Quantum Computers

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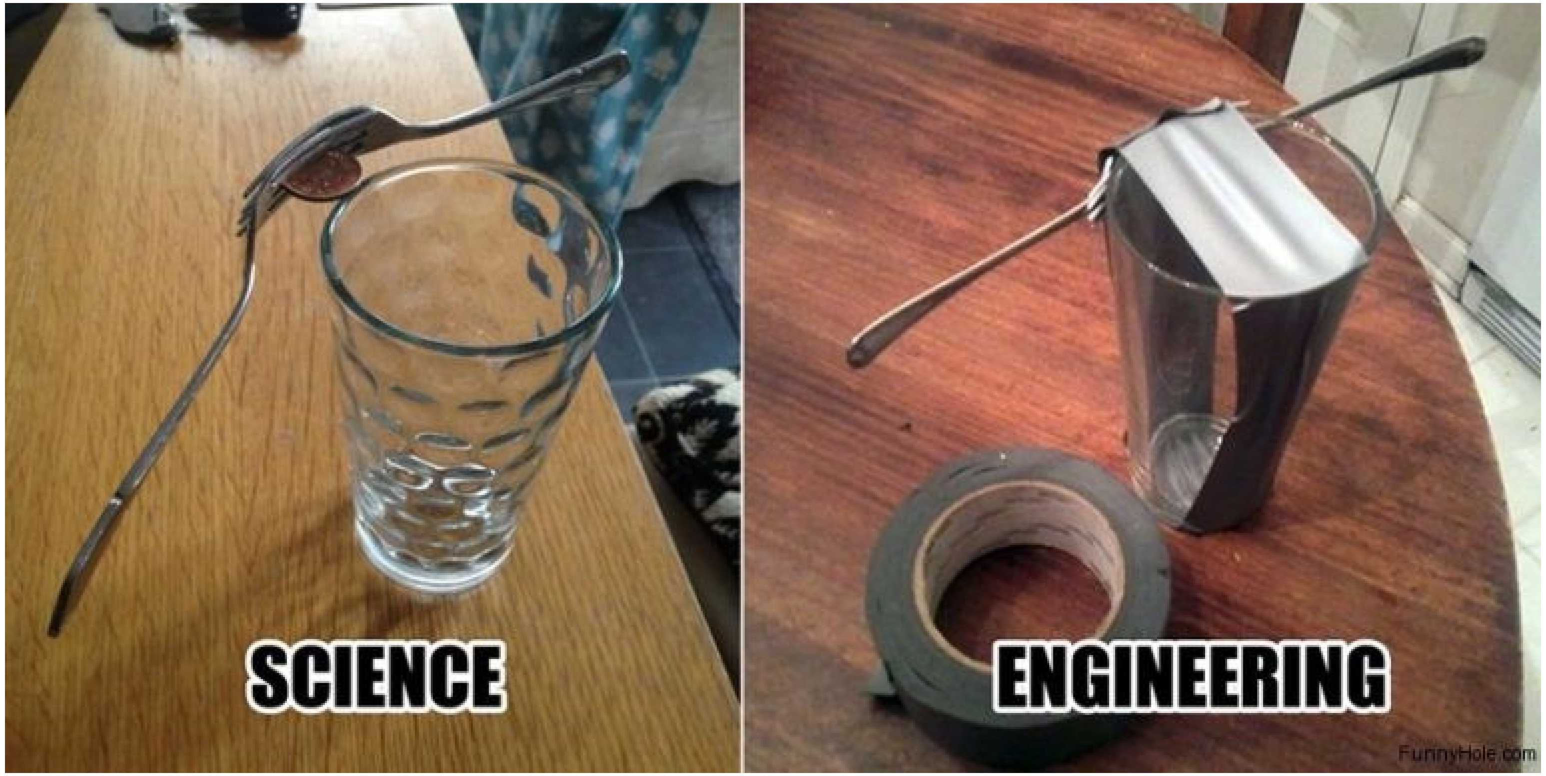
Disclaimer



Quantum Computers

Classical Digital Computers

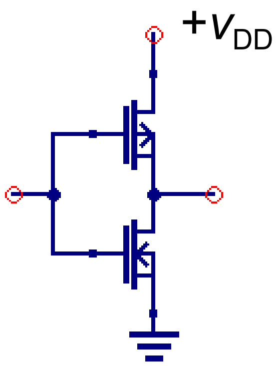
Why quantum computers?

Basics of QM

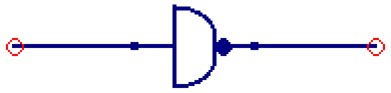
- Spin-Qubits
- Optical qubits
- Superconducting Qubits
- Topological Qubits

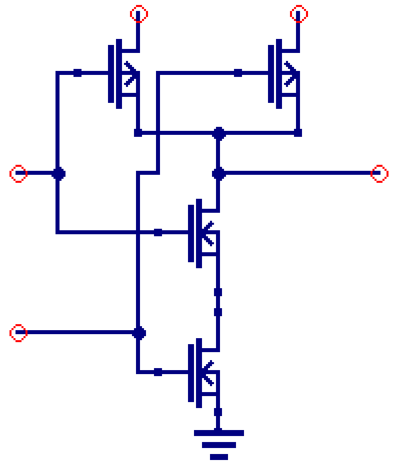
Classical Computing

- We build digital electronics using CMOS
- Boolean Logic
- Classical Bit – 0/1 (Defined as a voltage level 0/+V_{dd})

