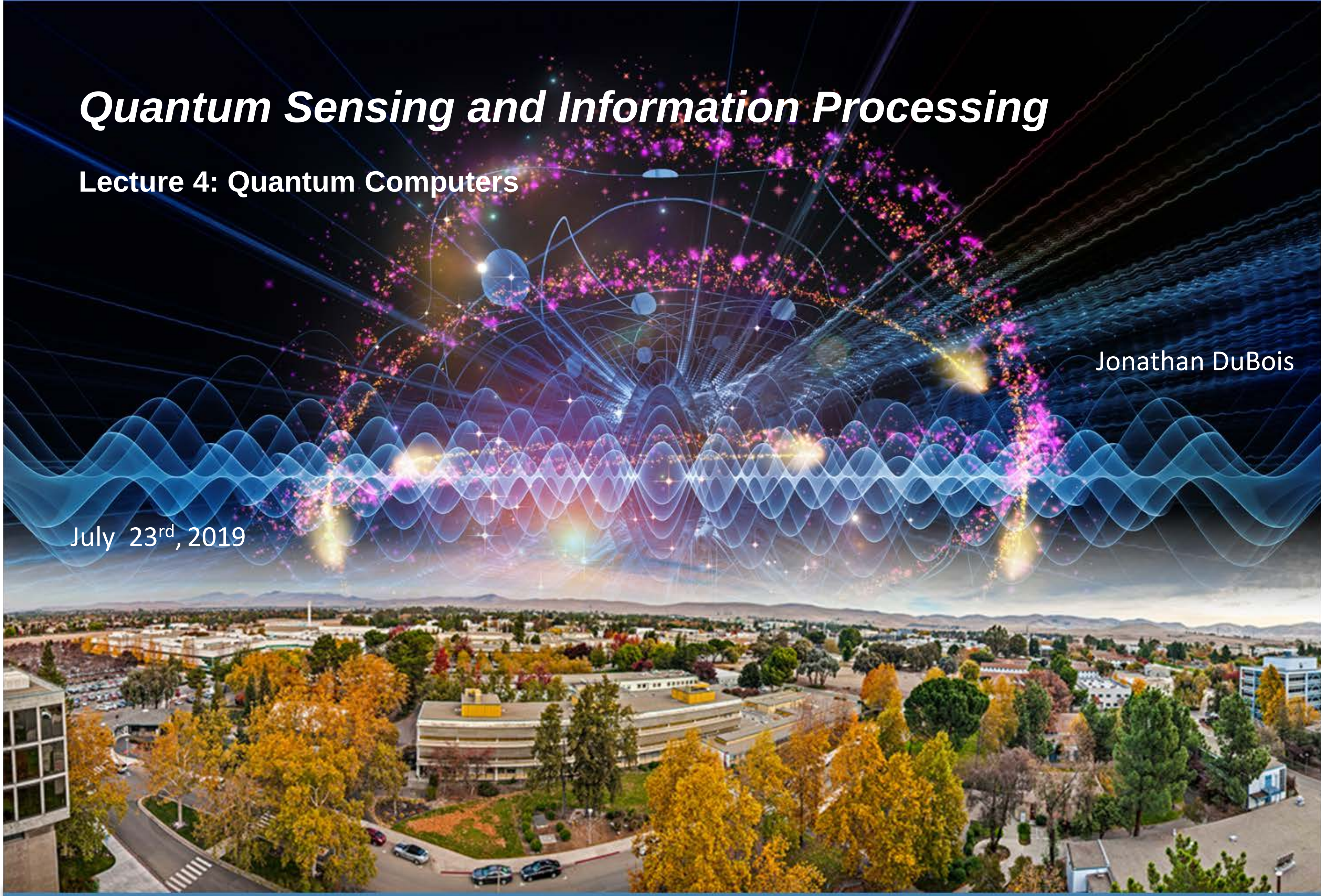
Quantum Sensing and Information Processing

Lecture 4: Quantum Computers

Jonathan DuBois

July 23rd, 2019



LLNL-PRES-785179

This work was performed under the auspices of the U.S. Department of Energy by Lawrence Livermore National Laboratory under contract DE-AC52-07NA27344. Lawrence Livermore National Security, LLC

Lawrence Livermore National Laboratory

Lecture Schedule

Quantum Computing Algorithms

Andreas Baertschi (LANL)

Wednesday, July 31st at 2:00 *and* Thursday, August 1st at 2:00

B543 Auditorium, R1001

Dr. Baertschi's lectures are co-sponsored by the Advanced Simulation and Computing Program (LANL) and the Center for Applied Scientific Computing (LLNL).

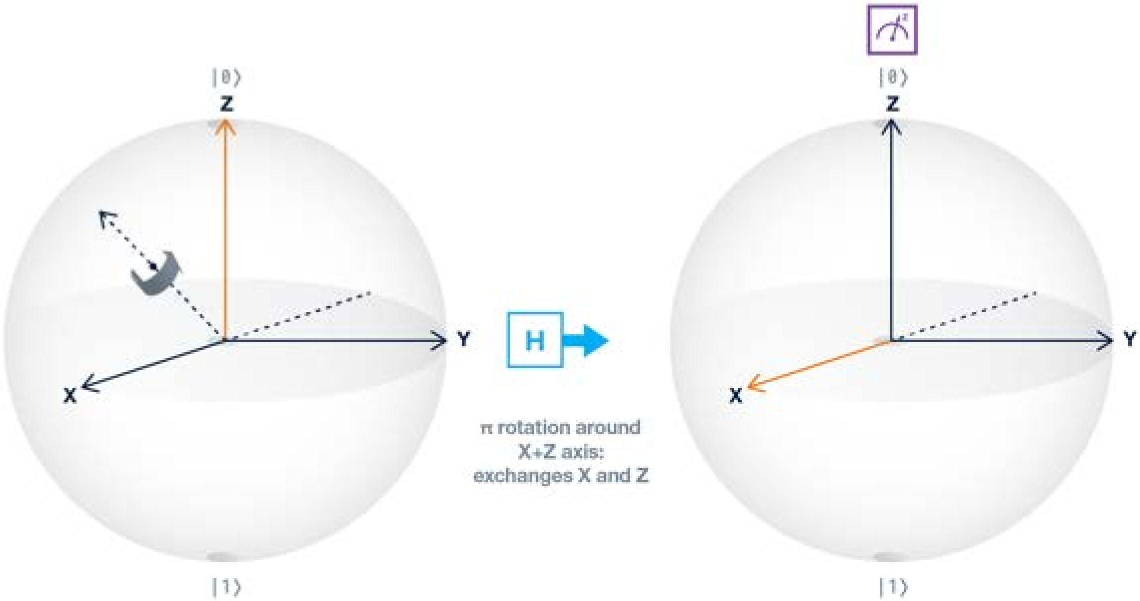
Schedule posted to Lab calendar – subscribe to receive updates

https://casis.llnl.gov/seminars/quantum_information

Review: What is quantum computing?

Classical states: 0 or 1 i.e. TRUE or FALSE

Quantum states: $\alpha|0\rangle + \beta|1\rangle$ $\alpha^2 + \beta^2 = 1$

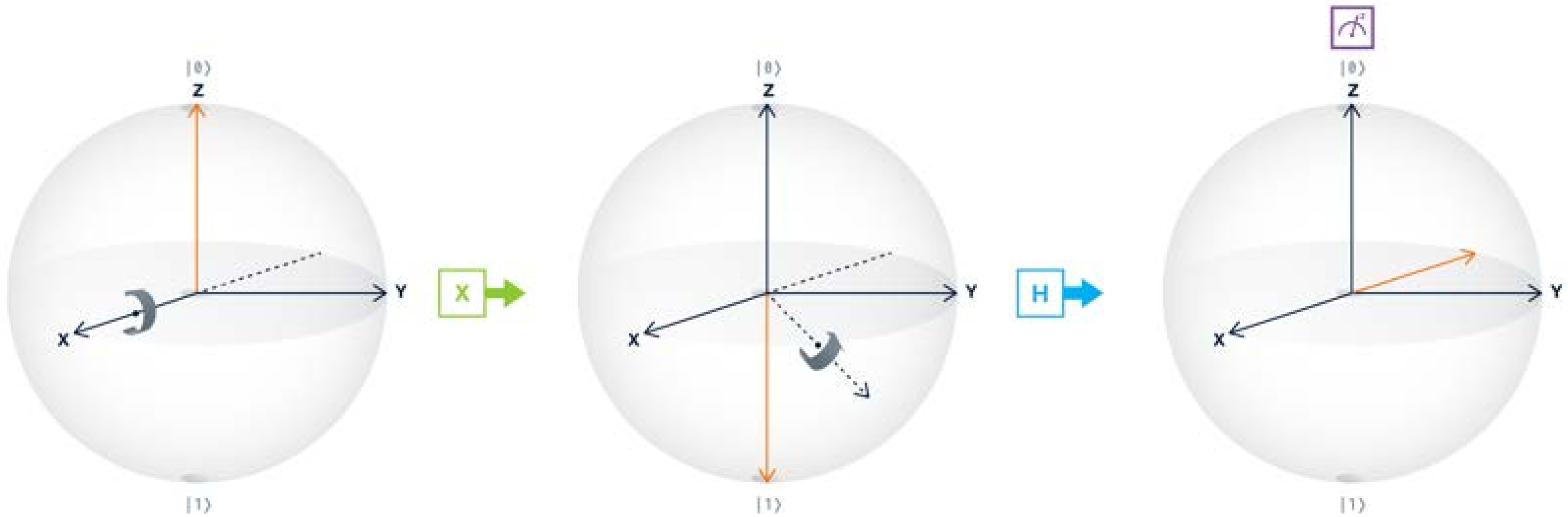


$$\frac{1}{\sqrt{2}}(|0\rangle - |1\rangle),$$

TRUE *and* FALSE

Review: What is quantum computing?

