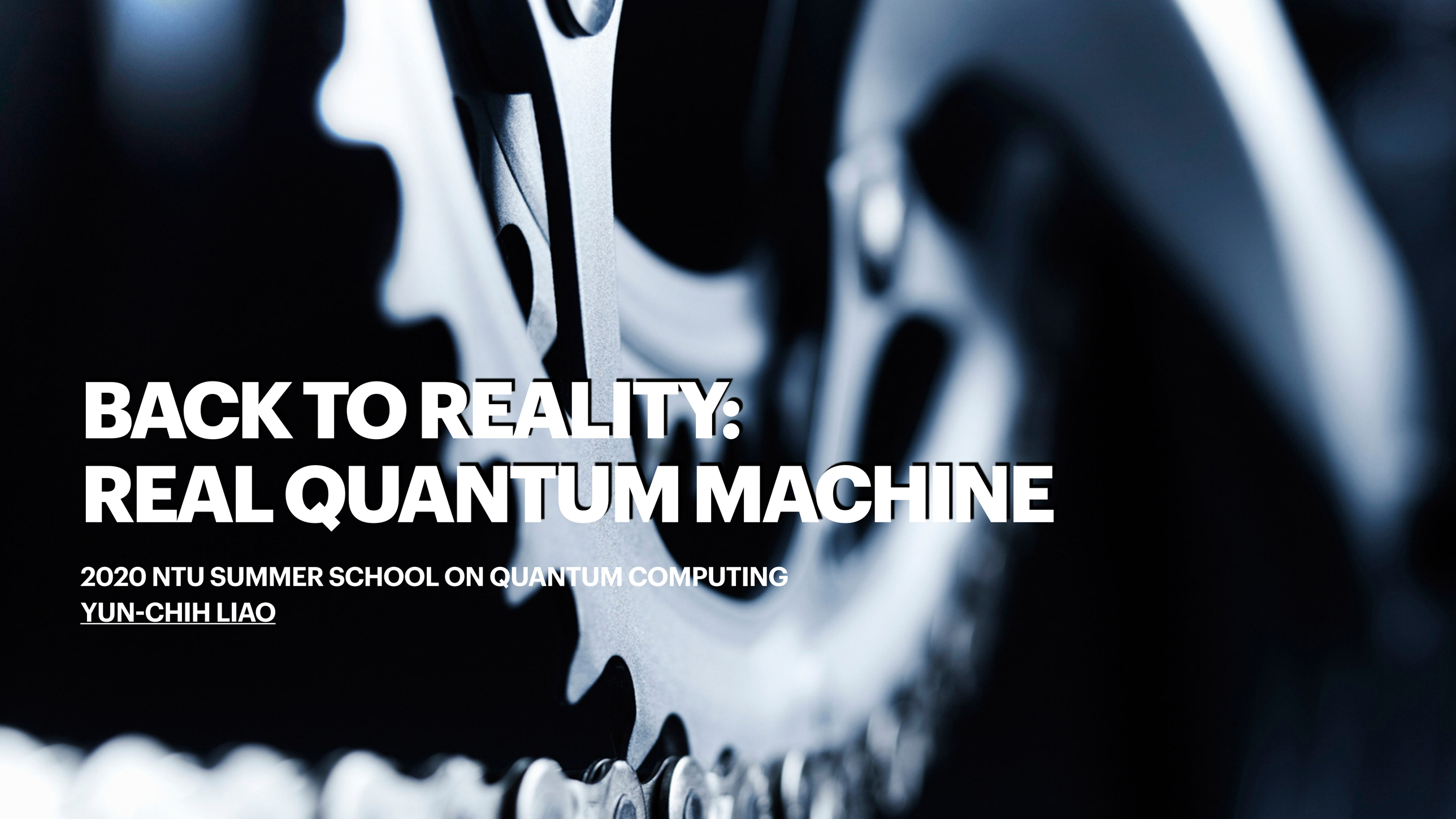


# BACK TO REALITY: REAL QUANTUM MACHINE

2020 NTU SUMMER SCHOOL ON QUANTUM COMPUTING

YUN-CHIH LIAO

# OUTLINE

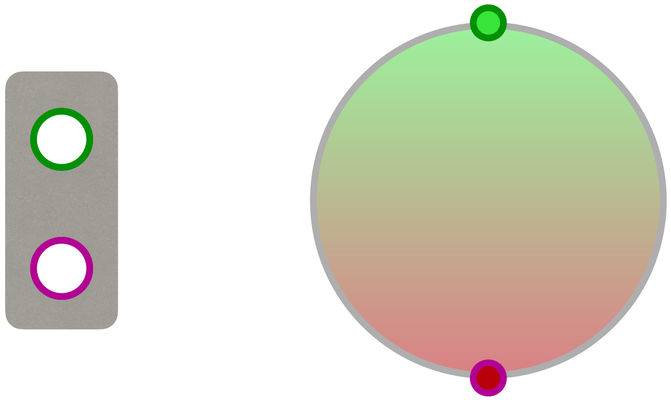
- Real Device
  - Duffing oscillator
  - Architecture
  - Transpiler
- Errors
  - Types & Sources
  - Noise model
  - Error correction

