Quantum Computing

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5 March 2018

This material is based upon work supported by the Assistant Secretary of Defense for Research and Engineering and the Office of the Director of National Intelligence (ODNI), Intelligence Advanced Research Projects Activity (IARPA), via Air Force Contract FA8721-05-C-0002 and/or FA8702-15-D-0001. Any opinions, findings, conclusions or recommendations expressed in this material are those of the author(s) and do not necessarily reflect the views of ODNI, IARPA, or the U.S. Government. The U.S. Government is authorized to reproduce and distribute reprints for Governmental purposes notwithstanding any copyright annotation thereon.


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Historical Perspective on Computing

Classical (Electronic) Computing

- **First vacuum tube**: (1907)
- **ENIAC**: (1946)
- **Transistor invented**: (1947)
- **First fully transistor-based computer: TX-0**: (1953)
- **30k transistors: i8088**: (1971)
- **4.5M transistors: Pentium**: (1998)
- **15B transistors: GP100**: (2016)

Quantum Computing

- **Quantum computer proposed**: (1981)
- **Shor’s algorithm developed**: (1994)
- **Several to tens of quantum bits manipulated**: (2010–18)

Progress on both quantum computing algorithms and hardware is supporting the exploration and development of a revolutionary approach to information processing.

Richard Feynman

Ions

SC qubits
Quantum Computing Applications

Linear Algebra (HHL)

Exponential speed-up is possible with continued progress on efficient data loading for large matrices.

Optimization

Quantum annealing may improve optimization with a faster time to more diverse and optimal solutions.

Molecular and Material Simulations

Accurate simulation of molecular and material properties that are poorly approximated by classical methods.

Search and Database (Grover)

Offers a polynomial speed-up that is useful within other quantum algorithms or with efficient data loading.

Quantum computing algorithms and applications continue to expand.
Computation vs. Optimization (Quantum Computing vs. Annealing)

**Computation**
Solve a problem deterministically to find: *its unique solution*

**Optimization**
From among many solutions, find: *those with highest possible quality*

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**Proven exponential speed-up over classical for few problems**
- e.g., Shor’s integer factoring algorithm
- Quantum fault-tolerance protocols can suppress decoherence

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**Computation**
Titan supercomputer

**Quantum Computing**
- Trapped ion qubits (MIT LL and Prof. Chuang/Ram)
- Superconducting qubits (MIT LL and Prof. Oliver/Orlando)

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**Computational power virtually unknown**
- Requirements on qubits appear to be substantially less
- Initial work by D-Wave Systems has led to efforts by Google and IARPA

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**Quantum Annealing**
Qubit Modalities

- **Trapped-Ion Qubit**
  - Gate time: 10–100 µs
  - Coherence time: 1–50 s

- **Superconducting Qubit**
  - Gate time: 10 ns
  - Coherence time: 100 µs

- **Ensemble NMR**
- **Neutral Atoms**
- **NV-Centers in Diamond**
- **Solid State Quantum Dots**
- **Electron Spin in Silicon**

**Figure of Merit: Coherence Time/Gate Time**

- **Best Performance**

- **Viable qubit for scaling**
- **Not yet demonstrated to be viable**

- $|0\rangle = |\begin{array}{c} 0 \\ 1 \end{array}\rangle$, $|1\rangle = |\begin{array}{c} 1 \\ 0 \end{array}\rangle$
Quantum Computing Experiments

Superconducting Qubits

Trapped Ion Qubits

Qubits must be sufficiently isolated from the classical environment, noise...

Classical control signals are used to initialize, manipulate, and measure qubits
Superconducting Qubits

- Manufactured/designed “atoms”
- Planar fabrication
- RF and microwave control
- 100 MHz gate operations
- “Moore’s Law” for coherence times

MIT and Lincoln Laboratory are at the forefront of superconducting qubit materials, fabrication, design, and extensible 3D integration

Oliver & Welander, MRS Bulletin (2013)
Technologies for 3D Integration of Superconducting Qubits

Three-Layer stack architecture with separate qubit and I/O layers separated by a TSV chip

Increase qubit coherence (unchanged by introducing additional layer)

Three-Layer stack architecture with separate qubit and I/O layers separated by a TSV chip

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Through-substrate vias

Through-substrate vias

Increase qubit coherence (unchanged by introducing additional layer)

Traveling wave parametric amplifiers (TWPAs)

Silicon substrate

Readout amplifiers and passive routing

Silicon substrate

Readout amplifiers and passive routing

Superconducting bumps

Superconducting bumps

Traveling wave parametric amplifiers (TWPAs)
Trapped Ion Qubits

- Electronic states of ionized atoms
- RF trapping, optical control
- Coupling via Coulomb interaction
- 100 kHz gate times
- High-fidelity preparation, control, and readout (99.9%–99.999%)
Trapped-Ion Quantum Processor
Collaboration Opportunities

• Challenging scientific and fundamental engineering questions remain to be addressed:
  – Spans many academic domains: material science, solid-state and atomic physics, electrical engineering, mathematics, and computer science
  – Collaborations and internships are important to addressing these key research challenges

• Progress is also enabled by specialized research infrastructure:
  – Test equipment and electronics
  – Software tools for experimental control, modeling, and simulation