Exceptional service in the national interest

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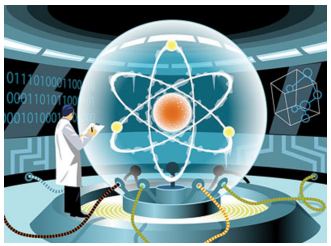
Quantum computing is and is not amazing

$$\left|\ \right\rangle = \sqrt{\frac{9}{10}}\left|\ \right\rangle + \sqrt{\frac{1}{10}}\left|\ \right\rangle$$



Kenneth Rudinger

U.S. DEPARTMENT OF ENERGY | NNSA National Nuclear Security Administration

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http://www.utahpeoplespost.com/2014/09/researchers-produced-atom-sounds/

Quantum computing is different

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If all the silicon in the world's crust were converted to Pentium chips, it would take the age of the universe to factor a 5,000-bit number.

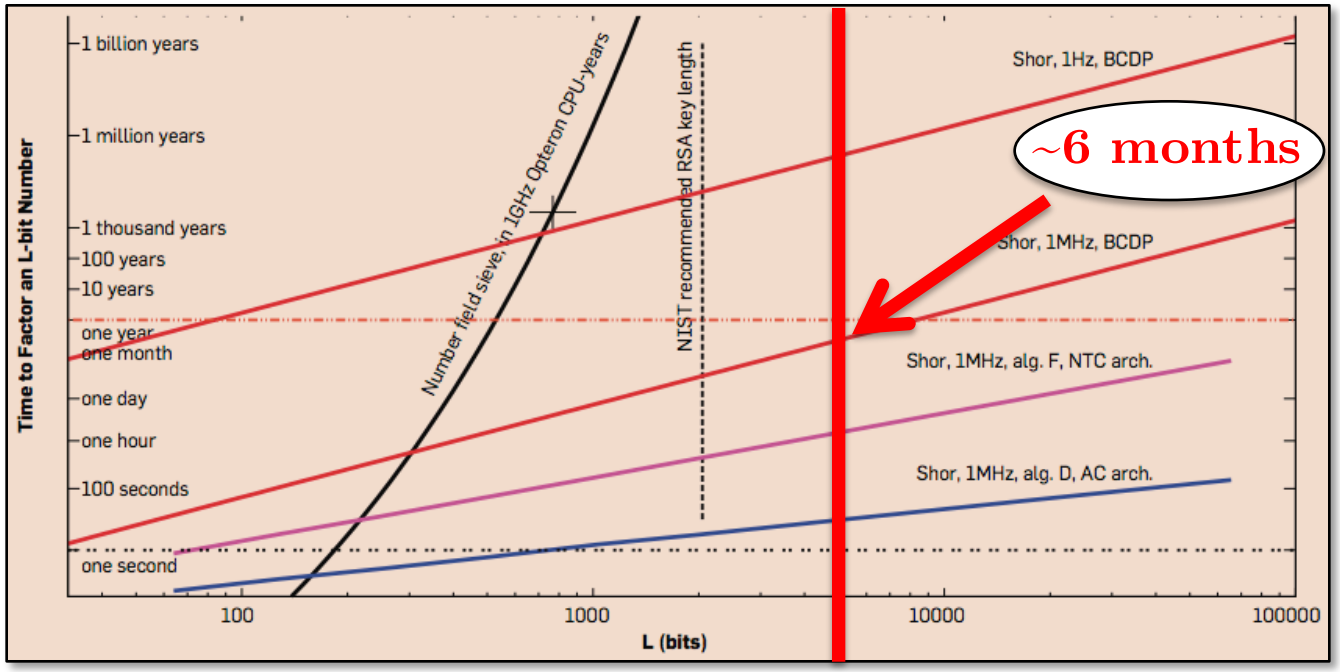

Image: NASA "Blue Marble," Apollo 17

A blueprint for building a quantum computer, R. van Meter & C. Horsman, *Comm. ACM*, (2013) doi:10.1145/2494568

Slide c/o: Andrew Landahl/Sandia

Overview

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- Classical information
- Quantum information
- What could you do with a quantum computer?
- What couldn't you do with a quantum computer?
- What do we need to get there?

