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ON

AMERICAN LEADERSHIP IN QUANTUM TECHNOLOGY

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Thank you Chairwoman Comstock, Chairman Weber, Ranking Member Lipinski, Ranking Member Veasy, and Members of the Subcommittees. I am pleased to come before you today to discuss quantum information science and technology, the Department of Energy's research efforts and interagency collaboration in this area, and where the U.S. stands relative to its international competition.

Introduction

Quantum Information Science (QIS), which includes quantum computing, is a rapidly evolving area of science with great scientific and technology import. It combines the important features of quantum theory, which was developed in the early Twentieth Century, with Information Theory, which was developed in the late 1940s. Because it will open new vistas for both science and technology development, and hence new commercial markets, the U.S. and other countries are increasing investments in related basic research and technology development. DOE and other U.S. Government (USG) agencies believe that QIS will continue to grow in importance in the coming decade and are planning appropriate investments accordingly.

QIS—including quantum science and instrumentation for next-generation computing, information, and other fields—arises from the synthesis of quantum theory and information theory. It springs from the recognition that uniquely quantum phenomena can be harnessed to advance information collection, processing, and fundamental understanding in ways that classical approaches can only do less efficiently, or not at all. Current and future QIS applications differ from earlier (and ongoing) applications of quantum mechanics, such as the laser, by exploiting distinct quantum behavior that does not have classical counterparts and does not arise in non-quantum systems, including:

- *Superposition*—quantum particles or systems exist across all their possible states at the same time, with corresponding probabilities, until measured.
- *Entanglement*—a superposition of states of multiple particles in which the properties of each particle are correlated with the others, regardless of distance.
- *Squeezing*—a method of manipulating noise in systems that obey the Heisenberg uncertainty principle, by permitting large uncertainty in one variable to improve precision in another correlated variable.

Quantum information concepts are proving increasingly important in advancing understanding across a surprisingly large range of fundamental science topics, including the search for dark matter, emergence of spacetime, testing of fundamental symmetries, the black hole information paradox, probing the interiors of biological cells, and possibly even photosynthesis and the navigation systems of migratory birds. Quantum approaches based on the characteristics listed above also show promise in providing new capabilities and tools to pursue fundamental research, such as advanced sensors and detectors. Furthermore, a wide range of applications of QIS are being explored including in sensing and metrology, communication, simulation, and computing. With these motivations, recent QIS advances have been rapid, and international and industry attention and investments have been growing.

Program offices within the Department of Energy's (DOE's) Office of Science (SC) have identified areas in which they have important or unique roles, and bring unusual capabilities to bear. Brief descriptions of these equities and contributions follow:

- *Advanced Scientific Computing Research (ASCR)*—Strong foci in research, partnerships, and provision of leadership-class computing and networking resources to the research community. Key elements include providing early access to new technology, exploring the DOE-relevant application space in partnership with other SC programs, and ensuring that application needs inform next-generation device design and basic research programs in applied mathematics, networking, and computer science.
- *Biological and Environmental Research (BER)*—QIS imaging and sensing approaches will expand experimental observation capabilities across varying environmental parameters or collocation of heterogeneous biological and physical materials. Understanding of biological, earth, and environmental systems via complex multi-scale models will be improved by development of faster and more powerful quantum computing devices, control systems, machine learning, and algorithms.
- *Basic Energy Sciences (BES)*—Contributions center on advancing the control of quantum coherence and entanglement to enable applications encompassing information processing, secure communication, sensors, energy generation, and control of chemical reactions. Collectively, research and user facilities offer the tools and infrastructure to enable collaborative integration of advanced synthesis, fabrication, characterization, theory, modeling, testing, benchmarking, and development-to-scale to advance QIS.

- *High Energy Physics (HEP)*—Primary emphases are on exploiting entanglement and QIS-driven technologies to address the HEP community's science drivers; developing new computational and foundational techniques; and broadly advancing the national QIS enterprise and ecosystem. With particular attention to partnerships, HEP plans a three-prong research approach including thrusts in Foundational QIS and Quantum Computing, Quantum Sensor Technology, and Experimental QIS.
- *Nuclear Physics (NP)*—Applications of quantum computing may include many-nucleon problems of relevance to nuclei, nuclear structure and reactions, and bulk nuclear matter. QIS may also impact solution of fundamental field theories that underlie nuclear physics, such as quantum chromodynamics. Experimental programs include manipulation and control of quantum systems such as trapped ions, and the DOE Isotope Program could produce enriched stable isotopes for novel quantum devices.

