Quantum Computers: What Are They Good For?

Rubem Mondaini

June 11th, 2024

UNIVERSITY OF HOUSTON

one year.

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Four Ways Quantum Computing Could Change

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Will it?

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How quantum computing could change the world

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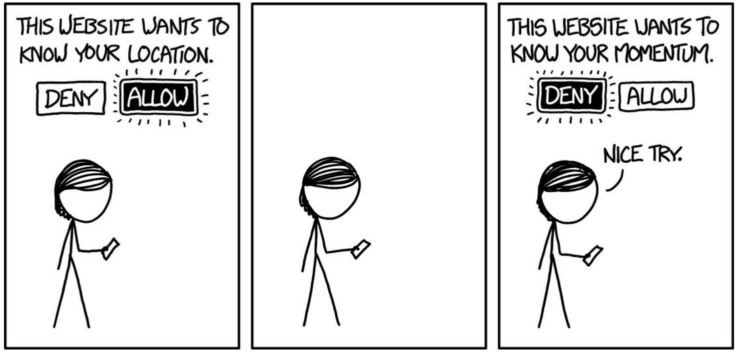
The quantum revolution: The way the world is

What quantum technology tells us about the true nature of reality

Quantum superposition and measurement

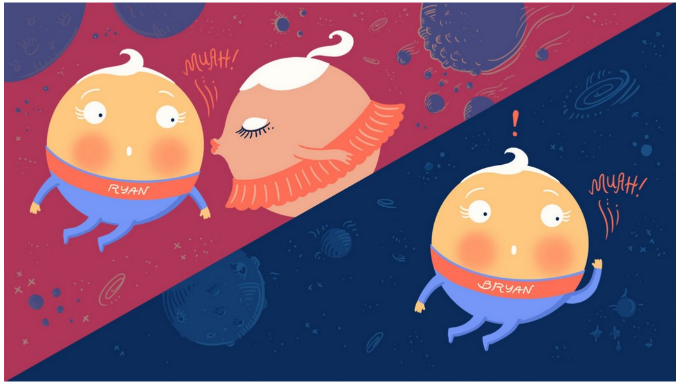
How these seemingly odd concepts can be used to perform quantum computations?

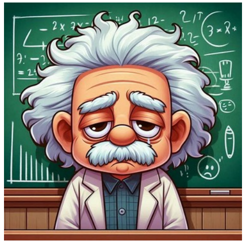
Quantum uncertainty principle



$$\Delta x \Delta p \geq \hbar/2$$

Quantum entanglement





(also known as "spooky action at distance"...)

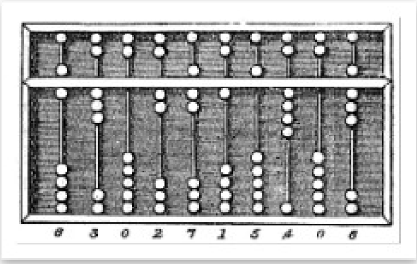
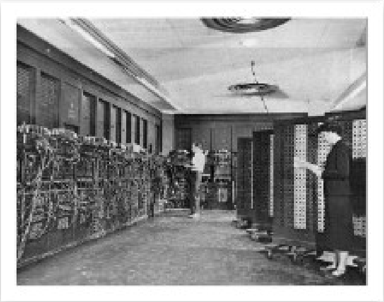
Computations

Classical

and

Quantum

Let's recall classical computation

classical bit

data units: **'0'** **'1'**

valid states: x = '0' **or** '1'

operations: **logical**

1-bit **NOT** =

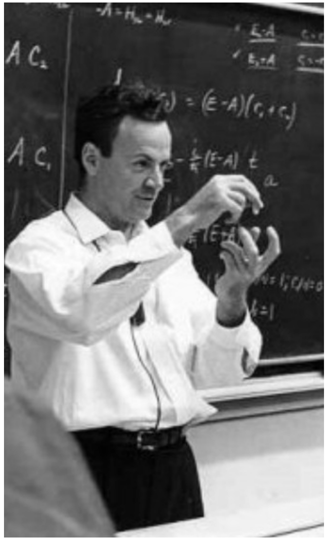
	in: 0	in: 1
out	1	0

2-bit **AND** =

	in: 0	in: 1
0	0	0
1	0	1

out

Quantum computation



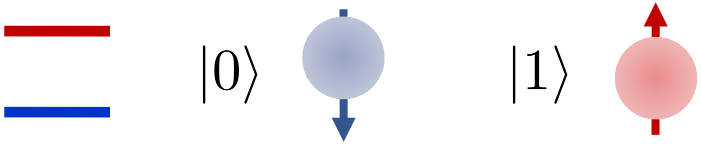
Richard Feynman

“Creating machines based on the laws of quantum mechanics instead of the laws of classical physics.” (1982)

[+ Benioff, Manin]

qubit = quantum bit

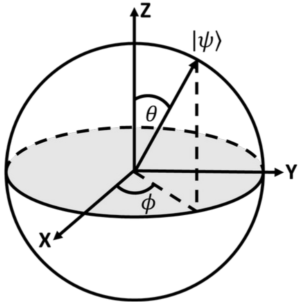
data units:



$|0\rangle$ $|1\rangle$

valid states:

$$|\psi\rangle = \cos\frac{\theta}{2}|0\rangle + \sin\frac{\theta}{2}e^{\mathrm{i}\phi}|1\rangle$$



operations: **unitary**

1-qubit

$$\sigma_x = \begin{pmatrix} 0 & 1 \\ 1 & 0 \end{pmatrix} \quad \sigma_y = \begin{pmatrix} 0 & i \\ -i & 0 \end{pmatrix}$$

