Quantum Information Science (QIS)

DOE/HEP PI Meeting 2018

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Office of High Energy Physics
Office of Science, U.S. Department of Energy
Quantum Information Science & Technology (QIST)

- Quantum Information Science (QIS) & Quantum Technology
- Quantum Information (QI) and QI Theory
- Quantum Computing (QC) and its applications
- Quantum Algorithms (and applications)
- Qubits and Associated Stability
- Quantum Error Correction (QEC)
- Quantum Cryptography
- Quantum Sensors (including entanglement and Squeezing)
- Quantum Entanglement
Quantum Information Science (QIS) in the DOE Office of Science (SC)

QIS is a thriving area of multidisciplinary science.
• It exploits particular quantum phenomena to measure, process, and transmit information in novel ways that greatly exceed existing capabilities.

QIS provides a basic foundation for numerous application areas.
• Potential transformative impact on SC grand challenges.

QIS is at a tipping point.
• Major companies are embracing QIS, foreign competition is expanding rapidly.

Progress in QIS is driven by basic research in physical sciences.
• DOE SC is the Nation’s leading supporter of basic research in physical sciences.
Science Committee Seeks to Launch a National Quantum Initiative

PLAN: to create a 10-year National Quantum Initiative aimed at increasing America’s strategic focus on quantum information science and technology development.

Jacob Taylor, Assistant Director for quantum information science, OSTP recently stressed the nascent nature of the field: “From my perspective, what we see is that there is a tremendous amount of fundamental science still to be done,”
NSTC SUBCOMMITTEE ON QUANTUM INFORMATION SCIENCE

Create and maintain a national strategy for Quantum information science. Coordinate current and future efforts across the agencies.

Co-chairs: DoE, NSF, NIST
How can QIS be harnessed to benefit the warfighter and enhance national security?

- Single-investigator and team awards to universities and international collaborations
- Math and physical sciences, computer and information science, engineering

How can QIS advance DOE’s science and energy mission?

- Single-investigator and team awards to universities; larger and longer-term investments at DOE labs and user facilities
- New effort, still evolving, will expand to include all 6 Office of Science programs
- NNSA also investing

How can QIS enhance our fundamental standards, documentary standards, and our ability to make precise measurements?

- DOC’s QIS research is performed at the National Institute of Standards and Technology (NIST)
- Fundamental standards (time, mass, etc.), sensors, cryptography standards, protocols for computing and communication, etc.

How can we improve our fundamental understanding of quantum science and information science?

- Single-investigator awards to universities; larger awards to university-based centers and collaborations
- Math and physical sciences, computer and information science, engineering

How can QIS advance DOE’s science and energy mission? How can QIS enhance our fundamental standards, documentary standards, and our ability to make precise measurements? How can we improve our fundamental understanding of quantum science and information science? How can DOE’s unique resources advance QIS? How can we improve our fundamental understanding of quantum science and information science? How can DOE’s unique resources advance QIS? How can QIS be harnessed to benefit the warfighter and enhance national security?
The Mission of the Energy Department is to ensure America’s security and prosperity by addressing its energy, environmental, and nuclear challenges through transformative science and technology solutions.

The mission of the Office of Science is 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.
<table>
<thead>
<tr>
<th>The DOE Office of Science Research Portfolio</th>
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<tbody>
<tr>
<td><strong>Basic Energy Sciences</strong></td>
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<tr>
<td>• Understanding, predicting, and ultimately controlling matter and energy flow at the electronic, atomic, and molecular levels</td>
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<tr>
<td><strong>Advanced Scientific Computing Research</strong></td>
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<tr>
<td>• Delivering world leading computational and networking capabilities to extend the frontiers of science and technology</td>
</tr>
<tr>
<td><strong>Biological and Environmental Research</strong></td>
</tr>
<tr>
<td>• Understanding complex biological, climatic, and environmental systems</td>
</tr>
<tr>
<td><strong>Fusion Energy Sciences</strong></td>
</tr>
<tr>
<td>• Building the scientific foundations for a fusion energy source</td>
</tr>
<tr>
<td><strong>High Energy Physics</strong></td>
</tr>
<tr>
<td>• Understanding how the universe works at its most fundamental level through research, projects, and facilities</td>
</tr>
<tr>
<td><strong>Nuclear Physics</strong></td>
</tr>
<tr>
<td>• Discovering, exploring, and understanding all forms of nuclear matter</td>
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</tbody>
</table>

[http://science.energy.gov/](http://science.energy.gov/)
... To understand how the universe works at its most fundamental level –
- It’s particles, interactions, space - time

HEP Paths for Discovery Science:
- projects, facilities, research program

Community Report P5 and Science Drivers

Research tools, techniques and technology developed along the way benefits society and the S&T ecosystem
How HEP and QIS got Entangled...

