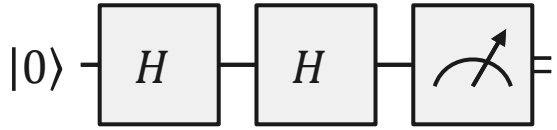
SAJID Lab
Smart & Advanced Junction of Intelligent Devices

EEE 6516 · QUANTUM COMPUTING

Quantum Computing

What it is, what it isn't, and why engineers build it



Week 1 · Lecture 0 · Introduction

Sajid Muhaimin Choudhury

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A refrigerator colder than outer space

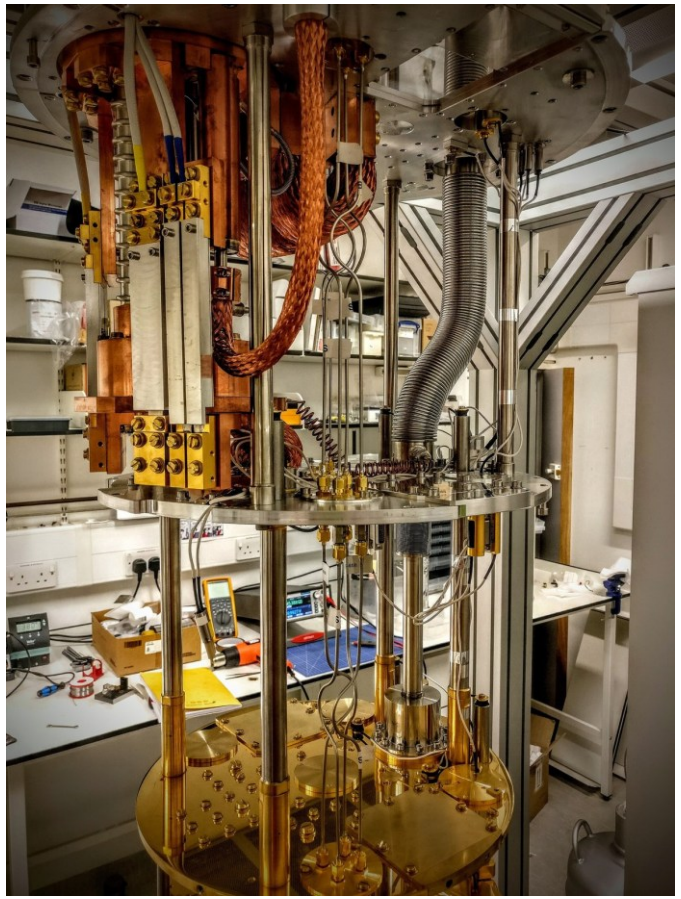


Photo: UCL Mathematical & Physical Sciences / Pavlos Apostolidis (LCN), CC BY 2.0, via Wikimedia Commons

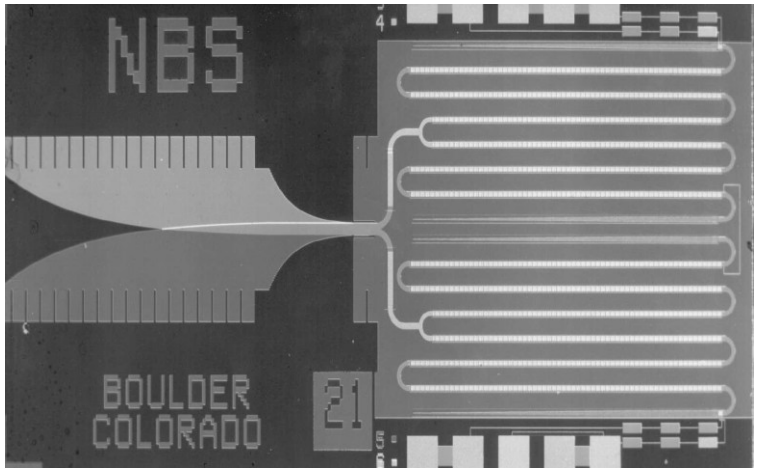
What sits at the bottom of this refrigerator?

Bottom stage: ≈ 10–20 mK

Coaxial lines carry GHz signals down, stage by stage

At 5 GHz, $hf/k_B \approx 0.24\,\mathrm{K}$: room temperature would drown the signal

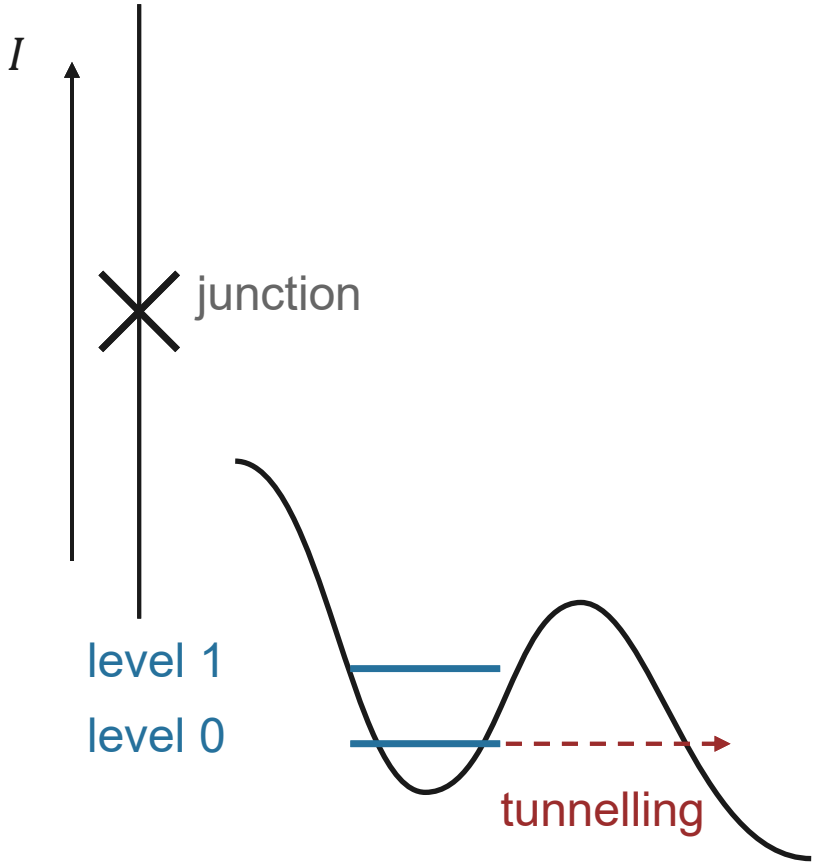
A circuit that won the 2025 Nobel Prize



Courtesy NIST (formerly NBS); public domain

Josephson junctions are already EE components:

