Quantum Information Science

(and Quantum Computing)

Presented to the

Fusion Energy Sciences Advisory Committee

by

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Introduction to Quantum Information Science (QIS)

Quantum Theory

"The universe is lumpy and fuzzy"

1900-1905: light and matter are quantized
1925-1926: mathematical formalism; uncertainty principle

Provides a basis for understanding physical processes ranging from sub-nuclear to the cosmological.

Applications include lasers, magnetic resonance imaging, atomic clocks, …

Classical Information Theory

"Information is physical"

1940s: information encoded in bits, manipulated with boolean algebra
1960s: information related to energy, entropy

Provides a basis for understanding communication and computation, allows efficient encoding and transmission of information.
Applications include computers, telecommunications networks, cryptanalysis …

Quantum Information Science

The combination of quantum theory and classical information theory provides powerful tools for scientific discovery and development of new technology.

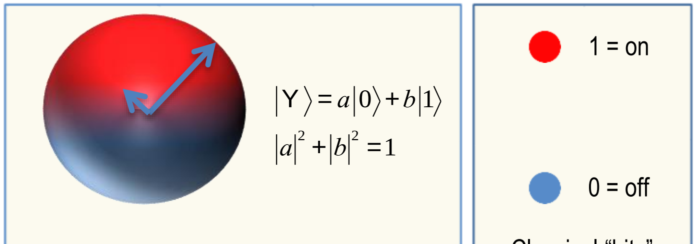
1970s: quantum optics; theoretical description of quantum information, quantum communication
1990s: Shor's algorithm (prime factorization), first quantum gates (theory and experiment)

Applications include information processing (including quantum computing), ultra-secure information encoding, high-fidelity communication, precise sensing, metrology, timekeeping, navigation, imaging …

Key Concepts

QIS applications differ from earlier applications of quantum mechanics by exploiting quantum properties to measure, process, and transmit information in novel ways that greatly exceed existing capabilities.

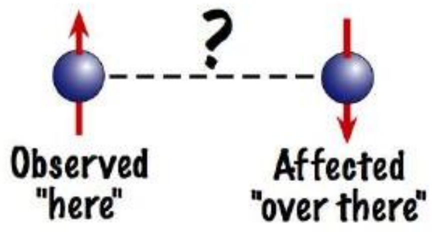
Superposition: *Quantum systems, including single particles, are described by a set of variables that can take on a range of values. Until the value of each variable is measured, the system is in a* ***superposition state*** *that includes all possible measurement outcomes with some probability.*



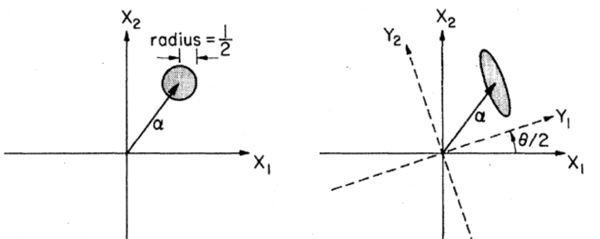
Quantum "qubits": state superposition

Classical "bits"

Entanglement: *An* ***entangled state*** *is a superposition of the states of multiple particles in which the properties of each particle are correlated with the properties of the other particles, even if the particles are separated by a large distance.*



Squeezing: *The uncertainty principle places a lower bound on the combined uncertainty in pairs of variables, but does not specify how the uncertainty is distributed between them. A* ***squeezed state*** *has the minimum allowed total uncertainty, but allows more precise determination of one variable than the other.*



PRD **23**, 8 (1981)

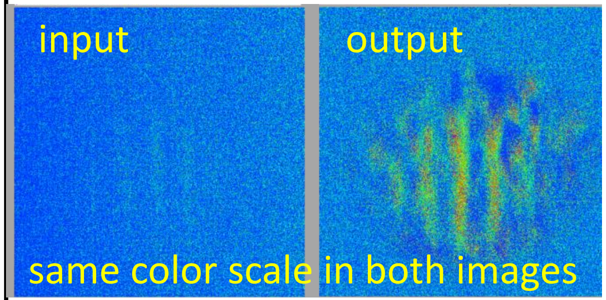
QIS Significance and Applications

QIS will provide the basic technological foundation for countless applications, including those in the following areas:

