Quantum Information Science

A Federal Perspective

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Applications of QIS

- Sensing and metrology
  - Navigation, gravimetry, magnetometry, medical imaging, precision timekeeping, improved detector sensitivity

- Communication
  - Secure communication including quantum key distribution, fingerprinting of data, quantum networking

- Simulation
  - Efficient simulation of quantum systems; quantum chemistry

- Computing
  - Shor’s algorithm (1994) allows efficient factoring of numbers on a general quantum computer
  - Quantum speedups anticipated for optimization, machine learning, software verification and validation, et al.
Quantum information concepts and approaches increasingly proving important

- Black hole information paradox
- Testing of fundamental symmetries
- Search for dark matter
- Emergence of spacetime
- Probing the interiors of biological cells
- Photosynthesis (?)
- Navigation of migratory birds (?)

Rapid growth in QIS-related publications, 2000-2015

Based on a Google Scholar search, excluding patents and citations, containing the terms “quantum information,” “quantum computing,” and “quantum communication.” Similar results obtained for patent searches.
Chartered as a formal subgroup of the National Science and Technology Council (NSTC), the Cabinet-level body that is the primary locus for interagency coordination and planning.

Meeting regularly since October 2014.

Participating: DoD, DOE, NIST, NSF, ODNI, OMB, OSTP.

- Sharing of information on existing agency programs and developments in the field.
- 2015 formal public Requests For Information.
- Workshops focusing on U.S. industry perspectives April 2015 and October 2017 at NIST.
- Publication of NSTC report in 2016...
Impediments to progress:
- institutional boundaries
- education/workforce needs
- technology and knowledge transfer
- materials and fabrication
- level and stability of funding

Path forward:
- stable, sustained core programs
- strategic targeted investments
- controlled growth, close monitoring, and adaptability

“QIS should be considered a priority for Federal coordination and investment”
About the DOE Office of Science (SC)

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.

Six interdisciplinary scientific program offices:
- Advanced Scientific Computing Research (ASCR)
- Basic Energy Sciences (BES)
- Biological and Environmental Research (BER)
- Fusion Energy Sciences (FES)
- High Energy Physics (HEP)
- Nuclear Physics (NP)
Some DOE-SC facts and figures...

- **Research**
  - Provides about half of total U.S. Federal support for basic research in the physical sciences
  - Supports about 19,000 Ph.D. scientists, graduate students, engineers, and support staff
  - Maintains U.S. and world leadership in high-performance computing
  - Continues to be the major U.S. supporter of physics, chemistry, materials sciences, and biology for discovery & for energy sciences

- **Resources**
  - Serves as steward for 10 of DOE’s 17 National Laboratories
  - Maintains the largest collection of scientific user facilities (aka research infrastructure) operated by a single organization in the world, used by more than 32,000 researchers each year, including (for example):
    - Synchrotron and x-ray free electron laser light sources
    - Observational and communications networks
    - Nanoscale Science Research Centers
    - High Performance Computing and Networking
Leveraging groundwork already established in DOE National Labs and academic groups to maximize SC’s impact on QIS. Examples include:

- Illustration of a topological insulator with a superconducting layer on top for detection of Majorana fermions (colored lines). Once identified and isolated, Majorana fermions could form the basis of qubits. Electrons (green) travel along the edges of the structure. Supported in part by the BES Energy Frontier Research Center (EFRC) program.

- Tensor networks are a key theoretical tool for understanding entanglement, topological order, and other aspects of quantum systems. They comprise a broad family of techniques (2D Multi-scale Entanglement Renormalization Ansatz (MERA) shown here).

- In April 2017, researchers successfully ran the largest ever simulation of a quantum computer at NERSC, LBNL. The simulation was made possible by the performance boost gained through the use of Roofline model during the optimization process. The Roofline model was developed by SciDAC Institutes; a flagship ASCR program.

- A laser cooled, RF confined ion trap at Argonne National Laboratory: trapped ions can be used as qubits and as quantum simulators.
DOE SC programs and DOE National Laboratories embody a wealth of knowledge and experience in key technologies to enable precision quantum sensors, quantum computing, and development of quantum analog simulators.

Fabrication of high-performance surface ion trap chips for quantum computation is a unique capability developed at Sandia National Laboratories.

(Top left) A graphical representation of nitrogen vacancy (NV) qubits fabricated within diamond.
(Right) These NVs were made in precise, dense arrays (μm = micrometers) for future quantum computers.
Work performed in part by MIT users at an NSRC.

Development of advanced superconducting radio frequency (SRF) cavities (as shown above from FNAL), cryogenics, and other technologies supporting development of qubits, their ensembles, quantum sensors, and quantum controls across DOE National Labs.
An Office of Science QIS Task Force identified SC-wide grand challenges that will potentially be transformed by quantum computing applications.

- Simulations of quantum many-body systems for materials discovery, chemical processes, and nuclear matter equation of state
- Simulations of quantum field theory and quantum dynamics
- Machine learning for large data sets and inverse molecular design
- Optimization for prediction of biological systems such as protein folding

Transformative Impact Through Partnership Programs among ASCR, BER, BES, HEP, NP

Algorithms, Software Tools, and Testbeds
Initial SC Research on Quantum Computing Applications

Office of Advanced Scientific Computing Research programs:

Quantum Algorithm Teams (QATs)
Aims to stimulate early investigations of quantum simulation and machine learning algorithms by focusing on key topics of research with relevance to problems of interest to SC. In FY17, 3 interdisciplinary teams led by LBNL, ORNL, and SNL were funded.

Quantum Testbed Pathfinder
Aims to initiate an exploration of the suitability of various implementations of quantum computing hardware for science applications. In FY17, 2 teams led by LBNL and ORNL were funded.

SC pilot projects:
Quantum annealing for machine learning to separate signal from background in Higgs data from the Large Hadron Collider (HEP/Caltech-FNAL)

Simulated particle scattering off a complex boundary condition by quantum algorithms (HEP-ASCR Pilot/ U. Maryland)
Cross-Cutting Applications in BER, BES, HEP, NP

- Superconducting qubit sensors for x-ray spectroscopy. As sensors improve, single-photon detection may become possible at far infrared and microwave wavelengths.
- Nanostructured single photon emitters and detectors could be integrated for sensing, communications, and computing systems at room temperature.
- Quantum sensors to perform dynamic, non-invasive visualization of subcellular biological processes.
- Quantum devices for environmental sensing in field settings for integrating multi-model and multi-scale data (e.g. quantum lidar).
- Quantum electron microscope for high resolution at very low doses for imaging of sensitive materials.
- Single photon detectors can expand the range of discovery for dark universe, non-Newtonian gravity, and new forces. Quantum error correction reduces noise in matter wave interferometry for such searches.
QIS – including quantum computing, simulation, sensing, and communications – are recognized by Federal agencies as holding promise for a broad range of applications and opening up new possibilities in fundamental research.

General purpose quantum computers offer the possibility of addressing tasks that conventional computing can only tackle far less efficiently, if at all; however, quantum computers with those capabilities may yet be far off, and considerable technical challenges remain.

Nearer-term and present-day systems for quantum simulation, annealing, and computing have the prospect for an immediate impact on the state of knowledge and technology.

Applications in the areas of sensing and metrology are already appearing, and more are on the near horizon.

DOE’s Office of Science has unique research and resources to advance the field of QIS, and to make use of QIS advancements to accelerate progress in a wide range of scientific and technical fields.