Quantum information science clearly represents an emerging field with cross-cutting importance in most of the program offices of DOE-SC. Both its fundamental and more applied aspects bear directly on the Office of Science mission: *the delivery of scientific discoveries and major scientific tools to transform our understanding of nature and to advance the energy, economic, and national security of the United States.* Furthermore, DOE is uniquely positioned to cover a wide range of QIS activities, with expertise and capabilities in frontier computing, quantum materials, quantum information, control systems, isotopes, and cryogenics spanning the National Laboratory system and multiple program offices. These considerations provide impetus now for community-building and initiatives across SC offices and with external counterparts. This document summarizes the interests, activities, and overall approach of the Office of Science in QIS.[*]

Background and Context for Federal Activity

Quantum information science has been a topic of interest to Federal agencies for some time, but has garnered greater attention in the past few years due to a confluence of events: theoretical and technological progress in the field, including the demonstration of multiple-qubit systems by numerous groups including companies; the advent of and controversies surrounding adiabatic quantum computers, or quantum annealers, on the open market; the slowing and apparently rapidly-approaching end of Moore's-law advancement in semiconductor technology; and aggressive investment by other nations. The rapid progress of the field is also signaled by the growth in QIS-related publications, as shown here for 2000-2015 (figure from *Advancing Quantum Information Science: National Challenges and Opportunities*, NSTC report of July 2016).

[*] For convenience, in this document the term "quantum information science" or "QIS" will be used as shorthand, but is intended to encompass the full range of activity associated with quantum information, including basic science, tools, engineering, technology, and applications.

Fifteen Years of Growth in QIS

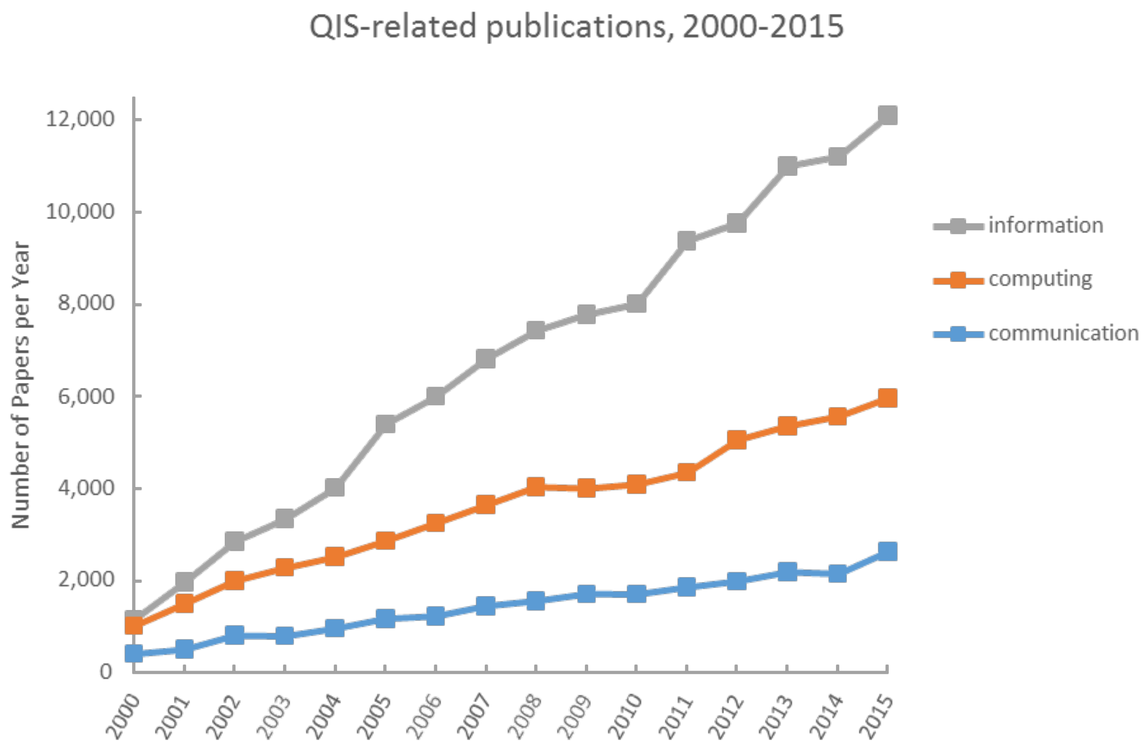

Figure 1. A Google Scholar search for publications (excluding patents and citations) containing the terms "quantum information," "quantum computing," and "quantum communication" illustrates how the field has grown in recent years.

