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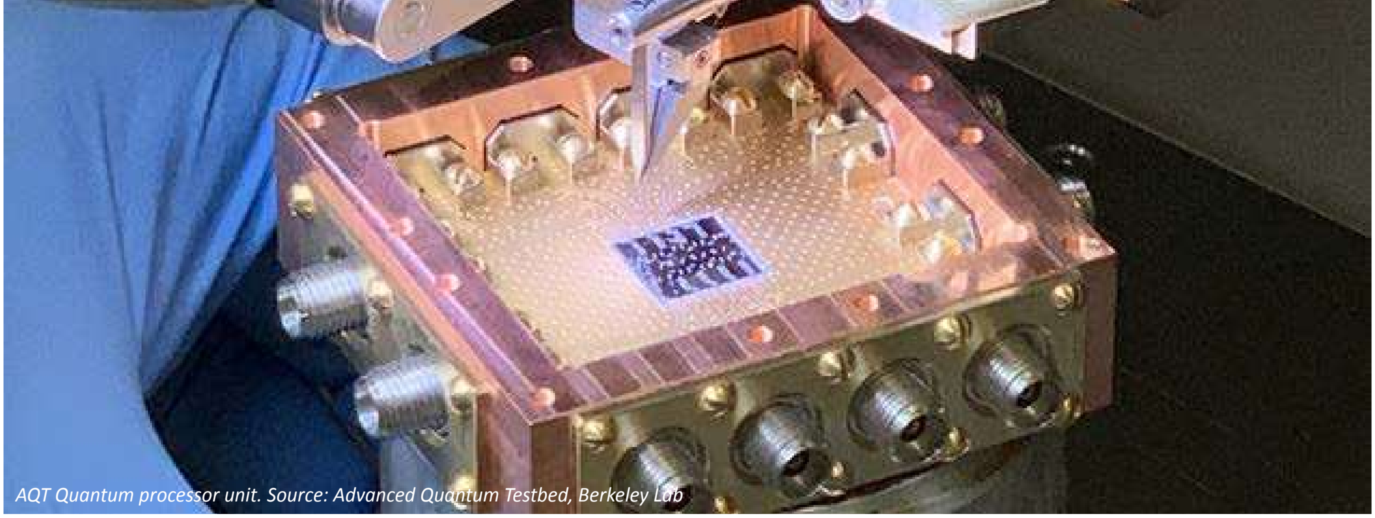
NSF Engineering Research Visioning Alliance

Engineering Research to Advance Quantum Technologies

Executive Summary


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. 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. 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.

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.

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NSF Engineering Research
Visioning Alliance

Our mission is to identify and develop bold and transformative new engineering research directions and to catalyze the engineering community's pursuit of innovative, high-impact research that benefits society.

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