. Most work, even on novel systems, occurs on more mature materials (i.e., rare earth oxides like yttrium orthovanadate), while novel materials research primarily takes place in Europe, Australia, and Japan (with some exceptions in the United States). Broader academic research in these processes should be conducted given that more obvious approaches have stalled.

Quantum Transduction without Parametric Nonlinearities

There is interest in using **atom-based systems for quantum transduction**, such as Rydberg states in cold atoms and rare-earth ensembles in solid-state. These systems do not require strong drive fields and, as a result, have some advantages. However, several challenges remain:

- The frequencies do not necessarily match superconducting qubit frequencies, so additional transduction is needed;
- Scaling of cold atom systems is required; and
- There is a lack of compatibility of such systems with superconducting microwave and integrated photonics platforms.

Novel Materials for True Topological Photonic Materials

Topological materials for electron transport are promising and offer opportunities for transport without backscattering losses. Photonic technologies would immensely benefit from a material platform with true topological protection, both for photon transport and for coupling between different chips.

Although topological photonics has been studied in dielectric materials using structures such as ring resonators, these types of structures only provide protection against a small subclass of losses and backscattering, which are not the dominant loss mechanism in current quantum photonic circuits. Research must move beyond these demonstrations toward material platforms that are truly topological with very low loss levels.

Such platforms call for the heterogeneous integration of materials with a true magnetic response, as opposed to emulations by dielectric structures. The solution would be particularly useful to minimize coupling losses between chips. This is a hard problem, as magnetic materials are often based on metals and complex metal oxides, which bring along inevitable losses.

Traditionally, the photonic community has been satisfied with coupling losses of a few dB at the interfaces. However, these losses are not compatible with the requirements of quantum photonics. The goal is to achieve topological photonic materials for broad application. This requires novel materials development.

This area has been underfunded due to the complexity of the problem, which requires heterogeneous integration of materials, such as magnetic materials with dielectrics. Achieving this integration will allow for low-loss interfaces between chips; it also has wide-ranging applicability to classical systems.

Development of Agnostic Transducers

Agnostic transducers are problematic due to the exceptional differences in scale of the qubit platform, ranging from millimeter to 100 nm (superconducting versus quantum dot spin). This directly affects the modal overlap. **A low-loss plasmonic way to concentrate the microwave mode to improve its overlap, which might enable an agnostic transducer, is needed.**

The other key element for agnostic transducers is isolation; without adequate isolators, it is hard to imagine an agnostic transducer due to different parameters/back action.

#3 Materials Engineering for Optical and Microwave Photon Generation and Detection

Materials engineering represents opportunities and challenges for generating and detecting quantum states of light in the optical and microwave domains. Systems of interest include

- **Color centers** in crystals;
- **Quantum dots**;
- **2D materials such as transition metal dichalcogenides for optical photons and superconducting qubits**;
- **2D materials such as graphene**; and
- **Josephson parametric amplifiers** for microwave photons.

Other relevant investigation opportunities are trapped ions and neutral atom systems for integrating photonic structures with these systems. In addition, discussion included materials challenges that limit photon coherence, photon number scaling, detection efficiency, number resolution, and other important metrics that impact their use in quantum information science and technology. Specific areas for high-impact research follow in this section.

Developing Next-Generation Quantum Materials and Devices

Predictive design, high-throughput characterization, and effective use of LLMs for discovering new materials are significant engineering challenges. Metrology tools with far greater sensitivity and in-line characterization tools are needed to evaluate materials processing steps at scale. Interdisciplinary collaboration is critical to advancing device technologies.

Materials Characterization

Novel approaches are needed to characterize quantum systems at relevant time and length scales. For example, single-atom doping in quantum dots, such as erbium-doped CeO_2 quantum dots, is currently impossible to identify using any structural or spectroscopic measurement approach.

Transformational Research in Quantum Materials

Typically, the scientists and engineers who work on materials, devices, characterization, and theory all work independently, which does not allow for the focused, large-scale efforts needed to create and discover fundamentally new materials. At the same time, existing materials do not tend to be used in transformative ways that enable new functionality. Experts must collaborate across domains for transformative discovery. The semiconductor industry offers valuable lessons here: after the transistor's discovery, early efforts were disjointed until the integrated circuit concept unified them, sparking interdisciplinary programs that accelerated circuit-scale development and led to Moore's Law. The quantum field is at a similar juncture, with companies now envisioning products with tens of thousands of qubits, much like the semiconductor growth roadmaps from past decades.

Extending Materials Engineering for Microwave Photons to Microwave Phonons and Magnons

The same questions being considered for generating microwave photons also apply to microwave phonons and magnons, which are the quanta of collective spin excitations in magnetic systems. These kinds of quantum materials have very different needs than those of superconducting microwave frequency photonic systems, such as transmons. Instead, the systems are exquisitely sensitive to much smaller-scale defects in lattices and surfaces, interactions with charge carriers, etc.

Cryogenic Packaging of Photonics

Cryogenic packaging of photonics is vital for many systems, whether just for the detectors or to couple to a microwave or optical qubit. Tuning sources in a cryogenic environment and making stable couplers requires considerable redevelopment in individual labs. The following are the key challenges in cryogenic packaging:

- **Low-loss coupling and efficient control:** Efficiently transferring light between optical fibers and on-chip photonic circuits at cryogenic temperatures is a major challenge.

- **Material compatibility:** Materials used in the packaging must be compatible with cryogenic conditions and not degrade or change their properties at low temperatures.
- **Hermetic sealing:** Creating a hermetically sealed package is crucial to prevent contamination and maintain the integrity of the cryogenic environment.
- **Thermal management:** Efficiently removing heat generated by the photonic devices is essential to maintain the desired cryogenic temperature.

Engineering a Materials Integration Platform

An important challenge is engineering a **materials integration platform** that can handle the arbitrary nature of atomic, molecular, and ion optical transitions from the ultraviolet to the mid-infrared spectra, as well as all the functions needed to implement full quantum optical systems on a chip.

The materials aspect includes the waveguide and passive component losses, the laser and optical gain, modulation and detection, and optical nonlinearities.

Exploring the Strong Interactions of Phonons with Other Quantum Systems

Many unexplored and important materials science and engineering opportunities exist in quantum phononic materials that leverage the strong interactions of phonons with other quantum systems. One example is the ongoing work on extremely dense and weakly interacting nuclear spin systems. These systems may contain novel couplings between phonons and nuclear spins that could be used in either direction to change the quantum properties of the spins or the phonons.

These types of opportunities for **engineering equilibrium and non-equilibrium states** of the baths for either of the spins or phonons may contain a tremendous amount of novel quantum many-body/condensed matter physics, as well as opportunities for engineering research in novel and technologically useful quantum materials.

Engineering for the Maturation of Quantum Materials

A large gap exists between the first discovery and the subsequent industrialization of a new technology. Bridging this gap requires both science and engineering phases.

Existing programs in proof-of-concept experiments and novel concepts are crucial, but they often lack a critical component: engineering-oriented research. This gap is particularly pronounced when it comes to improving reproducibility, increasing test throughput, ensuring compatibility with industrial-scale equipment, and identifying key performance metrics that can be used to validate device quality. The time from discovering a new material to its mass production often exceeds 10 years; examples from the field of computing include the transition from aluminum to copper for interconnecting transistors and the use of high dielectric constant materials--despite billions of dollars in investment from numerous semiconductor companies. The evolution of materials in the computing space underscores the need for substantial investment in the quantum space to solve materials challenges.

For example, determining an acceptable level of surface roughness for a given device performance is essential but often challenging. Without engineering-oriented explorations in place, it is difficult to transfer novel technology to the industrial setting, which tends to be increasingly conservative. Furthermore, this gap has become even more significant with reduced corporate R&D investments and materials-oriented venture capital funding over the years.