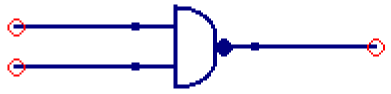


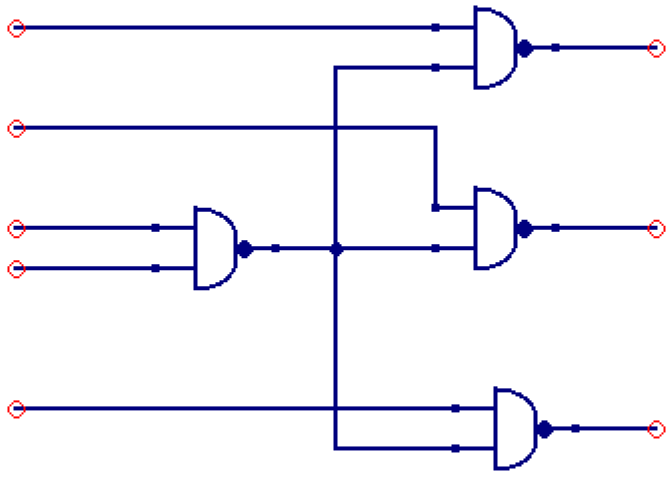
Inverter





NAND

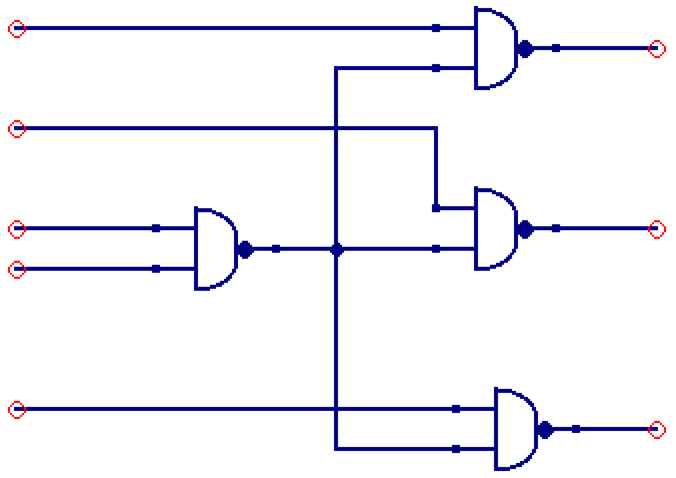




Logic is built by connecting gates

Classical Computing

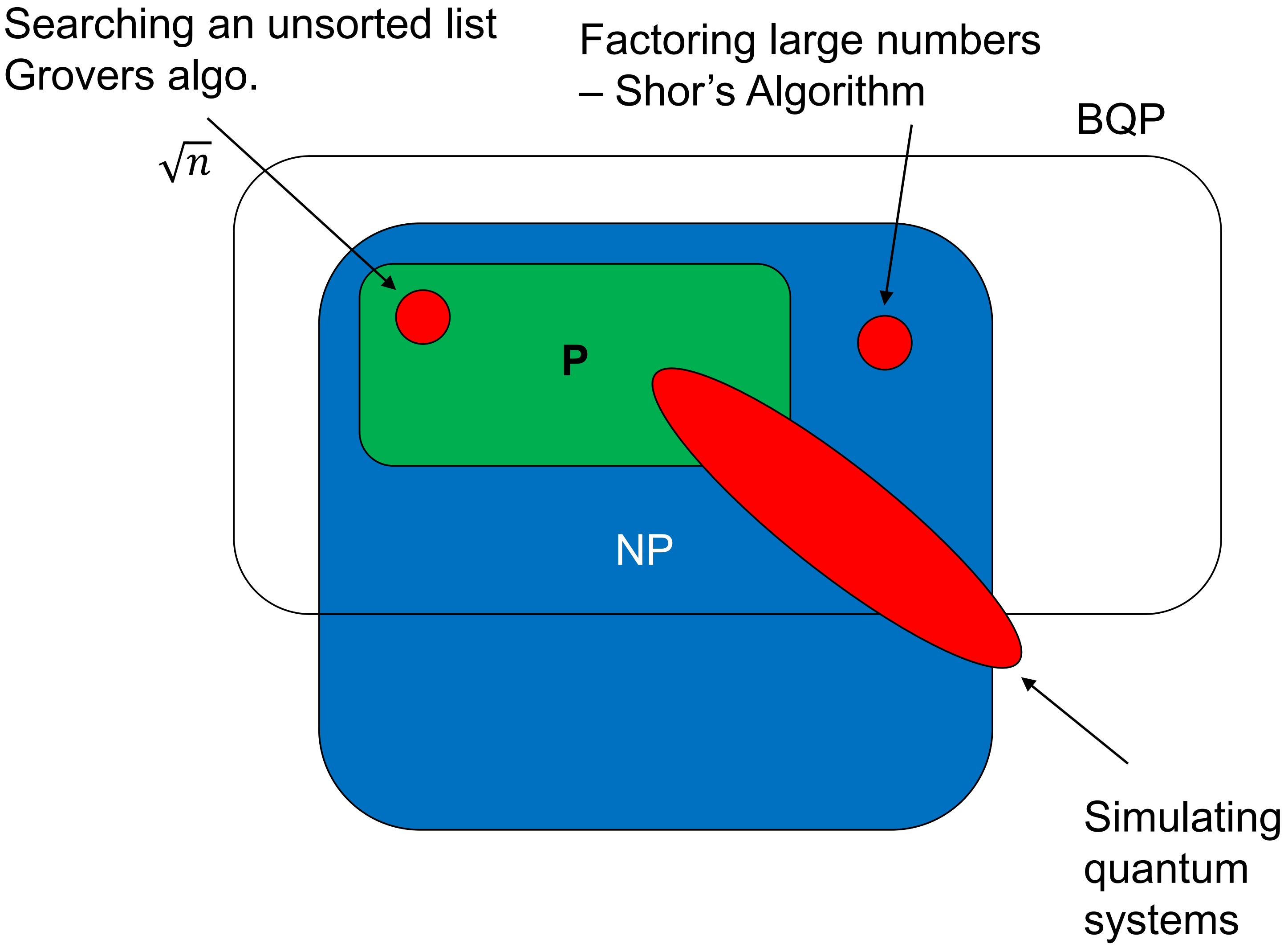
- We build digital electronics using CMOS
- Boolean Logic
- Classical Bit – 0/1



- Very rubust!
- Modern CPU – billions of transistors (logic and memory)
- We can keep a logical state for years
- We can easily copy a bit
- *Mainly through irreversible computing*

However – some problems are *hard* to solve on a classical computer

Computing Complexity



- P – *easy* to solve and check on a classical computer ~O(N)
- NP – easy to check – hard to solve on a classical computer ~O(2^N)
- BQP – easy to solve on a quantum computer. ~O(N)
- **BQP is larger then P**
- *Some* problems in P can be more efficiently solved by a quantum computer

Note – it is still ***not*** known if $P = NP$.

