AWS re:Invent

NOV. 29 – DEC. 3, 2021 | LAS VEGAS, NV

QTC303

The path to a fault-tolerant quantum computer

Fernando Brandao
Head of Quantum Algorithms
AWS Center for Quantum Computing

Nadia Carlsten
Head of Product
AWS Center for Quantum Computing

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Agenda

The AWS Center for Quantum Computing

Challenges of building quantum computers

Implementing quantum error correction

Scaling to useful applications

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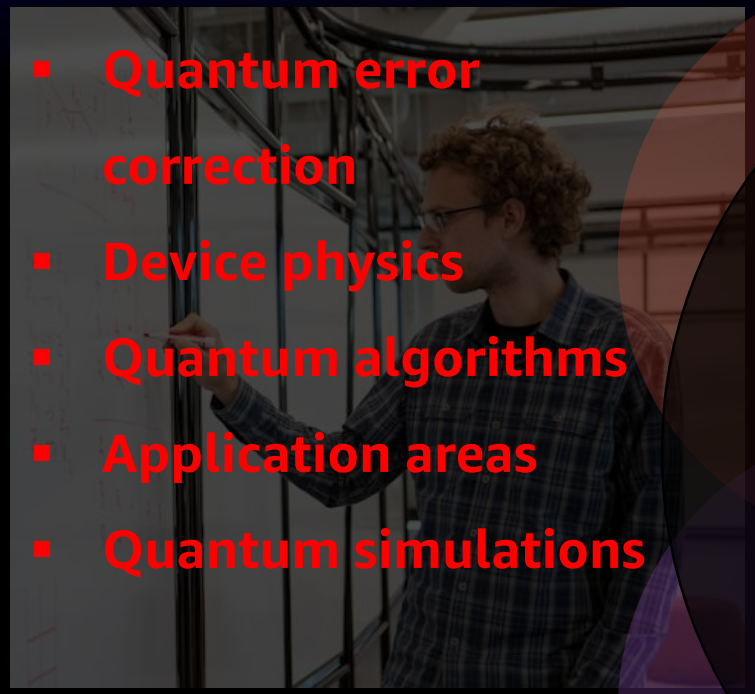
The AWS Center for Quantum Computing

- Dedicated facility in Pasadena, CA
- Houses quantum R&D teams
- Located on Caltech campus
- “Think Big”: Accelerate development of quantum technologies



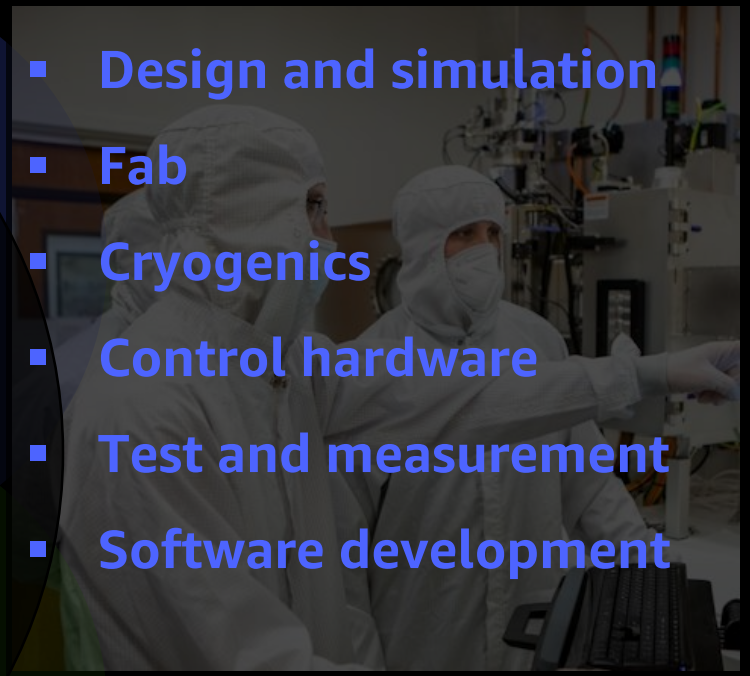
R&D focus areas

Theory



- Quantum error correction
- Device physics
- Quantum algorithms
- Application areas
- Quantum simulations

Hardware



- Design and simulation
- Fab
- Cryogenics
- Control hardware
- Test and measurement
- Software development

Scalable, high-fidelity quantum computers

Amazon Scholars

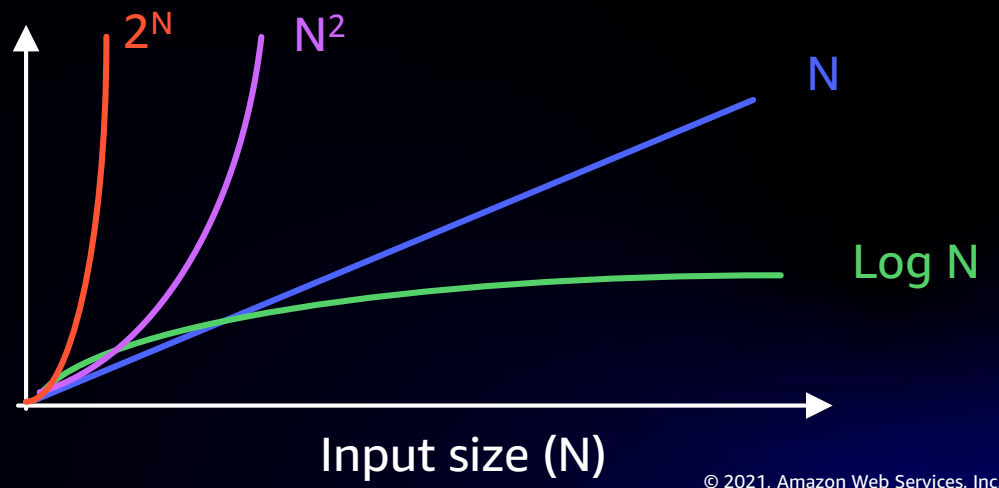
Research collaborations

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Quantum computing

> **Using the physical laws of the microscopic world (quantum mechanics) to perform computation in new and improved ways**

- A new paradigm in computing:
  not **10x** performance improvement but **10^X**
- Speed up solutions to hard problems that can't be solved efficiently with classical computers



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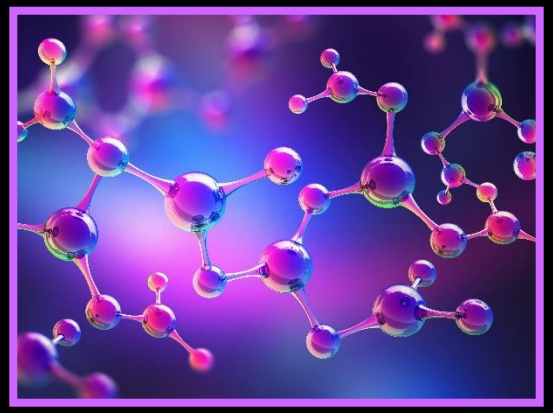
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Potential of quantum computing

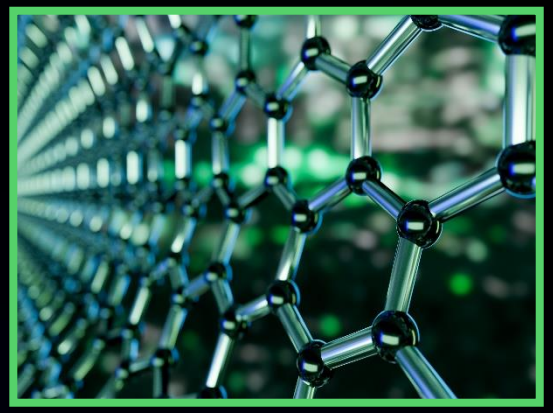
- Search for algorithms that have “quantum advantage”
- Promising for solving certain problems that impact many industries and customers