this NBS chip (c. 1985–88) chains 3020 of them into a voltage standard.



energy vs. junction phase (sketch)

Nobel Prize in Physics 2025

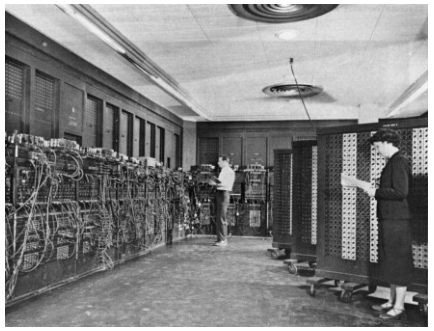
"for the discovery of macroscopic quantum mechanical tunnelling and energy quantisation in an electric circuit"

John Clarke · Michel H. Devoret · John M. Martinis

UC Berkeley, 1984–85; chip ≈ 1 cm

EXPERIMENT 1984–85

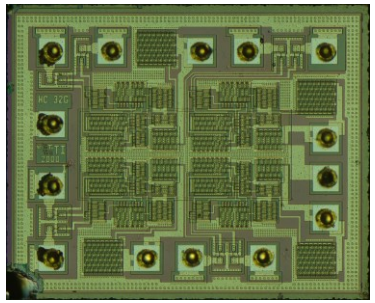
You already know more than you think



U.S. Army photo; public domain



Replica. Photo: Mister rf, CC BY-SA 4.0, via Wikimedia Commons



TI 74HC32 die. Photo: Cole L, CC BY-SA 2.0, via Wikimedia Commons

You already know	You will meet
logic gates, truth tables	quantum gates — always reversible
matrices, eigenvectors	operators and measurement
phasors: magnitude and phase	amplitudes: magnitude and phase, squared → probability
probability, histograms	the Born rule and shot statistics
coax, resonators, lasers, detectors	how qubits are controlled and read out

YOUR TURN · PREDICT

Can you run this gate backwards?

AND

a	b	a·b
0	0	0
0	1	0
1	0	0
1	1	1

NOT

a	ā
0	1
1	0

CNOT

a	b	a	a⊕b
0	0	0	0
0	1	0	1
1	0	1	1
1	1	1	0

CNOT: the first output copies a; the second is a XOR b.

Think · 45 seconds

You see only the output. Can you always tell me the input?

A AND only

B NOT only

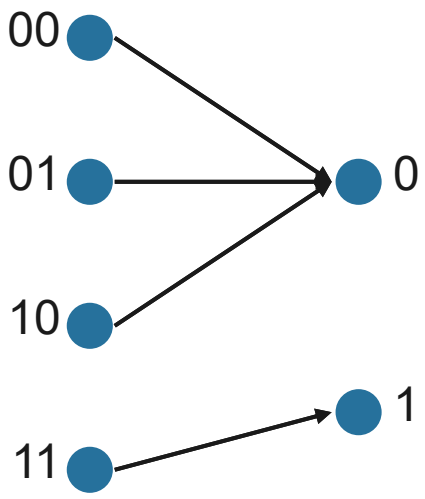
C NOT and CNOT

D all three

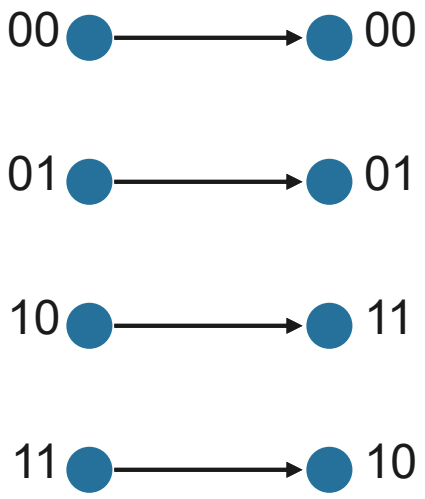
ANSWER

C: NOT and CNOT can be undone; AND cannot

AND: 4 → 2



CNOT: 4 → 4



AND merges three inputs into 0: information is lost. CNOT only reorders the four patterns.

Erasing one bit at temperature T costs at least $k_B T \ln 2 \approx 2.9 \times 10^{-21}$ J at 300 K (Landauer; measured 2012).

CMOS gates dissipate far more than this bound: the point is logical, not practical.

Quantum mechanics allows only reversible gates: every quantum gate is a unitary matrix (Lecture 2).

Reversibility is required by physics, not chosen to save energy.