Sensing and Metrology

Improved sensitivity:
- magnetometry
- gravimetry
- inertial and rotation sensors
- low-noise imaging
- precision timing

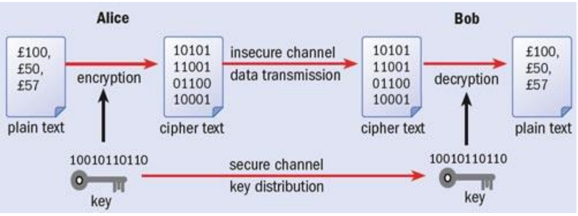
Example: noiseless amplification



Communication

Quantum information transfer:
- technically challenging (“no cloning”)
- for distributed sensor networks
- long-distance information exchange
- inside a quantum computer

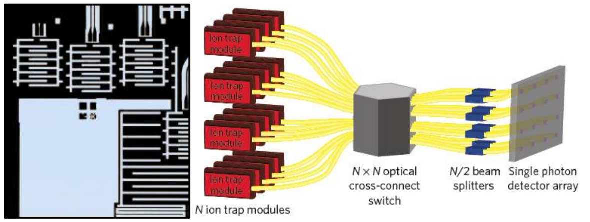
Secure information exchange:
- eavesdroppers easily detected
- “quantum fingerprinting”



Simulation/Computing

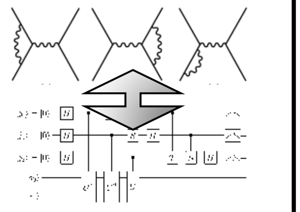
“Analog” simulation:
- model materials and chemicals

“Digital” computing:
- significant speedup for select problems
- fully programmable
- many possible technologies
- applications in factorization, search algorithms, optimization (?)
- potential not yet fully understood

