

Realizing the Promise of Quantum Computing

William D. Oliver

Massachusetts Institute of Technology

14 April 2026

EQUS
ENGINEERING QUANTUM SYSTEMS

equs.mit.edu
Engineering Quantum Systems



**RESEARCH LABORATORY
OF ELECTRONICS AT MIT**



LINCOLN LABORATORY
MASSACHUSETTS INSTITUTE OF TECHNOLOGY



SOLVAY CONFERENCE 1927

ON ELECTRONS AND PHOTONS

Auguste PICARD Émile HENRIOT Paul EHRENFEST Édouard HERZEN Théophile de DONDER Erwin SCHRÖDINGER Jules-Émile VERSCHAFFELT Wolfgang PAULI Werner HEISENBERG Ralph H. FOWLER Leon BRILLOUIN
Peter DEBYE Martin KNUDSEN Lawrence BRAGG Hans KRAMERS Paul DIRAC Arthur COMPTON Louis de BROGLIE Max BORN Niels BOHR
Irving LANGMUIR Max PLANCK Marie CURIE Hendrik LORENTZ Albert EINSTEIN Paul LANGEVIN Charles-Eugène GUYÉ Charles T. R. WILSON Owen W. RICHARDSON



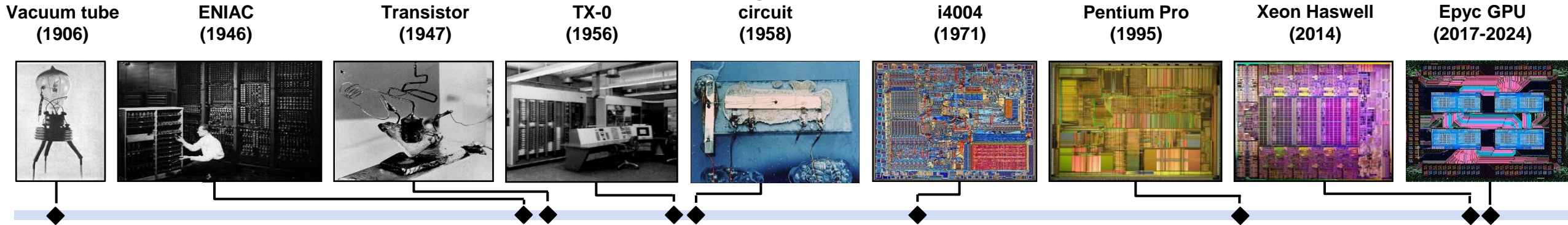
First Quantum Revolution (Quantum 1.0)

17 of 29 attendees were/became Nobel Prize Laureates

2025 was the International Year of Quantum Science and Technology

Computing Development Timeline

Classical Computing (Electronic)



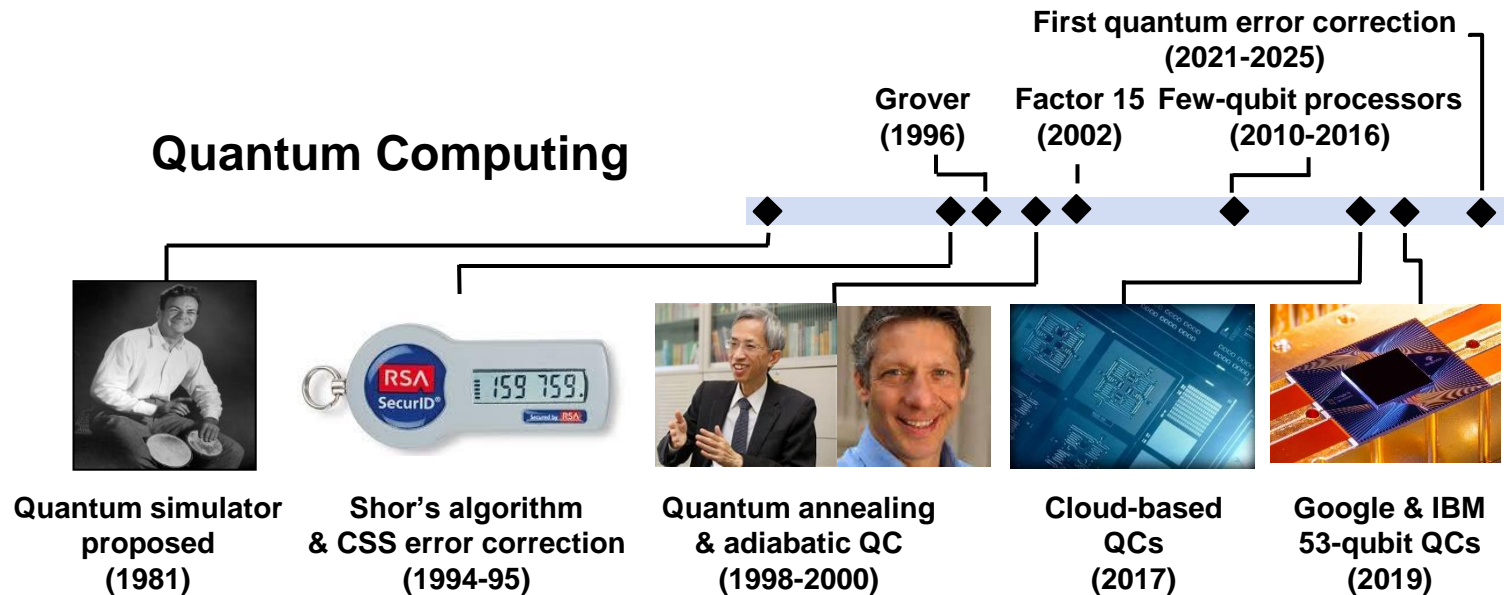
Quantum 1.0 – foundation for our present economic and information security

Quantum 2.0 – holds the promise to similarly impact the 21st century

We must be in the game to play

This is a game we must win

Quantum Computing



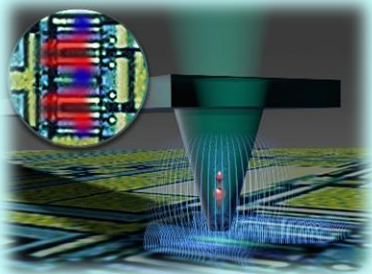
Promise of Quantum Technologies

Sensing

at the extremes
for physical & life sciences



Quantum trojan
detection in
microelectronics



Advanced
LIGO
gravitational
astronomy



(Remote sensing, biology, APNav, ...)



Communication

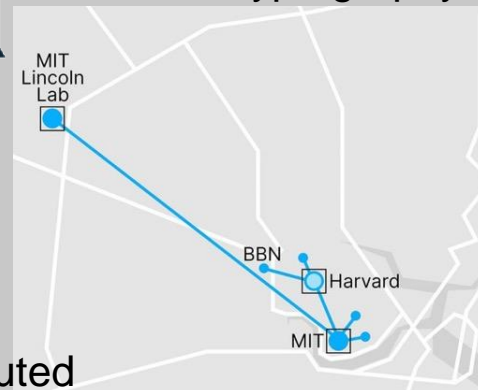
with unbreakable encryption



Secure
cryptography



Distributed
computing

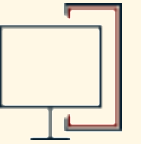


(Secure communication, zero-trust, ...)



