OFFICE OF THE DIRECTOR OF NATIONAL INTELLIGENCE

Quantum Computing Research
at IARPA

Brad Blakestad, PhD
IARPA Program Manager

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INTELLIGENCE ADVANCED RESEARCH PROJECTS ACTIVITY (IARPA)

What is Quantum Information?

"*Quantum information is a radical departure in information technology, more fundamentally different from current technology than the digital computer is from the abacus*" —W.D. PhIlips, 1997 Nobel Prize in Physics

Born from the synthesis of two disciplines

Quantum Mechanics
(theoretical basis for semiconductor microelectronics and photonics underpinning post-industrial information economy)

Information Science
(Quantifies information content, provides framework for efficient communication and information processing)

The Next Quantum Revolution

- Information can be characterized, quantified, and processed using the basic rules of quantum mechanics.

- Quantum information science (QIS) exploits quantum properties of light and matter to acquire, process, transmit information in ways greatly exceeding existing capabilities.

Quantum Tech: Why We Do It
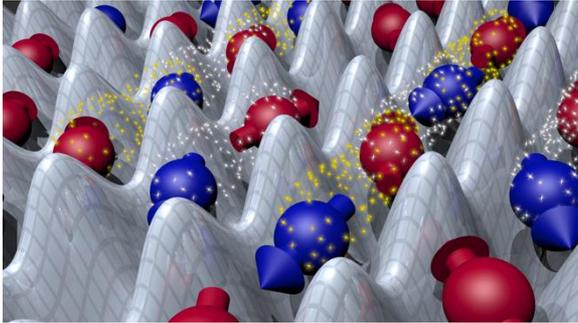
New Materials and Drug Discovery

- Calculate the properties of materials.
- Save on time-consuming approximate techniques on conventional high performance computers.
  - Materials calculations are 2nd-largest use of DOE's National Energy Research Scientific Comp Center.
- Computationally design new drugs.

Sensing and Metrology

- Adapt cold atom inertial sensors for use as gravimeters for Earth system monitoring.
  - Pinpoint the location of mineral deposits, etc.
- Develop the most precise timekeeping devices in the world (à la NIST's quantum logic clock).
- Increase sensitivity and reduce noise in digital images.

- Photon sources, measurement techniques developed for quantum communication will:
  - Improve calibration of light-sensitive detectors,
  - Enable detection of trace elements in low-absorption and quantity-limited samples.
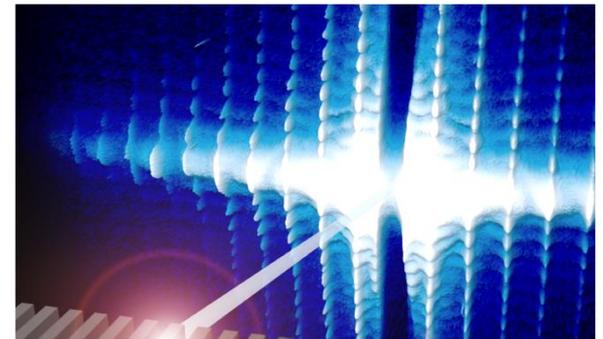
Quantum Tech: Why We Do It
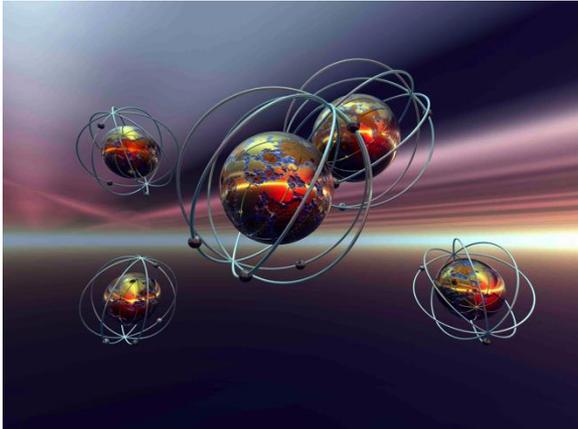
Navigation

- GPS networks can be jammed or physically attacked.
- Absent GPS, we rely on inertial navigation systems that measure acceleration and rotation.
  - Replace less accurate gyroscopes with QIS-based cold atom sensors.
  - Navigate accurately without GPS for ≥100x longer.