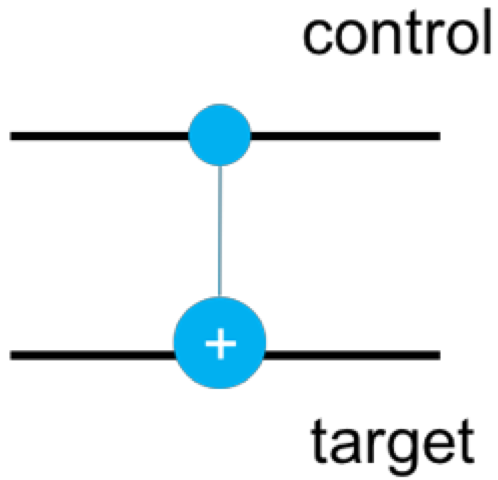
Quantum gates: move states



Single qubit gates can be thought of as rotations around different axes

Review: Adding more qubits

Two qubit quantum gates: move two qubit quantum states



Starting state → Ending State

|00> → |00>

|10> → |10>

|01> → |11>

|11> → |01>

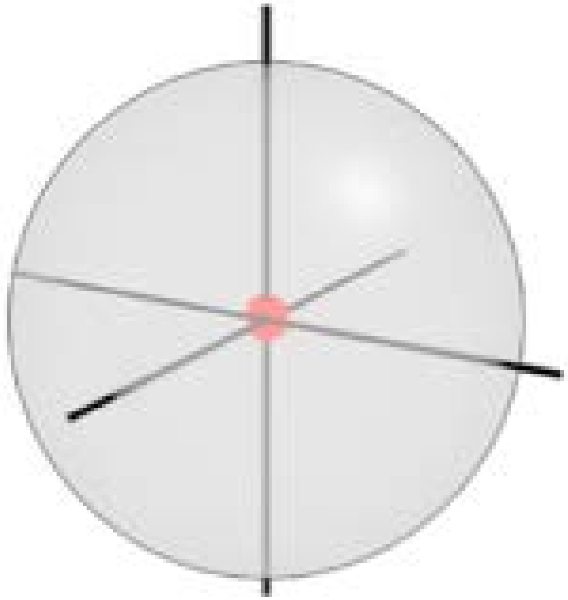
A small set of single qubit gates combined with this two qubit CNOT gate form a complete set.

By combining sequences of these gates, every possible quantum state can be transformed into every other possible state

Review: What can (and does) go wrong?

"Dephasing"

"Decoherence"

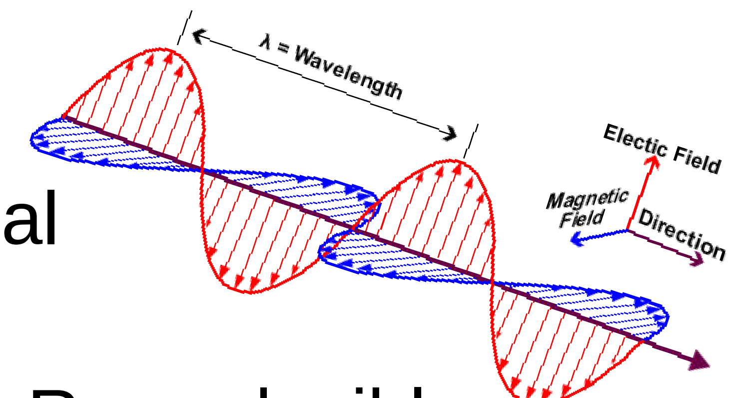


Control errors and interactions with the environment add random perturbations to the state.

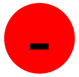
Quantum coherence is lost by 'measurement' from environment TRUE and FALSE becomes TRUE or FALSE

Review: ingredients for a quantum device

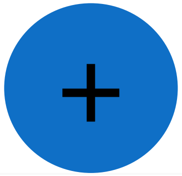
Classical compute and control system



Quantum classical interface



Reproducible,
Isolated quantum system



Review: Systems challenges

High speed electronics

- Cryogenics
- High Vacuum
- Multiscale Materials
- Vibration isolation
- EM Shielding

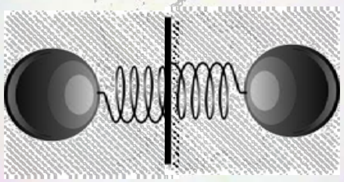
~Kilowatts 10^3 W

~Meters

300 K

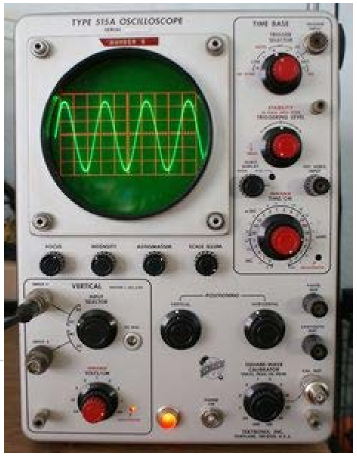
10^{-3} K

10^{-10} to 10^{-6} M



Yoctowatts 10^{-24} W

RF engineering / photonics



- Quantum limited amplifiers
- Isolators / circulators
- Filters

Micro / nanofab, 3D integration

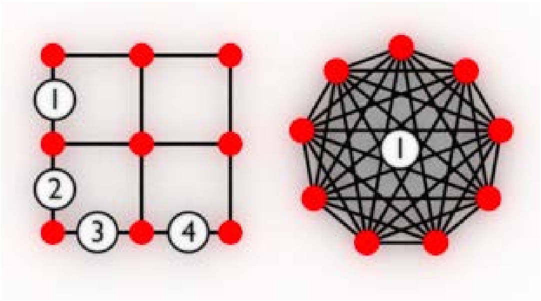
How to build a quantum computer!

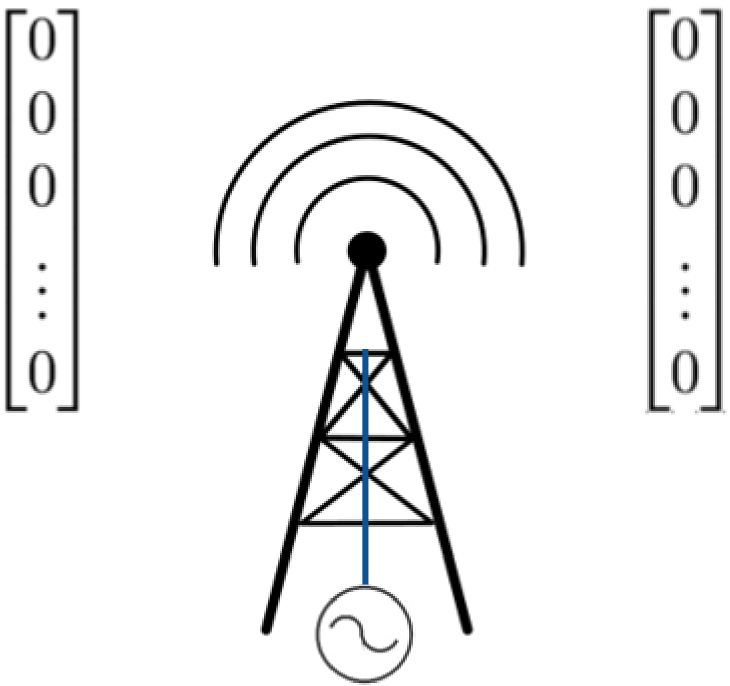
1) **Choose a quantum system** (easy part)
   - Solid state: Superconducting circuits, Semiconductor quantum dots, Defect centers in materials, Topological materials
   - Nature's made: Ions, neutral atoms, individual electrons, nuclear spin

2) **Isolate it from the classical environment** (hard)
   - Vacuum, Cryogenics, EM shielding, Vibration isolation..