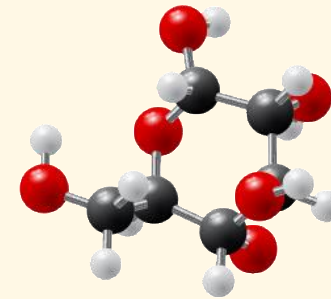
Computation

with exponential speedup



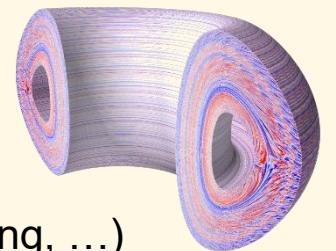
Quantum Simulation

(quantum chemistry,
materials science,
plasma simulation, ...)



Optimization

(financial portfolios,
scheduling, AI training, ...)



(Pharma, finance, operations research, ...)

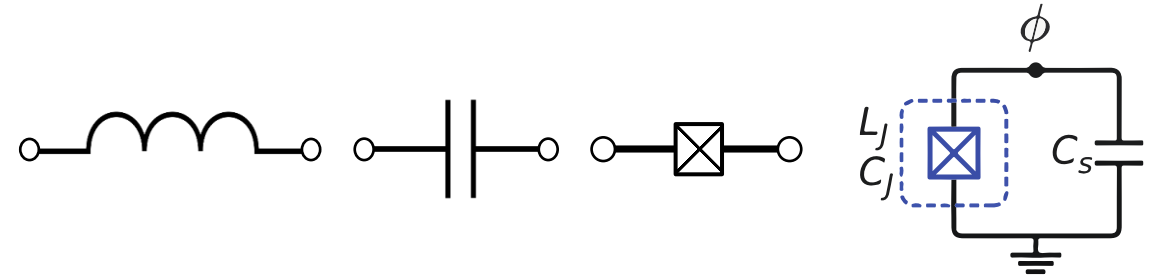


Qubits: Logic Elements of a QC

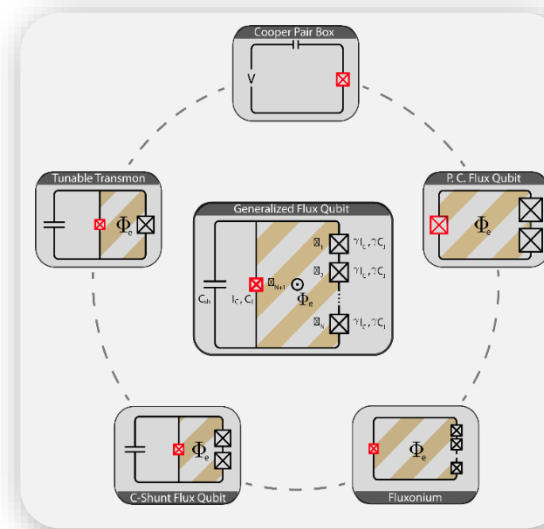
Protons, Neutrons, and Electrons



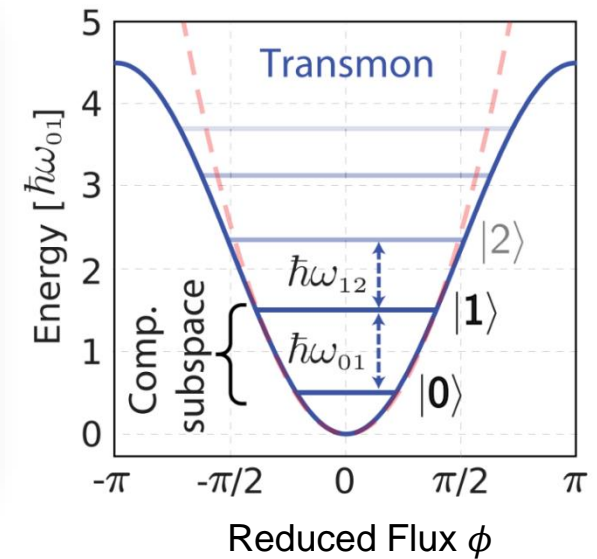
Inductors, Capacitors, and Josephson Junctions



1 H Hydrogen 1.008	2 He Helium 4.003																	
3 Li Lithium 6.94	4 Be Beryllium 9.012	5 B Boron 10.81	6 C Carbon 12.011	7 N Nitrogen 14.007	8 O Oxygen 15.999	9 F Fluorine 18.998	10 Ne Neon 20.180											
11 Na Sodium 22.990	12 Mg Magnesium 24.305	13 Al Aluminum 26.982	14 Si Silicon 28.085	15 P Phosphorus 30.974	16 S Sulfur 32.06	17 Cl Chlorine 35.45	18 Ar Argon 39.948											
19 K Potassium 39.098	20 Ca Calcium 40.078	21 Sc Scandium 44.956	22 Ti Titanium 47.867	23 V Vanadium 50.942	24 Cr Chromium 51.996	25 Mn Manganese 54.938	26 Fe Iron 55.845	27 Co Cobalt 58.933	28 Ni Nickel 58.693	29 Cu Copper 63.546	30 Zn Zinc 65.38	31 Ga Gallium 69.723	32 Ge Germanium 72.630	33 As Arsenic 74.922	34 Se Selenium 78.97	35 Br Bromine 79.904	36 Kr Krypton 83.798	
37 Rb Rubidium 85.468	38 Sr Strontium 87.62	39 Y Yttrium 88.906	40 Zr Zirconium 91.224	41 Nb Niobium 92.906	42 Mo Molybdenum 95.95	43 Tc Technetium (97)	44 Ru Ruthenium 101.07	45 Rh Rhodium 102.906	46 Pd Palladium 106.42	47 Ag Silver 107.866	48 Cd Cadmium 112.411	49 In Indium 114.818	50 Sn Tin 118.710	51 Sb Antimony 121.760	52 Te Tellurium 127.60	53 I Iodine 126.905	54 Xe Xenon 131.29	
55 Cs Cesium 132.905	56 Ba Barium 137.327	* 57 - 70 Lanthanide series	71 Lu Lutetium 174.967	72 Hf Hafnium 178.49	73 Ta Tantalum 180.948	74 W Tungsten 183.84	75 Re Rhenium 186.207	76 Os Osmium 190.23	77 Ir Iridium 192.225	78 Pt Platinum 195.084	79 Au Gold 196.967	80 Hg Mercury 200.597	81 Tl Thallium 204.38	82 Pb Lead 207.2	83 Bi Bismuth 208.980	84 Po Polonium (209)	85 At Astatine (221)	86 Rn Radon 222
87 Fr Francium (223)	88 Ra Radium (226)	** 89 - 103 Actinide series	103 Lr Lawrencium (262)	104 Rf Rutherfordium (261)	105 Db Dubnium (262)	106 Sg Seaborgium (263)	107 Bh Bohrium (264)	108 Hs Hassium (265)	109 Mt Meitnerium (266)	110 Ds Darmstadtium (267)	111 Rg Roentgenium (268)	112 Cn Copernicium (284)	113 Nh Nihonium (284)	114 Fl Flerovium (285)	115 Mc Moscovium (286)	116 Lv Livermorium (293)	117 Ts Tennessine (294)	118 Og Oganesson (294)
89 La Lanthanum 138.905	90 Ce Cerium 140.118	91 Pr Praseodymium 140.908	92 Nd Neodymium 144.242	93 Pm Promethium (145)	94 Sm Samarium 150.36	95 Eu Europium 151.964	96 Gd Gadolinium 157.25	97 Tb Terbium 158.925	98 Dy Dysprosium 162.502	99 Ho Holmium 164.930	100 Er Erbium 167.259	101 Tm Thulium 168.934	102 Yb Ytterbium 173.049					
89 Ac Actinium (227)	90 Th Thorium 232.038	91 Pa Protactinium 231.036	92 U Uranium 238.029	93 Np Neptunium (237)	94 Pu Plutonium (244)	95 Am Americium (243)	96 Cm Curium (247)	97 Bk Berkelium (247)	98 Cf Californium (251)	99 Es Einsteinium (252)	100 Fm Fermium (257)	101 Md Mendelevium (258)	102 No Nobelium (259)					

