Quantum Computation and Simulation

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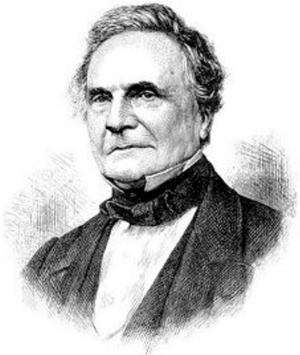
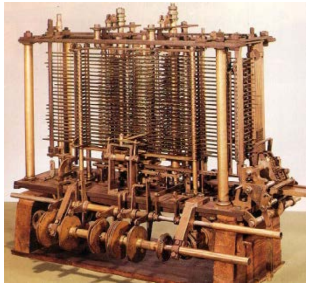
JOINT QUANTUM INSTITUTE

JOINT CENTER FOR QUANTUM INFORMATION AND COMPUTER SCIENCE

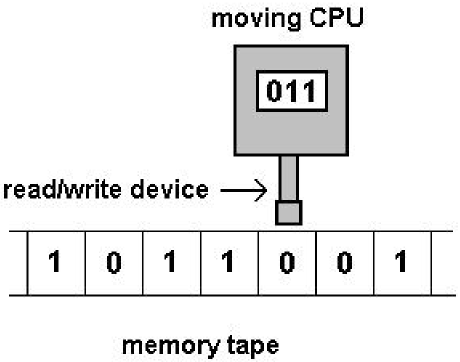
Computer Science and Information Theory

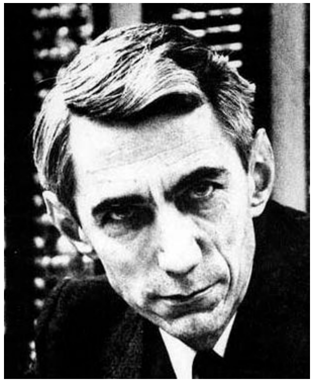


Charles Babbage (1791-1871)
mechanical difference engine



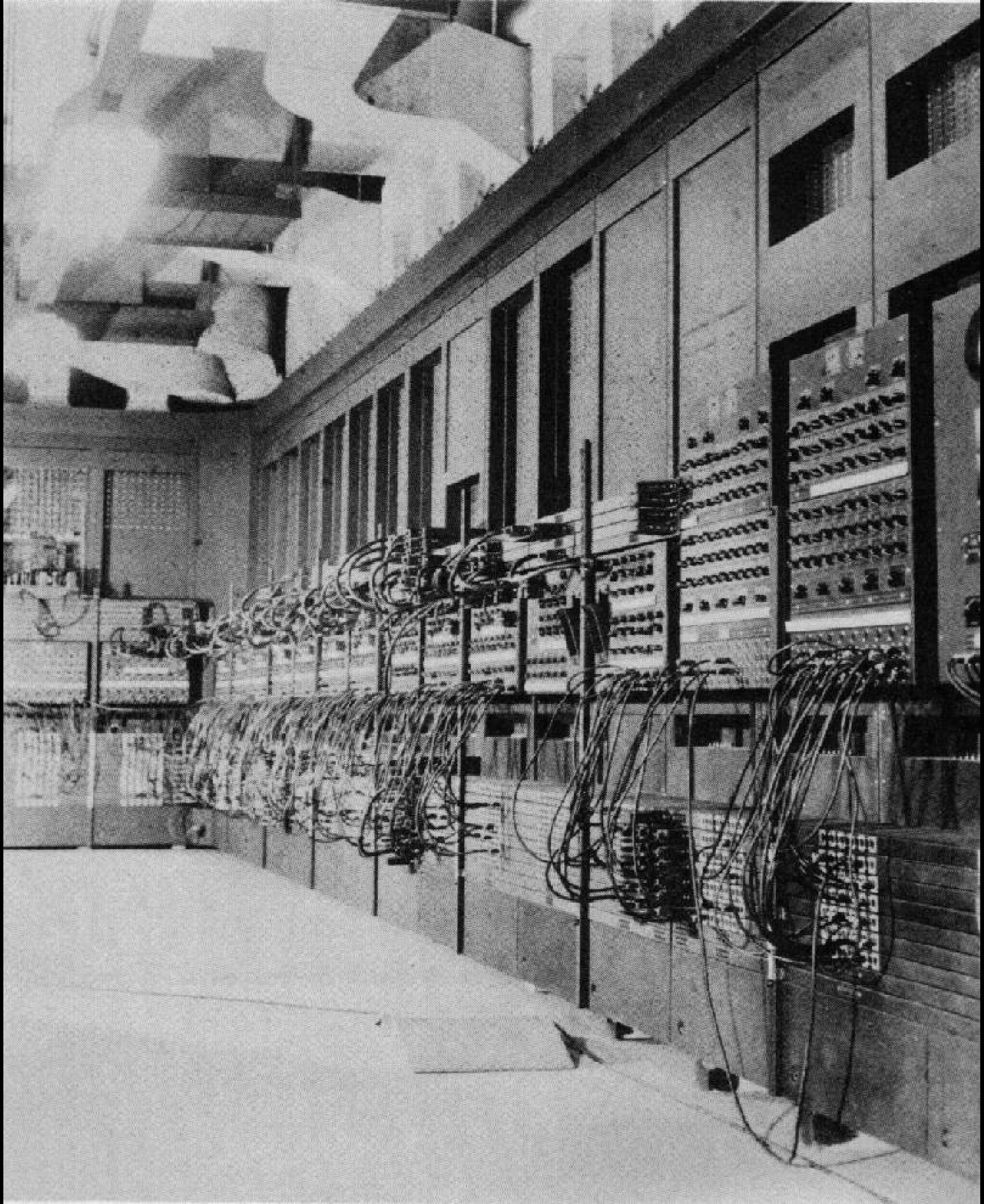
Alan Turing (1912-1954)
universal computing machines