https://github.com/ycldingo/QuantumComputing_2020Summer

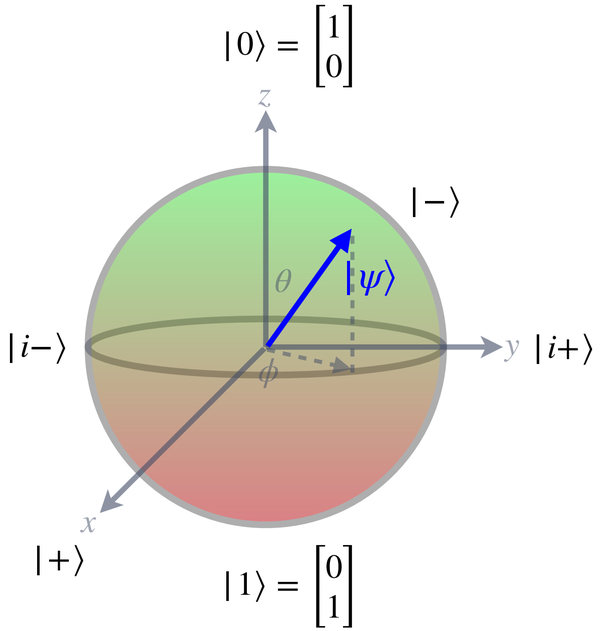
***Do you remember……, or not :)***

# THE ‘SPHERE’

## From bits to qubits



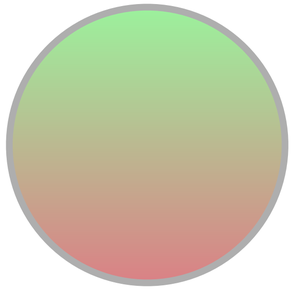
## Bloch sphere



# DIRAC NOTATION

## Single qubit state

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



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

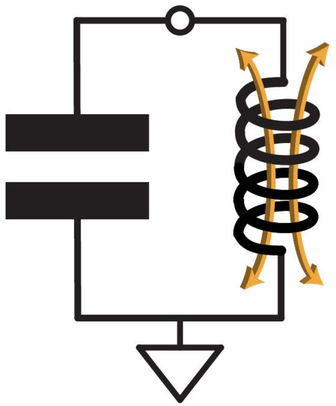
## Bipartite quantum state

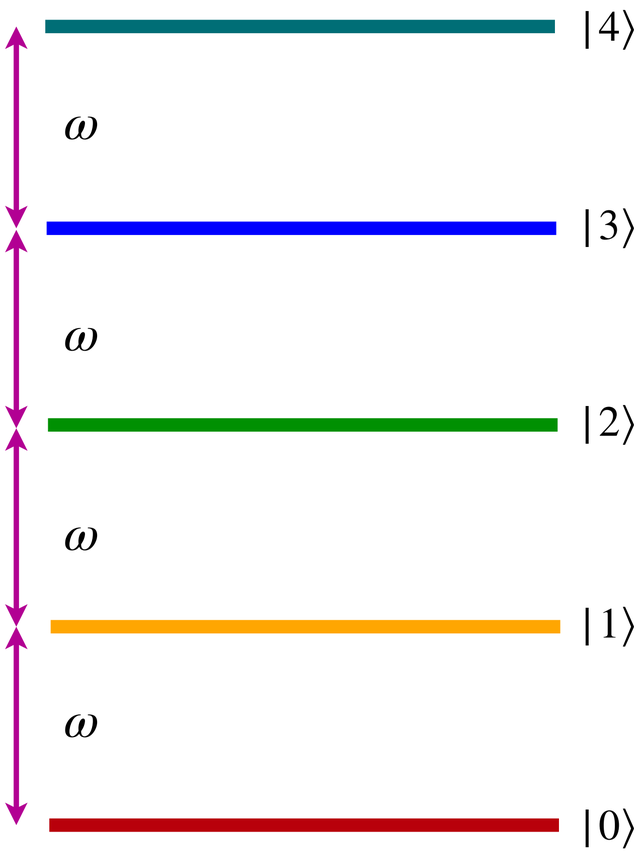
Basis: $\{|00\rangle, |01\rangle, |10\rangle, |11\rangle\}$

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

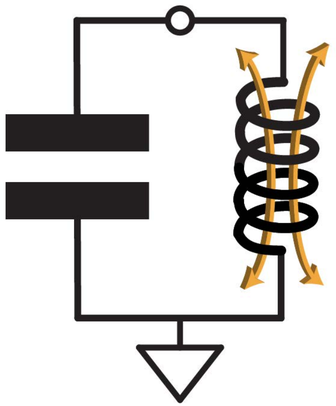
# *How do qubits become real?*

# BUILD QUBIT FROM OSCILLATOR

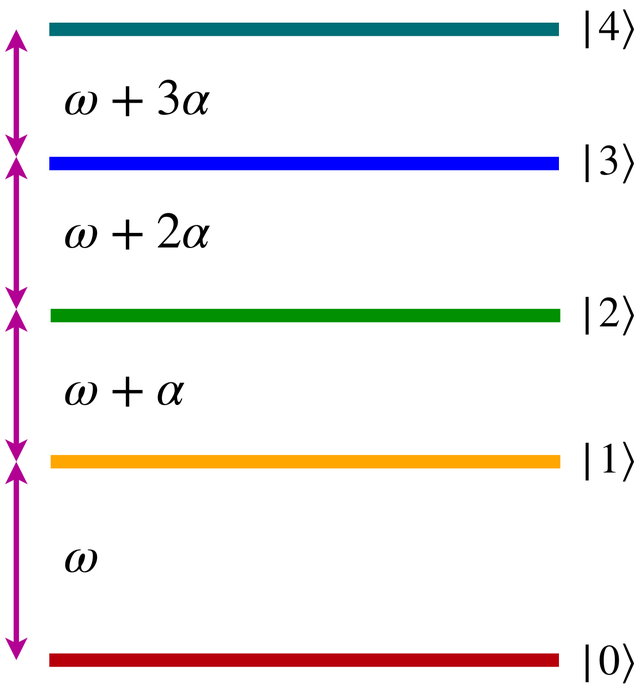


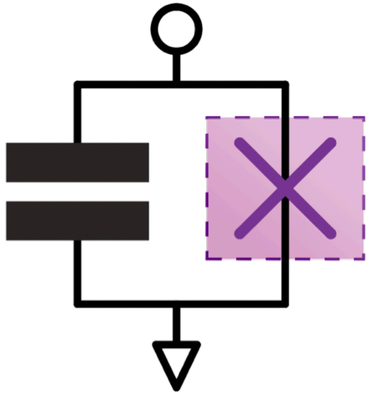



# BUILD QUBIT FROM OSCILLATOR

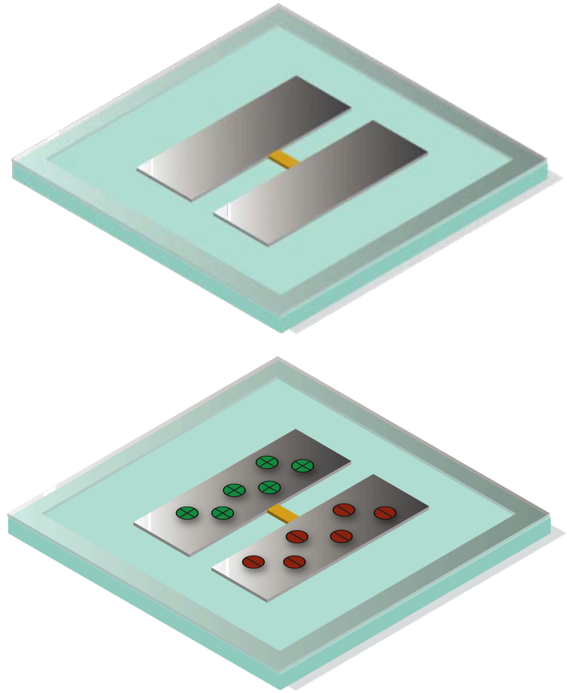


oscillator



Duffing oscillator

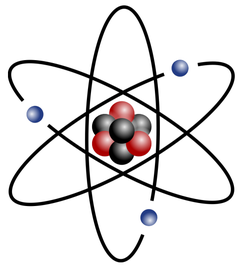


# ROADMAP

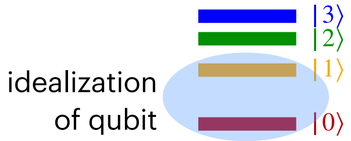
*“Quantum phenomena do not occur in a Hilbert space, they occur in a laboratory.”*