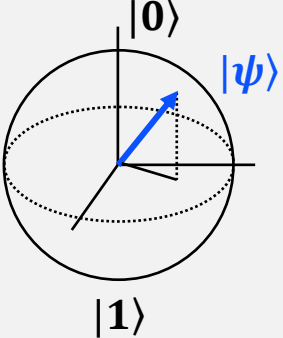


F. Yan et. al., arXiv:2006.04130 (2020)



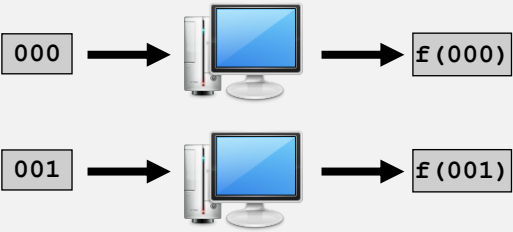
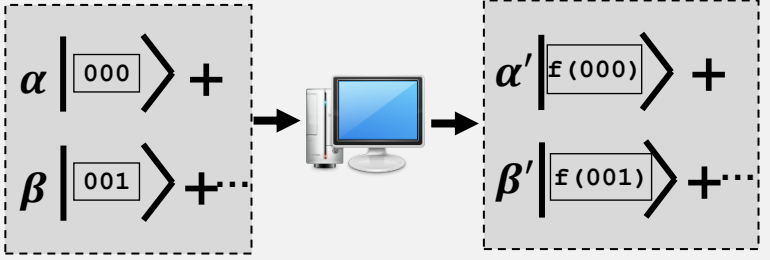
Quantum technologies are based on natural atoms or circuits that mimic their properties

How is a Quantum Computer Different?

	Classical Computer	Quantum Computer
Fundamental logic element	“Bit” : classical bit (transistor, spin in magnetic memory, ...)	“Qubit” : quantum bit (any coherent two-level system)
State	0 “Or” 1	 <p>Superposition: $\alpha 0\rangle + \beta 1\rangle$</p> <p> 0> “And” 1></p>
Measurement	<ul style="list-style-type: none"> • <i>Discrete</i> states • Deterministic measurement: Ex: Set as 1, measure as 1 	<ul style="list-style-type: none"> • <i>Quantum superposition</i> states • Probabilistic measurement: E.g., If $\alpha = \beta$, 50% 0>, 50% 1>

Quantum computers rely on encoding information in a fundamentally different way than classical computers

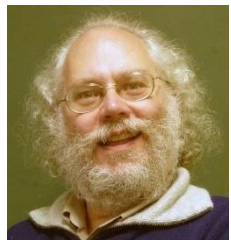
How is a Quantum Computer Different?

Fundamental logic element	Classical Computer “Bit” : classical bit (transistor, spin in magnetic memory, ...)	Quantum Computer “Qubit” : quantum bit (any coherent two-level system)
Computing	<ul style="list-style-type: none"> N bits: One of 2^N states 000, 001, ..., 111 (N = 3) Change a bit: new calculation (classical parallelism) 	<ul style="list-style-type: none"> N qubits: 2^N components in one state $\alpha 000\rangle + \beta 001\rangle + \dots + \gamma 111\rangle$ (N = 3) Quantum parallelism & interference 

How do we take advantage of this hardware?
(see optional videos for visual intuition)

Quantum Algorithm Primitives and Speed-Up

Algorithm	Classical Time	Quantum Time	Speedup	Limitation
Simulation¹ (materials, chemistry, pharma)	2^N (for N atoms)	N^c	Exp. in space, polynomial in time	Mapping problem to qubits
Factoring² (crypto, number theoretic)	2^N (for N digits)	N^3	Exponential	Classical runtime limit unproven
Linear systems³ ($Ax=b$)	2^N (for N digits)	$\sim N$	Exponential	Strict conditions, e.g. sparse matrix
Optimization⁴ (finance, tasking, ...)	2^N	?	?	Empirical
Search⁵ (unsorted / unstructured data)	N	\sqrt{N}	Polynomial (\sqrt{N})	Data loading



Peter Shor²
Math



Ike Chuang²
EECS, Physics



Seth Lloyd^{1,3}
Mech. Eng.



Aram Harrow³
Physics



Eddie Farhi⁴
Physics, Google



Michael Sipser⁴
Math



Anand Natarajan
EECS

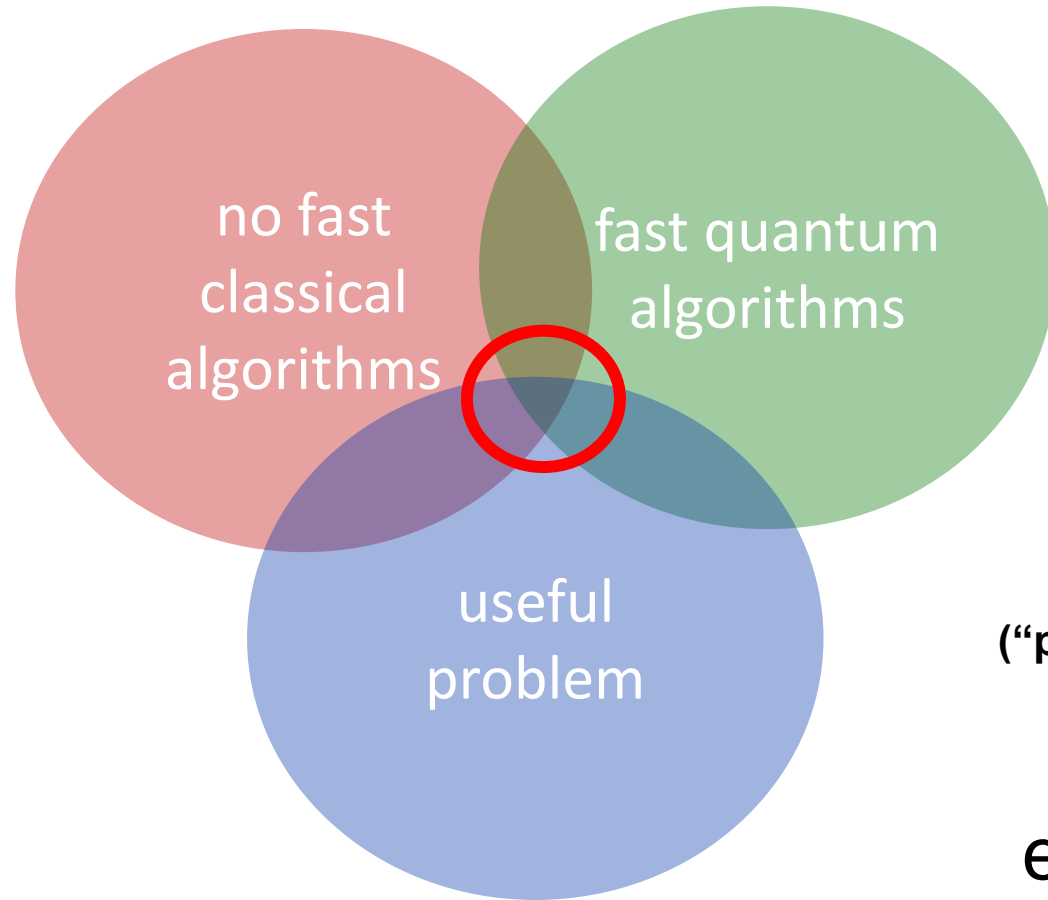


Michael Carbin
EECS



Troy Van Voorhis
Chemistry

Types of Quantum Advantage



Two Types of Quantum Advantage

- System size,
- Time to solution,
- Other resources

$$\propto A(N) \exp(\beta N)$$

Improve the prefactor
("polynomial improvement")