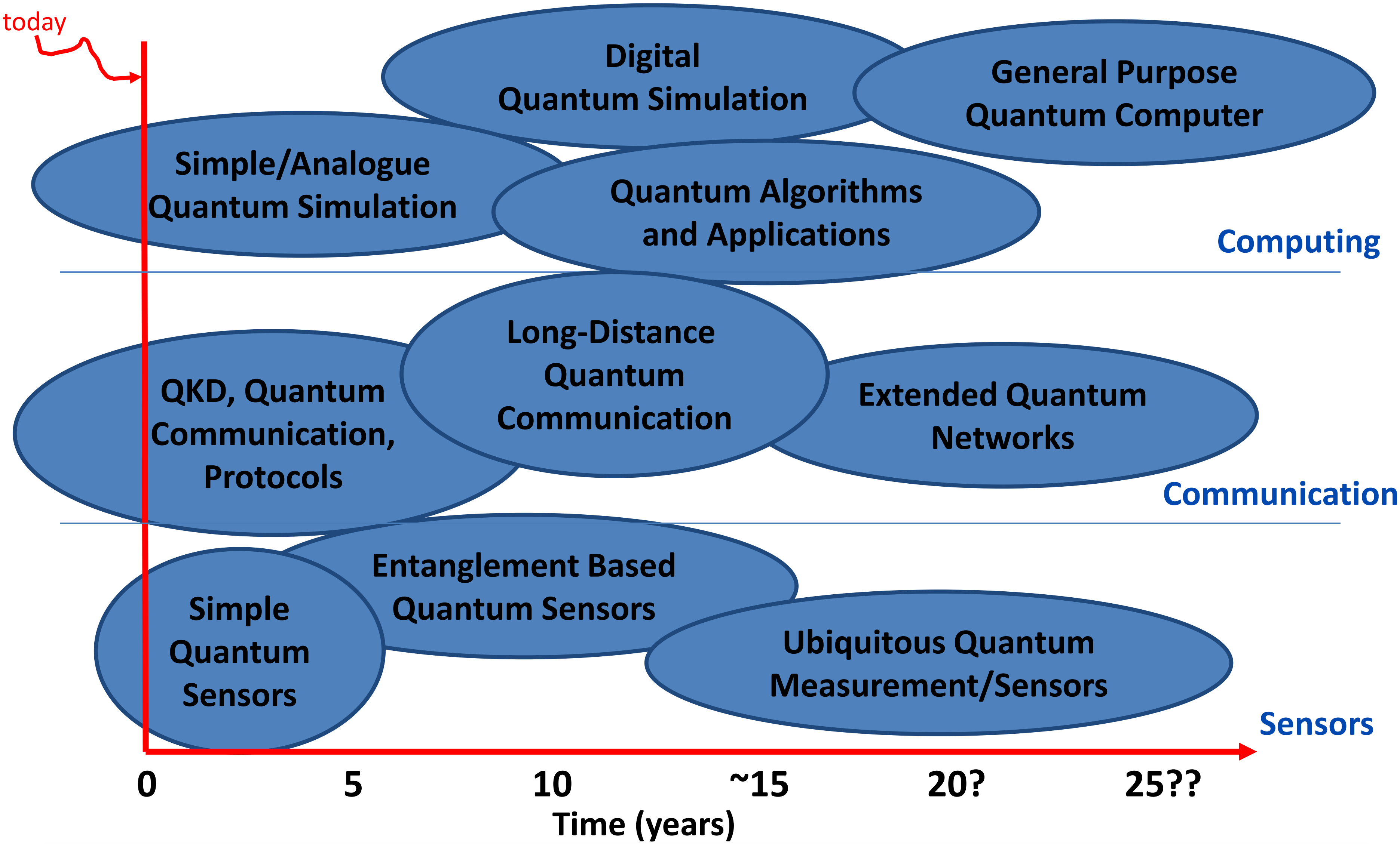


Basic Science

- Basic research in the physical sciences will continue to drive progress in QIS
- QIS research will continue to lead to innovation in other fields (e.g., high energy physics)
- QIS techniques and technology will impact experimental research in all fields
- QIS modeling and computational methods will drive scientific discovery (e.g., materials)



Quantum Information/Technology Landscape



Strategic Impacts of QIS

National Security

- Cryptography and cryptanalysis
- Robust, reliable inertial navigation
- Detection of underground structures
- New materials for military ships, aircraft, electronics
- Quantum-secure ground-to-satellite communication
- Robust, secure GPS

Economic Competitiveness

- New products based on quantum properties
  - Metrology, sensors, communications, imaging tools, quantum computing, cryptography
- Quantum-secure communications networks, unforgeable virtual money, quantum fingerprinting
- New industries to create and market these technologies
- Expanded opportunities for existing companies
- International marketplace; Leverage by owning intellectual property

Frontiers of Science

- Discovery of new materials using quantum simulations
- New, fundamental insights in nuclear & particle physics, cosmology, astronomy
- New sensors, detectors, imaging capabilities across all physical science domains
- Further advances in quantum mechanics itself
- Pushing boundaries in other fields (e.g., light sources that serve life sciences communities)

Quantum Information Science is at a Tipping Point

Sustained USG investments over 20+ years have set the stage for rapid progress in application of QIS. Within the last five years,

U.S. and international companies are embracing QIS

- Major IT industries: Google, Microsoft, IBM, Intel
- Technology companies: Lockheed-Martin, Northrop Grumman, Battelle, BBN, Toshiba
- New companies: AOSense, MagiQ, ColdQuanta, Zyvex, D-Wave (Canadian)
- *U.S. companies are making significant investments in research in both the U.S. and abroad*