Three things called “superposition”

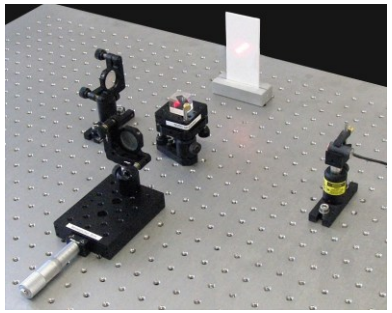
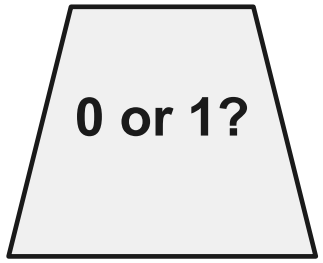


Photo: FL0, CC BY-SA 3.0, via Wikimedia Commons



$$\frac{1}{\sqrt{2}}(|0\rangle + |1\rangle)$$

1 Signals: $v(t) = A\cos\omega_1 t + B\cos\omega_2 t$
read A and B again and again

2 A hidden coin: 0 or 1, you just don't know

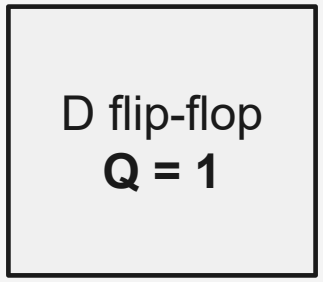
3 A qubit: one measurement → one bit

2000 shots each	usual (Z) basis: 0 / 1	rotated (X) basis: 0 / 1
coin (mixture)	998 / 1002	1025 / 975
qubit (|0⟩ + |1⟩)/√2	973 / 1027	2000 / 0

SIMULATION

Reading a bit vs measuring a qubit

Classical bit (a flip-flop)



read → 1
read → 1
read → 1

Reading reveals a stored value.

Reading again gives the same value.

Qubit

$$\Pr(0) = |\alpha|^2 = 0.8536$$

first 30 measurements:

`001001000000000000000000000000`

1000 shots: 864 zeros

expected 853.6, standard deviation 11.2

After a measurement the state is the outcome.

SIMULATION

YOUR TURN · PREDICT

One photon, two beam splitters

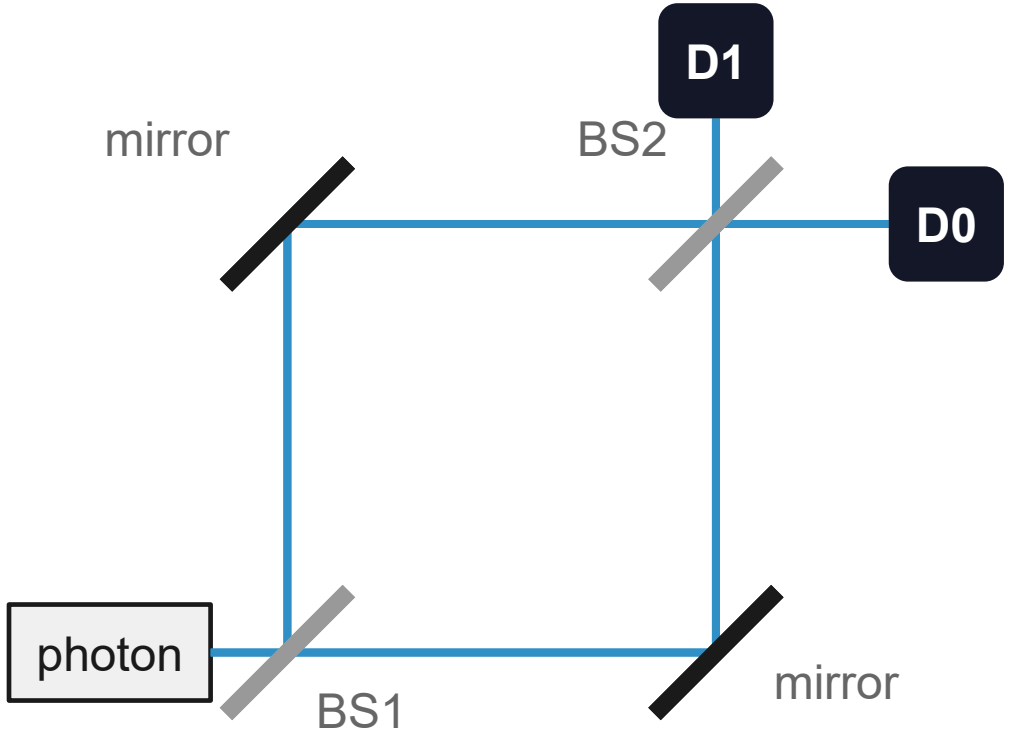




Photo: Anders Sandberg, CC BY 2.0, via Wikimedia Commons

Real single-photon optics: a beam splitter and detectors that click

Predict · 60 seconds

One photon enters. Both arms are the same length; each beam splitter is 50:50.

Where is it detected?