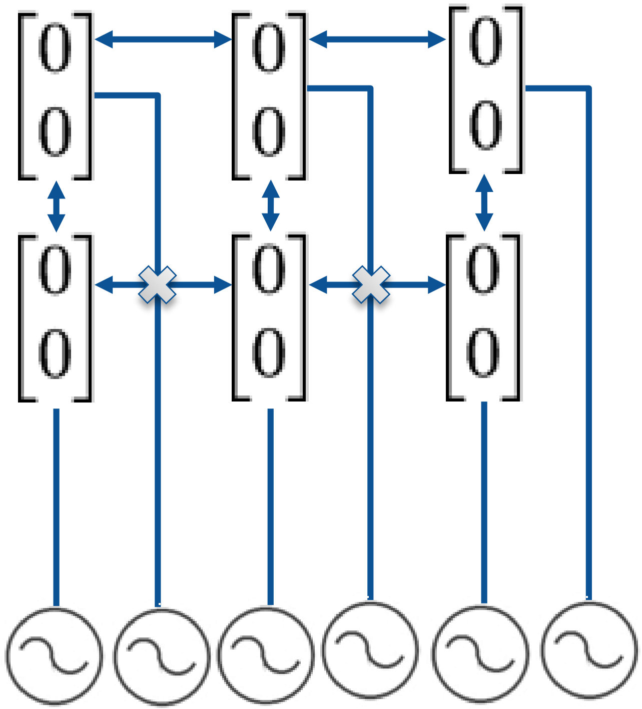
3) **Find a way to control it reliably** (while isolated ???)
   - Provide signals to control quantum dynamics
   - Measure the quantum state
   - Apply feedback to correct errors

Routing control and coupling:



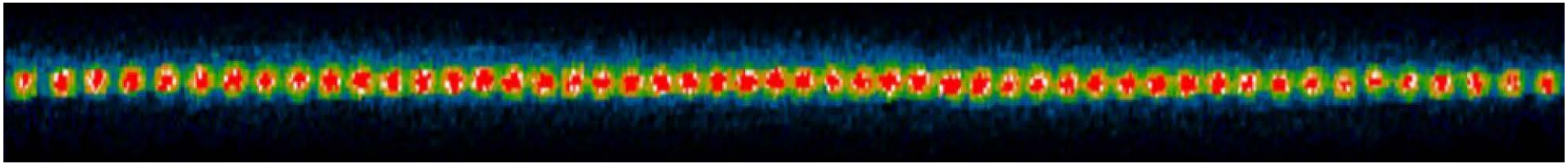


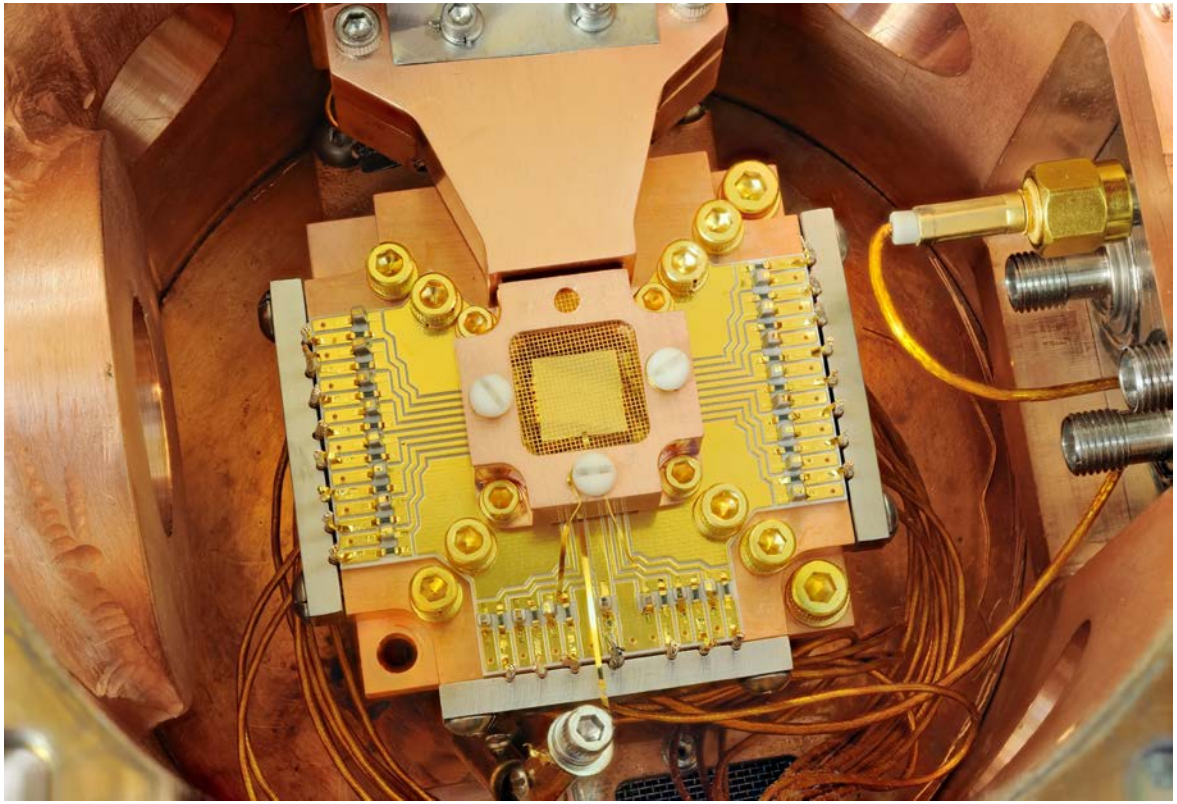
Single classical control channel with frequency multiplexed signal drives all qudits.



Multiple waveform generators drive individually connected qubits.