Cryptography



Simulating physics



Material science



Optimization

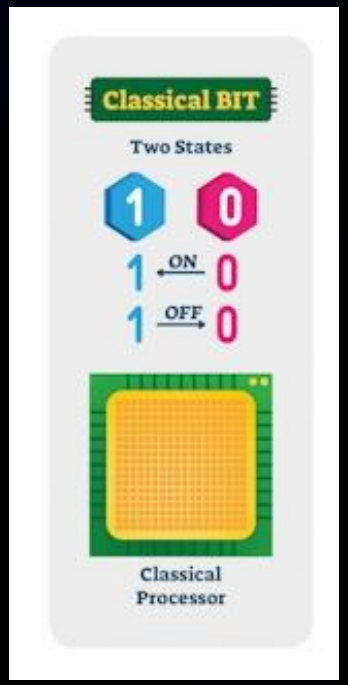
- But requires many qubits that can perform gate operations reliably

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How is a quantum computer different?

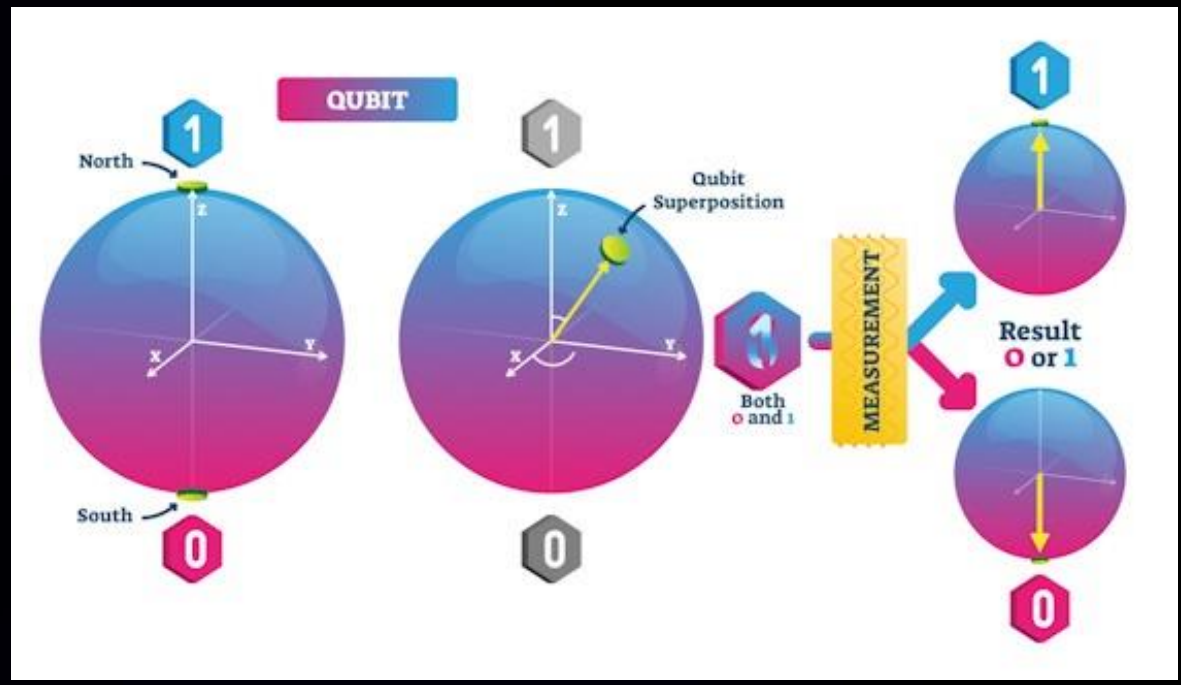
1 – STORING INFORMATION



2 logic states

Classical parallelism

Requires more time or more resources



Superposition

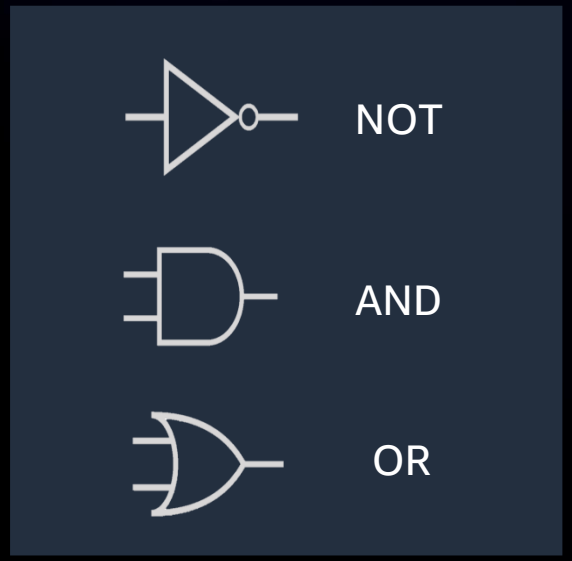
Quantum parallelism

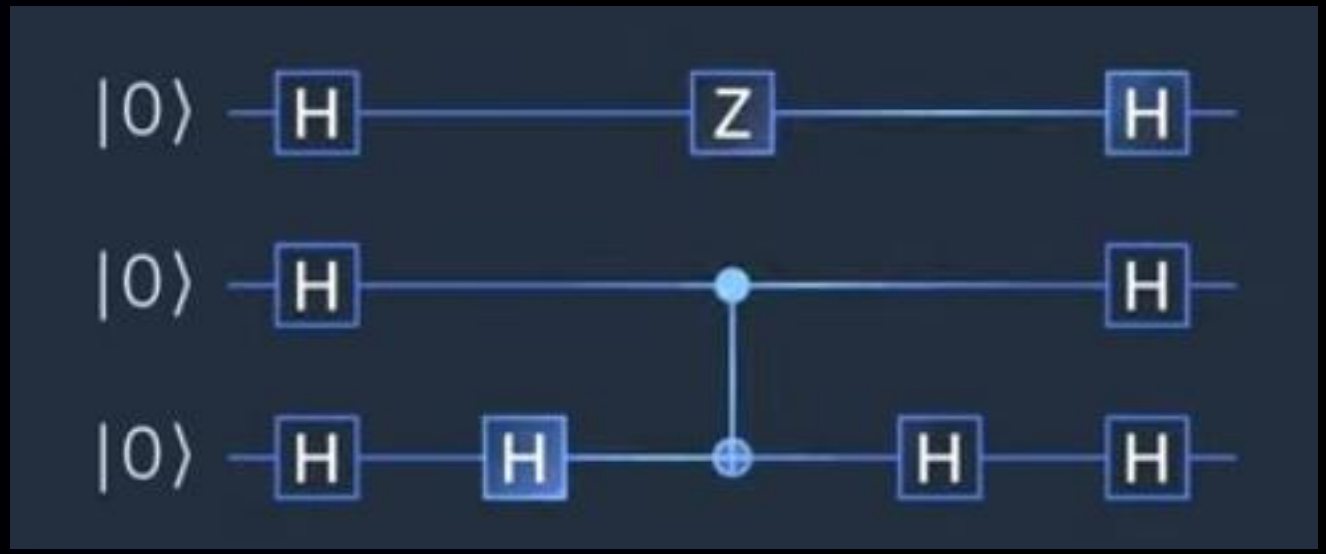
Single superposition state can carry aspects of all 2^N components

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How is a quantum computer different?