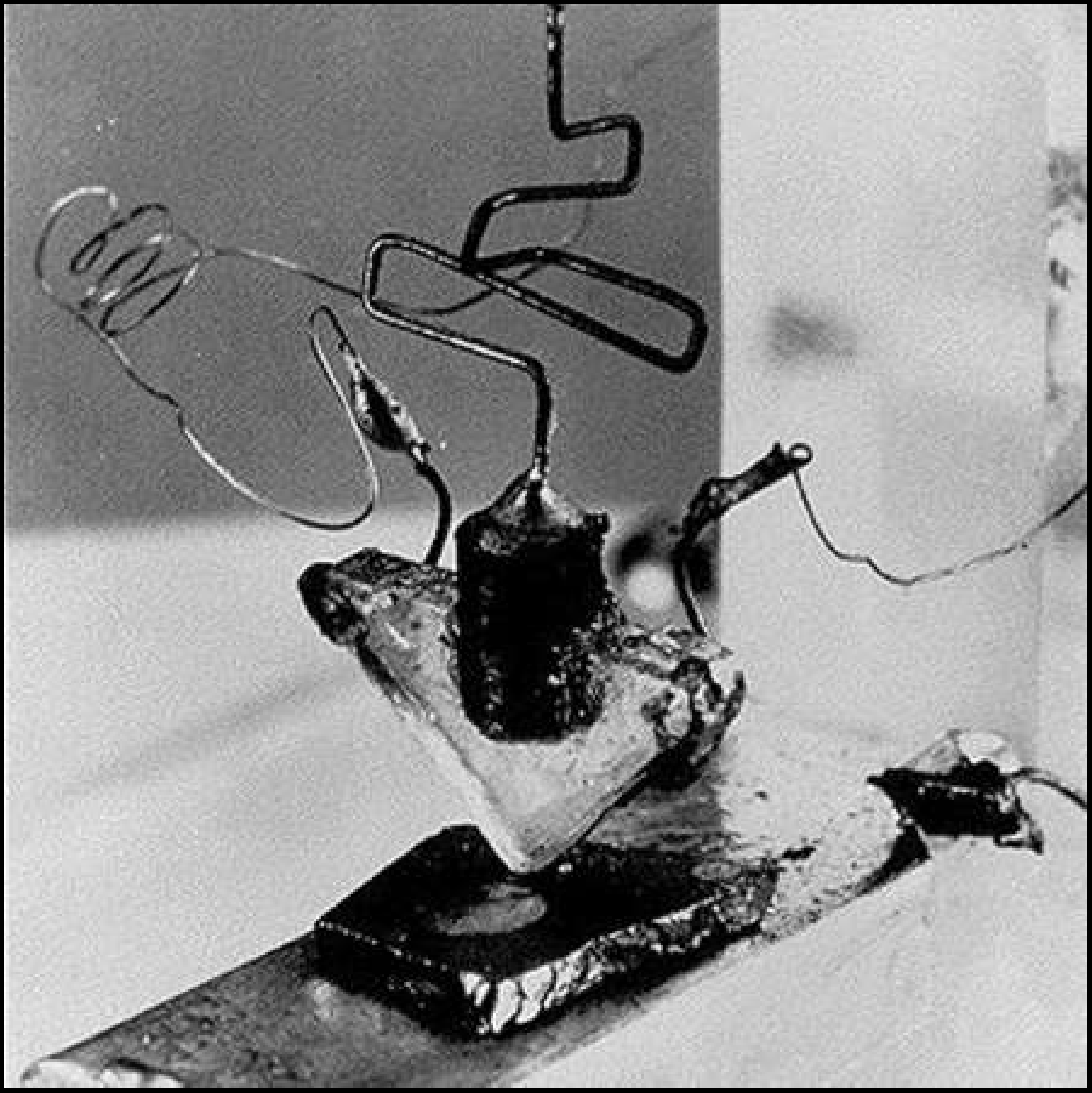


Claude Shannon (1916-2001)
quantify information: the bit

$$H = -\sum_{i=1}^{k} p_i \log_2 p_i$$

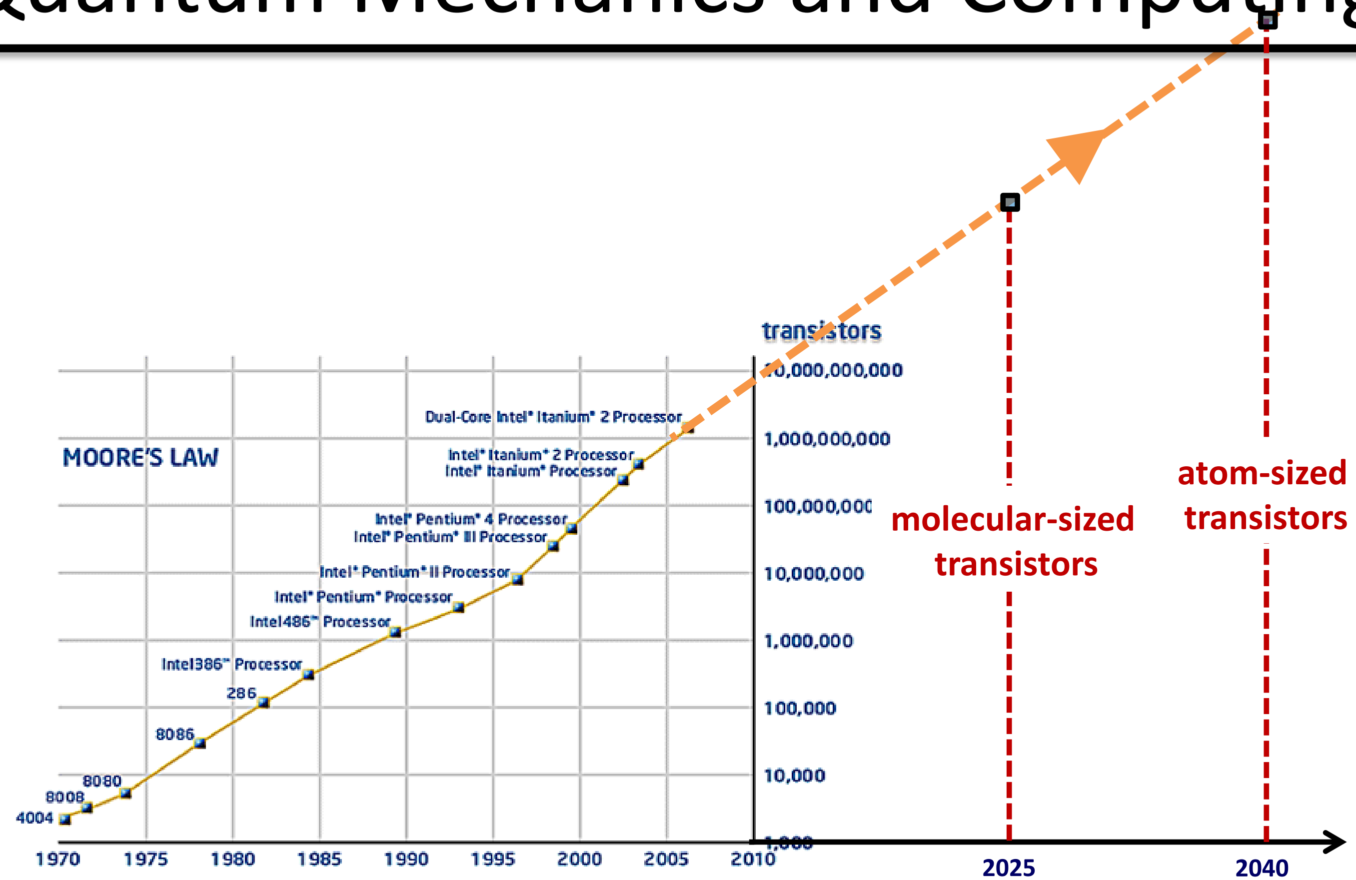


ENIAC
(1946)



The first solid-state transistor
(Bardeen, Brattain & Shockley, 1947)

Quantum Mechanics and Computing



Richard Feynman

***"There's Plenty of Room at the Bottom"* (1959)**

"When we get to the very, very small world – say circuits of seven atoms – we have a lot of new things that would happen that represent **completely new opportunities for design**.