Overview

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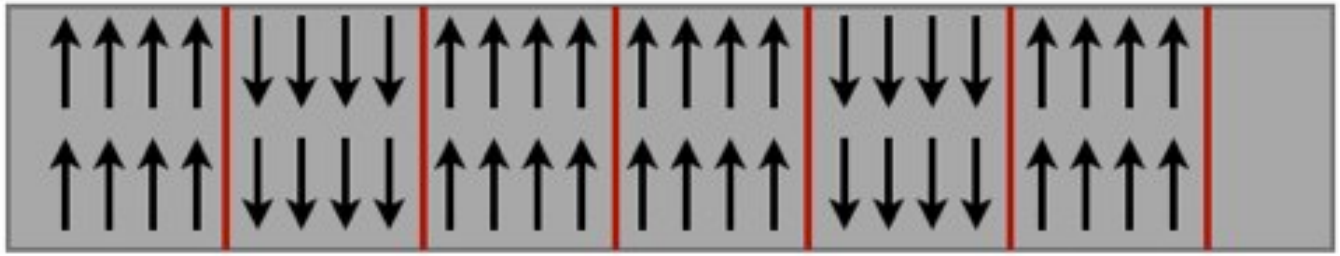
- High-level talk
- Take-aways:
  - 1. The axioms governing quantum computation are *different* from those governing classical computation.
  - 2. Quantum computers will be able to perform *certain* computational tasks faster as a result.
  - 3. This is *not true* for general tasks.
  - 4. The quantum speedups will probably still have tremendous societal impact.

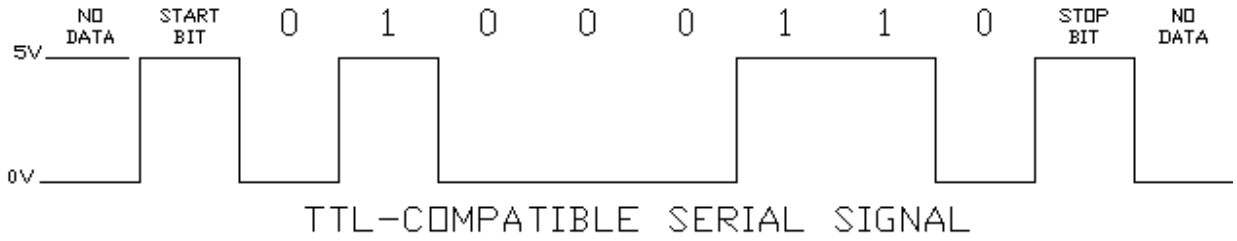
All the rest is commentary.

Classical information

Classical information is made up of bits.

0110110100010





https://www.wired.com/2012/07/breaking-bad-magnets-how-do-they-work/ http://playground.arduino.cc/uploads/Main/UnoWin2k-RS232-vs-TTL.gif

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"Information is physical."

-Rolf Landauer (1927-1999)

What can we do with information?

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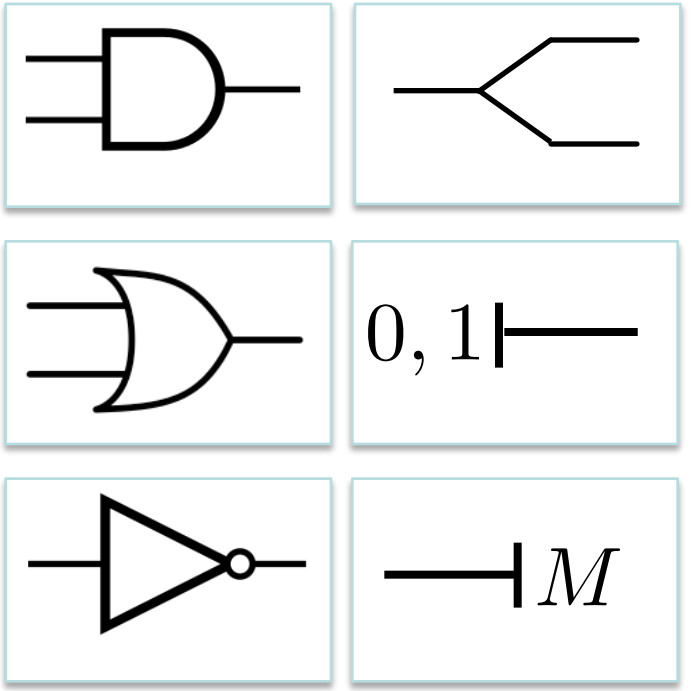
- Run algorithms!
  - Searching
  - Sorting
  - Arithmetic
  - ...
  - Machine learning

- Operate on the bits



Operations are done physically!