It is very ***hard*** to build a quantum computer…

Basics of Quantum Mechanics

A state is a vector (ray) in a complex Hilbert Space

Dimension of space – possible eigenstates of the state

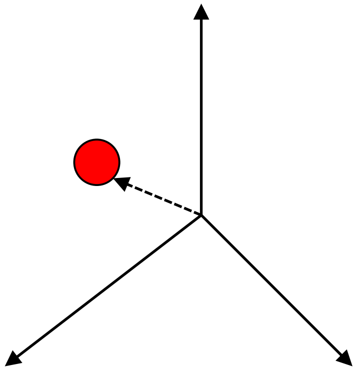
For quantum computation – **two dimensional Hilbert space**

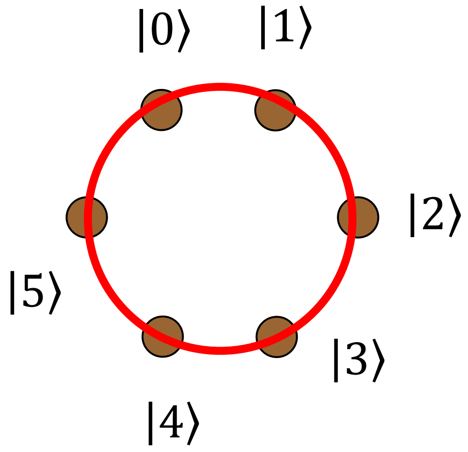
Example - Spin ½ particle - $|\uparrow\rangle\ or \downarrow\rangle$

Spin can either be ‘up’ or ‘down’

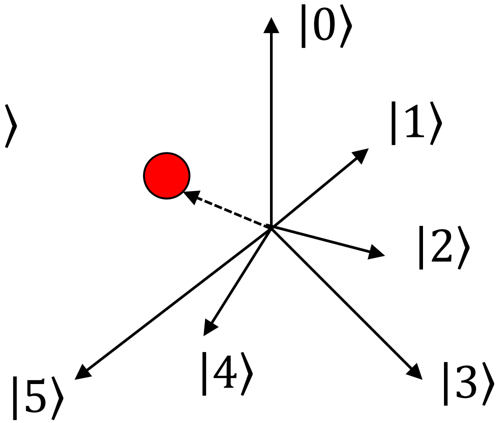
Basics of Quantum Mechanics

- A state of a system is a vector (ray) in a complex vector (Hilbert) Space.
- Denoted $|x\rangle$ using Dirac notation. *(You can think of this as a vector in 3D space.)*
- Orthonormal basis vectors – various observables (Energy, position, momentum, spin direction…).
- A state can be in a superposition of the basis vectors

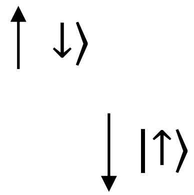


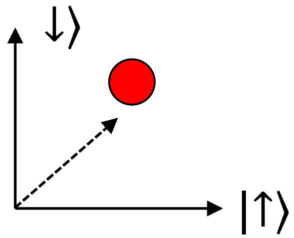


Example – the position of an electron on a molecule

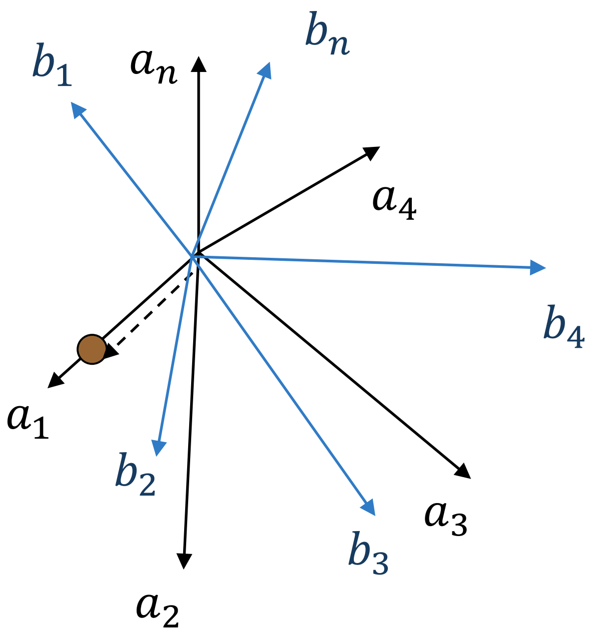


Example – spin of a electron





Basics of Quantum Mechanics



Depending on the choise of basis – the state of an particle can be described using different basis vectors!