2- PERFORMING GATE OPERATIONS





Classical gates
implement Boolean logic

Single qubit and two-qubit gates
implement quantum algorithms

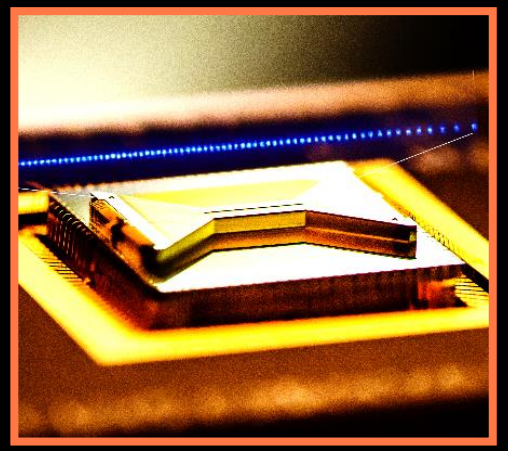
A universal, fault-tolerant quantum computer can implement any algorithm

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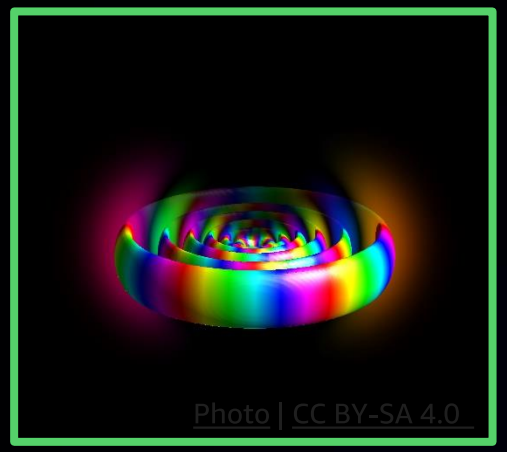
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How to build a quantum computer

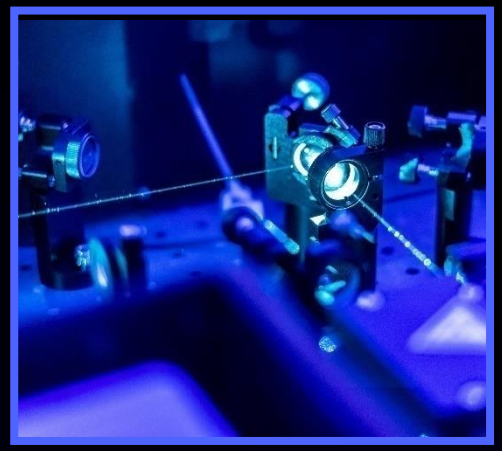
- Many ways to physically realize a qubit
- Different types of NISQ computers starting to become available
- Different approaches have different tradeoffs



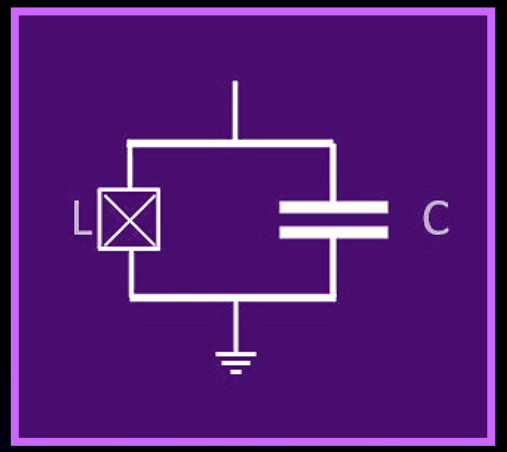
Trapped ion



Rydberg atoms



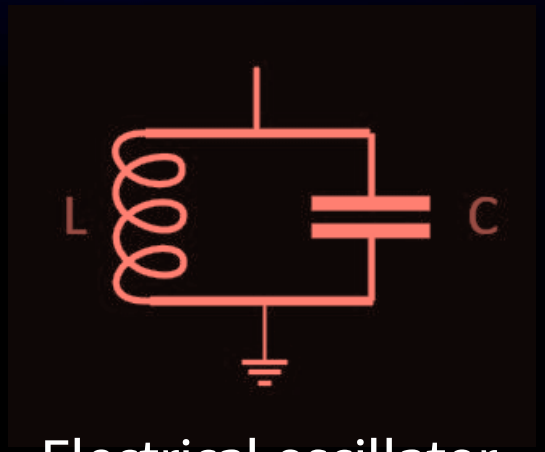
Photonics



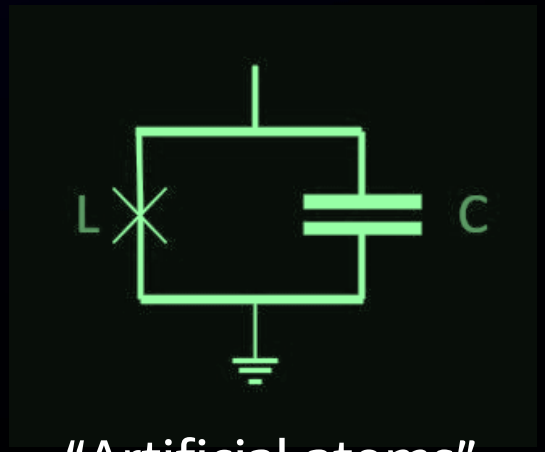
Superconducting

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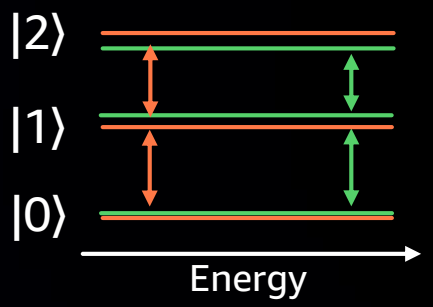
Superconducting qubits



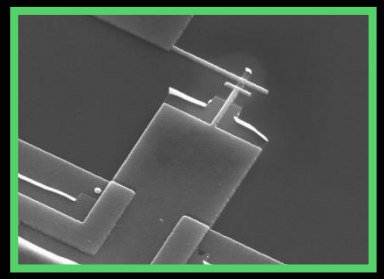
Electrical oscillator



“Artificial atoms”



Anharmonicity



Josephson Junction

Several advantages

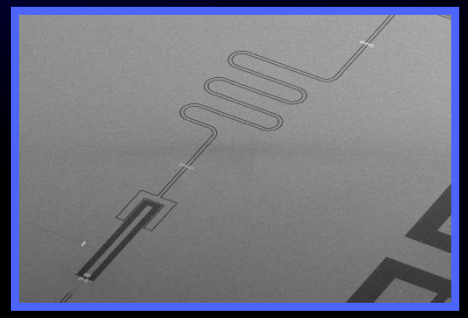
- Manufactured using microfabrication techniques
- Very fast gates
- Scalable
- Building blocks for more complex architectures



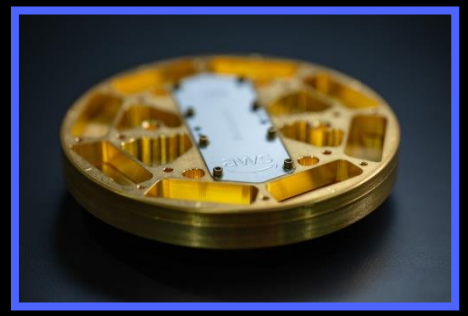
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Superconducting quantum computer



