Methods in quantum computing

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Today

1. Quantum physics
2. Selected physical architectures

Announcement

New problem set will be released this weekend. You will also get your the first homework back and graded.

Physical architectures

advantages

qubits - physical particles or artificial (advanatges for both)

must be a way to satisfy DiVincenzo's criteria

Hardware in 2022

spin qubits - UNSW - Diraq, SQC
- Delft U.
- Intel

⋮

~ fidelities > 99%
< 20 qubits

ion traps ~ 50 qubits
- former Honeywell (Quantinuum)
IONQ, Harvard, USyd, Colorado

photonics / optics - MQ, UTS, Brisbane
- PSIQUANTUM, XANADU

superconducting qubits - UTS
- IBM, Google, Rigetti
- MIT, Santa Barbara,
Yale...

NMR

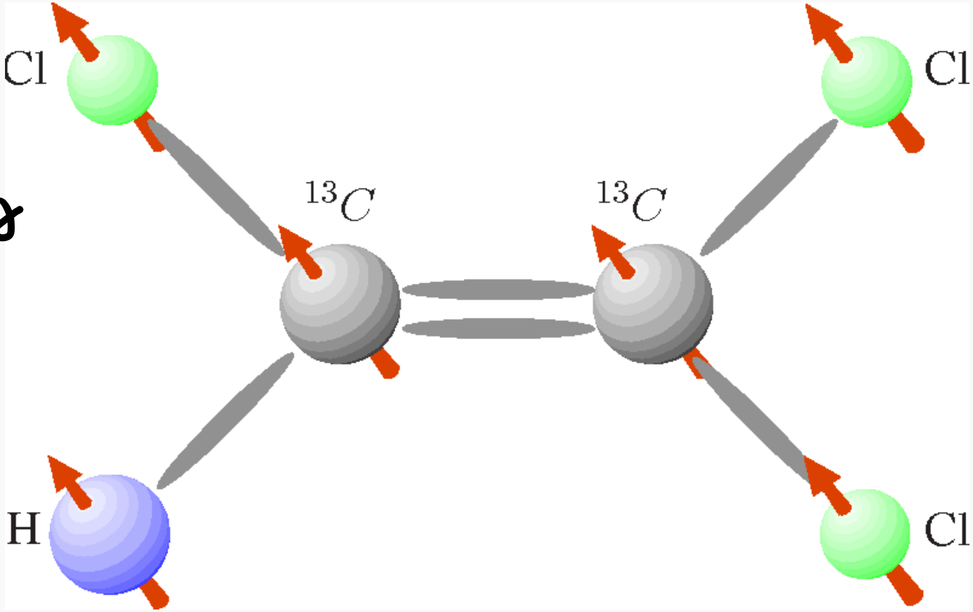
nuclear magnetic resonance

not scalable < 15 qubits

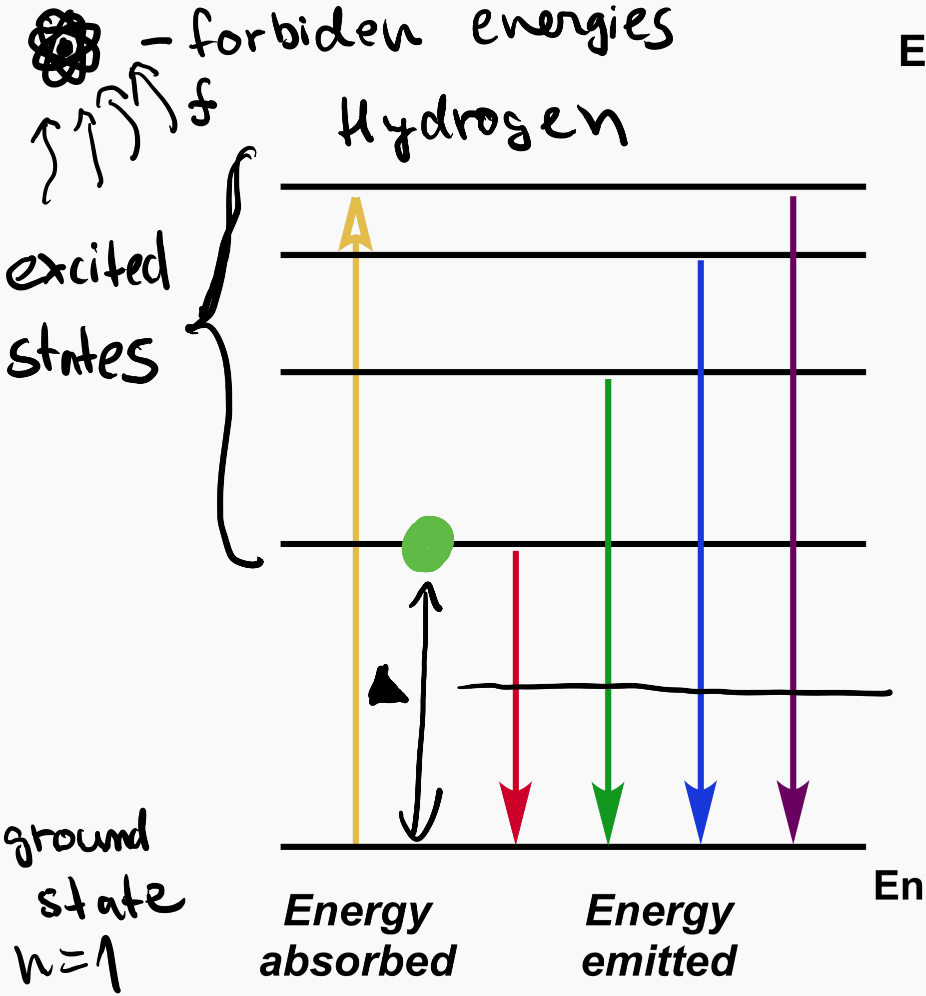
low purity

randomized benchmarking

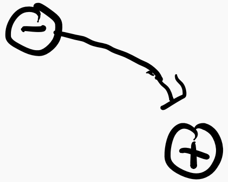
Hamiltonian learning



Quantized energy levels



Excited state		Ground state
6	410 nm →	2
5	434 nm →	2
4	486 nm →	2
3	656 nm →	2



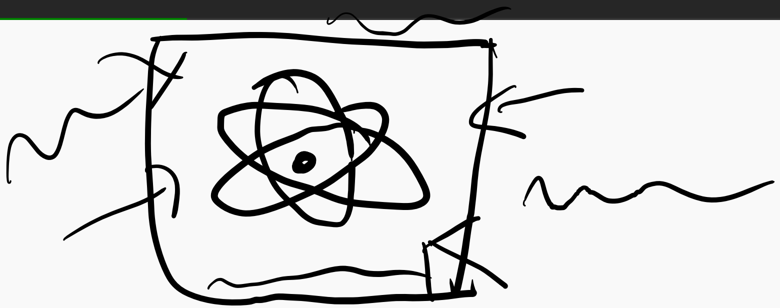
***n* = 2**
Energy level

