Building an ***Interesting*** Quantum Computer…

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Postdocs & grad students wanted!

Overview

Where are "we" today?

We will build (in next ~ 5 years) ***interesting*** quantum devices:

= complexity that CANNOT EVER be classically simulated

(> 50 qubits or equivalent)

Now beginning a new era where a merger is needed:

quantum device physics	
systems engineering	"quantum computer science"
information thy./algorithms	

Outstanding questions: what's the best architecture?

how much overhead for error correction (QEC)?

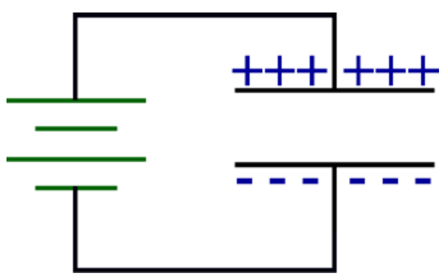
who will be the first to build something ***useful*** ?

Still lots of innovation in physics, engineering, and theory ahead!

Classical vs. Quantum Bits

Information as state of a two-level quantum system

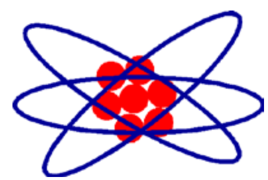
<u>Classical bit</u>



values 0 or 1

(never in between!)

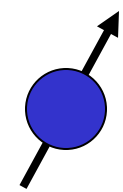
<u>Quantum bits (or "qubits")</u>



single atom

$|g\rangle = |0\rangle$

define: $|e\rangle = |1\rangle$



single spin

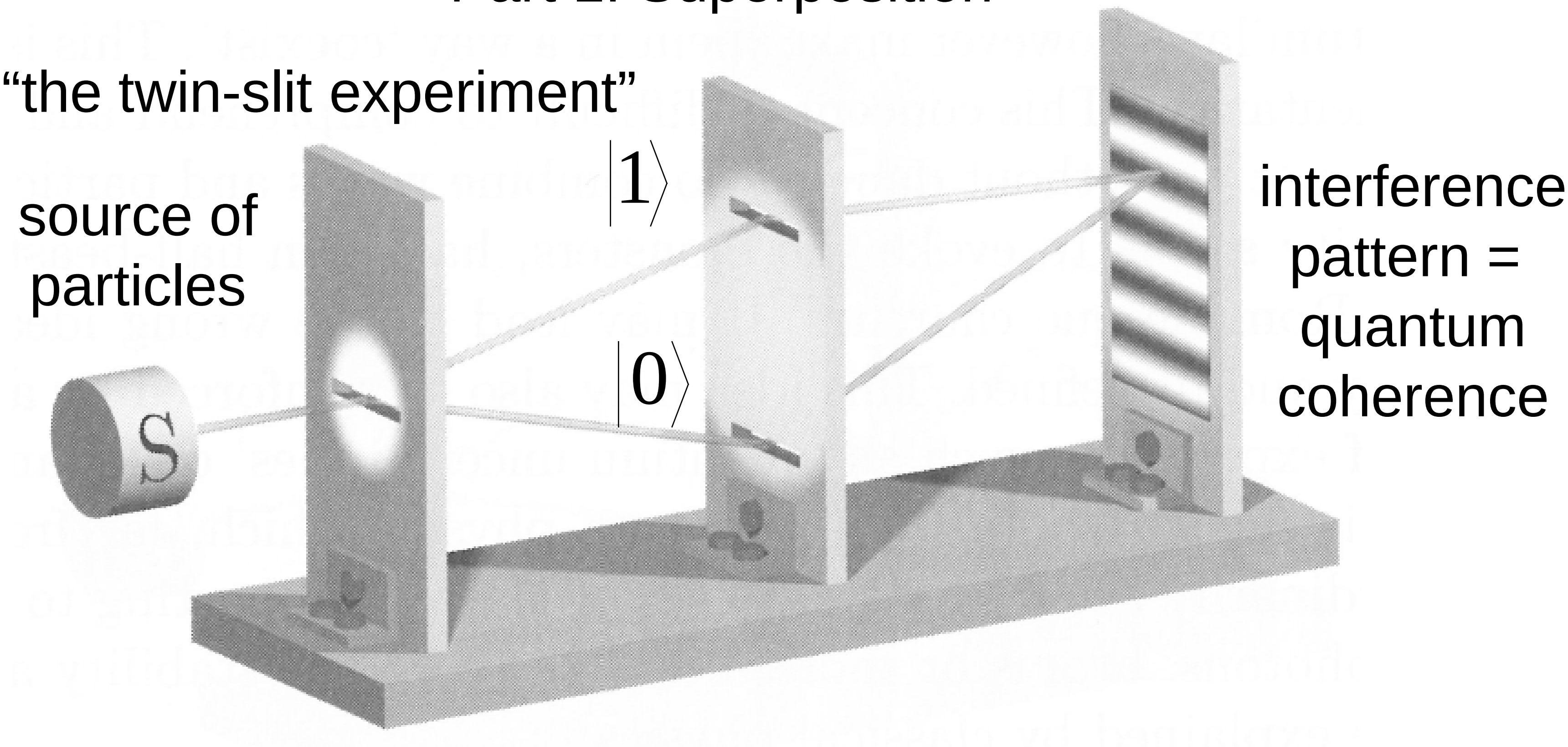
$|\uparrow\rangle = |0\rangle$

$|\downarrow\rangle = |1\rangle$

superposition: $|\Psi\rangle = \alpha|0\rangle + \beta|1\rangle$

What's so special about the quantum world?

Part 1: Superposition



Classical objects go ***either*** one way or the other.

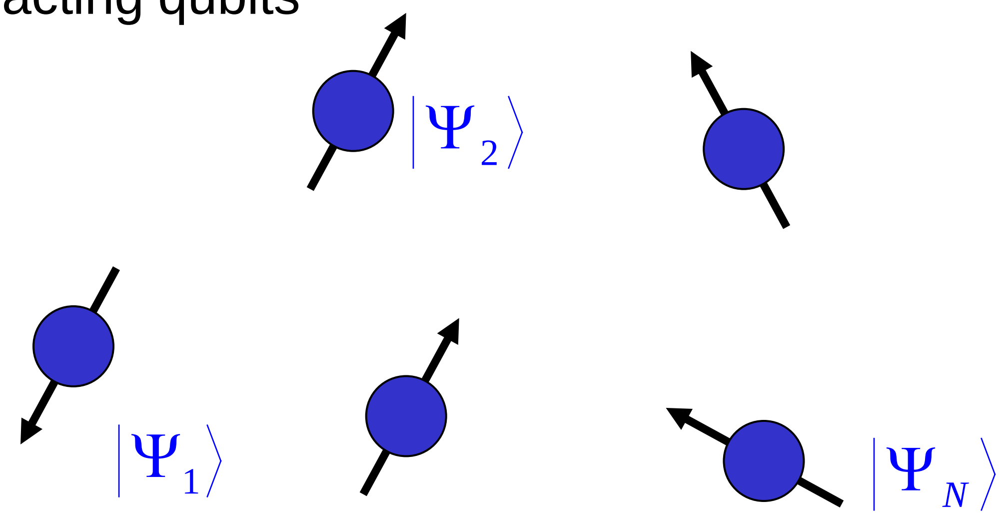
Quantum objects (electrons, photons) go ***both*** ways.

Gives a quantum computation an inherent kind of parallelism!

What's so special about the quantum world?

Part 2: Entanglement, or when more is (exponentially) different!