Qubit chip



Package



Shielding





Dilution refrigerator

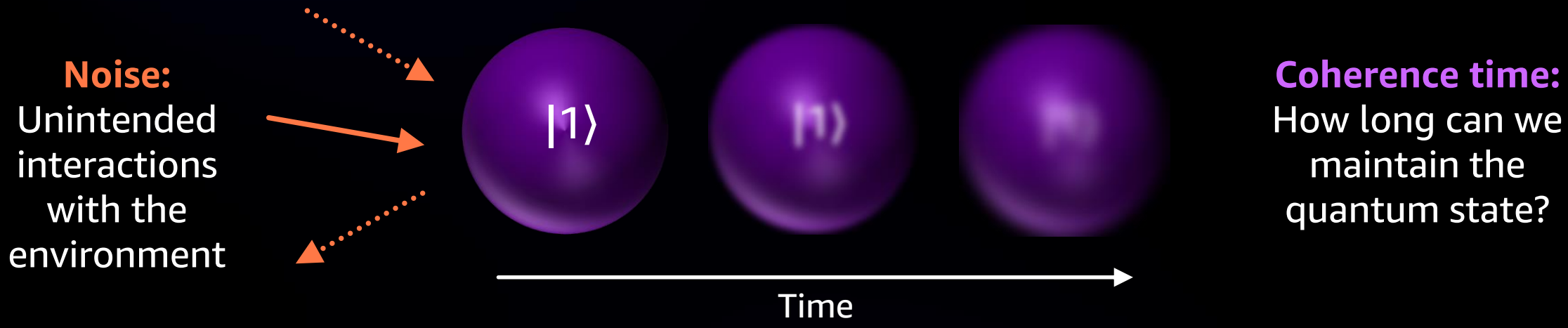


Control electronics

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Making qubits more robust

- Protecting quantum information from noise



- Controlling noise is crucial since algorithms that have quantum advantage require low error rates

> **Fault tolerance: errors are detected and corrected to suppress error growth with each gate operation and produce an accurate answer at the end of the computation**

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Lowering error rates

1. **Noise filtering:** reduce the amplitude of the noise
   - Cooling and shielding systems
   - Design and packaging of processor
2. **Hardware-level error protection:** reduce errors at the physical level
   - Materials and processing improvements
3. **Quantum error correction:** detect and correct errors
   - Redundant encoding of information

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Error correction

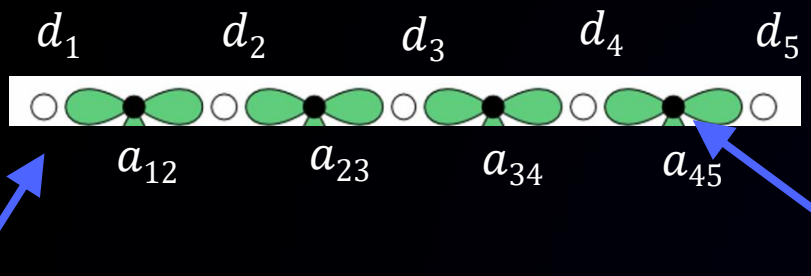
Protects computation from errors using redundancy

Repetition code $0 \rightarrow 00000$ = “0”

$1 \rightarrow 11111$ = “1”

One logical bit (“0” or “1”) constructed from 5 physical bits

Can correct up to 2 bit flips $(p_{\text{logical error}} \sim (p_{\text{physical error}})^3)$



$$a_{12} = d_1 + d_2 \bmod 2$$

data bit

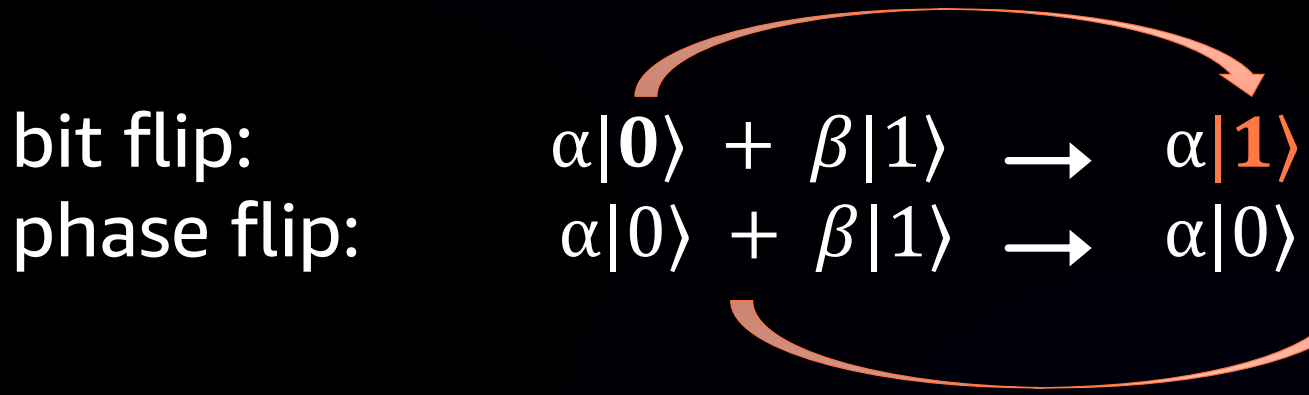
ancilla bit

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Quantum error correction

Is it possible even in principle? Qubits are more complicated

Two types of errors on a qubit ($\alpha|0\rangle + \beta|1\rangle$)



Cannot measure data qubits directly, otherwise collapse the state

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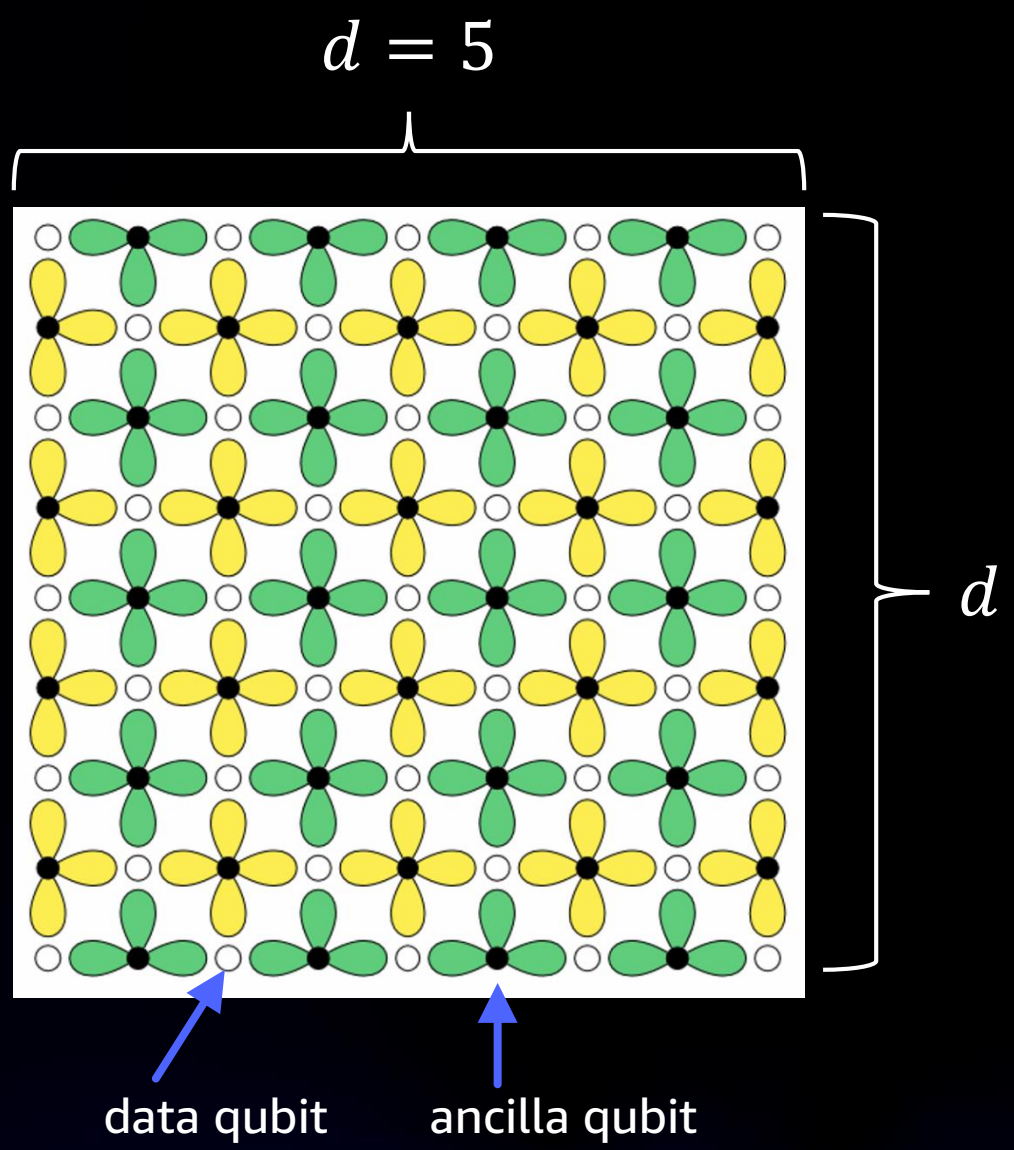
Quantum error correction