Magnetometry

- The most sensitive magnetometers are bulky and expensive due to the need for liquid cryogens.
- NV diamond centers are sensitive to small magnetic fields, microscopic, and can be brought extremely close to biological samples without causing damage.
- Map the position of magnetic molecules in living cells at room temperature.
- Wide-range of potential applications in biology and medicine.
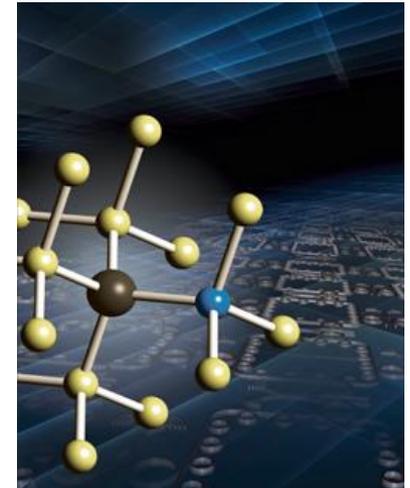
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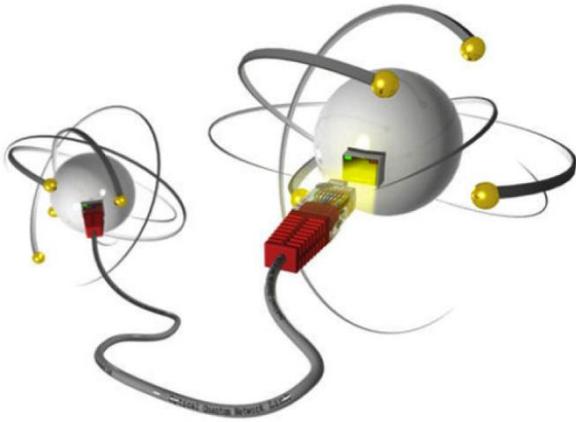
Communication

- Pursue quantum networks to connect distributed quantum sensors.
  - Ultra-secure communication networks.

Computing

- Process information and perform certain computations much more efficiently than is possible using conventional computers.
  - Aid in strategic decision-making.
- Quantum computing (QC) hardware is at the laboratory prototype stage and progressing steadily.
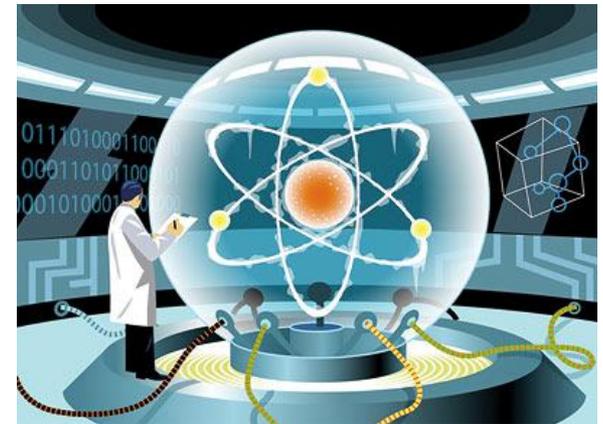
How Quantum Computers Work

Today's Computers

- Work by manipulating bits that exist in either one of two states: 0 or 1.

Quantum Computers

- Not limited to two states.
  - Encode information as quantum bits, or qubits, which can exist in superposition.
  - Due to superposition, quantum computers can represent either 0 or 1, or both simultaneously.
- Entangled qubits allow multiple numbers to be represented simultaneously: |000>.

A quantum computer can work on a million computations at once, while your desktop PC works on one.

Multiple computations simultaneously means computer power can be exponential.

How Quantum Computers Work

How can we represent data in quantum rather than classical states?

- Find a mechanical system where two states can be used to represent binary numbers.

- The "quantum" bits can be physically implemented using the energy levels of atoms, ions, photons, electrons, current states in superconductors, etc.

  o The ground state represents |0>, an excited state represents |1>.

- Together with their control devices, they act as a computer memory and processor.

