Quantum Computing quick-start

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Goal: to develop basic and strong intuition around fundamental concepts in quantum science and technology. Minimal math for now :)

- Where do we stand?
- Information and it’s processing
- How to approach quantum algorithms?
- The Pauli and Hadamard operators
- **Hand-on: simulating quantum logic circuits**

: ask an LLM

: derive this by hand

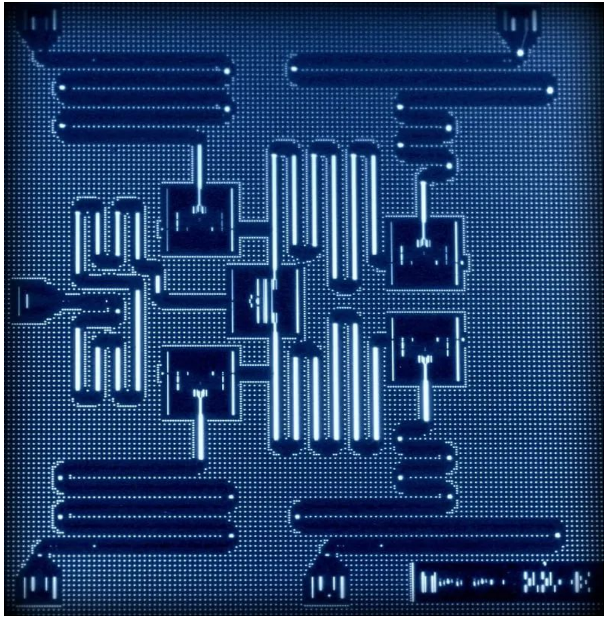
: food for thought

Further readings down here

The **Past** of QC

IBM Q 2015

IQOQI Innsbruck 90's - present



- Very few qubits
- Hard to control
- High gate errors

The **Present** of QC

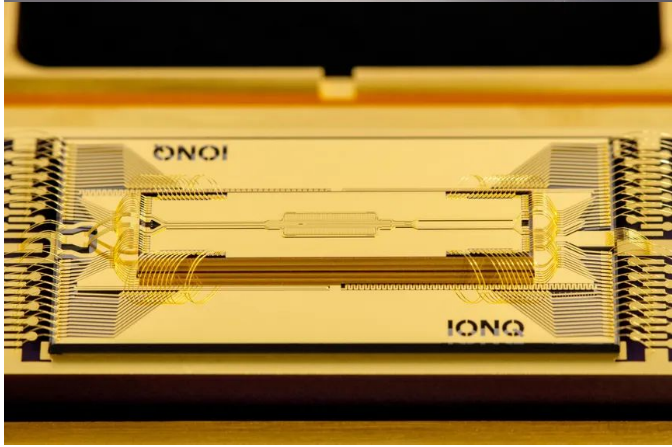
Superconducting

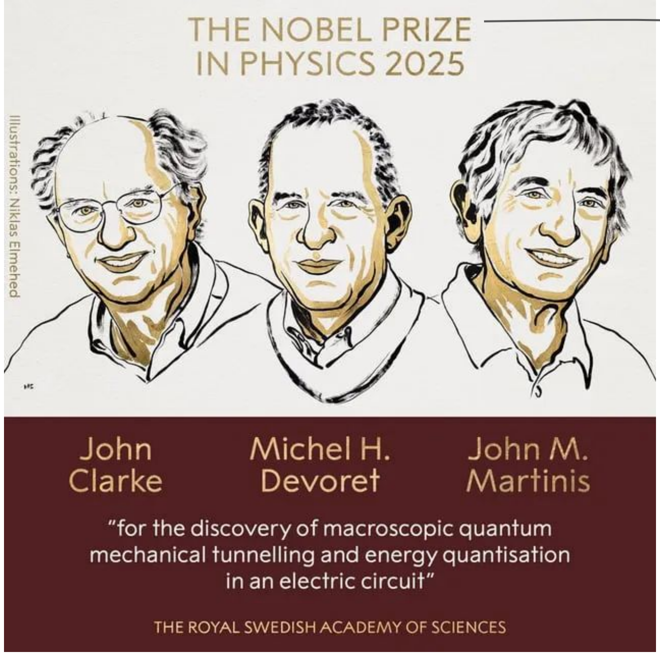
Google Q 2024 (Willow device)