Foreign competition is expanding rapidly

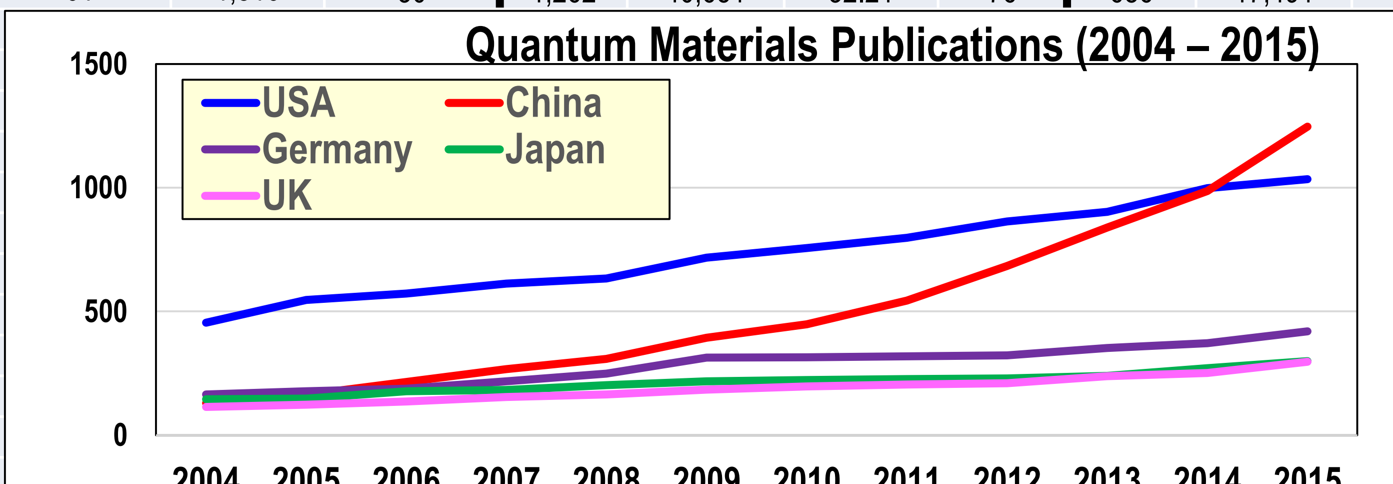
- Some foreign investment levels are approaching those in the U.S.
- Foreign governments are implementing focused QIS initiatives
  - China, UK, Germany, Canada, Japan, Italy, Australia, Netherlands, EU
- Lucrative research opportunities abroad are attracting top-tier U.S. researchers
- If current trends persist, some countries may exceed U.S. capabilities within a decade

But significant challenges lie ahead

- QIS is inherently multidisciplinary – barriers exist between disciplines in both universities and federal funding agencies
- Research performers perceive stability and predictability of funding as issues
- Poor alignment of workforce with employment opportunities and required skills

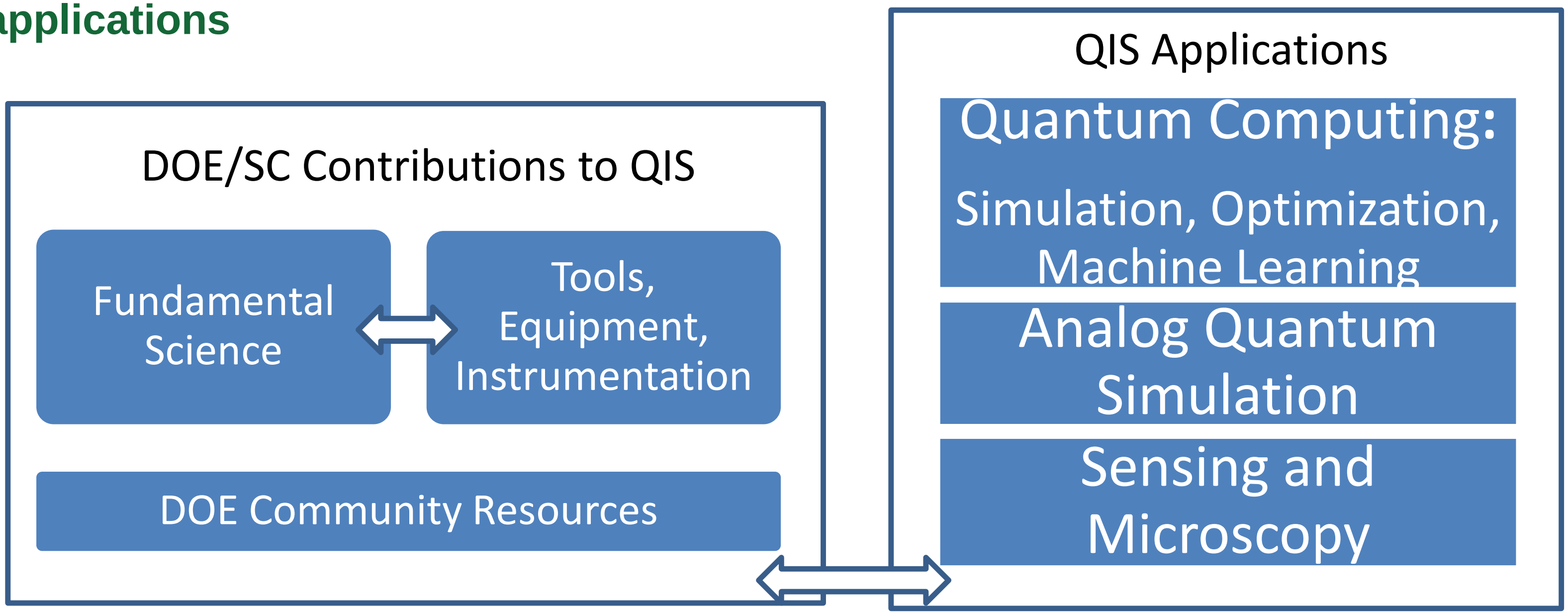
Quantum Materials & Quantum Chemistry: Web of Science Stats (2004 – 2015)