The primary mechanism for high-level coordination of science and technology activities across Federal agencies is the National Science and Technology Council (NSTC), an internal-to-government body that is nominally chaired by the President and includes Cabinet-level (or, for independent agencies, Director-level) representation. The work of the NSTC is carried out through its many subgroups. In January 2009, an NSTC Subcommittee released a document entitled *A Federal Vision for Quantum Information Science*. While this addressed the challenges and opportunities at the time, further action in the next few years was limited. With subsequent rapid developments in the field, however, a new Interagency Working Group on Quantum Information Science was chartered under the NSTC in October of 2014. That body, which is co-chaired by DOE, the National Science Foundation (NSF), and the National Institute of Standards and Technology (NIST), issued a report titled *Advancing Quantum Information Science: National Challenges and Opportunities* in July 2016[†]. The report identified the major challenges to progress in QIS as: institutional boundaries; education/workforce needs; technology and

[†] https://www.whitehouse.gov/sites/whitehouse.gov/files/images/Quantum_Info_Sci_Report_2016_07_22%20final.pdf

knowledge transfer; materials and fabrication; and level and stability of funding. It highlighted a path forward founded on stable, sustained core programs; strategic targeted investments; and controlled growth, close monitoring, and adaptability, and emphasized that "QIS should be considered a priority for Federal coordination and investment." Building on release of that report, the Office of Science and Technology Policy in the Executive Office of the President, with assistance from the QIS Working Group of the NSTC, hosted a Forum on QIS at the White House complex in October 2016.

The NSTC Interagency Working Group on QIS continues to meet to exchange information, monitor developments, coordinate agency activities, and plan next steps. In addition, individual agencies—including DOE—have hosted or supported a large number of QIS workshops or symposia and issued other studies in recent years (see References for a partial listing). Other agencies have also taken further action, such as the creation of a multi-directorate QIS "metaprogram" by NSF in 2016 and inclusion of "The Quantum Leap" that includes this topical area among NSF's 10 "Big Ideas" driving the long-term research agenda for the agency.

Efforts in QIS also relate to, and are referenced in, other major Federal initiatives. Qubit development and quantum computing are viewed as one path for post-Moore's-Law computing in the National Strategic Computing Initiative. Other connections include overlaps or synergies with the National Nanotechnology Initiative, the Materials Genome Initiative, and coordinated Federal efforts in optics and photonics.

DOE Role in the Federal Interagency Context

The DOE National Laboratory system is unique in the Nation with a history and proven track record of creating multidisciplinary scientific capabilities that are beyond the scope of academic and industrial institutions and to which the government requires assured access. Several of DOE's National Laboratories have been fostering research in various areas of QIS as well as related topics in computer science and applied mathematics. HEP groups at several laboratories, including Fermi National Accelerator Laboratory, SLAC National Accelerator Laboratory, Lawrence Berkeley National Laboratory (LBNL), and Argonne National Laboratory (ANL) are engaged in QIS technology research and development, quantum sensors, and in developing related techniques for data analysis. User and other facilities provide opportunities for possible interactions with other agencies and the researchers they support; for example, the BES-managed Nanoscale Science Research Center (NSRC) user facilities offer opportunities for synergies across the lab complex. NP groups at ANL, Brookhaven National Laboratory, Thomas Jefferson National Accelerator Facility, Los Alamos National Laboratory (LANL), LBNL and Oak Ridge National Laboratory (ORNL) are engaged in the development and implementation of sensors, research and development on superconducting radio frequency (SRF) devices, cryogenic polarized nuclear spin targets, polarimetry, and atom trapping techniques, which may be useful in advancing QIS technology. Sandia National Laboratory is regarded as a world leader in the fabrication and operation of ion traps for qubit experimentation, and has ongoing activities in other QIS areas including validation and verification of quantum devices. LANL hosts a D-Wave quantum annealer that is available as a resource across the lab complex. ORNL fosters collaborations with external partners via its Quantum Computing Institute, and is the location of enriched stable isotope production capabilities developed for the DOE Isotope Program.