A D0 half the time, D1 half the time

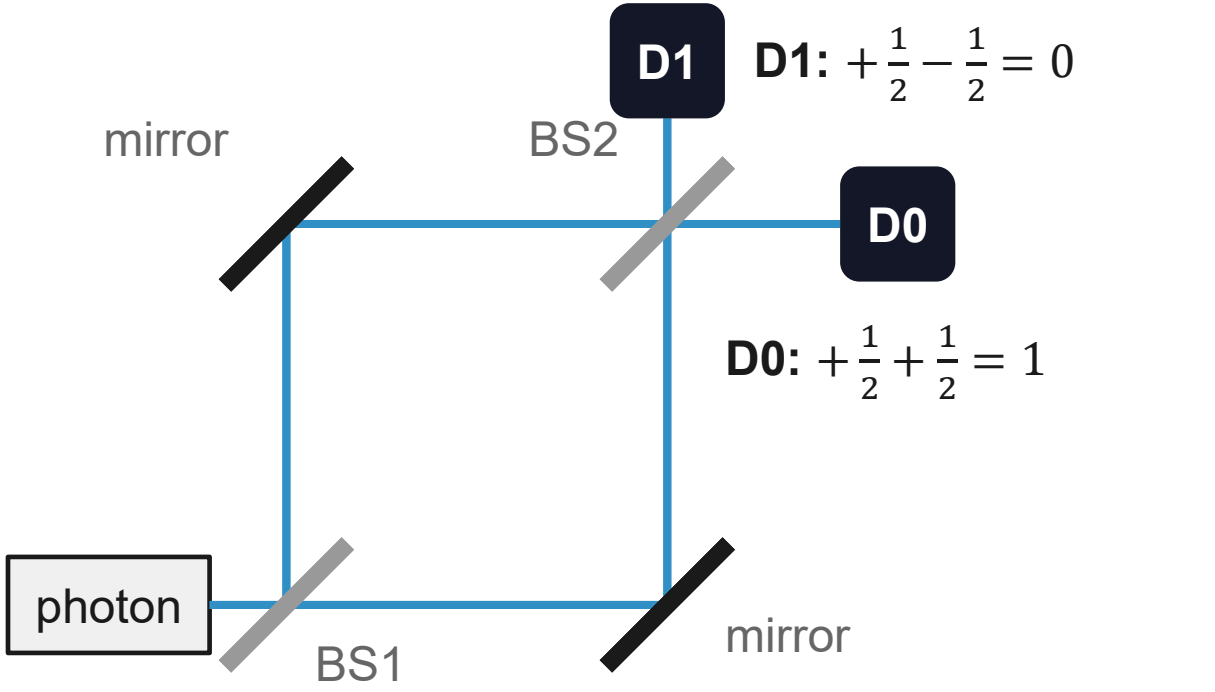
B always D0

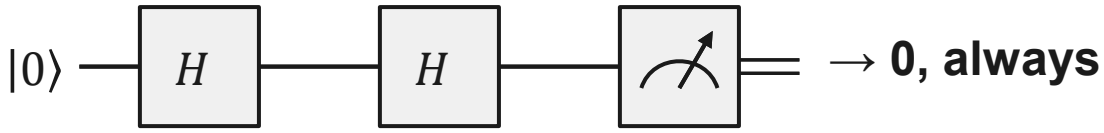
C always D1

D it depends on the photon

ANSWER

B: always D0 — amplitudes add, then square






```
recorded: H @ H|0> = [1. 0.]
```

Each route to a detector carries an amplitude ±½. Indistinguishable routes add first:

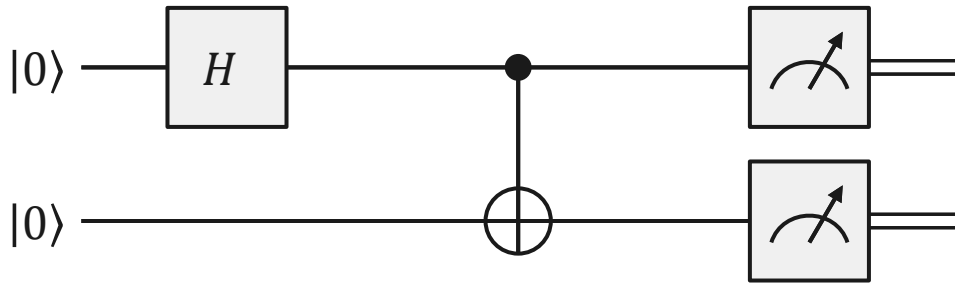
D0: ½ + ½ = 1, D1: ½ − ½ = 0. Probabilities could never cancel like this.

Block one arm and each detector fires half the time.

Single-photon interference was observed with > 98 % visibility (Grangier, Roger & Aspect, 1986).

Algorithms are choreographed interference: wrong answers cancel.

Entanglement: correlations no pair of coins can fake



$$\frac{1}{\sqrt{2}}(|00\rangle + |11\rangle)$$

Each side alone sees 0 or 1 at random, whatever the other side does:

no signal travels.

2000 shots	usual (Z) basis	rotated (X) basis
entangled	00: 1072, 11: 928	00: 995, 11: 1005
two copied coins	00: 1041, 11: 959	00: 522, 01: 519 10: 472, 11: 487

SIMULATION

Real pairs violate Bell's inequality: Aspect et al. 1982; loophole-free tests 2015; Nobel Prize 2022.

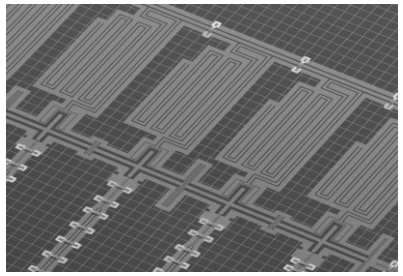
EXPERIMENT

COMMON MISTAKES

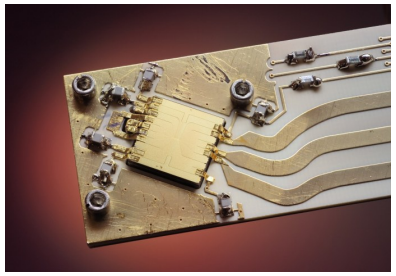
Five myths, five corrections

✗ Myth	✓ What is true
“It tries every answer at once.”	One run gives one outcome; the power is interference (S10).
“Exponentially faster at everything.”	Only for specific problems; Grover's search is quadratic (S20).
“Entanglement sends signals faster than light.”	No: each side alone sees 50/50 (S11).
“More qubits means a more powerful computer.”	Error rates and connectivity matter as much (S18).
“My laptop simulator is a quantum computer.”	It is a classical program needing $16 \cdot 2^n$ bytes (S17).