Perhaps as early as 2016, superconducting qubit fabrication was dismissively referred to as an “engineering problem.” In 2024, superconducting qubits are still fabricated using non-standard approaches that remain difficult to scale, such as electron-beam lithography and double-angle evaporation. There is little understanding of how to engineer superior barriers, and only recent efforts examine reducing resonator loss.

Nearly every research group in this area leverages the same small set of problematic fabrication methods. The engineering phase was far from over a decade ago, as it is far from over now. Similar issues persist in many other challenging quantum-oriented fields.

Source: iStock

Quantum and Biology

The origins of quantum in biology can be traced back to the 1920s through the 1940s, involving several quantum physicists.[18] In 1932, Niels Bohr gave his famous “Light and Life” lecture at a Copenhagen conference, connecting theoretical implications of quantum mechanics to the life sciences.[19] Also in the 1930s, German physicist Pascual Jordan published *Physics and the Secret of Organic Life*, asking if atomic and quantum physics laws were important for life.

In 1944, Erwin Schrödinger published *What is Life?*, which discussed the applications of quantum mechanics in biology. In the book, Schrödinger introduced the idea of an “aperiodic crystal” that could contain genetic information in its chemical bonds and suggested that mutations could be caused by “quantum leaps.”

Quantum biology is an emerging field that explores applications of quantum mechanics and theoretical chemistry to aspects of biology that cannot be accurately described or measured by the classical laws of physics.[20] The Quantum and Biology challenge area explored the dynamic interplay of how quantum-enabled technologies can be applied to elucidate biological and biomedical processes and how quantum processes in nature can inform the development of new technologies. Understanding fundamental quantum interactions in biological systems is essential to determine the properties of the next level of organization in biological systems.

Three topics were selected that are particularly promising for exploration and discussion: quantum sensing and biology, quantum for medical sensing/imaging, and quantum inspired by nature.

#4

Quantum Sensing and Biology

Quantum sensing leverages quantum coherence for biological applications, allowing for unprecedented sensitivity and spatial resolution in measurements, potentially revolutionizing fields like biomedical imaging and single-cell spectroscopy.[21,22] The development of quantum-enabled sensors represents a critical frontier in advancing various fields, from understanding basic biology to sensing contaminants and enhancing disease diagnostics. The current state of sensor technology often falls short of meeting the demands of these applications.

Traditional methods encounter challenges with sensitivity, resolution, and the complexity of strongly correlated systems, necessitating a paradigm shift toward quantum-enabled solutions. Quantum-enabled sensors promise unprecedented sensitivity and specificity for biosensing, revolutionizing fields from environmental monitoring to *in vitro* disease diagnostics.

Relevant quantum technology examples include nitrogen-vacancy centers in diamonds, trapped ion systems, and the use of squeezed light and entangled photons.[23] This challenge area focused on quantum sensing applications for *in vitro* methods and the interdisciplinary research needed to develop quantum-enabled technology tailored to understanding underlying biological changes and diagnostics toward precision medicine. This section describes specific areas for high-impact research.

New Materials for Quantum Sensing

Advances in biocompatible quantum materials are required to enable detection of weak biological signals with high temporal and spatial resolution in real time. Progress in this area remains limited because biological systems constitute wet, noisy, and thermally active environments. Quantum materials with high sensitivity are particularly susceptible to environmental coupling—through local electromagnetic, vibrational, and thermal interactions—which leads to rapid decoherence and loss of quantum signal fidelity. **Developing predictive computational frameworks capable of modeling molecular-scale interactions in such environments** will be critical for guiding material design and optimizing coherence performance in biological contexts.

Use of AI/ML Techniques

Connection with AI and ML techniques that can learn from noisy signals and sparse data to generate models that connect biological outputs, such as Fourier neural operators, is also necessary. The connection between mechanical processes such as turbulence and fracture is very well connected to data science, but connections to quantum biology are almost non-existent.

Interaction of Magnetic Fields with Biomacromolecules

Computational simulations are needed to understand how magnetic fields interact with individual biomacromolecules, which are hard to crystallize or characterize at small spatiotemporal scales. These would allow for rapid screening of potential proteins for experimental characterization. Few computational platforms have been developed specifically to look at magnetic field interactions with biomacromolecules.

Control of Chemical Reactions

Engineering research into **precise quantum control of chemical reactions** can pave the way to controlling cellular fates and therapeutics and better understanding of biological processes through analyzing input and output. Quantum control can be imposed by classical and quantum fields. One can consider connecting a noisy intermediate-scale quantum (NISQ) or mini quantum computer through a transduction device that enables strong coupling to a single biological molecule. Such a device could write the excitation in and read it out as the molecule interacts with the environment.

Networked Sensing for Biological Systems

In the near term, a classical network of sensors will offer greater resolution than a quantum sensor. In the long term, **entanglement-enhanced networks** can measure the spatial or temporal resolution of biological dynamics in a way that is impossible with individual sensors.[24]

Entangled states offer the ability for co-design to be well-paired with the biological signal to be studied. Entangled quantum networks allow for resources from quantum computation and error correction to pre-process the sample data that would be lost in classical post-processing.

In the far long term, heterogeneous entangled network systems could find correlations between different fields of the system.

Detectors for Ultra-High Sensitivity Measurements

Even ultra-weak signals can reveal critical biological insights—for example, early indicators of cancer or the biochemical effects of drugs. Monitoring nerve-to-muscle signal transduction could, for instance, expose early signs of neurological diseases like Parkinson's. Similarly, tracking the slight temperature changes during cell division may offer clues to cancer onset.

These signals—such as picotesla-level magnetic fields, microvolt electrical fields, subtle mechanical strains, or single-cell thermal shifts—carry valuable diagnostic information. However, detecting them requires sensors capable of measuring extremely weak, localized signals, e.g., cell temperatures or muscle magnetic fields, down to the picotesla range over time.[25]

- **Ultra-weak biomagnetic fields** 10^{-12}T from muscle, nerve, or cardiac activity can be detected non-invasively with room-temperature, solid-state sensors.
- **Single-cell thermometry** reveals minute thermal variations during division—potential indicators of cancer—using advanced quantum nanodiamond probes.
- **Combined sensing** of magnetic, electrical, temperature, and strain signals at single-cell resolution is essential for early diagnostics and understanding cellular processes.

To support such applications, we need **high-sensitivity, high-spatial-resolution tools** designed specifically to capture ultra-weak signals in real time across biological contexts.

#5

Quantum for Medical Sensing and Imaging

Medical sensing and imaging devices encounter unique challenges. These devices must be rapid, quantitative, reliable, and able to operate in complex biological environments.

Human imaging techniques have requirements for safety and biocompatibility and must be non-destructive and non- or minimally invasive. While many approved medical sensing and imaging systems are currently available, they lack the desired sensitivity and spatial and temporal resolution, and may suffer from long acquisition times.

Quantum techniques can enable sensing and multi-dimensional imaging with high sensitivity and high spatial and temporal resolution. Examples include quantum-enhanced magnetic resonance imaging (MRI), multimodal imaging, structured illumination techniques, and injectable emitters. For endoscopic imaging, structured illumination through multimode fibers allows for imaging through scattering media, while multimode-squeezed light improves resolution and tissue classification.

This challenge sub-area focused on the potential of quantum-enabled medical sensing and imaging technology in the demanding clinical space. Specific areas for high-impact research are described in this section.