Trapped ions

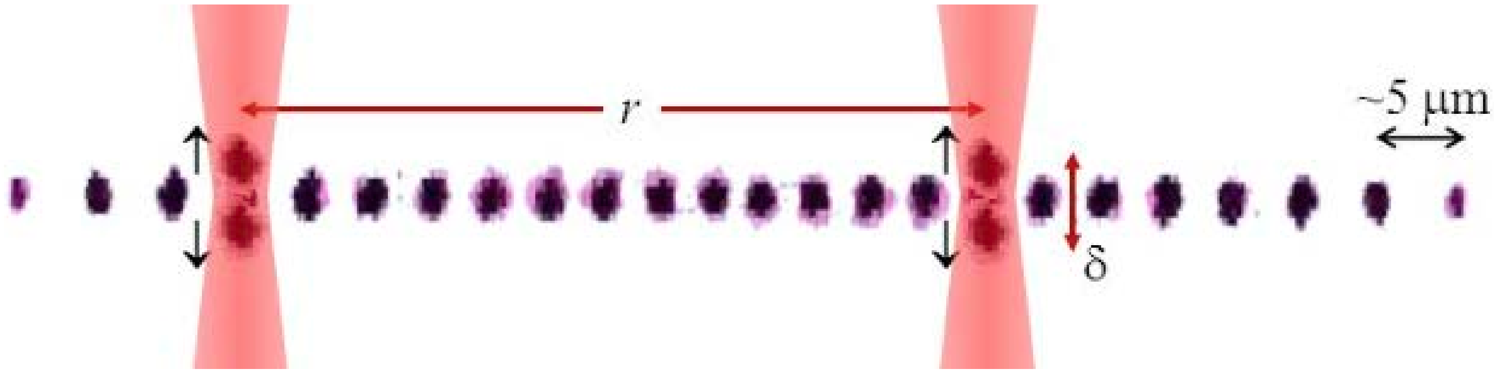


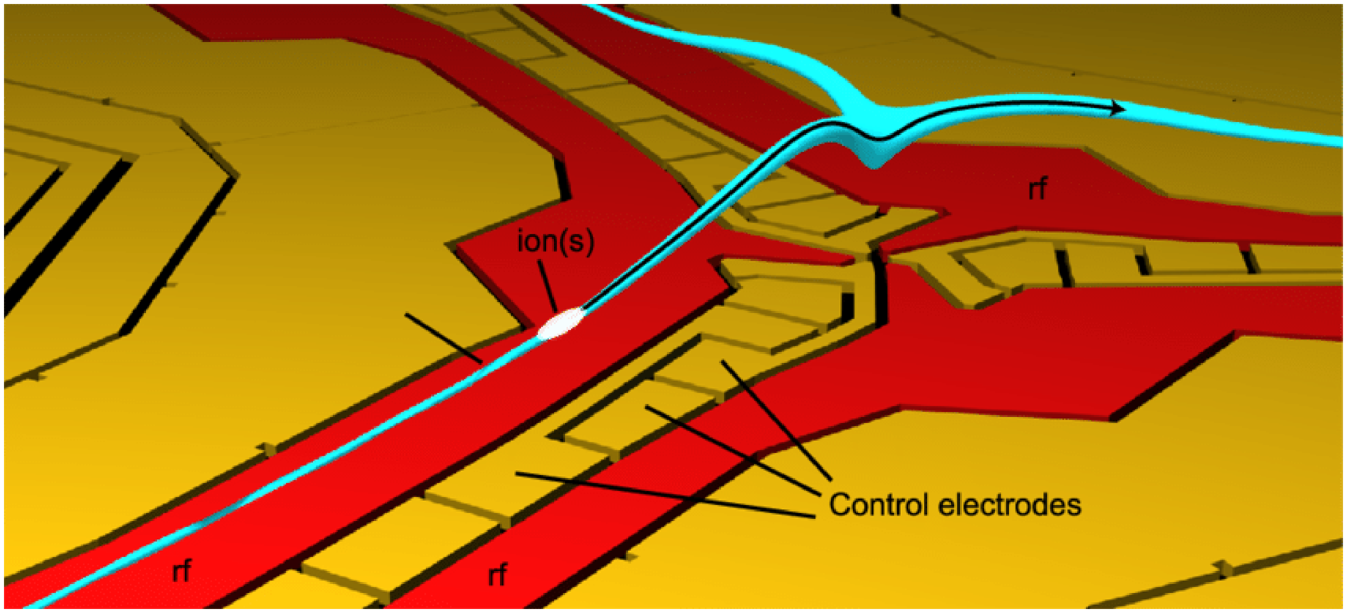


Quantum information is stored & manipulated in states of individual coupled ions.

https://en.wikipedia.org/wiki/Trapped_ion_quantum_computer

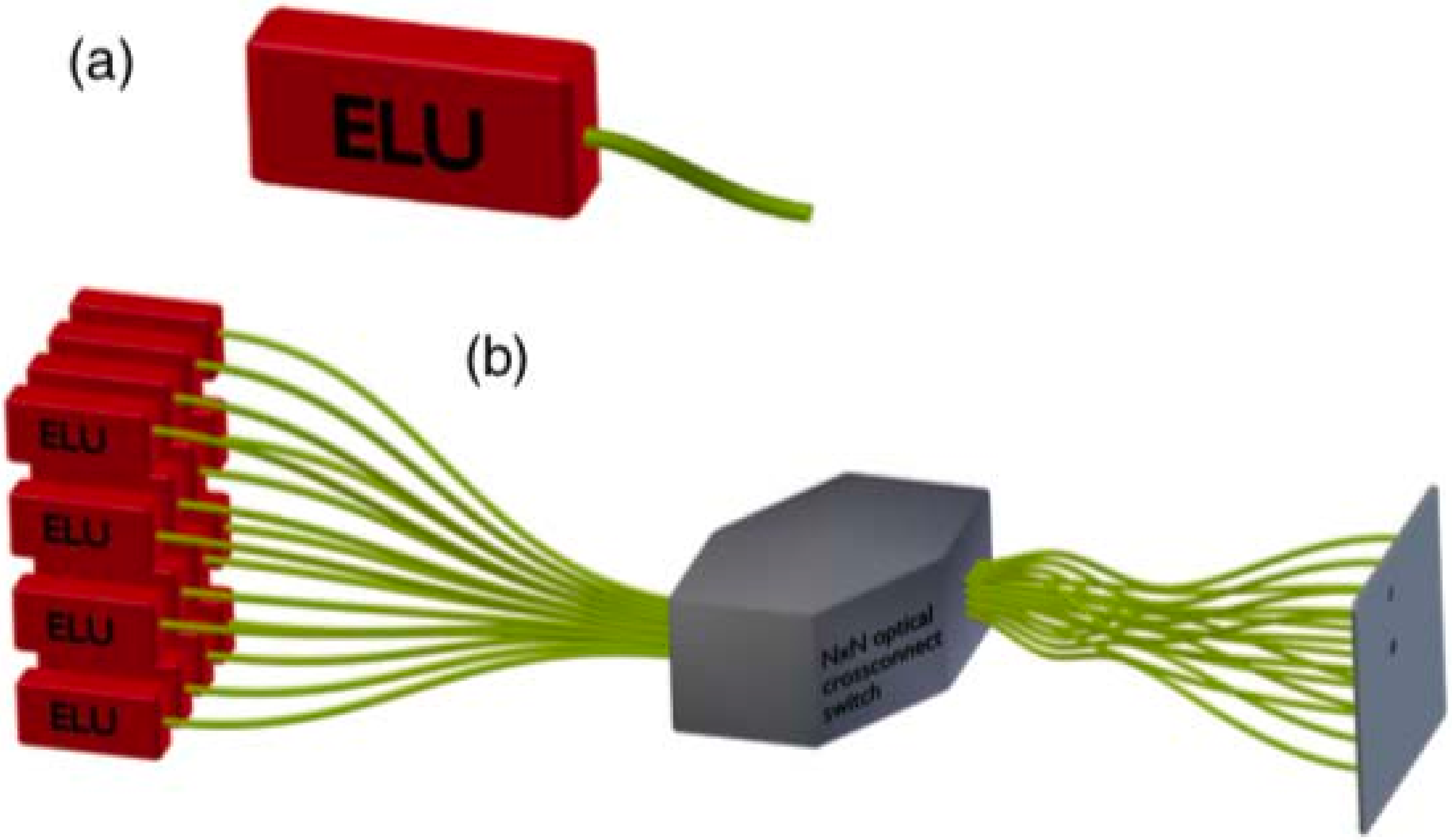
Trapping shuttling and addressing ions





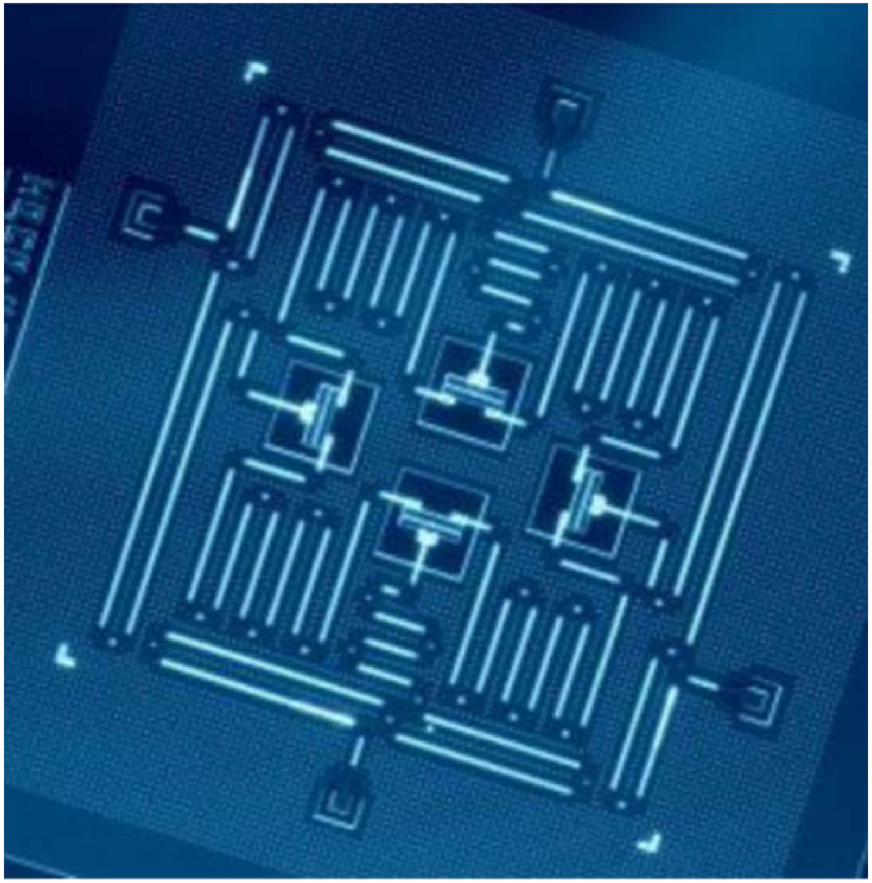
Scalable ion traps for quantum information processing
New Journal of Physics 12(3) · 2010

(Notional) scaling with photonic interconnects



Phys. Rev. A **89**, 022317 (2014)

Photonic / Superconducting (planar)