Trapped Ions

IonQ Inc. (Forte device)

- Handful of qubits
- Early utility applications
- High errors for deep circuits
- Early use of error correction





"[…] to reward individuals and organizations that have conferred the **greatest benefit to humankind** in the fields of physics, […]"

Quantum Computing and Networking Expected to Create Up to $880B in Economic Value by 2040

IONQ

Machine Learning	Optimization	Simulation	Cryptography	Communication
Automotive: AV AI Algorithms $1B-$10B	**Logistics:** Network Optimization $50B-$100B	**Pharma:** Drug Discovery $40B-$80B	**Government:** Encryption, Decryption (Cyber Security) $20B-$40B	Security, Networks, and Services $24B-$36B
Finance: AML and Anti-fraud $20B-$30B	**Insurance:** Risk Management $10B-$20B	**Aerospace:** CFD $10B-$20B	**Corporate:** Encryption (Cyber Security) $20B-$40B	
Tech: Search/Ads Optimization $50B-$100B	**Finance:** Portfolio Optimization $20B-$50B	**Chemistry:** Catalyst Design $20B-$50B		
Other Use Cases $25B-$110B	**Aerospace:** Route Optimization $20B-$50B	**Energy:** Solar Conversion $10B-$30B		
		Finance: Market Simulation $20B-$35B		
		Other Use Cases $75B-$115B		

Quantum machine learning applications to impact most, if not all, industries

Sources: BCG, The Long-Term Forecast for Quantum Computing Still Looks Bright, June 2024, McKinsey, Quantum Technology Monitor, April 2024
Note: Value creation market sizes estimated at technology maturity

6 IonQ Investor Updates

What will the "cloud" equivalent innovation of Q technologies be???

Ref. IonQ August 2025 Investor Presentation

The **Future** of QC

- Different paradigms have different bottlenecks
- Error correction is essential
- Algorithms and applications to be discovered
- Small local area networks
- The *quantum-classical race*

"A calculator like the ENIAC today is equipped with 18,000 vacuum tubes and weighs 30 tons, computers in the future may have only 1,000 vacuum tubes and perhaps weigh only 1.5 tons."

*- Popular Mechanics, March **1949***

Ref. IBM's Roadmap   Ref. IonQ's Roadmap

Classical VS Quantum Computing

Classical computation can be described by it's quantum counterpart (C ⊂ Q)

What is information?

Information is the ability to distinguish reliably between possible alternatives.

✦ Strictly defined along with *entropy.*

What is information processing?

The set of mechanisms that change which alternatives are distinguishable

	Classical	*Quantum*
Information	$\vert 0\rangle$ or $\vert 1\rangle$	$\vert\psi\rangle = ?$
Processing	Logic gates (AND, XOR, ...)	Unitary $U^\dagger = U^{-1}$ and Linear without noise

How to Approach Quantum Algorithms

The general idea (not restrictive)

Superpose ⟶ *Entangle* ⟶ *Interfere*

$$\boxed{|\psi\rangle = a\,|0\rangle + b\,|1\rangle}$$

$$a, b \in \mathbb{C}$$

$$|a|^2 + |b|^2 = 1$$

<u>Born's rule :</u>
(loose definition)