Quantum-Enhanced Diagnostics and Therapeutics

A new generation of quantum biological tools is currently limited to *in vitro* research; that is, experiments performed outside living organisms, such as in cell cultures or lab-on-chip systems. Advances in engineering could soon move these technologies into *in vivo* settings, meaning within living organisms or clinical settings, marking a major leap from laboratory prototypes to real-world medical applications.[26]

Potential breakthroughs include:

- **Wearable quantum diagnostics:** Biodegradable skin patches that continuously measure physiological signals at molecular precision.
- **Implanted quantum sensors:** Biocompatible magnetometers and quantum probes embedded in tissues like the brain for real-time monitoring.
- **Non-optical sensing methods:** Detecting weak signals (e.g., heat, magnetic fields) deep within the body to enable technologies such as single-cell MRI and nano nuclear magnetic resonance.
- **Quantum-assisted drug delivery:** Combining techniques like encapsulation, toxicity monitoring, and targeting in live subjects.
- **Hybrid quantum–classical therapeutics:** Integrating quantum-triggered effects with modalities like ultrasound, magnetic fields, or X-rays for precise, non-toxic treatment.[27]

Bioimaging Using Quantum Techniques

A quantum imaging system uses paired photons to form microscopic images that are difficult or impossible to achieve via classical methods.[28,29,30,31] To take these systems further, a new discipline has recently emerged—quantum imaging. Several aspects of optical imaging techniques limit their biological applications, including shot noise, diffraction-limited resolution, phototoxicity, and temporal resolution. Simultaneous optimization of these parameters is a fundamental challenge in classical optics.

Relying on quantum properties may enable better optimization to overcome the classical limits in a way that traditional techniques, such as super-resolution, do not solve. Currently, most measurements are qualitative, whereas quantitative measurements are needed for many applications. Successful engineering research in quantum techniques could lead to:

- **Early disease detection,** including cancerous cell and viral particle detection with minimal invasivity; and
- **Quantitative imaging** for quantitative-enabled medicine.

Deep Tissue Imaging

Existing quantum-based imaging technologies, such as MRI, have low temporal and spatial resolution. Coupling structural and/or component imaging integration with existing techniques (such as MRI or positron emission tomography) for dimensional information will lead to reliable, early-stage diagnostics with superior performance.

Adding the capability of molecular imaging enables functional imaging, which is essential to study both health and disease. Theranostics (combined diagnostics and therapy to create customized treatment options for patients) is greatly enabled by deep and functional imaging. Traditional optical techniques for imaging the skin, eye, and endoscopically accessible tissues can benefit from quantum technologies that enable faster imaging and deeper penetration through highly scattering tissue.

#6

Quantum Inspired by Nature

While significant strides have been made in understanding how nature employs quantum phenomena, the current state of knowledge remains insufficient for fully unraveling the intricacies of these processes. Many questions linger regarding the precise mechanisms through which biological systems harness quantum coherence, entanglement, and superposition to perform remarkable tasks.

Moreover, translating these insights into practical applications poses numerous challenges, including scalability, control, and stability. Engineering research plays a crucial role in bridging this gap by leveraging our understanding of nature's quantum strategies to unlock the full potential of nature-inspired quantum technologies, paving the way for transformative advancements in science and technology.

This challenge sub-area explored how engineering research in nanotechnology, materials science, control theory, and AI can help design and optimize quantum-enabled devices and systems inspired by nature's ingenuity. Specific areas for high-impact research are described in this section.

Bio-Inspired Quantum Applications

Evidence for quantum phenomena in biology is increasing, but whether they play a key role in shaping biology remains controversial. However, utilizing the known effects to induce bio effects presents an opportunity for new bio-applications. The complexity inside a cell may provide many minute baths consisting of hydrophobic enclaves at the submicron scale instead of a large universal bath. These finite-sized baths would interact with and be changed by the biomolecules undergoing quantum reactions. **Understanding the role of these finite baths in nontrivial quantum phenomena in biology** could inspire new tool development and novel applications in quantum sensing and computing.

Bio Quantum Tools

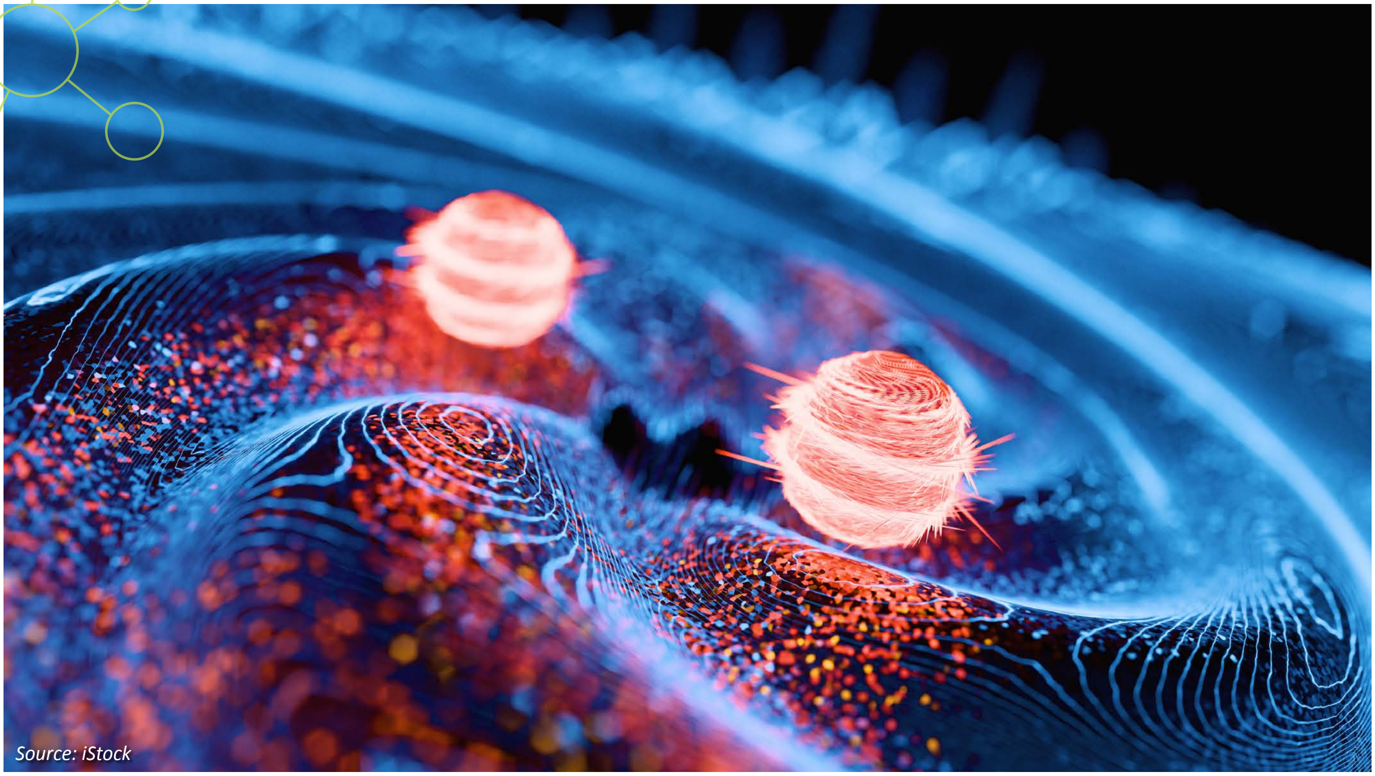
Leveraging recent advances in quantum-limited sensors and integrated control circuitry can significantly enhance the measurement of weak quantum signals in biological materials. **Integrating nitrogen-vacancy centers in diamond with complementary metal oxide semiconductor (CMOS) photonic circuits, avalanche photo diodes, and magnetic antennas** can achieve up to four orders of magnitude higher readout efficiency than traditional methods like confocal microscopy.

Additionally, exploring **silicon and silicon carbide vacancy centers** offers scalable alternatives with very large-scale integration fabrication. Innovations in silicon optomechanical crystals allow for single GHz phonon detection, which is crucial for quantum coherence in biological systems. Integrating single-photon detectors with these sensors can significantly improve signal-to-noise ratios, potentially transforming the detection of weak quantum signals. Combining these technologies with entangled sensor networks could enhance sensitivity further. **Advanced tools and biocompatible sensor materials** are needed to probe quantum dynamics in living cells, including those discussed using plasmonic cavities.

