June 30, 2020 @Quantum Computing Workshop

Quantum Computing ?

Yun-Chih Liao
IBM Quantum Computer Hub at National Taiwan University

Outline

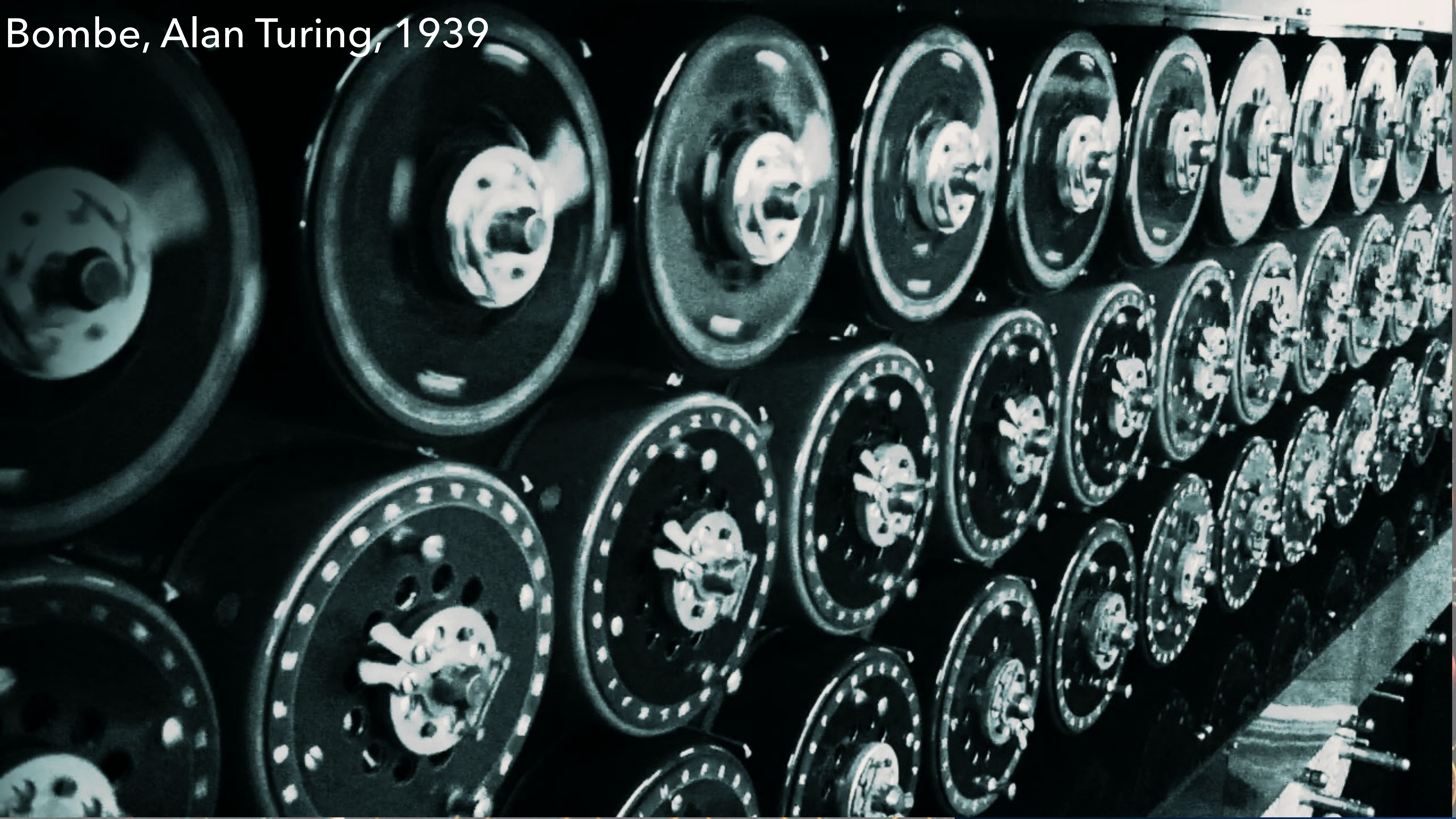
History

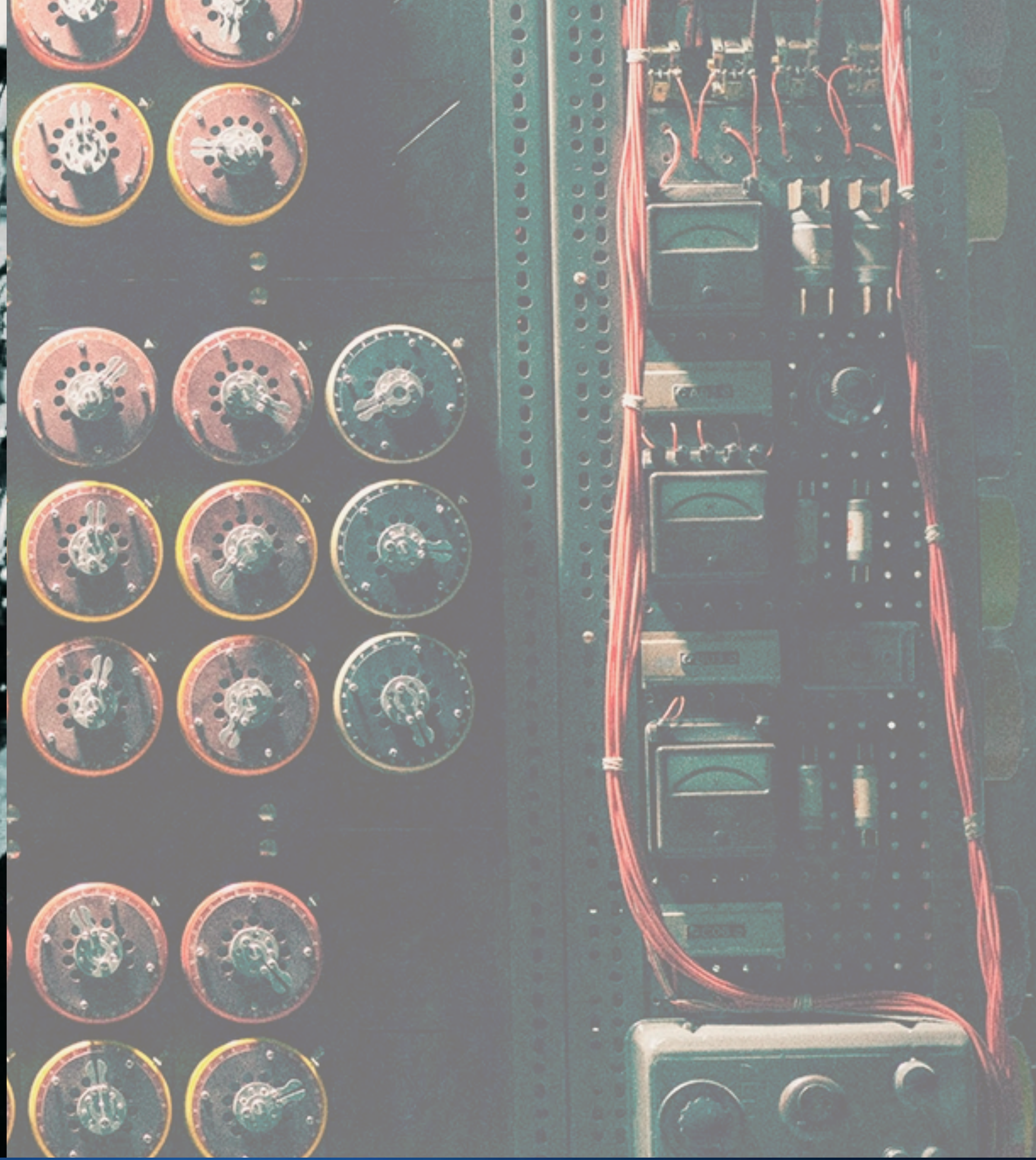
Background

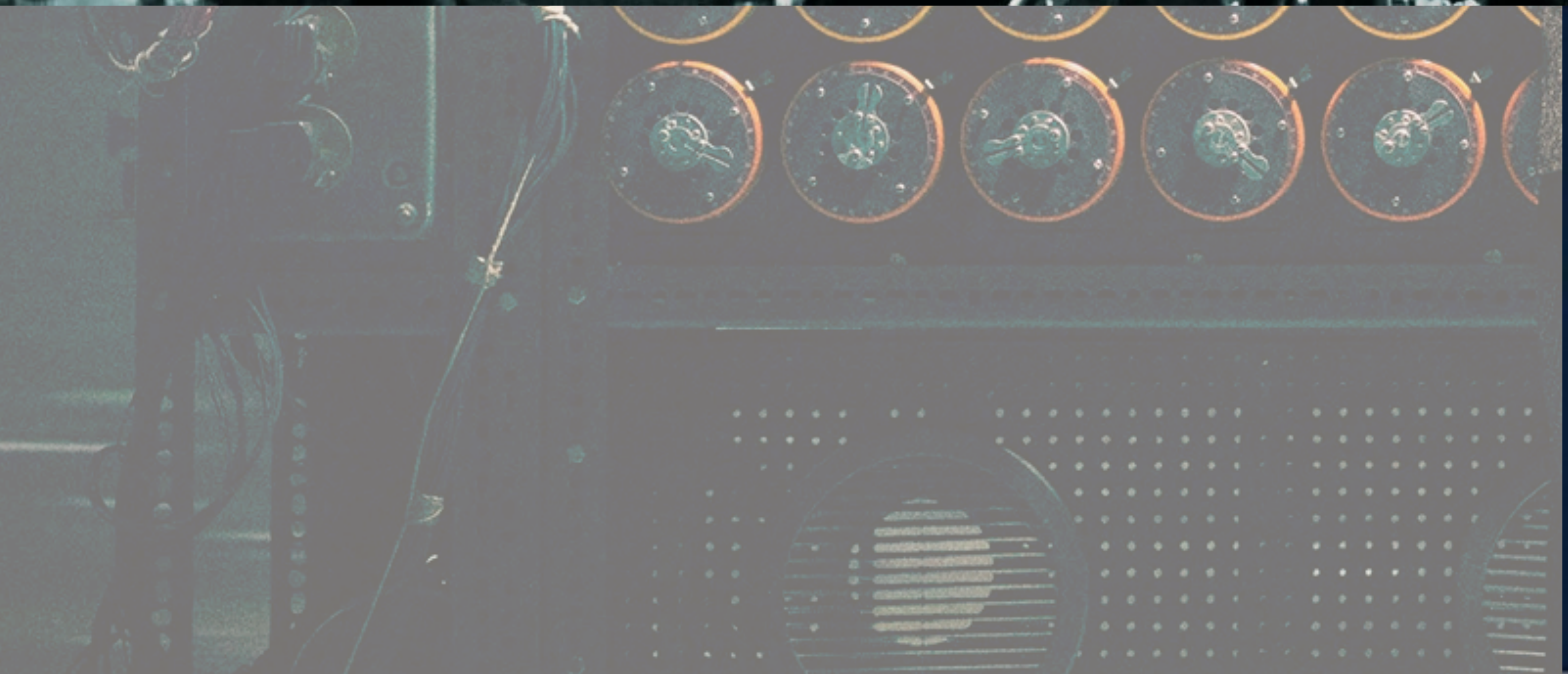
Quantum Language

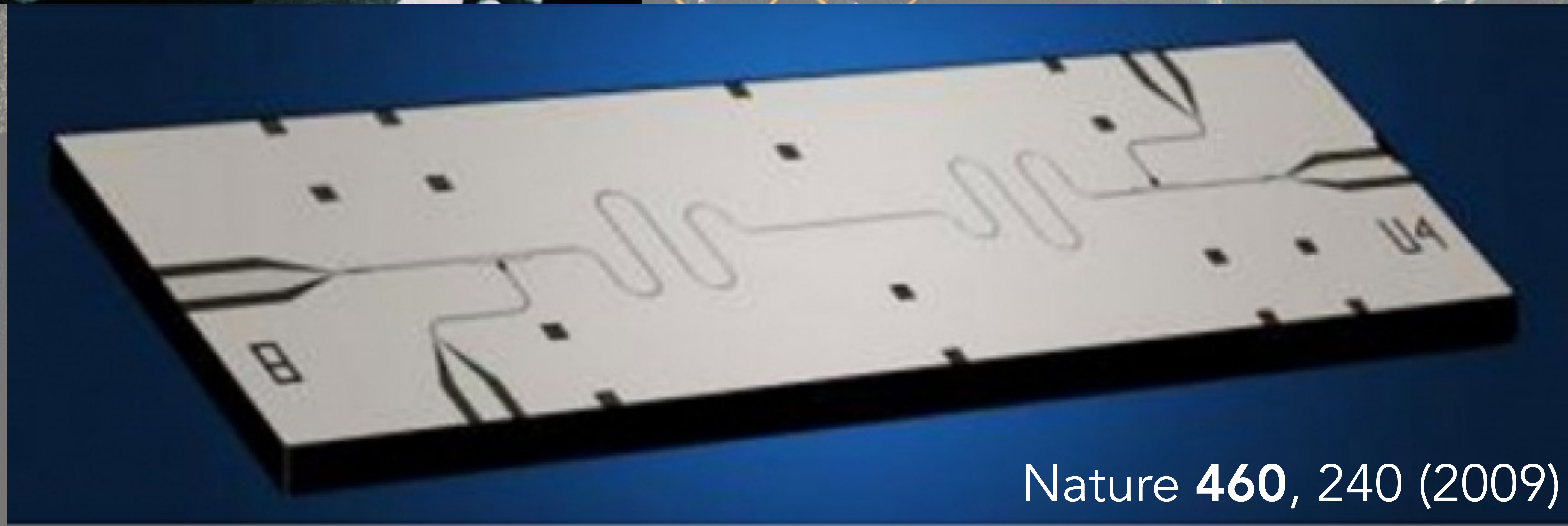
Quantum Computers

Bombe, Alan Turing, 1939









Nature **460**, 240 (2009)

History

1980

Paul Benioff

Proposes quantum Turing machine model

1985

Paul Deutsch

Theoretical universal quantum computer

1993

Dan Simon

Quantum computer would be exponentially faster than conventional computer

1994

Peter Shor

Shor 's algorithm

1995

NIST & CalTech

Cools and traps ion to a quantum state

1997

MIT

First quantum computer (based on NMR)