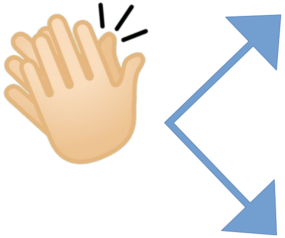
$$\sigma_z = \begin{pmatrix} 1 & 0 \\ 0 & -1 \end{pmatrix} \quad H = \frac{1}{\sqrt{2}}\begin{pmatrix} 1 & 1 \\ 1 & -1 \end{pmatrix}$$

2-qubits

$$\mathrm{CNOT} = \begin{pmatrix} 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 0 & 1 \\ 0 & 0 & 1 & 0 \end{pmatrix}$$

$|\psi\rangle = \alpha|0\rangle + \beta|1\rangle$ What does that mean? **Quantum superposition**

Spinning coin analogy



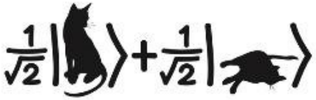
Measurement

Probability $\propto$

$|\alpha|^2$

$|\beta|^2$

Schrodinger's cat



$P_{\text{dead}} = 1/2$

$P_{\text{alive}} = 1/2$

How about **entanglement**?

Two coins

Possible outcomes

Entangled coins/states:

- Obtaining H/T for the first → defines the outcome of the second

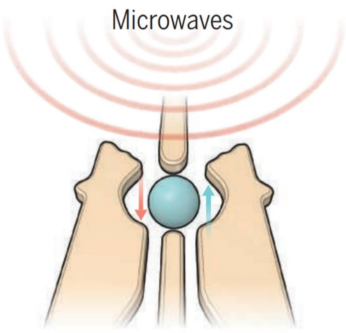
Ex.: $|\phi^+\rangle = \frac{1}{\sqrt{2}}\big(|$  $\rangle + |$  $\rangle\big)$

- Coins can no longer be thought of being independent, they are *entangled*
- Curiosity: 300 coins → $2^{300} \approx 10^{90}$ states > # atoms in the universe ≈ 10^{80}

Existing **qubit** platforms

[Science, **354** 6316]

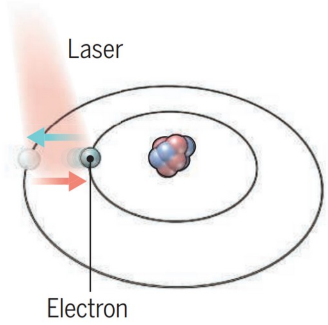
Silicon quantum dots



- “Artificial atoms” made by adding an electron to a small piece of pure silicon.
- Microwaves control the electron’s quantum state.

Intel, HRL, QuTech
UNSW, Delft, RIKEN, ...

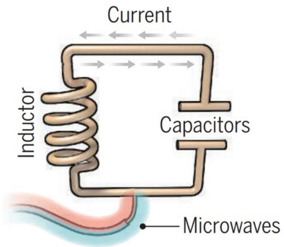
Trapped ions



- Ions, have quantum energies that depend on the location of electrons.
- Tuned lasers cool and trap the ions, and put them in superposition states.

IonQ, Honeywell
Maryland, ...

Superconducting loops

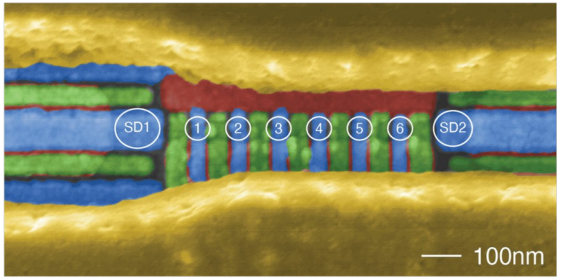


- Resistance-free current oscillates back and forth around a circuit loop
- Injected microwave signal excites the current into superposition states
- Emulates a quantum anharmonic oscillator

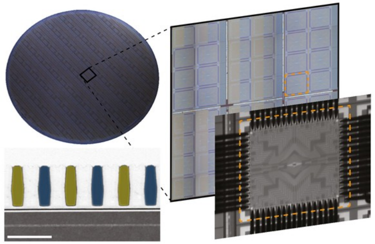
Google, IBM, …
ZJU, UESTC, ...

Building many of them – **Noisy intermediate quantum devices**

Silicon quantum dots

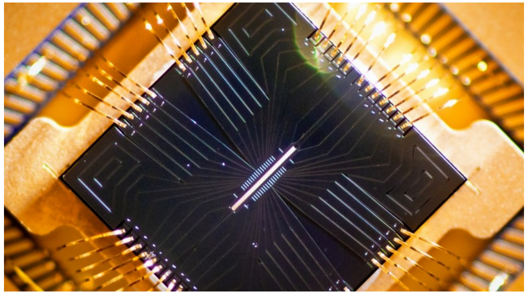


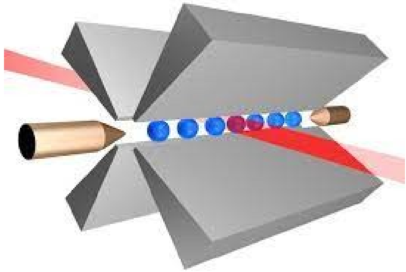
[Qutech 2022]



[Intel 2024]

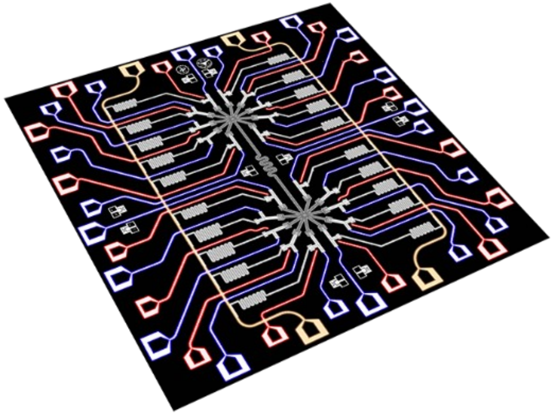
Trapped ions



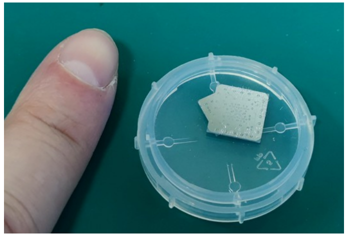


[Maryland, IonQ]