Energy absorbed

Energy emitted

Figure 1: The simplest version of energy levels and spectrum of hydrogen.

Emission and absorption



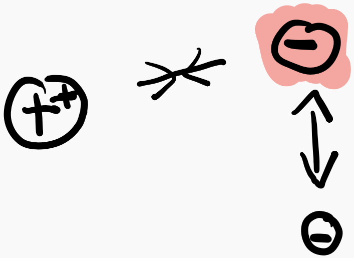
The photon will have an energy corresponding to the difference between the energy levels and we can also compute its frequency f and wavelength λ as

$$f = \frac{E}{h}, \quad \lambda = \frac{hc}{E} \tag{1}$$

where E stands for energy, h is the Planck constant, and c is the speed of light

Hamiltonian

Energy operator



1) potential energy from the nucleus

2) E_K

The allowed energies are then the eigenvalues E_i of the Hamiltonian and allowed states are their corresponding eigenvectors $|\psi_i\rangle$

real numbers

Hermitian matrix

$$H|\psi_i\rangle = E_i|\psi_i\rangle\,. \tag{2}$$

Hamiltonian will also determine how the system evolves in time through the (time-dependent) Schrödinger equation

$$\underbrace{e^{-iHt}}_{\text{exponentiation of an exp-large matrix}}|\psi(0)\rangle$$

eigenstate

$$e^{-iE_jt}|\psi_j(0)\rangle$$

number

$$i\hbar\frac{d}{dt}|\psi(t)\rangle = H|\psi(t)\rangle\,. \tag{3}$$

1

↳matrix

The state with the lowest energy is known as the ground state.