Towards quantum computing

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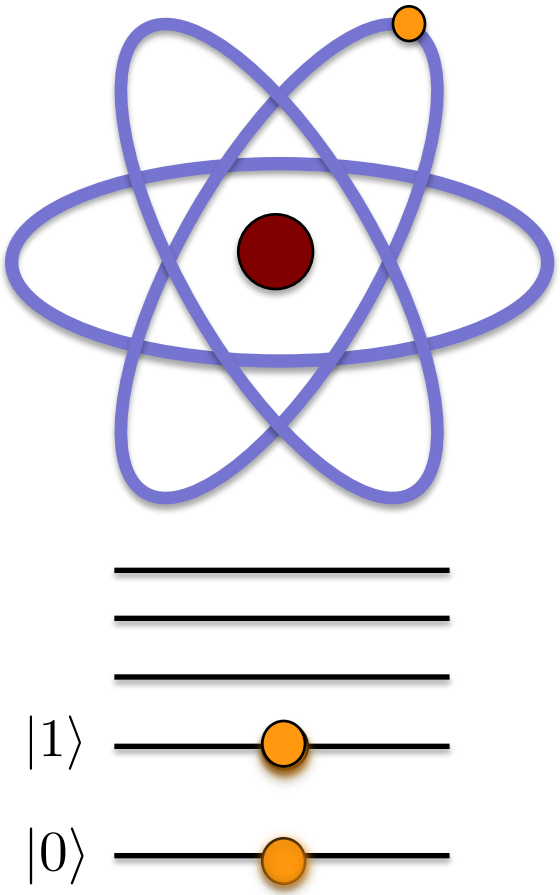
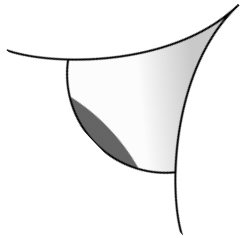
- Classical physics (Newton, Maxwell, etc.) is *incomplete.*
- Need quantum mechanics to explain low-energy, low-temperature, small-scale phenomena.
- If the rules of physics are not what we thought, and information is physical, then are the rules of computation not what we thought?
- Yes!

Quantum systems





$$|1\rangle$$
$$|0\rangle$$
$$\frac{1}{\sqrt{2}}\left(|0\rangle + |1\rangle\right)$$
$$|1\rangle$$

"Axioms" for QC

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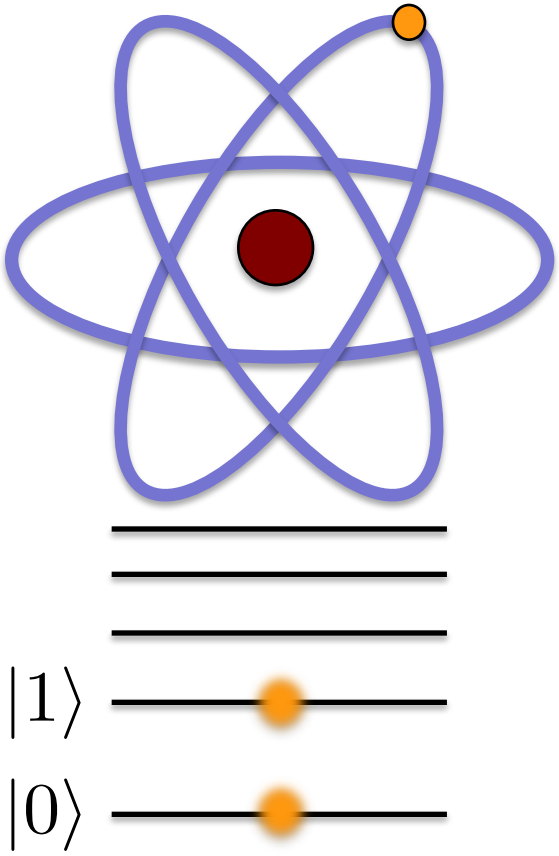
- ~~Schrodinger equation, uncertainty principle, etc.~~
- Physical observables are *quantized*.
- Describe two-level state ("qubit") as:

$$|\psi\rangle = \alpha|0\rangle + \beta|1\rangle \longleftrightarrow \vec{\psi} = \begin{pmatrix} \alpha \\ \beta \end{pmatrix}$$

$$\alpha, \beta \in \mathbb{C}$$

- "Superposition" $\Leftrightarrow$ "(Normalized) linear combination"
- $\Pr(0) = |\alpha|^2$; $\Pr(1) = |\beta|^2$

  "Collapsing the wavefunction."



What about multiple qubits?

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- n-qubit state is superposition of up to 2^n basis states:

$$|\psi\rangle = \alpha_0|0\ldots0\rangle + \ldots + \alpha_{2^n-1}|1\ldots1\rangle$$

- Need an exponential number of parameters to describe n qubit system.
- State can be *entangled*!

$$|\psi\rangle = \frac{1}{\sqrt{2}}\left(|00\rangle + |11\rangle\right)$$

- Such states can have *non-classical* correlations.

"Axioms" for QC

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- n-qubit state is described by up to 2^n complex amplitudes.
- Measurement yields one of 2^n outcomes.
- Valid operation on state ("logic gate") is any unitary map.

$$|\psi\rangle \rightarrow U|\psi\rangle \qquad U^\dagger U = I$$

$$U|0\rangle = \frac{1}{\sqrt{2}}(|0\rangle + |1\rangle)$$

That's it!

Quantum logic

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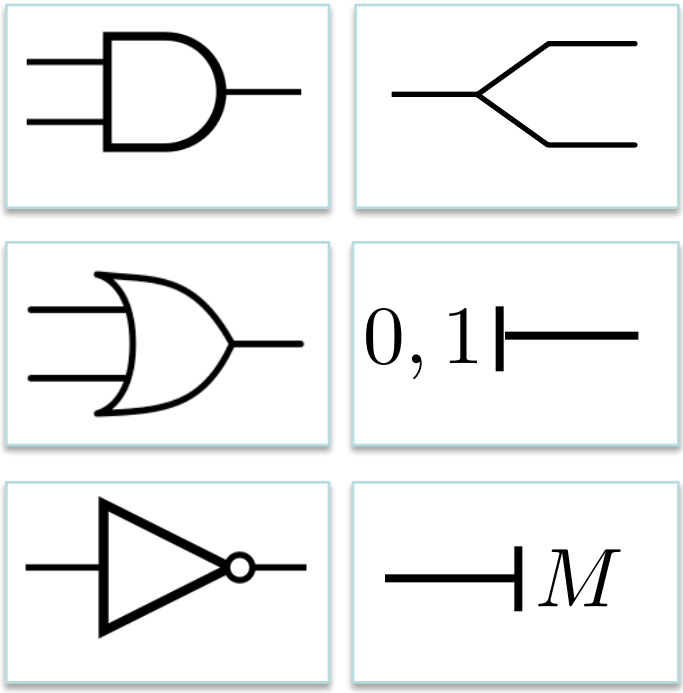
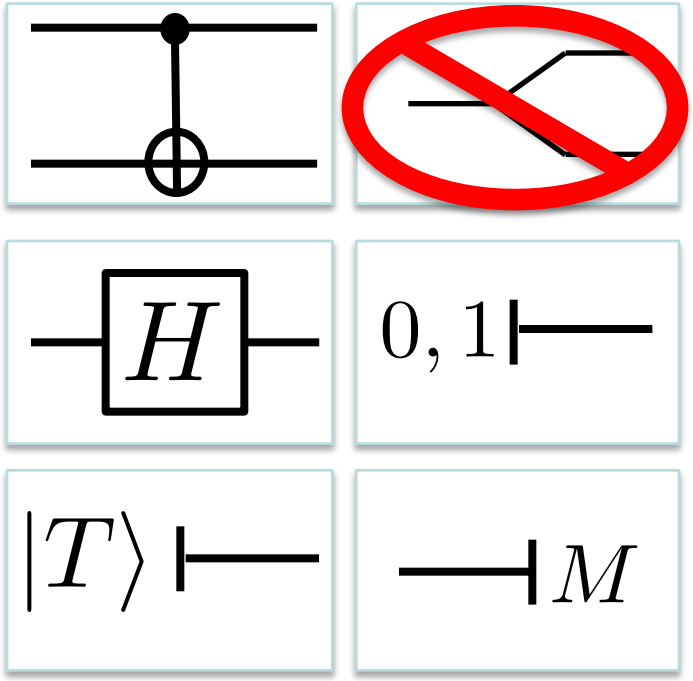
Classical gates