$|\psi\rangle = |a_1\rangle$

$|\psi\rangle = a|b_1\rangle + b|b_2\rangle + c|b_3\rangle + \cdots$

Ex: Difference between position and momentum eigenstates

Uncertainty relation $[x, p] = -i\hbar$

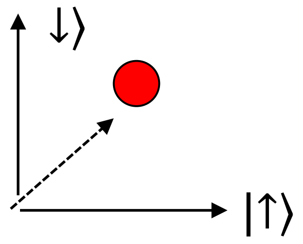
Coefficients α, β, γ are complex numbers

State is normalized: $|\alpha|^2 + |\beta|^2 + |\gamma|^2 + \cdots = 1$

Can be expressed in various bases (observables)

- Energy
- Position
- Momentum
- …

Basics of Quantum Mechanics



For quantum computation – **effective 2D dimensional Hilbert space**
This is called a quantum bit (qubit, qbit)

$$|\psi\rangle = \alpha|0\rangle + \beta|1\rangle = \alpha|\uparrow\rangle + \beta|\downarrow\rangle$$

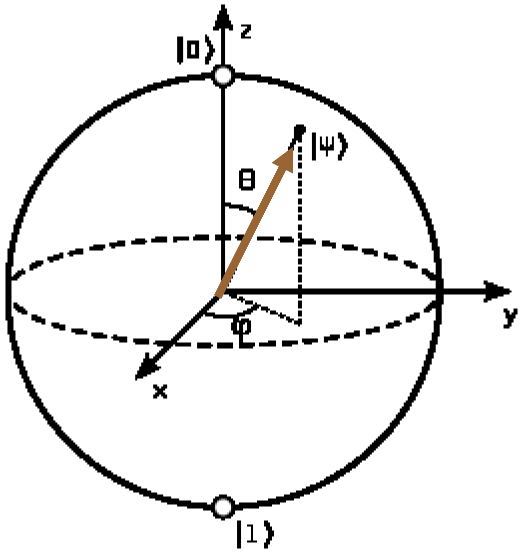
- Example - Spin ½ particle - $|\uparrow\rangle\ \downarrow\rangle$: 2 dimensional Hilbert space

$$|\psi\rangle = \alpha|0\rangle + \beta|1\rangle \qquad \binom{\alpha}{\beta}$$

Matrix representation of a state

α anb β – two complex numbers
State is normalized: $\alpha^2 + \beta^2 = 1$

Quantum Bit – two level system



Bloch Sphere representation

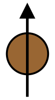
Computational basis (with spins)

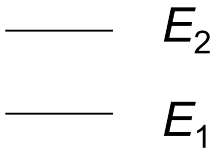
- Spin up in z-direction
- Spin down in z-direction

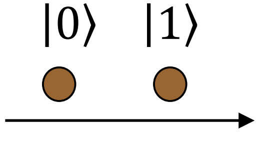
Spin in x-direction? $|S_x\rangle = \frac{1}{\sqrt{2}}|0\rangle + \frac{1}{\sqrt{2}}|1\rangle$

Quantum system with only two distinct (energy) states

- Spin ½ particle (spin)
- Double quantum dot (position)
- Atom (orbitals)







Normalized
Complex coeff.

$$|\psi\rangle = \alpha|0\rangle + \beta|1\rangle$$

$$|\psi\rangle = \sin\left(\frac{\theta}{2}\right)|0\rangle + \cos\left(\frac{\theta}{2}\right)e^{i\phi}\,|1\rangle \qquad \begin{pmatrix}\alpha\\ \beta\end{pmatrix}$$

For one spin ½ particle – the Bloch sphere represent the spatial orientation of the spin!

Many qubits

Qubit A

Qubit B

$$|\psi\rangle_A = \alpha_A|0\rangle_A + \beta_A|1\rangle_A$$

$$|\psi\rangle_B = \alpha_B|0\rangle_B + \beta_B|1\rangle_B$$

Tensor product

$$|\psi\rangle = |0\rangle_A \otimes |1\rangle_B = \overset{\text{A}}{|0}\underset{\text{B}}{1\rangle}$$

H_A

H_B

Example: Two non-interacting qubits – *product* state

$$|\psi\rangle = |\psi\rangle_A \otimes |\psi\rangle_B = \alpha_A\alpha_B|00\rangle + \beta_A\alpha_B|10\rangle + \alpha_A\beta_B|01\rangle + \beta_A\beta_B|11\rangle$$

Example: Two correlated qubits – *entangled* state

$$|\psi\rangle = \frac{1}{\sqrt{2}}(|10\rangle + |01\rangle)$$

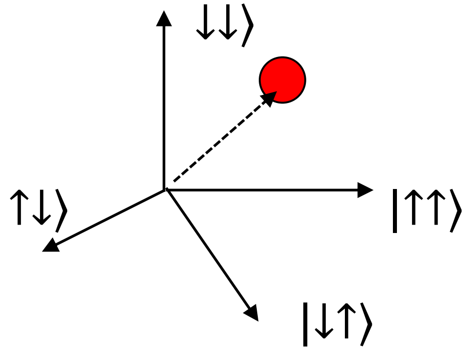
This can NOT be written as a product state!

N Coupled qbits requires 2^N complex numbers to describe

N=100 : $2^{100} \approx 10^{30}$ complex numbers

Example: General 2 qubit state

$$|\psi\rangle = \alpha|00\rangle + \beta|10\rangle + \gamma|01\rangle + \delta|11\rangle$$



Superposition of 2-bit states

$$|\psi\rangle = \frac{1}{\sqrt{2}}[|0\rangle + |1\rangle]$$

one spins – 2 states $|\downarrow\uparrow\rangle$

$$|\psi\rangle = \frac{1}{\sqrt{4}}[|00\rangle + |10\rangle + |01\rangle + |11\rangle]$$

Two spins – 4 states

$$|\psi\rangle = \frac{1}{\sqrt{8}}[|000\rangle + |001\rangle + |010\rangle + |100\rangle + |011\rangle + |110\rangle + |101\rangle + |111\rangle]$$

Three spins – 8 states

$$|\psi\rangle = \cdots.$$

100 spin ½ : $2^{100} = 10^{30}$ dimensional space

$$|\psi\rangle = \cdots.$$

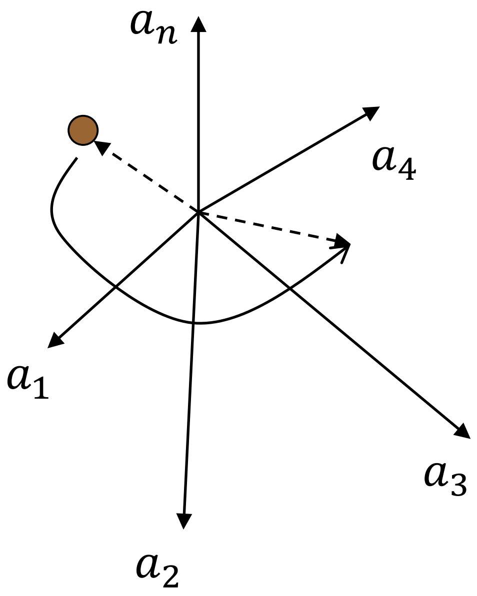
300 spin ½ : $2^{300} = 10^{90}$ dimensional space

- There are 10^{80} atoms in the observable universe
- Hilbert spaces are big!