				Quantum Materials				Quantum Chemistry			
Country	Population (M)	GDP ($B)	GDP/PC ($K)	# papers	Total Citations	Avg. Citations	h-index	# papers	Total Citations	Avg. Citations	h-index
USA	322	18,036	56	8,887	435,947	49.05	266	4,459	173,140	38.06	163
China	1,373	11,182	8.1	6,225	157,889	25.36	155	2,709	48,366	17.85	90
Germany	82	3,365	41	3,406	107,079	31.44	135	2,029	72,044	35.51	100
Japan	127	4,124	32	2,559	72,391	28.29	115	851	17,397	20.44	57
UK	65	2,858	44	2,259	114,171	50.54	113	904	42,342	46.84	79
France	64	2,420	38	1,867	60,317	32.31	92	1,192	40,733	34.17	75
India	1,292	2,073	1.6	1,614	25,417	15.75	64	710	10,471	14.75	40
South Korea	51	1,378	27	1,515	42,562	28.09	81	255	9,625	37.75	41
Italy	61	1,816	30	1,262	40,651	32.21	76	686	17,491	25.5	59
Canada										2.79	58
Russia										0.72	37
Spain										4.14	58
Taiwan										3.28	30
Switzerland										1.18	56
Australia										9.58	43
Poland										6.31	36
Netherlands										7.09	47
Sweden										0.44	50
Brazil										4.11	27
Singapore										7.21	25
Belgium										2.11	41



DOE 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, science for next-generation advances, and mission-focused applications**



Fundamental Science That Advances QIS

ASCR
Quantum algorithms; uncertainty quantification and verification & validation methods; software stack; quantum networks

BES
Synthesis, characterization, theory, modeling, and instrumentation to advance quantum materials & chemical phenomena

HEP
Black hole physics; quantum gravity and quantum error correction; fundamental aspects of entanglement

NP
Isotopes and trapped ions for quantum devices; lattice quantum chromodynamics

Quantum Field Theory and Topology

Control of Quantum Phenomena

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**

Fundamental Science That Advances QIS

We will leverage the groundwork already established in DOE National Labs and the academic groups to maximize SC's impact on QIS. Examples include:

In April 2017, the researchers have successfully run 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.

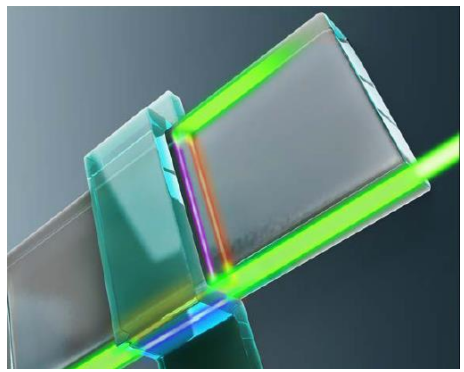
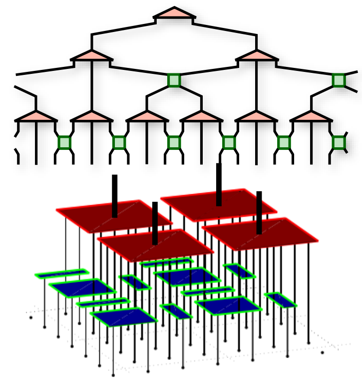
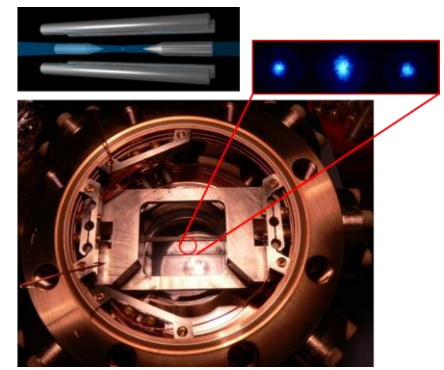