2001

Emanuel Knill, Raymond Laflamme & Gerard Milburn

Shows that optical quantum computing is possible

2009

Yale University

First electronic quantum processor

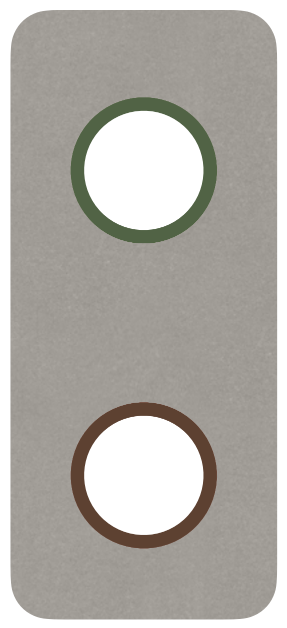
2016

IBM

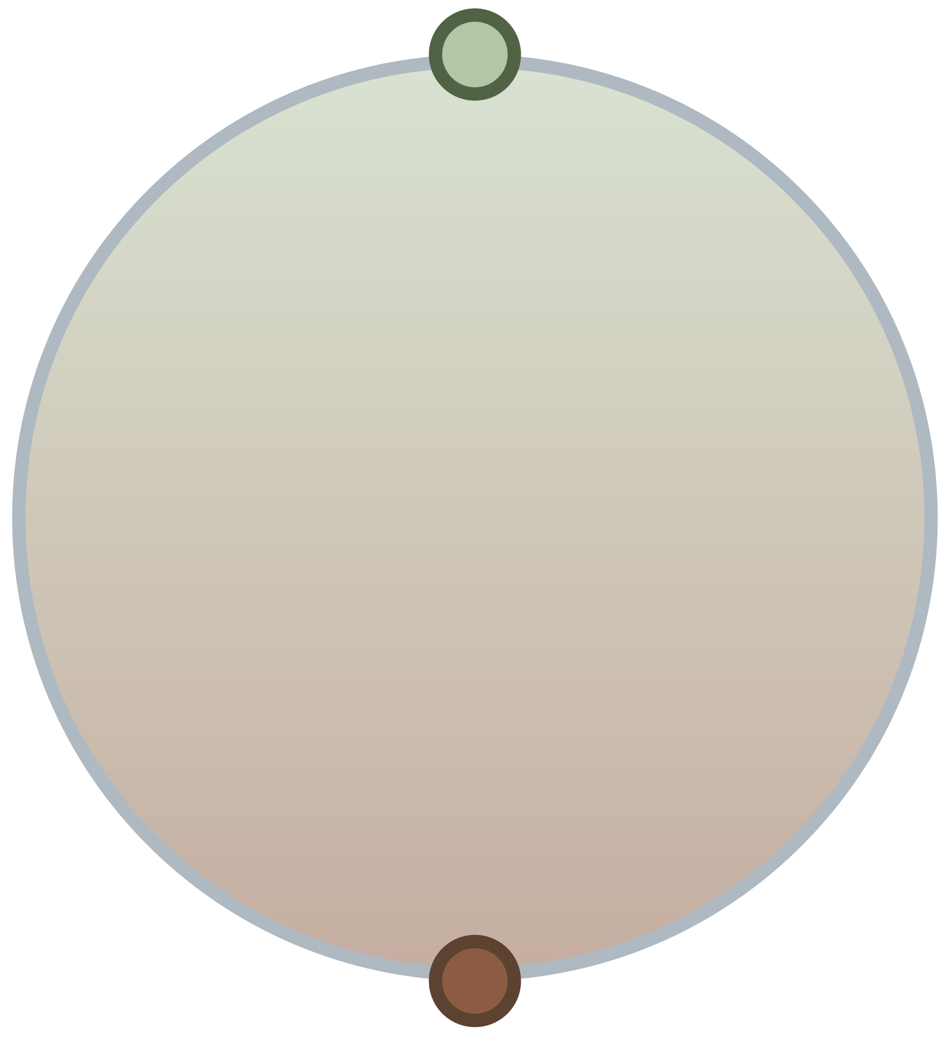
Releases Quantum Experience

Classical V.S. Quantum

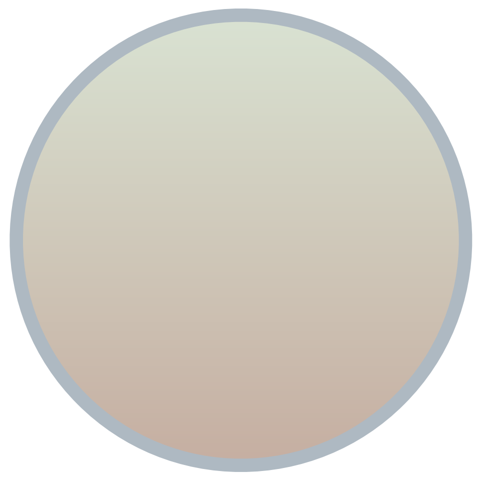
- Bit



- Qubit

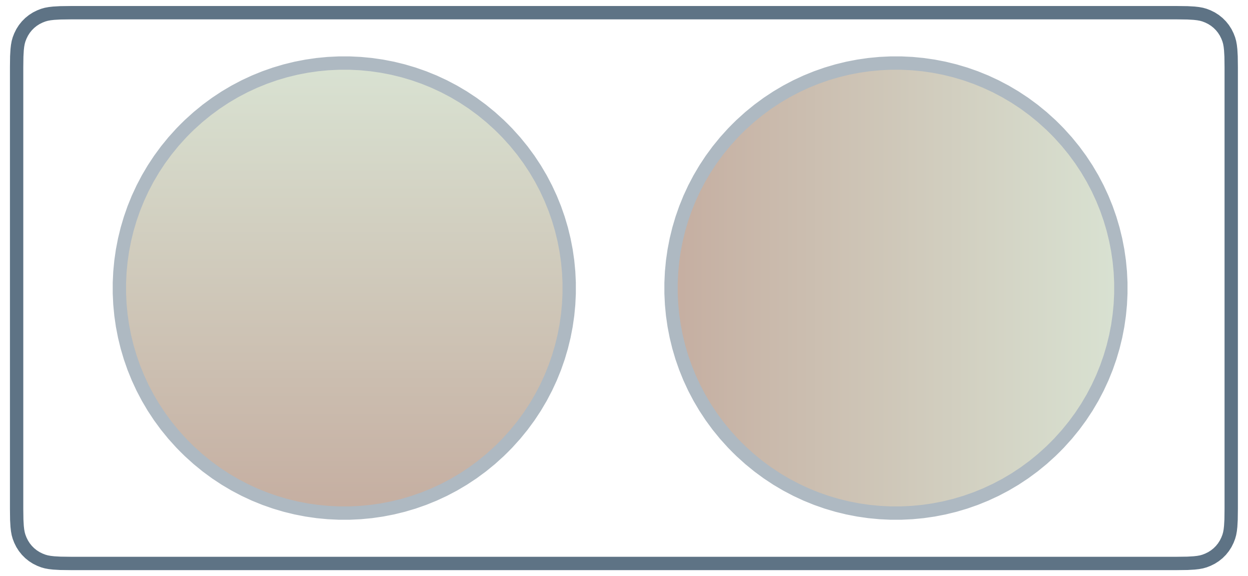


States



$$|\psi\rangle = \begin{bmatrix}\alpha \\ \beta\end{bmatrix}$$

Basis: $\{\,|0\rangle, |1\rangle\,\}$

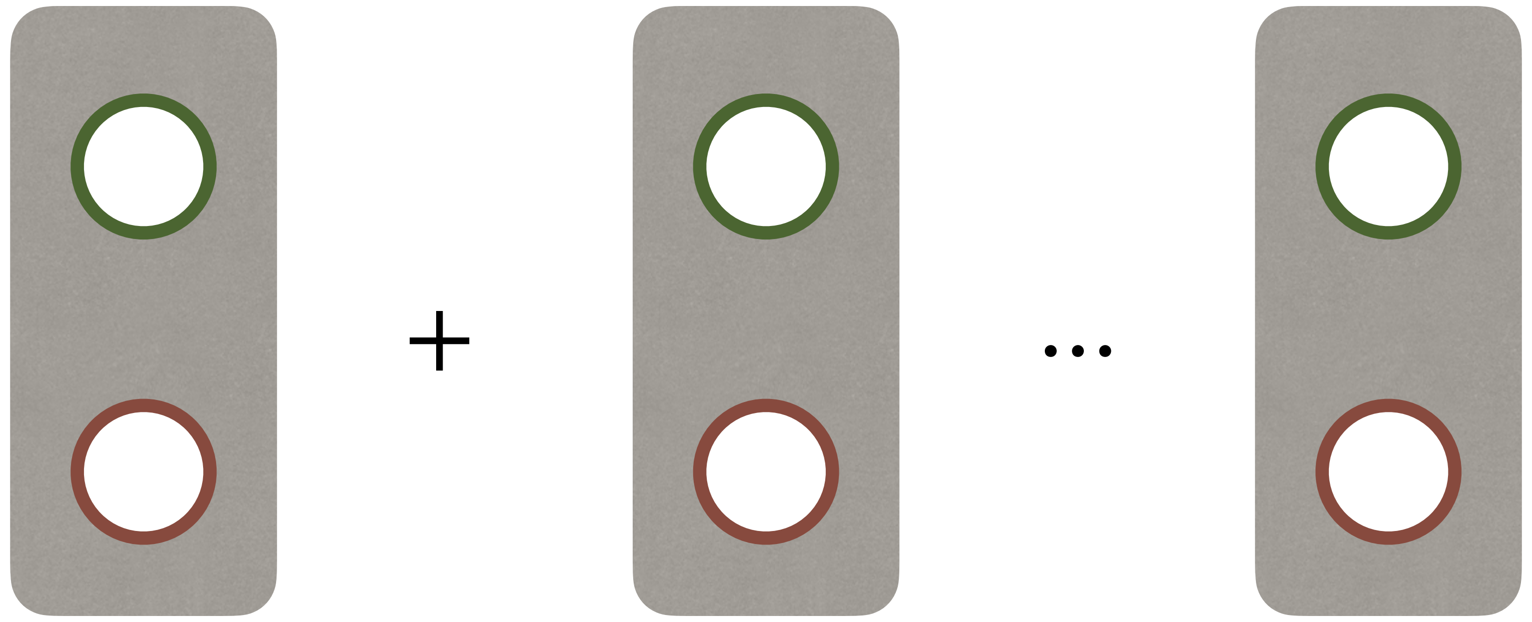


$$|\psi_1\rangle \otimes |\psi_2\rangle = \begin{bmatrix}\alpha \\ \beta\end{bmatrix} \otimes \begin{bmatrix}\gamma \\ \delta\end{bmatrix} = |\psi_1\psi_2\rangle$$