Computational Quantum Models for Biological Systems

Current quantum emulators and simulators focus on media and systems that are far from the biological paradigm. For example, multiscale and layered quantum-classical hybrid calculations are needed along the lines of the multi-physics simulation software COMSOL and similar products. Investigating and understanding the emergence of quantum coherence via superposition and entanglement at various time and spatial scales is an outstanding question in biology, with very few known or investigated examples.

Integration of AI and ML in a quantum bio software equivalent is an untouched topic, but will likely play an important role. Because classical computers cannot address many of today's open quantum system problems, and certainly not those with the addition of multiscale aspects, two kinds of toolsets are required: one run on classical computers (simulations) and the other run on quantum hardware (emulators).


Source: iStock

Quantum and Computing

Quantum and computing are immensely broad topics undergoing rapid progress because of tremendous government and private investment. When the performance, scale, and cost of quantum computing reach a critical threshold, often referred to as practical quantum advantage, this technology is expected to change the computing landscape. Hybrid systems of classical and quantum will then be able to address problems currently unsolvable by classical approaches (see Figure 2).

While many avenues of research and development are required to bring production-level quantum computing into the mainstream, for this challenge sub-area participants focused on three of the most challenging ones: qubit and processor development, interconnects and components, and scalable cryogenic systems.

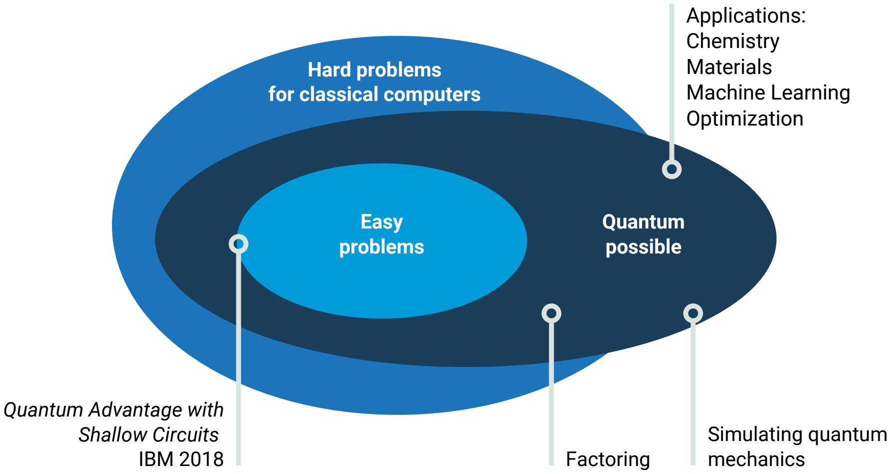


Figure 2, Potential for quantum computing, illustrated by the types of problems solvable and unsolvable by classical approaches and a set only solvable by quantum or hybrid classical and quantum approaches. Source: Quantum Algorithm Zoo. (quantumalgorithmzoo.org).

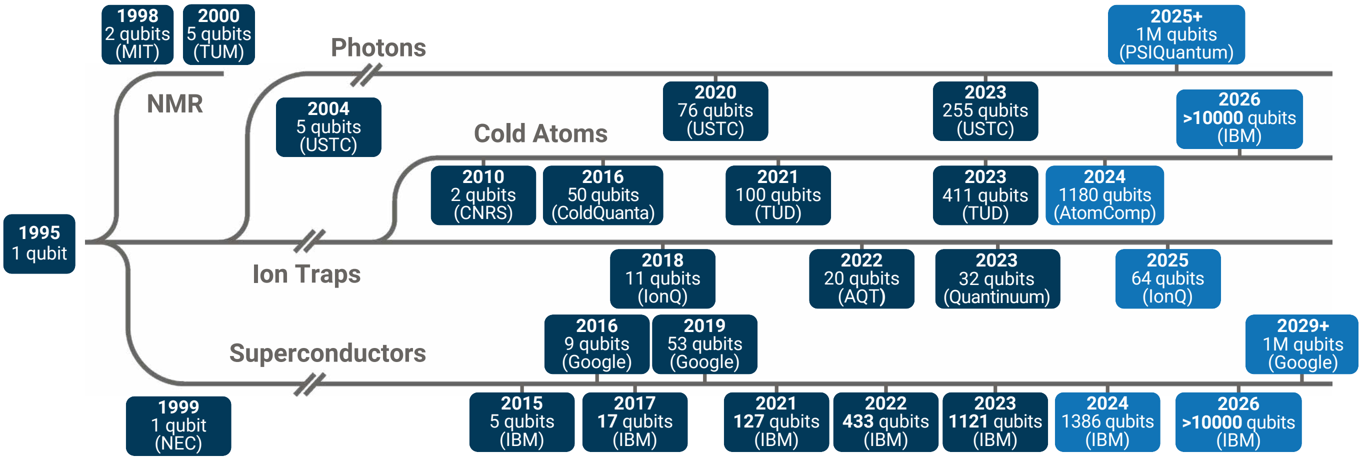
#7

Qubit and Processor Development

Achieving quantum advantage will require high-performance and scalable quantum devices/processors with modalities including trapped ions, photons, quantum dots, neutral atoms, superconducting transmons, and others. It will also require associated control electronics, taming error correction, and developing the necessary hardware and software capable of running target applications on these large systems. Figure 3 depicts a scaling roadmap for several of the many modalities of qubits through about 2026. An unstated dependency for some quantum computing modalities is that the field of cryo-engineering must grow and evolve to support these coming needs.

The software that underlies the applications and operation of such large systems is in its infancy and must grow concurrently. Today, quantum software is more nascent than mainstream, but there are already significant high-performance computing software and AI communities that could be tapped to accelerate development efforts for quantum.

This sub-area explored several of the major challenges in developing quantum devices, their control electronics, and software needed to achieve scale. It describes specific areas for high-impact research.



- AtomComp = Atom Computing
- AQT = Alpine Quantum Technologies
- ColdQuanta = Now known as Infleqtion
- CNRS = Centre National de la Recherche Scientifique
- Google = Google Sycamore Processor
- IBM = International Business Machines Corp.
- IonQ = IonQ, Inc.
- MIT = Massachusetts Institute of Technology

- NEC = NEC Corporation of America
- PSIQuantum = PsiQuantum
- Quantinuum = Quantinuum
- QuEra = QuEra Computing
- TUM = Technical University of Munich
- TUD = Technical University of Darmstadt
- USTC = University of Science and Technology of China

Figure 3 illustrates the advances in quantum computing in terms of qubits and near-term projections of capabilities. Although the number of qubits alone is not sufficient to judge the capabilities of a quantum computer, many research developments have greatly increased how many qubits can be hosted in one. With enough high-quality qubits, researchers could work toward developing a universal quantum computer that could handle many more computations than a classical computer can. (Source: Klaus Liegener, Oliver Morsch, Guido Pupillo; Solving quantum chemistry problems on quantum computers. Physics Today 1 September 2024; 77 (9): 34–42. Used with permission.)

System Design Approach and Test Bed for Hardware and Software Frameworks

Quantum software is becoming too complex to manage low-level hardware details during application development. Instead, developers need a human-readable, device-independent layer—much like the way traditional programming languages hide machine code from developers. This abstraction lets developers express quantum algorithms clearly, while optimizing compilers automatically handle mapping onto hardware, scheduling, and calibration. Frameworks like the Quantum Hardware Abstraction Layer and language-agnostic tools (e.g., Qrisp, XACC) are designed precisely for this purpose.[32]

We need a **zero-overhead, multilayer abstraction stack** that cleanly separates each stage of quantum software, e.g.:
- **Control pulses** for the analog hardware;
- **Register allocation** on physical qubits;
- **QEC** to build logical qubits;
- **Logical register management**; and
- **Application-level code** with formal correctness guarantees.