Start with N non-interacting qubits



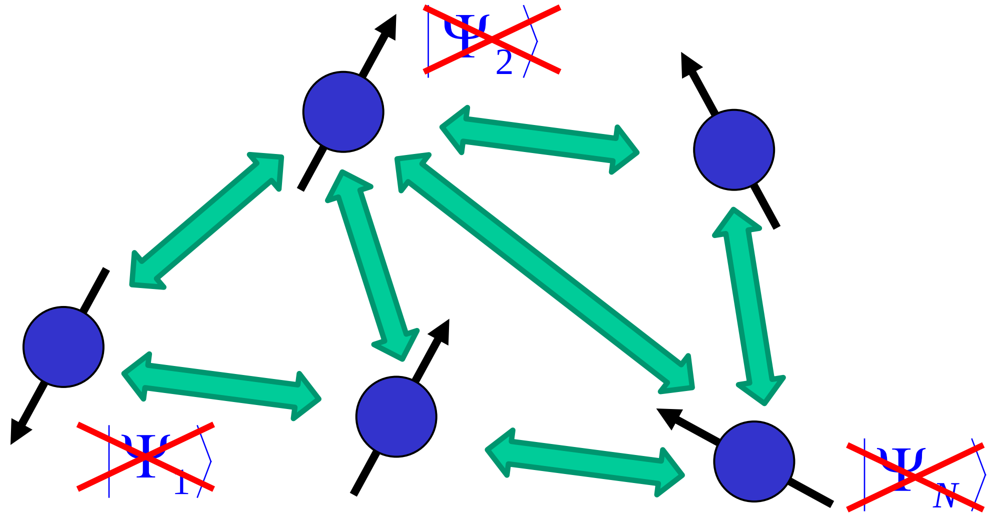
$$|\Psi_{tot}\rangle = (\alpha_1|0\rangle + \beta_1|1\rangle) \otimes (\alpha_2|0\rangle + \beta_2|1\rangle) \otimes \ldots (\alpha_N|0\rangle + \beta_N|1\rangle)$$

"Product" state (non-interacting) of N qubits: ~ N bits of info

What’s so special about the quantum world?

Part 2: Entanglement, or when more is (exponentially) different!

Most general state of N (=5) interacting qubits:



$$|\Psi_{tot}\rangle = c_1|00001\rangle + c_2|00010\rangle + \ldots + c_{64}|11111\rangle$$

Now we need 2^N (=64) separate complex amplitudes for the state

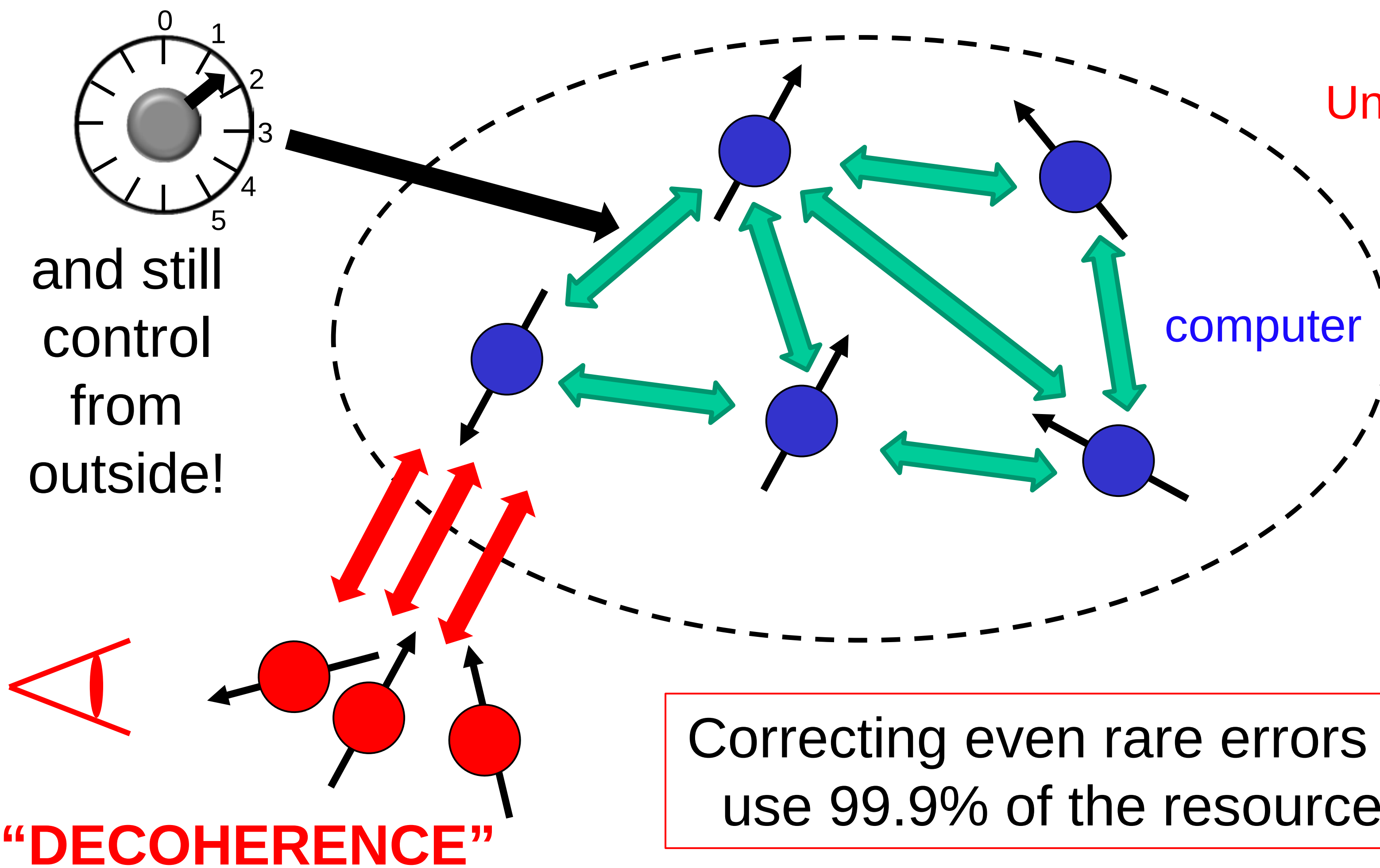
Entangled state of N qubits: ~ $2^*(2^N\text{-}1)$ bits of info!

And simulating a 200-qubit machine requires ~ 10^{60} classical bits!

What’s the catch?

Part 3: Decoherence and Errors

Want qubits to interact strongly w/ each other, but nothing else!



Correcting even rare errors will use 99.9% of the resources!

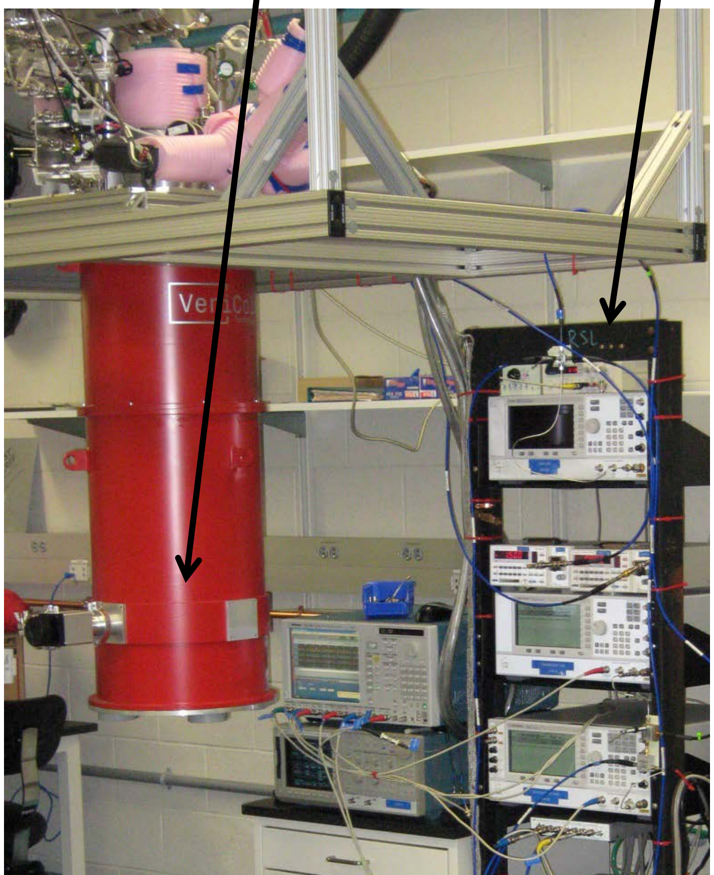
Qubit Research Combines Many Technologies