Basis: $\{\,|00\rangle, |01\rangle, |10\rangle, |11\rangle\,\}$

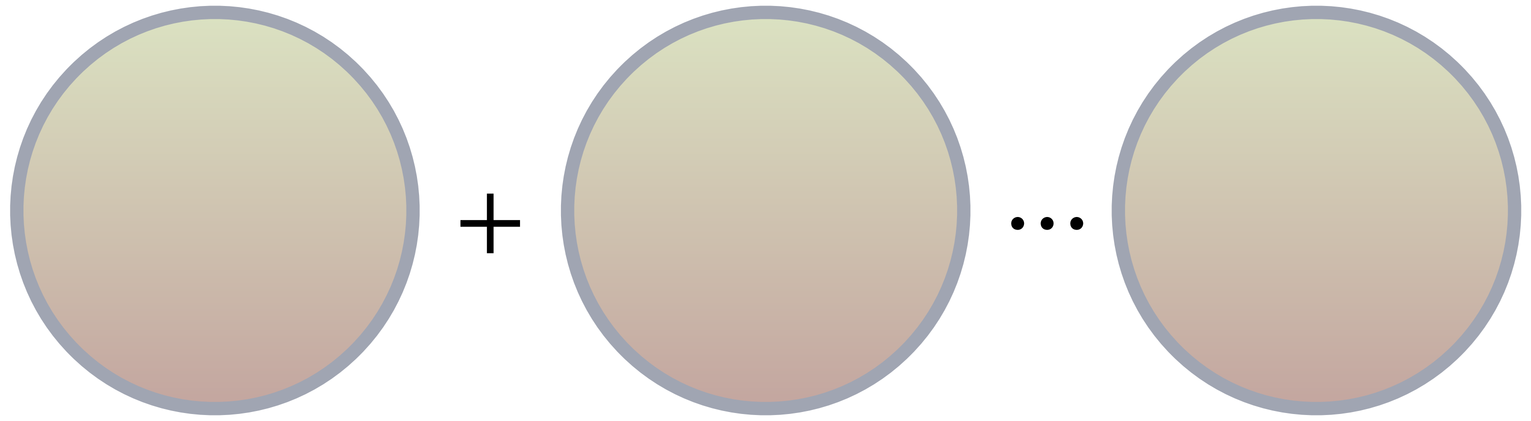
Speedup computational time

- Conventional



$1 + 1 \cdots 1$

- Quantum



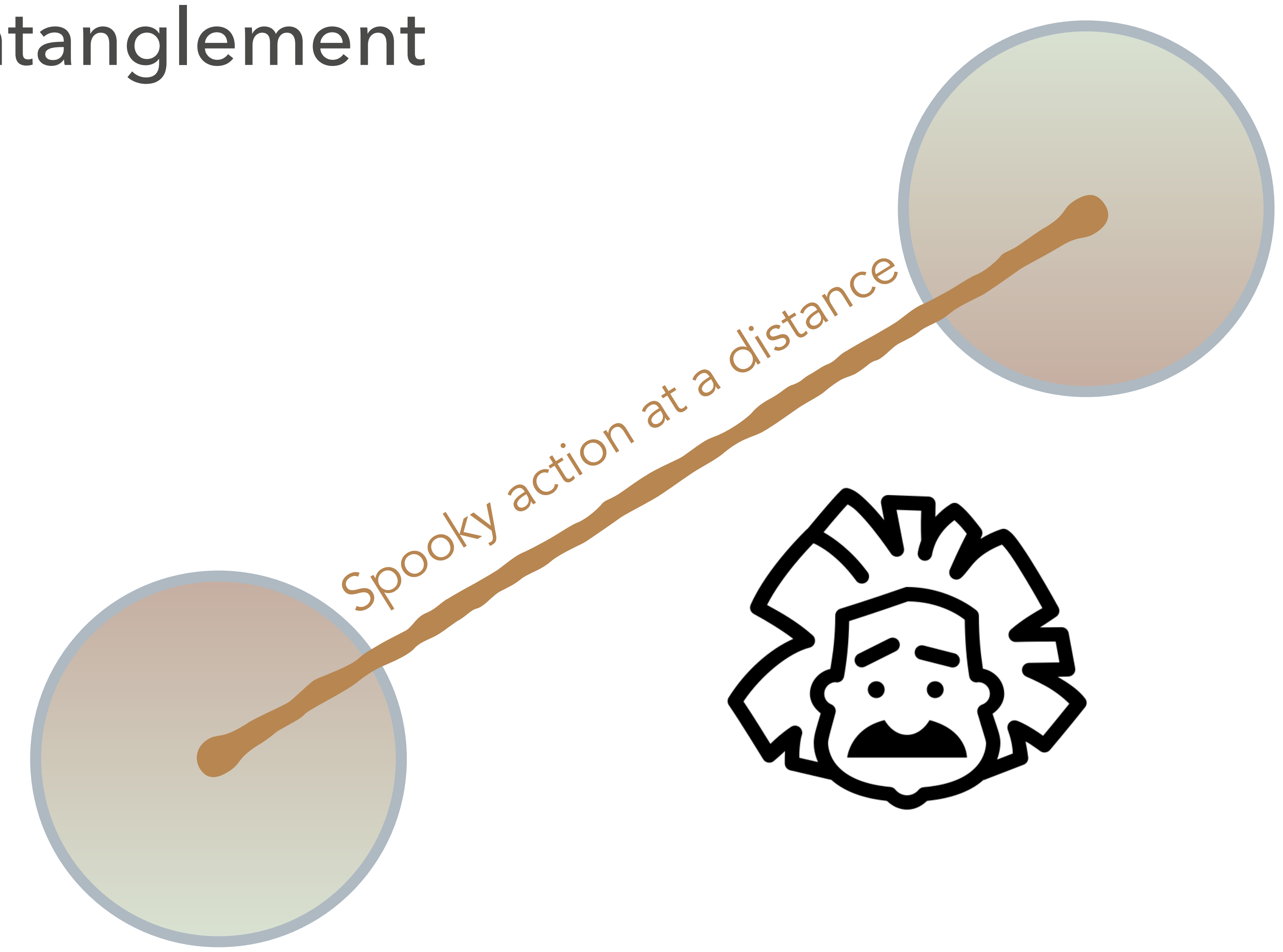
$2 \times 2 \cdots 2$

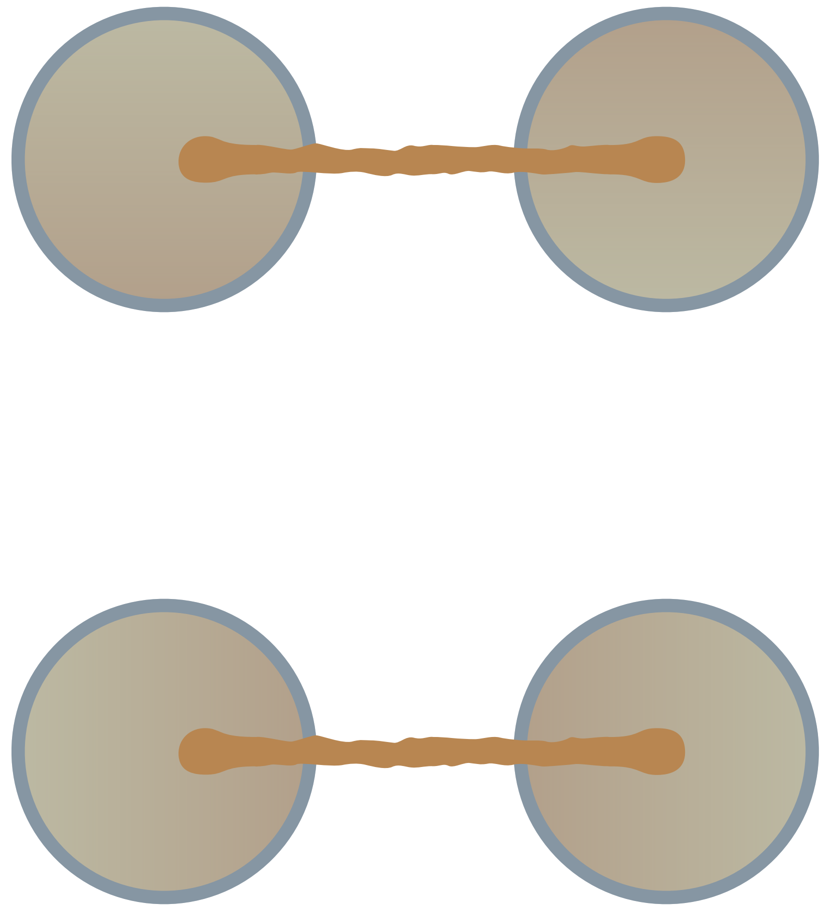
$N \longrightarrow 2^N$

Exponentially speedup!

Why so powerful ?

- Entanglement



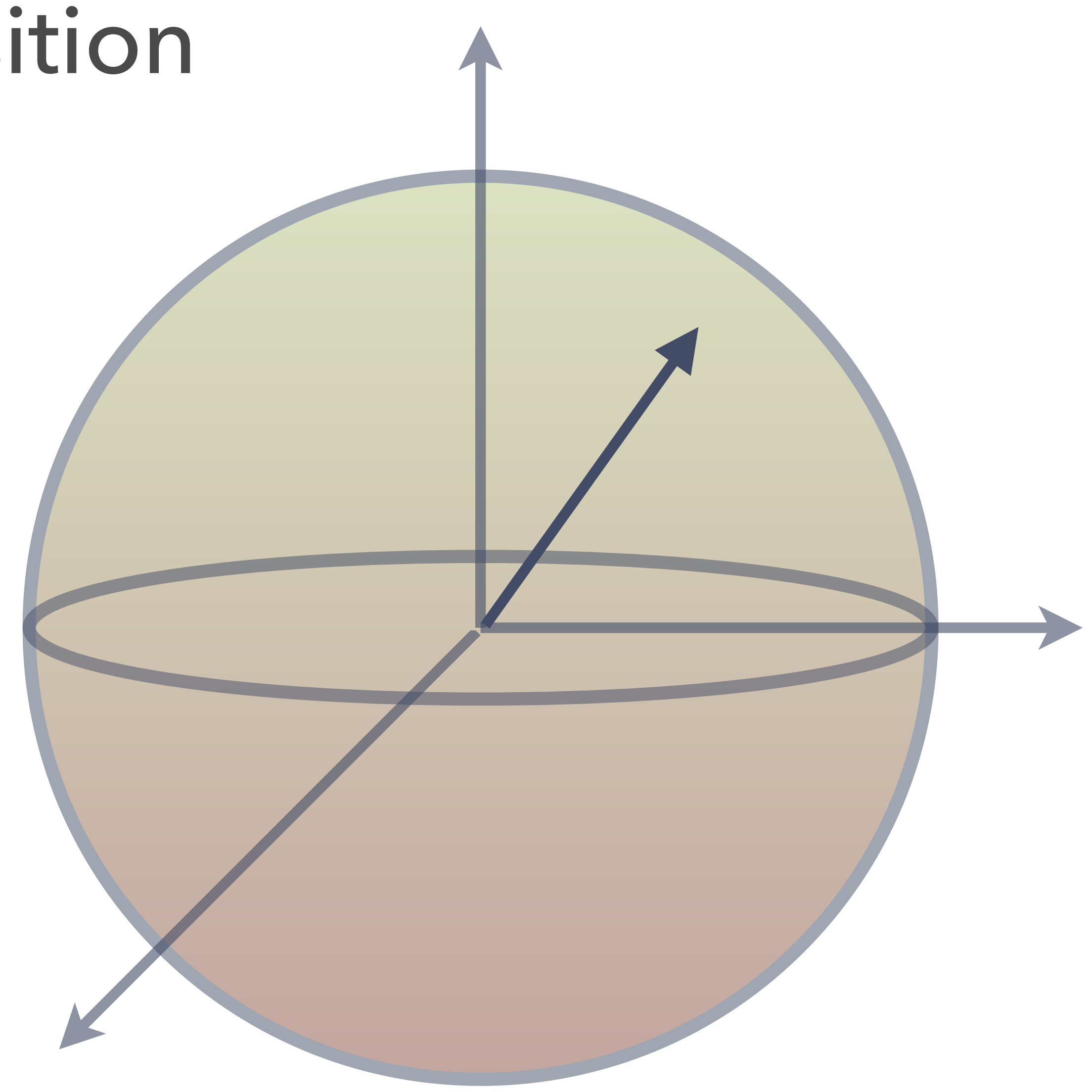


speedup quantum algorithms

Why so powerful ?