At each layer, we need:
- **Design-rule checks** to catch misuse early;
- **Co-design/optimization** between layers (for speed, error handling, resources); and
- **Visualization/debug tools** to help engineers understand the system's correctness and performance.

This area would significantly benefit from a new approach and structure that mirrors classic compiler and OS design—modular, efficient, portable, and essential for scaling quantum software development.

Scalable Manufacturing Technology

There are many modalities of quantum computing today. None of the approaches currently has a path to scalable manufacturing technologies that will reduce the cost per qubit as the manufacturing volume grows, both increasing exponentially.

The key technology enablers, akin to integrated circuits technology for CMOS for classical digital computers, will depend on the specific qubit platform. However, common technology areas include innovations in integrated optics, microwave engineering, cryogenics, microfabrication (including lithography and etching technologies), and software engineering. The manufacturing processes developed must enable the full system-scale integration of quantum computers.

Benchmarking Strategies Consistent with Practical Use Cases

Developing "realistic" use cases from impactful applications is essential. Quantum chemistry problems and solutions are an important application area. Performing end-to-end scalability assessment of use cases is necessary, working backward from high-value applications to quantum processing units (QPUs) and systems.

The use cases could be application-specific, and the architecture could be specially built for the specific application. This can lead to grand challenge problems that demonstrate capabilities and advantages. Applications that demonstrate the feasibility and the practical benefits of quantum computers are rare.

Direct funding for quantum application development is scarce. Near- to mid-term value must be demonstrated to make this area attractive for industry funding.

#8 Interconnects and Components

The cryostats today hold thousands of qubits that need to be interfaced to and from room temperature subsystems. This implies top-to-bottom refrigerator wiring for input and output signaling that has excellent low loss, high-speed electrical properties, as well as high thermal resistance to mitigate heat transfer between cooling stages. Future requirements are that they occupy minimal volume and have a density that is high enough to enable much larger refrigerator payloads in terms of numbers of qubits and QPUs.

Today's systems lack novel high-density interconnect subsystems. Significant R&D is needed to develop interconnects that achieve high reliability and can interface with processors of many modalities. These interconnects must link subsystems and cryogenic systems together.

Other essential elements of quantum systems include isolators, quantum logic arrays, and low-noise amplifiers. While some devices exist, there is a critical need for miniaturized high-performance isolators and amplifiers. Specific areas for high-impact engineering research are described in this section.

Deterministic Entanglement Distribution and Mode Engineering

Advancing distributed entanglement is essential to scale quantum computing advances. The major limitation of the current communications network is probabilistic entanglement generation. Scalable entanglement creation requires addressing engineering challenges, including:

- **Scalable, strong interaction between stationary qubits and flying qubits**;
- **Seamless mode engineering** (transduction) for developing an interface between different or similar quantum processors;
- **Heterogeneous integration of quantum materials** for quantum interconnect; and
- **Interconnection of hybrid disparate platforms** connecting nodes of a "smaller" (1,000-5,000) number of qubits.

Networked Quantum Processors

Quantum network links have only been demonstrated in isolation, connecting individual qubits. Efforts are underway to scale this to multi-node networks.

However, no facility provides two or more networked quantum processors with multi-qubit and high-fidelity local operations on a standing link that includes the necessary transduction, synchronization, repeaters, and other technology. Such a facility is needed for external researchers to access networked application/protocol development on a physical networked quantum system. This will help researchers discover areas for improvement of systems and protocols and reveal new applications.

This effort does not focus on the number of nodes and the distances covered. Instead, it focuses on having functional processors connected. It aims for a standing link with open access similar to current standalone quantum processors. An **in-use quantum network** will inspire and propel hardware application co-development/design in quantum networking.

Quantum Computing Architecture: Algorithms, Software, QEC

Large-scale, fault-tolerant quantum computers are likely to be modular. However, there is little research work underway on the implications of such architectures for algorithms, software, and QEC. For example, what are the threshold metrics for interconnections for QEC in a modular architecture for fidelity and efficiency? With current QEC codes, one needs thousands or tens of thousands of physical qubits per logical qubit. Research is also needed to understand the implications of having a logical qubit spread over multiple QPU modules. Early work has directly addressed this, but the focus is on error-corrected, logical qubit counts rather than physical qubits.[33]

Algorithms must be developed that can handle the modular architecture in a way that does not degrade the performance of the quantum system or the transitions between different quantum computing models or architectures.

A full stack that accounts for the device's physical capabilities and constraints and informs the algorithm's distribution is essential. Additionally, a large-scale distributed quantum computing system may need to be quantum-hybrid, using different modalities for different components, such as the QPU, memory, and networking.

#9

Scalable Cryogenic Systems

While commercial cryogenic systems exist for experimental use, **high thermal capacity, interconnectable, vibration-isolated, low-cost, low-power systems** do not yet exist for large-scale systems. They will be required to enable large, powerful systems able to address meaningful problems.

Depending upon the qubit processor implementation, whether at 4K for trapped ions or milli K for superconducting qubits, various limitations must be addressed. For example, a single dilution refrigerator might only support thousands of qubits due to thermal capacity and volumetric limitations, yet tens of thousands to hundreds of thousands of qubits will be required to address meaningful problems.

Trapped ion systems encounter problems at scale due to background gas collisions. Vacuum technology, cryogenic or otherwise, will be necessary to improve vacuum conditions while allowing optical and electrical integration via optical access and ultra-high vacuum with pressures 10^{-12}T. (Note that atmospheric pressure at standard temperature and sea level is 760 Torr.)

To address the scale of hundreds of thousands or millions of qubits, new modalities are needed to manage systems’ reliability, availability, and serviceability. Monitoring and identification of failures happening inside the refrigerator are also essential. Specific areas for high-impact engineering research are described in this section.

Vacuum Conditions for Large-Scale Trapped-Ion Quantum Processors

The prevailing view is that **ion trap systems must be integrated with traditional cryostats to achieve the necessary vacuum conditions.**[34] **Additionally, they need to be optically integrated via fiber connections and on-chip optics or microphotonics**. No unified strategy exists to integrate both of these scaling prerequisites or to find alternatives to generate the necessary vacuum conditions via new vacuum chamber designs, materials, pumps, etc.

IBM quantum dilution refrigerator. Source: IBM

Maintenance in a Cryogenic Environment

New modalities are required to manage the reliability, availability, and serviceability of systems to address the scale of hundreds of thousands or millions of qubits, when less than approximately 10,000 fit inside a single refrigerator or unit cell. This implies that **unit cell refrigerators on the order of 10,000 qubits** will need to be cascaded to achieve large-scale systems. For example, 10-unit cells can be used to make 100,000 qubit systems.

The ability to maintain electronics and support cryogenic infrastructure is paramount. When workloads might be required to run for weeks or months, single or even multiple component failures need to be managed. To enable computation to continue with minimal interruption may require storing the state of a set of unit cells while it is taken offline for maintenance or repair and re-cool, or the use of redundancy to route around a down unit cell (as is done in today's classical mainframes).

Thus, monitoring and identifying failures inside the refrigerator and working around these is critical. If larger refrigerators are built, robotic or other automated means may be needed to swap failed components or replace loads while also enabling the computation to continue. Research opportunities include **failure detection systems and technologies, quantum memory to store existing states of unit cells during repair or maintenance, and automated replacement of failed components within the cryogenic environment**.

Scalable Qubit Modalities and Cryogenic Packaging

Even before the cryogenic operation, challenges exist with the package assembly due to complicated and sensitive connectors and cables that cannot be automated today.

The following must be developed to make significant advances:
- **Predictive and improved models for existing superconducting qubits**;
- **New superconducting qubits**, such as Bosonic systems, that have a smaller footprint are easy to manufacture in a scalable way and require less classical error correction;
- **New packaging systems for QPUs** that enable easy replacement of chips with 1mm+ qubits (1 million+ qubits, such as Microsoft's Majorana 1 architecture or like classical superconducting CMOS control chips within a cryostat); and
- **New cooling techniques that rely less on helium-3**, such as recent developments on helium-4 cryogenic systems.[35]

These developments are critical because making chips with high yields requires complex fabrication. It will be necessary to upskill fabrication workers and machines to work with novel materials.