Atoms on a small scale behave like nothing on a large scale, for they satisfy the laws of quantum mechanics…"

Application 1. Quantum Factoring

P. Shor (1994)

A quantum computer can factor numbers **exponentially faster** than classical computers

15 = 3 × 5 (…easy)
38647884621009387621432325631 = **?** × **?**

Importance: cryptanalysis

public key cryptography relies on inability to factor large numbers

Application 2: Quantum Search

L. Grover (1997)

A quantum computer can finding a marked entry in an unsorted database **quadratically faster** than classical computers

(e.g., given a phone number, finding the owner's name in a phonebook)

Importance: "satisfiability" problems

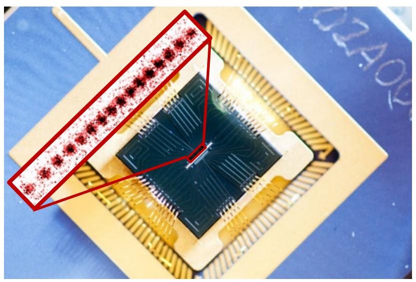
- fast searching of big data
- inverting complex functions
- determining the median or other global properties of data
- pattern recognition; machine vision

Application 3: Quantum Simulation

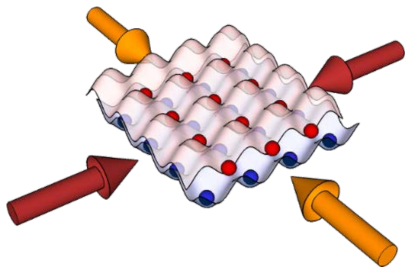
Quantum modelling is hard: *N* quantum systems require solution to 2^N coupled eqns

$$i\hbar \frac{\partial \Psi}{\partial t} = H\Psi$$

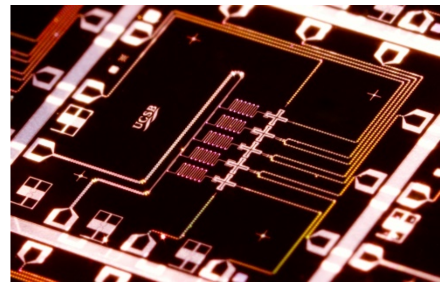
Alternative approach: Implement model of interacting system on a ***quantum simulator***, or "standard" set of qubits with programmable interactions



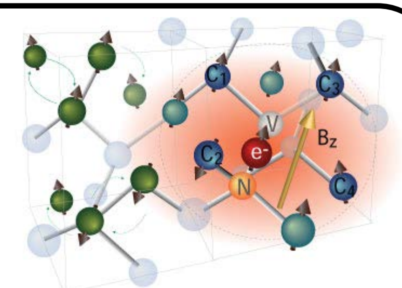
Atomic ions



Trapped atoms

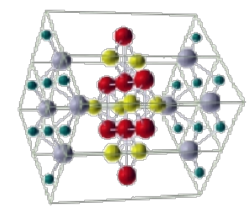


Superconductors

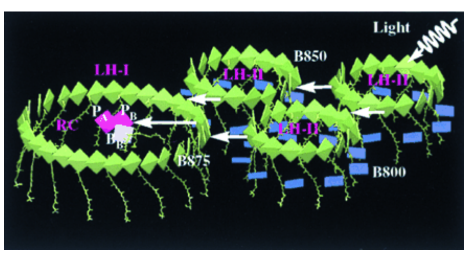


NV-diamond

Quantum Material Design Understand exotic material properties or design new quantum materials from the bottom up



high-T_C super-conductor

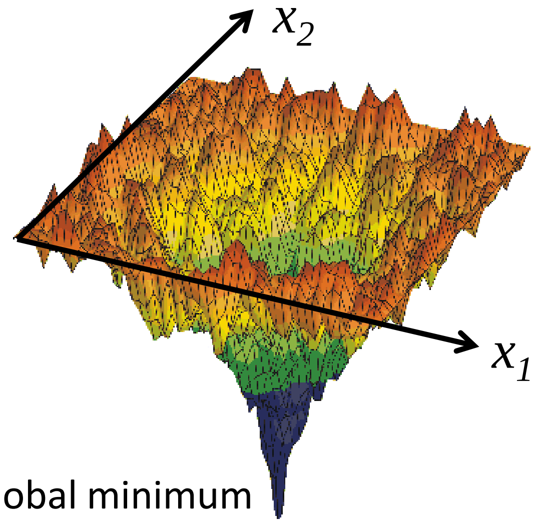


Energy and Light Harvesting Use quantum simulator to program QCD lattice gauge theories, test ideas connecting cosmology to information theory (AdS-CFT etc..)