- HEP has been working with the community, SC, and other agencies to identify its QIS connections since 2014, including participation in the NSTC Interagency Working Group.

- Workshops and community reports inform program growth:
  - **Jan. 2015:** ASCR-HEP Study Group on “Grand Challenges at the Interface of Quantum Information Science, Particle Physics, and Computing”
  - **Feb. 2015:** BES-HEP Round Table Discussion on “Common Problems in Condensed Matter and High Energy Physics”
  - **Feb. 2016:** HEP-ASCR Roundtable on “Quantum Sensors at the Intersections of Fundamental Science, Quantum Information Science and Computing”
  - **July 2016:** NSTC report on “Advancing Quantum Information Science: National Challenges and Opportunities” (HEP Participation)
Foundational concepts and mathematical formulations that explore black hole physics and how black holes scramble information lead to new ways to study how qubits stabilize in the laboratory & fault tolerance.

Quantum Error Correction Codes Improve techniques to understand the Cosmos and the emergence of Space Time.
Simulating Black Holes?

- Simulate the quantum information dynamics of a black hole
- Black Holes (BH) perform fast scrambling of Information
- Quantum circuits in the lab can parallel this type of fast scrambling dynamics and used to explore the famed BH information paradox - that one can retrieve information that has fallen beyond the event horizon so long as the BH dynamics are both unitary and scrambling.
- In turn, these experiments may help improve qubit stabilization
Most qubits are also precision quantum sensors

New ways to explore dark universe and elusive neutrinos

HEP expertise and technology can advance QIS- example

Technology underpinning giant particle accelerators

Can be adapted and developed to make better qubits

Development of advanced superconducting radio frequency (SRF) cavities (example from FNAL), cryogenics, and other technologies supporting development of qubits, their ensembles, quantum sensors, and quantum controls across DOE National Labs.
QIS Based Discovery for Science Drivers

- Quantum Sensors using QIS
- Foundational Gauge theory using Entanglement
- Quantum computing on annealers
- Quantum algorithms for particle physics
- QI and Emerging Space time
- Quantum simulations on entangled Qubits

HEP techniques can make better sensors and add foundational insight for QIS
FY 2017 HEP Pilots in QIS

HEP has supported a few modest pilot projects involving quantum information science in both National Laboratories and universities mostly via partnerships

- Simulated particle scattering off a complex boundary condition by quantum algorithms (HEP/ASCR/U Maryland Stephen Jordan)
- Quantum pattern recognition for real time data tracking & quantum algorithms for exponentially increased storage (HEP/LBNL Illya Shapoval)
- Black hole information paradox pilot experiment (HEP/LBNL Norman Yao)
- Quantum annealing for ML to separate signal/background in Higgs LHC data (HEP/Caltech-FNAL Maria Spiropulo) published in Nature
- Entanglement & quantum chaos: toy models, holography, spin chains (HEP-BES/Princeton Juan Maldacena & Shivaji Sondhi)
HEP-QIS Programmatic Thrusts

- **Qubits & the Universe**
  - (Theory, Simulation, Emulation Experiments)

- **Gauge theory, analog simulations, entanglement**
  - (Connecting field theory to qubits)

- **Quantum Computing for HEP**

- **Early stage HEP expertise for QIS technology**

- **HEP-QIS Interdisciplinary Research, Research Technology, Discovery**

- **HEP-QIS (small) experiments, early tech research**
HEP-QIS Program Objectives

- HEP-QIS Objectives: The HEP QIS Thrust is intended to forge new routes to scientific discovery along the HEP mission and P5 science drivers invoking interdisciplinary advances in the convergent field of QIS, and their intersection with expertise, techniques, and technology developed within the HEP community.

- The goals of the HEP QIS Thrust include developing interdisciplinary consortia that positively impact both HEP and QIS fields.