This requires investment in developing **low-temperature superconducting CMOS control systems that need fewer connectors to room-temperature systems and are plug-and-play for QPUs**. In addition, today's manufacturers focus exclusively on known technologies. Investment is needed in academic engineering to develop scalable systems that rely on other technologies.

Digital Twins for Cryogenic Systems

Building and testing devices in cryogenic environments is costly. A **high-fidelity multi-physics simulation tool or digital twin** must be developed to lower the barrier to research and development and shorten design feedback loops.

The inherent engineering challenge is that many cryogenic subsystems have never been thoroughly characterized. The digital twin could enable research for mechanical engineering considerations (thermal expansion, out-gassing, etc.), coupling properties (light leaks in couplers leading to decoherence, hot spots due to classical control), and quantum properties (phonon coupling, etc.). This kind of tooling will also enable "cryo-less" R&D, similar to today's fabless manufacturing.

Such a digital twin could serve both industry and academic labs in a cryo-as-a-service model, leveraging open-source standards, design rules, and guidelines for fair use.

Source: Canva

Quantum and AI

Quantum computing and AI are two of the most transformative technologies of this century. Although distinct, their intersection promises to redefine problem-solving capabilities across various disparate domains. The convergence of quantum computing and AI holds transformative potential. Quantum computing could significantly accelerate AI by optimizing complex algorithms and processing vast datasets more efficiently. For instance, quantum algorithms might enhance AI models, leading to more accurate predictions and faster training times.

Conversely, AI can aid quantum computing by improving quantum algorithm design and error correction methods. AI techniques can help identify and mitigate errors in quantum computations, which is a significant challenge in current quantum hardware.

#10 Algorithms for NISQ Processors

This challenge sub-area explored quantum algorithms that can be run on near-term quantum processors, such as sampling problems, quantum optimization algorithms, and quantum annealers. It includes other NISQ primitives, such as algorithmic accelerators in otherwise classical AI/ML algorithms, leading to hybrid quantum-classical special-purpose processors. Applications include image classification, graphical inference problems, graph similarity, and variational eigensolvers for energy-minimization problems.

The traditional approach to handling errors in quantum computing is the framework of fault-tolerant quantum computers based on error correction. Recent progress has expanded that view dramatically so that many errors can effectively be suppressed or mitigated without adopting QEC using control or circuit design innovations.

There are many research opportunities for exploring approaches to manage the negative impact of errors in quantum processors on the target applications of interest in the context of specific hardware. Specific areas for high-impact research are described in this section.

Quantum Data Assimilation

Quantum data assimilation (qDA) has the potential to make an immediate and notable impact on quantum uncertainty quantification, aiming at improved accuracy in quantifying the errors in the system of “AI algorithms + NISQ processors.” **Physics-driven and data-driven models and algorithms** must be developed that target understanding errors in terms of their sources, magnitudes, space-time evolution/coupling, nonlinear interactions, frequency, and residence, etc. While error correction and mitigation methods are important, separating errors and understanding their impact is more meaningful. Error correction may provide an answer that appears “correct” if a “correct” answer is known. However, assessing the impact of errors can increase confidence in the final answer.

Assimilation of quantum data/information from advanced quantum measurements and sensors is critical. New data, including their types, formats, and volumes, from new quantum sensors may be available or in development in many science, technology, engineering, and mathematics (STEM) fields. Data assimilation algorithms will need to adapt from classical high-performance computing to quantum computing.

qDA shares many foundational theories with AI/ML, such as control theory, information theory, and mathematical and statistical theories, but in some sense, qDA is more physics-driven AI/ML than math-driven. Another perspective is assimilating error information into the system instead of or in addition to the data itself. Adding “perturbation” helps understand the generation, propagation, interaction, and transmission of errors. The approach of adding perturbation is self-consistent in physics and compatible in mathematics.

Quantum ML/AI Algorithms with Quantum versus Classical Data

Classical data sets may be stored for a long time, so most quantum data sets start from classical data sets. The advantages that **data models in the quantum domain** provide are an area for engineering research to explore. Collecting quantum data directly and feeding it into a quantum processor could change the landscape significantly. The impact of shallow or short-lived quantum actions on quantum-domain data is an area ripe for thorough investigation, and identifying the challenges in implementing this approach is essential. A concerted research agenda is needed to identify and develop the infrastructure necessary for designing a new AI framework around quantum processors.

Use cases in two domains, materials science and biology, were identified for ML/AI algorithms using quantum data. For materials, quantum AI-driven processing could be leveraged for simulations and discovery, such as molecular spin qubits with excellent decoherence properties and desired emission properties. In biology, NISQ processors could be used to discover hard-to-classically-simulate protein structures, an approach that, in turn, could lend itself to quantum-enhanced drug discovery.

Quantum NISQ Architecture, Co-design, and Software Tools

Engineering research is needed to develop **a software stack that enables developers to write algorithms in a high-level, input-size-independent, architecture-independent manner** and automatically compile and optimize them to different kinds of quantum computers. The software stack should be end-to-end and modular, with design input from all stakeholders. Engineering research is also needed to create **error-resilient algorithms** that can run on NISQ architectures. Participants noted that an open-source software ecosystem that diversifies and democratizes the use of quantum computing could contribute to rapid advancement across a range of R&D efforts.

Suppressing and Mitigating Errors in Quantum Computing

Many errors can effectively be suppressed or mitigated without adopting QEC using control or circuit design innovations.[36] There is large, unexplored research potential for various **approaches to manage the negative impact of errors in quantum processors** on the target applications of interest in the context of specific hardware.[37]

Engineering research is needed into **techniques for analyzing an algorithm at the abstract, circuit, and physical levels**. The resulting knowledge will inform the ability to determine which parts are more sensitive to noise. Appropriately tailoring the degree of error mitigation, suppression, and correction can then be explored.

#11

Classical AI for Quantum

A considerable opportunity exists for leveraging classical ML and AI to accelerate the development of better, cheaper, or more powerful quantum processors, including quantum architectures, quantum codes, bosonic quantum circuits for hard-to-produce quantum states, and characterization of quantum states. It remains an open question whether additional computational capability that quantum computing brings to the table can be utilized to develop a new class of AI algorithms and methods that surpass classical AI capabilities for various practical use cases. Specific areas for high-impact engineering research in classical ML and AI for quantum are considered in this section.

Hybridizing ML Algorithms for Augmenting Quantum Computing Partial Discretization Equations

This engineering research topic addresses the application layer of the full software stack. The key is to discretize partial discretization equations (PDEs) on multilevel space-time neural networks. Multilevel space-time neural networks can be viewed as a substitute for the discrete grids used in traditional numerical solutions of PDEs. These multilevel networks are hierarchical and in the space-time domain. ML algorithms can then be integrated into the solution process for PDEs on quantum computers or simulators.

The potential for this approach becomes obvious when neural networks are seen as analogous to the traditional multigrid in both space and time. **Mapping the space-time multigrid-type neural networks to quantum algorithms** is the nascent aspect of this research direction.

AI-Aided Design of High-performance Quantum Computers

For large-scale, high-performance quantum computers, the performance of the qubit systems must reach exponentially diminishing error levels, eventually checked by the fundamental limits of a given system, not the classical control. This requires **improvements in the design of the qubit substrate, control systems, and system architectures**.

The engineering process for implementing such solutions requires constant system characterization, and quantum measurements are expensive. New AI-aided approaches can be developed to make this process much more efficient and cost-effective, speeding up the iterations within the engineering design process. This approach could be extended to optimize non-performance aspects of quantum computer design, such as cost, manufacturability, reliability, and deployability within the operating environment.