Quantum gates



Exponential speedups?

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- If n two-level quantum systems ("qubits") are described by $O(2^n)$ numbers, does this always give us an exponential speedup?
- No!
- Holevo's theorem:
  - Can only *retrieve* n bits of information from n qubits.

If you take just one piece of information from this blog: Quantum computers would not solve hard search problems instantaneously by simply trying all the possible solutions at once.

-Scott Aaronson

- Given rules of quantum computation, *turns out* there are certain tasks we can perform faster.

http://www.scottaaronson.com/blog/

Quantum algorithms

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Polynomial to exponential speedups

- **Integer factoring, discrete logarithms**
  - Breaks RSA, Diffie-Hellman, elliptic-curve cryptography
- **Quantum simulation**
  - Condensed matter physics
  - Quantum field theory
  - Chemical dynamics- pharmaceuticals, fuels, materials
- **Database searching**
- **Semidefinite programming**

Over 50 more!

http://math.nist.gov/quantum/zoo

Slide in part c/o: Andrew Landahl/Sandia

Quantum chemistry

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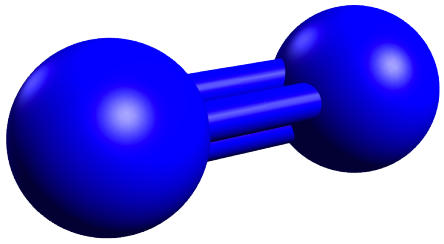
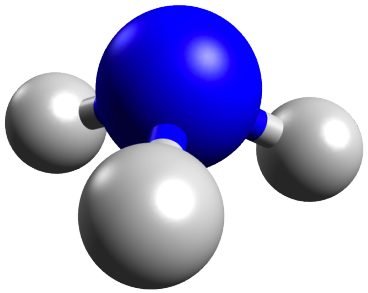
With only 200 error-free qubits, a quantum computer could unravel biological nitrogen fixation [1]. Currently, the Haber-Bosch process consumes 2% of the world's annual energy supply.

Nitrogen



Ammonia



Reiher *et al.*, arXiv:1605.03590 (2016)

Images: Andrew Baczewski/Sandia. Slide: Andrew Landahl/Sandia
Wikipedia, Rabe!, "Pear Leaf;" Sharon Loxton "Haber Process."

Where are the quantum computers?!