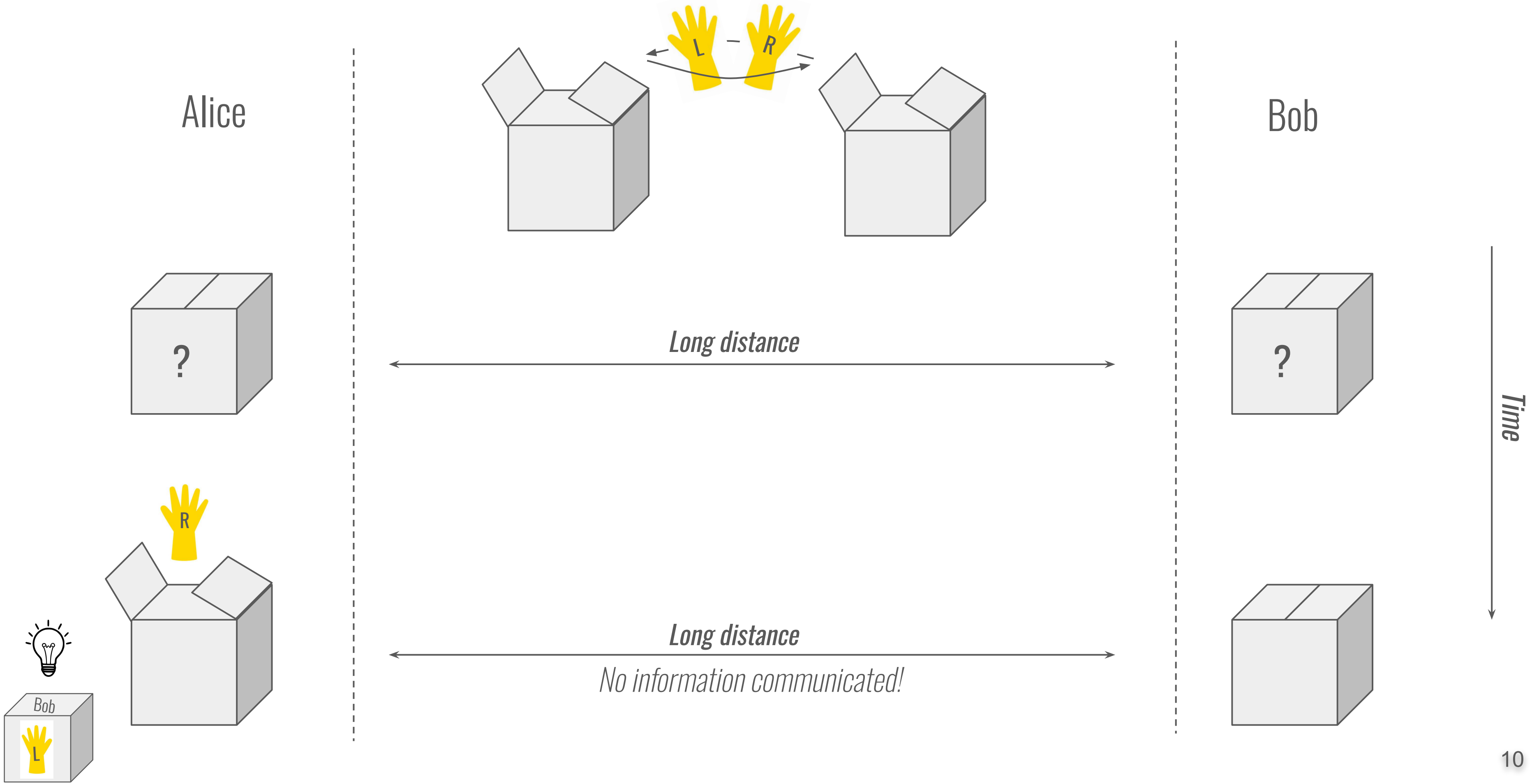
The probability of a quantum system being measured in some state $|\phi\rangle$ is given by the absolute value squared of $|\phi\rangle$.

Thus providing the statistical interpretation of quantum mechanics.

Example: for $|\psi\rangle$ the probability of measuring $|0\rangle$ is $P(0) = |a|^2$.