Spin qubit

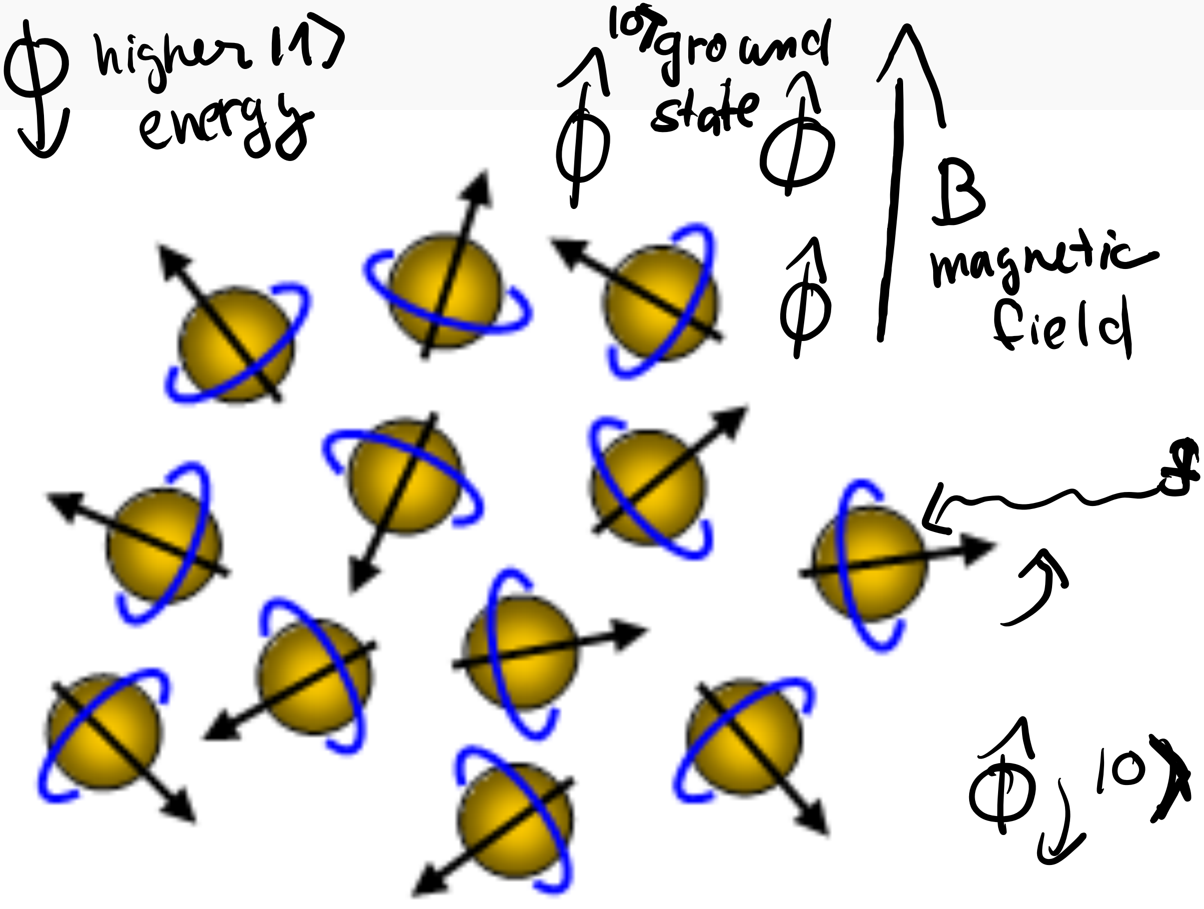
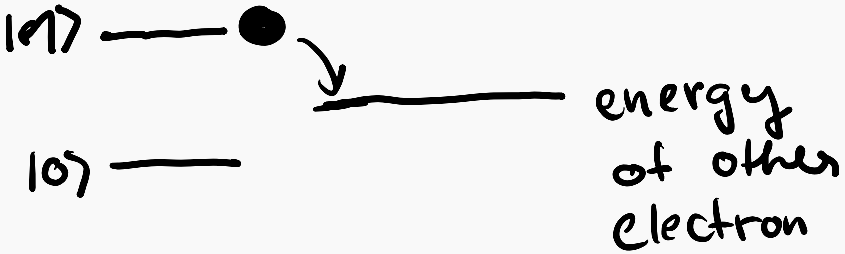


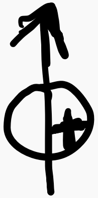
Figure 1

Excitation

Measurement



Nuclear spin



UNSW

Sydney (UNSW) is one of the world leaders in silicon qubits with different groups pursuing either nuclear or electron spin and different manufacturing techniques. While building spin qubits was proposed in the 90s, manufacturing the first qubits and their interaction proved to be challenging. Two qubit fidelities above 99% were demonstrated this year by three different groups including UNSW.

Strengths and limitations

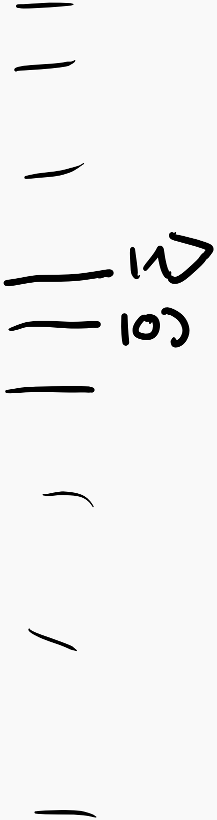
+ some approaches have very good prospects for scalability

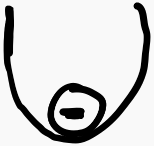
+ error rates below the threshold have been demonstrated

+ very fast gates (but perhaps too fast)