Superconducting quantum circuits



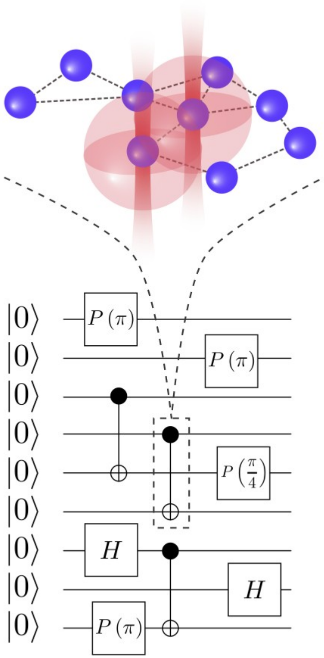
[IOP, ZJU]



How it works?

Digital

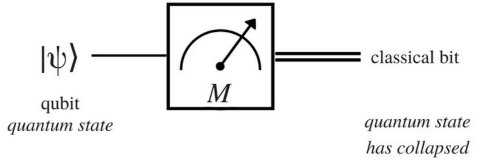
- Platform agnostic
- Possibility of error detection/ correction



[QuEra Computing Inc.]

Qubits are “measured”

Measurements ‘destroys’ the quantum state.



bitstring

0
1
0
1
1
0
0

Composing many shots

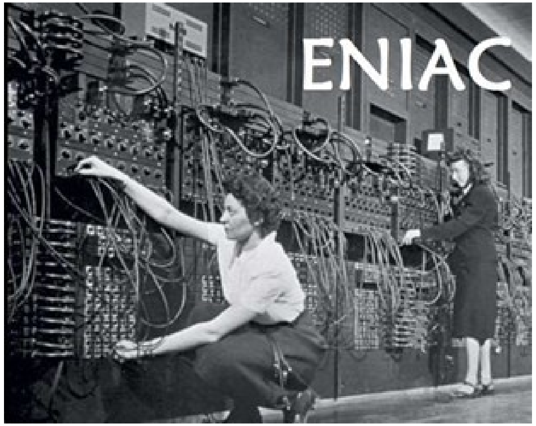
probability of each string

reconstruct the final state

Large number of states → **small** output

The more things change, the more they stay the same…

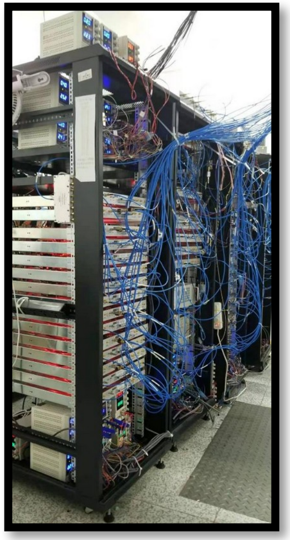
First general-purpose digital computer

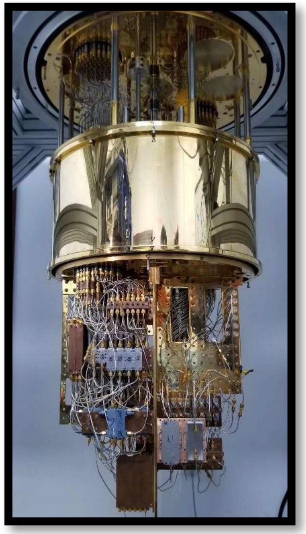


- 30 tons
- 18,000 vacuum tubes
- 1,500 relays
- +100,000 of resistors, capacitors and inductors,

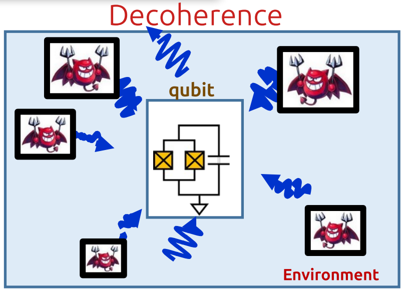
= add or subtract 5,000 times per second!

SC quantum circuit





- 36-qubits (121 available)
- Fully programmable
- Emulates dynamics of $\hat{H}$ with dim = 9B states
- Operates at 20mK…

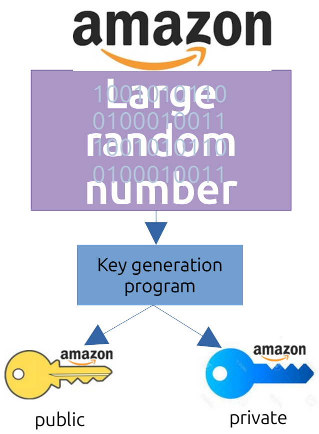


Quantum Computers: What Are They Good For?