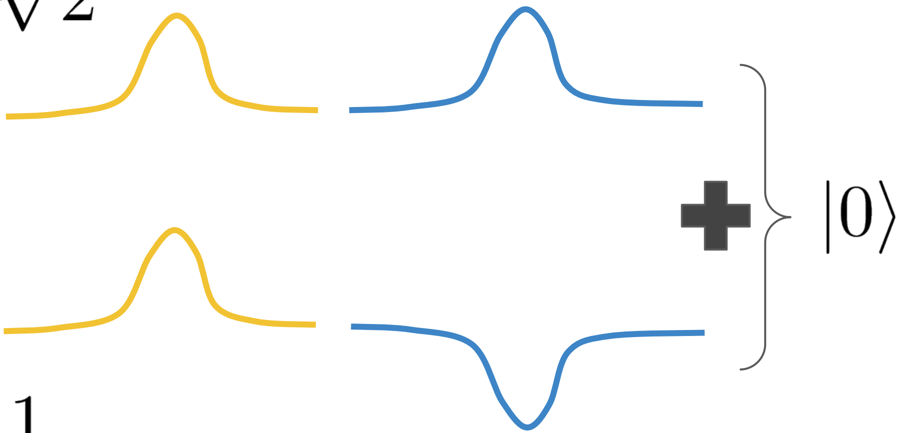
see also Born's rule wiki

Entanglement as Passive Measurement



Probability <u>amplitudes</u> associated with different possible paths of a quantum system are combined, to increase the possibility of an outcome (constructively) or to decrease it (destructively).

$$\frac{1}{\sqrt{2}}\left(|0\rangle \quad + \quad e^{i0}\,|1\rangle\right)$$



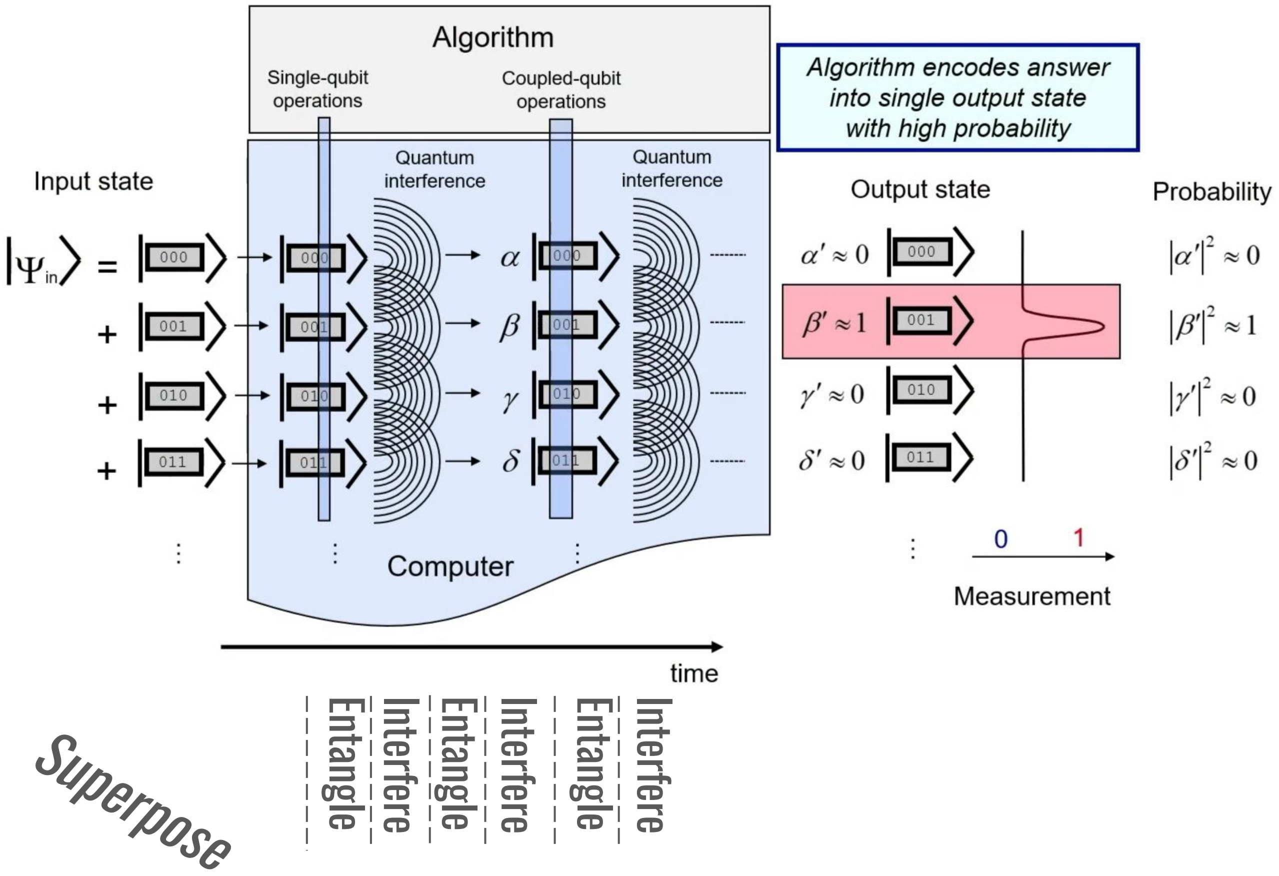
$$\frac{1}{\sqrt{2}}\left(|0\rangle \quad + \quad e^{i\pi}\,|1\rangle\right)$$