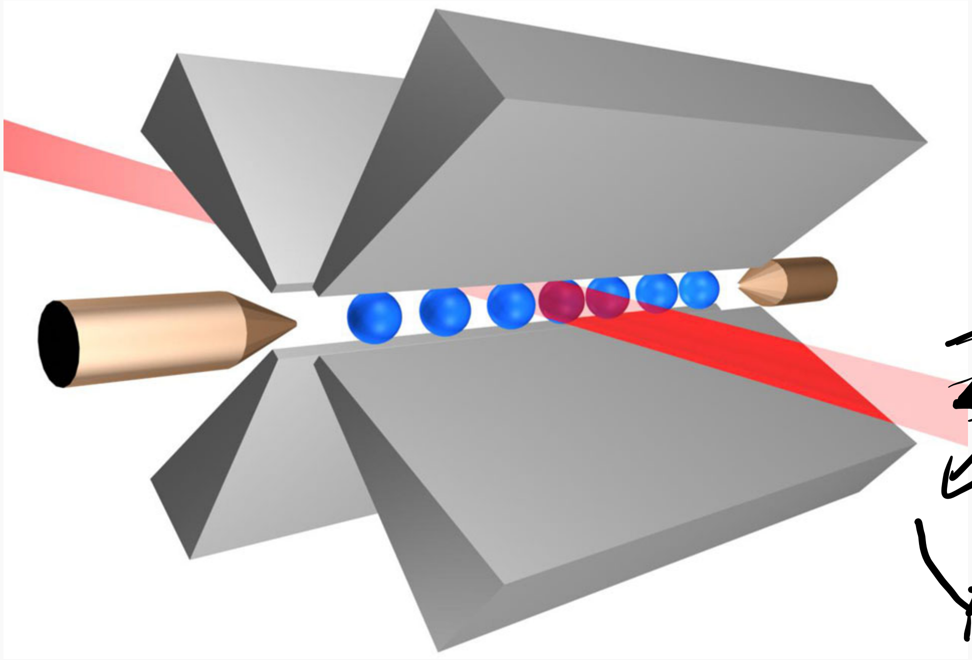
– building the first few qubits is incredibly challenging

Ion traps



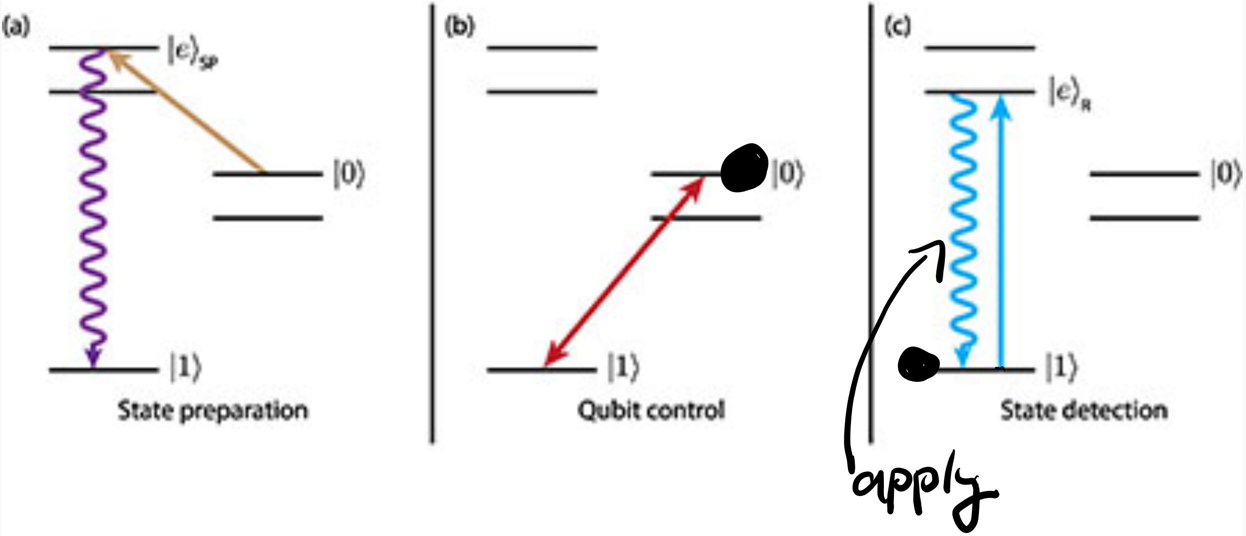


static electric field in 3D doesn't have a minimum.