—Asher Peres

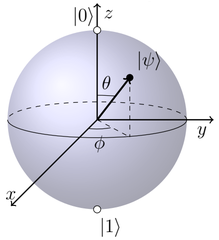
realization



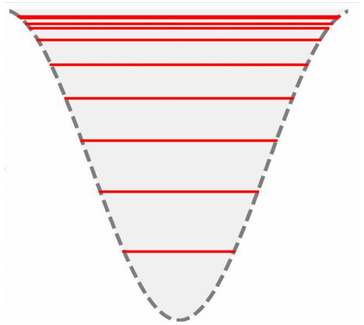
**energy levels**



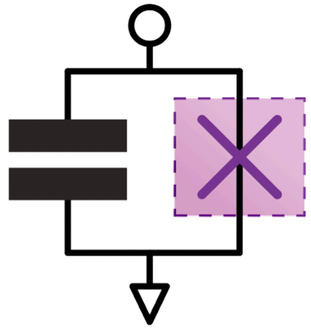

Hilbert space



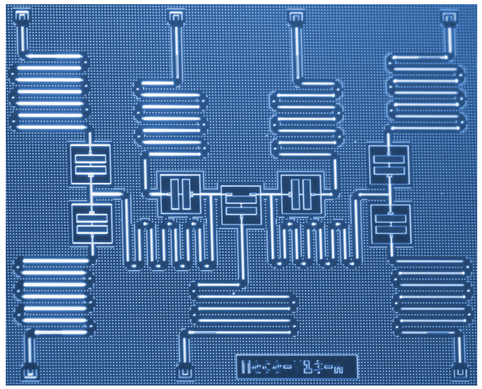