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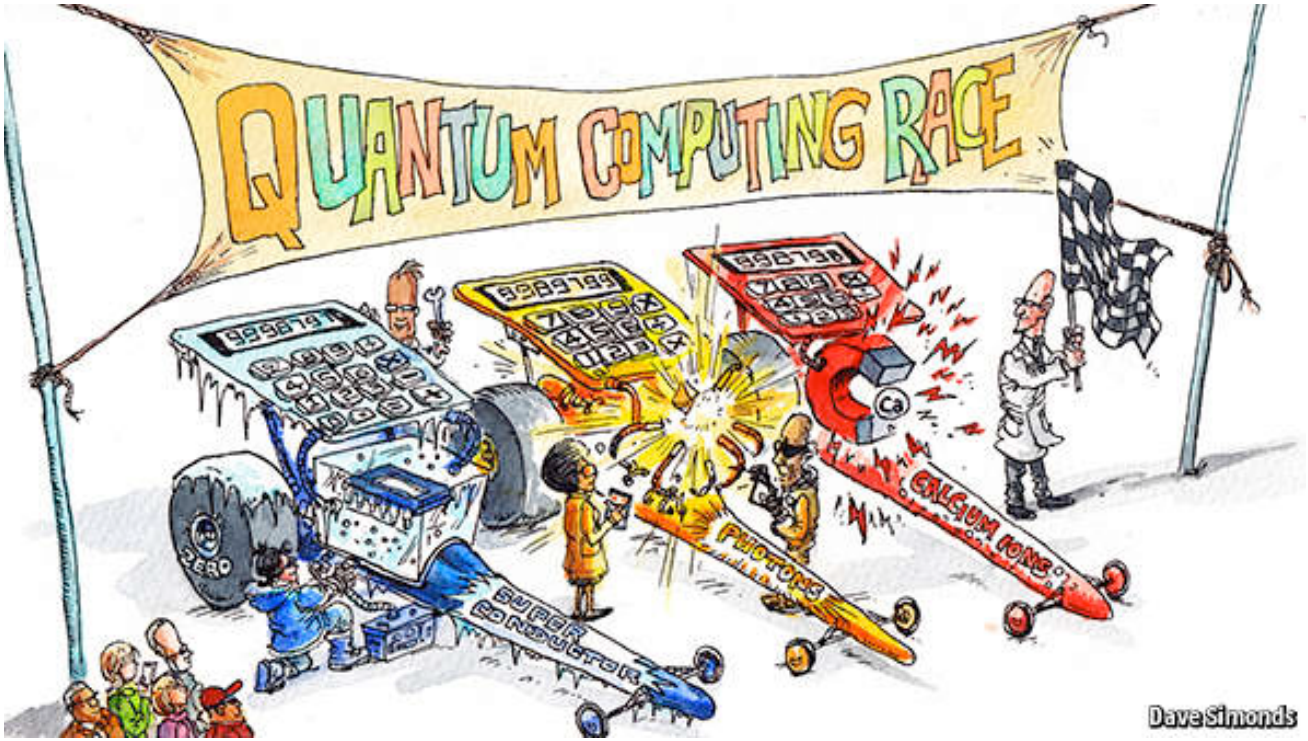

Quantum chips

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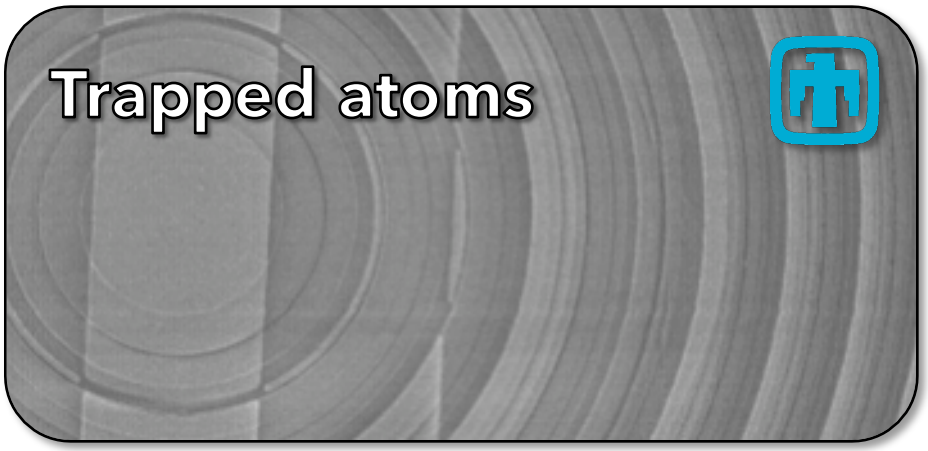