DOE's National Laboratories thus have unique attributes that are complementary to those of other agencies and can address gaps identified in the national ecosystem for quantum information science and technology. The DOE labs are well-equipped to address challenging problems in fundamental research that require sustained focus or are too large in scope for a university research group. DOE's labs additionally stand out in their ability to fabricate and characterize novel materials and devices, their expertise in using high-performance computing resources, and their diverse range of high-caliber scientists and engineers that can form the basis of interdisciplinary teams.

As noted earlier, DOE has been an active participant in ongoing interagency coordination on QIS, including co-chairing the NSTC Interagency Working Group in this area. Program offices in SC have invited representatives of other agencies to participate in QIS-related workshops and roundtables, and vice versa. In addition, various opportunities exist for informal or formal collaborations going forward, in which DOE's National Laboratory or other programmatic assets can accelerate progress in areas where other agencies have related mission-driven interests. For example, ASCR's interests overlap with several other agencies. ASCR shares with the Department of Defense (DoD) and the Intelligence Advanced Research Projects Activity an interest in advancing quantum computing technology, but with an application focus on science. In contrast with—but complementary to—NSF's blue-sky research approach, ASCR focuses on DOE-specific computing applications, research, and development to make the best use of DOE's high performance computing (HPC) resources. HEP has noted synergistic intellectual and technological interests and expertise with NIST and DoD in the areas of foundational quantum information, entanglement, and quantum sensors, and is exploring potential collaborations or other coordination in these areas.

International Landscape

Worldwide interest in quantum information science and technology has increased substantially in the past five years. While the U.S. remains a leader in the field, other nations have made new investments and developed long-term strategies that have already shifted the geographic distribution of top-tier research groups. Both academic researchers and industry have noted the U.S. Government's comparative silence relative to foreign governments' strong statements of support for quantum information science and technology. Academic researchers in the U.S. have expressed concern that their foreign counterparts have better access to supporting technologies such as novel materials and custom optics. A summary of foreign QIS activity to date follows:

- The largest quantum information science and technology programs outside the U.S. are in the European Union (EU) and China. In 2016, the EU announced a €1 billion ($1.1 billion), 10-year Flagship initiative that is still in the planning stage. This is only the third EU Flagship project in future and emerging technologies; the prior ones, launched in 2013, are on Graphene and the Human Brain Project. China dominates Asian investment in QIS research and development with a large, rapidly growing program that initially focused on secure communication, including the widely publicized launch of an experimental quantum communications satellite in 2016, and is now expanding to other areas. The Chinese program includes industry partnership and lucrative offers to recruit top talent abroad.

- The U.K. and Canada have made high-profile investments in a broad range of efforts that are smaller than those in the EU and China but large relative to each nation's overall science and technology effort. The U.K.'s program centers around four hubs, each of which is a partnership between universities and industry focused on a specific set of technologies (sensors, imaging, networking, and computing). The U.K. has also invested heavily (more than £200 million/$255 million USD) in student and postdoctoral training. Canada's program, in contrast to all the others, was spearheaded by private investment aiming to make Waterloo the quantum analogue to Silicon Valley. This has established the Perimeter Institute and University of Waterloo as leaders in QIS ranging from blue-sky theory to practical devices and algorithms, and led to a large award ($76 million CAD/$56 million USD) in 2016 from the Canada First Research Excellence Fund.
- Australia and the Netherlands have made targeted, high-profile investments in quantum computing. Australia's 2016 National Innovation and Science Agenda included a $70 million AUD ($53 million USD) public-private partnership to advance quantum computing for commercial applications that is complementary to a new $33 million AUD ($25 million USD) fundamental research effort to support the scale-up of silicon quantum integrated circuits. The Netherlands' 2015 investment of €135 million ($144 million) in a center focused on superconducting and silicon-based computing technologies in Delft has attracted additional investment from U.S. industry, including $50 million from Intel. The Netherlands is also home to a government-funded quantum software research center.
- A number of countries without a coordinated national QIS agenda or initiative nonetheless have strong, well-funded research groups. These include Germany, Austria, Switzerland, Japan, and Singapore. Other countries that have not traditionally been leaders in QIS, such as Russia and Brazil, appear to be building national research communities.