Ion trap qubits

spectrum



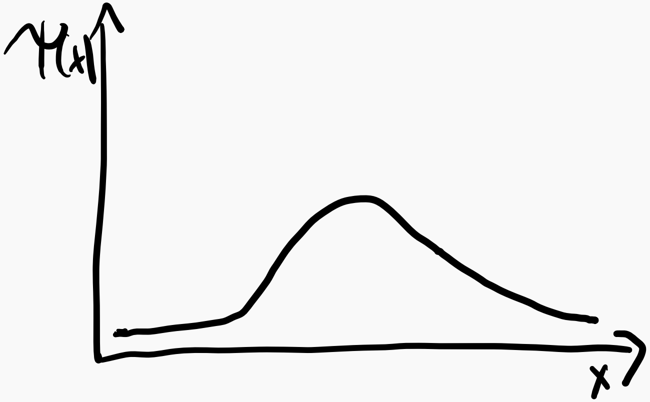
Strengths and limitations of ion traps

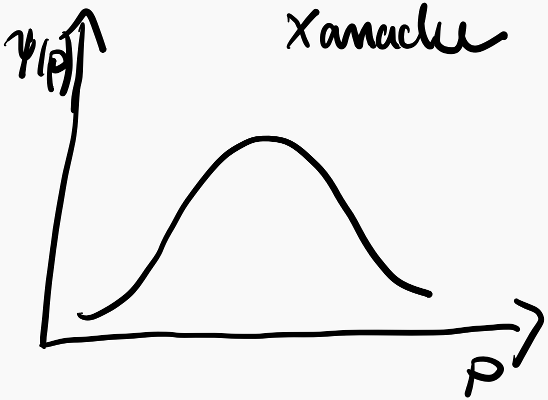
+ ions create identical qubits (but the control is not uniform)
+ lowest gate errors out of all approaches
− very slow gates
− About 50 ions is the maximum for a trap without using individual control. Coupling different traps has not been very successful so far.

Photonic qubits

Photons are elementary particles that can be used as qubits. Different properties of a photon can be used for computation. One is to give the photon two possible paths it can travel in and call one of their state $|0\rangle$ and another $|1\rangle$. These states are known as modes. Another approach is known as continuous variables quantum computation.

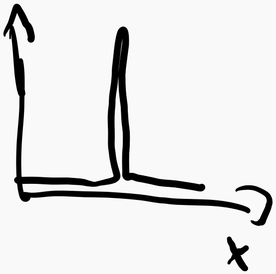
Continuous variables quantum computation





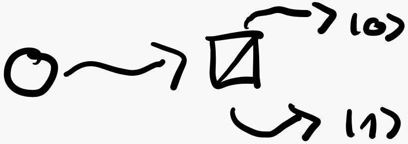
$$|\psi(x)\rangle = \int_x \psi(x) \, |x\rangle \tag{4}$$