A quantum state can represent a huge number of 0’s and 1’ **simultaneously**!

Quantum System Dynamics

$$|\psi(t)\rangle = \alpha(t)|a_1\rangle + \beta(t)|a_2\rangle + \gamma(t)|a_3\rangle + \cdots$$



A quantum system evolves in time set by the Schrödinger Equation, where *H* is the Hamilton operator.

$$i\hbar \frac{d}{dt}|\psi(t)\rangle = \hat{H}(t)|\psi(t)\rangle$$

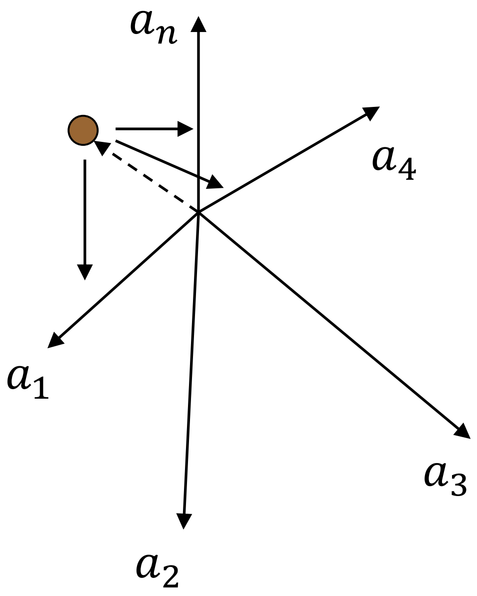
$$\hat{H} = \frac{\hat{p}^{\,2}}{2m} + V(\hat{x})$$ Electron in potential

$$\hat{H} = -\gamma B_z \sigma_z$$ Spin in magnetic field

- This give a set of coupled differential equations for the coefficients α β γ…
- By applying an Hamiltonian to a quantum state – move the state in the Hilbert space over time. We can in this way control a quantum state.
- This is ***deterministic and time reversible!***

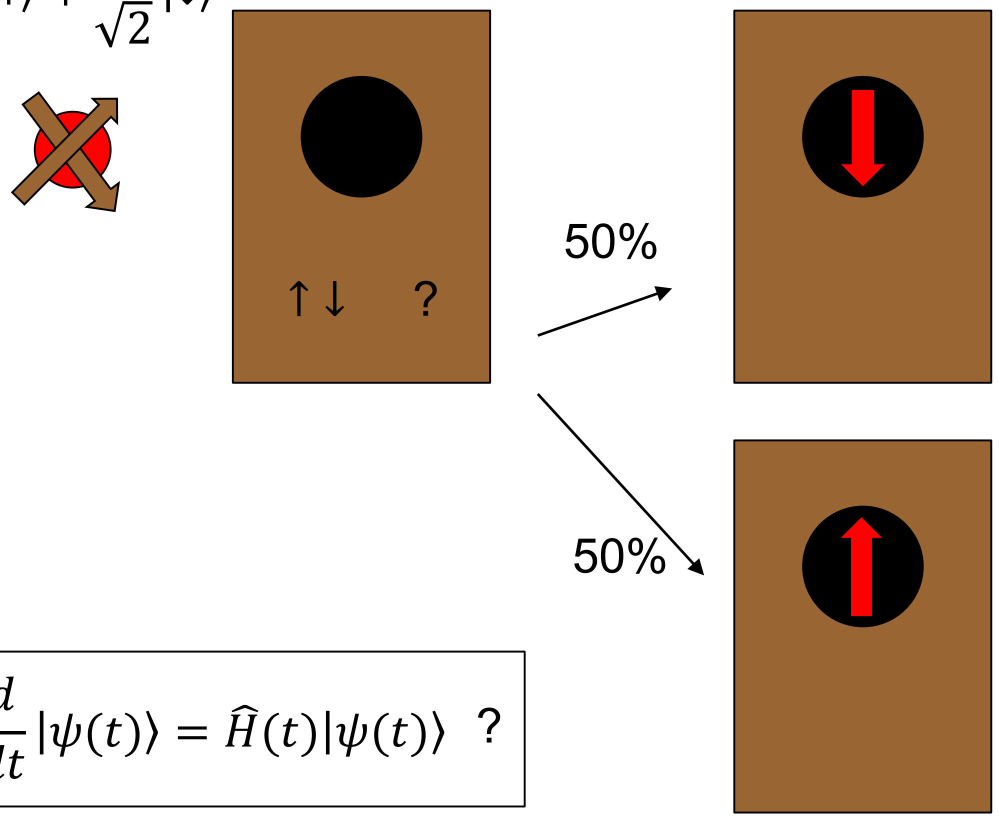
Measurement in Quantum Mechanics

$$|\psi\rangle = \alpha|a_1\rangle + \beta|a_2\rangle + \gamma|a_3\rangle + \cdots$$



Measurement – apparatus which determines an observable (Energy, position, Spin direction…)

$$|\psi\rangle = \frac{1}{\sqrt{2}}|\uparrow\rangle + \frac{1}{\sqrt{2}}|\downarrow\rangle$$