Quantum Field Theories Program QCD lattice gauge theories, test ideas connecting cosmology to information theory (AdS-CFT etc..)

Application 4: Quantum Optimization

Minimizing complex (nonlinear) functions by "simultaneously sampling" entire space through quantum superposition

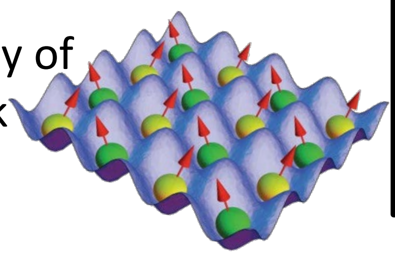


Relevant to
- Logistics
- Operations Research
- VLSI design
- Finance

Example: quadratic optimization

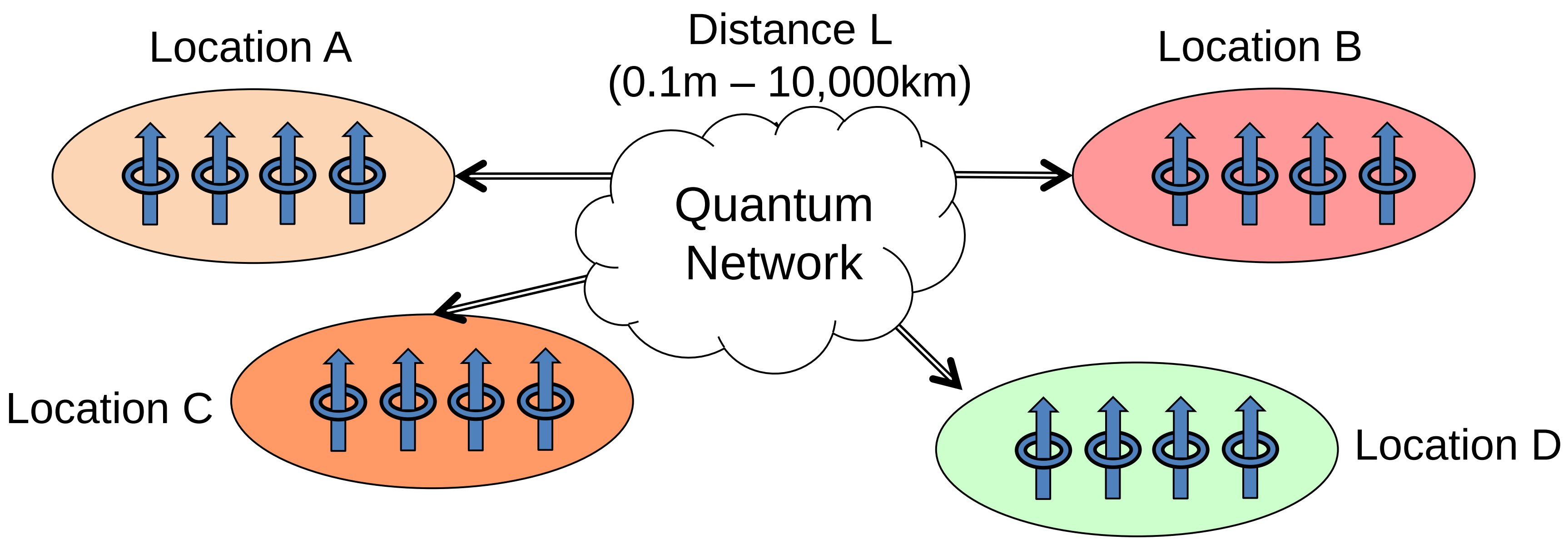
Minimize $f(x_1, x_2, \ldots) = \sum_{i<j} q_{ij} x_i x_j + \sum_i c_i x_i$

this function maps to energy of quantum magnetic network



Killer Application?
- could crack a large class of intractable problems: factoring, "traveling salesman" problem, etc..
- BUT not known if there is always a quantum speedup