Circuit Synthesis and Parameter Optimization

Quantum computers are scaling to hundreds of qubits and are on track to grow several orders of magnitude larger. Many are already too intractable to simulate. Classical AI's role is critical at this stage of development because many tools do not scale. For example, brute force methods in the quantum software development toolchain may work for a few dozen qubits but become unusable for hundreds if the algorithms have quadratic complexity. The engineering research opportunities in this area include:

- **Using AI tools to find smaller and approximate circuits**, respecting and taking advantage of the qubit connectivity within the hardware.
- **Synthesizing circuits for bosonic systems**.
- **Designing approximate quantum-enhanced receivers** for optical communications, sensing, target discrimination, and super-resolution imaging by using, for example, AI-inspired optimization of diffractive neural networks.
- **Developing AI tools for optimizing hardware-aware compilation** based on the availability of "gates" (e.g., motional degrees of freedom in ions, dipolar interactions in Rydberg arrays, and amount of squeezing for photonic quantum computers). This would be enhanced by community-accepted standardization of hardware descriptions.
- **Creating better debugging tools** for quantum circuit compilation.

QEC and Mitigation Techniques

For QEC, there are known families of codes and code modification techniques to change their parameters. The search space is too large to evaluate all codes exhaustively. **AI could be leveraged to generate and modify codes for a given cost that could be automatically evaluated.**

Codes also have "gadgets" (the actual term of art) that perform fault-tolerant non-Clifford logical operations. These are small circuits, and potentially additional qubits connected to the code, that execute a particular operation, ideally in a fault-tolerant fashion. Gadgets are currently hand-designed on a per-code basis without a standard overarching theory behind them, but they can be numerically evaluated for correctness, fault tolerance, and depth. **Generative AI could be trained on known gadgets using known codes to find new gadgets.**

In annealing-based quantum computation, error mitigation methods can be applied during problem formulation and embedding. Current proposals involve repetition codes, but other strategies are possible. For current applications, hardware performance is generally considered adequate. However, effective strategies have so far only been applied manually in isolated cases; automating this process will become important as problem sizes increase.

The goal of this research is to be able to describe any generic error-correcting method (including non-well-defined code) and the operations on that code. **Engineering research is needed to evaluate its efficacy, train generative AI to create new codes, and develop tools to evaluate the codes automatically.**

#12

Quantum Intelligent Sensors and Networks

This challenge sub-area explored pushing classical-inspired ML computations (such as support vector machines, deep neural networks, online neural networks, and image data classification algorithms) into the quantum domain. Techniques could involve information-bearing photonic or magnetic fields to allow for quantum processing on the information-bearing field in the context of optical sensing, magnetometry, optomechanical sensors, spectroscopy, and other technology.

These techniques are currently impossible in the post-detection electronic domain (after the noise) but can result in higher-efficacy classification and inferences on optically encoded information. Applications may be possible for light detection and ranging, imaging, hyperspectral imaging, telescopes, space domain awareness, microscopy, and other areas. Specific areas for high-impact engineering research in quantum intelligent sensors and networks are considered in this section.

Solution-Adaptive Methods for Quantum Real-time ML Algorithms

Real-time quantum data sensing and acquisition for correcting trajectories or simulations are essential to many applications, such as subsurface applications (e.g., computational acoustic wave imaging for carbon sequestration) and space exploration.

Although quantum sensors provide measurements with extreme accuracy and efficiency, sensing and acquiring data selectively at necessary locations and rates is still ideal. ML algorithms can then operate on lean data in near real time, guiding new measurements adaptively directed by solution.

Systems are often large, complex, and nonlinear. Since the solutions sought are unknown, applying solution-adaptive methods for quantum real-time ML applications poses a challenge. Developing solution-based criteria to guide the ML and quantum sensing in near real time is essential. This research is needed by applications requiring that ML work with lean data, wherein the ML result is immediately applied to guide the next-step sensing in near real time and under extreme environments.

Algorithms for Intelligent Quantum Sensor Networks

Quantum AI algorithms for intelligent sensor networks are considered very promising because of the great initial promise shown by quantum sensor networks themselves. Intelligent quantum sensor networks leverage quantum sensors and AI algorithms for enhanced sensing capabilities, enabling applications in various fields like health care, transportation, and security by detecting minute changes in physical phenomena.[38,39]

Engineering research is required to **develop algorithms to exploit the enormous bounty of data returned by quantum sensors**, which are often discarded in current scenarios. Conventional AI methods can inspire and be adapted to integrate data collection and data analysis on quantum data from sensor networks.

Components of this type of system must be designed from scratch. In the near term, promising opportunities for developing efficient and effective subprocesses and components can be identified. To accomplish this, engineering research is needed to create **new methods for integrating quantum computing with quantum sensors**, such as adding quantum input and output capabilities to the computational component.

Novel hybrid approaches are also required, such as distributed computation or parallel heterogeneous platforms capable of tightly integrating quantum and classical computations, as well as quantum and classical sensors. This work will likely require the development of new ways of measuring performance.

Sensor Applications for Networking

Quantum sensors must be connected from many different physical modalities to a quantum computer or quantum processor, and engineering research is needed to **develop ways to network both similar and different kinds of quantum sensors**. There are potentially many different quantum sensors for photons, gravity waves, atoms, pressure, magnetic fields, stress, and even temperatures. Engineering research should play a role in prioritizing which sensors are needed for a given application.

Novel Quantum Machine Learning Compilations Pursuant to Native Sensor Information Domain

Quantum sensors have only recently become available. Addressing the quantum circuit synthesis/realization problem for quantum AI for intelligent sensors involves several key considerations. The Solovay-Kitaev theorem, which applies to discrete quantum computation, can be adapted to the continuous variable (CV) domain, showing that a finite set of Gaussian gates can efficiently approximate any desired Gaussian unitary operation. One challenge for engineering research is **investigating the existence of a CV version of the Solovay-Kitaev algorithm**

for CV circuit synthesis and identifying native "knobs" that can be tuned and learned. Other engineering research directions in this arena include:

- **Training a cluster state** for measurement-based quantum computation (MBQC) for photonic quantum information processing, including optimizing graph topology or hypergraph state for optimal sensor measurements;
- **Performing Hamiltonian learning for native domains** using restricted Boltzmann Machines; and
- **Incorporating quantum operations in the native domain** using naturally available quantum operations.

The intersection of quantum sensing and machine learning is an example of an area where highly interdisciplinary collaboration should be considered. Engineering researchers in this area (thought to be best for photonic domain computations) should combine their expertise with researchers in MBQC studies as well as experts in ML and sensing, plus experts in the relevant field of study for the use case (e.g., biology and astronomy).

Conclusion

Although quantum computing has gained significant scientific and public attention at the theory and prototype levels over the past decade, it still lacks the cross-disciplinary engineering required to enable scalable, practical, field-deployable quantum systems needed to achieve an impact on society. In addition to computing, other technologies are needed to solve high-value, open problems in the field, like quantum sensing and quantum and AI-enabled materials discoveries.

It is worth noting that quantum technologies have the promise to bring even greater disruptions to solving global societal challenges than the semiconductor industry did. Quantum computing will enable society to solve problems that are intractable with even the largest supercomputers in use today.

China and Europe are making substantial investments to advance quantum research. Although the United States possesses thought leadership in this early stage of the quantum era, significant U.S. investments are needed for the nation to maintain this strategic lead in the future. In the context of lessons learned from a lack of sustained public investment in the semiconductor industry, now is the time to ensure that the United States retains leadership through strategic investment in quantum rather than allowing the nation's advantageous position to erode over time.

This report identifies key research challenges and opportunities to spearhead future directions and help maintain U.S. leadership, focusing on four broad areas in which the engineering community can make notable impact. Taken together, engineering research in quantum materials, biology, computing, and AI offers the potential for breakthroughs in a range of disciplines; in medicine alone, there are rich opportunities to drive life-saving results in imaging, sensing, diagnostics, and therapeutics.