Excited State

Ground State

Nucleus

Electron

Light pulse of frequency λ for time interval t

State |0>

State |1>
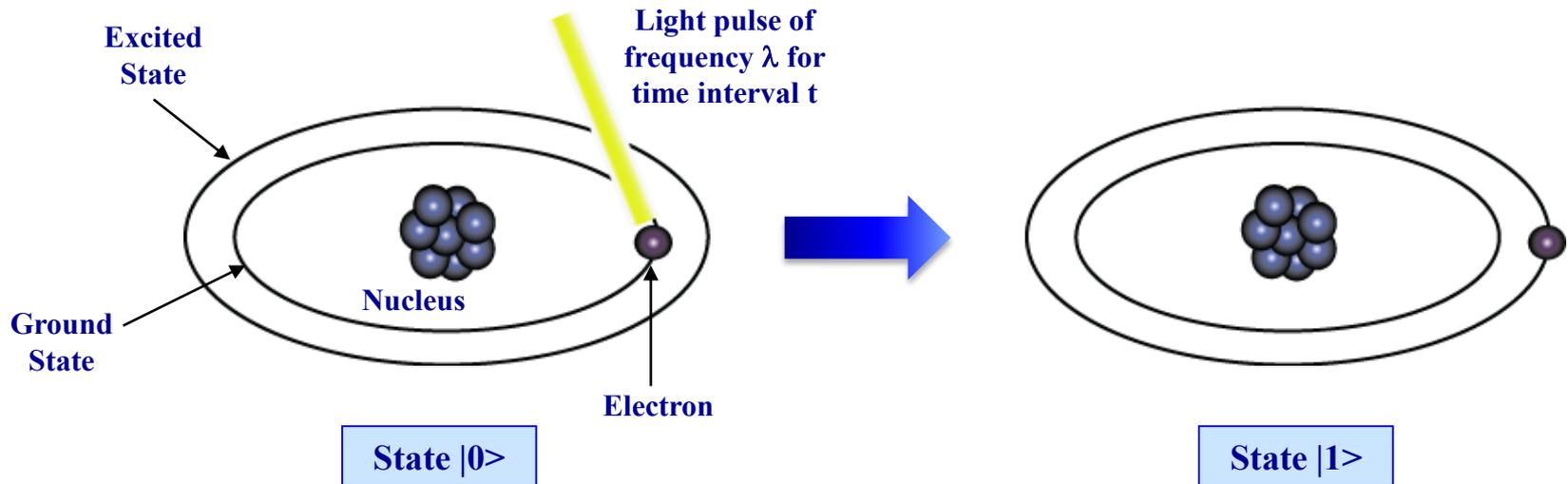
What To Do With a Quantum Computer?

Factorization of Large Integer Numbers
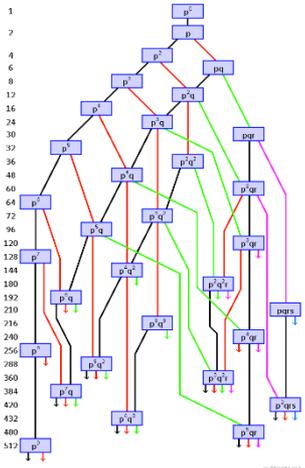
- Exponential speedup
- Relevant for:
  - RSA code,
  - Internet commerce,
  - Banking.

Quantum Search Algorithm
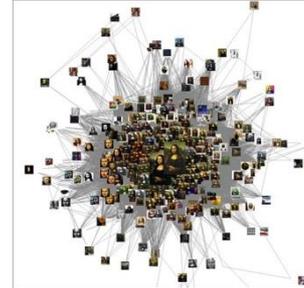
- Algebraic speedup
- Relevant for:
  - Process optimization,
  - Industry,
  - Military.

Quantum Cryptography

message to Bob

Alice

Transmit encoded info

Eve (eavesdropper)