**anharmonic oscillator**



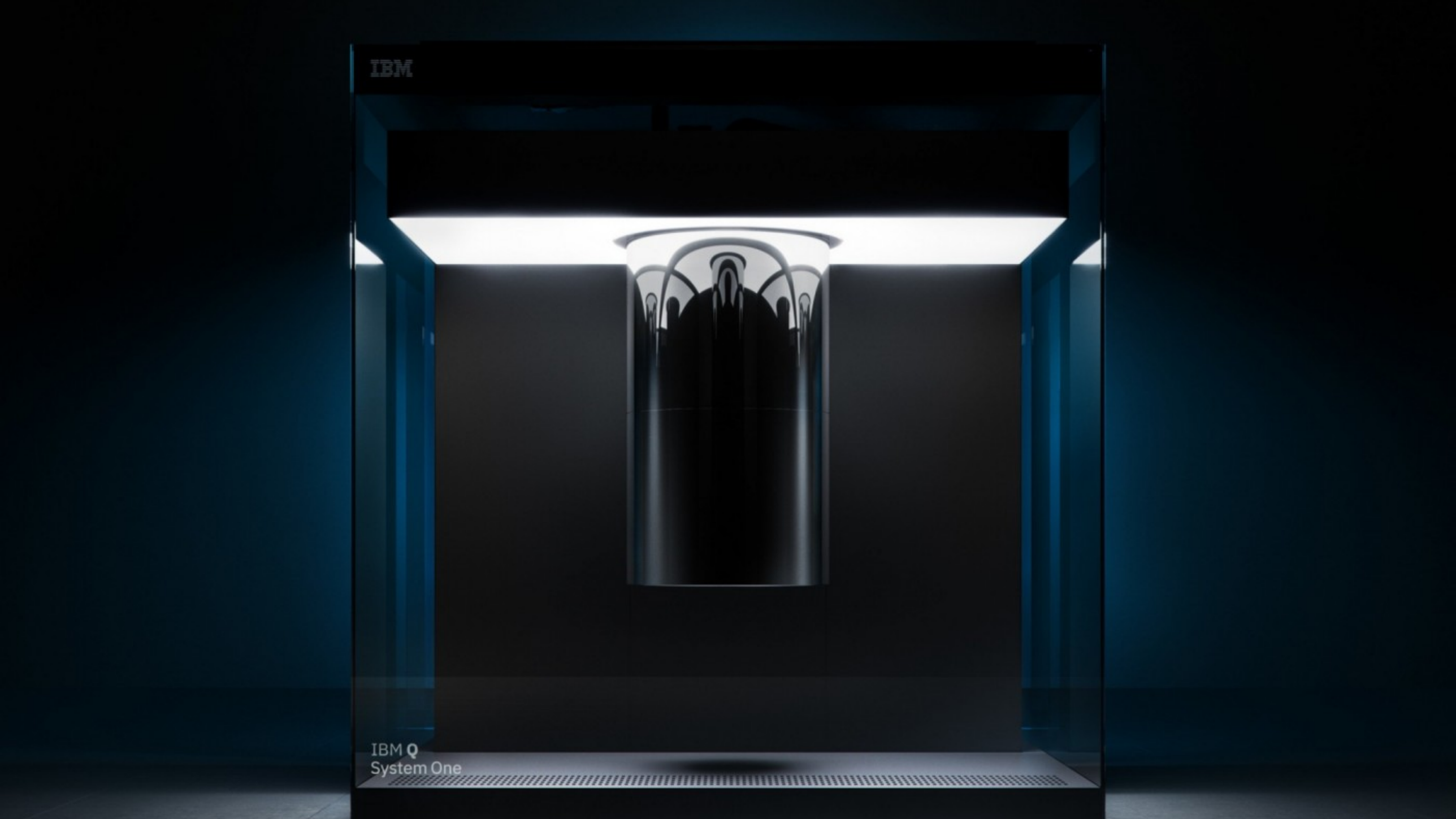
**physical circuit model**

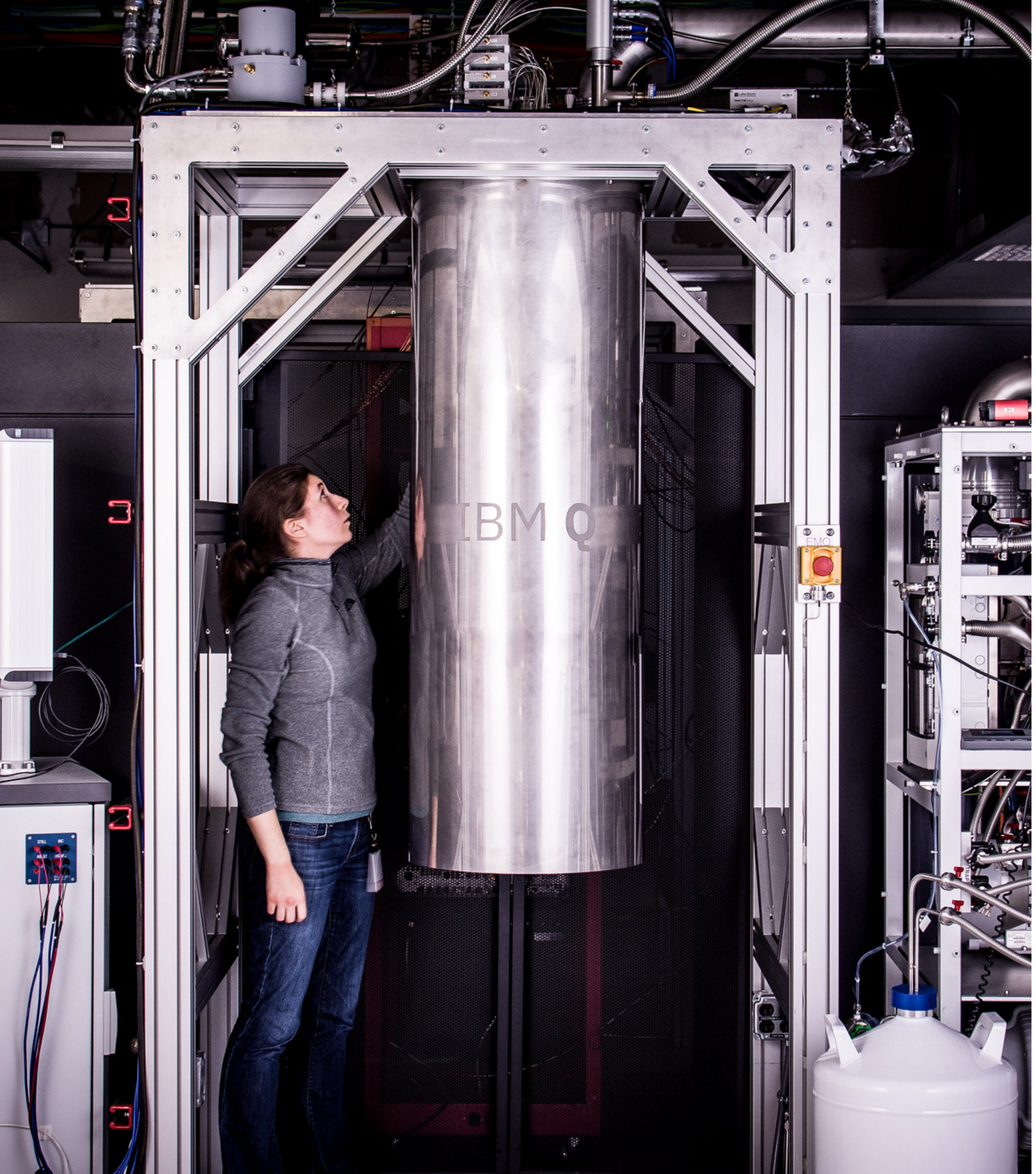


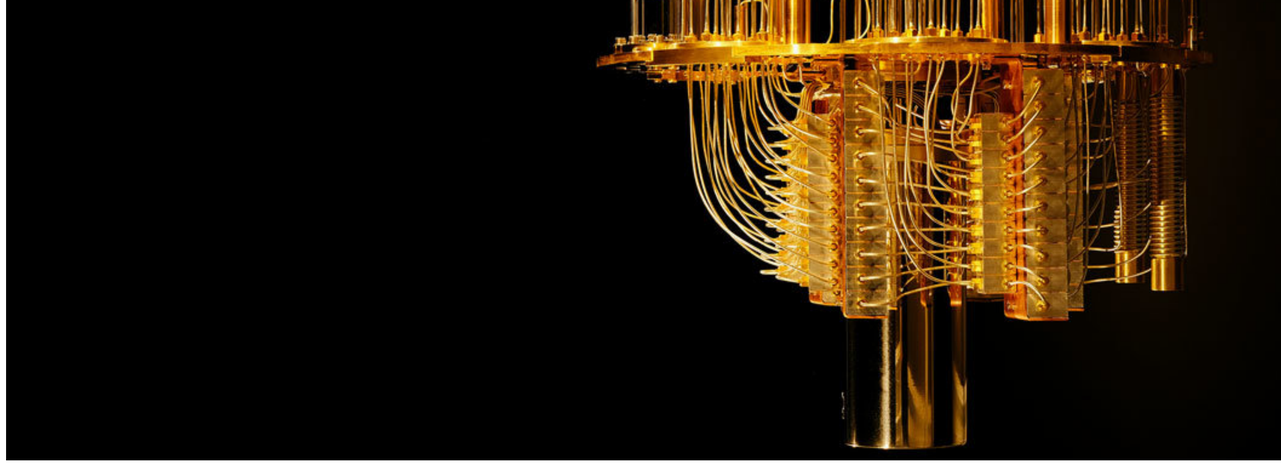
**physical layout**

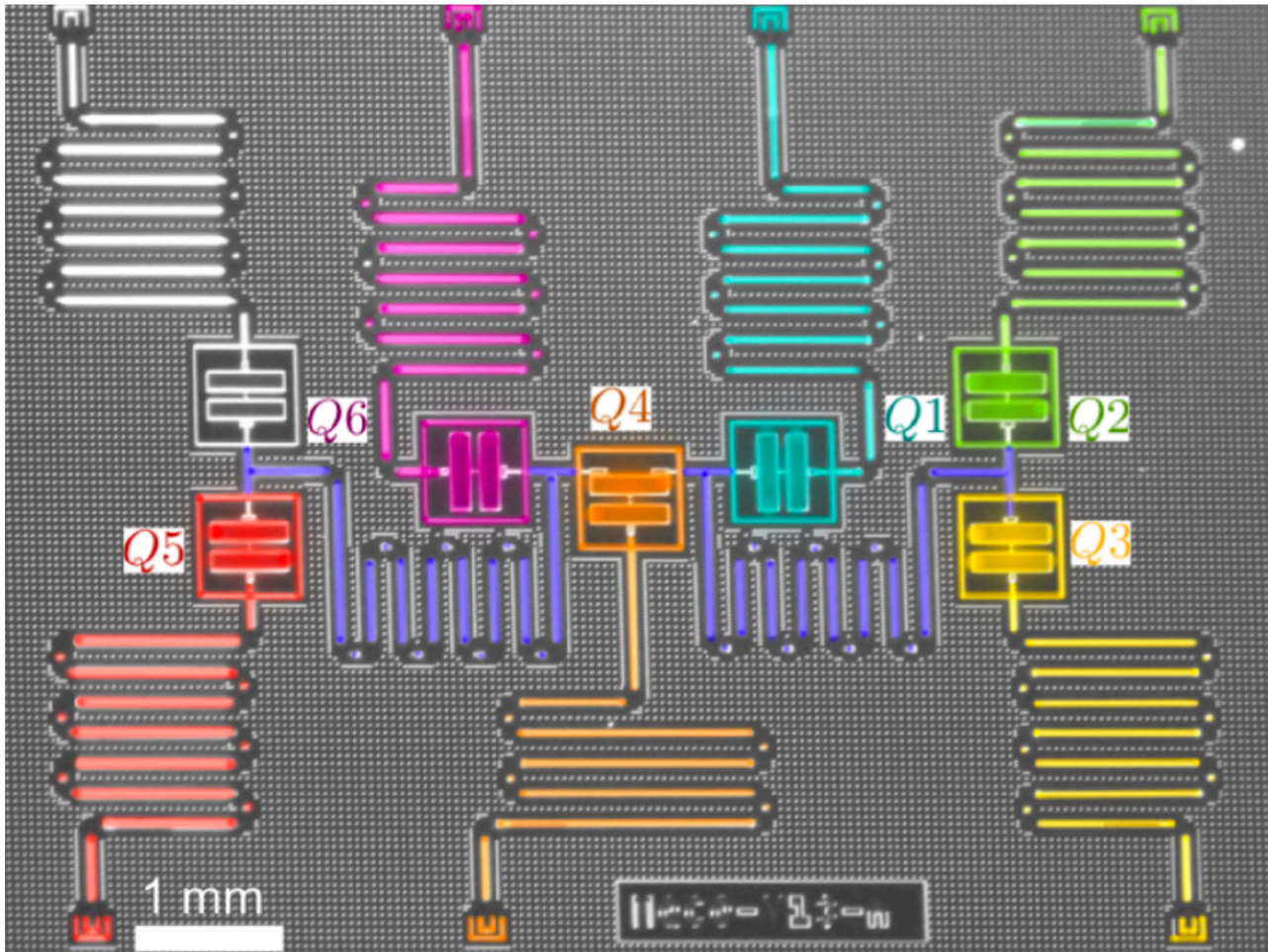