During a measurement of an observable ***a***
State collapses to an eigenstate with probability

$$P_n = |\langle a_n|\psi\rangle|^2$$

- **Not deterministic and NOT time reversible!**

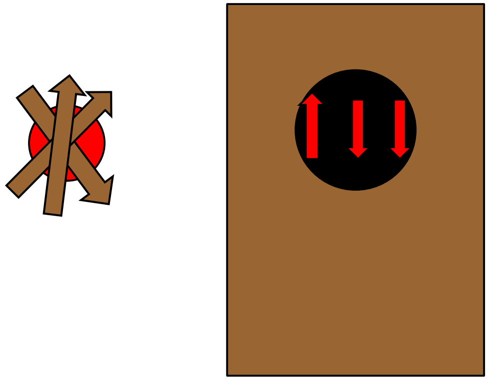
$$\boxed{i\hbar\frac{d}{dt}|\psi(t)\rangle = \hat{H}(t)|\psi(t)\rangle \ ?}$$

Measurement of states

$$N = 100 \ \leftrightarrow 10^{30}\ states$$

$$|\psi\rangle = \frac{1}{\sqrt{2^N}}[|000 \ldots\rangle + |001 \ldots\rangle + |010 \ldots\rangle + |100 \ldots\rangle + |011 \ldots\rangle + |110 \ldots\rangle + \cdots]$$

Measure all qubits

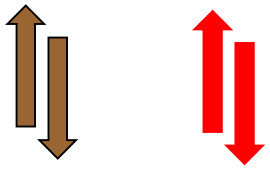


Will randomly select **ONE** of the states with equal probability!

Gives 100 bits of information or out 10^{30}

Direct application of quantum parallelism is not an easy task!

Entangeled state

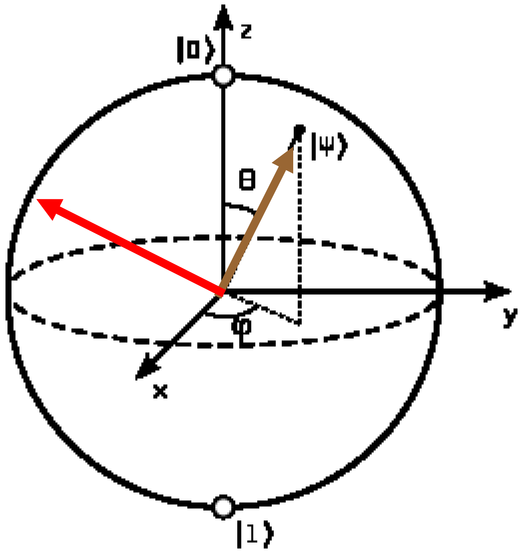


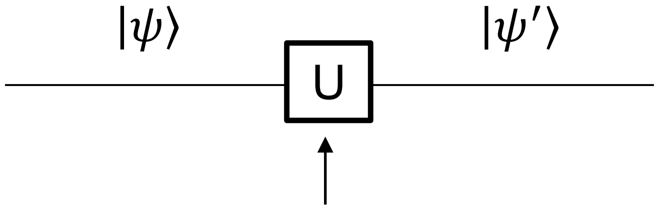
$$|\psi\rangle = \frac{1}{\sqrt{2}}(|10\rangle + |01\rangle)$$

1) Separate two entangled qubits (by light years (!))
2) Measure qubit A (will show 0 or 1 with 50%)
3) If A shows $|0\rangle_A$ - we now know that qubit B is $|1\rangle_B$

4) Spooky action at a distance!

Single quantum Gate – Bloch Sphere rotation





Let H(t) act on $|\psi\rangle$ for some time t_0.

Quantum gates are reversible!

$$|\psi\rangle = \sin\left(\frac{\theta}{2}\right)|0\rangle + \cos\left(\frac{\theta}{2}\right)e^{i\phi}\,|1\rangle$$

$$|\psi\rangle = \alpha|0\rangle + \beta|1\rangle \qquad \begin{pmatrix}\alpha\\ \beta\end{pmatrix}$$

Matrix representation of a state

These can in general be build by applying time varying *B/E* field to a spin/position qbit in *x,y* and *z* direction for a fixed time.

NOT gate π rotation around x axis $|0\rangle \rightarrow |1\rangle$ $\begin{bmatrix}0 & 1\\ 1 & 0\end{bmatrix}$

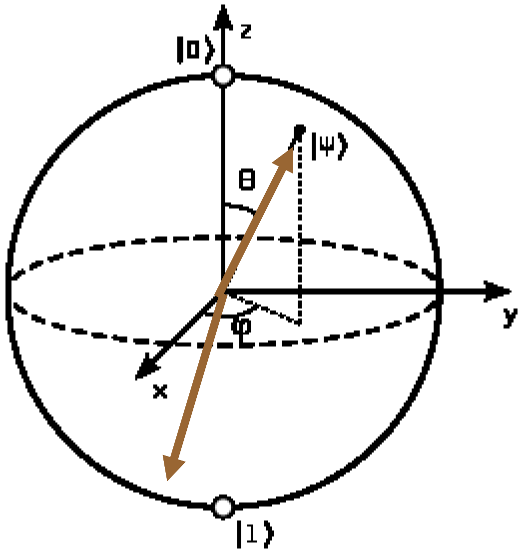
Matrix representation of a operator

Hadamard gate:$|0\rangle \rightarrow \frac{1}{\sqrt{2}}(|0\rangle + |1\rangle)$ $\frac{1}{\sqrt{2}}\begin{bmatrix}1 & 1\\ 1 & -1\end{bmatrix}$

Matrix representation of a operator

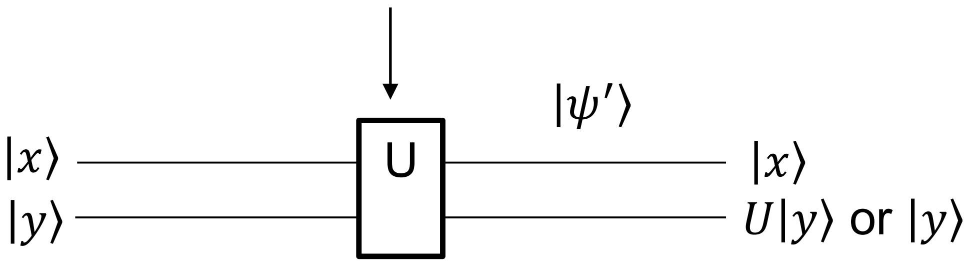
These also work on superpositions: $|\psi\rangle = \alpha|0\rangle + \beta|1\rangle$

Quantum Gate – Controlled Gate



$$|\psi\rangle = \sin\left(\frac{\theta}{2}\right)|0\rangle + \cos\left(\frac{\theta}{2}\right)e^{i\phi}\,|1\rangle$$

Let H(t) act on *x* and *y* for some time t_0.