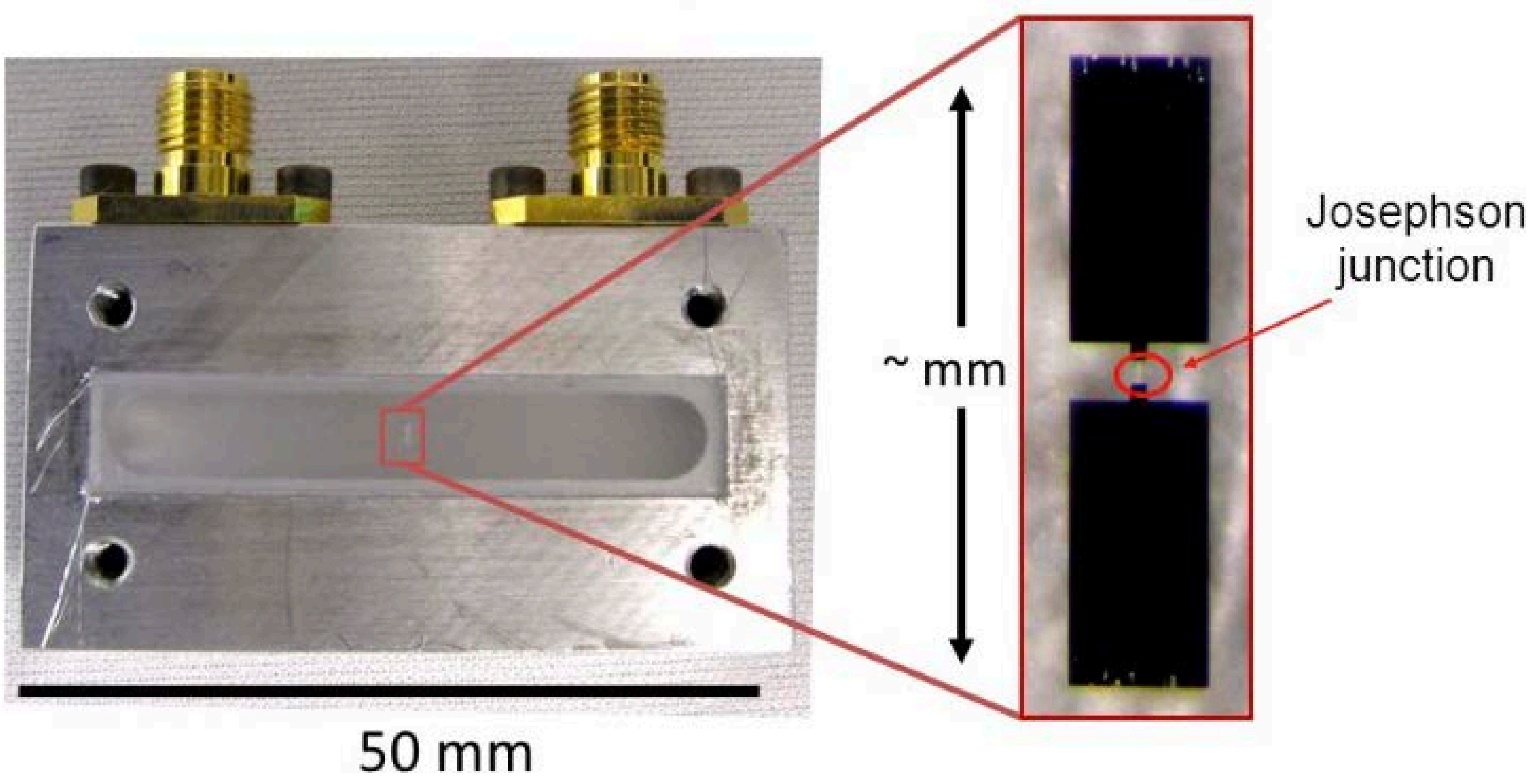


Four superconducting transmon qubits, four quantum busses, and four readout resonators fabricated by IBM

(npj Quantum Information 2017)

https://en.wikipedia.org/wiki/Superconducting_quantum_computing

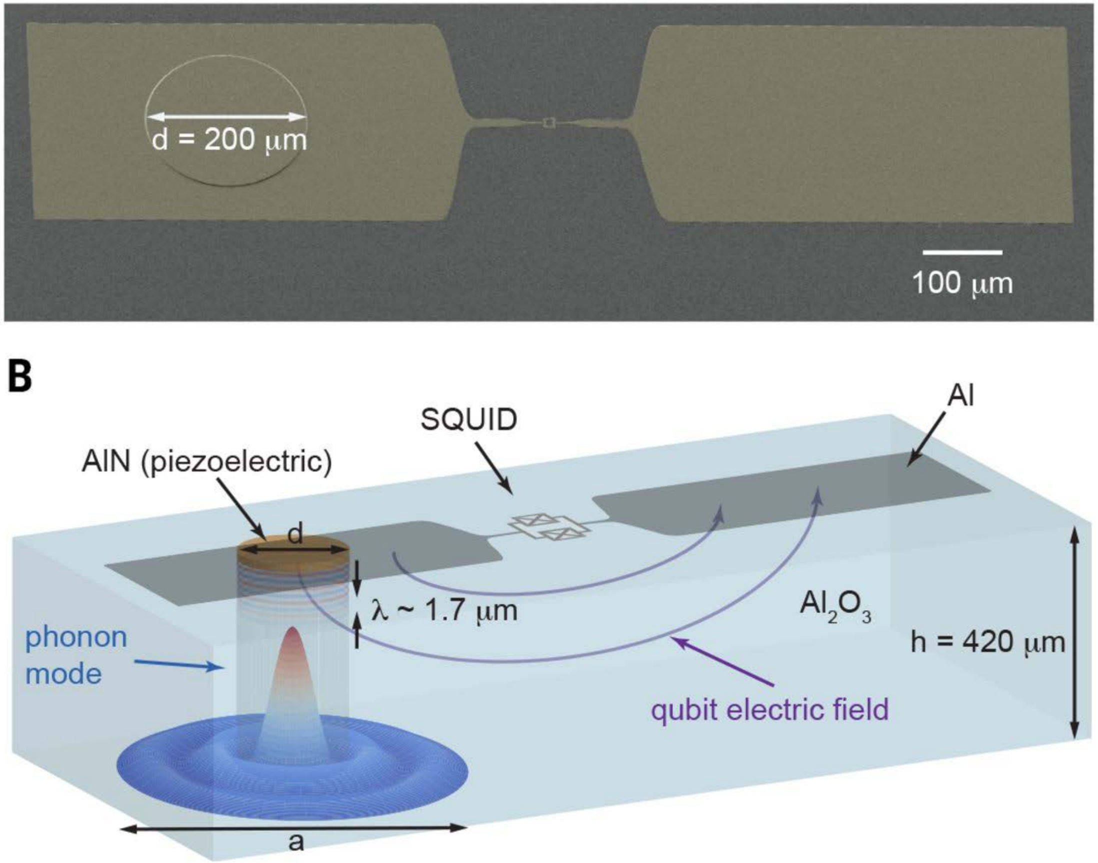
Superconducting (3D Transmon)



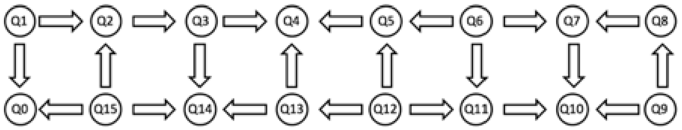
Lots and lots of design freedom…

Superconducting
(3D Transmon + coherent phonon + …)