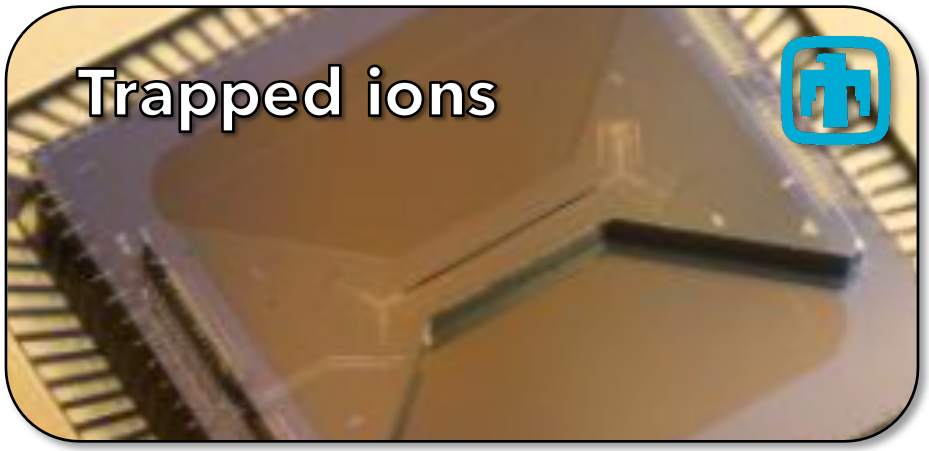

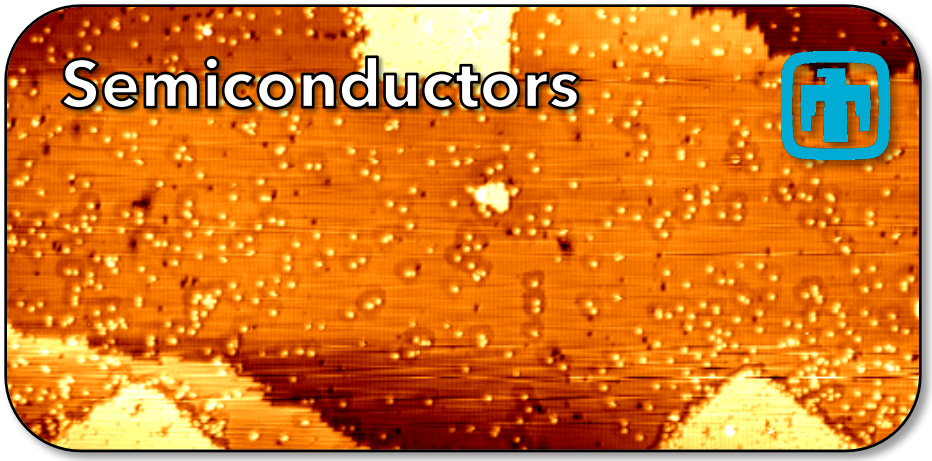

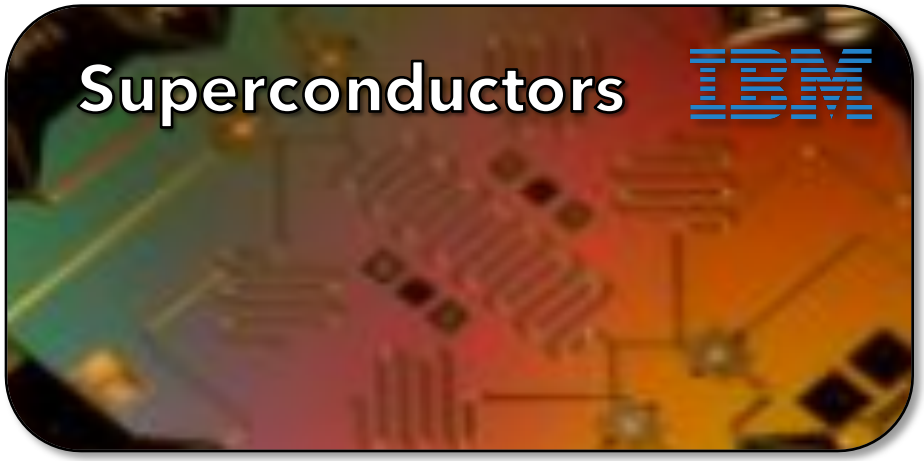

Images: Sandia, IBM

Slide c/o Andrew Landahl/Sandia

Competing technologies

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- Trapped atoms, ions
  - Qubit is single valence electron in ion or atom.
    - Sandia, UMD, UW, USydney, NIST, IonQ …
- Semiconductors
  - Qubit is localized electron or quasiparticle in semiconductor device.
    - Sandia, UW, UNSW, Princeton, Microsoft* …
- Superconductors
  - Qubit is in state of superconducting circuit.
    - UW, TUDelft, Google, IBM**, Rigetti …

All have advantages and disadvantages

*Hybrid technology

**https://quantumexperience.ng.bluemix.net/qx/

Building qubits is hard!

