

The Essence of Quantum Information Processing

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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



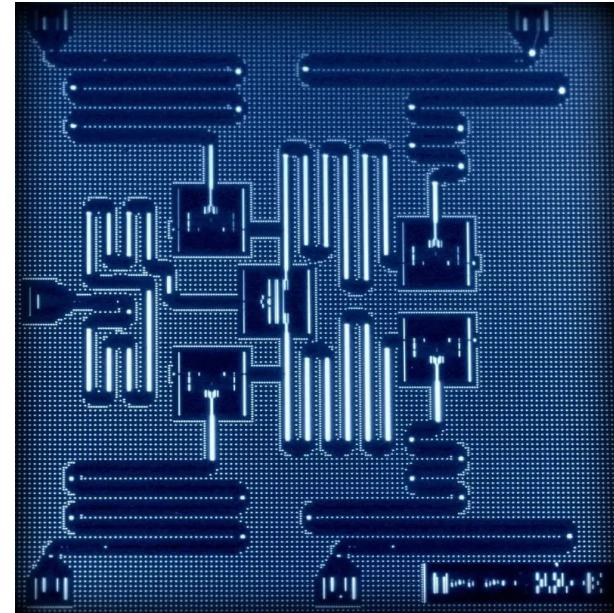
: derive this by hand



: food for thought

The Past of QC

IBM Q 2015



100Q 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



Historical Recognition for Quantum Technologies

THE NOBEL PRIZE
IN PHYSICS 2025

Illustrations: Niklas Elmehed



John
Clarke

Michel H.
Devoret

John M.
Martinis

"for the discovery of macroscopic quantum mechanical tunnelling and energy quantisation in an electric circuit"

THE ROYAL SWEDISH ACADEMY OF SCIENCES



What will the “cloud” equivalent innovation of Q technologies be???

“[...] 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



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	
Finance: AML and Anti-fraud \$20B-\$30B	Insurance: Risk Management \$10B-\$20B	Aerospace: CFD \$10B-\$20B		
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	Corporate: Encryption (Cyber Security) \$20B-\$40B	Security, Networks, and Services \$24B-\$36B

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

- 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

Classical VS Quantum Computing

Classical computation can be described by it's quantum counterpart ($C \subset Q$)

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	$ 0\rangle$ or $ 1\rangle$	$ \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*

$$|\psi\rangle = a|0\rangle + b|1\rangle$$

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

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

Born's rule :

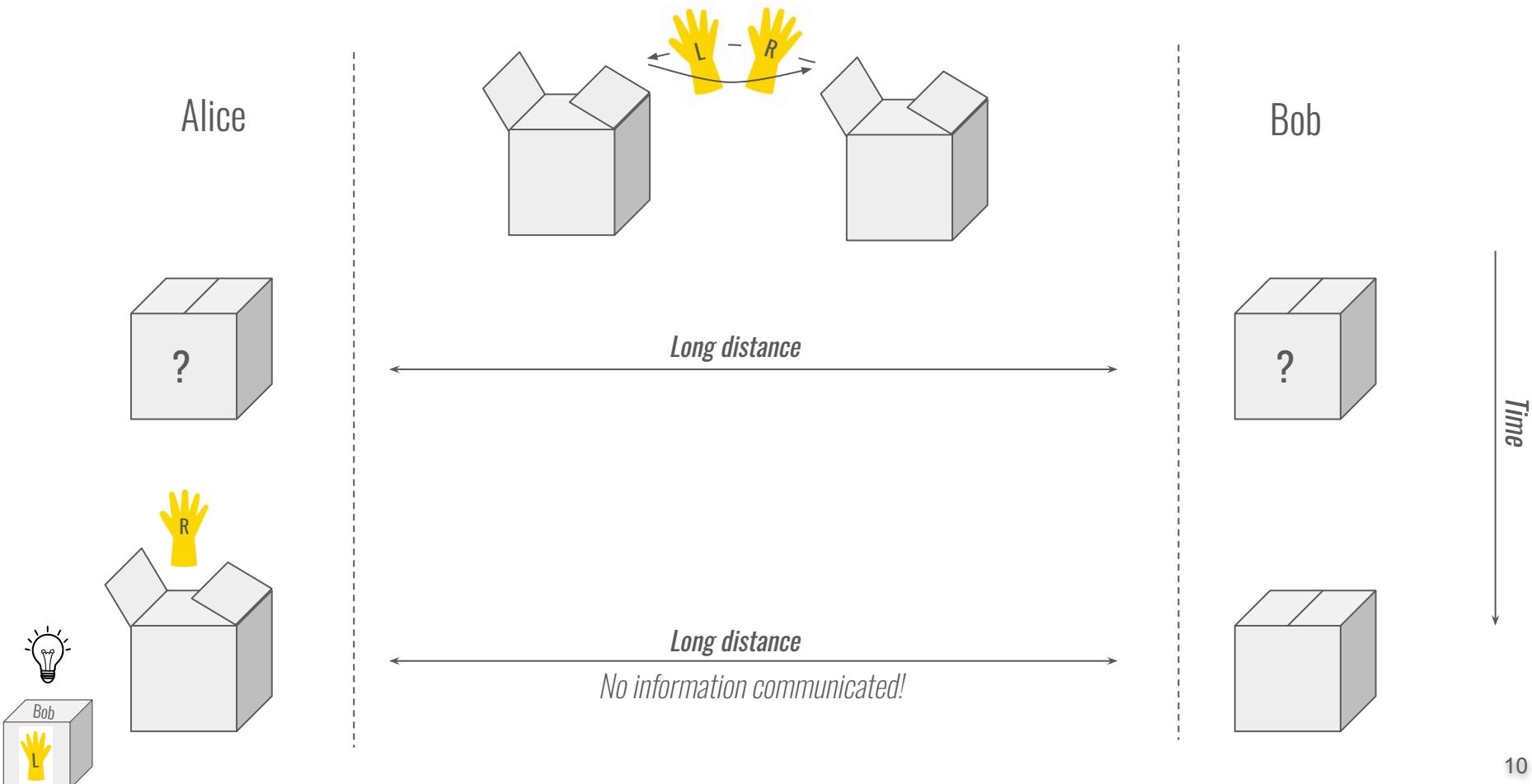
(loose definition)