Low Temperatures

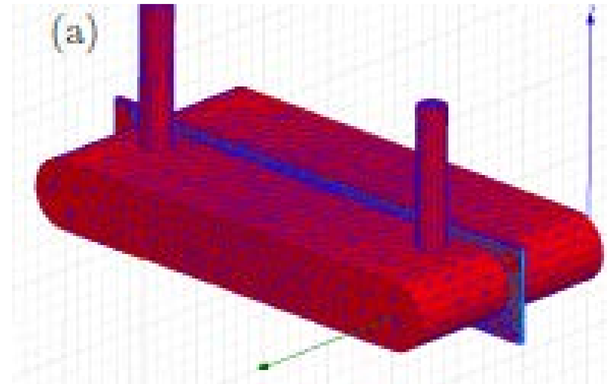
Cryogen-free dilution refrigerator
T = 0.01 K

High-Speed Control

Microwave signals
FPGA feedback
quantum-limited msmts.

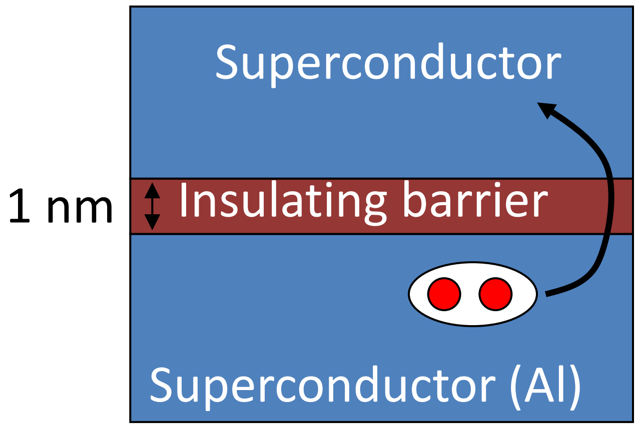


RF Simulation & Custom Design

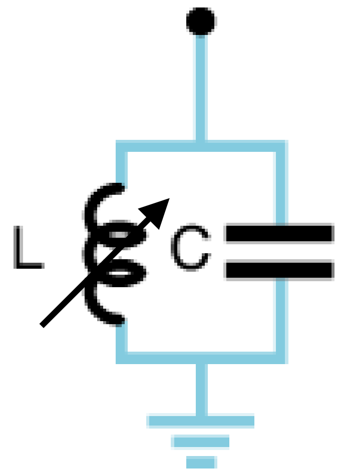


Superconducting Devices & Materials

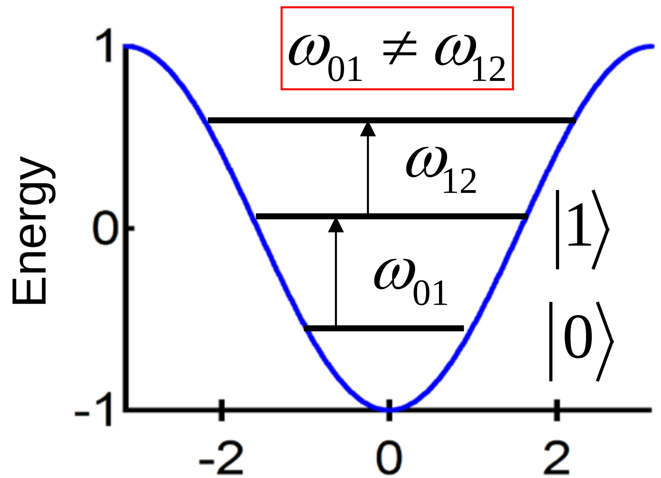
Superconducting Qubits



Josephson junction
(dissipation-free!)



Non-linear
electromagnetic
oscillator



$\omega_{01} \sim 5-10\ \mathbf{GHz}$

$\hbar\omega/\mathbf{k}_B \sim 0.25\ \mathbf{K}$

Bit energy: ~ 10 μeV or 10^{-24} J
few yocto-Joules!

"Voltage level:" 1 μV (RMS)

Logical "0": ground state

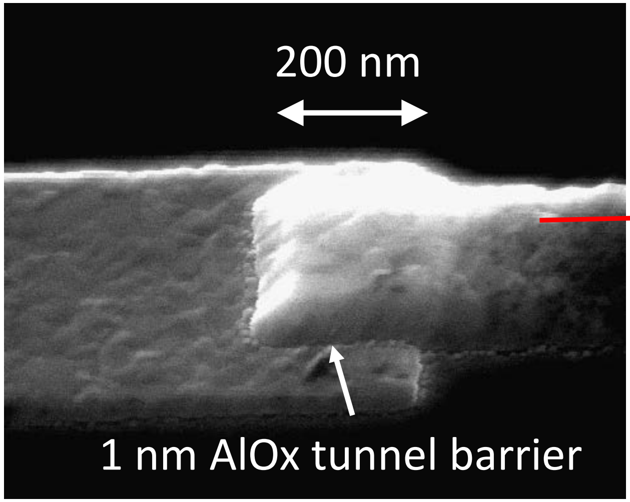
Logical "1": one μ-wave "photon"

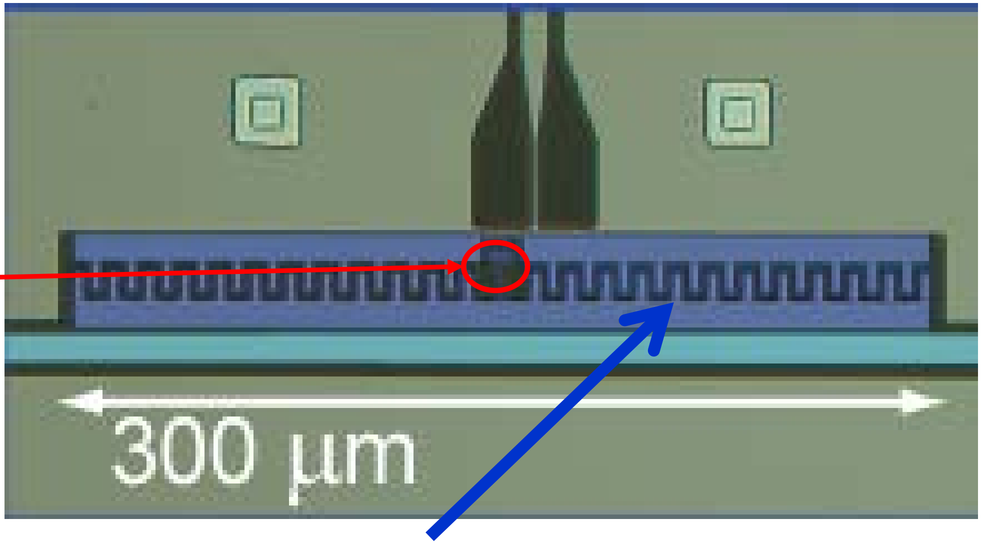
Excite & control with GHz signal on wires: gate time ~ 20 ns

Superconductivity should prevent losses (gapped!)