If intercepted, info is transformed

Bob

Info arrives transformed, indicating interception

?
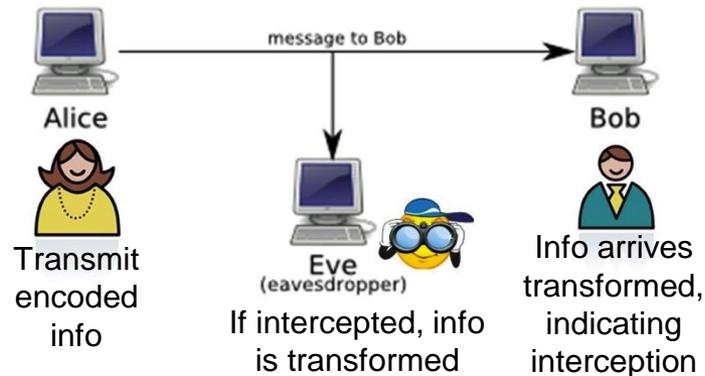
Quantum Simulation/Optimization
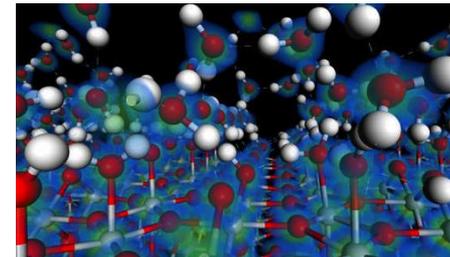
Design products for:
- Pharmaceutical Industry
- Nanoelectronics

IARPA Quantum Computing Programs to Date

Quantum Computer
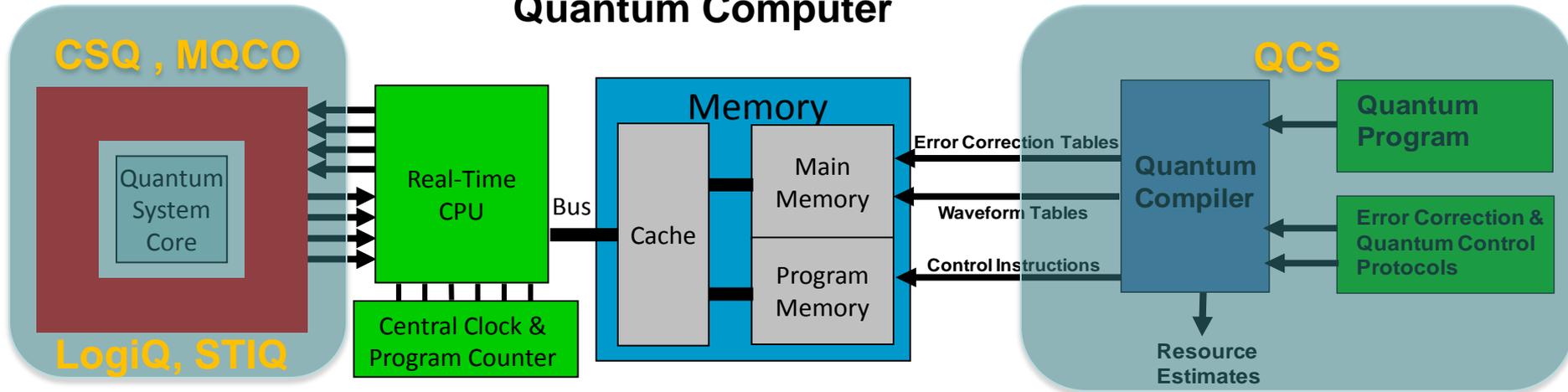
CSQ **2009-2014: Coherent Superconducting Qubits (K.F. Roenigk)**

Develop superconducting qubits with 10-fold lifetime through innovative designs, materials and fab

MQCO **2010-2015: Multi-Qubit Coherent Operations (D.L. Moehring)**

Address scalability issues (crosstalk, control, fabrication/yield, and footprint) in multi-qubit systems

QCS **2012-2014: Quantum Computer Science (M.I. Heiligman)**

Estimate and reduce resources required to implement quantum applications on simplified hardware