Illustration of a topological insulator with a superconducting layer on top for detection of Majorana fermions (colored lines). Once identified and isolated, Majorana fermions could form the basis of qubits. Electrons (green) travel along the edges of the structure. Supported in part by the BES Energy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

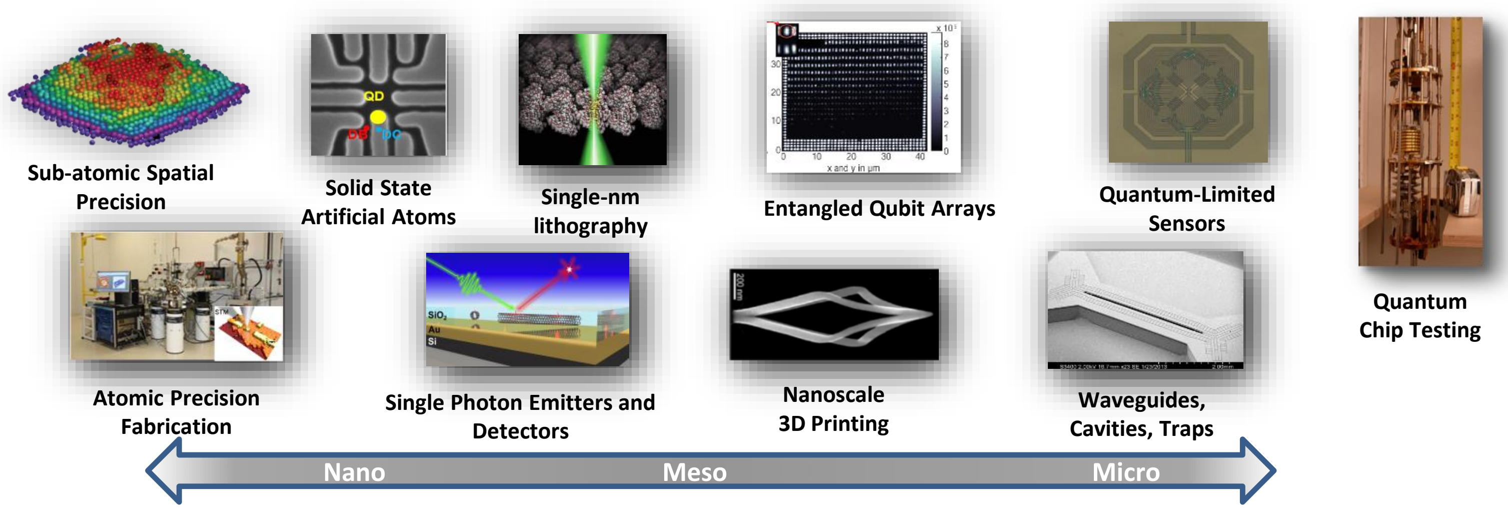


A laser cooled, RF confined ion trap at Argonne National Laboratory: trapped ions can be used as qubits and as quantum simulators.

Fundamental Science That Advances QIS

Quantum Integration Across Scales

- BES Nanoscale Science Research Centers user facilities are key to the synthesis and characterization of materials and structures from nano-components to prototype-scale quantum systems.
    - Integration and testing couple closely to theory, design, and systems efforts
    - Co-located with National Lab x-ray, neutron, computing, and microfabrication facilities for understanding and scale-up of quantum structures
    - Next-generation qubits and sensors
- BES research broadly advances understanding and use of quantum materials and chemical phenomena, integrating theory and experimental science



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

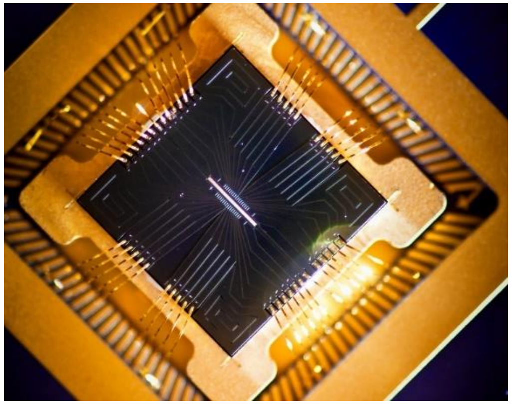
- Extensive nanoscience tools for quantum structure synthesis and integration
- Detectors and metrology
- Quantum sensors enabling precision measurements
- Quantum computational tools
- Superconducting RF cavities, laser cooling, neutral ion traps, spin manipulation technology, and isotope production