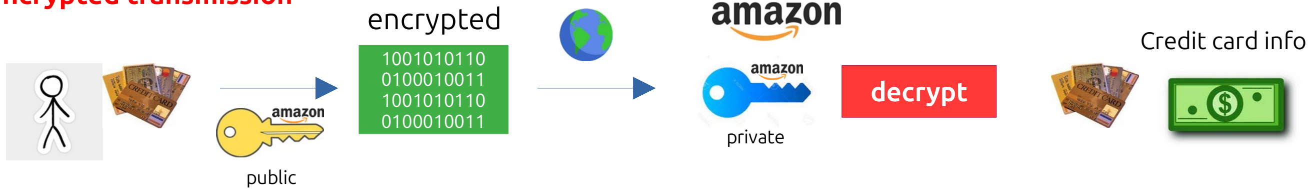
- ✅ Quantum processing
- ✅ Quantum communication
- ✅ Quantum memory

Code cracking – factoring large prime numbers

1) Key generation



2) encrypted transmission

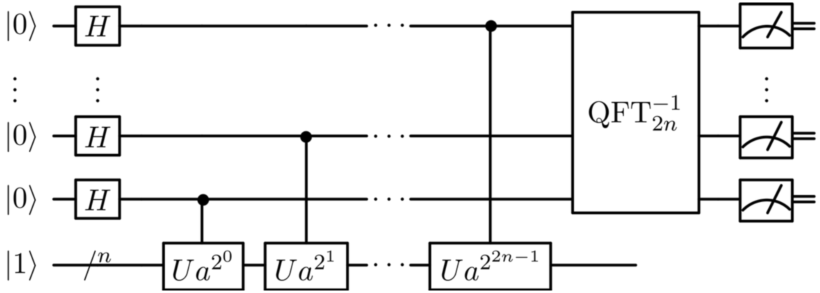


Based on: $$(m^e)^d \equiv m \pmod{n} \quad \text{where} \quad n = \overbrace{pq}^{\text{Prime numbers}}$$

→ (n, e) Scrambles the data

→ To unscramble, one needs one of the primes

- Shor algorithm – quantum circuit to find prime factors of an integer +classical routines



In practice: n = 15 or 21 have been demonstrated so far

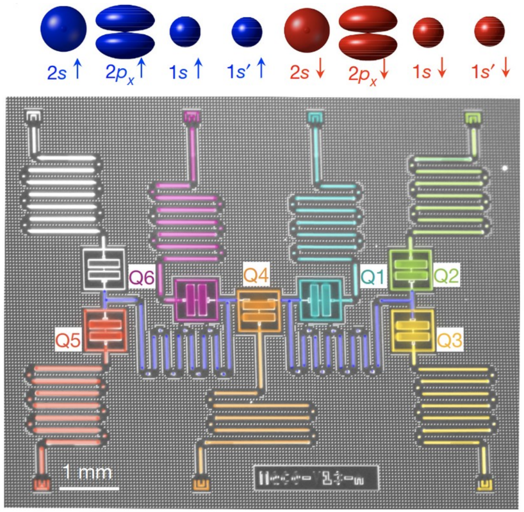
[Nature 414, 883 (2001)]
[Nature Photonics 6, 773 (2012)]

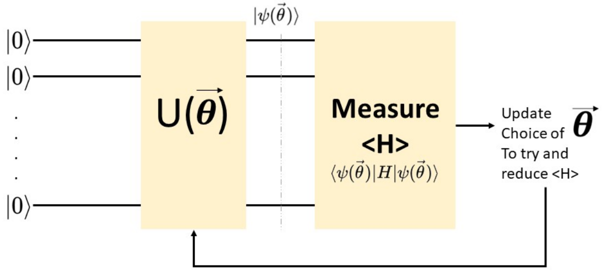
Quantum Computational Chemistry

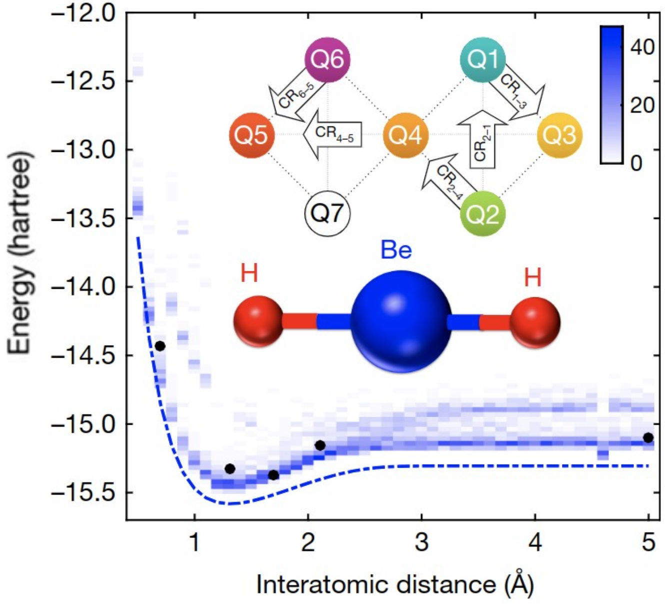
→ Finding the lowest energy states of molecules – dictates the structure of the molecule and how it will interact with other molecules.

→ critical for chemists to design new molecules, reactions, and chemical processes for industrial applications.