For both initial state: $P(1) = 0.5$

For the combine state: $P(1) = 0$

We added two scenarios with non-zero probability for $|1\rangle$ and got $P(1) = 0$.

see also [Mach–Zehnder interferometer]



Algorithm
Single-qubit operations
Coupled-qubit operations
Algorithm encodes answer into single output state with high probability
Input state
Quantum interference
Quantum interference
Output state
Probability
$|\Psi_{in}\rangle = |000\rangle + |001\rangle + |010\rangle + |011\rangle$
α β γ δ
$\alpha' \approx 0$ $\beta' \approx 1$ $\gamma' \approx 0$ $\delta' \approx 0$
$|\alpha'|^2 \approx 0$ $|\beta'|^2 \approx 1$ $|\gamma'|^2 \approx 0$ $|\delta'|^2 \approx 0$
Computer
0 1
Measurement
time
Superpose
Entangle
Interfere
Entangle
Interfere
Entangle
Interfere

The Pauli Operators

Defined by their action on the *computational basis*...

$$X|0\rangle = |1\rangle \qquad Y|0\rangle = i|1\rangle \qquad Z|0\rangle = |0\rangle$$

$$X|1\rangle = |0\rangle \qquad Y|1\rangle = -i|0\rangle \qquad Z|1\rangle = -|1\rangle$$

X is also known as a *bit-flip*, while **Z** as a *phase-flip*.

Are Paulis unitary? □

The Hadamard Operation

Creates superposition from the *computational states...*

$$H\,|0\rangle = \frac{|0\rangle + |1\rangle}{\sqrt{2}} \equiv |+\rangle \qquad H\,|1\rangle = \frac{|0\rangle - |1\rangle}{\sqrt{2}} \equiv |-\rangle$$

$$H = \frac{X + Z}{\sqrt{2}}$$

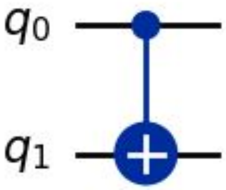
see also Discrete Fourier Transform Matrix

What are Controlled Unitaries?

They constitute an example of multi-qubit gates.

These apply an operation to sub-system subject to the state of another.

Example: controlled-NOT (aka CX)



If q0 is $|0\rangle$ do nothing.

If q0 is $|1\rangle$ flip q1.

Effectively applying q1 □ (q0 XOR q1)

If q0 is superposed it entangles the qubits…

References and Additional Reading

[1] B. Schumacher and M. Westmoreland, *Quantum Processes Systems, and Information*. Cambridge: Cambridge University Press, 2010.

[2] N. D. Mermin, *Quantum Computer Science: An Introduction*. Cambridge: Cambridge University Press, 2007.

Is it about time?

Interest form

TUC-Qtech student group

- Organize workshops
- Participate in online events
- Paper reviews
- Group projects
- others...