- Entanglement

- Superposition

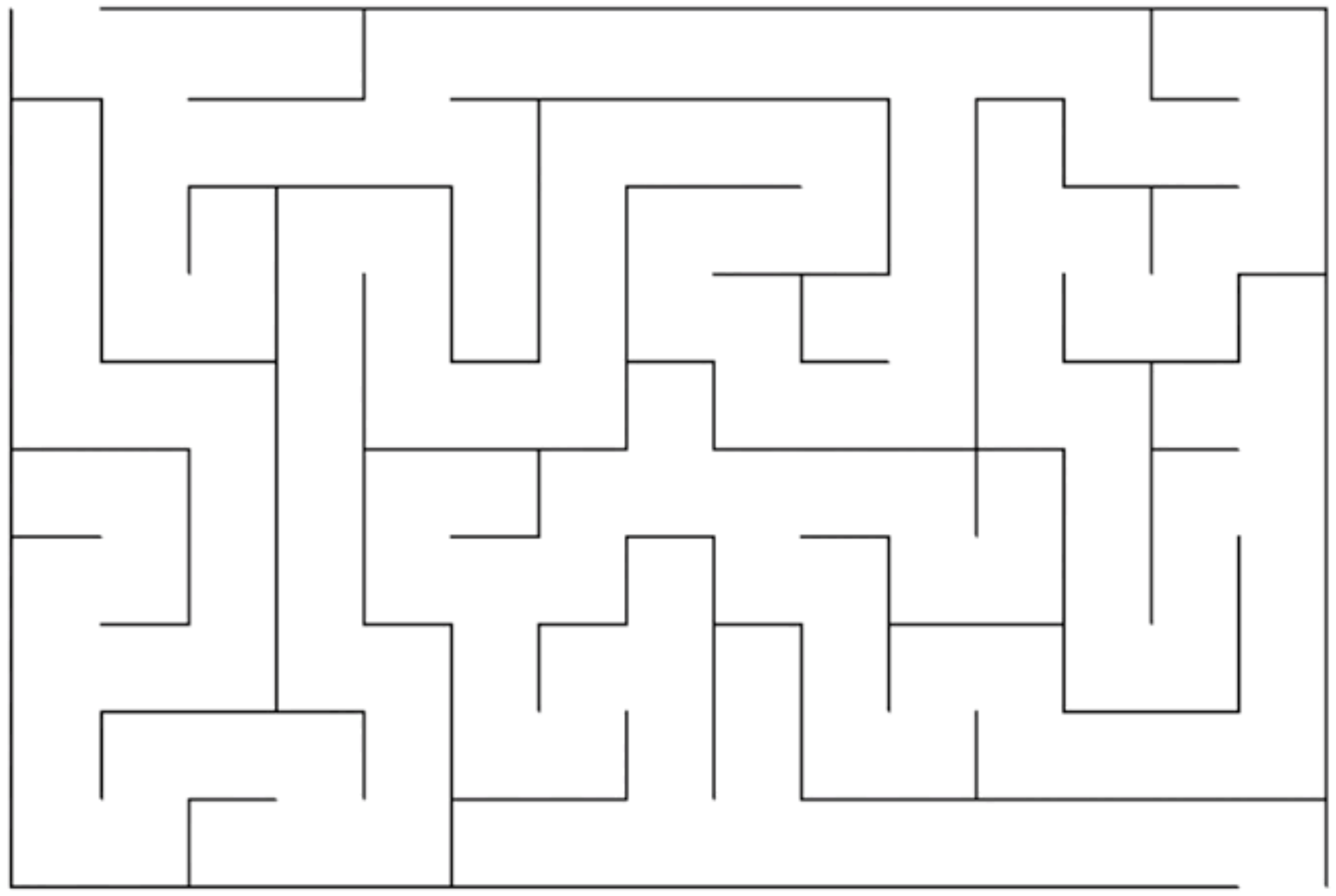


$$\alpha \,|0\rangle + \beta \,|1\rangle$$

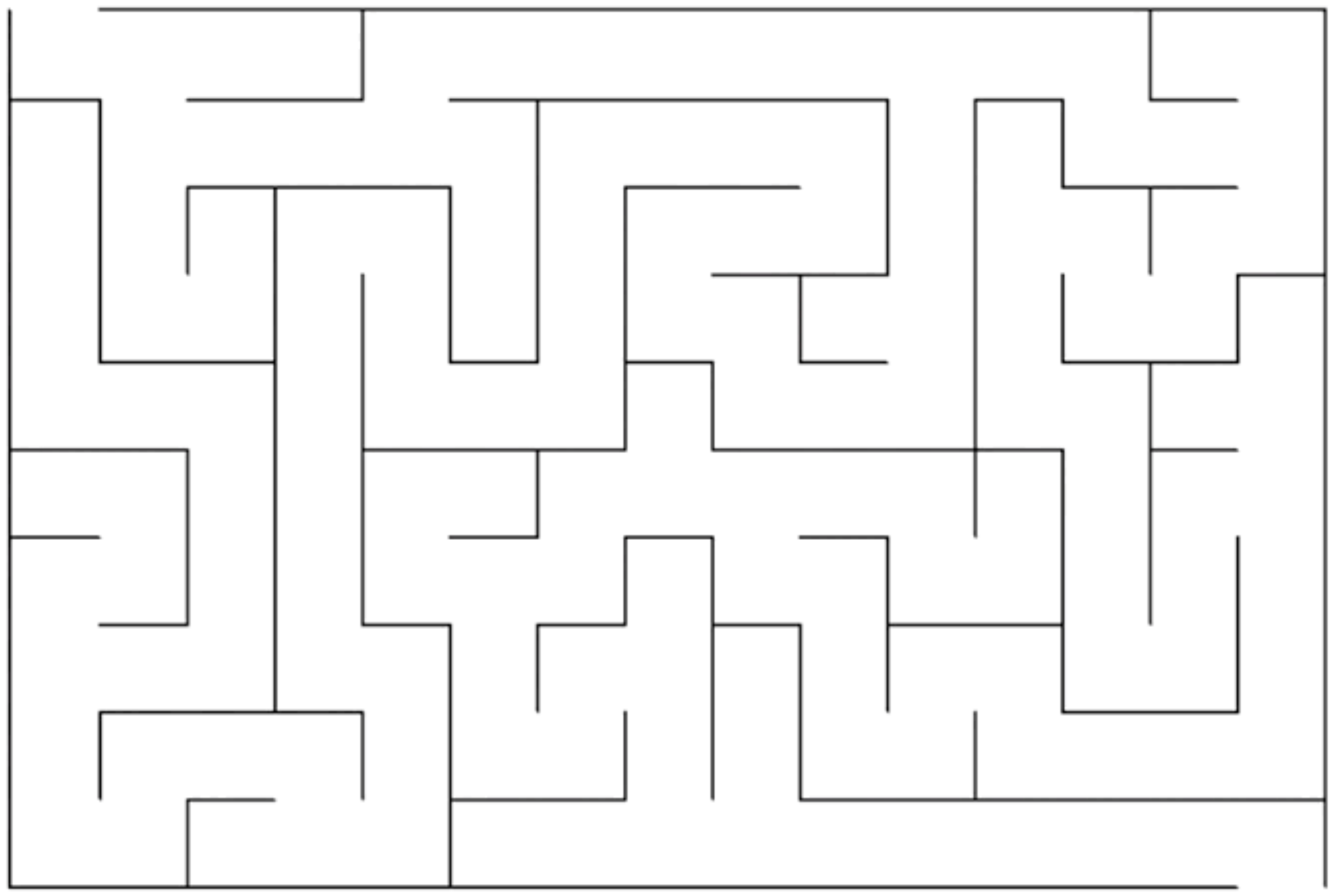

SUPERPOSITION
0
1
Natasha Hanacek/NIST

When we are in a complex maze......

- Conventional Computer



- Quantum Computer



Quantum Language

Notations

- **States**
  - $|\psi\rangle$: ket-vector $|\psi\rangle = \begin{bmatrix} \alpha \\ \beta \\ \gamma \end{bmatrix}$
  - $\langle\psi|$: bra-vector $\langle\psi| = \begin{bmatrix} \alpha* & \beta* & \gamma* \end{bmatrix}$
  - $|\psi_1\rangle\, |\psi_2\rangle = |\psi_1\rangle \otimes |\psi_2\rangle$: tensor product

$$|\psi_1\rangle = \begin{bmatrix} 1 & -1 \\ 0 & i \\ -1+i & 1-i \end{bmatrix} \qquad |\psi_2\rangle = \begin{bmatrix} i \\ -1 \end{bmatrix}$$

$$|\psi_1\rangle \otimes |\psi_2\rangle = \begin{bmatrix} 1 \cdot \begin{bmatrix} i \\ -1 \end{bmatrix} & -1 \cdot \begin{bmatrix} i \\ -1 \end{bmatrix} \\ 0 \cdot \begin{bmatrix} i \\ -1 \end{bmatrix} & i \cdot \begin{bmatrix} i \\ -1 \end{bmatrix} \\ (-1+i) \cdot \begin{bmatrix} i \\ -1 \end{bmatrix} & (1-i) \cdot \begin{bmatrix} i \\ -1 \end{bmatrix} \end{bmatrix} = \begin{bmatrix} i & -i \\ -1 & 1 \\ 0 & -1 \\ 0 & -i \\ -1-i & 1+i \\ 1-i & -1+i \end{bmatrix}$$

- **Operators**
  - $U^\dagger = \left(U^T\right)^* = (U*)^T$: Hermitian conjugate
  - $\langle\psi|\, U\, |\psi\rangle = \langle\psi|\, U^\dagger\, |\psi\rangle \equiv \langle U\rangle$: expectation value

$$= \begin{bmatrix} \alpha* & \beta* & \gamma* \end{bmatrix} \begin{bmatrix} a & b & c \\ d & f & g \\ h & j & k \end{bmatrix} \begin{bmatrix} \alpha \\ \beta \\ \gamma \end{bmatrix}$$

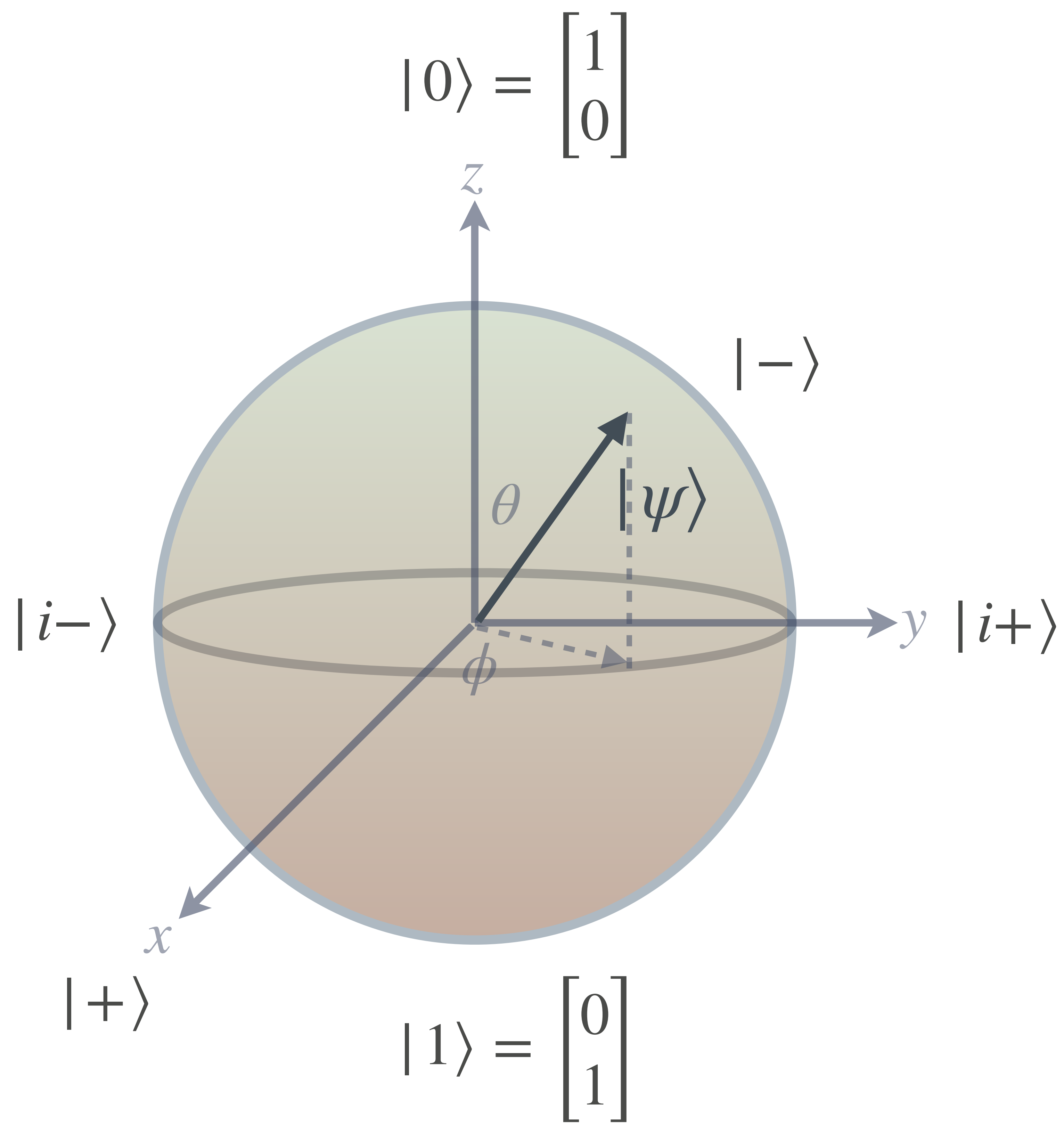
$$U = \begin{bmatrix} a & b & c \\ d & f & g \\ h & j & k \end{bmatrix}$$

Bloch sphere

- Geometrical representation of the state

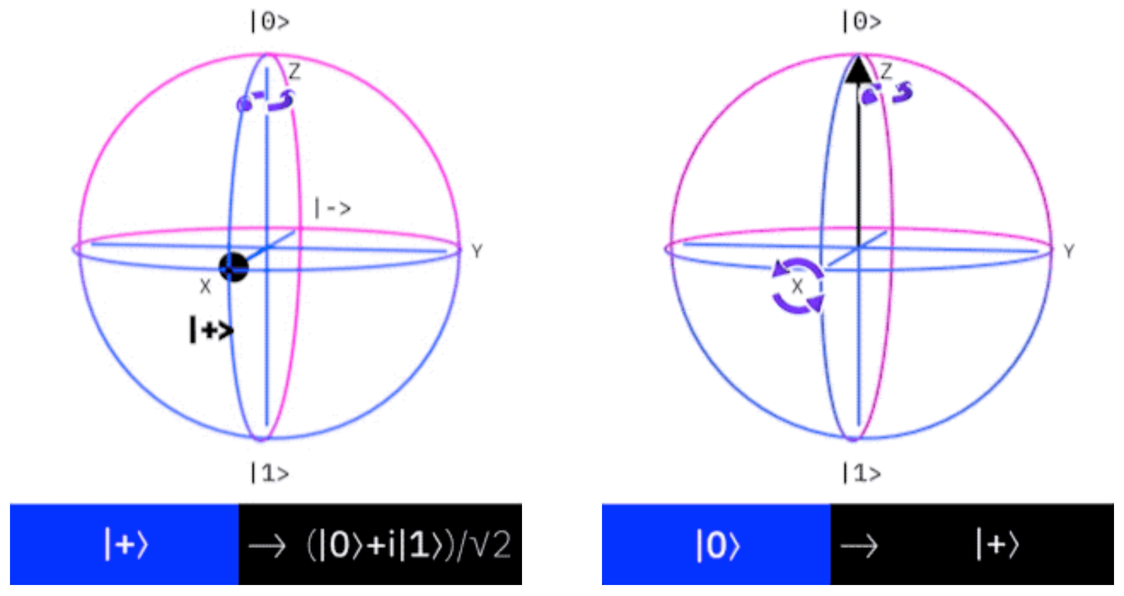
$$|\psi\rangle = \alpha\,|0\rangle + \beta\,|1\rangle$$
$$= e^{ir}\left(\cos\frac{\theta}{2} + e^{i\phi}\sin\frac{\theta}{2}\right)$$

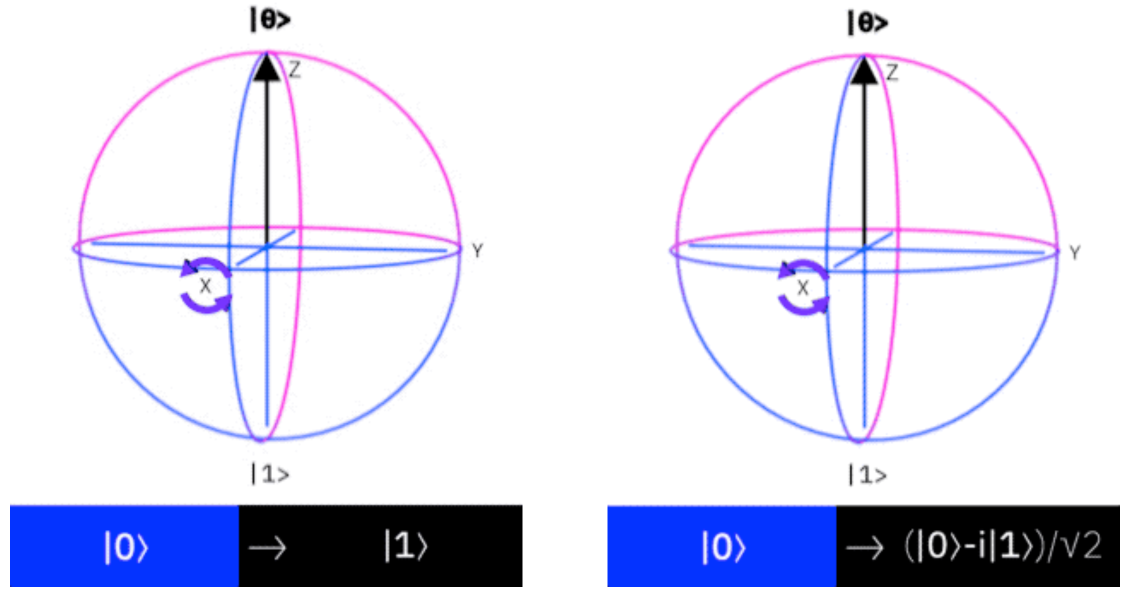
$$|\pm\rangle = \frac{1}{\sqrt{2}}\left(|0\rangle \pm |1\rangle\right)$$
$$|i\pm\rangle = \frac{1}{\sqrt{2}}\left(|0\rangle \pm i\,|1\rangle\right)$$