Engineering research is needed to develop the materials and processes for quantum technologies that are radically different from what we use today. Whereas today's integrated circuits rely on bulk properties of materials, tomorrow's quantum computers will be governed by surface properties and defects that are far more subtle and harder to control at scale. Moreover, the United States needs to own semiconductor fabrication operations for quantum technology leadership—for special recipe considerations if not for production volume—and U.S. companies should own and control the fabrication facilities within our borders. Coordinated, collaborative action across sectors must be taken now to enable the nation to remain at the forefront of what will be the transformative era of quantum.

Appendix A: Visioning Event Participants

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Endnotes

1. Quantum Consortium. (2024, October 28). *Celebrating 5 years of QED-C. Quantum Consortium.* quantumconsortium.org/blog/celebrating-5-years-of-qed-c/
2. *Quantum 2025: A vision for quantum technologies in Europe*. European Commission. quantum2025.org/en/
3. National Quantum Initiative. (2022, February 1). *SCQIS releases Strategic Plan for QIST workforce*. quantum.gov/scqis-releases-strategic-plan-for-qist-workforce/
4. Duncombe, J. (2025, March 12). *Not all quantum jobs require quantum skills | physics today | AIP Publishing.* pubs.aip.org/physicstoday/online/44122/Not-all-quantum-jobs-require-quantum-skills
5. Liao, S.-K., et al. (2017). Satellite-to-ground quantum key distribution. *Nature*, 549, 43–47. doi.org/10.1038/nature23655
6. Zhu, X., et al. (2023). China's progress in quantum computation: Road to scalable quantum processors. *Nature Communications*, 14, 2131. doi.org/10.1038/s41467-023-38183-3
7. Arute, F., et al. (2019). Quantum supremacy using a programmable superconducting processor. *Nature*, 574(7779), 505-510. doi.org/10.1038/s41586-019-1666-5
8. Quantum Technology Flagship. (n.d.). *Introduction to the quantum flagship*. Quantum Flagship. qt.eu/about-quantum-flagship/
9. Quantum Technology Flagship. (n.d.). *Funding opportunities*. Quantum Flagship. qt.eu/funding-opportunities/
10. National Academy of Sciences. (2022). *Quantum computing: Progress and opportunities*. National Academies Press. doi.org/10.17226/26442
11. Engineering Research Visioning Alliance. 2024. AI Engineering: A Strategic Research Framework to Benefit Society. Columbia, SC: SSRN. dx.doi.org/10.2139/4778388
12. Warner, H. K., et al. (2025, April 2). *Coherent control of a superconducting qubit using light*. Nature News. nature.com/articles/s41567-025-02812-0
13. Hoang, T. B., Akselrod, G. M., Argyropoulos, C., Huang, J., Smith, D. R., & Mikkelsen, M. H. (2015). Ultrafast spontaneous emission source using plasmonic nanoantennas. *Nature Communications*, 6(1), 1–7. doi.org/10.1038/ncomms8788
14. Gerard, J. M., Sermage, B., Gayral, B., LeGrand, B., Costard, E., & Thierry-Mieg, V. (1998, August 3). Physical Review Letters. prl.aps.org/
15. Vahala, K. J. (2003, August 14). *Optical microcavities*. Nature News. nature.com/articles/nature01939#citeas
16. Lodahl, P., Stobbe, S., & Mahmoodian, S. (2015, May 11). *Interfacing single photons and single quantum dots with photonic nanostructures | rev. mod. phys*. Reviews of Modern Physics. https://journals.aps.org/rmp/abstract/10.1103/RevModPhys.87.347
17. Kiley, M. (2023, December 5). *Small science, big impact on the U.S. economy!*. National Nanotechnology Initiative. nano.gov/node/5669
18. McFadden J., Al-Khalili, J. (2018, December 12). *The origins of Quantum Biology*. Proceedings. Mathematical, physical, and engineering sciences. pubmed.ncbi.nlm.nih.gov/30602940/
19. Stent, G. (2011). Light and life: Niels Bohr's legacy to contemporary biology. Genome. 31. 11-15. 10.1139/g89-005.
20. Marais, Al., et al., “The Future of Quantum Biology,” J. R. Soc. Interface15: 20180640, 2018.
21. Chikkaraddy, R., et al. (2016, July 7). Single-molecule strong coupling at room temperature in plasmonic nanocavities. Nature. pubmed.ncbi.nlm.nih.gov/27296227/
22. Zhang, J., Liu, Y., et al. (2017, March 6). Quantum feedback: Theory, experiments, and applications. sciencedirect.com/science/article/abs/pii/S0370157317300479?via%3Dihub
23. Kucsko G., et al. Nanometre-scale thermometry in a living cell. Nature. 2013 Aug 1;500(7460):54-8. doi: 10.1038/nature12373. PMID: 23903748; PMCID: PMC4221854.
24. Brady, A. J., et al. (2023). Entanglement-enhanced optomechanical sensor array with application to dark matter searches. *Communications Physics*, 6(1), 237. nature.com/articles/s42005-023-01357-z
25. Liou, S.-H. (2022, May 27). *Magnetic Sensors with a Picotesla Magnetic Field Sensitivity at Room Temperature*. Magnetic sensors with a PICOTESLA magnetic field sensitivity at room temperature. serdp-estcp.mil/projects/details/90d194ad-e1e6-4973-826d-fafe3c2b0037
26. Shanahan, L., et al. (2025, March 18). Q-BIC: A biocompatible integrated chip for in vitro and in vivo ... PRX Life. journals.aps.org/prxlife/abstract/10.1103/PRXLife.3.013016
27. Awick, A., and Alvarez, G.A. (2023, March 28). *Quantum sensing tools to characterize physical, chemical and biological processes with Magnetic Resonance*. Journal of Magnetic Resonance Open. sciencedirect.com/science/article/pii/S2666441023000213
28. Bowen, W. P., et al. (2023, November 24). *Quantum Light Microscopy*. arXiv.org. arxiv.org/abs/2311.05807
29. Laissue, P. P., et al. (2017, June 29). *Assessing phototoxicity in live fluorescence imaging*. Nature News. nature.com/articles/nmeth.4344
30. Casacio, C. A., et al. (2021, June 9). *Quantum-enhanced nonlinear microscopy*. Nature News. nature.com/articles/s41586-021-03528-w
31. Moreau, P.-A., et al. (2019, May 28). *Imaging with quantum states of light*. Nature News. nature.com/articles/s42254-019-0056-0
32. Seidel, R., et al. (2024, June 20). *QRISP: A framework for compilable high-level programming of GATE-based Quantum Computers*. arXiv.org. doi.org/10.48550/arXiv.2406.14792
33. Akahoshi, Y., et al. (2024, March 5). PRX Quantum. link.aps.org/doi/10.1103/PRXQuantum.5.010337
34. Kiley, M. (2023, December 5). Small science, big impact on the U.S. economy! | National Nanotechnology Initiative. nano.gov/node/5669
35. Swayne, M. (2024, April 22). Chinese researchers make advance in helium-cooling system for Quantum. The Quantum Insider. thequantuminsider.com/2022/04/08/chinese-researchers-make-advance-in-helium-cooling-system-for-quantum
36. Temme, K., Bravyi, S., and Gambetta, J. M. (2017, November 6). Error mitigation for short-depth quantum circuits. journals.aps.org/prl/abstract/10.1103/PhysRevLett.119.180509
37. Endo, S., Cai, et al. (2020, July 30). Hybrid quantum-classical algorithms and quantum error mitigation. journals.jps.jp/doi/10.7566/JPSJ.90.032001?mobileUi=0
38. Huang, Hsin-Yuan, et al. *Quantum Advantage in learning from experiments*. Science. (2022, June 9). science.org/doi/10.1126/science.abn7293
39. Chikkaraddy, R. , 2016, op. cit.

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