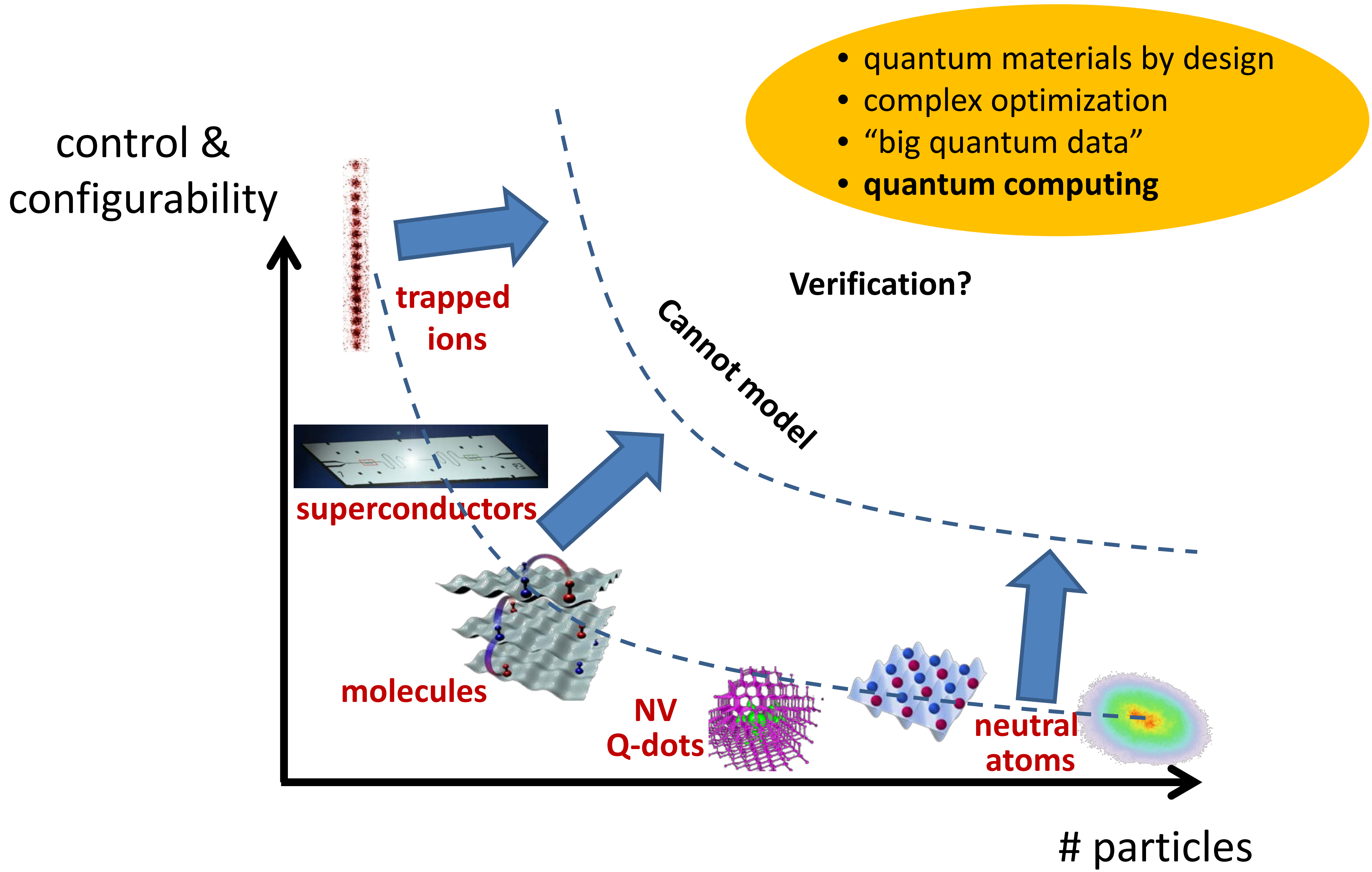
Application 5: Quantum Networks



Uses of a quantum network

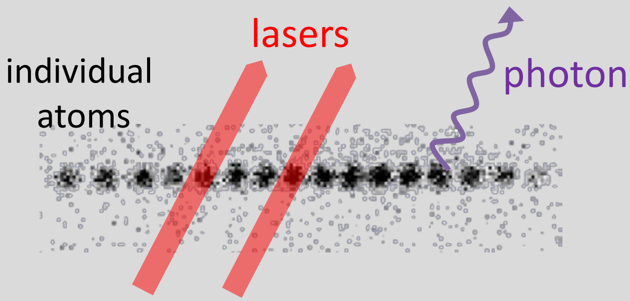
- Secret key generation: cryptography
- Certifiable random number generation
- Quantum repeaters ("amplifiers")
- Distributed quantum entanglement for optimal decision making
- *Large-scale quantum computing*