Transmon Qubit

Josephson tunnel junction





Aluminum electrodes
with ~ 10^{10} electrons

Properties of qubit are engineered, via fabrication or tuning

Advantages of "transmon" design:

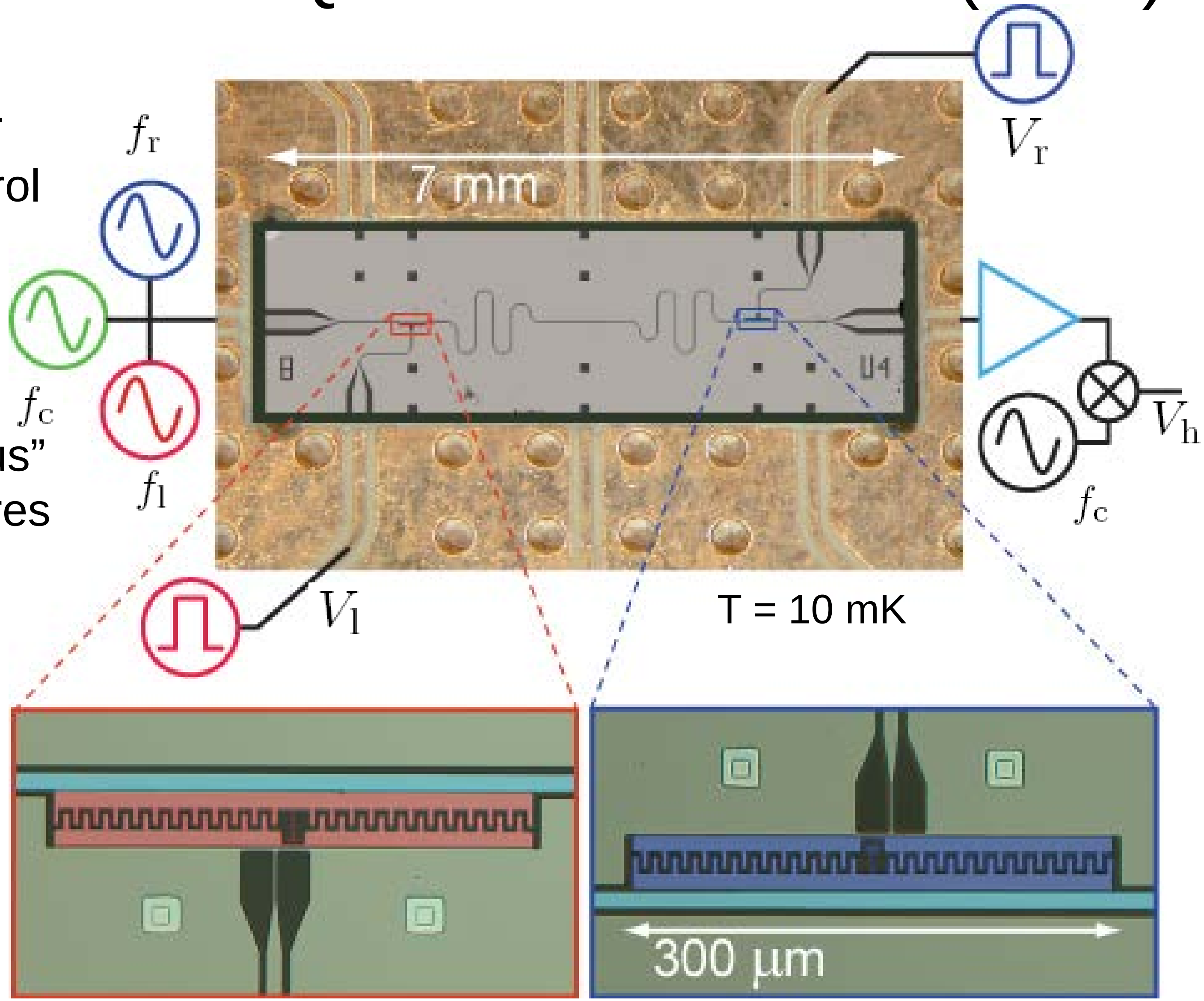
Simple (smallest number of parts to debug)
Hidden from environment (no DC properties)

Other practitioners (many!): UCSB, Berkeley, Princeton, Delft, Zurich, Saclay, Chicago…

The First Solid-State Quantum Processor (2009)

<u>"Circuit QED"</u>

- all electrical control & measurement
- entanglement "bus" via photons on wires (microwave transmission line cavity)

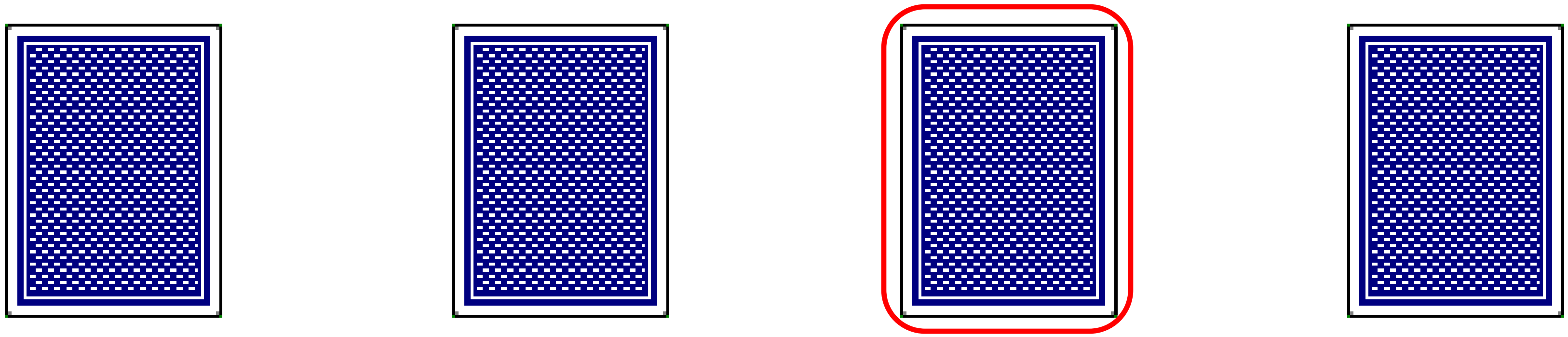


Algorithms: DiCarlo et al., *Nature* **460**, 240 (2009).