e.g., $N \rightarrow N^{1/2}$

Reduce exp. to polynomial
("exponential improvement")

e.g., $2^N \rightarrow N^3$

Exponential Growth

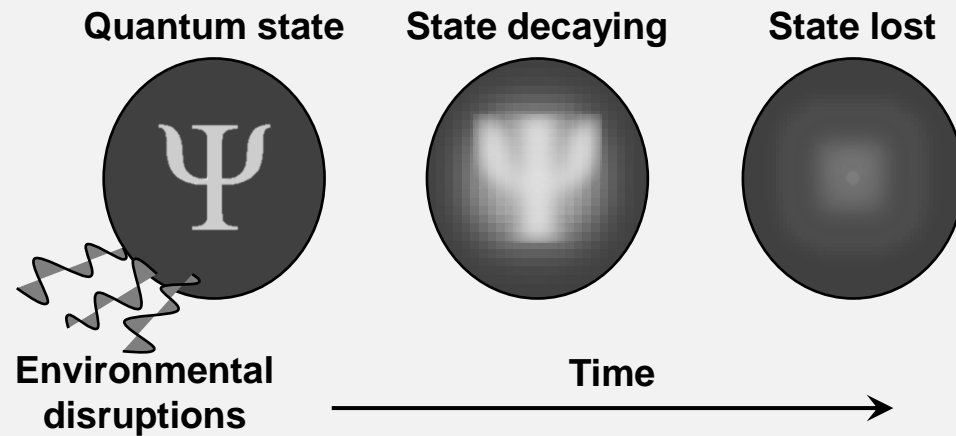
Simulating quantum computers (QCs) on classical computers

How much classical memory would be required?

Qubits	Size of simulator
30	laptop
50	supercomputer
80	all computers on Earth
160	all Si atoms in Earth
300	> all atoms than in known universe

Coherence & Gate Time

Coherence time t_{coh} : The qubit's lifetime



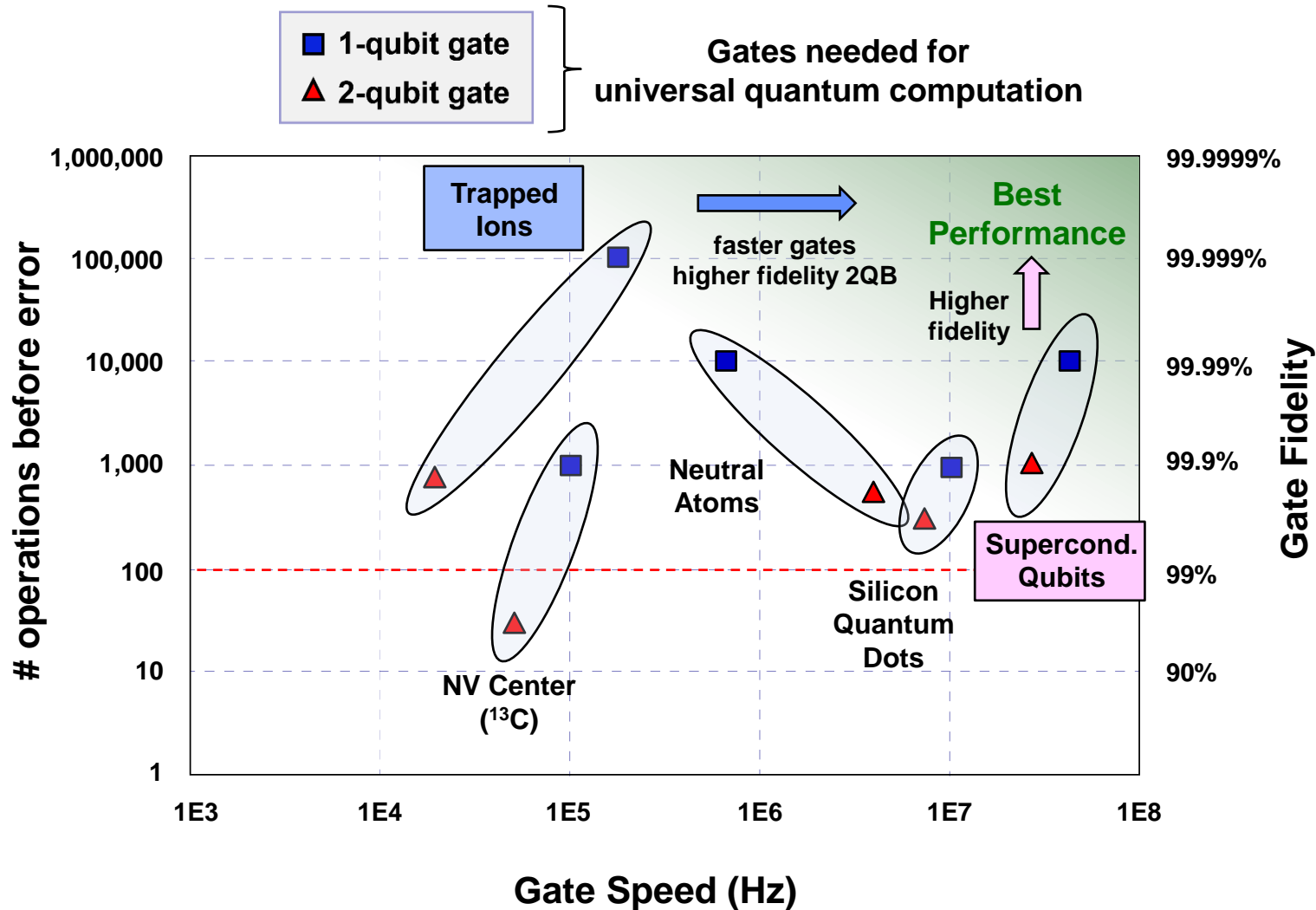
Gate time t_{gate} : Time required for a single gate operation

Figure of Merit * : # of gates per coherence time = $t_{\text{coh}}/t_{\text{gate}}$

(* Rigorous metric: gate & readout fidelity)