Operations - Quantum gates

- Single-qubit gate
  - Hadamard H
  - Phase S
  - $\pi/8$ T
  - Rotation X Y Z Rx Ry Rz
- Multi-qubit gate
  - CNOT
  - Controlled-rotation cH cRz
  - SWAP





$$\begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & \alpha & \beta \\ 0 & 0 & \gamma & \delta \end{bmatrix}$$

controlled-rotation

$$\begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix}$$

SWAP

Input		Output	
Control	Target	Control	Target
$\vert 0\rangle$	$\vert 0\rangle$	$\vert 0\rangle$	$\vert 0\rangle$
$\vert 0\rangle$	$\vert 1\rangle$	$\vert 0\rangle$	$\vert 1\rangle$
$\vert 1\rangle$	$\vert 0\rangle$	$\vert 1\rangle$	$\vert 1\rangle$
$\vert 1\rangle$	$\vert 1\rangle$	$\vert 1\rangle$	$\vert 0\rangle$

Resources/Circuit Composer/Block glossary

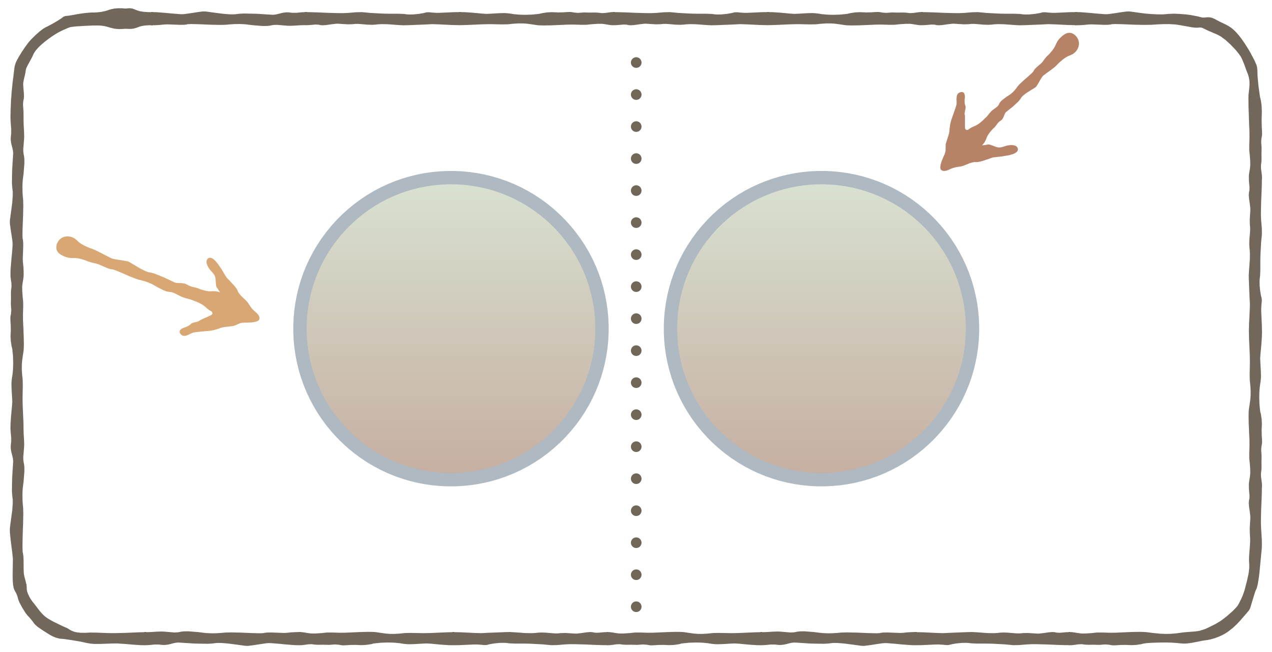
Operate only one of the qubits ?

- Do “nothing to Q1 + NOT gate on Q2” ?
- nothing = Identity gate ID

$$I = \begin{bmatrix} 1 & 0 \\ 0 & 1 \end{bmatrix}$$

- operate independently:

$$I^{(1)} X^{(2)} = X^{(2)} = (I \otimes I)\,(I \otimes X) = (I \otimes X)$$



Quantum Computers

Requirements for physical realization

- Scalable physical system
- Ability to initialize the state
- Long decoherence time $>$ operation time
- A universal set of quantum gates
- Capability to qubit-specific measurement

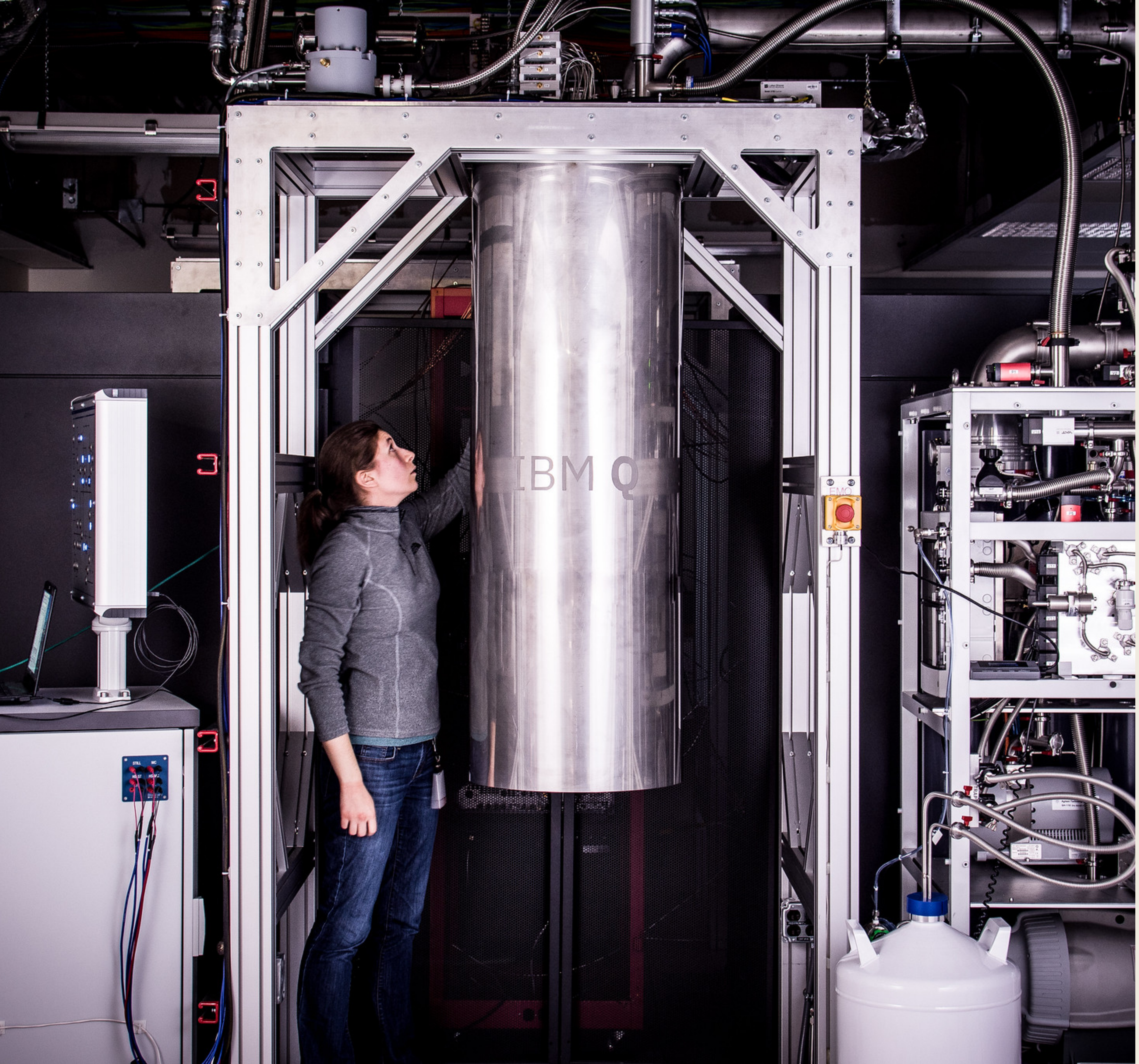
Fortschr. Phys. **48**, 771-783 (2000)

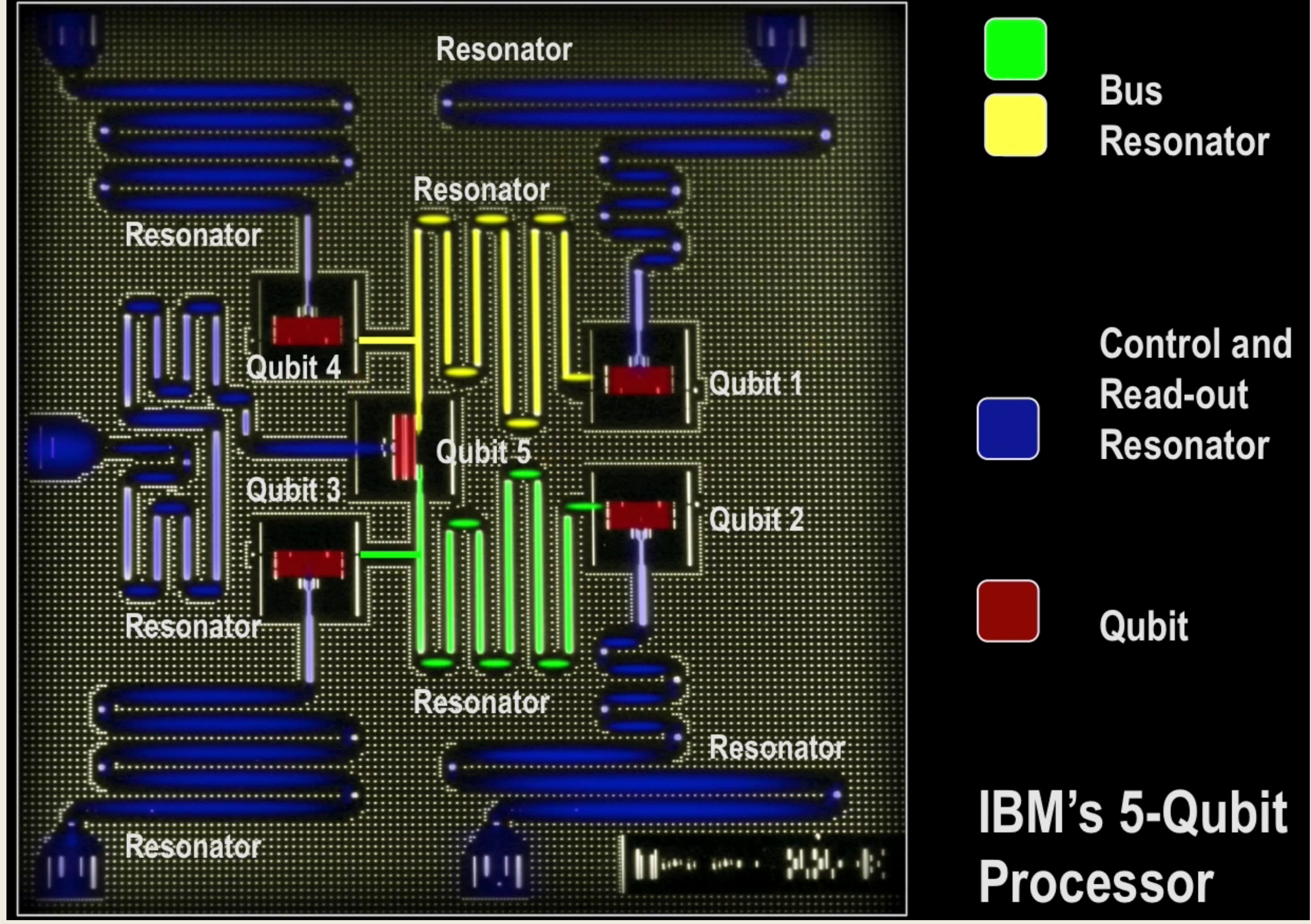
Implements

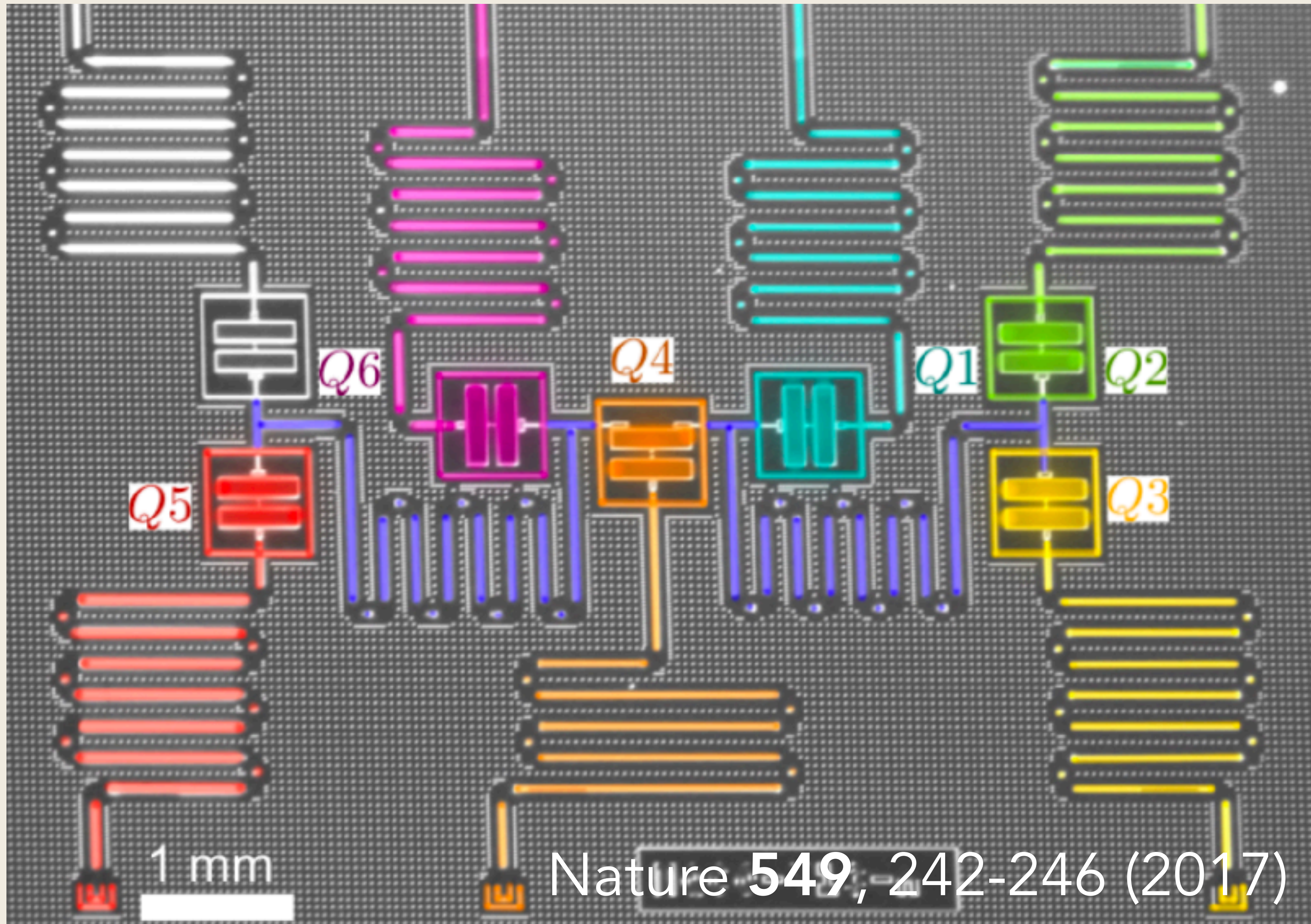
- Photons, electrons, nucleus
- NMR
- Quantum dots
- Nature atoms
- Diamonds
- Semiconductors
- Superconductors