- Some weighted more for HEP – some for QIS

- Foundational HEP-QIS Research
  - Theory, Computing & Simulation Experiments
  - Quantum Computing for HEP
  - Novel sensors using entanglement & Squeezing
  - HEP Technology for QIS

Credit – Microsoft Bing search
HEP Inter Agency QIS Partnerships

DOD – HEP coordinated QIS partnerships

- We have two Pilots on the Cosmos and Qubits Theme

NIST - HEP coordinated partnerships – in planning

- Mission synergy to understand fundamental constants and Beyond Standard Model Physics.
- Quantum Sensors and precision instrumentation for HEP Detectors and fundamental physics research
Quantum Information Science Enabled Discovery (QuantISED) for High Energy Physics [DE-FOA-0001893/LAB 18-1893] (Funding Opportunity Announcement)

Objective: Forge new routes to scientific discovery along HEP mission and P5 science drivers, invoking interdisciplinary advances in the convergent field of QIS, and intersection with expertise, techniques, technology developed in HEP community

Track 1: Pioneering Pilots (Topics A or B): Novel concepts, test problems, design studies (TRL 1)

Track 2: HEP-QIS Consortia (Topic A only): Address P5, small experiments, early research on tools (TRL 1-2) [required a DOE Lab partner]

Out of Scope:
- General quantum computing algorithms or computing hardware
- Requests for basic research within the mission space of other SC programs
- Purchase of equipment or instruments exceeding 10% of the total project
- or $20,000 whichever is less
Future Opportunities – Stay Tuned

- DE-FOA-0001893/LAB 18-1893 Closed on April 16th.
- Office of Science (SC) also had Calls from BES and ASCR
- SC announcement of awards expected Sept. 2018
- Future opportunities are anticipated for 2019
- Influencing Factors: Appropriations, DOE Directives
- Anticipated thrust areas may partially evolve
- Will look for Pioneering Pilots for new Ideas
- Refer Bill’s excellent talk for process and details on FOAs
- HEP-QIS is outside the traditional HEP sub programs *
- Requires interdisciplinary partnerships
- HEP – QIS strategy aligned to SC QIS Strategy

* Talk to your PM about other HEP Sub Programs
SC’s QIS Strategy

- Builds on community input
- Highlights DOE/SC’s unique strengths
- Leverages groundwork already established
- Focuses on cross-cutting themes among programs
- Targets impactful contributions and mission-focused applications

DOE/SC Contributions to QIS

- Fundamental Science
- Tools, Equipment, Instrumentation

DOE Community Resources

QIS Applications

- Quantum Computing: Simulation, Optimization, Machine Learning
- Analog Quantum Simulation
- Sensing and Microscopy
**SC Unique Strengths**

- Intellectual capital accumulated for more than a half-century
- Successful track record of forming interdisciplinary yet focused science teams for large-scale and long-term investments
- Demonstrated leadership in launching internationally-recognized SC-wide collaborative programs

<table>
<thead>
<tr>
<th>ASCR</th>
<th>BES</th>
<th>HEP</th>
<th>NP</th>
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<tbody>
<tr>
<td>Quantum algorithms; uncertainty quantification and verification &amp; validation methods; software stack; quantum networks</td>
<td>Synthesis, characterization, modeling, and instrumentation to advance quantum chemistry and materials</td>
<td>Black hole physics; quantum gravity/ error correction; field theory, entanglement, qubits &amp; sensors</td>
<td>Isotopes and trapped ions for quantum devices; lattice quantum chromodynamics</td>
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**Quantum Field Theory and Topology**

**Control of Quantum Phenomena**
Tools, Equipment, Instrumentation

Quantum Computing Hardware

ASCR’s Testbeds Program:
• Research into device architectures and system integration optimized for science applications
• Development of hybrid platforms and quantum/classical coprocessors
• Early access to new quantum computing hardware for the research community

Tool R&D for QIS
• Extensive nanoscience tools for quantum structure synthesis and integration
• Detectors and metrology
• Quantum sensors enabling precision measurements
• Quantum computational tools
• Superconducting RF cavities, laser cooling, neutral ion traps, spin manipulation technology, and isotope production

Key DOE-SC Contributions:
• Well-established co-design practices in computer hardware development
• Experience in collaborations with industry and core competencies in delivering major projects involving equipment, tools, and instrumentation for discovery and implementation
• Demonstrated success in generating leading scientific tools with and for the international user community
### World-Class National Laboratory resources

- Advanced fabrication capabilities, (e.g. Microsystems & Engineering Sciences Applications (MESA) facility at SNL)
- Specialized synthesis and characterization capabilities (e.g. Enriched Stable Isotope Prototype production plant)
- Internal research computing capabilities, experimental equipment, and prototypes (e.g. D-Wave)
- Engineered physical spaces (e.g. EM-shielded rooms, low-vibration chambers, deep shafts)

### Focused programs and intellectual property

- Internships and visiting programs for students and faculty
- National Laboratory technical assistance programs
- Access to intellectual property developed at National Laboratories via technology licensing agreements
- Early Career Research Program
- Small Business Innovation Research
- Computational Science Graduate Fellowship

### User Facilities include:

- Synchrotron and x-ray free electron laser light sources
- Observational and communications networks
- Nanoscale Science Research Centers
- High Performance Computing and Network
Some of the questions Feynman asked starting in the seventies:

Can a classical, universal computer simulate any physical system?