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.

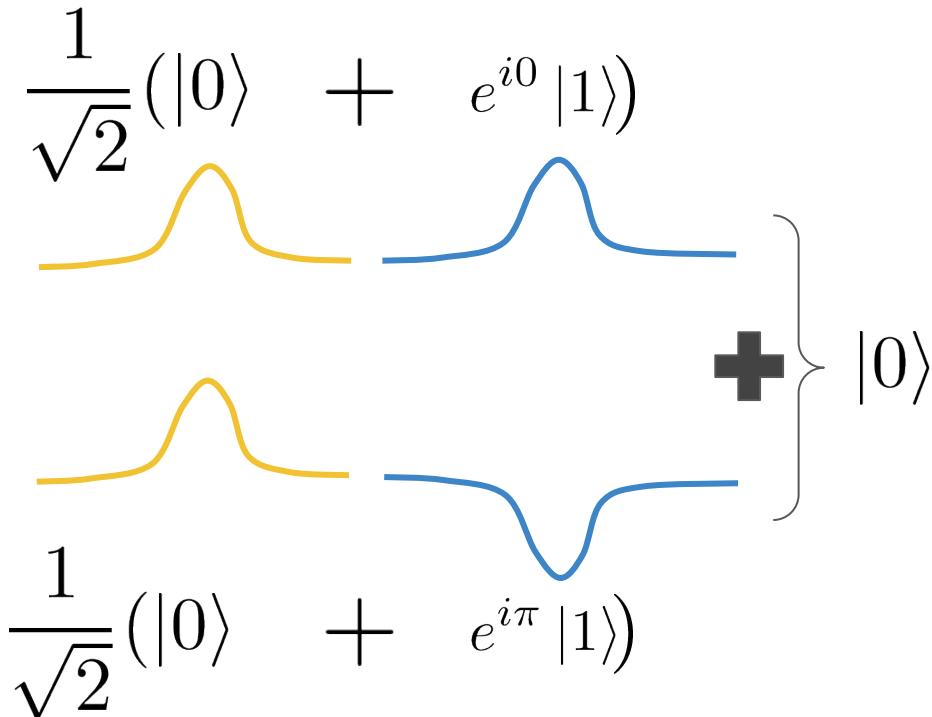
Example: for $|\psi\rangle$ the probability of measuring $|0\rangle$ is $P(0) = |a|^2$.