**idealization** → **physical reality**


IBM
IBM Q
System One

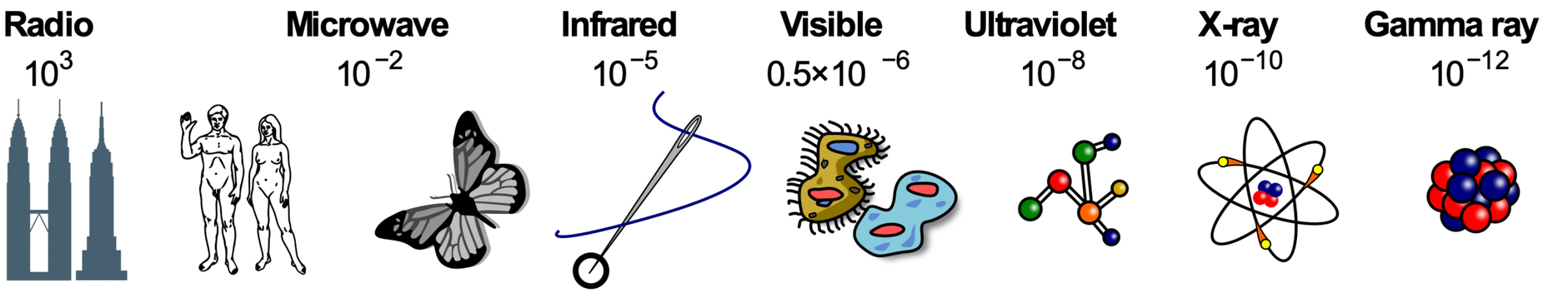

IBM Q



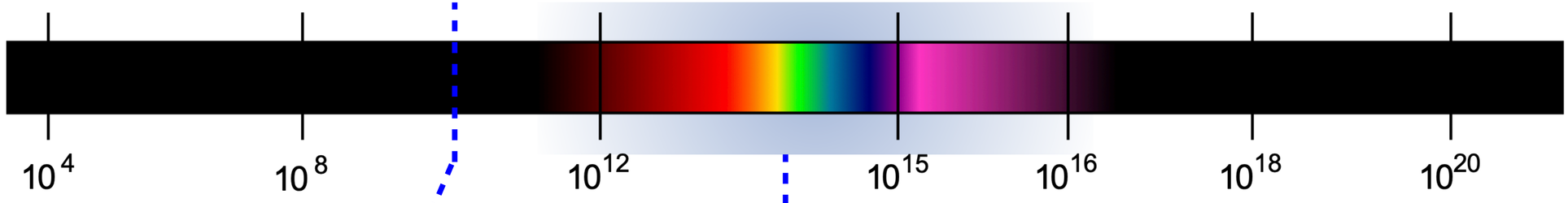

Q6
Q4
Q1
Q2
Q5
Q3
1 mm

wavelength (m)

object scale

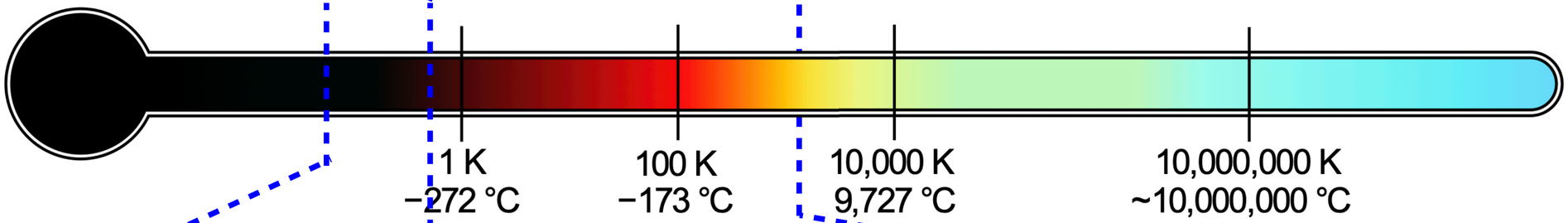



frequency (Hz)