Summary of Scientific Challenges and Office of Science-Specific Efforts

Quantum Science—Coherence and Entanglement of Quantum States

Materials and Synthesis

Real quantum materials require synthesis. There remains a fundamental science gap that is an obstacle to the long-term goal of "synthesis by design." This goal requires establishing generalized rules of assembly for complex materials in a variety of platforms, in order to determine, understand, and control reaction/synthesis/deposition/assembly pathways for metastable, kinetically stabilized, and thermodynamic phases of quantum materials. Resulting new functionalities could include superconductivity and robust entangled states approaching room temperature, or dissipationless charge and spin transport relevant to quantum computation, neuromorphic computing, and ultra-low loss digital computation beyond silicon. Conversely, understanding of fundamentals of competitive heat/electron transfer could demonstrate limitations on quantum computation. Research on materials synthesis and processing falls largely within the purview of BES. In addition, the DOE Isotope Program, managed by NP, is developing the capability to produce kilogram quantities of enriched stable isotopes in a cost-effective manner. This may be useful in the synthesis of new materials for research and development studies of solid-state qubit systems.

Instrumentation for Quantum Control: Sensing and Metrology

Existing capabilities and instrumentation development for measurement and control of quantum phenomena are widespread across SC program offices. In BER, there is particular interest in development of sensors that combine quantum metrology and quantum imaging for more accurate measurements using optical sensor systems, such as Lidar (Light Detection and Ranging) instruments at the Atmospheric Radiation Measurement facility. Another BER focus is development of highly precise sensors to allow single molecule nuclear magnetic resonance of biomolecules. For HEP, the possibility exists of development of specialized cavity sensors for detecting new particles and quanta in previously inaccessible frequencies and with greater sensitivity than currently available. Some of the technologies being developed for quantum computing are also candidates for sophisticated sensors for particle physics experiments. HEP also has a strong interest in the use of atomic interferometry and entanglement for discoveries of the unknown and Beyond Standard Model physics. Similarly, NP anticipates that development of detectors and SRF technology for nuclear physics experiments may be relevant to instrumentation for quantum control. Examples include use of highly efficient quantum dot sensors for light collection in experiments to search for lepton number violation in nuclear decays, and exploitation of quantum effects for precision measurements of the electric dipole moment of nuclei to search for violations of fundamental symmetries of nature. BES efforts employ a variety of characterization techniques that have relevance for QIS. Scattering, spectroscopy, and imaging of quantum materials using neutrons, x-rays, and electrons as probes over a broad range of length and time scales can characterize their phenomenological behavior, lead to the discovery of new materials, and inform theories that predict and explain their properties. These tools can also contribute to development of quantum sensors and detectors.

Theory and Modeling of Quantum Entanglement

Research within the scope of HEP at the intersection of particle physics and QIS has formulated relationships between quantum fields, black hole physics, and information entanglement, invoking quantum error correction codes and quantum gravity. Tensor networks provide new models to understand fields, particles, and their interactions. New quantum algorithms and simulations that can incorporate scattering dynamics in hitherto static lattice quantum chromodynamics (QCD) analyses are planned. BES further notes that quantum computing could enable fast algorithms for computation of quantum entanglement. Theory efforts could analyze entanglement entropy in systems with known solutions. Decoherence in entangled systems could potentially be understood via molecular magnets, through their evolution into systems with weakly interacting spins. ASCR plans to explore partnerships with other SC offices (BES, HEP, BER, and NP) to develop tools and algorithms for modeling and simulations, in order to accelerate the computation and understanding of quantum entanglement in different systems.