Long coherence times are insufficient, it's the number of gates before an error

Qubit Modalities



MIT Campus



Ike Chuang
Physics, EECS

MIT Lincoln Lab



Rajeev Ram
EECS



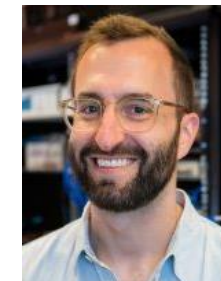
John Chiaverini
LL, RLE



Will Oliver
EECS, Physics



Kevin O'Brien
EECS



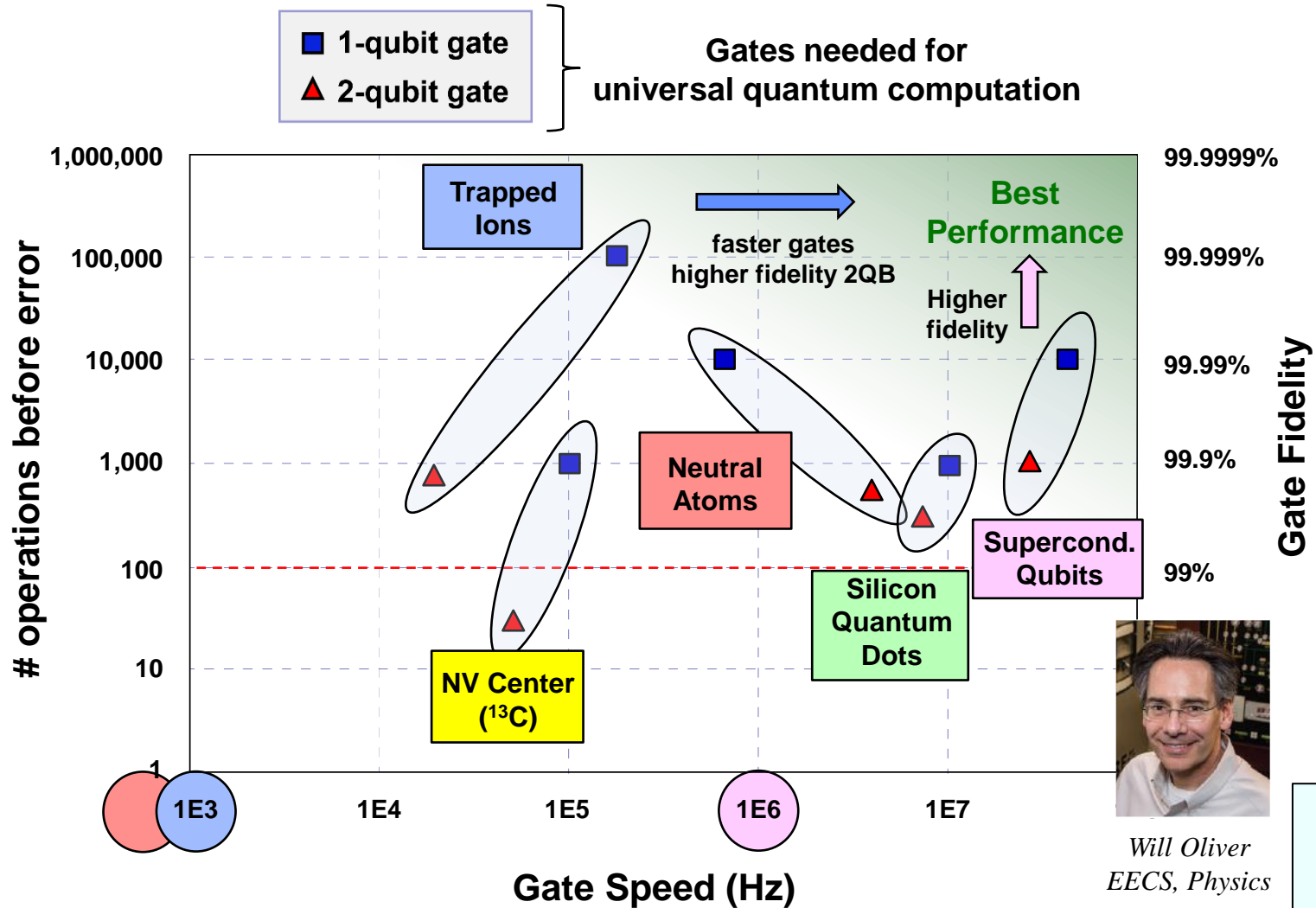
Jeff Grover
RLE



Kyle Serniak
LL

and large teams at MIT & LL

Qubit Modalities



Vladin Vuletic
MIT Physics



Wolfgang Ketterle
MIT Physics



Martin Zwierlein
MIT Physics



Dirk Englund
EECS



Paola Cappellaro
NSE



Danielle Braje
QuIN



Will Oliver
EECS, Physics

Gate Fidelity

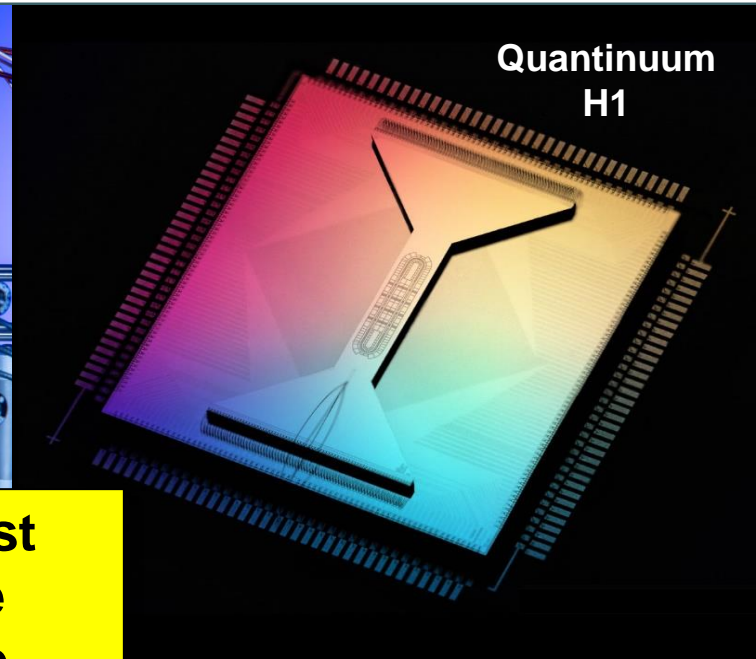
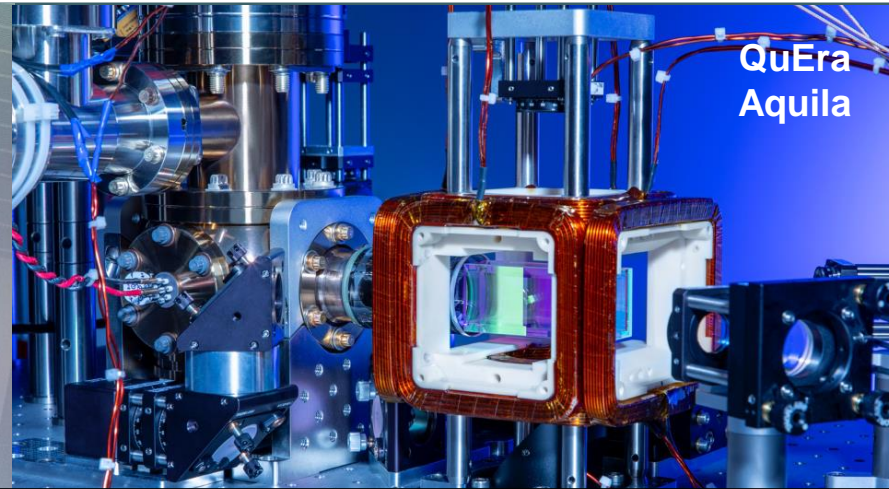
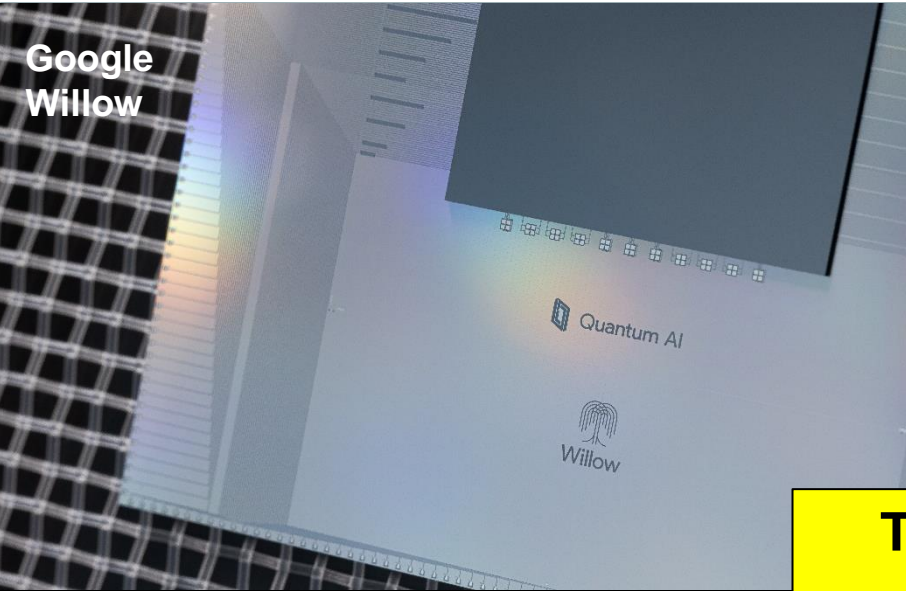
99.9999%
 99.999%
 99.99%
 99.9%
 99%