A quantum card trick

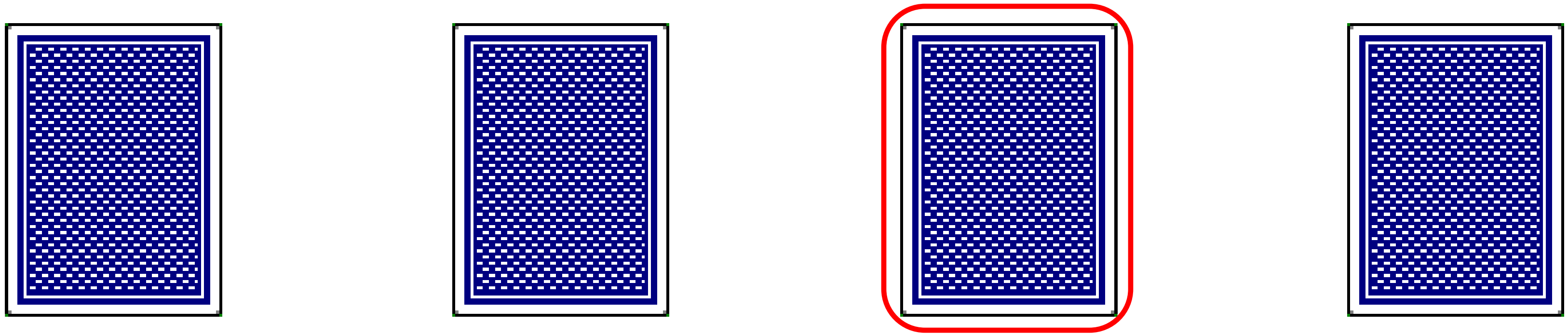
find the red card

A classical search



2.25 guesses on average

The quantum search



peeks under all cards at once, finds answer in one try

A quantum card trick

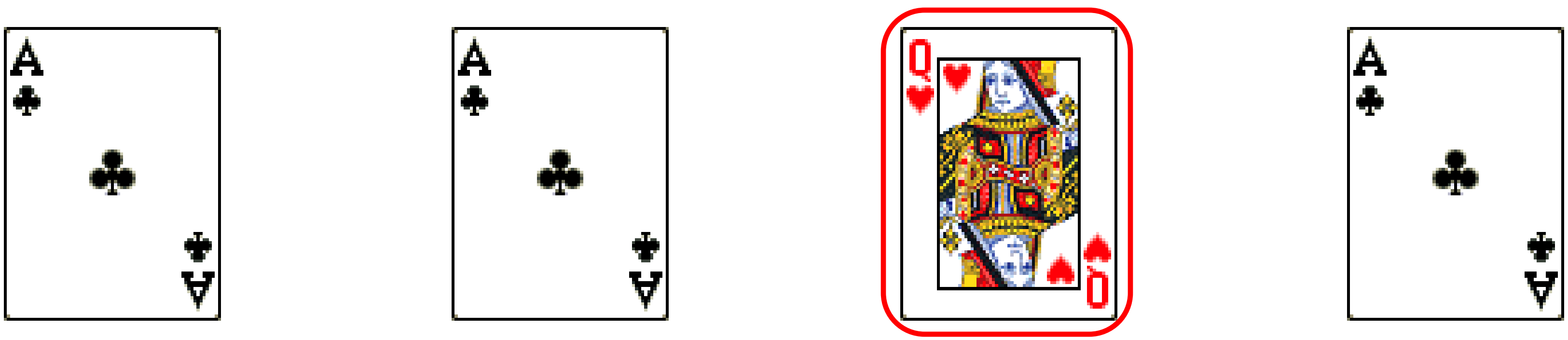
find the red card

Showed all the hallmarks of a quantum algorithm:

- Speedup thru quantum parallelism
- Use of entanglement
- Quantum coherence

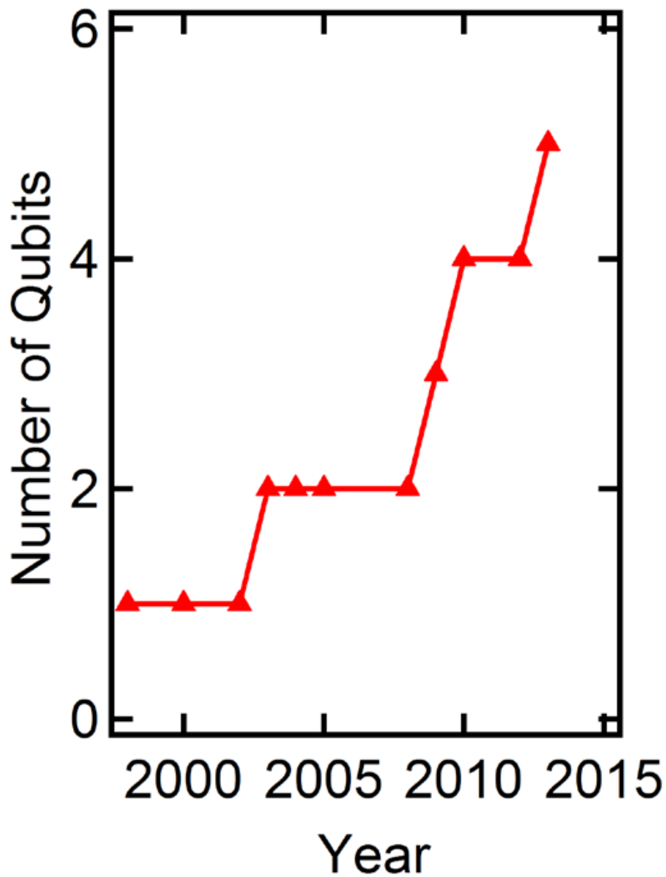
~ 100 ns total run time
80% success probability
(1 μs lifetimes then)