and so on……

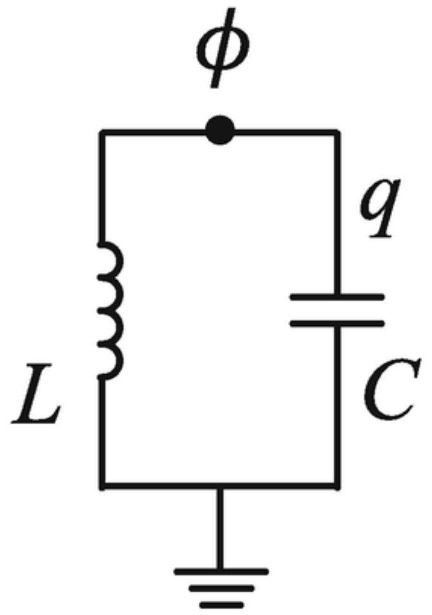

Quantum Computing
Intersecting science, systems and design.
IBM Q System One
IBM


IBM Q

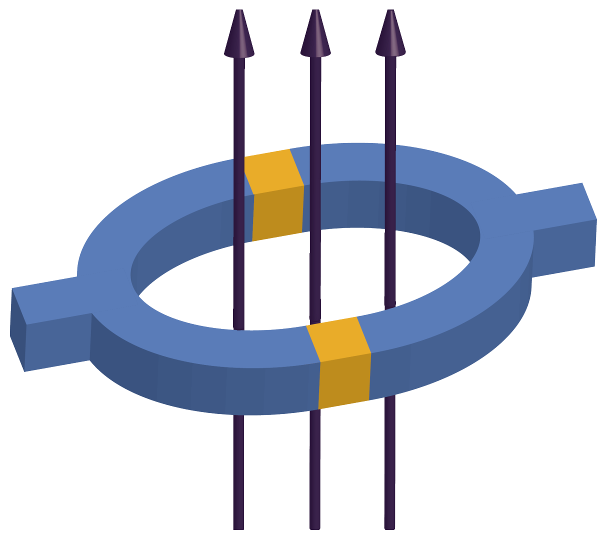

Resonator
Resonator
Resonator
Qubit 4
Qubit 1
Qubit 5
Qubit 3
Qubit 2
Resonator
Resonator
Resonator
Resonator
Bus
Resonator
Control and
Read-out
Resonator
Qubit
IBM's 5-Qubit
Processor


Q6
Q4
Q1
Q2
Q5
Q3
1 mm
Nature **549**, 242-246 (2017)