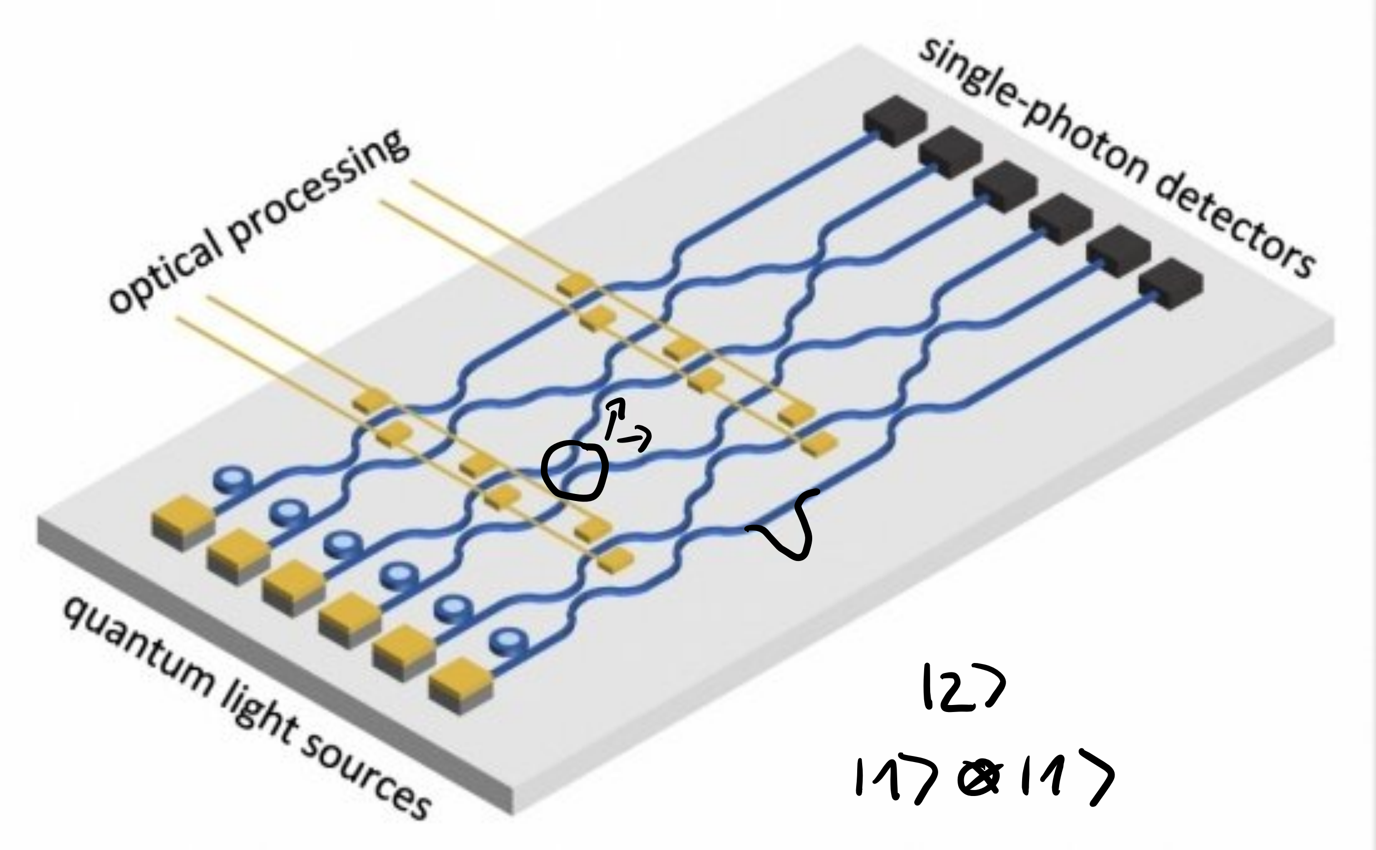
uncertainly principle



Linear optics

on chip or free space





$|2\rangle$

$|1\rangle \otimes |1\rangle$

Figure 2: Quantum photonic on a chip. Source: Galan Moody

Linear optics elements

mirrors, phase shifters, beamsplitters

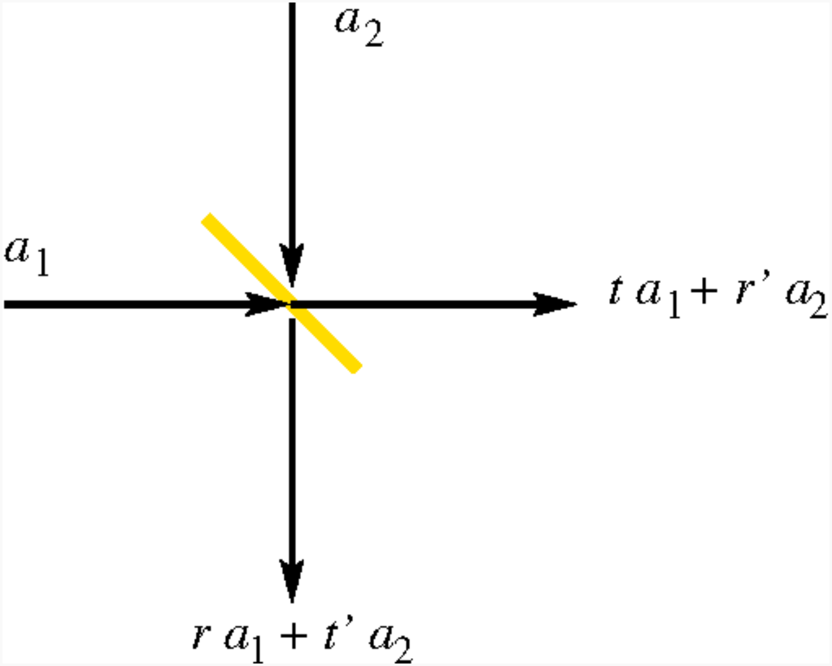


Figure 3: Beamsplitter can split a beam of light into two. If the light consists of a single photon, it will create a superposition across two different modes.

Credit University of Potsdam

Quantum computing with linear optics

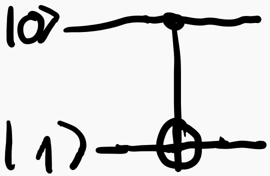
$$f(q_1+q_2) = f(q_1) + f(q_2)$$

Full quantum computation requires the addition of a nonlinearity.

Nonlinear materials exist but they are very lossy creating decoherence.

Another approach was proposed by Knill, Laflamme, and Milburn (KLM protocol). This approach shows how to perform universal quantum computation using only linear photonic, ancillae, and measurements.

Based on the outcome of the measurement, further gates are applied adaptively.