Iterative (hybrid) algorithm: Variational Quantum Eigensolver







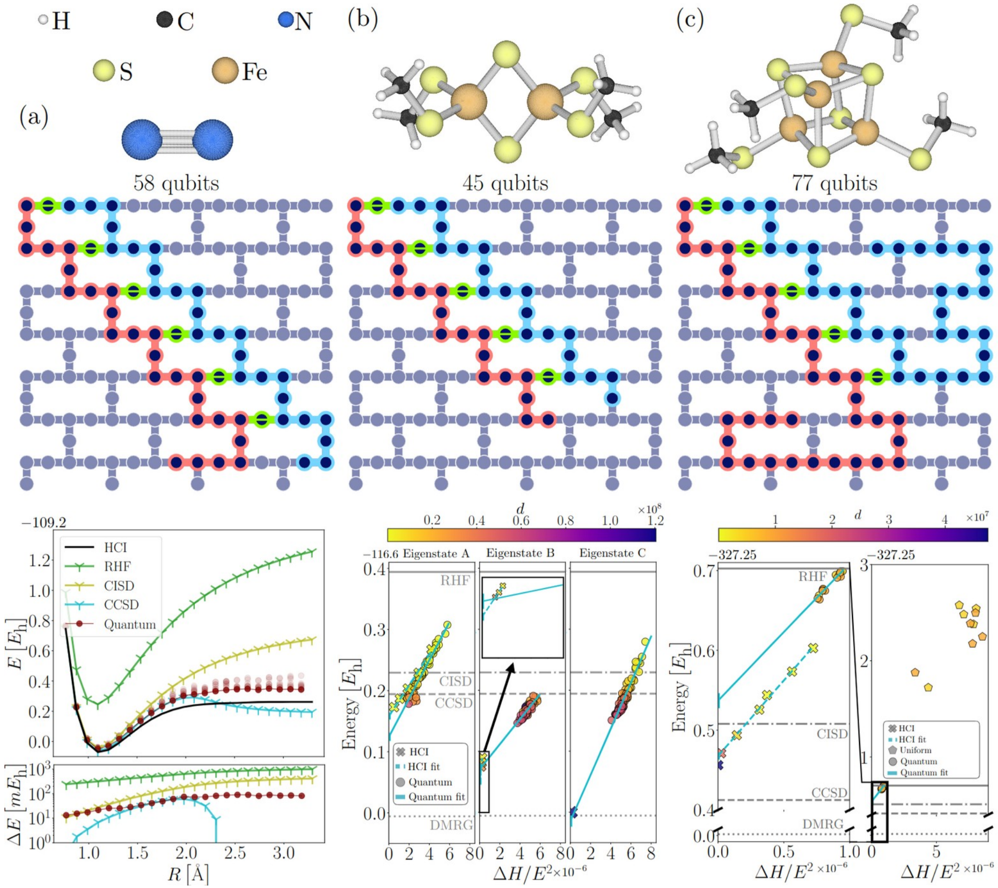
IBM

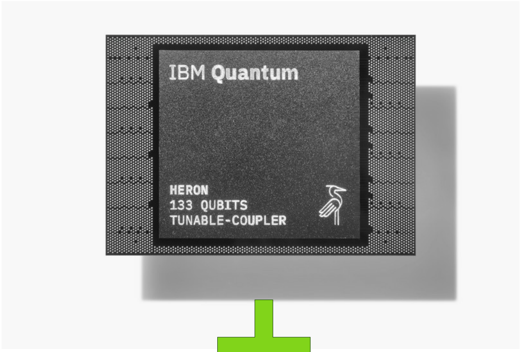
[Kandala et al. Nature 549, 242 (2017)]

[See also Science 369, 1084 (2020) Google's in H_{12} chains]

Quantum Computational Chemistry – last month's (preprint)

Robledo-Moreno et al. "*Chemistry Beyond Exact Solutions on a Quantum-Centric Supercomputer*"
arXiv:2405.05068





Quantum Finance?

nature reviews physics

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Review Article | Published: 11 July 2023

Quantum computing for finance

Dylan Herman, Cody Googin, Xiaoyuan Liu, Yue Sun, Alexey Galda, Ilya Safro, Marco Pistoia & Yuri Alexeev

Nature Reviews Physics **5**, 450–465 (2023) | Cite this article

npj | Quantum Information

ARTICLE **OPEN**

Quantum risk analysis

Stefan Woerner[1] and Daniel J. Egger[1]

→ Applications for finance problems, such as portfolio optimization, risk estimation …

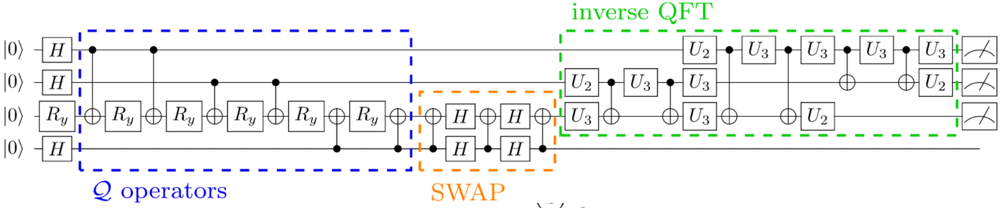
Quantum Amplitude Estimation → used to estimate risk measures with a quadratic speed-up over classical Monte Carlo simulation.

Example:

Mean value of a bond with a given probability of rate change $r \to \delta r$

$$V = \frac{(1-p)V_F}{1+r+\delta r} + \frac{pV_F}{1+r} = (1-p)V_{\text{low}} + pV_{\text{high}}$$

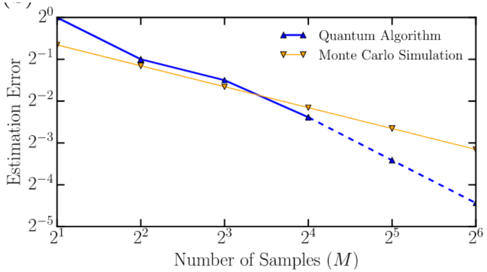
$\mathcal{A} = R_y(\theta_p)$ $\quad \theta_p = 2\sin^{-1}(\sqrt{p})$ $\quad \mathcal{A}|0\rangle = \sqrt{1-p}|0\rangle + \sqrt{p}|1\rangle$



Ancilla (measurement) qubits

$m = 3$

	M samples	Error
Quantum Algorithm		$\mathcal{O}(M^{-1})$
Monte Carlo		$\mathcal{O}(M^{-1/2})$

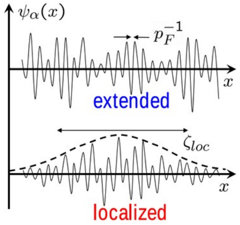


[Woerner, Egger npj Quantum Information (2019)5:15]