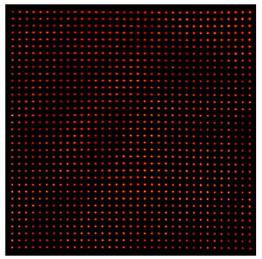
Same mathematics, four very different machines



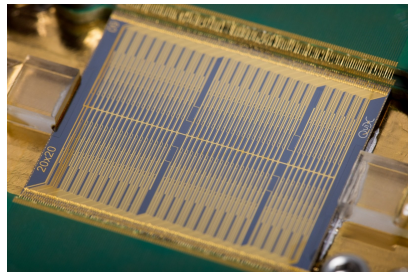
SEM image: FMNLab, CC BY 4.0, via Wikimedia Commons



Credit: Y. Colombe/NIST; public domain



Preston Huft, CC BY 4.0, via Wikimedia Commons



Taballione et al., Quantum 7, 1071 (2023), Fig. 1a, CC BY 4.0; resized

Superconducting
Qubit: circuit levels
Control: microwaves
Readout: resonator
At ≈ 10–20 mK

Trapped ions
Qubit: levels of an ion
Control: lasers, microwaves
Readout: glow or dark
Held in vacuum

Neutral atoms
Qubit: levels of an atom
Control: lasers
Readout: camera image
Array set by light

Photons
Qubit: path or mode
Control: interferometers
Readout: detectors
Main error: loss

Same mathematics, different engineering. No platform is best at everything.

Inside a superconducting quantum computer



Photo: UCL Mathematical & Physical Sciences / Pavlos Apostolidis (LCN), CC BY 2.0, via Wikimedia Commons

Room temperature
waveform generator → IQ mixer | digitiser

↓ ↑

Cold stages
attenuators and filters (down) | amplifier (up)

↓ ↑

Bottom stage ≈ 10–20 mK
qubit chip + readout resonator

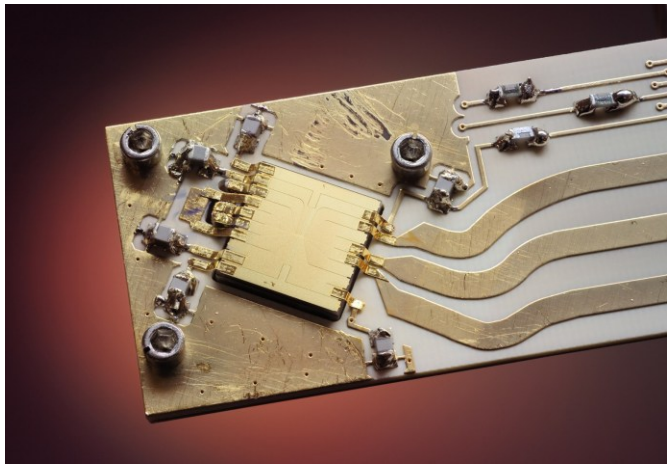
drive pulses go down (blue); a few-photon readout signal comes up (green)

	value (year)
qubit frequency	≈ 5 GHz (2019 review)
mean T1, Willow (105 qubits)	68 µs (2024/25)
two-qubit CZ gate	99.4 % in ≈ 40 ns (2014)

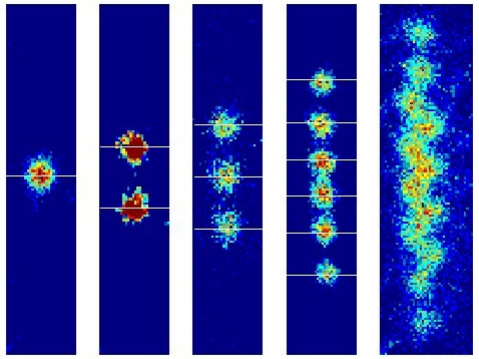
Best reported transmon T1: up to 1.68 ms (2025) — a record, not typical.

EXPERIMENT

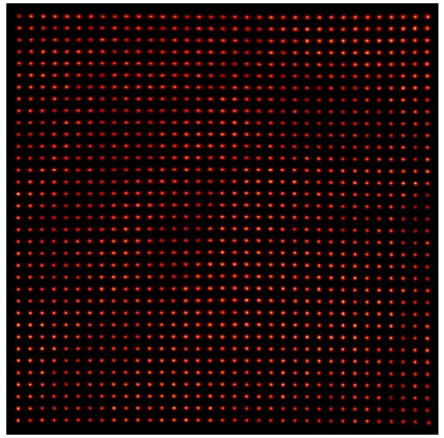
Atoms held by fields and light



Credit: Y. Colombe/NIST; public domain



Credit: Signe Seidelin and John Chiaverini/NIST; public domain



Preston Huft, CC BY 4.0, via Wikimedia Commons

Ions: |1⟩ glows, |0⟩ stays dark

prepare + read 99.93 %; one-qubit gate 99.9999 % (2014)