Surface code

$$p_{\text{Logical}}(p_{\text{phys}}, d) = 0.1(100p_{\text{phys}})^{(d+1)/2}$$

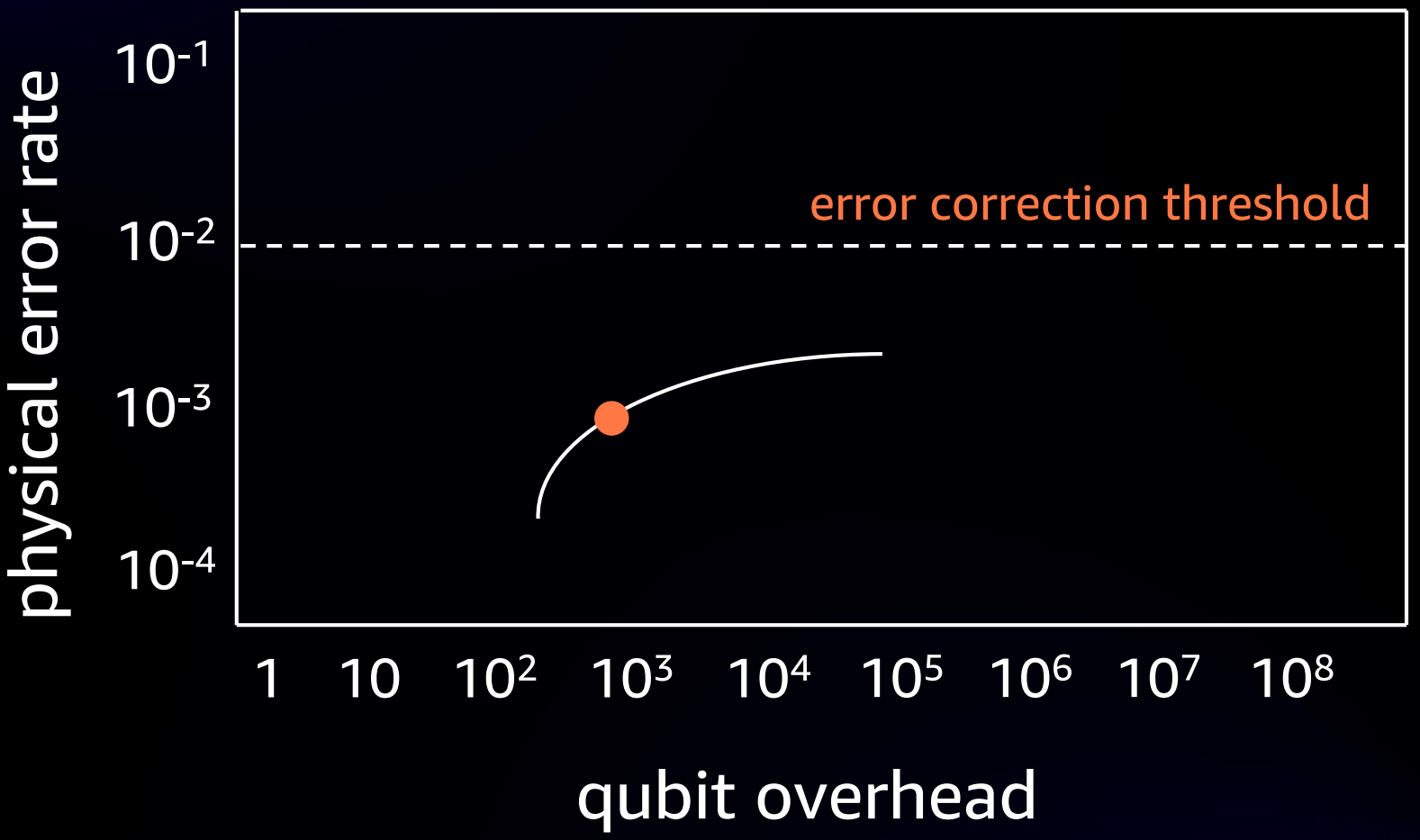
#qubits per logical qubit $2d^2 - d$

	d = 5	d = 9	d = 15
$P_{physical}$ = 0.5%	1.2%	0.3%	4×10^{-4}
$P_{physical}$ = 0.1%	10^{-4}	10^{-6}	10^{-9}
#qubits	45	153	435



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Quantum error correction overhead



For target logical error rate: 10^{-10}

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Quantum error correction overhead