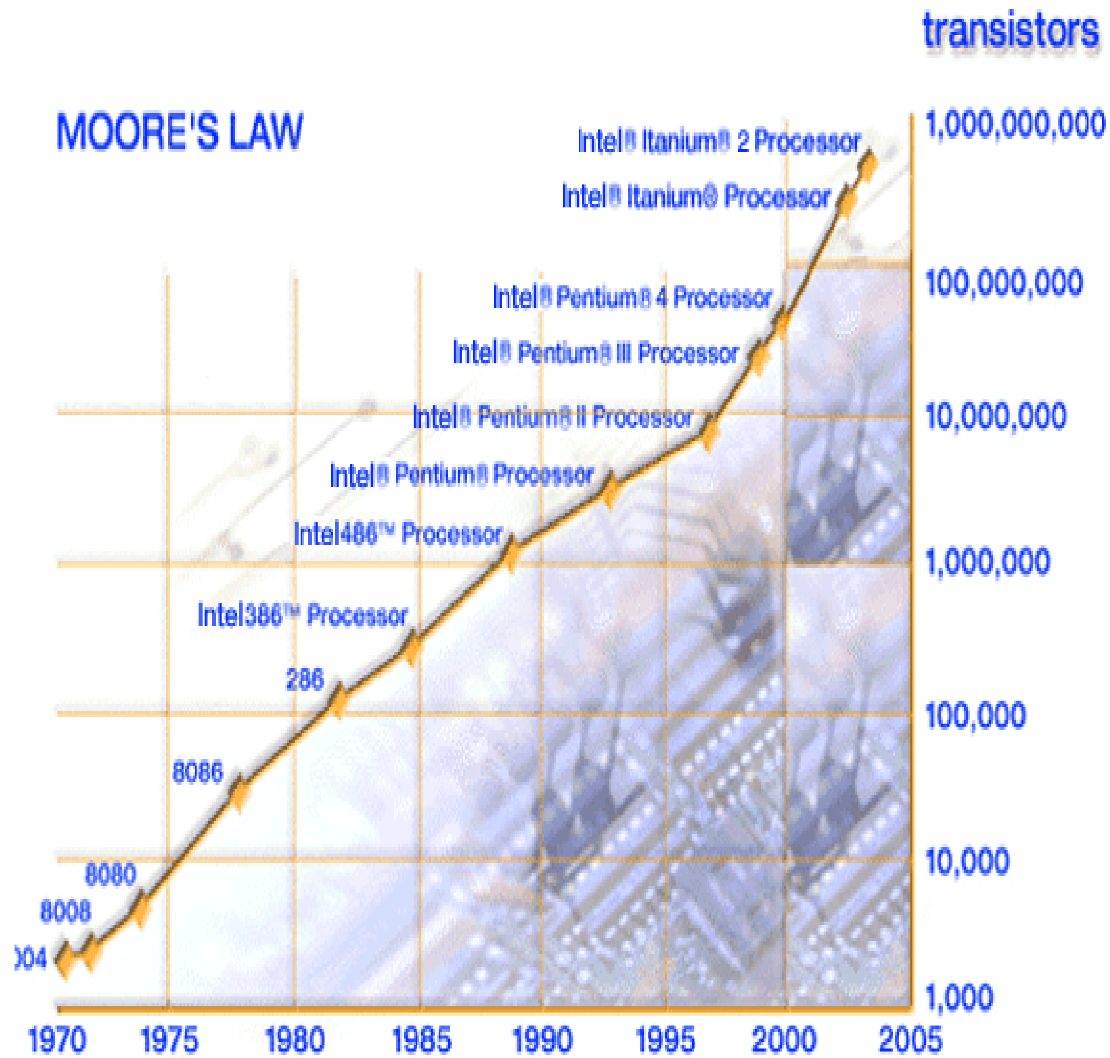
The quantum search



peeks under all cards at once, finds answer in one try

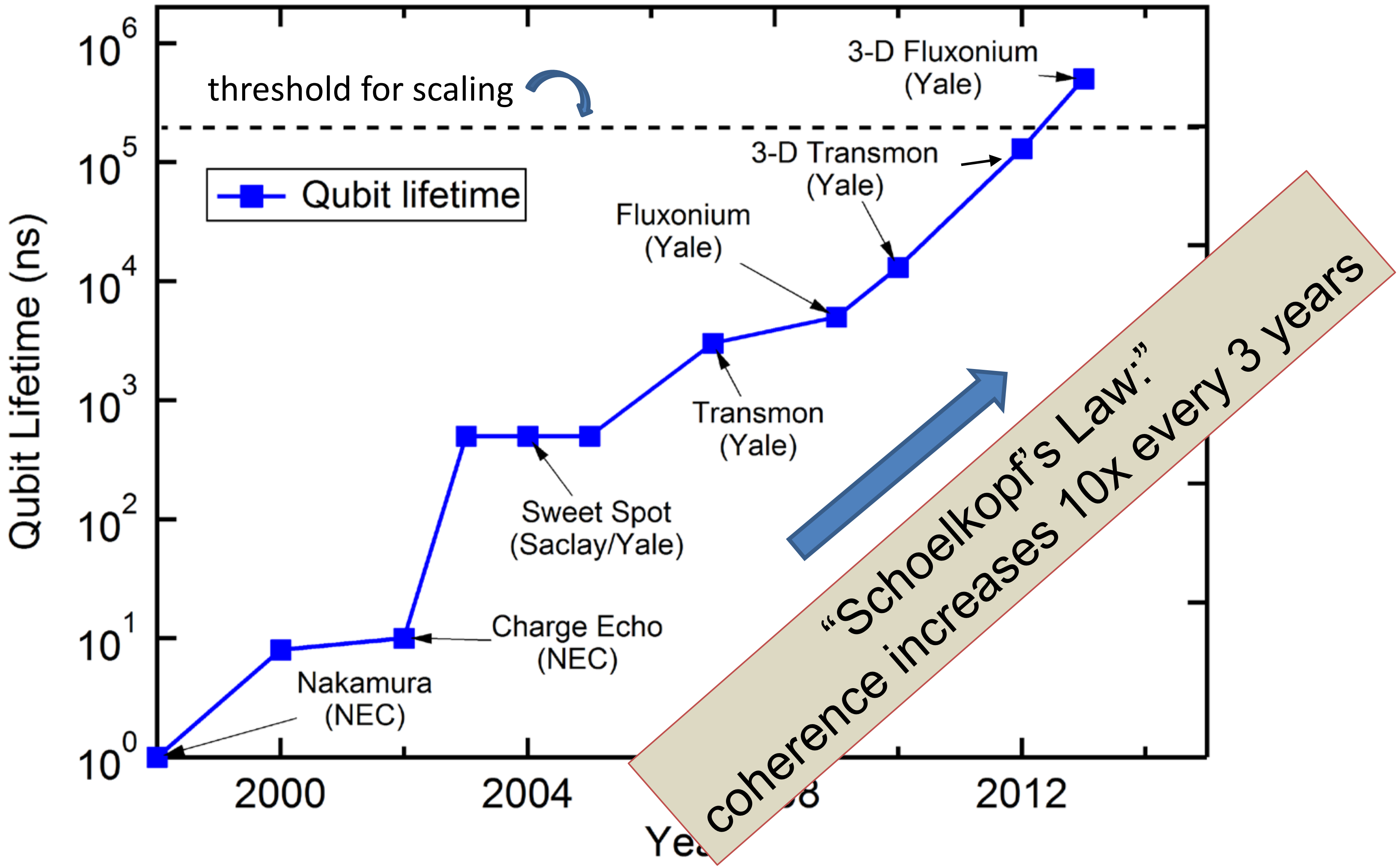
Progress in Superconducting Qubits





Improving the Coherence of Quantum Bits

how long before your quantum bit “forgets” its information?



Stages of Quantum Computing?

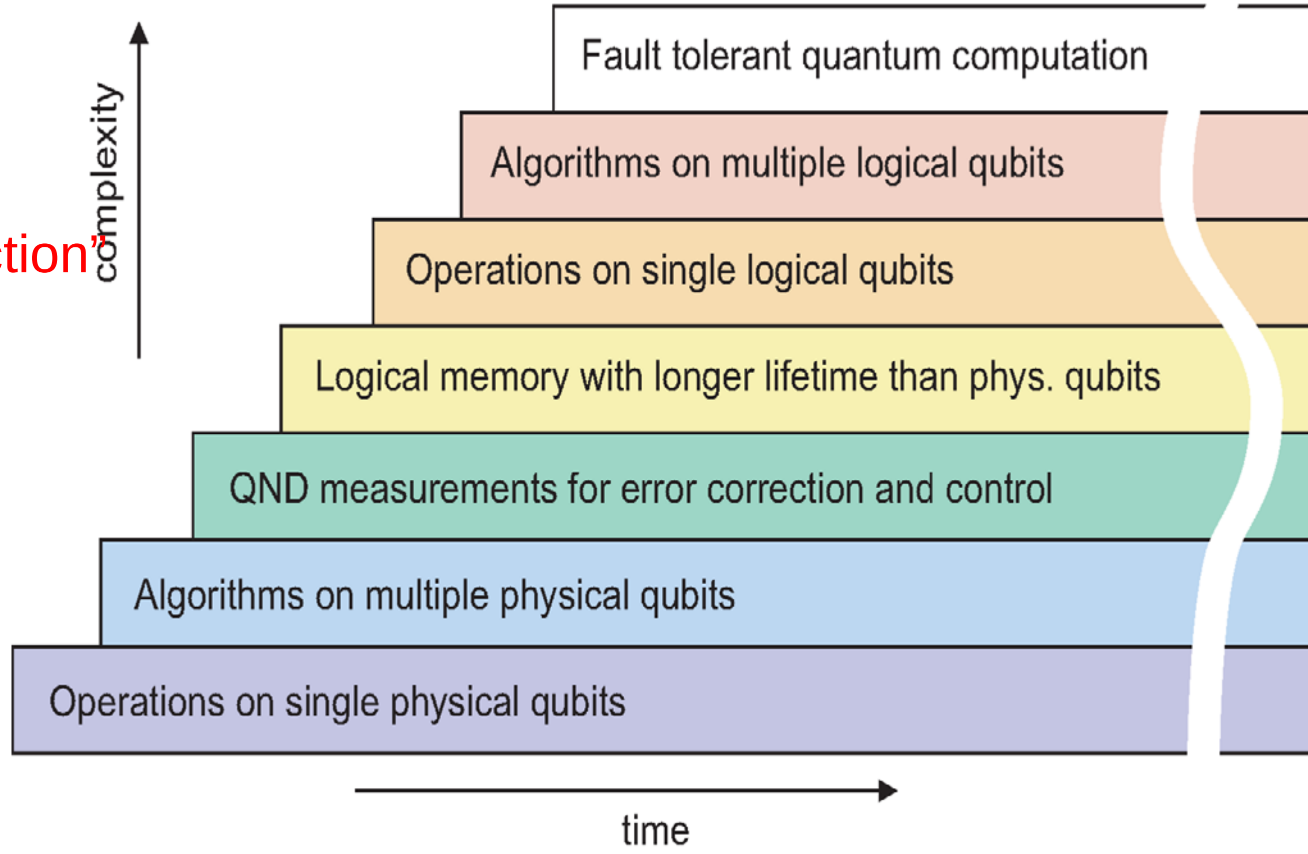
"Age of Qu. Error Correction"

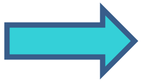
"Age of Qu. Feedback"

"Age of Measurement"

"Age of Entanglement"

"Age of Coherence"



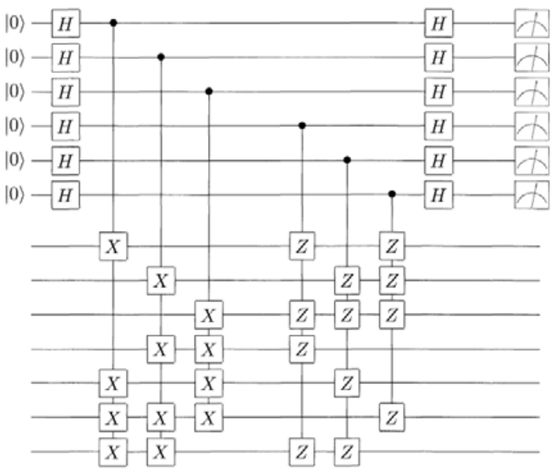


"We" are ~ here (also ions, Rydbergs, q-dots, …)