Implementation of Quantum Hardware



Leading Quantum Computer Hardware Candidates

Trapped Atomic Ions



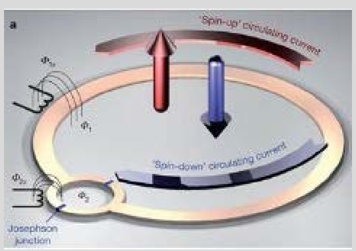
Atomic qubits connected through laser forces on motion or photons

FEATURES & STATE-OF-ART
- very long (>>1 sec) memory
- 5-20 qubits demonstrated
- **atomic qubits all identical**
- **connections reconfigurable**

CHALLENGES
- lasers & optics
- high vacuum
- 4K cryogenics
- **engineering needed**

Investments:	IARPA	Lockheed
	DoD	Honeywell
	Sandia	UK Gov’t

Superconducting Circuits



Superconducting qubit: right or left current

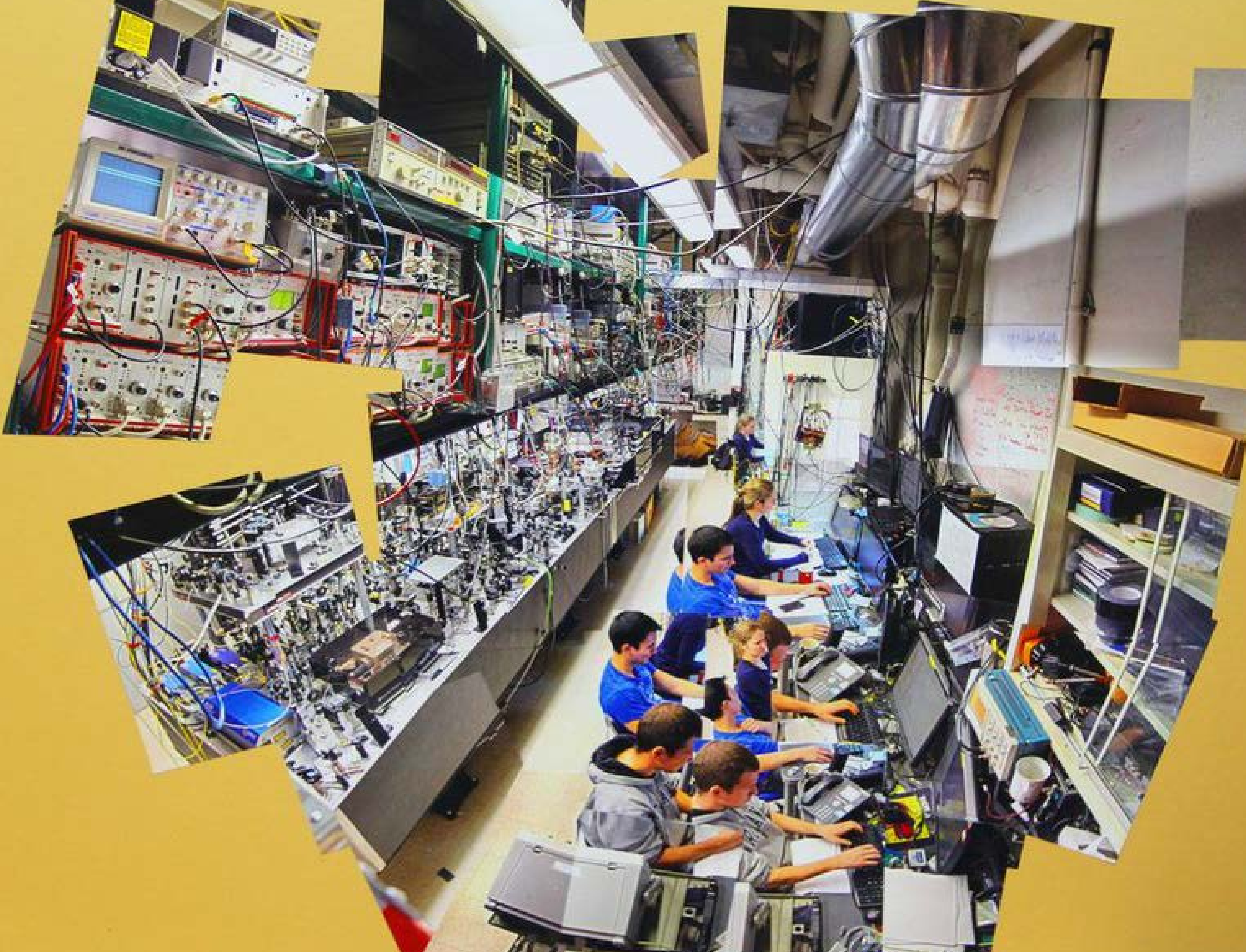
FEATURES & STATE-OF-ART
- connected with wires
- fast gates
- 5-10 qubits demonstrated
- **printable circuits and VLSI**