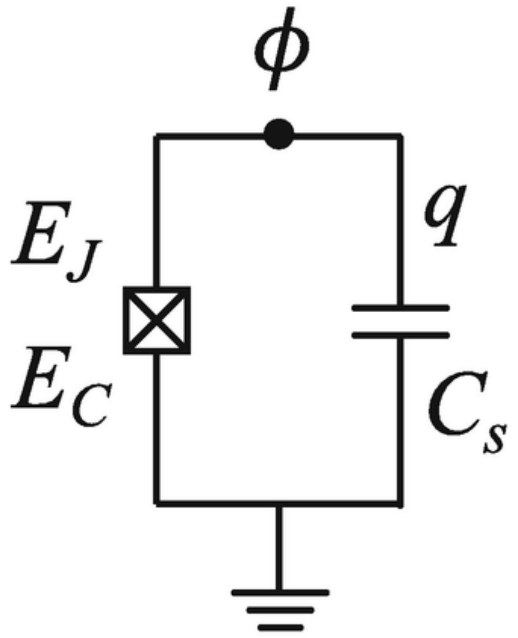
Superconducting circuit



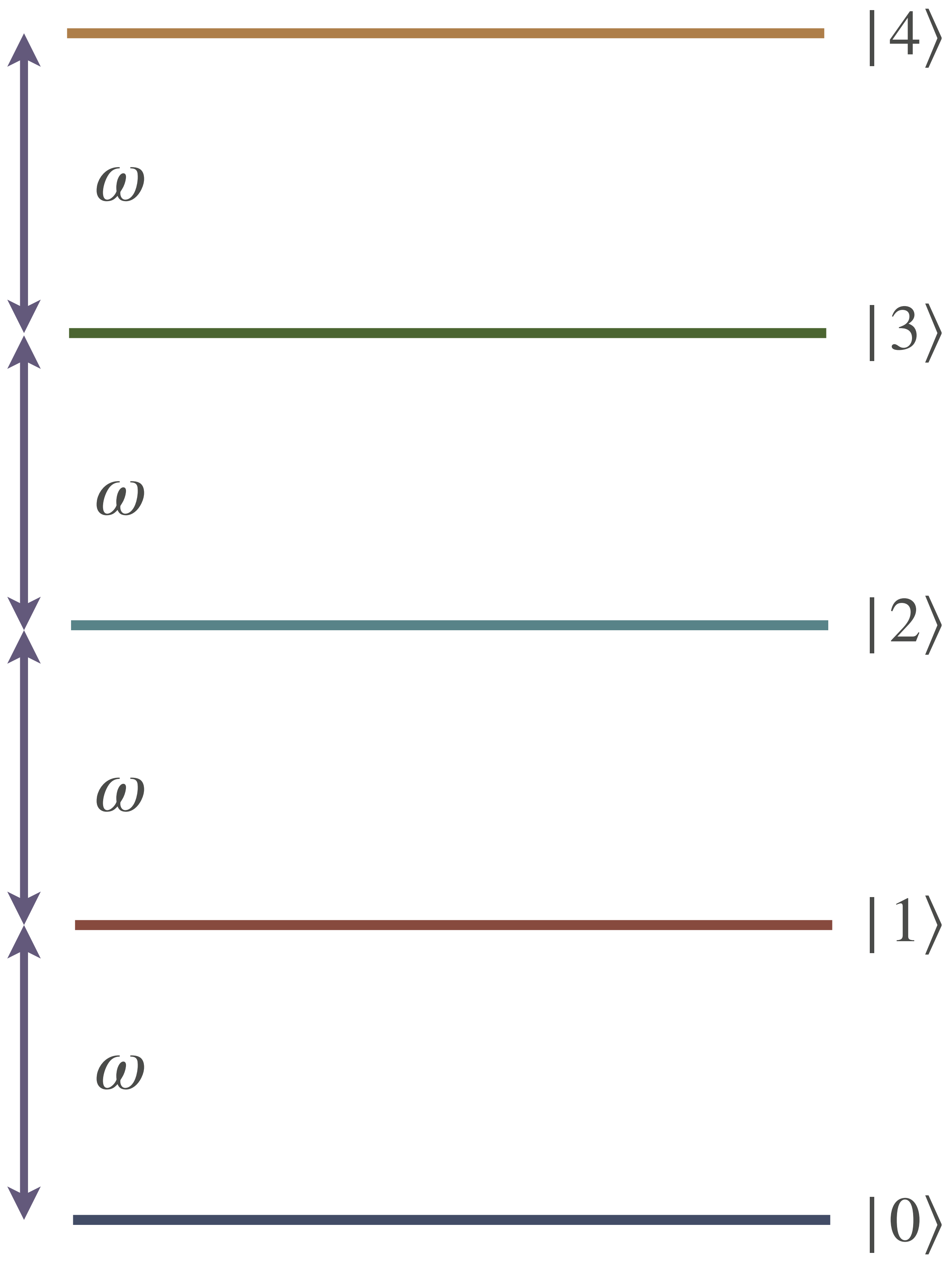
Harmonic



Josephson junction

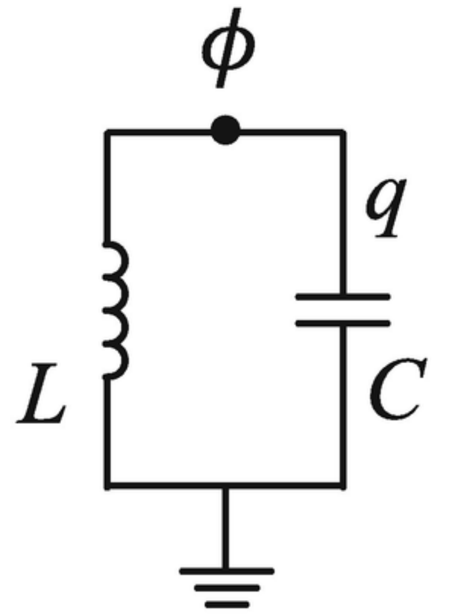


Nonlinear

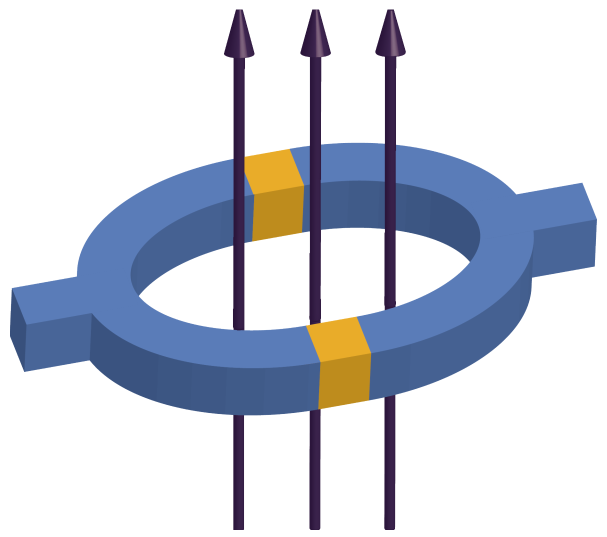


$\alpha < 0$

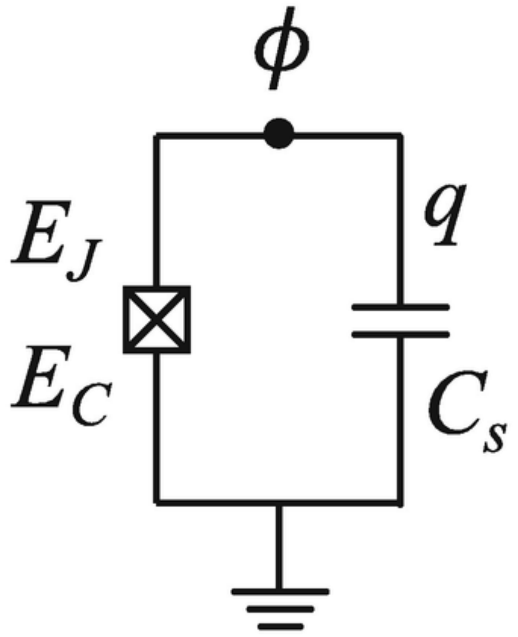
Superconducting circuit



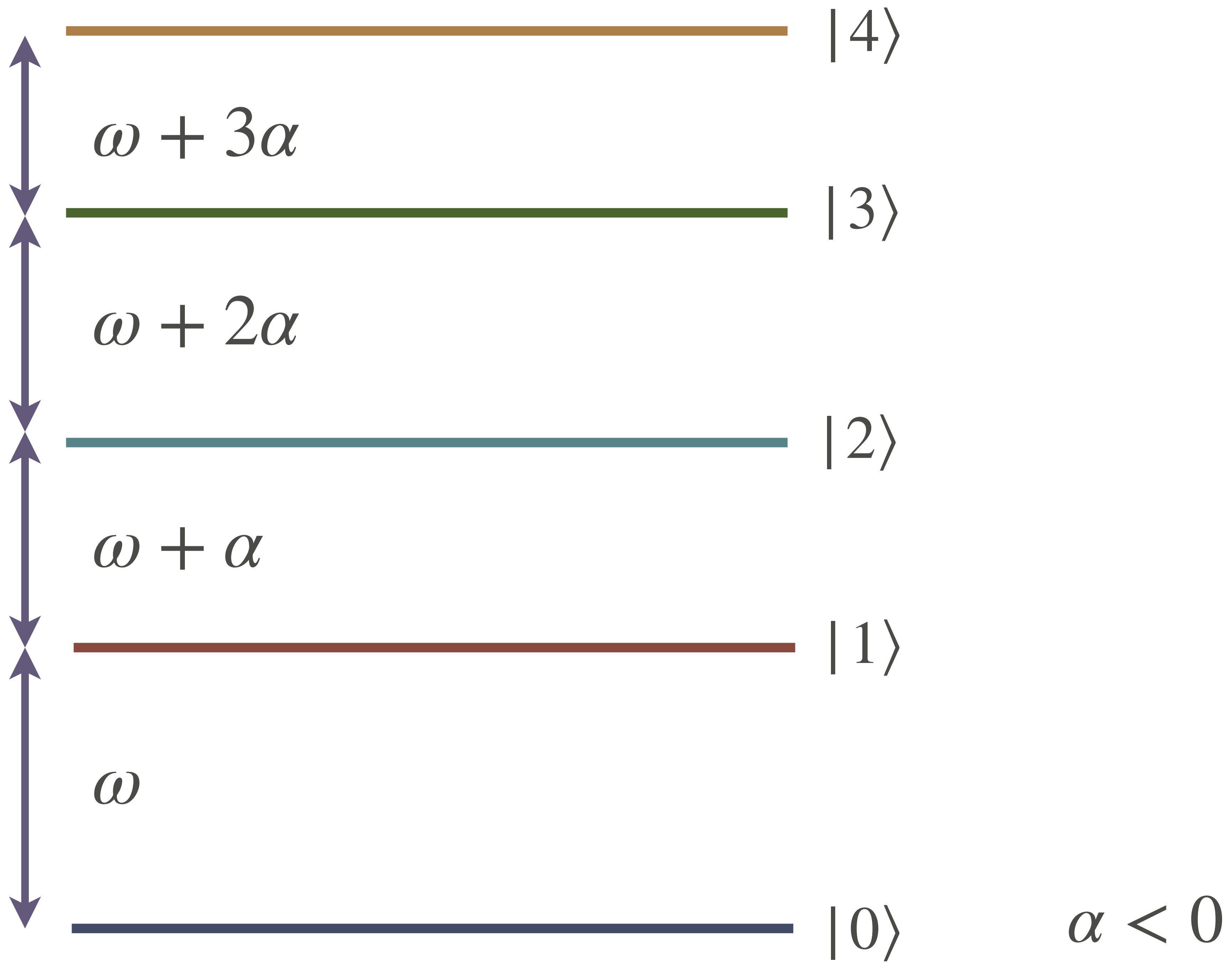
Harmonic



Josephson junction



Nonlinear



THE MARCH TO ABSOLUTE ZERO (or minus 459.67 degrees Fahrenheit)
4 KELVIN
QUBIT SIGNAL AMPLIFIER
One of two amplifying stages is cooled to a temperature of 4 Kelvin.
Attenuation is applied at each stage in the refrigerator in order to protect qubits from thermal noise during the process of sending
Inside Look: Quantum Computer
Harnessing the power of a quantum processor requires maintaining constant temperatures near absolute zero. Here's a look at how a dilution refrigerator, made from more than 2,000 components, exploits the mixing properties of two helium isotopes to create such an environment.
SUPERCONDUCTING COAXIAL LINES
In order to minimize energy loss, the coaxial lines that direct signals between the first and second amplifying stages are made out of superconductors.
CRYOGENIC ISOLATORS
QUANTUM AMPLIFIERS
Quantum amplifiers inside of a magnetic shield capture and amplify processor readout signals while minimizing noise.
Resonator
Resonator
Resonator
Qubit 4
Qubit 1
Qubit 5
Qubit 3
Qubit 2
Resonator
Resonator
Resonator
Resonator
Bus
Resonator
Control and Read-out Resonator
Qubit
IBM's 5-Qubit Processor
1 From the composer / QISKit the job is sent to the cloud where it is queued and then sent to a control/measurement computer
2 Microwave electronics mix signal down to a frequency that can be digitized
3 Measurement pulses go down same coax after the control pulses
4 Measurement pulses interact with qubits via readout resonators and are reflected back
5 Measurement pulses are routed by circulators, and isolators prevent noise from getting to the qubits
6 Amplifiers at 4K
7 Microwave electronics mix signal down to a frequency that can be digitized
8 Mixed-down signals are digitized by a classical computer and the result is classified as 0 or 1
9 Results are sent back to you over the cloud
qc.measure (q[0], c[0])
qc.measure (q[1], c[1])
1
1
IBM Q

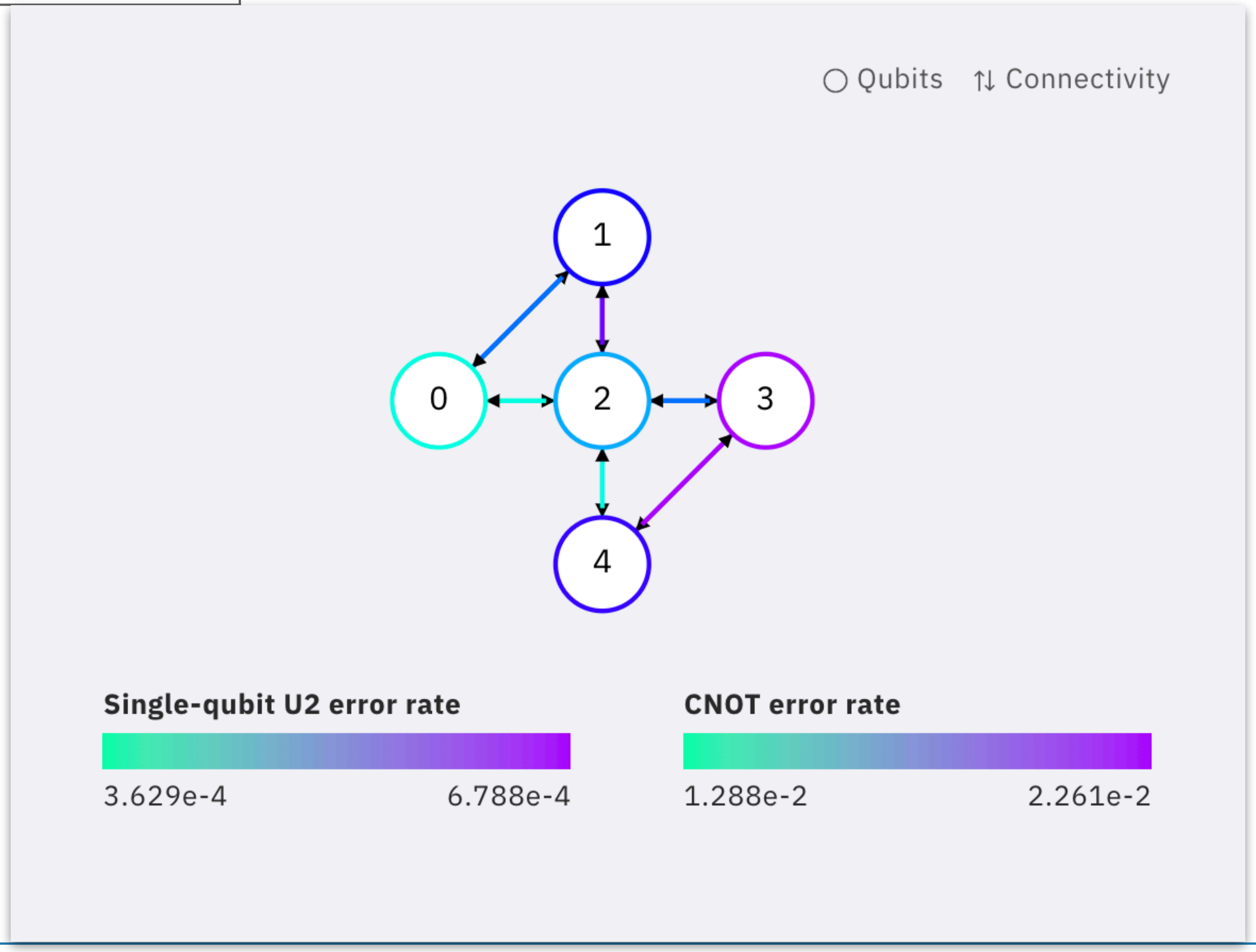
Nutrition Fact of Qubit

#	T1 (µs)	T2 (µs)	Frequency (GHz)	Readout error	Single-qubit U2 error rate
0	73.38	95.40	5.286	8.500E-03	3.629E-04
1	72.95	77.21	5.238	3.050E-02	5.608E-04
2	60.03	76.74	5.030	2.100E-02	4.458E-04
3	40.19	39.87	5.296	3.750E-02	6.788E-04
4	60.25	56.50	5.084	1.500E-02	5.997E-04

#	CNOT error rate
0	cx0_1: 1.615E-02, cx0_2: 1.380E-02
1	cx1_0: 1.615E-02, cx1_2: 2.076E-02
2	cx2_0: 1.380E-02, cx2_1: 2.076E-02, cx2_3: 1.628E-02, cx2_4: 1.288E-02
3	cx3_2: 1.628E-02, cx3_4: 2.261E-02
4	cx4_2: 1.288E-02, cx4_3: 2.261E-02

March 24, 2020 21:23:06 GMT +0800

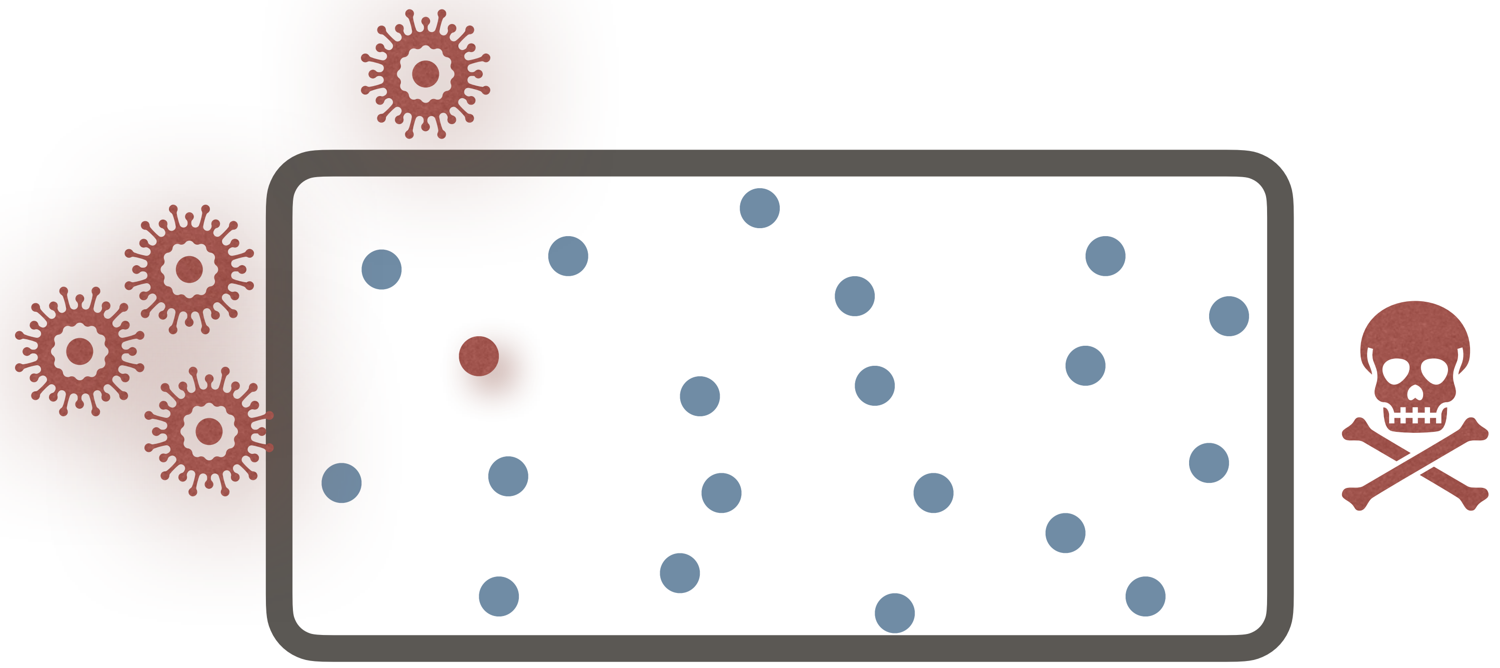
Dashboard/Your Backends/[device_name]/Download Calibrations