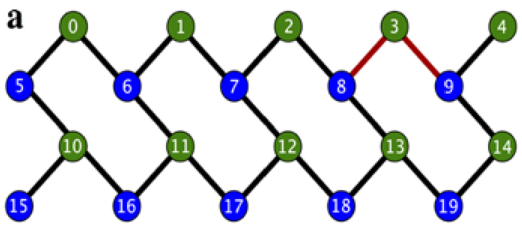
A



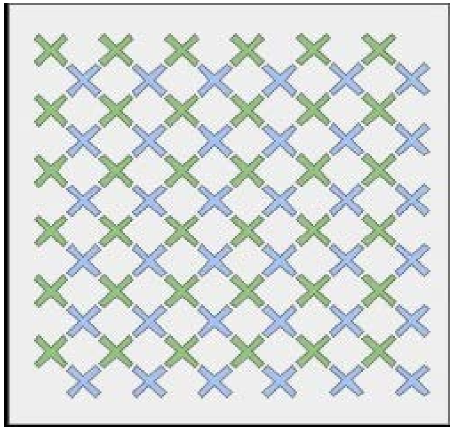
Scaling up from a single qubit



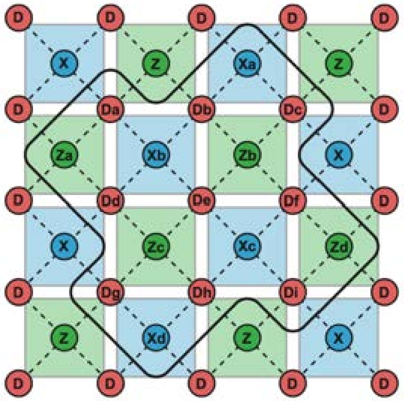
16-qubit backend: IBM Q team



Connectivity of Rigetti 19Q



Google “Bristlecone” nearest neighbor layout

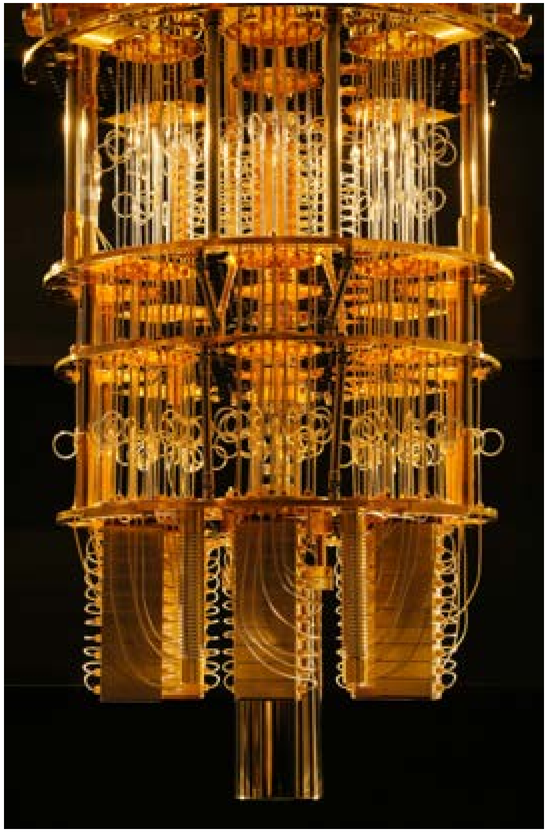


Layout of a surface-code fabric, Versluis et al.

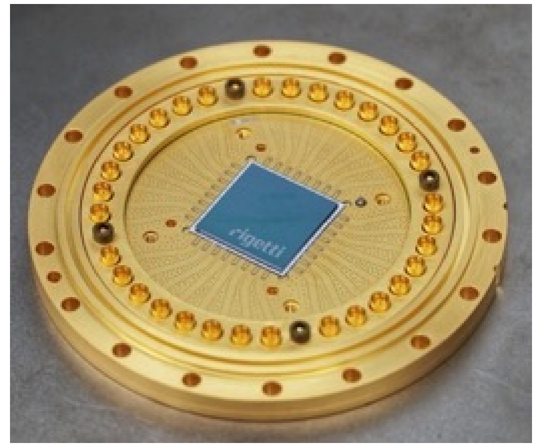
Major challenges in routing signals..

Coulomb interaction is long range so underlying physical Hamiltonian is inherently nonlocal. Canonical design seeks to minimize ‘crosstalk’

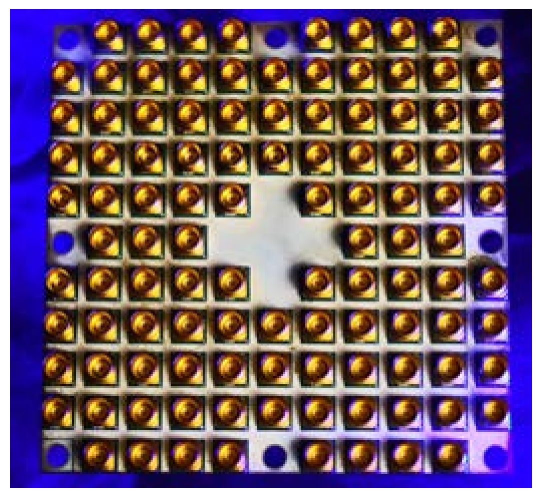
Control complexity, cost and fidelity bottlenecks are intertwined



An IBM Q cryostat used to keep IBM's 50-qubit quantum computer cold in the IBM Q lab in Yorktown Heights, New York.



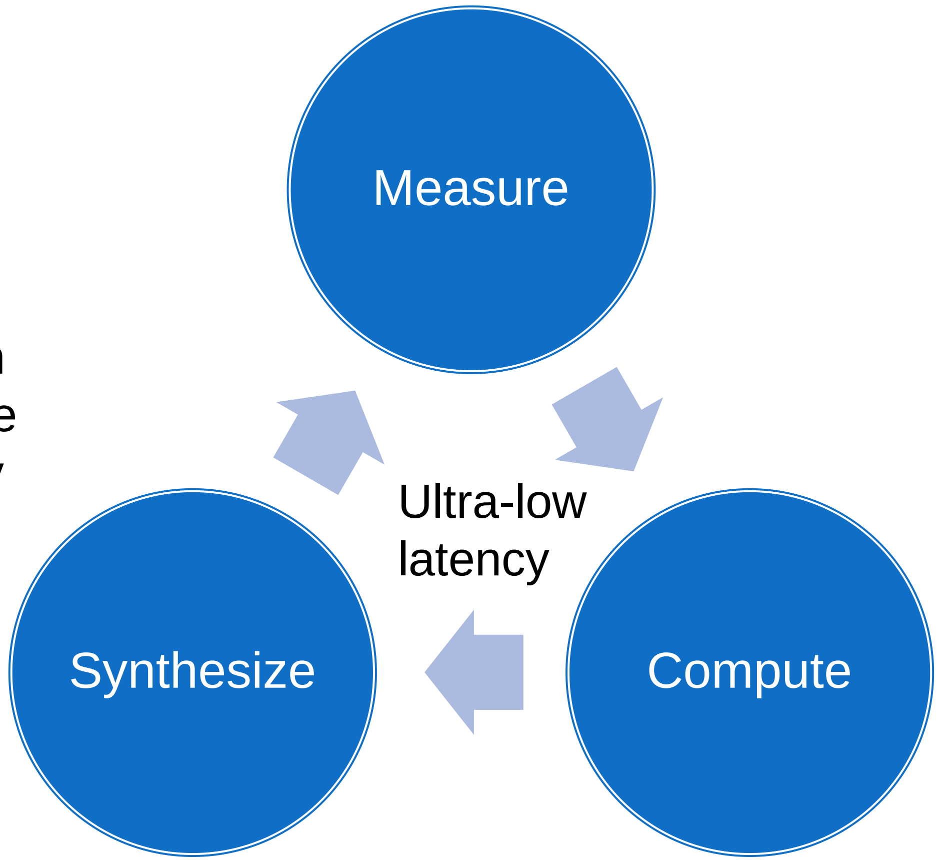
Rigetti Computing "Acorn" with RF connections.



Intel 49 qubit quantum test chip "Tangle Lake," with RF connections.

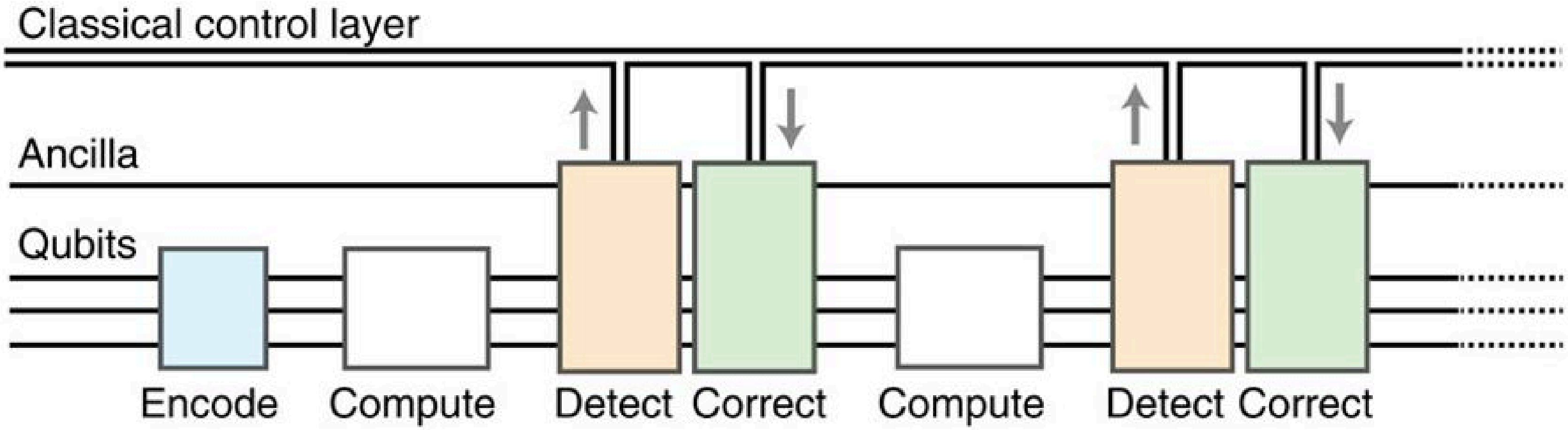
Classical control electronics / photonics in QC