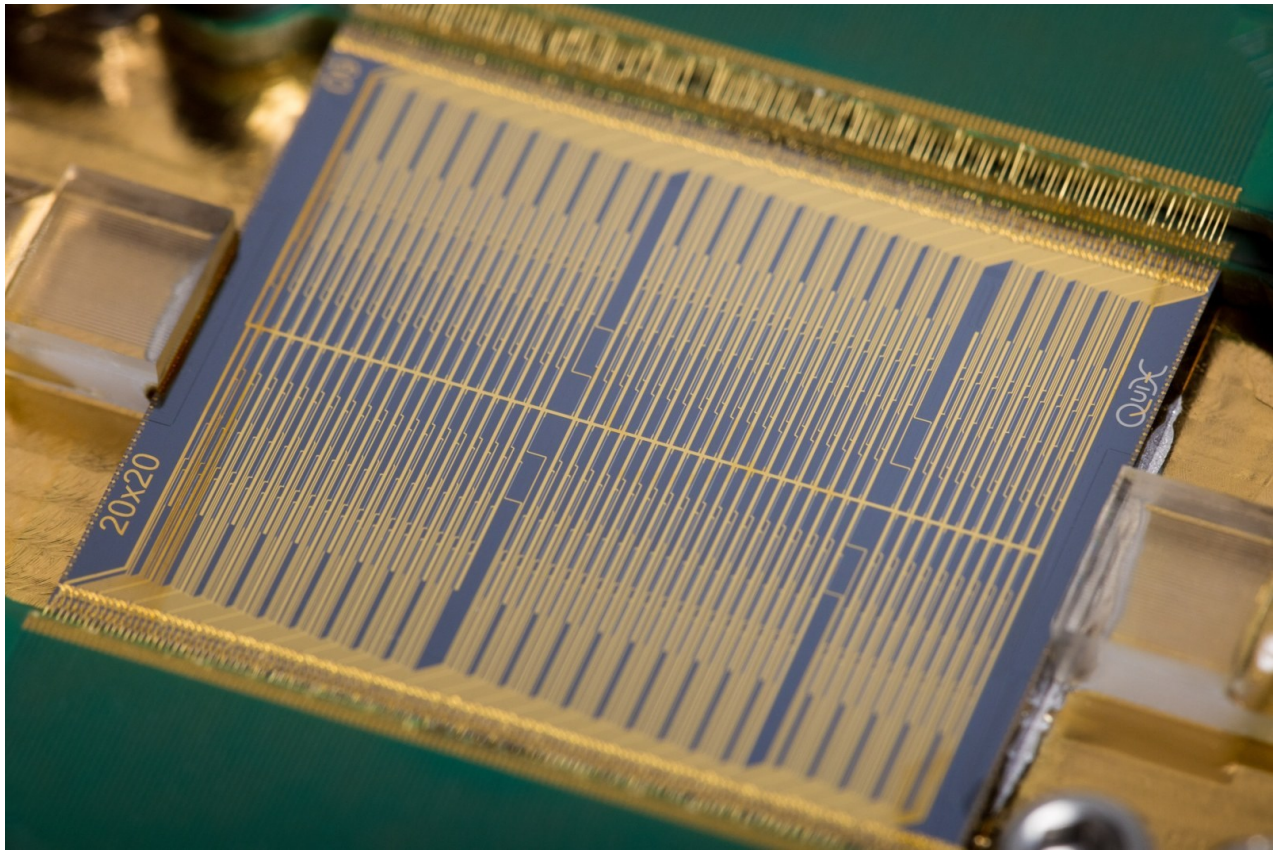
two-qubit gate 99.9 % — at 100 μs per gate (2016)

EXPERIMENT

Atoms: 60 atoms entangled in parallel at 99.5 % (2023)

48 logical qubits with an error-detecting code (2024)

Photons: qubits that travel



Taballione et al., Quantum 7, 1071 (2023), Fig. 1a, CC BY 4.0; resized

380 tiny heaters = 380 phase shifters

an integrated version of the interferometer in S9

natural for sending qubits over fibre

Two-qubit fusion: 99.22 % (2025),
conditional on detecting the photons; loss not included

PROTOTYPE

Your laptop simulator is not a quantum computer

qubits n	amplitudes 2^n	memory
10	1,024	16 KiB
30	1,073,741,824	16 GiB
50	1,125,899,906,842,624	16 PiB

16 bytes per complex amplitude: 30 qubits fit in a laptop; 50 do not fit anywhere simple.

SIMULATION

Your tools (all free, all local)

NumPy → Qiskit + Qiskit Aer, QuTiP

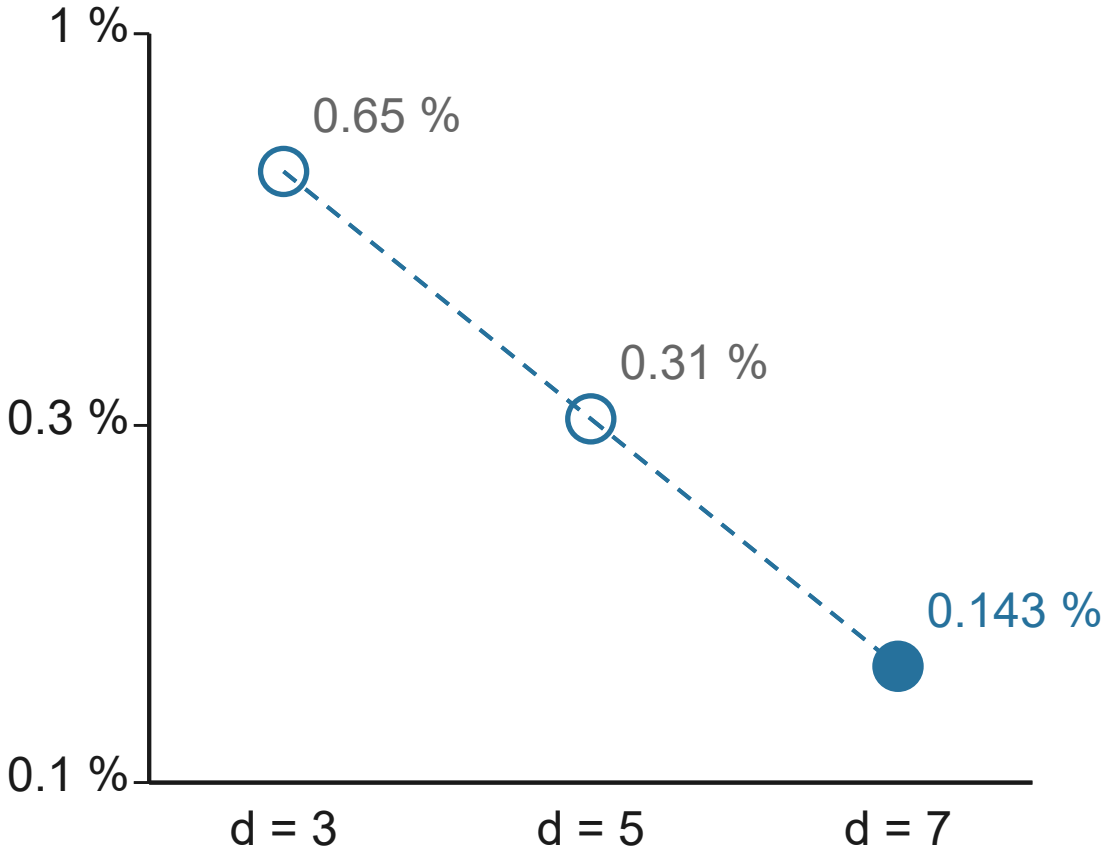
Cirq and PennyLane from Lecture 7

Stim for error correction

Apache-2.0 / BSD-3 licences; no account, no cloud

A simulator is exact but exponentially costly. It is not quantum hardware.