Factor 2,048-digit number

Target: 6,200 logical qubits @ 10^{-12} error rate

Needs: 20M qubits @ 10^{-3} physical error rate

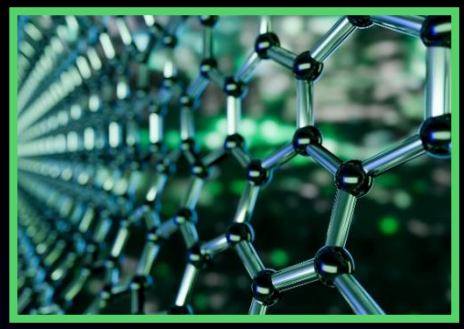


Cryptography

Simulate 8x8 Hubbard model

Target: 128 logical qubits @ 10^{-10} error rate

Needs: 320K qubits @ 10^{-3} physical error rate



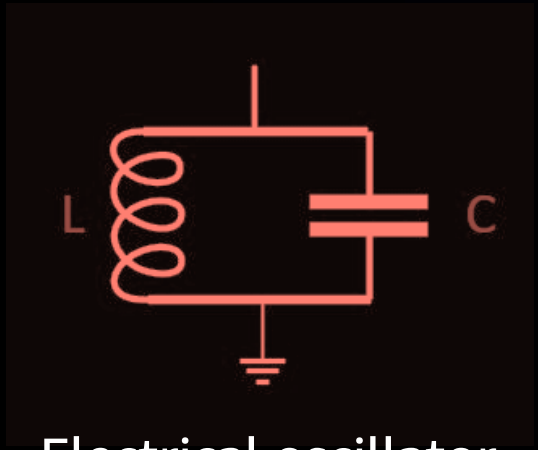
Material science

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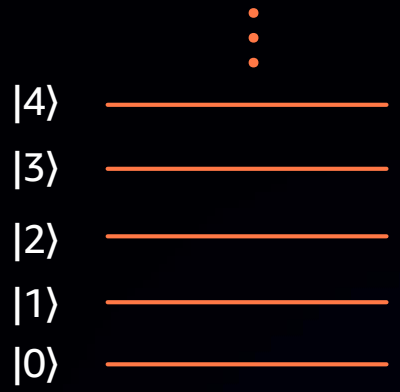
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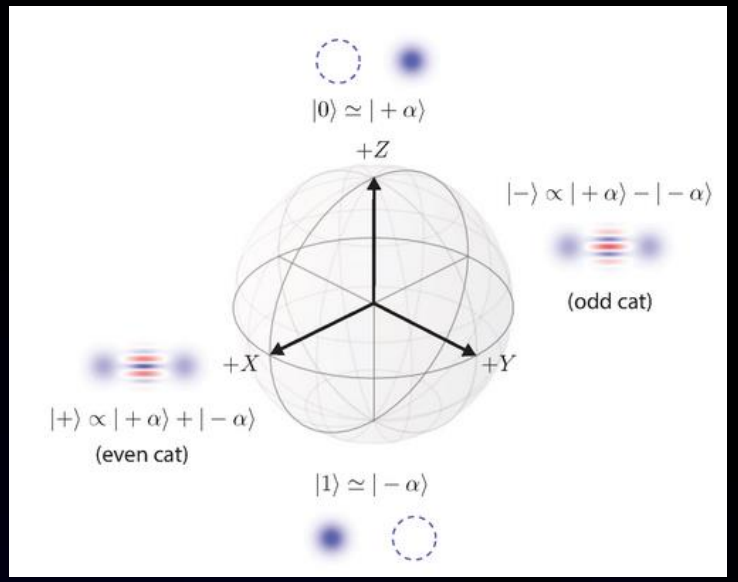
Hardware-efficient error correction

The better the physical qubits, the lower the error-correction overhead; one can even go beyond qubits for more efficient error correction (for example, cat qubits in harmonic oscillator)



Electrical oscillator



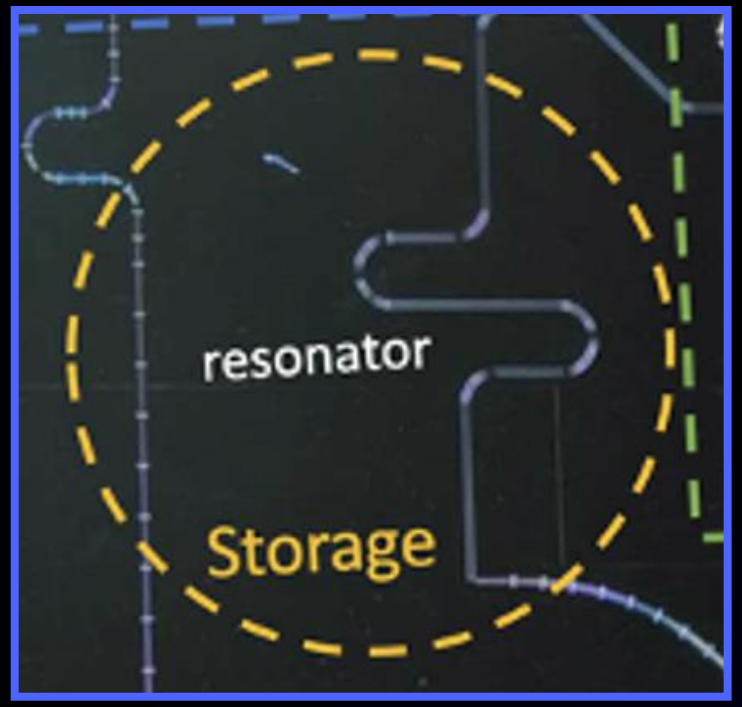


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Different types of oscillators

We want microwave oscillators in order to talk to superconducting qubits

E&M



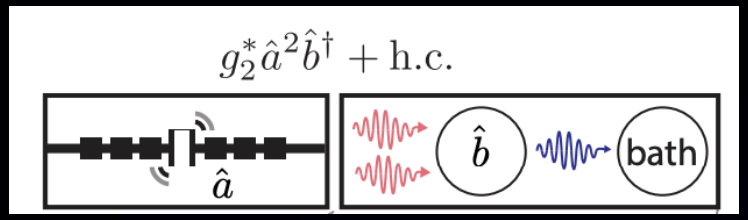
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Biasing the noise

There are 2 type of errors to correct in quantum case, and we can correct each by different strategies; we can make “cat” qubits robust to bit flips at hardware level

Bit-flip errors are very unlikely if stabilized by engineered dissipation of pairs of photons



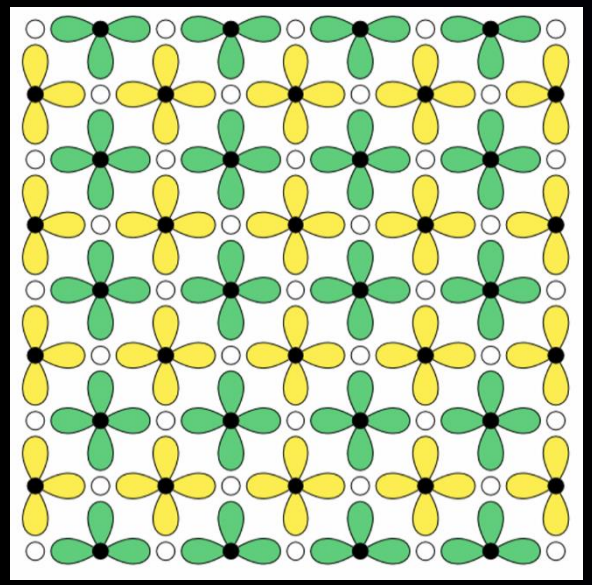
Biased-noise qubit: Bit-flip errors are much less likely than phase-flip errors (by a factor $\exp[-2\alpha^2]$)

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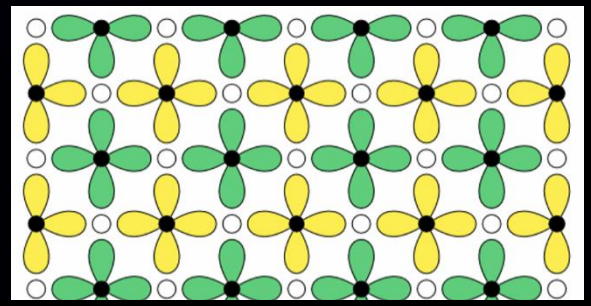
Reducing overhead