Requires High
- Net Bandwidth
- Dynamic range
- Phase stability

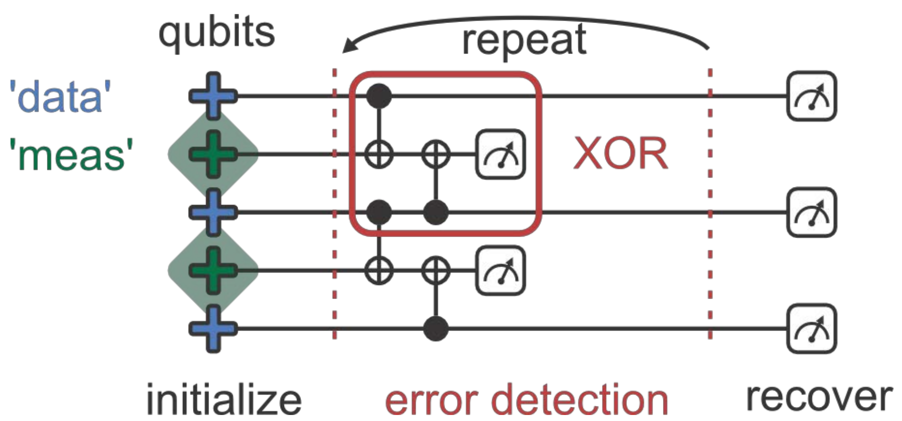


- Error syndrome decoding
- Online system learning & characterization

feedback control for error correction



Nature Communications **7**, 11526 (2016)



Time to measure, calculate error and send correction must be less than time for new errors to occur.

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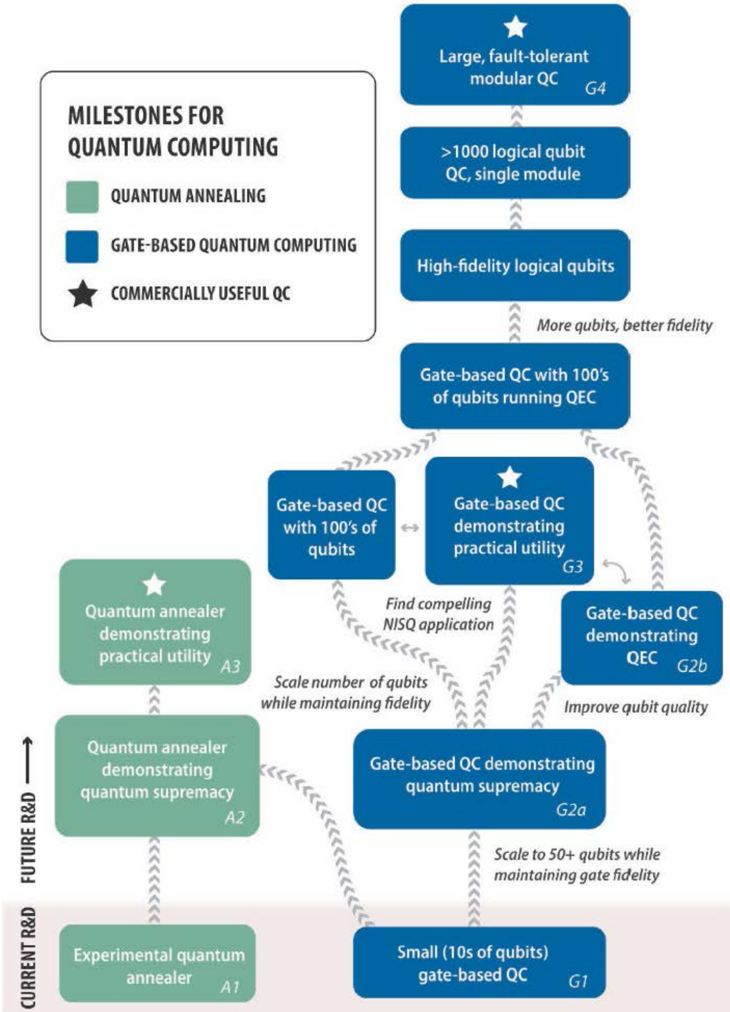
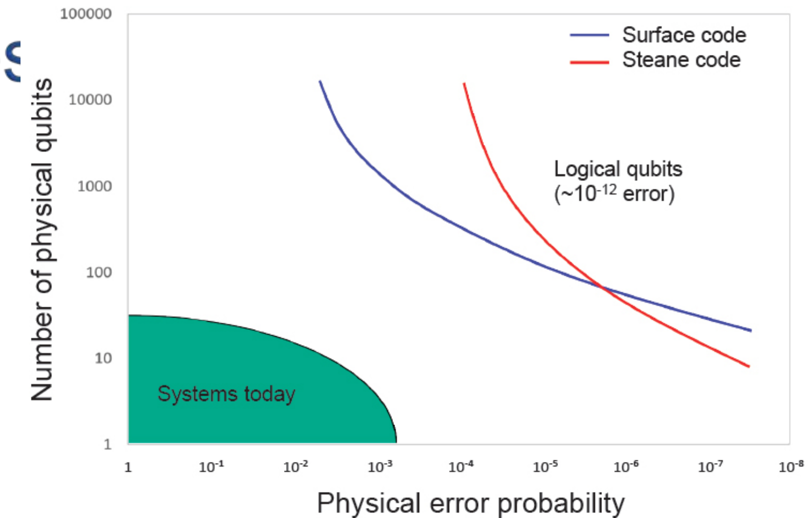
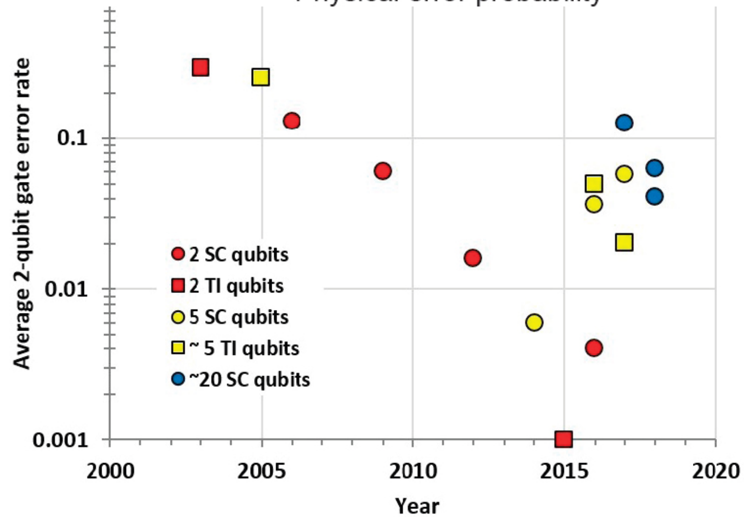






Quantum Computing: Progress and Prospects National Academy (2019)

What's available today?