Solving (or giving hints) on some very hard Physics problems

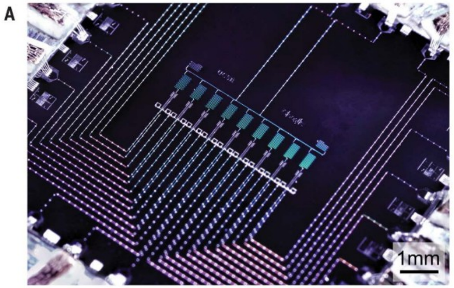
→ Localization of quantum particles in the presence of interactions (many-body localization)

Localization under disorder + interactions

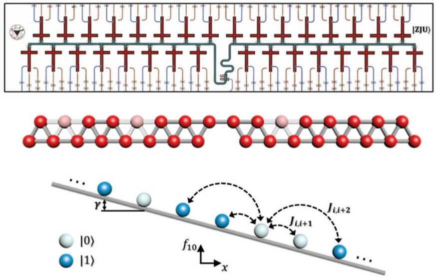


Nobel Prize 1977

PW Anderson

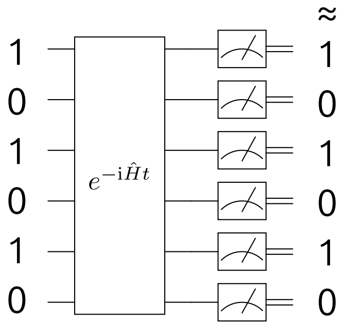


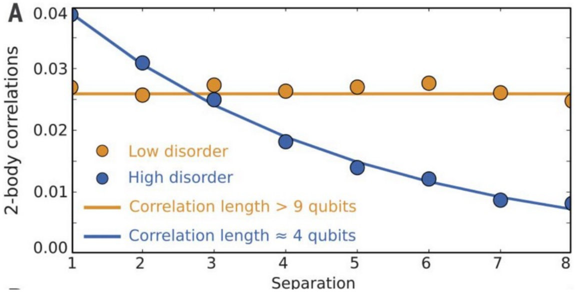
[Roushan *et al*., Science **358**, 1175 (2017)]



[Guo, …, **RM*** Phys. Rev. Lett. **127**, 240502 (2021)]

Loosely speaking





[Neil *et al.* Science 360 (6385), 195 (2018)]

Local quantum memory? Maybe we don't need a quantum computer for that…

[see also Guo, **RM***, Nature Physics 17, 234 (2021)]

Quantum Communication

- Probing entanglement at large distances

Science

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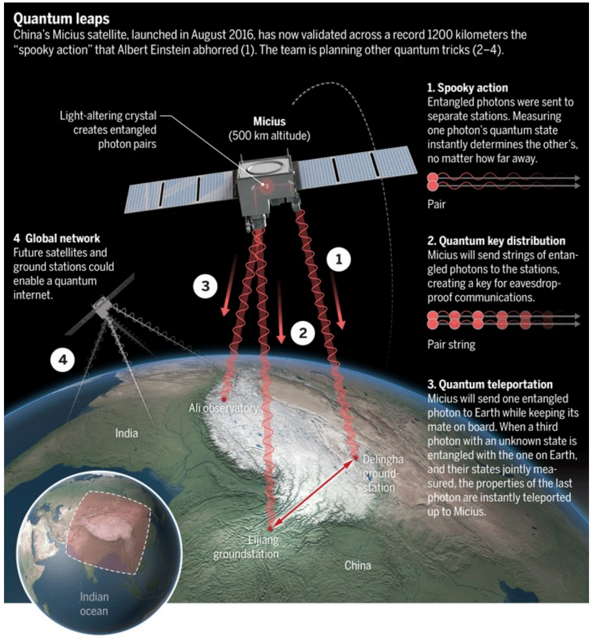
RESEARCH ARTICLE

Satellite-based entanglement distribution over 1200 kilometers

JUAN YIN, YUAN CAO, YU-HUAI LI, SHENG-KAI LIAO, LIANG ZHANG, JI-GANG REN, WEN-QI CAI, WEI-YUE LIU, BO LI, [...], AND JIAN-WEI PAN +24 authors

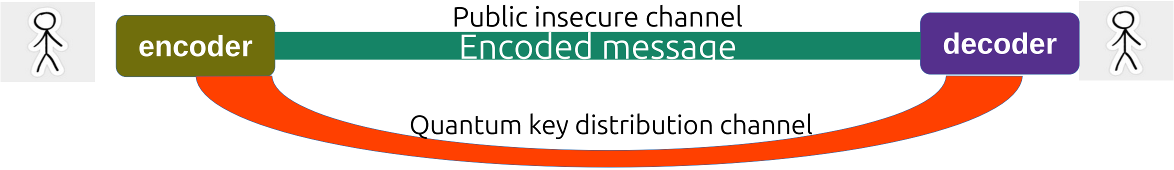
Authors Info & Affiliations

SCIENCE • 16 Jun 2017 • Vol 356, Issue 6343 • pp. 1140-1144 • DOI: 10.1126/science.aan3211



Pair of entangled photons sent to receivers 1200km (~745 miles) apart
→ one photon's quantum state instantly determines the other's

- Quantum key distribution

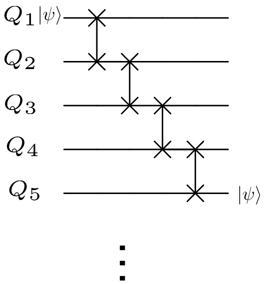


act of **measurement** of an eavesdropper destroys the key!

Can we investigate the "channel" as a "quantum wire"?
Quantum state transfer!