Stripped surface codes for biased noise

$p_{\text{bitflip}} = p_{\text{phaseflip}}$



$p_{\text{bitflip}} < p_{\text{phaseflip}}$



$p_{\text{bitflip}} \ll p_{\text{phaseflip}}$



Repetition code

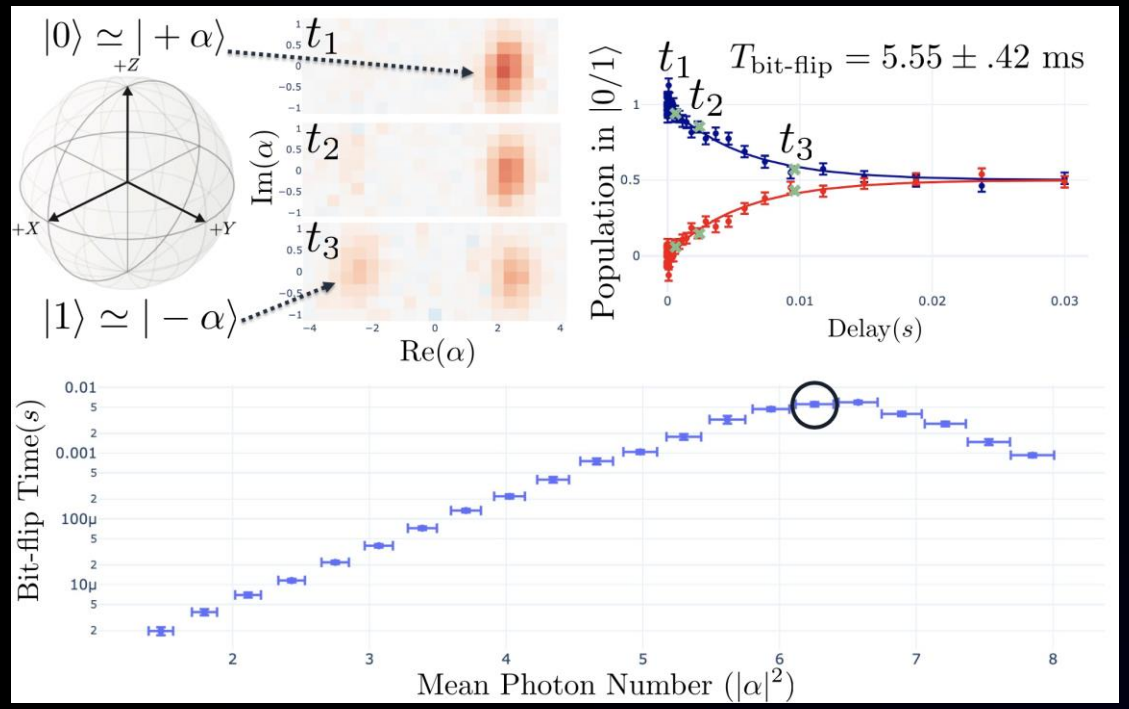
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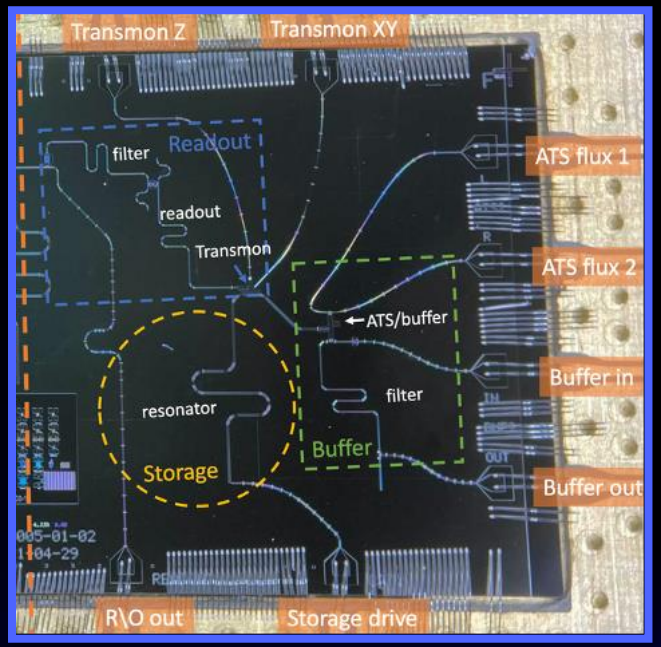
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Cats at work in the lab

We recently stabilized a cat **in the lab** at the AWS Center for Quantum Computing

Got a **x3500** improvement in coherence time against bit-flip errors



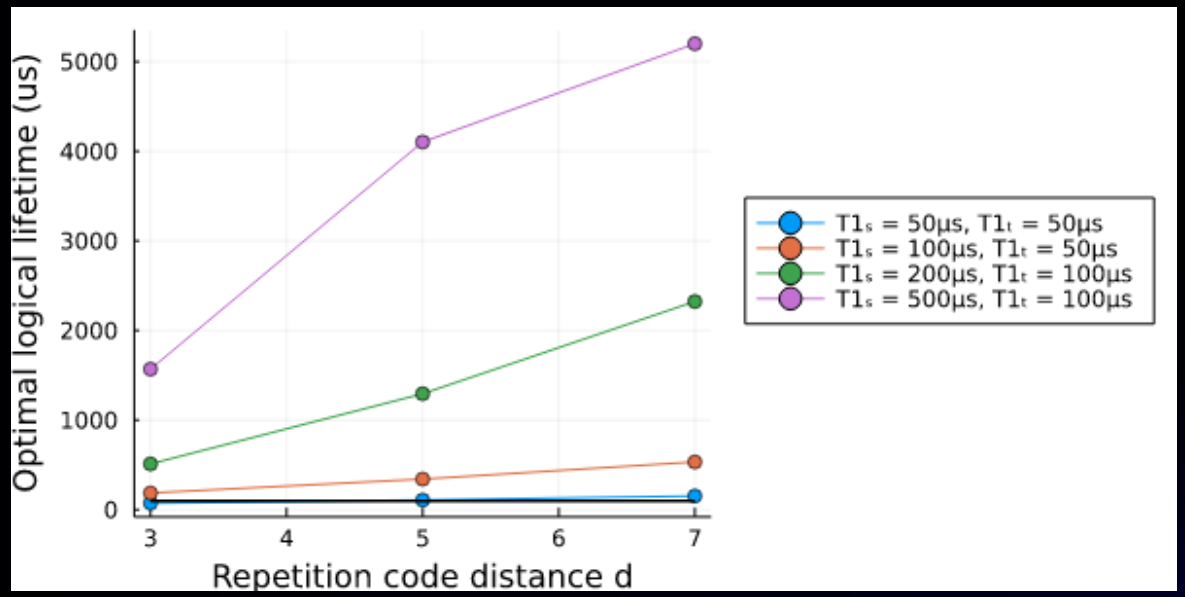


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Logical qubit with cats

Building logical qubit beyond break-even point ($p_{Logical} < p_{physical}$) would be a big milestone on the road to fault-tolerant quantum computing

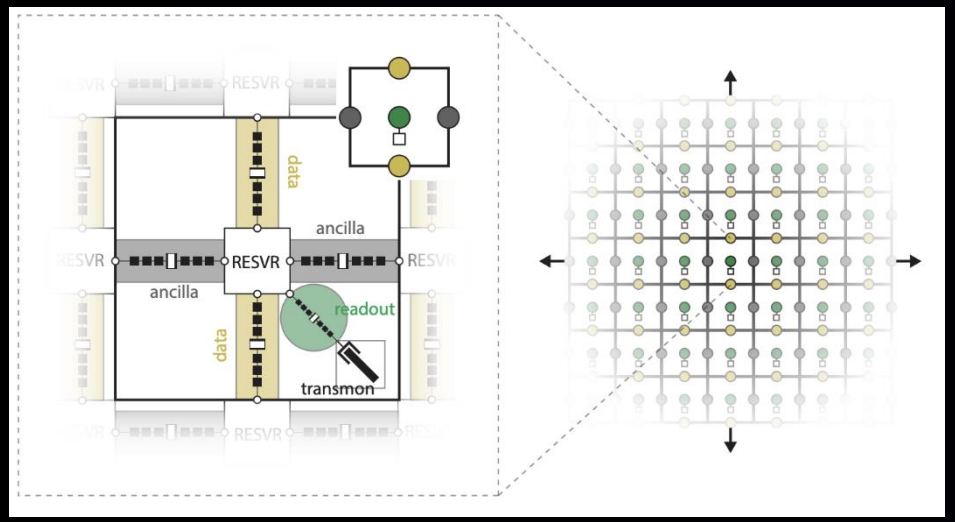
Repetition cat code is an interesting candidate