Noise — and a logical qubit that improved with size



filled: measured; open: implied by Λ = 2.14

Surface-code memory, Nature 2025

101 qubits, distance 7: 0.143 % error per cycle

error ÷ 2.14 for each step 3 → 5 → 7

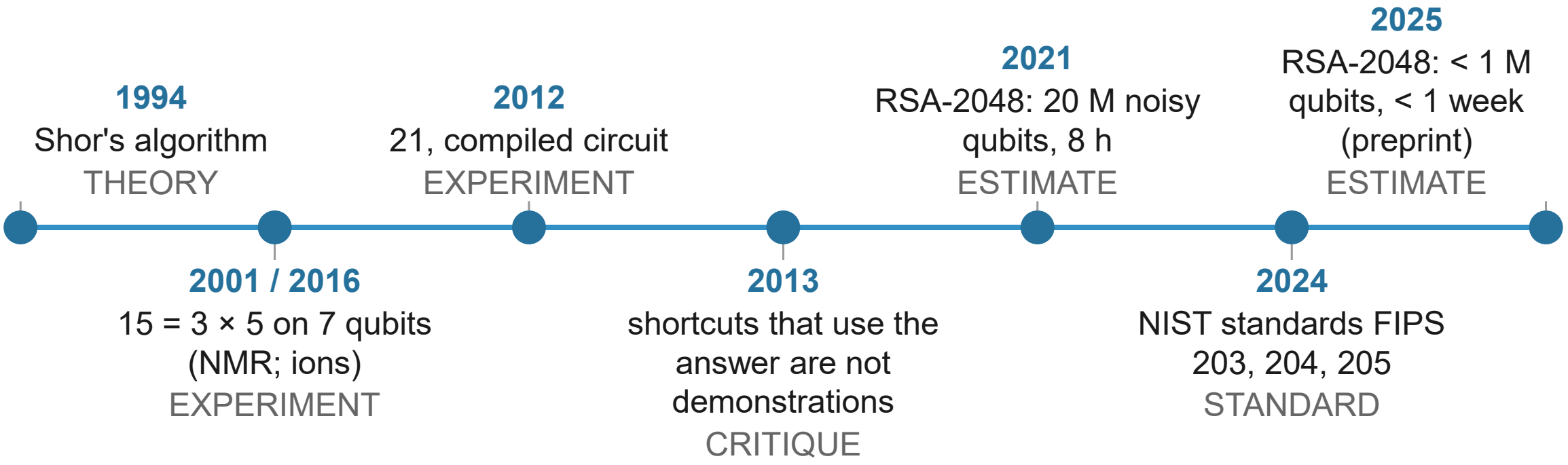
lives 2.4 × longer than its best physical qubit

decoder keeps up: 63 µs latency at a 1.1 µs cycle (separate 72-qubit chip)

EXPERIMENT 2024/25

NISQ (Preskill 2018): noisy intermediate-scale quantum — today's machines

Shor's algorithm and the 2048-bit lock



Estimates assume 0.1 % gate error, 1 μs cycle, 10 μs reaction time. NIST draft plan: 112-bit public-key algorithms deprecated after 2030.

The evidence ladder

Chemistry

ESTIMATE
FeMoco target ≈ 4 M qubits, < 4 days

EXPERIMENT
H_2, BeH_2 (≤ 6 qubits) computed — classically easy

ANALYSIS 2023
no evidence of generic exponential advantage

Search

THEORY
Grover: about $\sqrt{N}$ queries, provably optimal

ANALYSIS 2021
gain lost to error-correction overheads on early machines

Machine learning

THEORY 2019
claimed recommender speed-up matched classically

EXPERIMENT 2022
learning about quantum systems: 40 qubits

THEORY 2018
large random circuits: vanishing gradients

Quantum machine learning is outside the syllabus core: an optional final-project direction.

YOUR TURN · EVALUATE

“200 seconds versus 10,000 years”

Pairs · 60 seconds

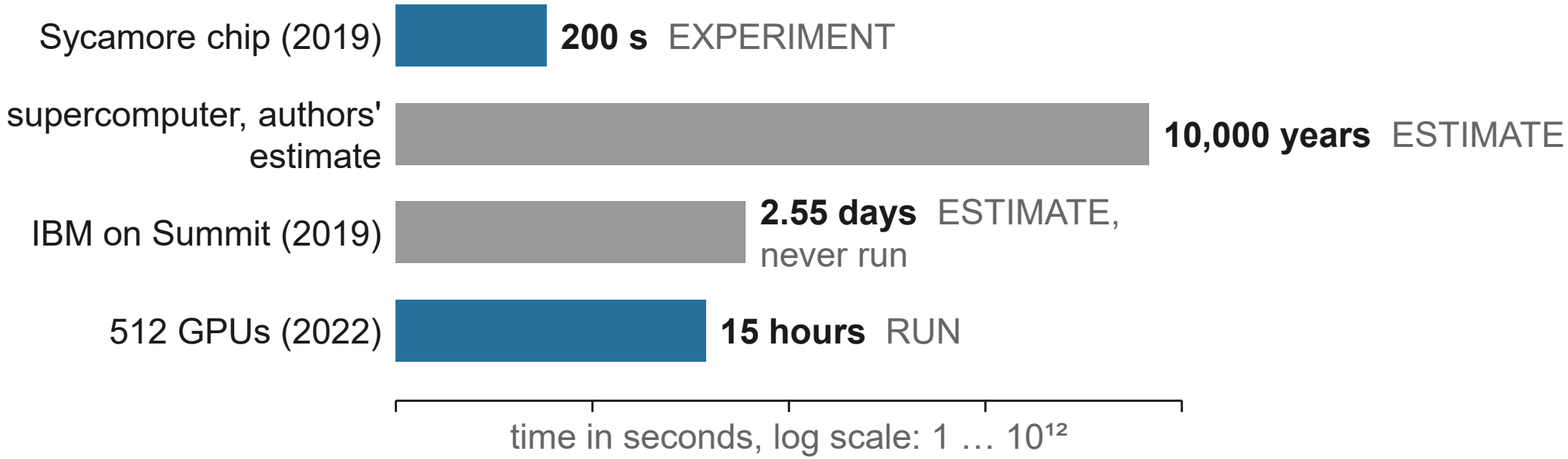
2019: a 53-qubit chip sampled one million outputs of a random circuit in about 200 s.