Quantum Communication - quantum state transfer in a quantum computer

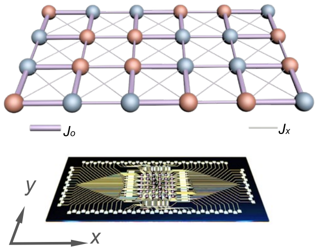
"SWAP train"

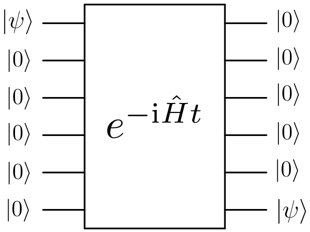


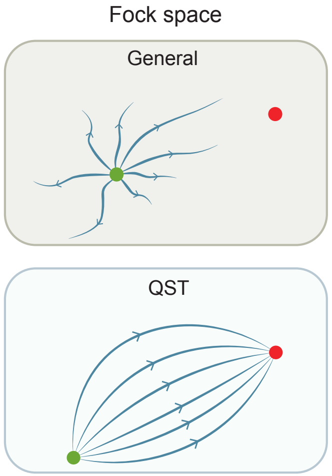
$$SWAP = \begin{pmatrix} 1 & 0 & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 0 & 1 \end{pmatrix}$$

: Swaps the state of two qubits

- Or: Multigate Hamiltonian evolution – "analog" mode – hybrid computation



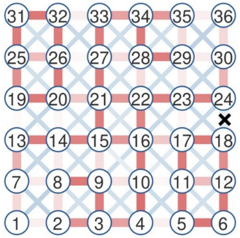


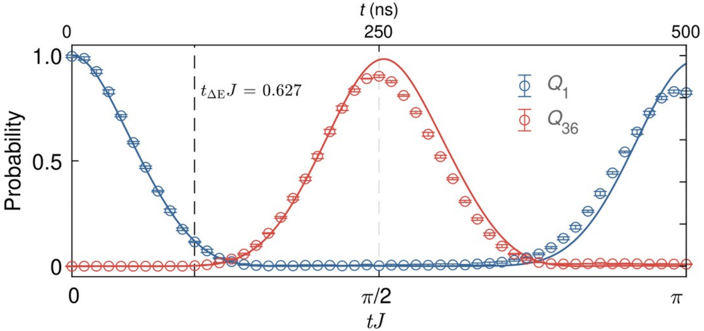


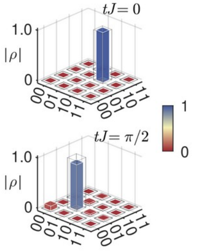
- Transfer of two-qubits maximally entangled states

$$|\Psi^-\rangle = \frac{|01\rangle - |10\rangle}{\sqrt{2}}$$

6x6:

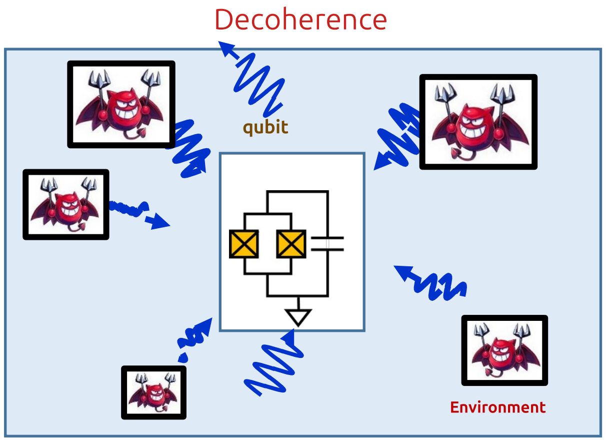






[L. Xiang, …, **RM***, Scalettar , Nat. Comm. 15 4918 (2024)]

What is the bottleneck? Quantumness of Qubits don’t last long and gates are not perfect…



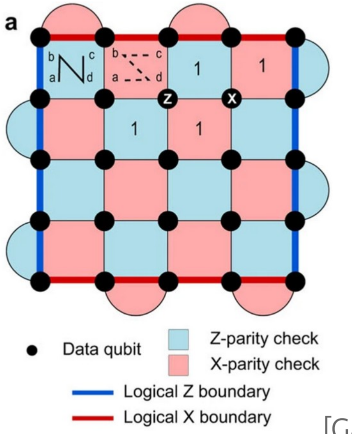
+noise

→ Solution:

- Quantum error correction
- Physical vs. Logical qubits

Several qubits working together as one to represent one qubit of information

→ **The goal**: even if one physical qubit “fails”, the remainder in the logical set recovers the information



- Set of **data encoding** + **low-depth checks** to ensure the information is preserved
- Active area of research and demonstration!

→ eg: “*Suppressing quantum errors by scaling a surface code logical qubit*” Google Quantum AI*, Nature **614**, 676 (2023)

[Gambetta, Chow, Steffen npj Quantum Information 3, 2 (2017)]

Take away message

Thank you!

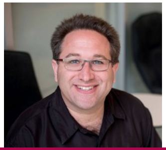
→ Quantum computers algorithmically apply the standard laws of quantum mechanics

→ Search of new problems **and** corresponding algorithms that can be implemented in QC's is a field of intense research

→ Avoid the hype: Quantum computers will likely not replace our classical computers any time soon. They are often designed for very specific tasks, and are doing so (currently) sub-optimally

→ **But there are many fun things that they can accomplish!**

"If you don't talk to your kids about quantum computing… someone else will."



Scott Aaronson (UT Austin)

Extra slides

Monte Carlo comes to the rescue!