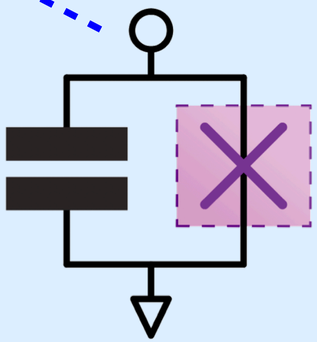

$\hbar\omega = k_B T$

temperature

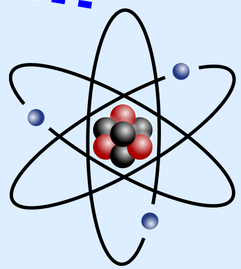



order of magnitude

$10^{-2}$ K

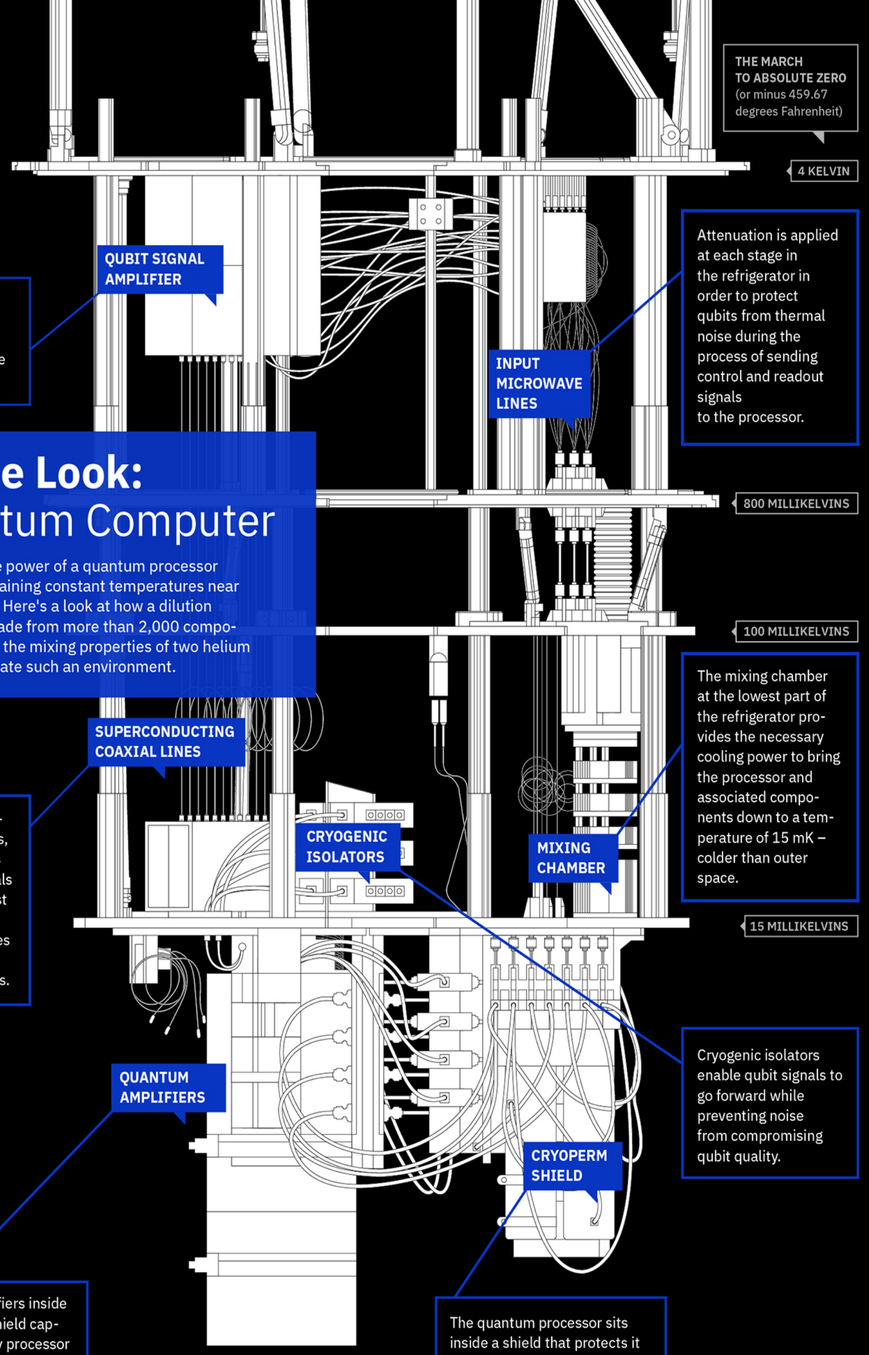



0.5 K, 10 GHz, 3 cm



# 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.



**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.

**INPUT MICROWAVE LINES**

Attenuation is applied at each stage in the refrigerator in order to protect qubits from thermal noise during the process of sending control and readout signals to the processor.

800 MILLIKELVINS

100 MILLIKELVINS

**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**

**MIXING CHAMBER**

The mixing chamber at the lowest part of the refrigerator provides the necessary cooling power to bring the processor and associated components down to a temperature of 15 mK – colder than outer space.

15 MILLIKELVINS

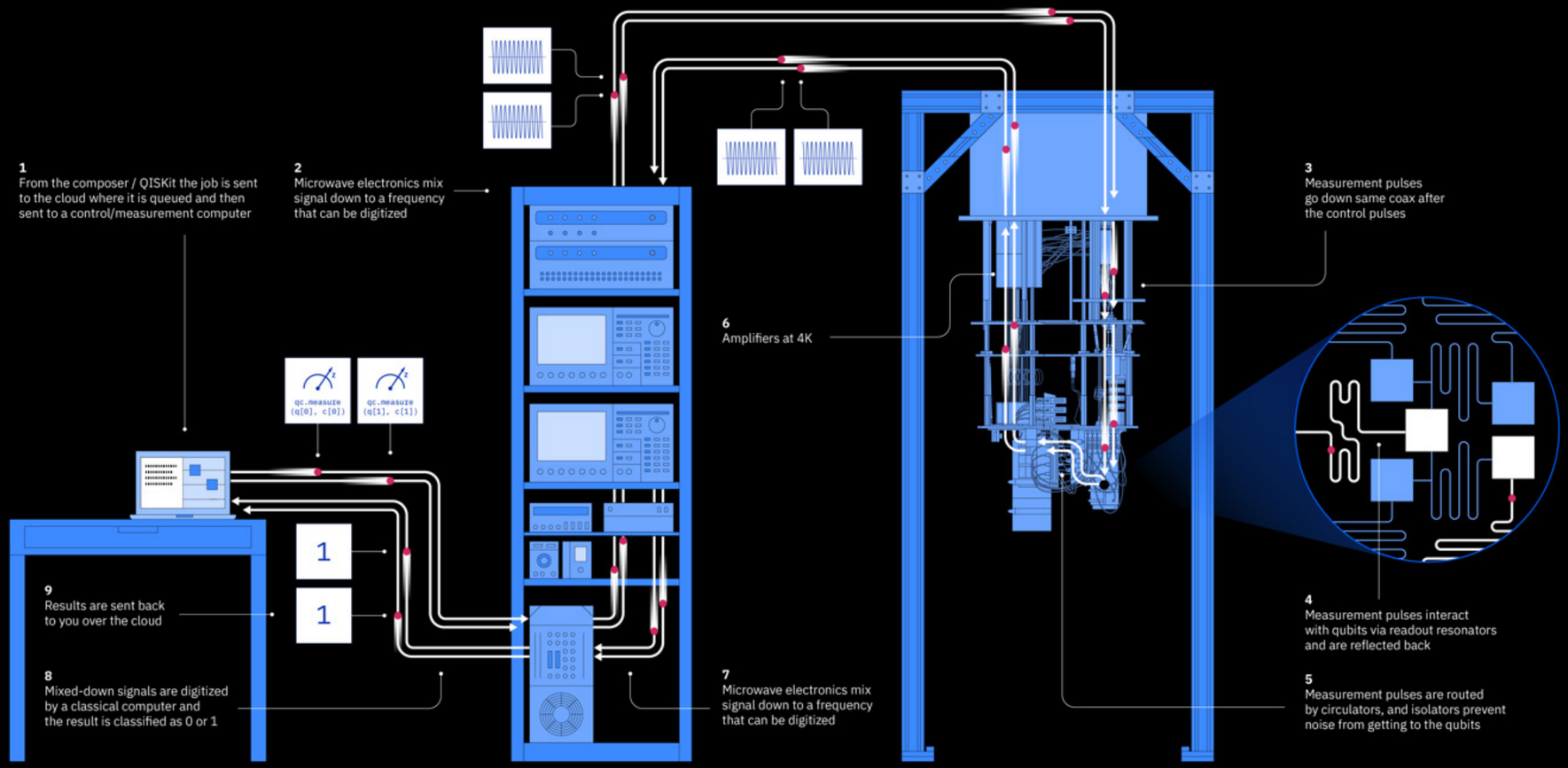
Cryogenic isolators enable qubit signals to go forward while preventing noise from compromising qubit quality.