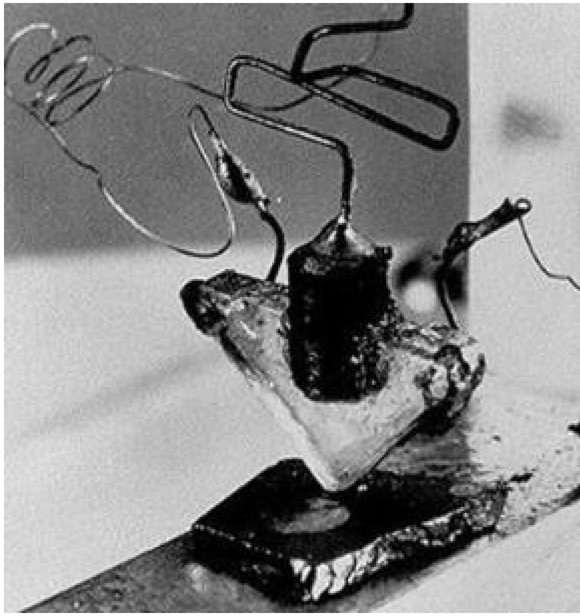
CHALLENGES
- short (10^{-6} sec) memory
- 0.05K cryogenics
- **all qubits different**
- **not reconfigurable**

LARGE Investments:	IARPA	Lincoln Labs
	DoD	Intel/Delft
	Google/UCSB	IBM

Others: still exploratory

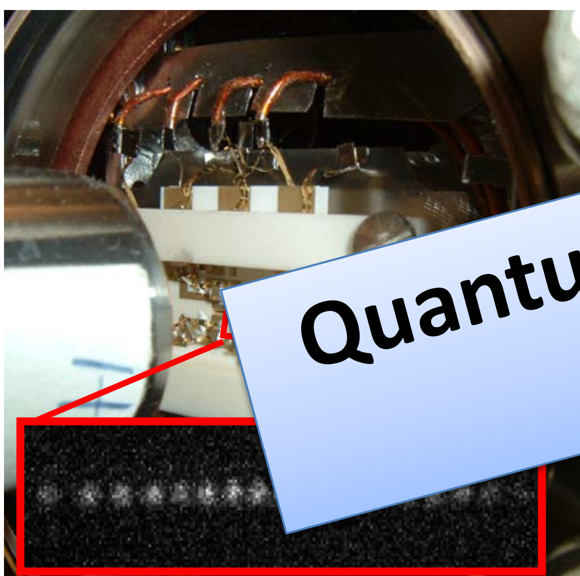
- NV-Diamond and other solid state “atoms”
- Atoms in optical lattices
- Semiconductor gated quantum dots



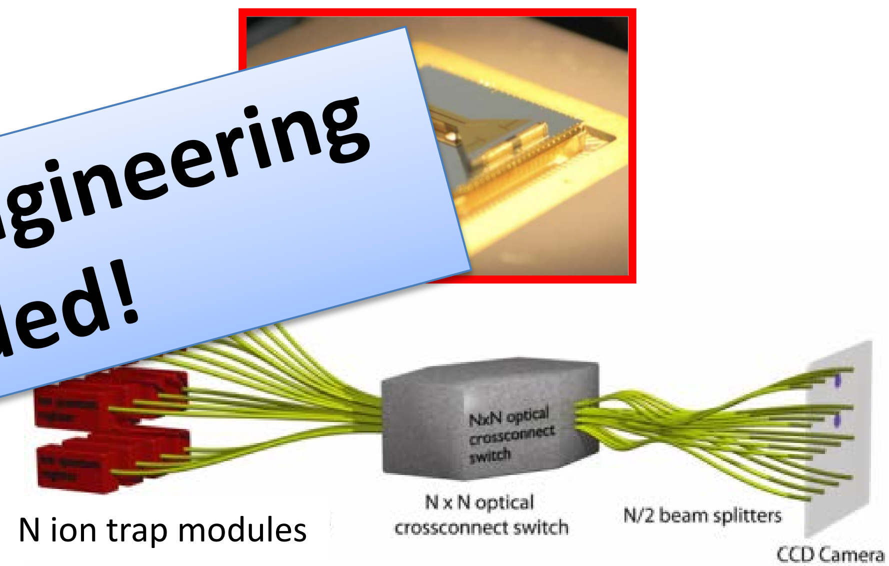


1947: first transistor

2000: integrated circuit



2015: qubit collection



Large scale quantum network?

Quantum Engineering Needed!