M. Devoret and RS, Science (2013)

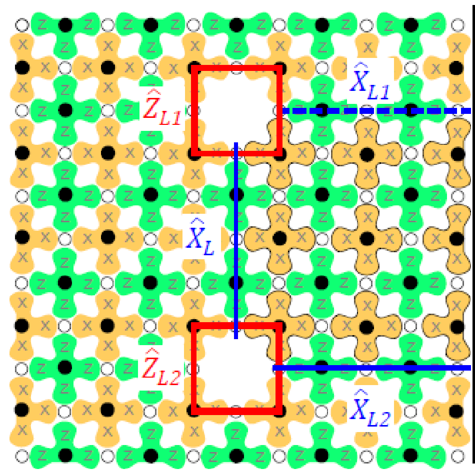
Different Error Correction Architectures

Standard QEC



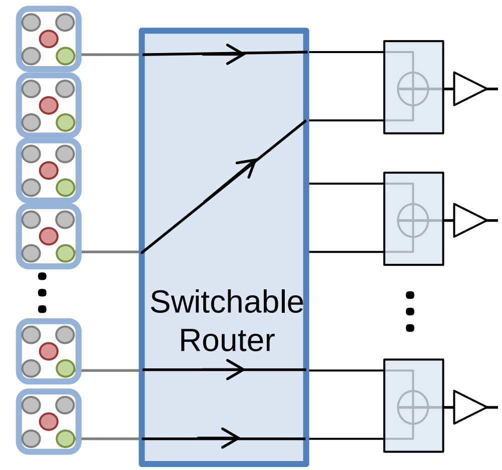
- 7 or 9 physical qubits per logical (+ concatenation!)
- threshold ~ 10^{-4}
- many ops., syndromes per QEC cycle

Surface Code



- 10^2 – 10^4 /logical
- threshold ~ 1%
- large system to see effects?

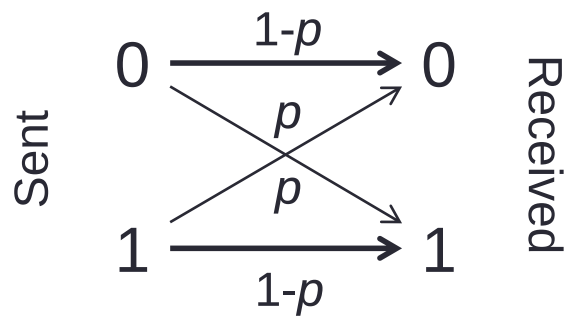
Modular Approach



- few qubits/ module
- good local gates (10^{-4}?) remote gates fair (90%?)
- then construct QEC as software layer?

Overhead required in known schemes: 1,000 actual qubits for every logical!!

Classical Error Correction



Probability p of having a bit flipped

Repetition code: redundantly encode, majority voting

$$0 \rightarrow 000$$
$$1 \rightarrow 111$$

Reduces classical error rate to $3p^2 - 2p^3$

Can we do this for quantum computing? Some reasons to think **no**:

- “No cloning” theorem
- Errors are continuous (or are they?)
- Measurements change the state

How Do You Correct ***Quantum*** Errors?

Replace physical qubit with a logical register of three qubits

$$\alpha|0\rangle + \beta|1\rangle \to \alpha|000\rangle + \beta|111\rangle$$

(e.g. Shor, Gottesman, …)

"a GHZ entangled state"

Now measure the quantum version of their parity:

$$\langle Z_1 Z_2 \rangle = +1 \text{ or } -1 \quad ?$$

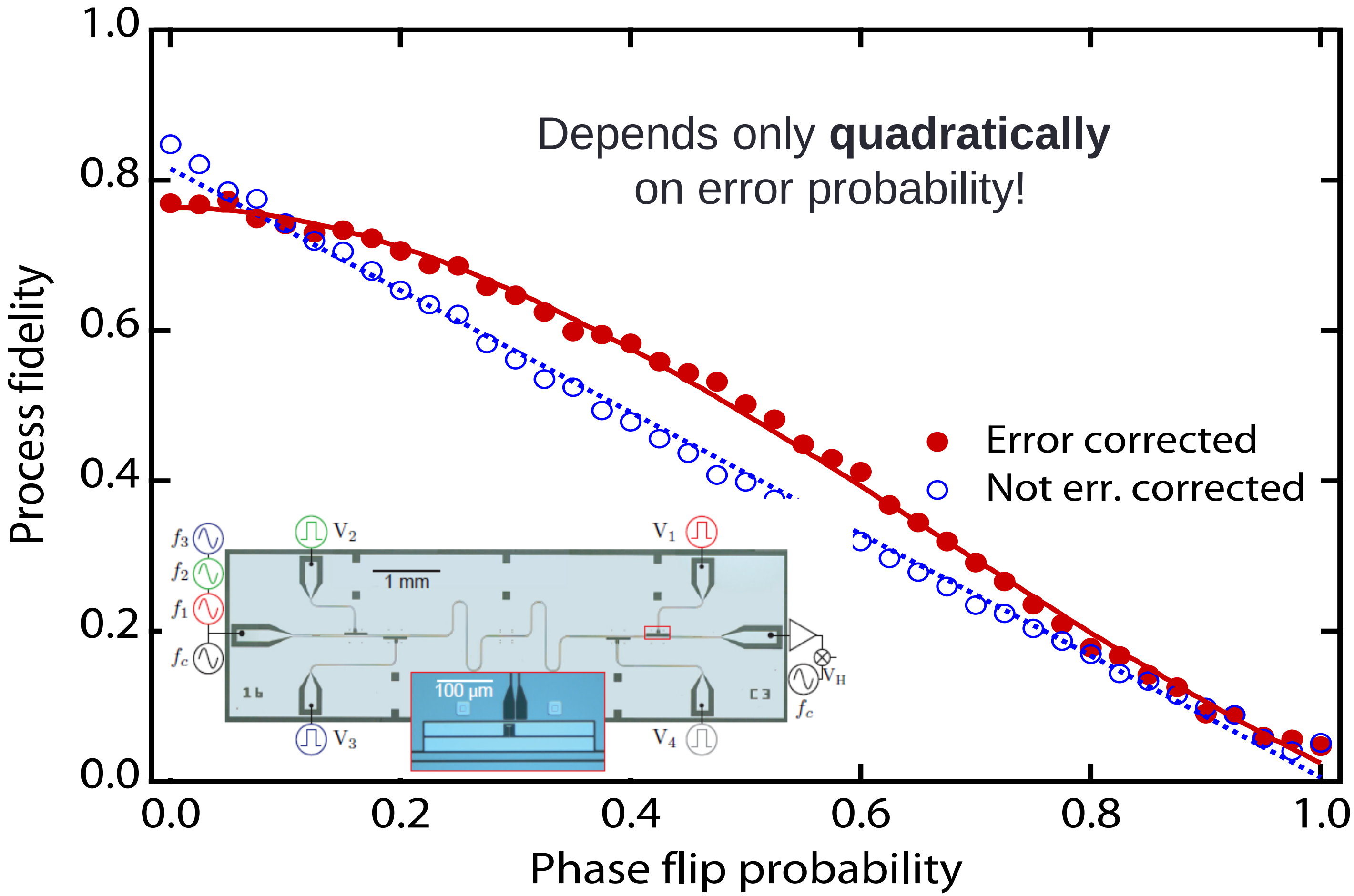
and tell me ***only*** the correlations!!