Quantum Devices and Systems for Computing, Information, and other Applications

Qubit Technologies

Many candidate systems have been explored or proposed for qubits, the basic building blocks for quantum computing that embody superposition of states. Implementing these systems involves a variety of issues, including not just the specific material properties but also manufacturability, scalability, stability, integration, and other concerns. Some potentially useful materials for qubit systems include Josephson junction arrays (high-temperature superconductors), trapped ions, quantum dots, nitrogen-vacancy complexes (NV centers) in diamond or other localized defect structures, topological insulators and two-dimensional electron gas (2DEG) systems that support the fractional quantum Hall effect, fractionally charged particles or Majorana fermions that lead to non-Abelian statistics, skyrmions miniaturized to the atomic level, and nano-magnets with non-Abelian anyons as excitations. DOE BES research and facilities already encompass investigations in many of these areas, and in particular the NSRC user facilities are well-suited to advance the fabrication and testing of these materials. In addition, the DOE Isotope Program, managed by NP, produces highly pure stable isotopes that could be used in the manufacture of solid-state qubits.

Quantum Sensors and Detectors

Almost any device developed as a qubit system for quantum computing can also be regarded as a quantum sensor, with potential applications to precision measurements and detection of particles across the entire range of topics of interest to SC. As such systems are explored, opportunities arise to exploit the extreme sensitivity of quantum materials for sensing and detection by understanding their electronic phase transitions. Electronic, magnetic, and structural properties and ultrafast dynamics can be investigated with tools including pump-probe experiments at femtosecond resolution, ultra-high field neutron scattering, angle-resolved photoemission, and scanning probe imaging. Ultrasensitive magnetometers can be constructed based on NV centers, and single-photon detectors based on quantum aspects of superconducting materials. The NSRCs under BES are capable of fabrication over the necessary spatial and temporal scales, and extensive characterization capabilities are available through other SC user facilities and National Laboratory capabilities. Development of detectors and superconducting radio-frequency technology for nuclear physics experiments may be relevant to instrumentation for quantum control. Note also that HEP has specifically identified development and use of quantum sensor technology across the HEP science drivers as a key part of the HEP plan for increased activity in QIS.

Fabrication and Testbeds

Testbeds provide the research community with access to early stage devices, accelerating through co-design the development of hardware well-suited to scientific computing as well as applications that make effective use of new hardware. They can potentially serve as standardized environments for examining the preservation of coherence, extent of entanglement, and other key criteria. In addition to testing and benchmarking of individual devices, testbeds can facilitate intercomparison of different devices and are a helpful tool for developing production-quality software for novel computing architectures. For these reasons, ASCR issued a program announcement to DOE National Laboratories for research into development of quantum testbeds in May 2017. Multidisciplinary efforts to explore the suitability of various implementations of quantum devices for science applications will advance engineering of quantum information systems and help to define and perhaps overcome practical limitations. Furthermore, device fabrication and testbeds will greatly benefit from strong collaboration between government agencies, academia, and industry. National Laboratory facilities are well-positioned in capabilities and infrastructure to enable the needed collaborative integration of advanced synthesis, fabrication, characterization, theory, modeling, testing, benchmarking, and development-to-scale.

Novel Architectures, Quantum Simulators/Emulators, and Systems-Level Control

Exploration of novel architectures ranging from the device level (qubit connectivity; hybrid systems of different types of qubits) through the system level (quantum/classical co-processors; quantum devices as HPC accelerators) will allow DOE to invest in the quantum computing technologies best-suited to mission needs. Some applications, such as quantum chemistry, appear to benefit from an approach that pairs classical feedback with inherently quantum processing. Other applications may run best on a larger quantum processor with classical computing only required for control. Qubit simulators will facilitate early exploration of architectures; emulators that parameterize key features of larger quantum devices will allow efficient system-level design that can proceed hand-in-hand with research and development in systems-level control.

Algorithms

Solving the wide variety of computational problems addressed by DOE and SC will require quantum computing to support a robust and versatile set of algorithms. Research into quantum speedups for basic primitives of applied mathematics such as linear algebra, integration, optimization, and graph theory will lay the groundwork to develop and optimize quantum simulation and machine learning algorithms for performing a wide variety of scientific computing tasks. An initial program announcement to DOE National Laboratories regarding the development of quantum algorithm teams was released by ASCR in May 2017.