If x=0 do nothing to qubit y
If x=1 apply rotation U to qubit y

CNOT Gate

If $x = |0\rangle$ then y=y
If $x = |1\rangle$ then apply NOT to y

- All controlled gates will be unitary
- Controlled Gates also work on super positions – quantum parallelism!

Universial set of quantum gates

CLIFFORD+T GATE SET

Gate	Symbol	Matrix
Hadamard Gate	H	$\frac{1}{\sqrt{2}}\begin{bmatrix}1 & 1\\1 & -1\end{bmatrix}$
T Gate	T	$\begin{bmatrix}1 & 0\\0 & e^{i\cdot\frac{\pi}{4}}\end{bmatrix}$
Hermitian of T Gate	$T^\dagger$	$\begin{bmatrix}1 & 0\\0 & e^{-i\cdot\frac{\pi}{4}}\end{bmatrix}$
Phase Gate	S	$\begin{bmatrix}1 & 0\\0 & i\end{bmatrix}$
Hermitian of Phase Gate	$S^\dagger$	$\begin{bmatrix}1 & 0\\0 & -i\end{bmatrix}$
Not Gate	$\oplus$	$\begin{bmatrix}0 & 1\\1 & 0\end{bmatrix}$
Feynman (CNOT) Gate	$\bullet$ / $\oplus$	$\begin{bmatrix}1 & 0 & 0 & 0\\0 & 1 & 0 & 0\\0 & 0 & 0 & 1\\0 & 0 & 1 & 0\end{bmatrix}$

Fig. 5: The Clifford+T gate quantum gate set.

These set of gates are 'universal'
Can implement **all logic functions**
NAND, NOR etc.

1 qbit gate – controlled rotation of Bloch Sphere

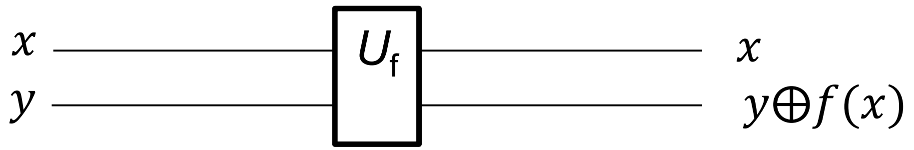
Controlled Gates – almost anyone will do, controlled NOT (CNOT) or controlled phase CPHASE most common.

$$H|0\rangle : \frac{1}{\sqrt{2}}\begin{bmatrix}1 & 1\\1 & -1\end{bmatrix}\begin{bmatrix}1\\0\end{bmatrix} = \frac{1}{\sqrt{2}}\begin{bmatrix}1\\1\end{bmatrix} \qquad H|0\rangle = \frac{1}{\sqrt{2}}(|0\rangle + |1\rangle)$$

$$|\psi\rangle = \alpha|00\rangle + \beta|10\rangle + \gamma|01\rangle + \delta|11\rangle$$

$$\longrightarrow \begin{pmatrix}\alpha\\\beta\\\gamma\\\delta\end{pmatrix}$$

Example - Deutsch's Algorithm



$f(x) = ?$

$f(0) \neq f(1)$ "balanced"

$f(0) = f(1)$ "constant"

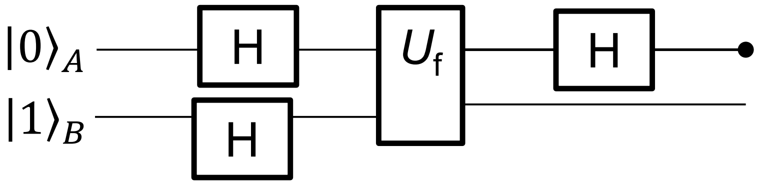
$f(x)$ takes a single bit {0,1} into a single output bit {0,1}.

x	?f	?f	?f	?f
0	0	0	1	1
1	0	1	0	1
	c	b	b	c

If we don't know if f(x) is "balanced" or "constant" – but would like to know

Classical Computer – calculate *f*(0) and *f*(1) and compare – need to evaluate *f* **twice**!

The quantum circuit below can achieve this by evaluating *f*(x) only **once!**



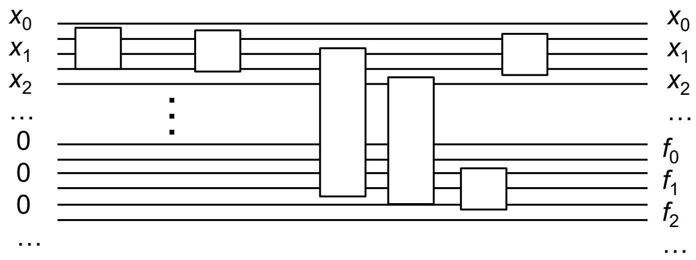
Measure qubit A → $|0\rangle$ $\quad f(0) = f(1)$

Measure qubit A → $|1\rangle$ $\quad f(0) \neq f(1)$

General Quantum Computing

NANO ELECTRONICS GROUP

$$|x\rangle|0\rangle \rightarrow |x\rangle|f(x)\rangle$$



Input register $\left[\frac{1}{\sqrt{2}}(|0\rangle + |1\rangle)\right]^N = \frac{1}{2^{N/2}} \sum_0^{2^N-1} |x\rangle$

This can be done with *N* Hadamard gates

$$|x\rangle|0\rangle \rightarrow \frac{1}{2^{N/2}} \sum_0^{2^N-1} |x\rangle\,|f(x)\rangle$$

By just computing the f(x) **once**, f(x) is "calculated" for all 2^N values!
N=100 – 10^{30} speedup!