Many outstanding research efforts in quantum at MIT campus and Lincoln Lab. Generalizes to many other areas not shown.

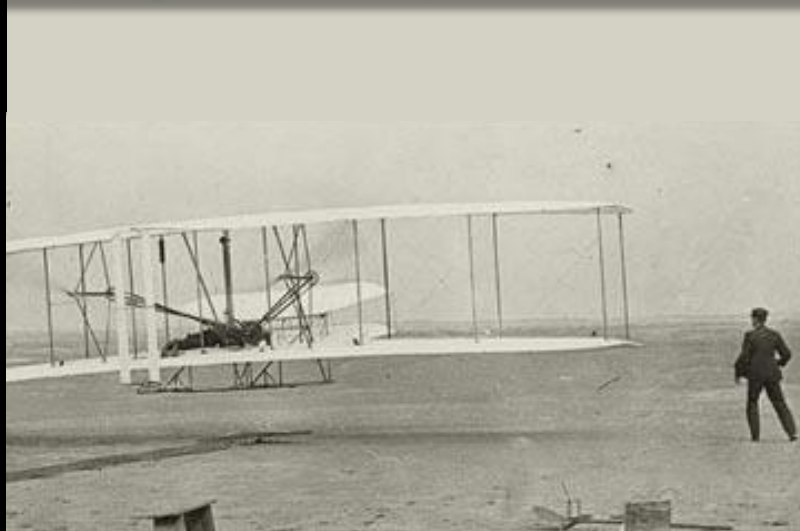
Qubit Modalities



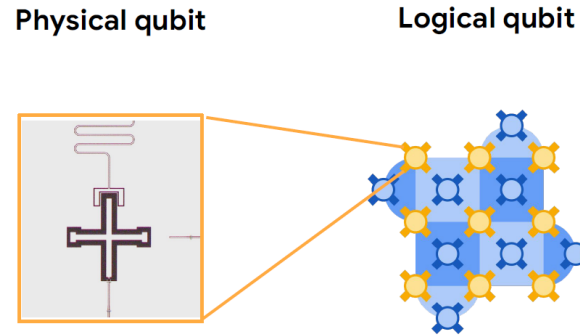
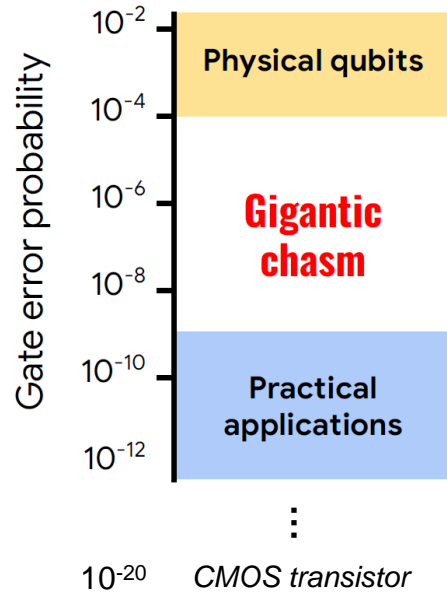
Commercial Quantum Processors Today



To realize the promise of QC, we must engineer quantum systems that are robust, reproducible, and extensible.

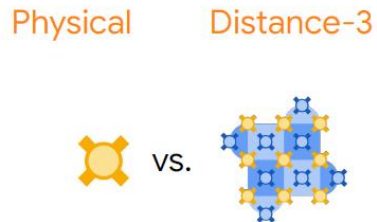


Grand Challenge: Active Quantum Error Correction

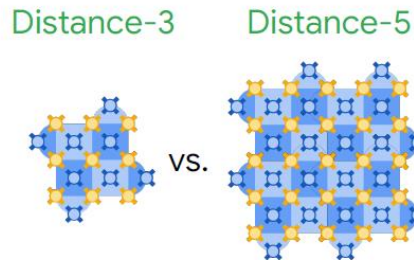


The promise of QEC:
Trade many **physical qubits** for 1 **excellent logical qubit**...
(As long as physical qubits are “good enough”)

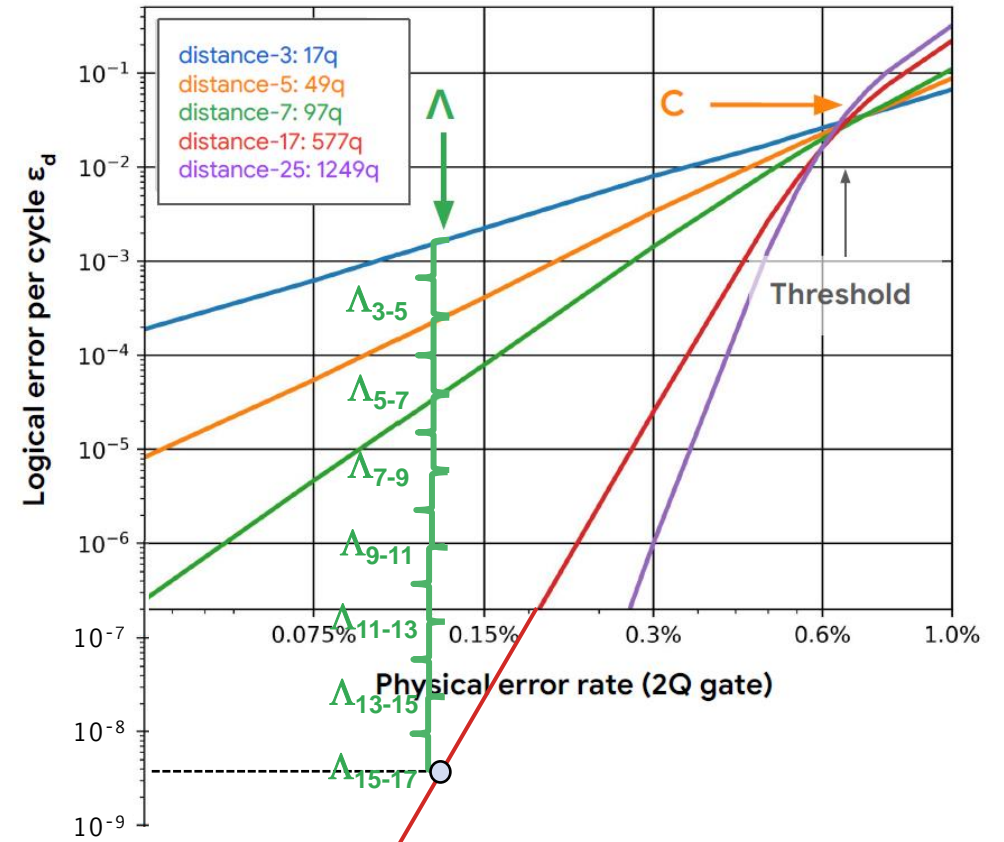
$$\text{Logical error per cycle } \epsilon_d = C \cdot \left(\frac{1}{\Lambda}\right)^{(\text{distance}+1)/2}$$