Software Implementation and Reliability

Practical realization of quantum computing's potential will depend not only on advances in hardware and algorithms but also on advances in optimizing languages and compilers to translate these abstract algorithms into concrete sequences of realizable quantum gates, and simulators to test and verify these sequences. A systematic research agenda to develop a software infrastructure from high-level languages to debuggers and benchmarking metrics, when executed in coordination with hardware and architecture design, will also lead to effective strategies that find balance between systems-level control and error correction.

Quantum Networks and Complexity

Significant research effort is needed to develop, test, and deploy continental scale Quantum Wide Area Networks (Q-WANs) composed of many nodes, multi-hops, multi-users, and high-speed optical quantum channels. Fundamental to this endeavor is the development of high-performance quantum communication network components needed to secure distributed quantum systems processing and sharing data sets over continental distances. Among them are a number of critical components such as quantum communication network hardware, architectures, and protocols; quantum-enabled software defined networks (Q-SDN); and all-optical network (AON) extension for quantum key distribution (QKD) and understanding QKD security loopholes.

Applications of Quantum Computing and Quantum Information

Early Science Applications

Initial scientific impacts and approaches that can be pursued prior to, or on the path towards, longer-term developments have been identified by SC program offices within their respective portfolios, as follows:

Advanced Scientific Computing Research (ASCR)

In partnership with HEP, ASCR sponsored a pilot project that seeks to develop fast quantum and classical algorithms for simulating quantum field theories. Such pilot projects will provide valuable feedback in the planning of larger partnership programs that target multiple science application areas. In addition, quantum testbeds will assist with meaningful evaluation and comparison of different materials, devices, algorithms, and approaches.

High Energy Physics (HEP)

HEP quantum computing interests include use of quantum machine learning and quantum devices for data analysis. Some of these tasks may be amenable to quantum annealing approaches that are available now, rather than requiring a general-purpose quantum computer far beyond what is currently achievable. To that end, HEP has sponsored a pilot project on using a D-Wave system for Higgs event classifier tests. In addition, the lattice QCD algorithms mentioned above are expected to be designed for quantum computers or simulators. HEP also supports several other QIS pilot efforts, including one jointly with BES on dynamics of highly-entangled quantum states that has already yielded several publications. Small-scale experiments to test foundational entanglement and quantum gravity predictions are planned.

Basic Energy Sciences (BES)

Early activity includes exploration of quantum many-body problems in magnetism, molecular magnetism, superconductivity, quantum chemistry, and topological states of matter. Near-term efforts could also include investigation of fractional quantum Hall effect, Heisenberg and multi-orbital Hubbard models as testbeds. Overlapping/complementary efforts with lattice QCD are under consideration as well.

Biological and Environmental Research (BER)

Identified areas of early science include: (1) Creation of novel quantum sensors / use of nanostructured quantum materials to perform noninvasive sensing, monitoring, and imaging of subcellular biological processes in microbes, microbial communities, and plants. This would enable understanding of biomolecular structure-function relationships and provide insights into the spatio-temporal nature of metabolism within/among cells. (2) Creation of novel quantum devices for environmental sensing and observations, able to be deployed at field sites relevant to bioenergy crop production, sensitive earth system geographies (e.g., Arctic permafrost), or radioactive contamination. These quantum devices would be optimized so multimodal data sets with spatial and temporal dimensions can be combined.

Nuclear Physics (NP)

A research group has been formed at the Institute of Nuclear Theory at the University of Washington in Seattle that will investigate possible applications of quantum computing to important problems in nuclear physics. Initial NP applications will likely be analogous to the existing applications in quantum chemistry, which are concerned with many-body quantum mechanical systems. In nuclear physics, the systems of greatest interest in this category are nuclei and bulk nuclear matter, which can be treated as many-fermion (neutron and proton) quantum mechanical systems interacting through pairwise and three-body nuclear forces. The standard quantum mechanical problems for these systems are the determination of ground-state energies and their many-body wavefunctions, the corresponding excited-state energies and wavefunctions (nuclear structure); quantum scattering problems (nuclear reactions); and more complicated time-dependent phenomena such as collective excitations and nuclear fission. Presumably the ultimate goal of QC research in NP will be to simulate the equations of QCD, the fundamental quantum field theory of quarks and gluons that underlies nuclear physics. Possible approaches to simulating simpler versions of quantum field theories, such as scalar field theories in two dimensions, would be early applications of great interest; practical algorithms for this type of problem have not yet been developed.