**QUANTUM AMPLIFIERS**

**CRYOPERM SHIELD**

Quantum amplifiers inside of a magnetic shield capture and amplify processor readout signals while minimizing noise.

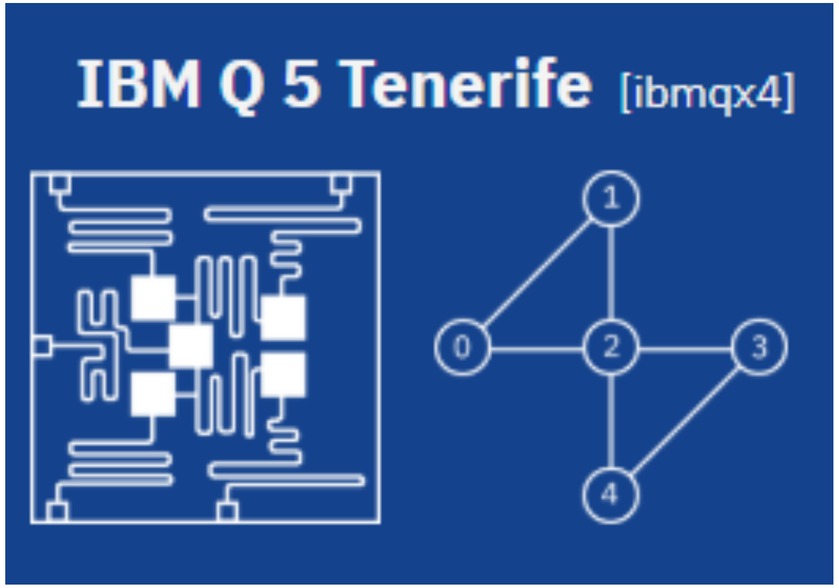
The quantum processor sits inside a shield that protects it from electromagnetic radiation in order to preserve its quality.


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
6
Amplifiers at 4K
qc.measure(q[0], c[0])
qc.measure(q[1], c[1])
1
1
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
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

***Talk to neighbors?***

# INTERACTION BETWEEN QUBITS

- Qubits talk to neighbors via some channels
  - Single-qubit gates
  - Multi-qubit  gates
- Chip structures
  - Coupling pattern
  - Operation routes



# TRANSPILER

**If building a quantum circuit like a blindman……**

- **Compatible with physical layout**
- **Optimize performance**

# The “Transpiler”

**DEMO-1: TRANSPILER**

***Can operations be always perfect?***

# ERRORS

- **WHERE** do they come from?
- **WHAT** is the influence?
- **HOW** to avoid them?

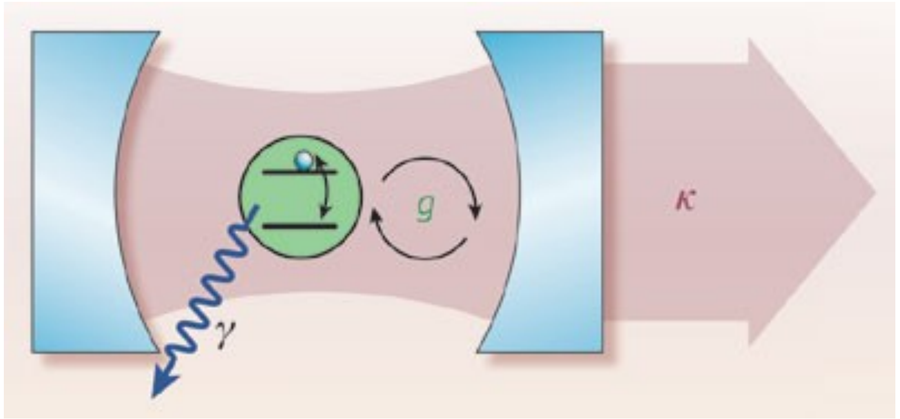
# How long can a qubit live?

DEMO-2: COHERENCE TIME OF QUBITS

# DEVICE'S "PERSONALITY"

- System flaws
  - Qubits, cavities, wires
- Information

$$\begin{pmatrix} \text{Energy} & \text{Phase} \\ \text{Phase} & \text{Energy} \end{pmatrix}$$

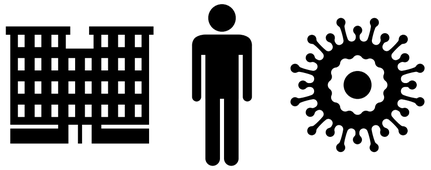


# DUMMING QUBITS

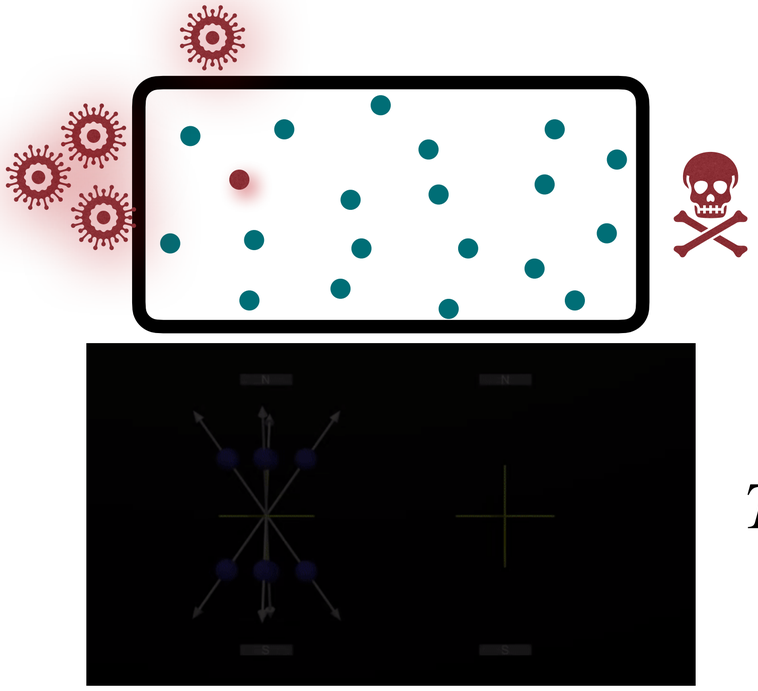
- Quantum errors
  - Pauli errors: bit-flip (X), phase-flip (Z), bit-phase (Y)
  - Depolarizing error: energy transitions, dephasing, ...
  - Thermal relaxation: due to $T_1$, $T_2$
- Classical errors
  - Readout error
  - Pulse error