Logical Qubits (LogiQ) Program

Build and operate a logical qubit with active error correction

Dr. Brad Blakestad

Cleverly encoding physical qubits into a logical qubit can protect against destructive decoherence and gate errors.
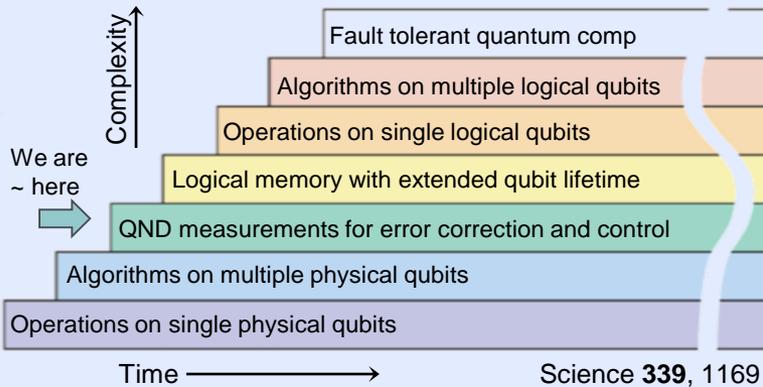
A logical qubit demonstration would validate the viability of quantum computers (next step to new era of computing).

Science **339**, 1169

Before LogiQ Program:

- Only proof-of-principle error correction, feedback and/or dynamical control.
- Operation fidelities below thresholds for relevant applications.
- Non-extensible architectures; system designs too large for near-term utility.

Demonstrate and manipulate a logical qubit that outperforms its constituent physical qubits in coherence times and gate fidelities.

Trapped Ions   Superconducting Qubits

Duke UNIVERSITY   Universität Innsbruck   IBM   TUDelft

Main Program Thrusts

Error Correction in logical qubit space

Improvement of **Physical Qubit Performance** to logical qubit needs

Theoretical model of coupled logical qubits with **Extensibility**

Supporting Government Agencies:
MIT Lincoln Lab, NIST, Sandia National Labs

Phase 1 (2016 – 2019)
Feasibility of concepts and demonstration of building blocks; Full control, functionality, feedback, of qubit architecture.

Phase 2 (2019 – 2021)
Logical qubit demo and characterization; Logical qubit surpasses physical qubits.

A Federal Vision for QIS

- Potential of QIS for economic and national competiveness prompted the U.S. to create in 2008 "A Federal Vision for Quantum Information Science".

- The Vision recognized the:
  - Great potential of the field,
  - Potential for disruptive technologies,
  - Need for sustained focused attention,
  - Need for agencies/departments to be adaptive to the needs of the field.

- USG has invested in quantum technologies since mid-1990s through DARPA, DoD, NSF, and IARPA.

- Interagency groups have been formed to explore quantum tech opportunities.