Key DOE-SC Contributions:

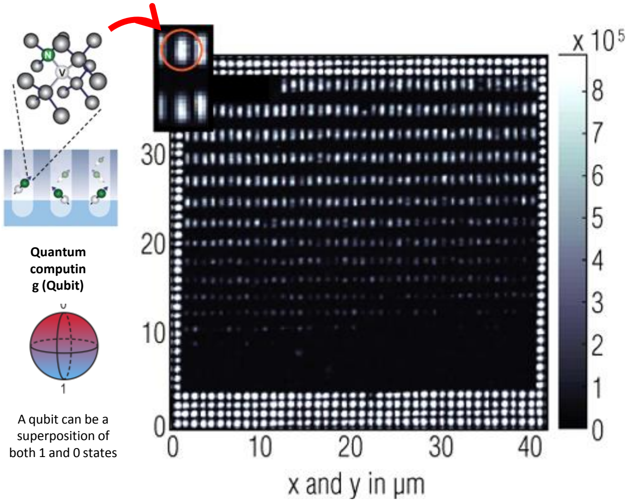
- Well-established co-design practices in computer hardware development
- History of fundamental research leading to prototype devices, characterization and synthesis tools, and techniques
- Experience in collaborations with industry and core competencies in delivering major projects involving equipment, tools, and instrumentation for discovery and implementation
- Demonstrated success in generating leading scientific tools with and for the international user community

Tools, Equipment, Instrumentation

DOE SC programs and DOE National Laboratories embody a wealth of knowledge and experience in key technologies to provide mechanisms 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.

DOE Community Resources

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

- Strong university and national laboratory research programs
- 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

User Facilities include:

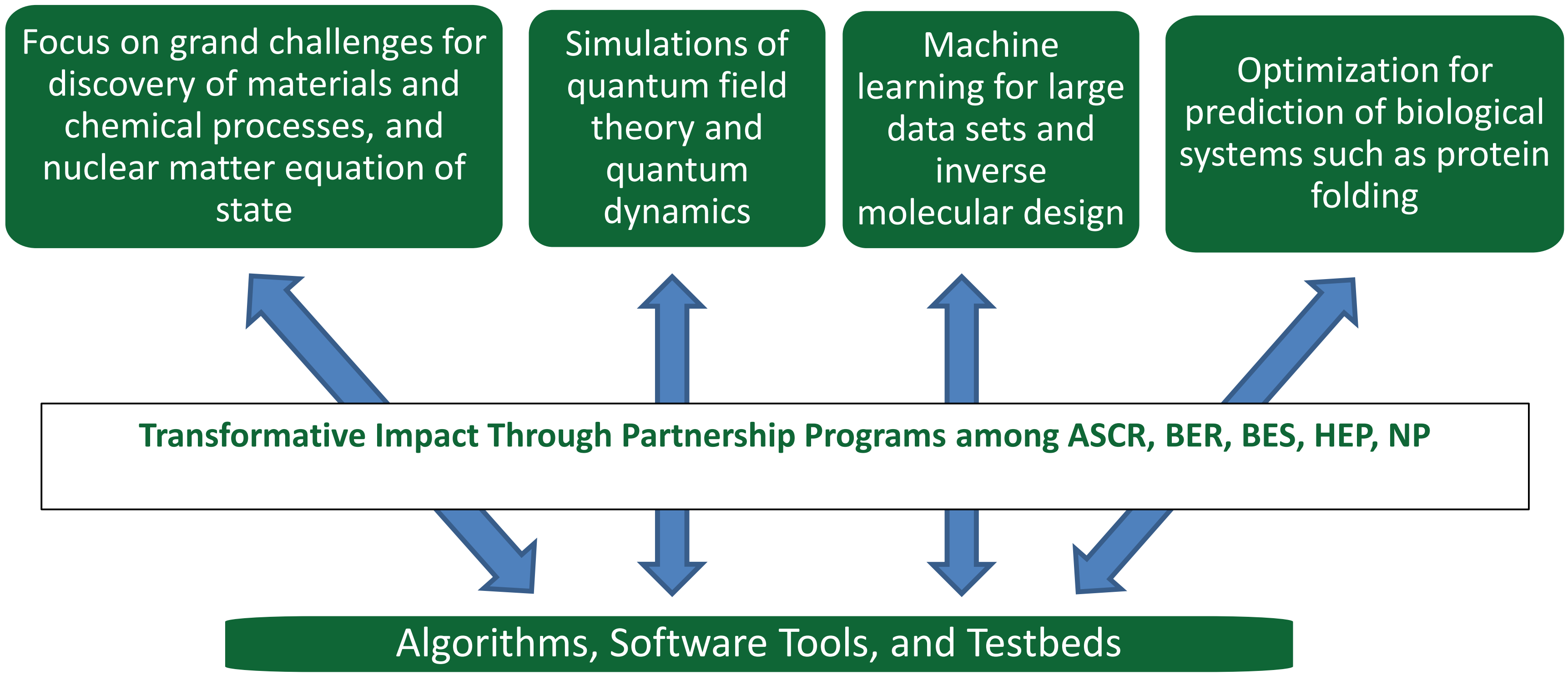
Synchrotron and x-ray free electron laser light sources