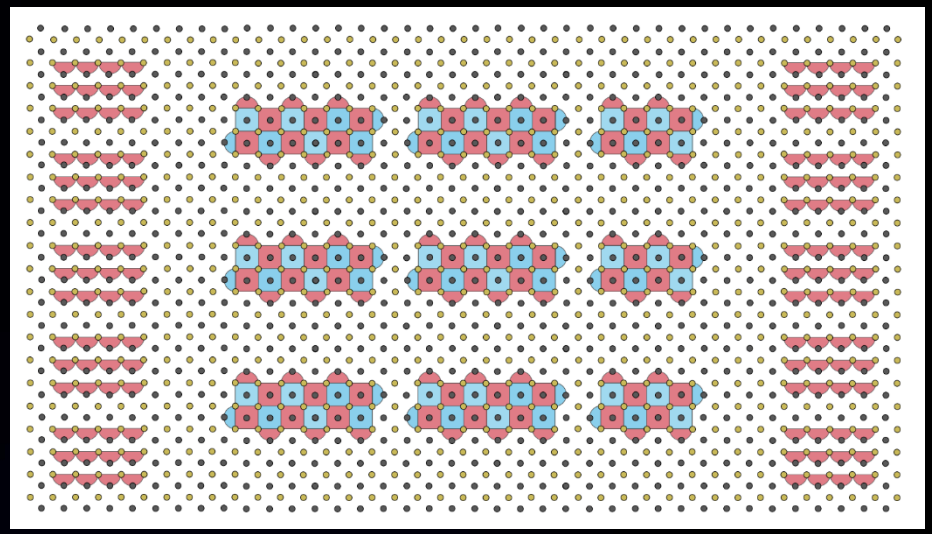
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Fault-tolerant architecture

We worked out details of a scalable quantum computer with cat qubits to assess long-term potential



Unit cell



architecture layout

Potential for **>10x** overhead reduction (for fixed gate error rates)
But also found it's harder to get good gates with cats

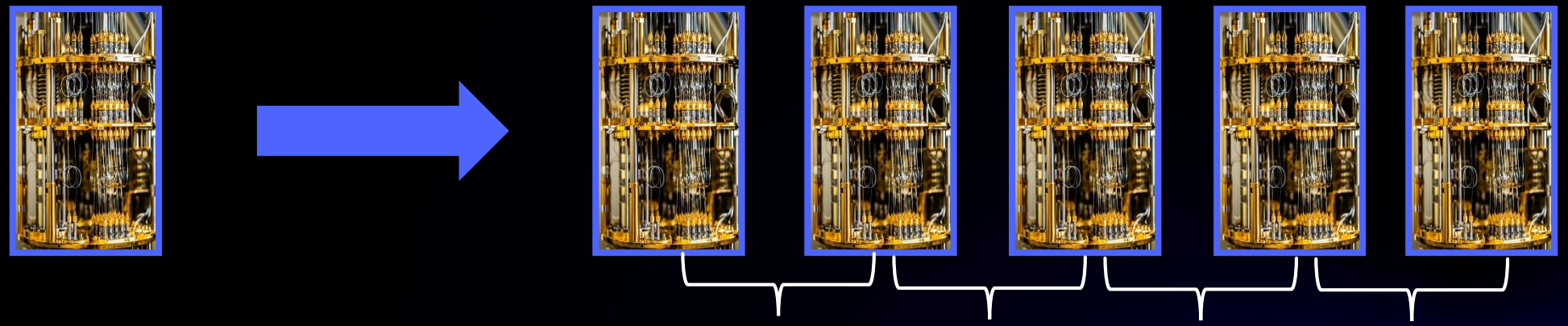
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Scaling challenges

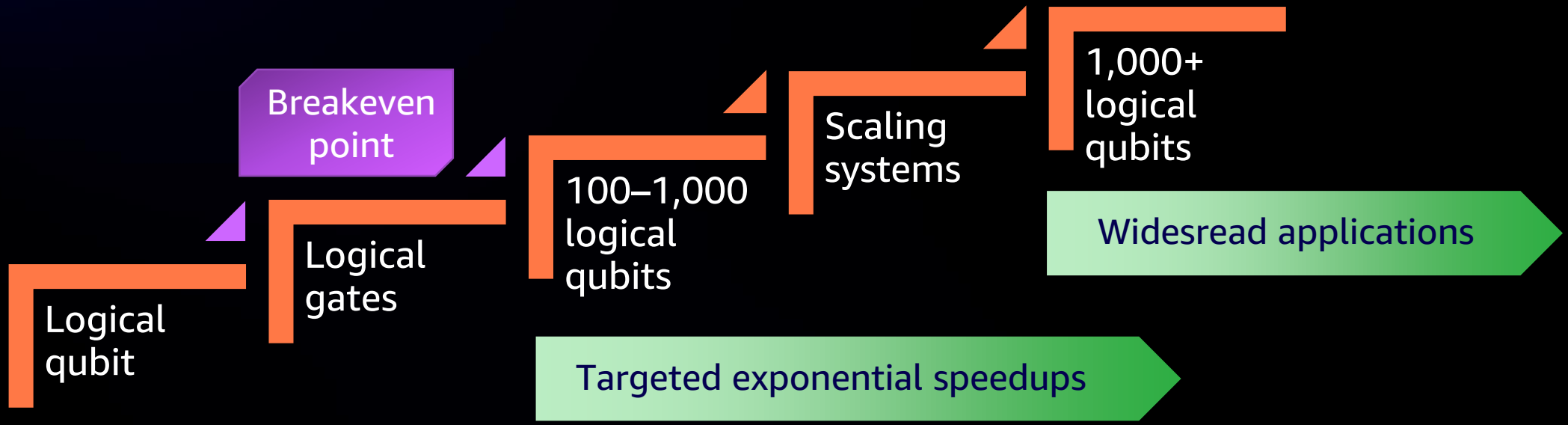
Building a fault-tolerant quantum computer with >100 logical qubits will require *at least* many thousands of physical components

Viable path with superconducting qubits for that regime but will require substantial engineering advances in cryogenics, software stack, and control



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Continuing the journey



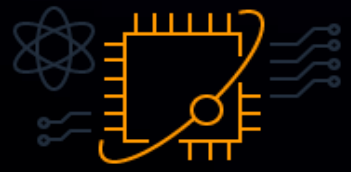
Improvements to physical hardware

Algorithm development

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Get started with quantum

Building a fault-tolerant quantum computer is a long-term effort, but you can engage with us today!



Amazon Braket

Fully managed quantum computing service

Access to multiple types of quantum processors



Amazon Quantum Solutions Lab

Expert guidance

Cross-discipline support and collaborative engagements with experts in quantum, HPC, and ML

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Thank you!

Nadia Carlsten
carlsten@amazon.com

Fernando Brandao
fbrandao@amazon.com

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