And in particular, what about quantum systems?

While we still don’t know the answers –  
  we have a lot of qubit systems to try working with!

Industry has made available test systems and there are exploratory systems in  
academia and Labs. As we move forward the QIST confluence of QUANTUM

*theory*information*entanglement*experiment*simulation*computing*technology ...

will help explore the unknown and other science drivers and a lot more along the way.
## International Competition in HPC Continues to Intensify – Slide from B. Helland

<table>
<thead>
<tr>
<th>#</th>
<th>Site</th>
<th>Manufacturer</th>
<th>Computer Model</th>
<th>Country</th>
<th>Cores</th>
<th>Rmax [Pflops]</th>
<th>Power [MW]</th>
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<tbody>
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<td>1</td>
<td>National Supercomputing Center in Wuxi</td>
<td>NRCPC</td>
<td>Sunway TaihuLight</td>
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<td>National University of Defense Technology</td>
<td>NUDT</td>
<td>Tianhe-2 DT TH-IVB-FEP, Xeon 12C 2.2GHz, IntelXeon Phi</td>
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<td>Swiss National Supercomputing Centre</td>
<td>Cray</td>
<td>Piz Daint Cray XC50, 2.6GHz, Aries, NVIDIA Tesla P100</td>
<td>Switzerland</td>
<td>361,760</td>
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<td>Japan Agency for Marine Earth-Science and Technology</td>
<td>ExaScaler</td>
<td>ZettaScaler 2.2 HPC System, Xeon D-1571 16C 1.3 GHz, Infiniband EDR, PEZY SC2, 700 MHz</td>
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<td>Titan Cray XK7, Opteron 16C 2.2GHz, Gemini, NVIDIA K20x</td>
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<td>IBM</td>
<td>Sequoia BlueGene/Q, Power BQC 16C 1.6GHz, Custom</td>
<td>USA</td>
<td>1,572,864</td>
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<td>7</td>
<td>Los Alamos NL / Sandia NL</td>
<td>Cray</td>
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<td>3.84</td>
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<td>8</td>
<td>Lawrence Berkeley National Laboratory</td>
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<td>Cori Cray XC40, Intel Xeons Phi 7250 68C 1.4 GHz, Aries</td>
<td>USA</td>
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<td>9</td>
<td>Joint Center for Advanced HPC</td>
<td>Fujitsu</td>
<td>Oakforest-PACS PRIMERGY CX1640 M1, Intel Xeons Phi 7250 68C 1.4 GHz, OmniPath</td>
<td>Japan</td>
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<td>RIKEN Advanced Institute for Computational Science</td>
<td>Fujitsu</td>
<td>K Computer SPARC64 VIIIfx 2.0GHz, Tofu Interconnect</td>
<td>Japan</td>
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### Quantum Technologies: A £1 billion future industry for the UK

Japan enters quantum computing race -- and offers free test drive

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### Quantum Canada Vision

A vibrant Canadian quantum ecosystem with world-leading R&D, innovative technologies, and globally reaching Canadian companies – all driving social, economic, and environmental solutions for Canada

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### Europe’s billion-euro quantum project takes shape

Engineering of Swedish Quantum Computer Set to Start

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China will open a $10 billion quantum computer center

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Russian Researchers Claim First Quantum-Safe Blockchain

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University of Melbourne joins IBM’s quantum computing club

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[11x419] China will open a $10 billion quantum computer center

[214x70] Europe’s billion-euro quantum project takes shape

[508x467] Engineering of Swedish Quantum Computer Set to Start

[133x221] Quantum Canada Vision

[34x199] A vibrant Canadian quantum ecosystem with world-leading R&D, innovative technologies, and globally reaching Canadian companies – all driving social, economic, and environmental solutions for Canada

[9x379] Russian Researchers Claim First Quantum-Safe Blockchain

[9x340] Quantum Technologies: A £1 billion future industry for the UK

[520x226] Japan enters quantum computing race -- and offers free test drive

[666x226] Quantum Technologies: A £1 billion future industry for the UK

[379x261] Quantum Technologies: A £1 billion future industry for the UK

[379x300] Quantum Technologies: A £1 billion future industry for the UK