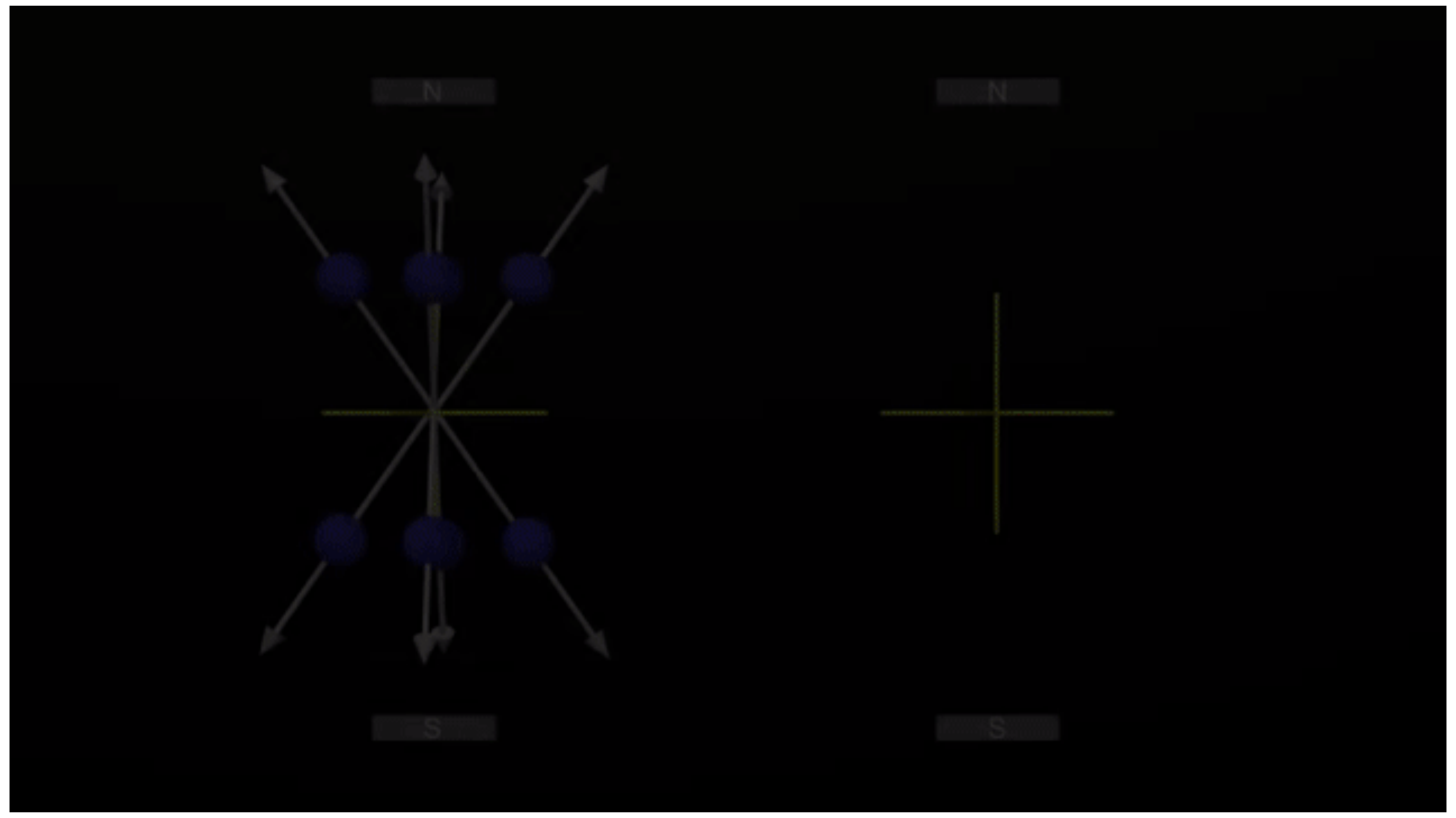


ibmq_5_yorktown - ibmqx2

Relaxation

- qubit-environment

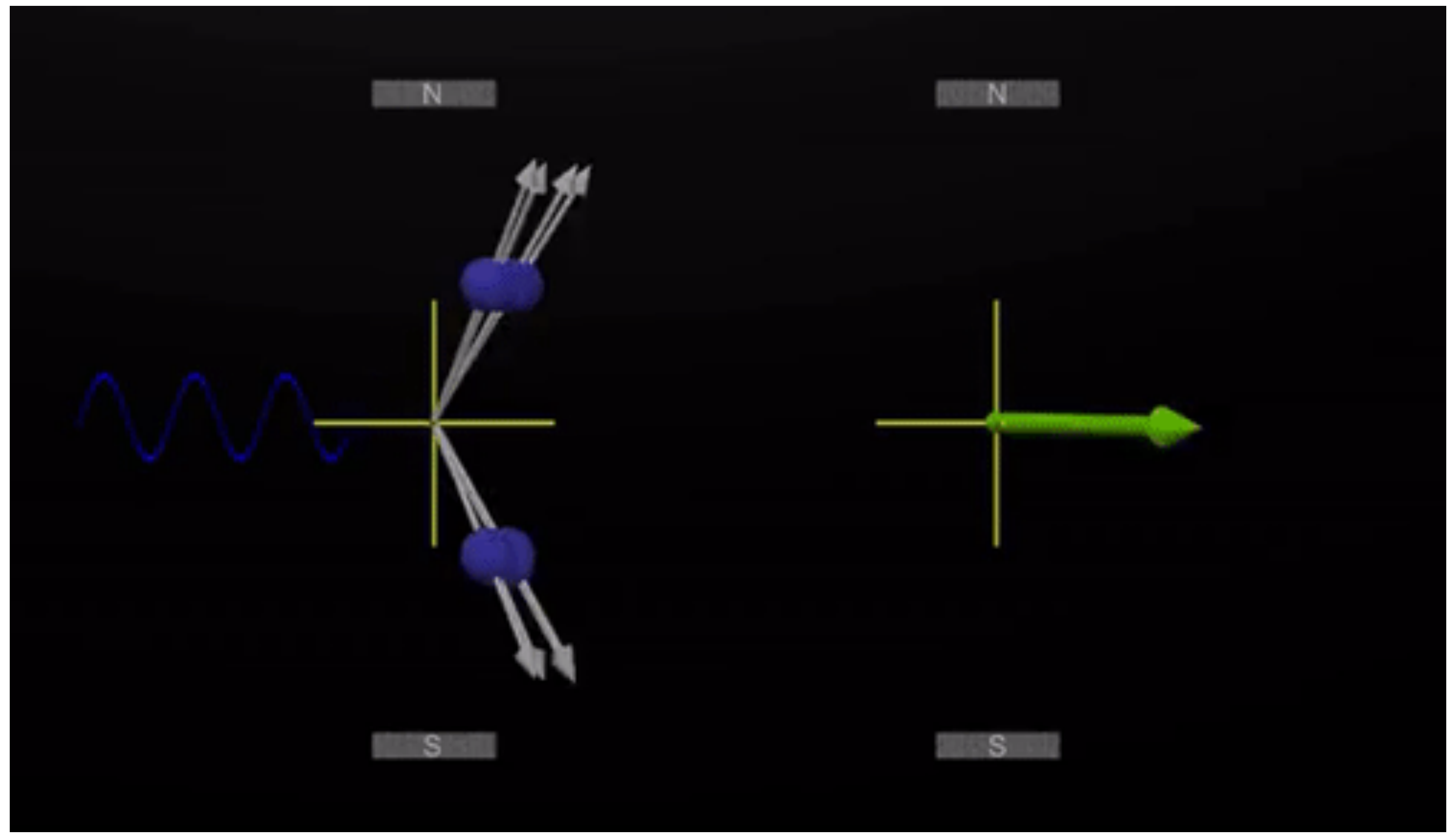




T_1

$$\begin{bmatrix} \rho_{11} & \rho_{12} \\ \rho_{21} & \rho_{22} \end{bmatrix}$$

- qubit-qubit



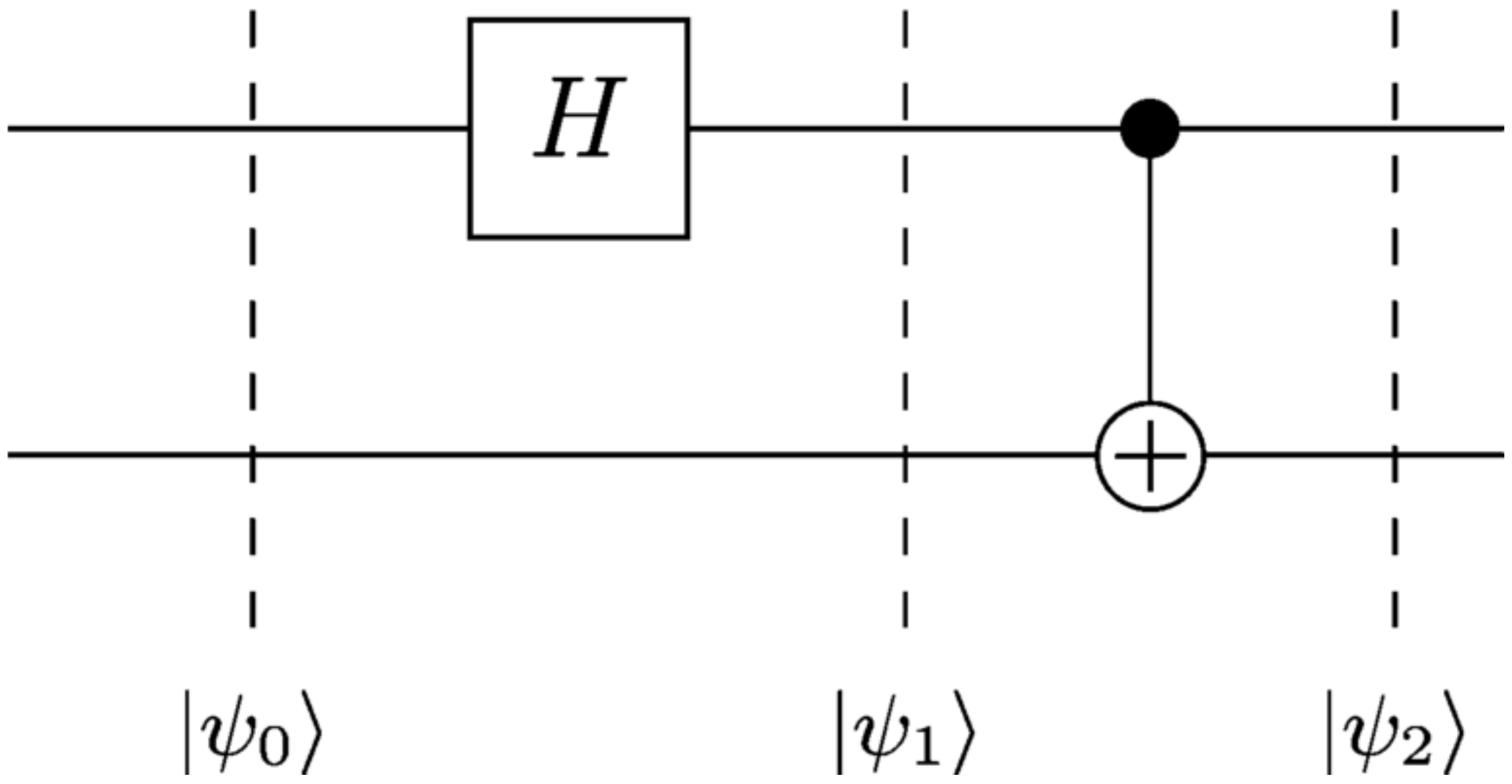
T_2

IBM Quantum Experience

Example - Entangled States

- Bell states

$$|\Phi^+\rangle = \frac{1}{\sqrt{2}}\big(|00\rangle + |11\rangle\big)$$
$$|\Phi^-\rangle = \frac{1}{\sqrt{2}}\big(|00\rangle - |11\rangle\big)$$
$$|\Psi^+\rangle = \frac{1}{\sqrt{2}}\big(|01\rangle + |10\rangle\big)$$
$$|\Psi^-\rangle = \frac{1}{\sqrt{2}}\big(|01\rangle - |10\rangle\big)$$



$$|\psi_2\rangle = CNOT \cdot (H \otimes I)\,|\psi_0\rangle$$

Measurement - projection

- Projection operator

$$\sum_m \mathbb{P}_m = \sum_m |m\rangle \underbrace{\langle m|}_{\text{measurement basis}}$$

- Probability of outcome m

$$p(m) = \langle \psi | \mathbb{P}_m \underbrace{|\psi\rangle}_{\text{system state}}$$

- Post-measurement state

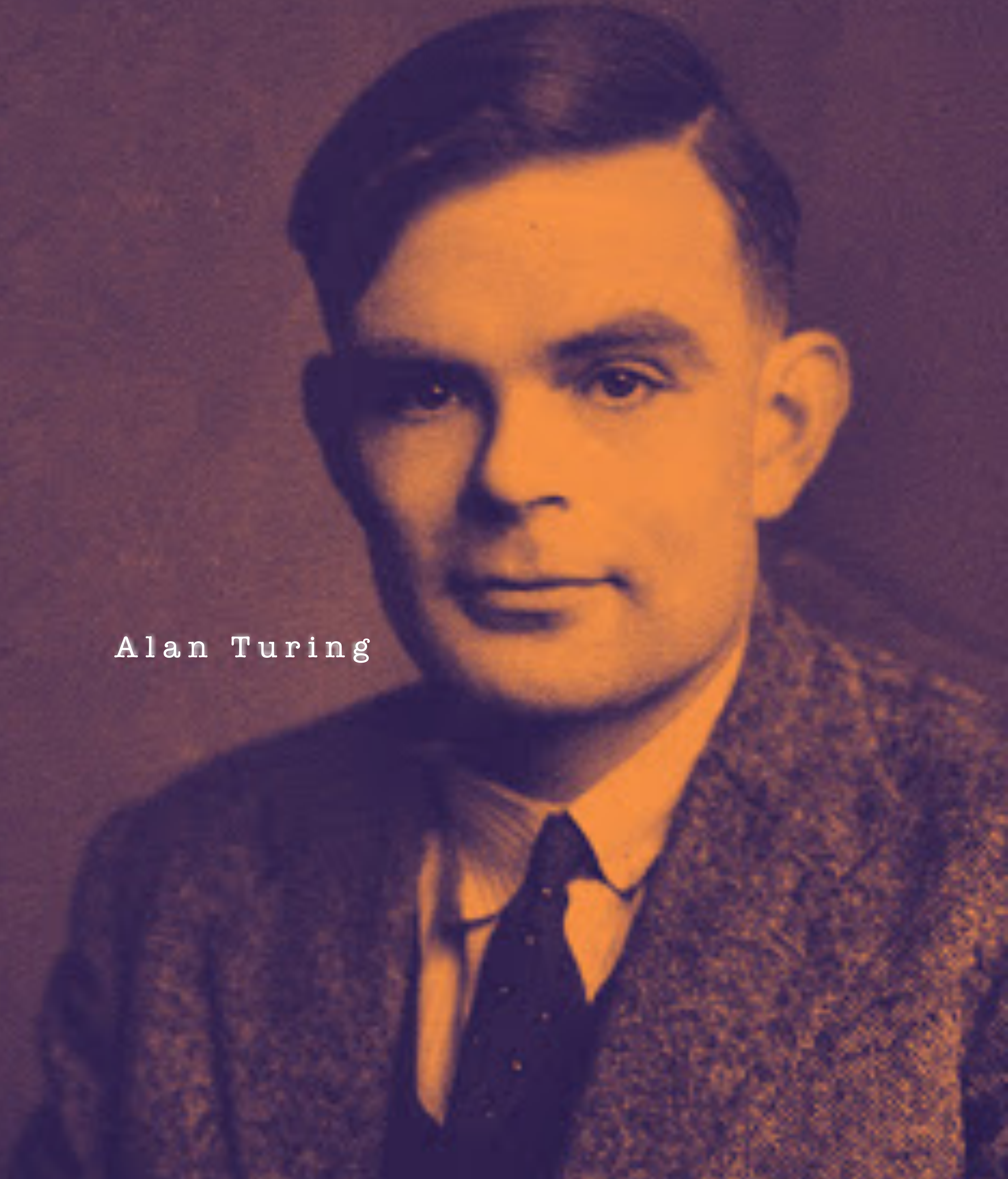
$$|\psi'\rangle = \frac{\mathbb{P}_m}{\sqrt{p(m)}} |\psi\rangle$$

- Default measurement basis

$$\{ |0\rangle, |1\rangle \}$$

How to change the measurement basis, e.g., to Bell states ?

Questions ?



Alan Turing