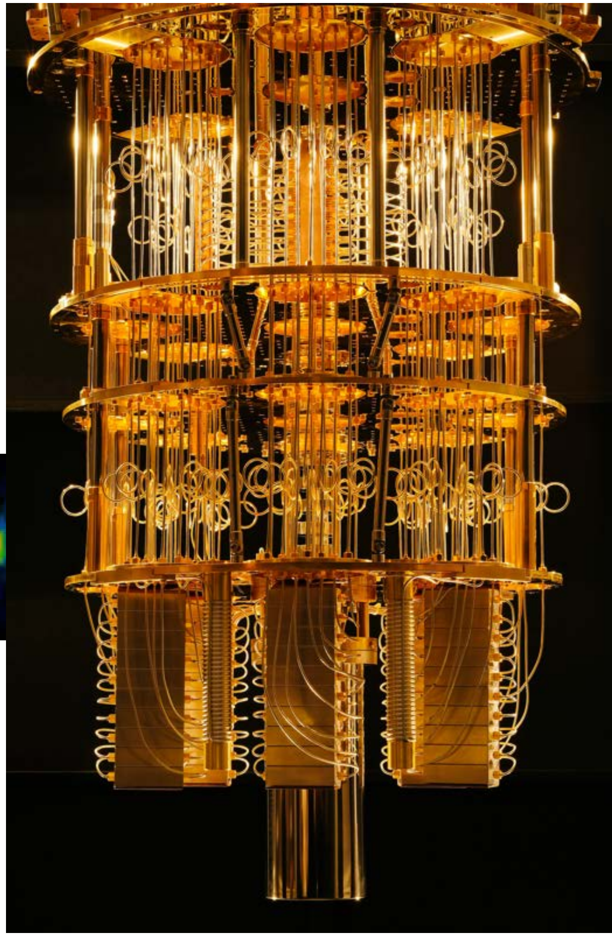
Superconducting:

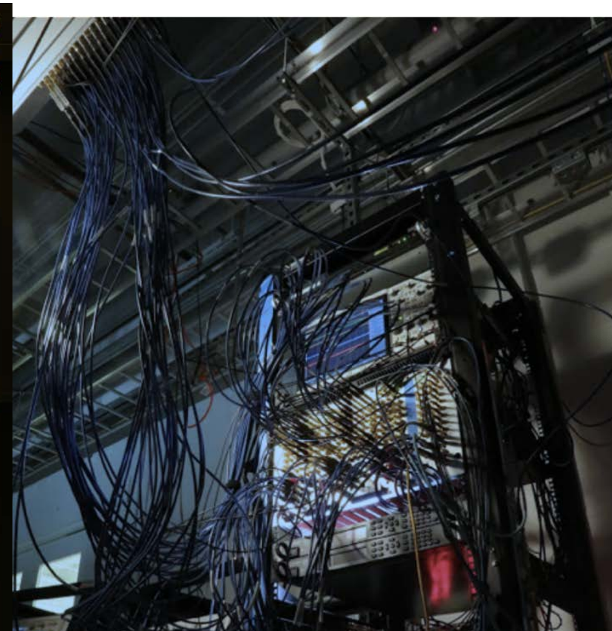
- LLNL testbed! ~6 qubits *experimental!*
- IBM 20 qubits (~6 effective) robust cloud access
- Rigetti 16 qubits (~5-6 effective) robust cloud access
- Google ?qubits (access by invitation)
- AQT ASCR testbed 8 qubits (access by proposal)

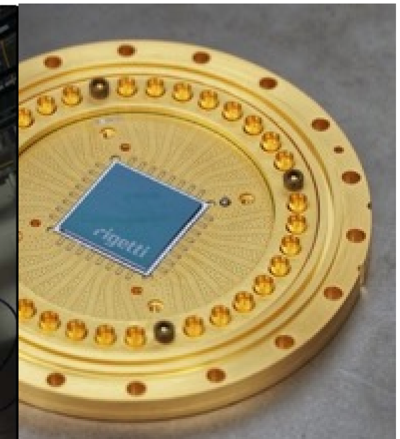
Trapped Ions

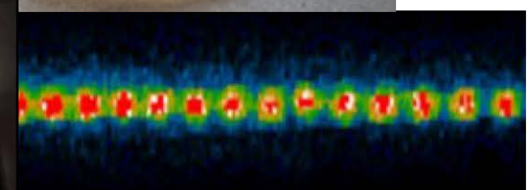
- IonQ 11 qubits (~11 effective) (access by invitation)
- Sandia ASCR testbed ~16 qubits (access by proposal)

Quantum computer ==
Systems engineering problem



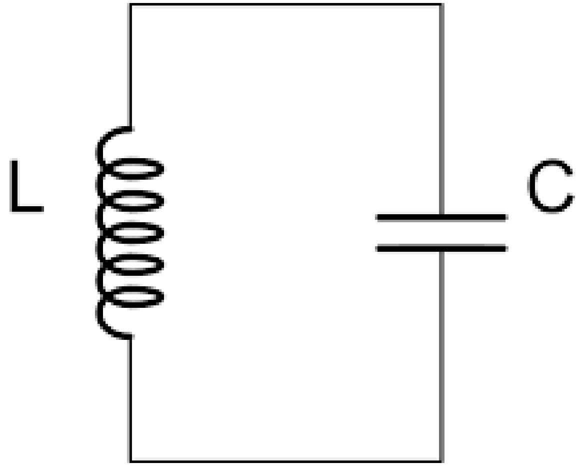




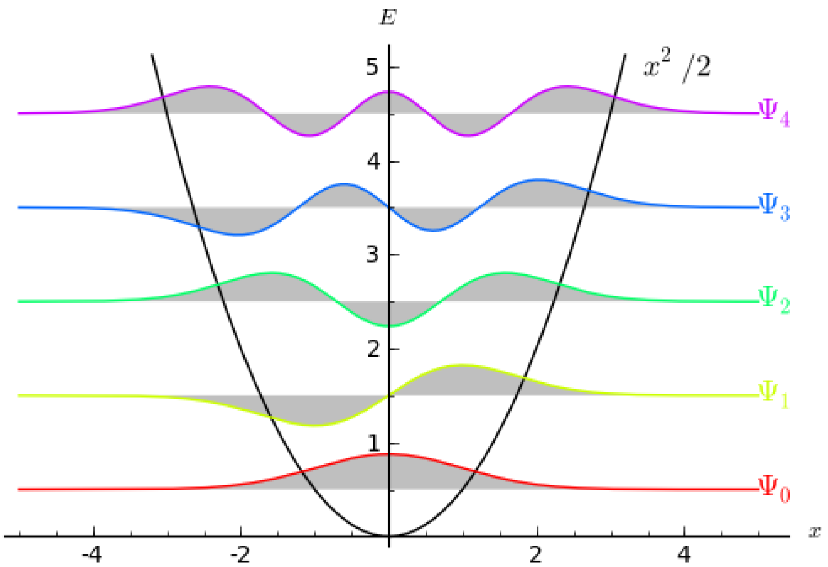


Back-up Slides

Superconducting quantum circuit oscillators

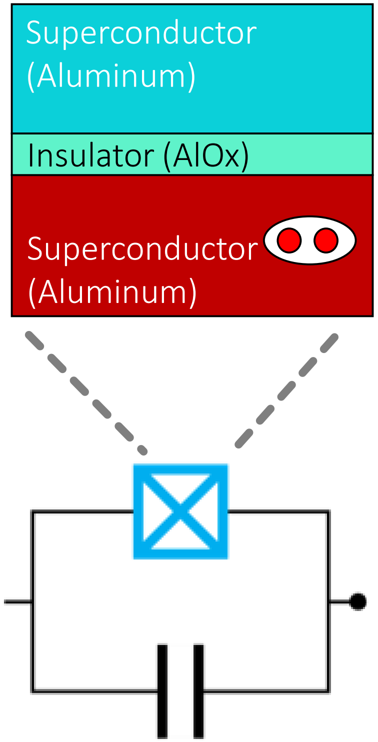


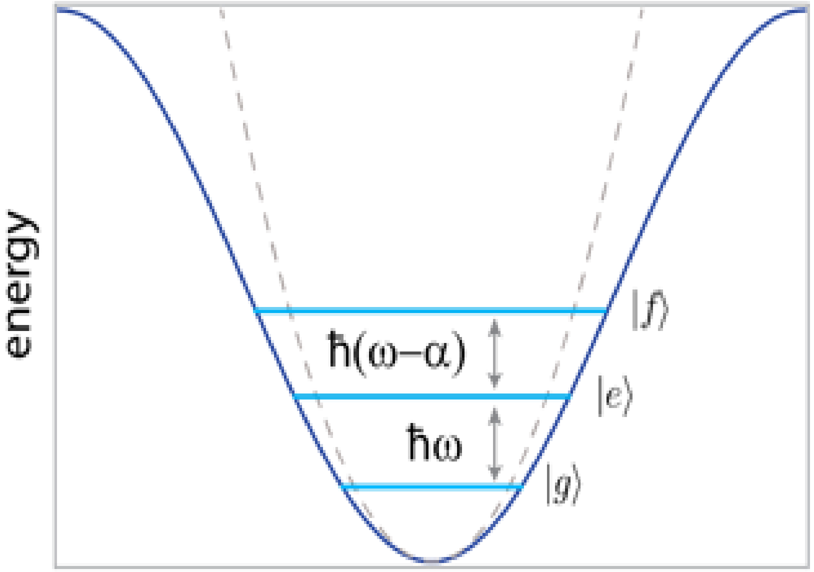
$$\omega_0 = \frac{1}{\sqrt{LC}}$$



Equally spaced energy levels

The importance of being nonlinear





Junction phase

A Quantum Engineer's Guide to Superconducting Qubits
https://arxiv.org/abs/1904.06560
Introduction to quantum electromagnetic circuits
International Journal of Circuit Theory and Applications
Volume 45 Issue 7, July 2017