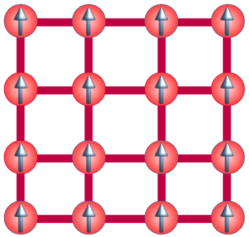
Ising model

$$E_{\{S\}} = -J \sum_{\langle i,j \rangle} S_i S_j, \quad S_i = \pm 1$$

$$p_{\{S\}}(T) \propto e^{-E_{\{S\}}/T}$$

Annealing: $T_{\text{high}} \to T_{\text{low}}$ proposing spin flips

Provides search to a low-energy configuration



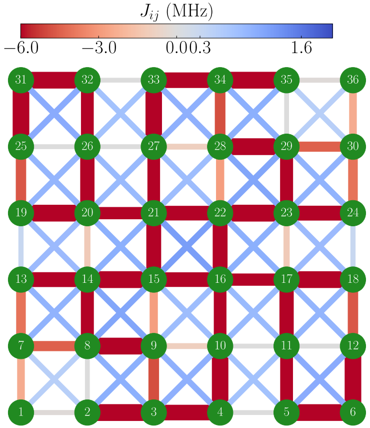
Quantum state transfer

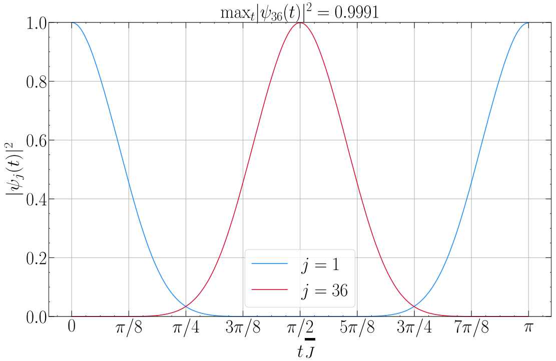
$$\tilde{F}(t^*) = 1 - |\langle \psi(t^*) | \psi_{\text{target}} \rangle|^2 \quad \text{with } |\psi(t^*)\rangle = e^{-\mathrm{i}\hat{H}t^*} |\psi(0)\rangle$$

$$p_{\{J_{ix}, J_{iy}, J_{\times}\}} \propto e^{-\tilde{F}/T}$$

Annealing: $T_{\text{high}} \to T_{\text{low}}$ proposing $\{J_{ix}, J_{iy}\}$ changes

Provides search to configuration that maximizes QST

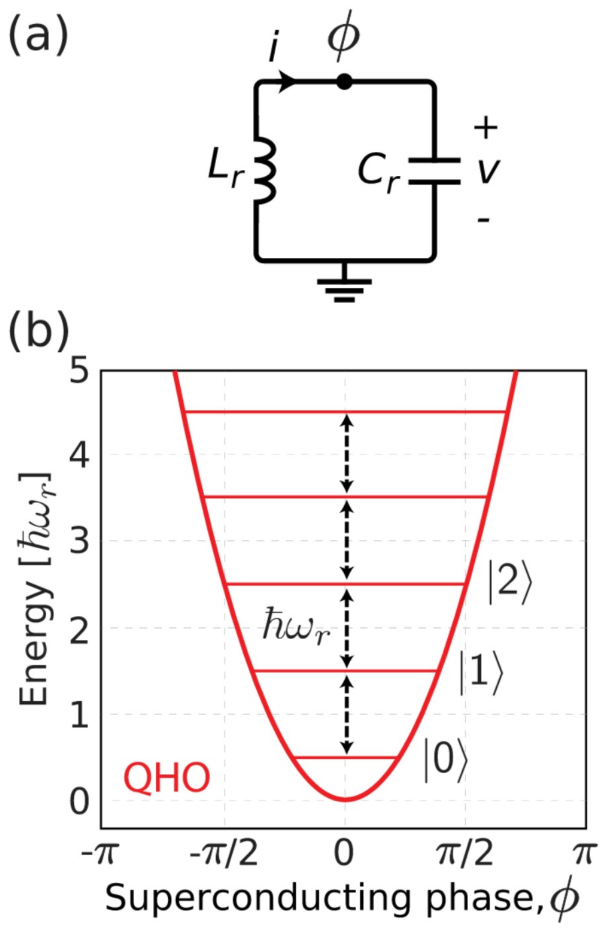




Appl. Phys. Rev. 6, 021318 (2019)

Transmon qubit:

LC oscillator



Classically

$$H = \frac{1}{2}CV^2 + \frac{1}{2}LI^2$$

$$\left(m = C \quad \omega = 1/\sqrt{LC} \rightarrow H = p^2/2m + m\omega^2 x^2/2\right)$$

Quantum

$$\hat{H} = 4E_C\hat{n}^2 + \frac{1}{2}E_L\phi^2$$

$$E_C = e^2/(2C)$$

$$E_L = (\Phi_0/2\pi)^2/L$$

$$n = n_{\text{zpf}} \times i(a - a^\dagger)$$

$$\phi = \phi_{\text{zpf}} \times (a + a^\dagger)$$

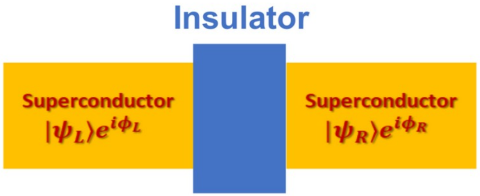
- equally spaced energy levels
- no selectivity

Second quantization: $H = \hbar\omega_r\left(a^\dagger a + \frac{1}{2}\right)$ $\qquad \omega_r = \sqrt{8E_LE_C}/\hbar = 1/\sqrt{LC}$

Appl. Phys. Rev. 6, 021318 (2019)

Transmon qubit:

Anharmonic LC oscillator



Josephson Junction

$$I = I_c \sin(\phi), \quad V = \frac{\hbar}{2e}\frac{d\phi}{dt}$$

nonlinear inductance

$$H = 4E_C n^2 - E_J \cos(\phi)$$

$$L_J = \frac{\Phi_0}{2\pi\sqrt{I_c^2 - I^2}}$$

$$\frac{H}{\hbar} = \boxed{\omega_{10}|1\rangle\langle 1|} + (2\omega_{10} + \eta)|2\rangle\langle 2|$$