Sensitive to overhead C

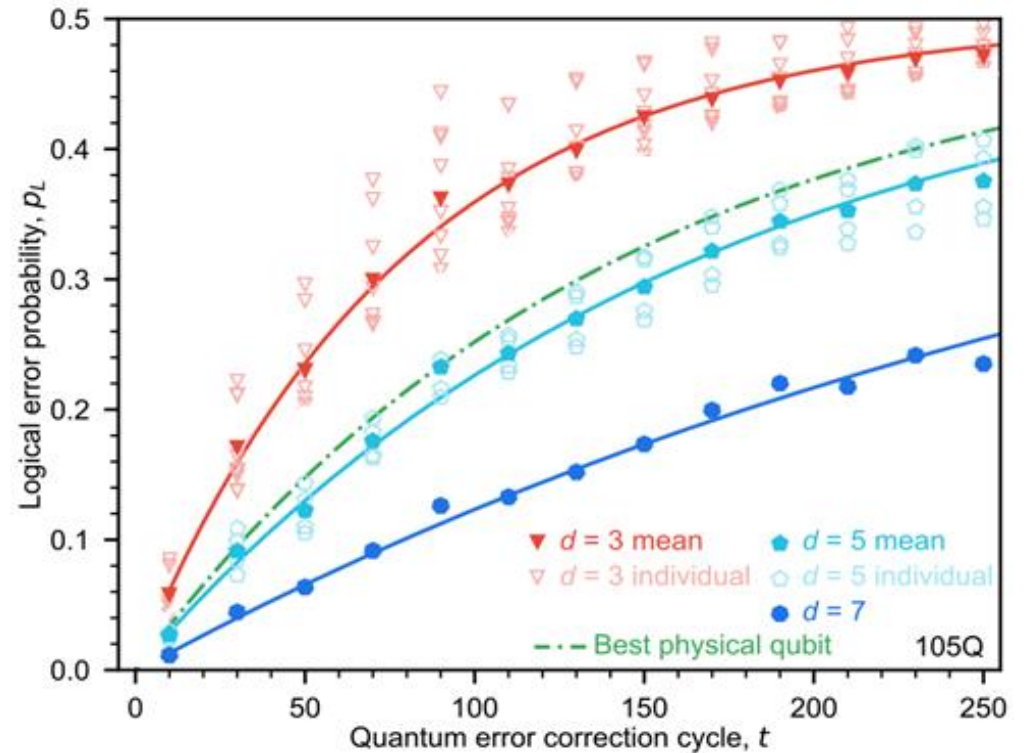
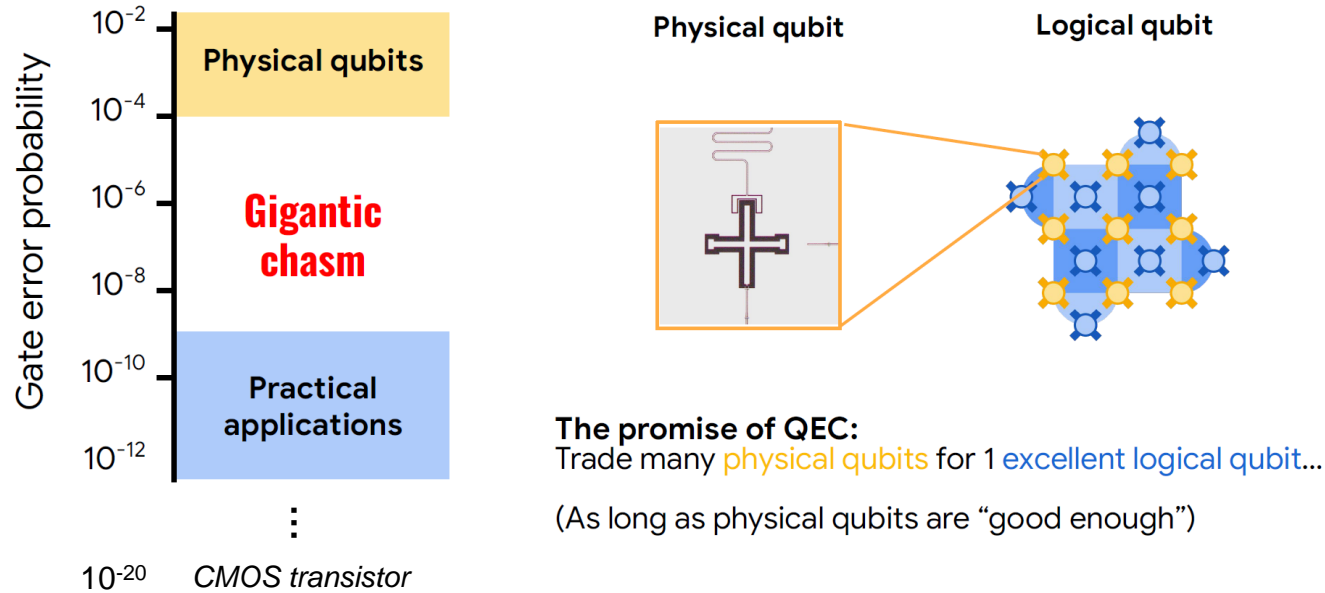


Sensitive to scaling Λ



No QEC (1 qubit) Physical error rate: 1×10^{-3}
@ D-3 (17 qubits) Logical error rate: 2×10^{-3}
@ D-17 (577 qubits) Logical error rate: 4×10^{-9}
600X qubits reduces error a factor $\approx 500,000(!)$

Grand Challenge: Active Quantum Error Correction



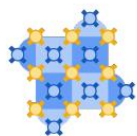
$$\text{Logical error per cycle } \epsilon_d = C \cdot \left(\frac{1}{\Lambda}\right)^{(\text{distance}+1)/2}$$

Physical



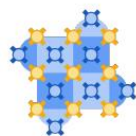
vs.

Distance-3



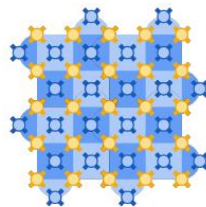
Sensitive to overhead C

Distance-3



vs.

Distance-5



Sensitive to scaling Λ

Google Quantum AI has demonstrated improved performance $d=3 \rightarrow d=7$.

IBM work on qLDPC codes and 3D integration; also ions, neutral atoms, ...