A Federal Vision for Quantum Information Science
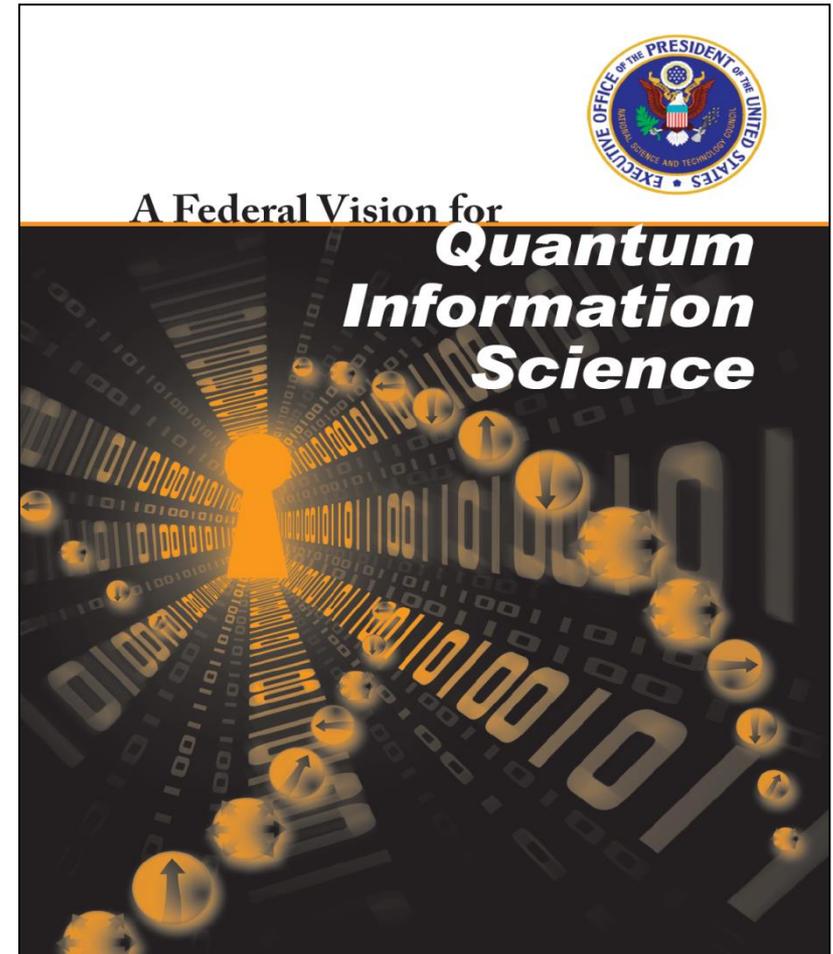
Getting There
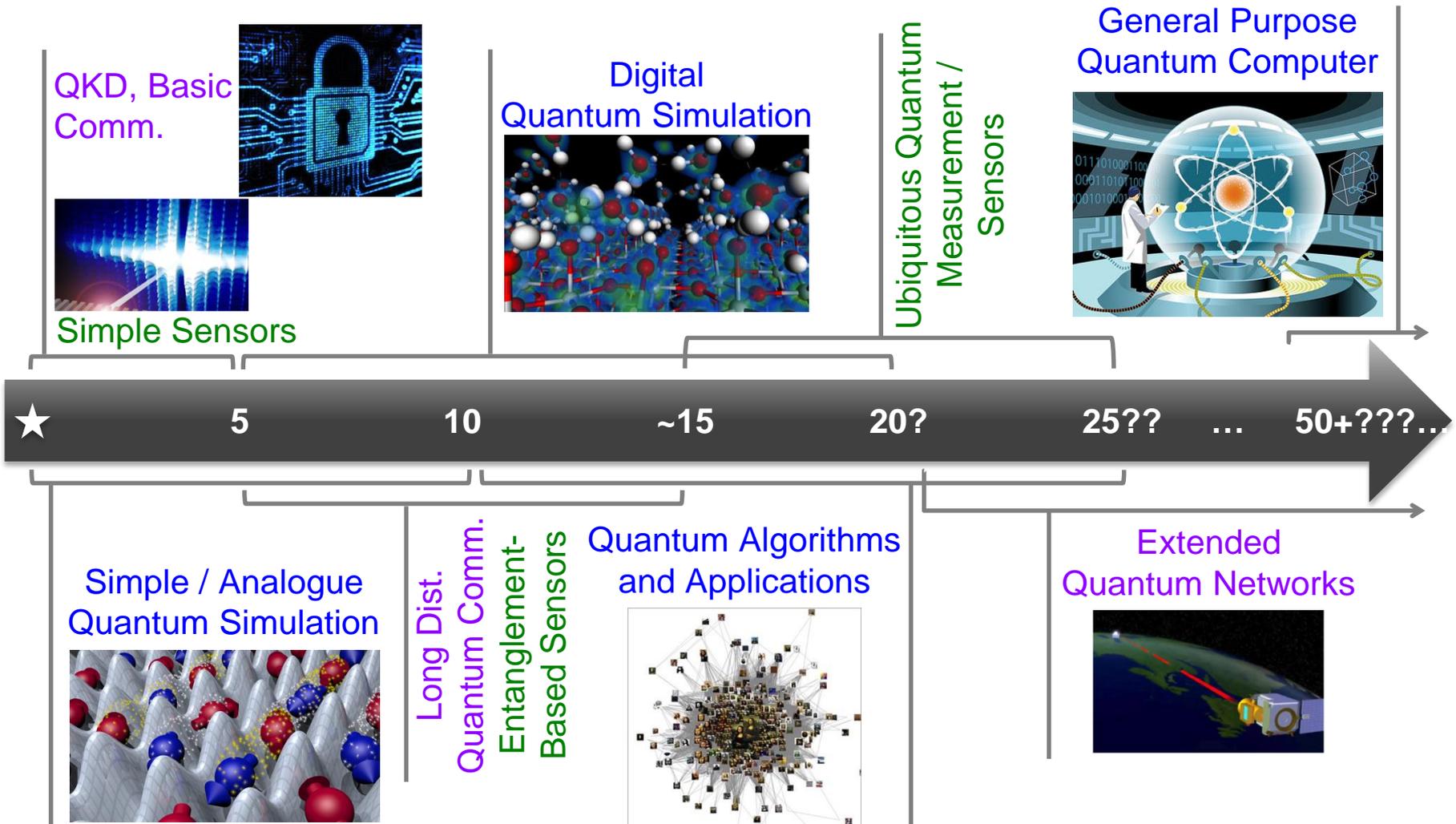
Isotope Requirements