Observational and communications networks

Nanoscale Science Research Centers

High Performance Computing and Network

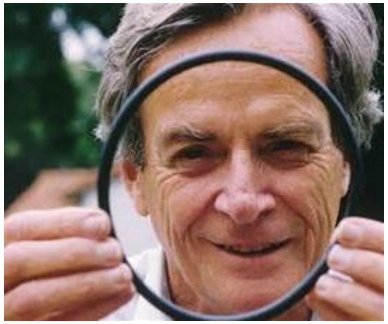
Quantum Computing Applications for SC Grand Challenges



Impacts of Quantum Computing

- ***National and economic security:***
  - Quantum computers could break all present-day public key encryption systems
  - Quantum encryption not susceptible to computational attack
- ***Physical sciences:***
  - Quantum simulations: materials design, pharmaceutical design, chemical processes, etc. – any problem that involves quantum mechanics
  - Broad non-computing impacts in new sensor and detector technologies:
    - Diamond NV (nitrogen-vacancy) centers are leading to previously unimaginable magnetic imaging systems
    - Chip-scale atomic clocks – precision timekeeping
    - Exquisitely sensitive magnetometers, accelerometers, gravimeters
    - Fundamentally new detectors and sensors in physical sciences, based on superposition, entanglement, and squeezing

DOE-Relevant Quantum Computing Applications

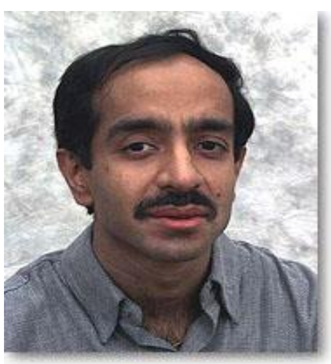


FEYNMAN QUANTUM SIMULATION: 1982

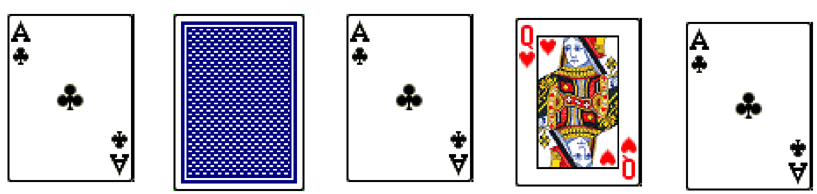
- Simulate physical systems in a quantum mechanical device
- Exponential speedups

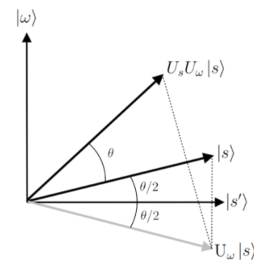
LLOYD, et al., LINEAR EQUATIONS SOLVER: 2010

- Applications shown for electromagnetic wave scattering
- Exponential speedups



GROVER'S SEARCH ALGORITHM:1996





Questions?