DOE-SC Collaborations and Longer-Term Directions

The 2015 DOE ASCR Workshop on Quantum Computing for Science made a compelling case for the potential of quantum computing's impact for a number and variety of problems of strategic importance to DOE and SC that are presently limited by the capabilities of conventional high-performance computing. ASCR is leveraging its 15-year experience with the Scientific Discovery through Advanced Computing (SciDAC) program to form partnerships with the other SC program offices via a similar but not necessarily identical model. The general approach will be to tap into the appropriate range of expertise in DOE national laboratories, universities, and other research organizations including industry, but also to ensure that the resulting tools, methods, and resources will be available to the wider QIS community.

Recent DOE reports on quantum sensors (HEP and ASCR) and quantum materials (BES) set out research directions and needs in greater detail. The sensors roundtable report identifies challenges where the science drivers identified earlier by the High Energy Physics Advisory Panel (HEPAP) Particle Physics Project Prioritization Panel (P5) could be pursued via small experiments using quantum entangled sensors and precision measurements beyond our conventional frontiers of study, and also addresses improved performance of qubit ensembles, optimization of quantum networks, materials development, hybrid technologies for multimodal functionality, and new theoretical approaches. The quantum materials workshop report details priority research directions in control and exploitation of electronic interactions and quantum fluctuations, harnessing of topological states, control of coherence and entanglement in nanostructures, and revolutionary tools to accelerate discovery and deployment of quantum materials. It also summarizes status, challenges, and opportunities in superconductivity and charge order, magnetism, transport and dynamics, topological behavior, and heterogeneity and nanostructure in quantum materials. For NP, it is envisioned that SciDAC and exascale computing collaborations, especially those involved in lattice QCD and many-body NP problems, will closely monitor progress in quantum computing and may adjust their research programs to take advantage of any useful developments. BER expects to engage in development of quantum computing/storage/information processing testbeds for multi-scale earth system modeling, and of biology testbeds that combine simulation methods with experimental data collection facilities so that real time feedback can be provided from computation to help guide the experiment. This would require extensive improvements in the scale of codes on supercomputers, real time analysis, better uncertainty quantification, improved load balancing, and methods for analysis of very large eigenvalue problems. Additional areas of considerable scientific interest across one or more program offices include quantum chemistry and applications to machine learning.

Conclusion

In conclusion, quantum information science and technology is rapidly evolving, will continue to grow in the coming decade. QIS holds great potential for broad range of near-term and long-term applications from sensing and metrology, communications, simulation, and quantum computing and is rapidly gaining international and industry attention. The DOE has been integrally engaged in the interagency and community planning to advance QIS research in the U.S. and the DOE laboratories are well positioned to bring their unique attributes and capabilities to bear on many of the scientific challenges and knowledge gaps we face. Federal coordination and investment is critical to continued U.S. scientific leadership in this area, with implications for not only advancing scientific discovery in a number of fields, but continued U.S. economic competitiveness and national security.

Thank you for the opportunity to come before you today to discuss the Department of Energy’s efforts in quantum information science. I look forward to discussion this topic with you and answering your questions.

References

Some selected documents from DOE SC, DOE National Laboratories, other Federal agencies, and major foreign entities are listed below. Many other workshops and symposia in QIS and related topics, organized by Federal agencies, professional societies, universities, and others, have been held in the past few years but are not included here.

- HEP-ASCR Study Group Report, Grand Challenges at the Interface of Quantum Information Science, Particle Physics, and Computing, 2015, https://science.energy.gov/~/media/hep/pdf/files/Banner%20PDFs/QIS_Study_Group_Report.pdf
- HEP-BES roundtable report, "Common Problems in Condensed Matter and High Energy Physics", 2015, https://science.energy.gov/~/media/hep/pdf/Reports/HEP-BES_Roundtable_Report.pdf
- LANL workshop report, "Materials Frontiers to Empower Quantum Computing", 2015, http://permalink.lanl.gov/object/tr?what=info:lanl-repo/lareport/LA-UR-15-24386
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- ASCR Quantum Testbeds Stakeholder Workshop, 2017, https://www.orau.gov/qtsws/default.htm