The authors estimated that the best supercomputer would need about 10,000 years.

With your neighbour: write two questions you would ask before believing the comparison.

ANSWER

The baseline moved



The quantum experiment was real; the classical baseline improved. The same happened in 2023–24, and Google's 'Quantum Echoes' (2025, ≈ 13,000 ×, estimated) is still under debate.

Always ask: which task, which baseline, measured or estimated, and when?

Your route through EEE 6516

Ch.	Lectures	A question you will be able to answer
1	1–2	How much memory does a 50-qubit state need? Why do amplitudes cancel?
2	3–5	How long must a microwave pulse be to flip a qubit? How many shots fix a probability?
3	6–7	Can you build a Toffoli from CNOTs? What do Qiskit's bit strings mean?
4	8–9	Can you teleport a qubit in simulation and beat the classical CHSH bound of 2?
5	10–11	For 8 items: how many Grover iterations, and how likely is success?
6	12–14	Can you factor 15 in simulation? What would RSA-2048 cost?
7	15–16	How does T1 = 100 μs degrade a Bell state?
8	17–18	Why does distance 7 beat distance 5 only below threshold?
9	19–20	Why does a 5 GHz transmon need ≈ 20 mK? How do ions, photons and atoms compare?

Why should an EEE graduate student take this course?

It is electrical engineering

a microwave circuit at 20 mK (S14)

lasers, waveguides, detectors (S15–S16)

error-correcting codes and real-time decoders (S18)

securing communication after Shor (S19)

EE/ECE departments teach it

MIT (EECS)
6.6410J Quantum Computation (Fall 2024)

Cornell (ECE)
ECE 5330 Quantum Physics and Engineering (Fall 2026)

Stony Brook (EE)
ESE 512 Intro. to Quantum Systems Eng. (Fall 2026)

Purdue (ECE, online)
Quantum Computing I–III series

Examples, not a ranking

Where it fits in your skills

You bring
linear algebra · phasors · probability · logic · EM, microwaves, optics · Python

You gain
qubit maths (CO1) · judging algorithms and hardware (CO2) · reproducible simulation (CO3)

It opens
research: devices, cryogenic microwaves, photonics, control, post-quantum security; further study

How you'll learn and how you'll be assessed

How you will learn

chapter handouts + slides on Teams

two 75-minute lectures every Tuesday

simulators on your own laptop

textbook: Nielsen & Chuang (2010)

Generative AI: limited use. Derivations, test design and interpretation are AI-free; you must explain every number.

Component	Weight	Notes
class tests	15 %	3 × 5 %, outside lectures
midterm simulation assignment	25 %	individual; Week 7
final project	30 %	reproduce a published result; groups of 2–3; Week 13
term final	30 %	—

I-grade, make-up and late-submission rules: course information sheet on Teams.

What an electrical engineer can build next

Microwave

model a readout resonator and its dispersive shift

Control / DSP

simulate a π pulse and its sensitivity to amplitude error

Coding theory

a repetition code in Stim and its threshold

Photonics

a two-beam-splitter interferometer and the HOM dip

Architecture

compare coupling graphs by transpiled CNOT count

Projects are simulations: none builds a fault-tolerant computer.

YOUR TURN · EXIT TICKET

Take away · Wonder about · Tell me

Take away

A qubit gives one bit when measured. Quantum computers work by making amplitudes interfere. Building one is an engineering battle against noise.

Wonder about

Will error-corrected machines arrive before classical algorithms catch up on the problems we care about? Nobody knows.

Exit ticket · 2 minutes

1 In one sentence: why does measuring a qubit not give you “all the answers”?

2 Which platform would you most like to work on, and why?

3 One thing you still find confusing.

Before Lecture 1

Lecture 1: from bits to qubits — the mathematics behind today's photon experiment

Install the environment (Ch. 1 §1.10); read §§1.1–1.4.

Exit ticket

Submit the three exit-ticket questions on Teams before you leave.

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• Slide 3: Courtesy NIST (formerly NBS) (PUBLIC_DOMAIN; Public domain (PD-USGov-NIST)) https://commons.wikimedia.org/wiki/File:NISTvoltChip.jpg

• Slide 4: U.S. Army photo (PUBLIC_DOMAIN; Public domain (PD-USGov-Military-Army)) https://commons.wikimedia.org/wiki/File:Glen_Beck_and_Betty_Snyder_program_the_ENIAC_in_building_328_at_the_Ballistic_Research_Laboratory.jpg

• Slide 4: Replica of the first transistor. Photo: Mister rf, CC BY-SA 4.0, via Wikimedia Commons (OPEN_LICENSE_APPROVED; CC BY-SA 4.0) https://commons.wikimedia.org/wiki/File:A_replica_of_the_first_working_transistor.jpg

• Slide 4: TI 74HC32 die. Photo: Cole L, CC BY-SA 2.0, via Wikimedia Commons (OPEN_LICENSE_APPROVED; CC BY-SA 2.0) https://commons.wikimedia.org/wiki/File:TI_HC32_Die_Shot_(4x2-Input_OR_Gate)_-_52871874720.png

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