Google Quantum AI (2024); Google Quantum AI (2023); Krinner (2021); Bluvstein (2024); Ryan-Anderson (2021); Zhao (2021); Postler (2021); Sundaresan (2022)

Thanks to A. Bourassa, Google Quantum-AI

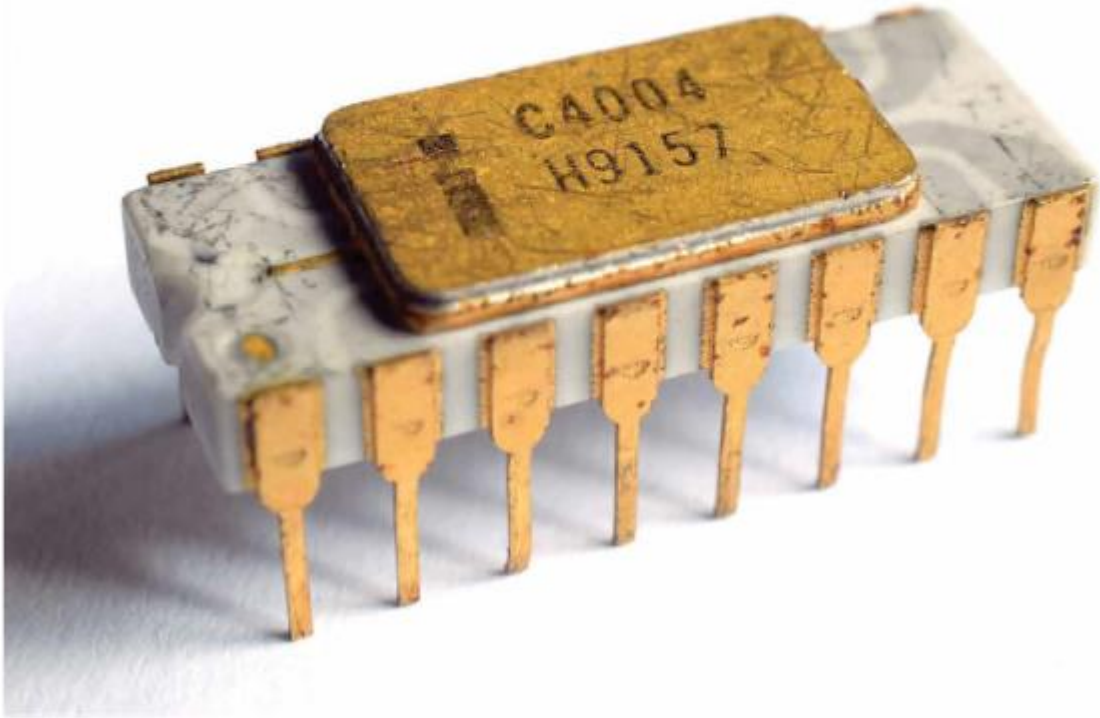
Jenson Huang (CEO, NVIDIA) 8 January 2025

2:17 – “We are merging quantum and classical to develop algorithms we can use someday. And, when is that someday? If you said 15 years for very useful quantum computers, that would be the early side, if you said 30 years that’s probably on the late side. But if you said 20 years, I think a whole bunch of us would believe it.”

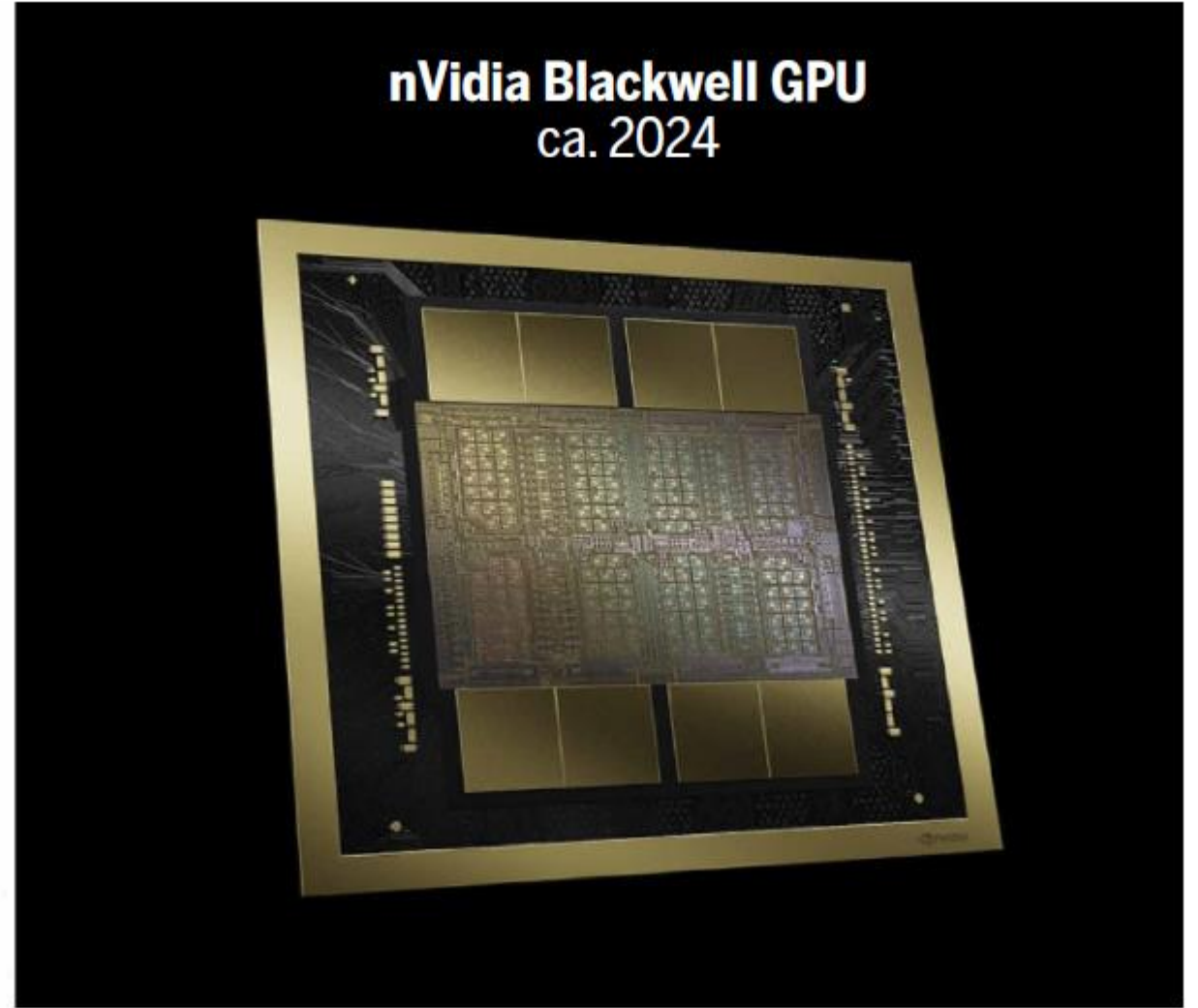
TRL Level and Maturity

both were TRL 9 in their era...

Intel 4004 processor
ca. 1971



nVidia Blackwell GPU
ca. 2024



Today's Reality with Quantum Computers (QCs)

- **QCs will not replace classical computers**
 - Quantum computers only solve certain tasks efficiently
 - Operating a quantum computer needs a classical computer
 - Less energy per problem solved (but not necessarily less per day)
- **We need more quantum algorithms (!)**
 - Very few commercial applications are known today
- **QCs will not break encryption soon**
 - Do not wait until a quantum computer can break RSA
 - Switch to post-quantum encryption now
- **Likely will need quantum error correction**