Strengths and weaknesses

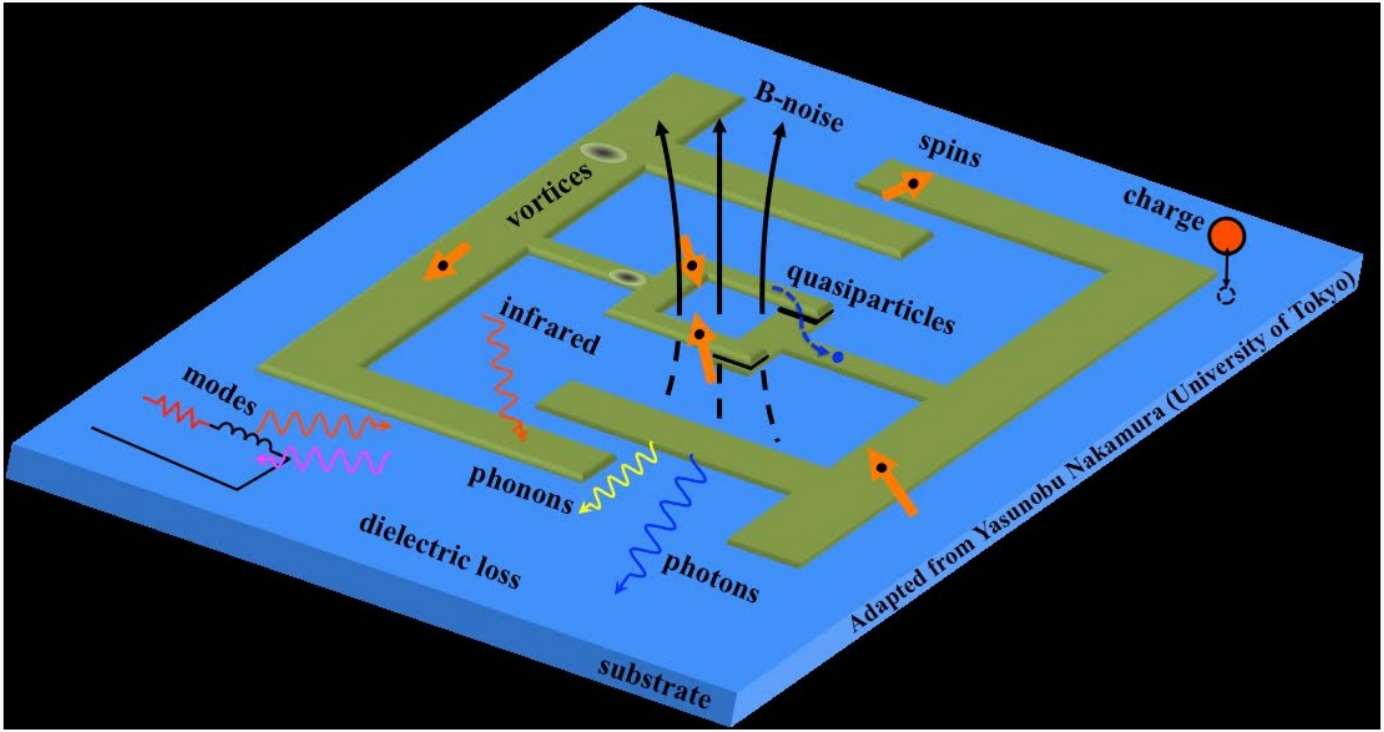
superconductors

temp~ few K

- \+ photons make "perfect" qubits
- \+ qubits don't need to be cooled (but still need low temperatures for superconducting detectors)
- \+ low intrinsic decoherence
- – lack of single photon sources
- – many gates are probabilistic
- – since photos travel at a speed of light, gates need to be perfectly timed
- – difficult error-correction

Superconducting qubits

"artificial atoms"



Adapted from Yasunobu Nakamura (University of Tokyo)

Superconductivity

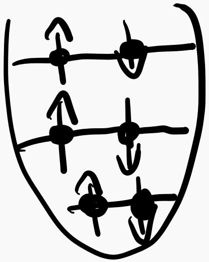
When a voltage U is applied to a regular conductor, a current starts I flowing through the circuit that is proportional to the voltage and inversely proportional to the resistance R of the circuit

$$I = \frac{U}{R}. \tag{5}$$

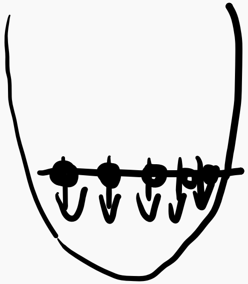
At very low temperatures (in the order of Kelvins, room temperature 300K), some materials become superconductors and have zero resistance. One of the effects that can be observed is that a current can flow through a superconductor without any voltage applied.

$R = 0$

Electrons and cooper pairs



fermions
electrons



bosons
Cooper pairs

Cooper pairs observe different statistics that electrons and in the superconductive regime, they can be all in the same quantum state. This collective behavior leads to quantum mechanical effects that are observable on a macroscopic scale.