Entanglement as Passive Measurement





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



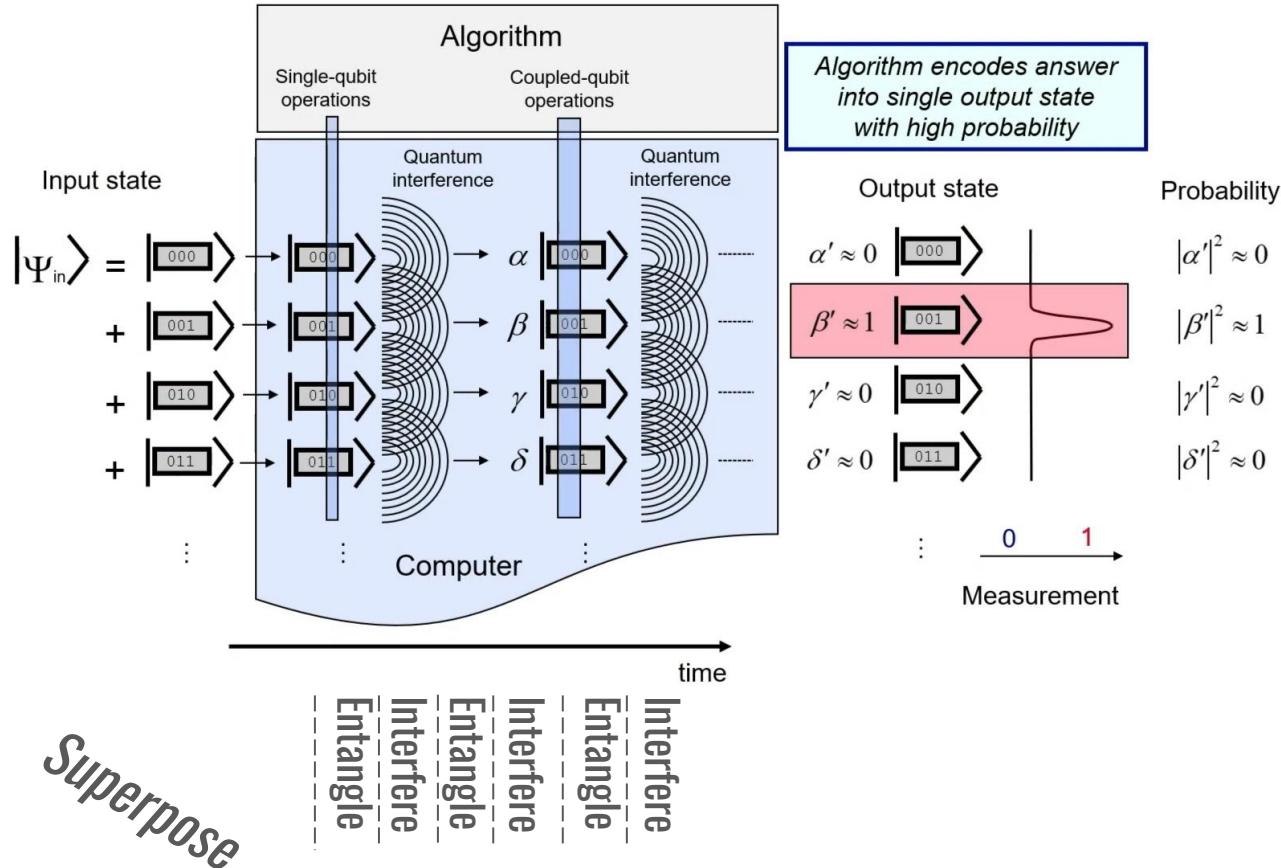
For both initial state: $P(1) = 0.5$

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](#)

How to Approach Quantum Algorithms



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

$$X |0\rangle = |1\rangle$$

$$Y |0\rangle = i |1\rangle$$

$$Z |0\rangle = |0\rangle$$

$$X |1\rangle = |0\rangle$$

$$Y |1\rangle = -i |0\rangle$$

$$Z |1\rangle = -|1\rangle$$

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

Creates superposition from the *computational states*...

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

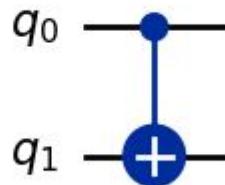
$$H = \frac{X + Z}{\sqrt{2}} \quad \square$$

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 q_0 is $|0\rangle$ do nothing.

If q_0 is $|1\rangle$ flip q_1 .

Effectively applying
 $q_1 \square (q_0 \text{ XOR } q_1)$

If q_0 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?



TUC-Qtech student group

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

Interest form