# RELAXATION

## COVID-19 MODEL

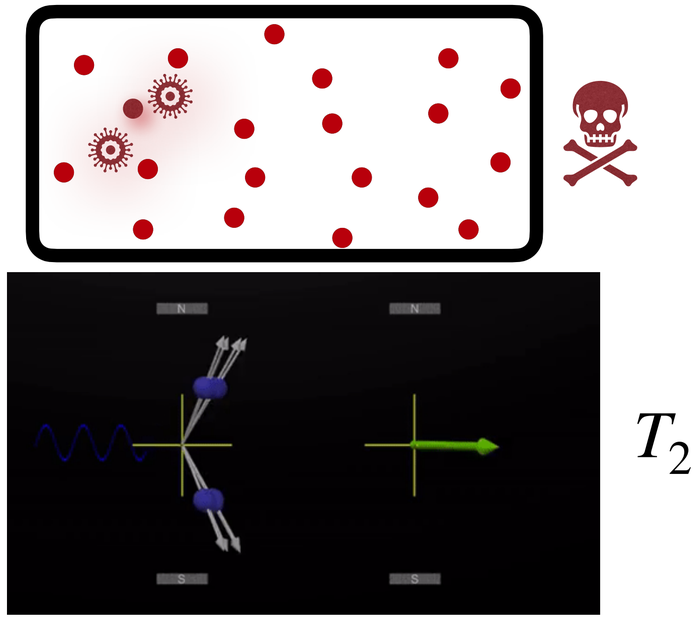


## qubit-environment



$T_1$

## qubit-qubit



$T_2$

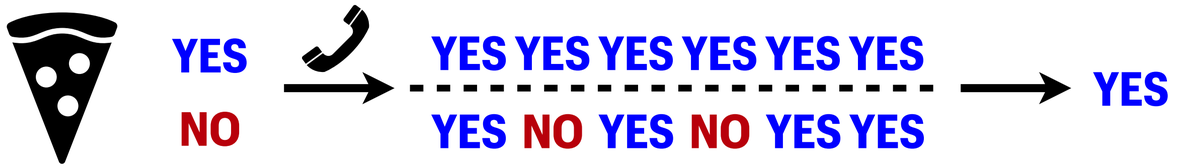
# Close to reality, far from ideal

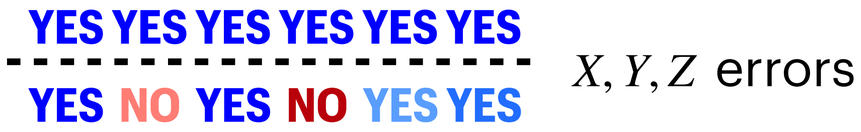
DEMO-3: NOISE MODEL

# *How to do with errors?*

# ERROR CORRECTION

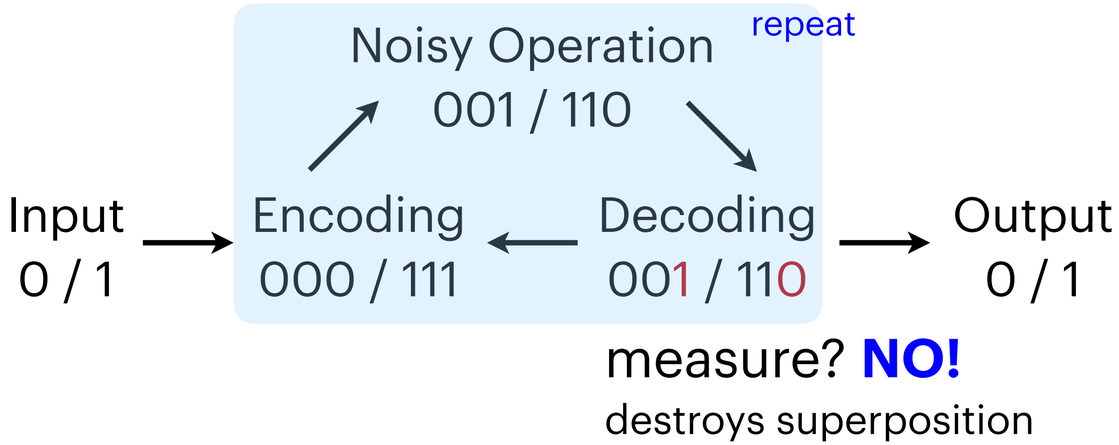
- Controls  on pulses
- Quantum error correction
  - Repetition code
    - Bit-flip
  - Surface code
    - Bit-flip
    - Phase-flip



# REPETITION CODE

## Code




measure? **NO!**

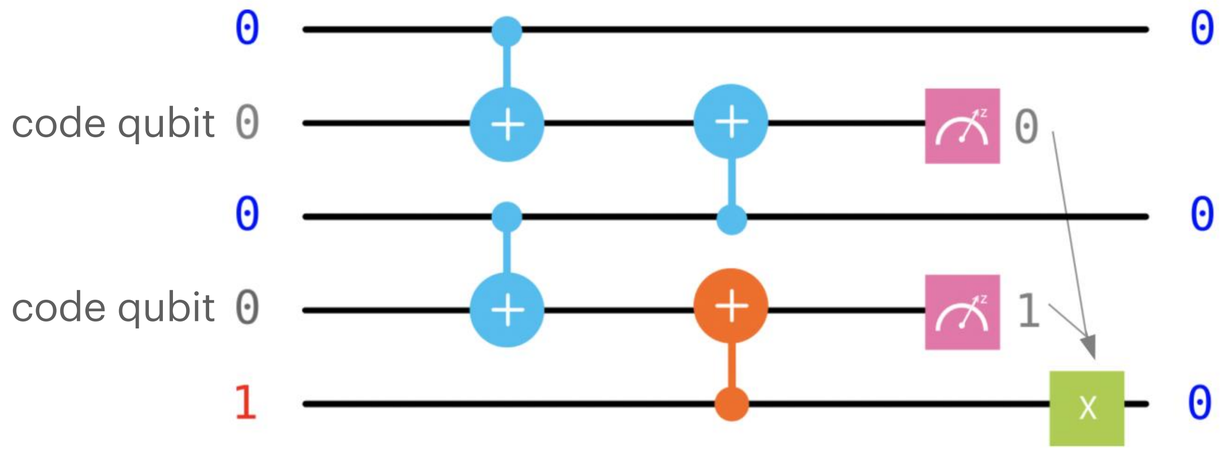
destroys superposition

## Solution

$$0 \quad 0 \quad 0 \quad 0 \quad 0 \quad 0 \quad 0$$
$$\downarrow$$
$$0 \quad 1 \quad 1 \quad 0 \quad 0 \quad 1 \quad 0$$
$$\downarrow$$
$$0 \neq 1 \quad 1 \neq 0 \quad 0 \neq 1 \neq 0$$

# CODE QUBITS

- **Code qubits ↤ comparison results**
  - **Initial state:** $|0\rangle$
  - **Target for 2 CNOT**




- **Implement:** *Nature* **519**, 66-69(2015)

# How to correct errors?

**DEMO-4: REPETITION CODE**

# QUESTIONS?