Flipped qubit	State	Z_1Z_2	Z_2Z_3
None	$\alpha\|000\rangle + \beta\|111\rangle$	+1	+1
Q_1	$\alpha\|100\rangle + \beta\|011\rangle$	-1	+1
Q_2	$\alpha\|010\rangle + \beta\|101\rangle$	-1	-1
Q_3	$\alpha\|001\rangle + \beta\|110\rangle$	+1	-1

Each error has a **different** observable! - The basis for the **bit flip code**

Performance of Bit-Flip Code

Experiment with 3 planar transmons in cavity



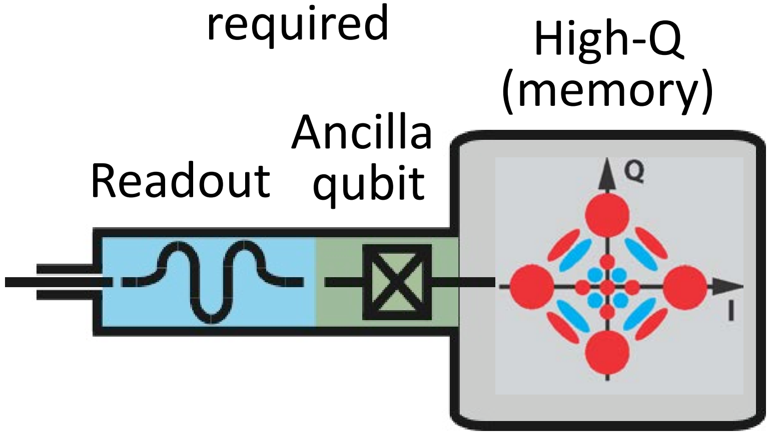
Challenge: QEC that actually makes lifetime longer!

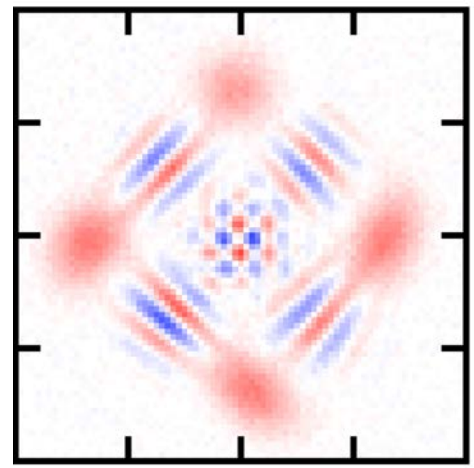
Bit flip code: Reed et al., *Nature 482* , 382 (2012).

or Can QEC be Hardware-Efficient?

"Cat codes": much less hardware required

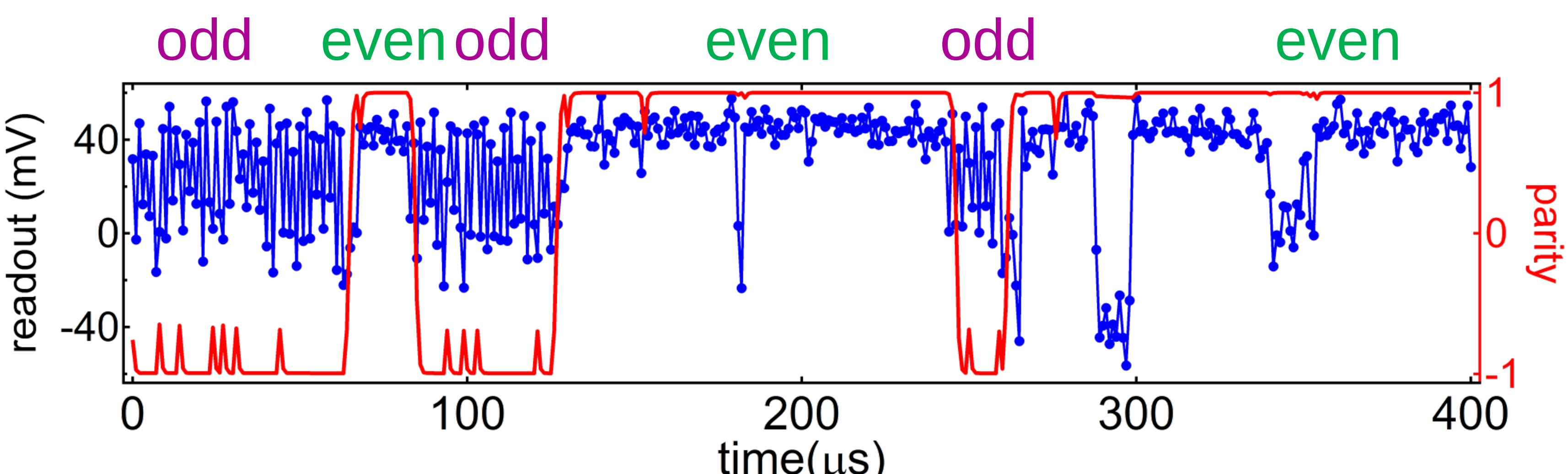
Leghtas, Mirrahimi, et al., PRL **111**, 120501(2013).



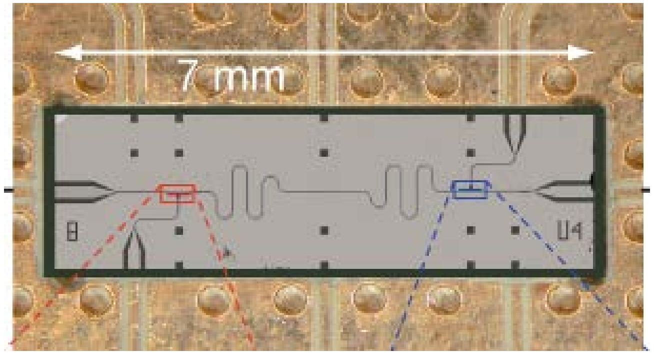


1st tracking of a parity or error syndrome in real-time:

Sun, Petrenko, et al., arXiv and Nature, July 24th

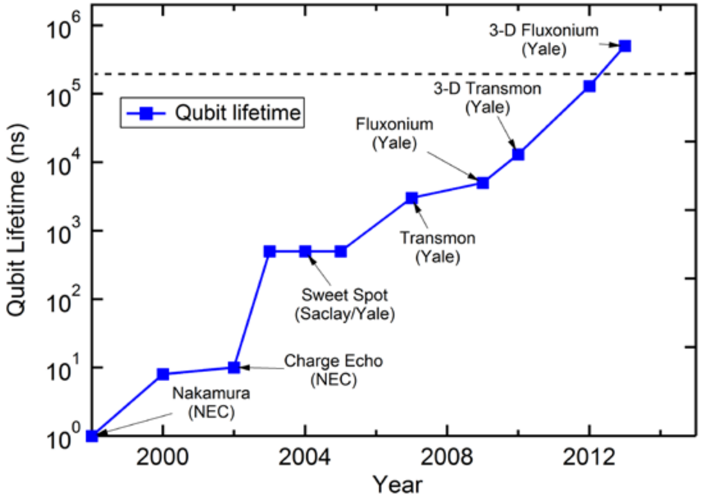


Summary



- Solid-state qubits are here!

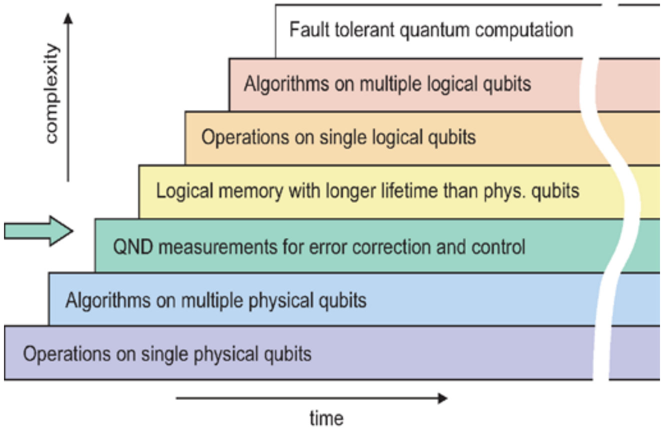
"Coherence scaling"



- Performance passing QEC threshold

  Qubits: T2 ~ 2*T1 ~ 0.0001 sec
  Cavities: T1 ~ 0.01 sec

- Now entering the stage of error correction, architectures, fault tolerance



Next challenge: error correction that actually makes lifetime longer!

END