Josephson junctions

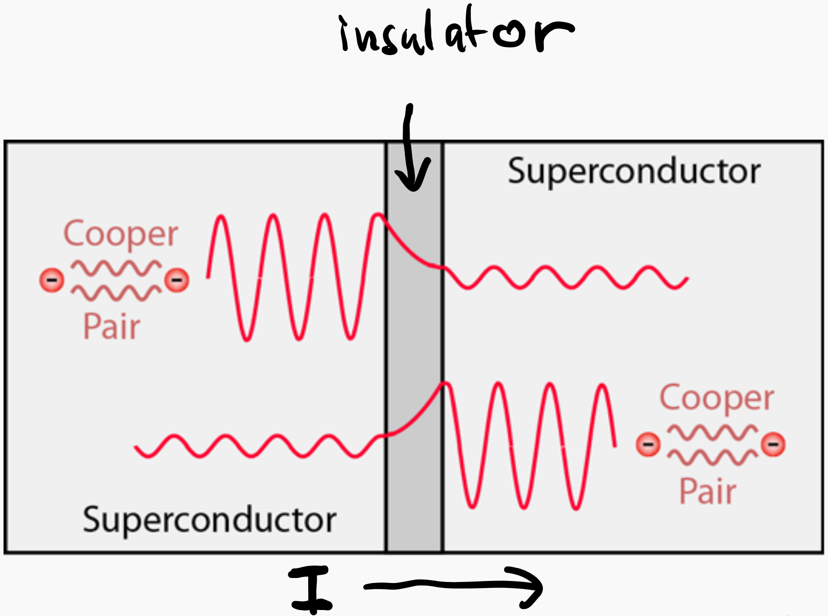


Figure 4: Josepson junction is an essential circuit element of superconducting qubits, source `http://hyperphysics.phy-astr.gsu.edu/`

Transmons

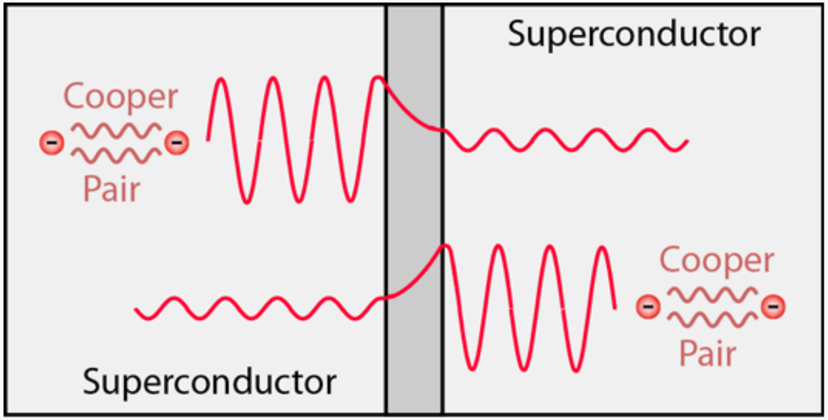


Figure 5: Josepson junction is an essential circuit element of superconducting qubits, source `http://hyperphysics.phy-astr.gsu.edu/`

Superconducting qubits

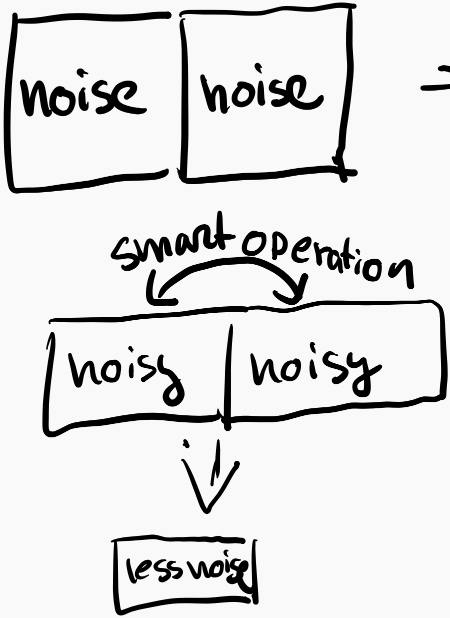
~127 qubits for IBM

~ 72 qubits Google

- + Error rates are relatively low
- – The qubits must be kept at mK temperatures. This is possible but requires a dilution refrigerator.
- – The qubits are quite large, coupled with control electronic makes building chips above 1000s of qubits too large for dilution refrigerators

Scaling up

Treshold theorem - Aharonov
Ben-Or
?


noise noise → more noise

smart operation
noisy noisy
↓
less noise

~1000 noisy qubits
↓
1 perfect

NISQ

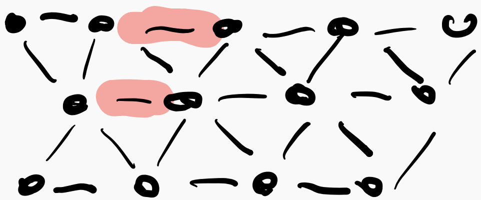
noisy intermediate scale quantum

↳ no error correction

↑ 10s - 100s of qubits

- shallow quantum circuits
- limited number of qubit

NP



↗ higher error

cross talk

Error correction

fault-tolerant quantum computer

how to
correct
errors

running large
algorithms
on q. comps
that are
error-free

Fault tolerant quantum computers