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- Quantum information is *fragile*.
- Small energy scales
- Low temperature
- Sensitive to environment
  - Heat
  - Light
  - Vibrations
  - Other qubits!
- Quantum states *decohere* quickly
  - E.g., IBM: $T_2 \approx 100$ μs; $T_{gate} \approx 100$ ns ➔ $T_2/T_{gate} \approx 1000$
- Quantum gates are noisy too!
  - Gate error rates ≈ 10^{-5} – 10^{-2}

Building qubits is hard!

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- Gate error rates ≈ 10^{-5} – 10^{-2}
- Modern transistors: 10^{-28}
- ENIAC: 10^{-15}
- Need error correction!

Slide c/o Andrew Landahl/Sandia

Quantum error correction

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- Take collection of *physical* qubits and encode in it a single *logical* qubit.
- Example – Repetition code:

$$|0\rangle \rightarrow |000\rangle$$
$$|1\rangle \rightarrow |111\rangle$$

- Corrects single bit flip errors
- For more general errors, use more complicated (and larger) codes.

Fault-tolerance

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- Quantum error correction (QEC) suppresses errors.
- Threshold theorem: If physical error rates are below some threshold, QEC can suppress noise to arbitrarily low levels.
  - Concatenation
  - Larger codes
- Most general threshold: error rate of $6.7 \cdot 10^{-4}$.
- That threshold surpassed at SNL!
  - … only for a single trapped-ion qubit.
- We have a ways to go!

Blume-Kohout *et al.* Nat. Comm. 14485 **8**, 2017.

Fault-tolerance cost

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Trading quality for quantity

Factoring a 2000-bit number:

- 10^{12} quops deep, 4,000 lqb wide (error-free)
- 10^{-3} error: 1.02 Gqb (physical).
- 10^{-4} error: 130 Mqb (physical).

- Best technologies today: 10-20 physical qubits.
- We have a ways to go!

Fowler *et al.*, Phys. Rev. A 86, 032324 (2012)

Slide in part c/o Andrew Landahl/Sandia

Future directions

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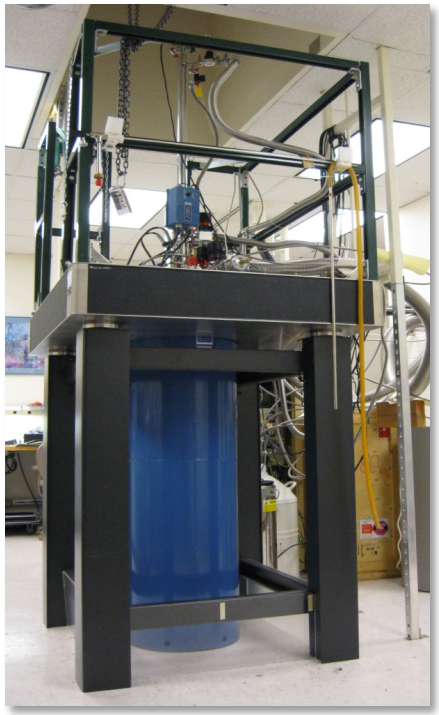
- Hardware
  - Getting physical error rates down
  - Solving scalability
    - Wires, lasers, fridges, etc.
  - …
- Software
  - Development of quantum programming languages (QASM, LIQU$i|>$, …)
  - Development of new algorithms



Developing quantum algorithms is like being a computer programmer

Take-aways (again!)

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- 1. The axioms governing quantum computation are *different* from those governing classical computation.
- 2. Quantum computers will be able to perform *certain* computational tasks faster as a result.
- 3. This is *not true* for general tasks.
- 4. The quantum speedups will probably still have tremendous societal impact.

- Thanks to Andrew Landahl (SNL) and you!