Importance of Isotopes for Q Computing
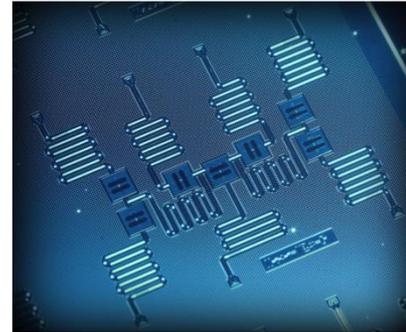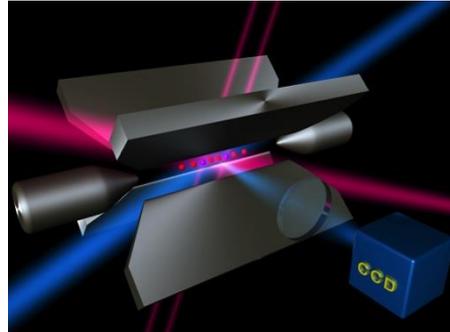
- Currently, the most advanced technologies from which qubits are built are superconductors and trapped ions.

- Qubit states are extraordinarily fragile regardless of qubit technology.

  - Ideally, a qubit would stay exactly as one leaves it, isolated from any unwanted influence that may alter its state and hence its information.

  - Unwanted influences include the environment around them, dissipation, heating.

    - *Can be solved by operating the qubits in a cryogenic environment.*

- Superconducting qubits take advantage of persistent currents (states with zero resistance) flowing in a metal at very low temperatures.

  - *Superconducting qubits (and quantum dots) require milliKelvin temperatures to operate.*

3He For Quantum Computing

- Dilution refrigerators use a combination of 3He and 4He to achieve the millikelvin temperatures needed for solid-state qubit systems.

> ***Availability of 3He is at the heart of success of a large part of QIS.***
>
> Success relies on outfitting cryo-systems requiring 3He to reach the low temperatures needed to operate superconducting and semiconducting QC devices.
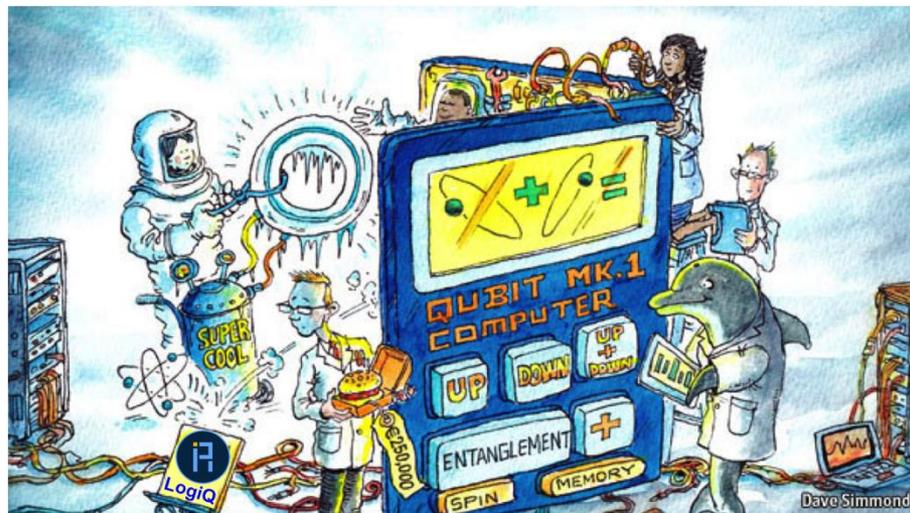
Point of Contact

Dr. Brad Blakestad

Program Manager

Office of the Director of National Intelligence
Intelligence Advanced Research Projects Activity
Washington, DC 20511

Phone: (301) 851-7514
Electronic mail: brad.blakestad@iarpa.gov