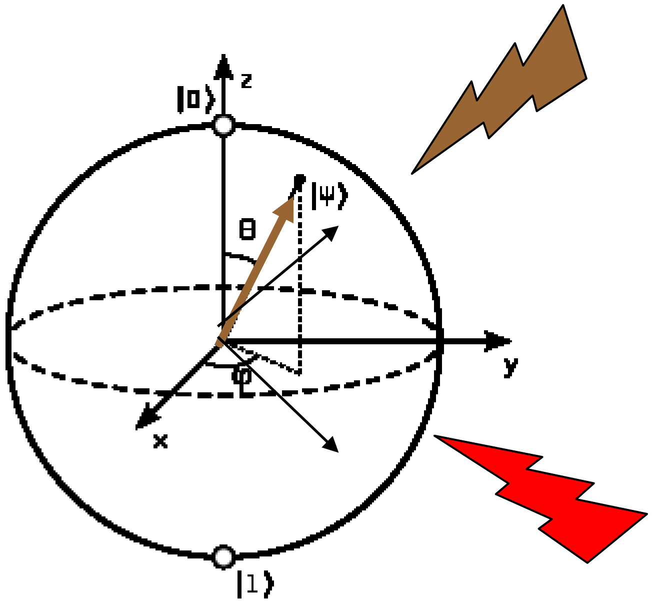
$$\frac{1}{2^{N/2}} \sum_0^{2^N-1} |x\rangle\,|f(x)\rangle \rightarrow |x_0\rangle|f(x_0)\rangle$$

Measurement of $|x\rangle$

However, a direct measurement of x gives only ONE random value of f(x_0)!

Need clever algorithms similar to Deutsch Problem to try and extract more information from the correlation between *x* and f(x)

Decoherence – random Bloch sphere rotation



A single qbit will couple to the environment (example for a single ½ spin)

- Nuclear spins
- Stray B-fields

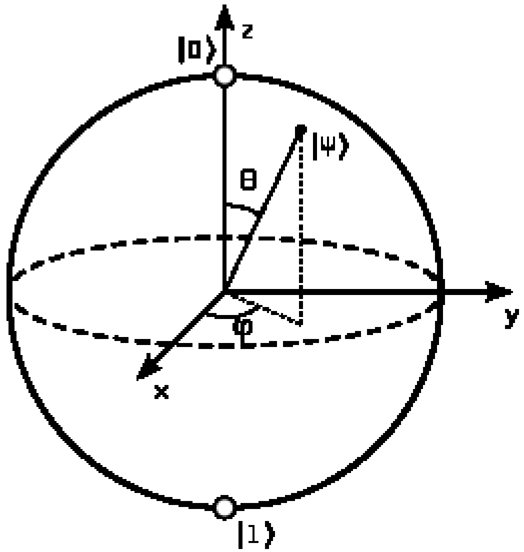
- Electrical fluctuations
- Interactions with photons
- Electrical Noise

Couples through spin-orbit interactions

This will induce random $H(t)$ which randomly shifts around the quantum state.

Quantum states can be very fragile. **nS – mS before the qbit is completely random.** Decoherance time (T1 / T2).

Decoherence – random Bloch sphere rotation



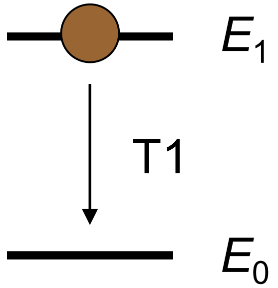
- T1 – Spin relaxation Time
- T2 - Decohrerance Time

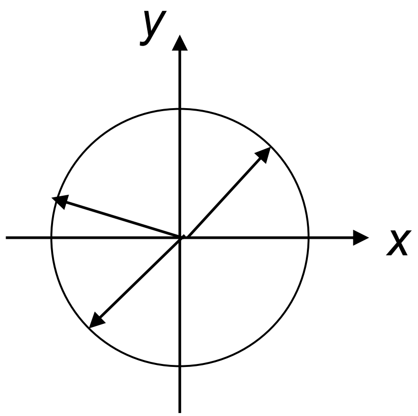
Given two distinct energy states for

If particle initially in E_1 – how long time until it is found in E_0?
T1 – Spin relaxation time

If particle in a superposition - how long until the phase relation between is lost?
T2 – decoherence time

These are measures of the ‘quality’ of a qbit. We need to do our gate operations shorter then T1 and T2.

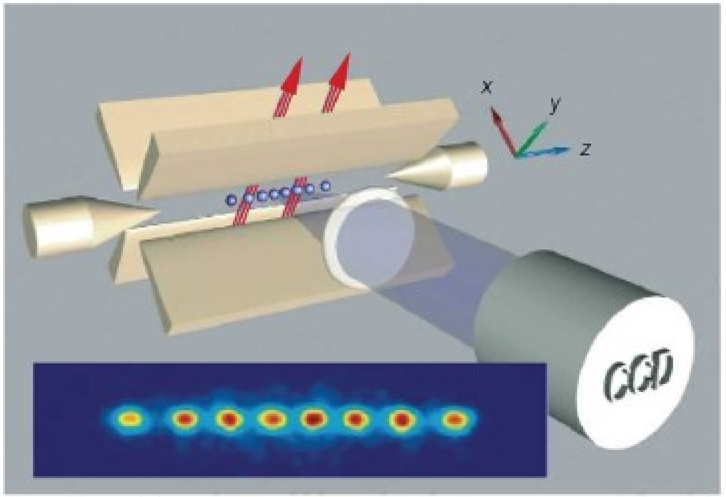




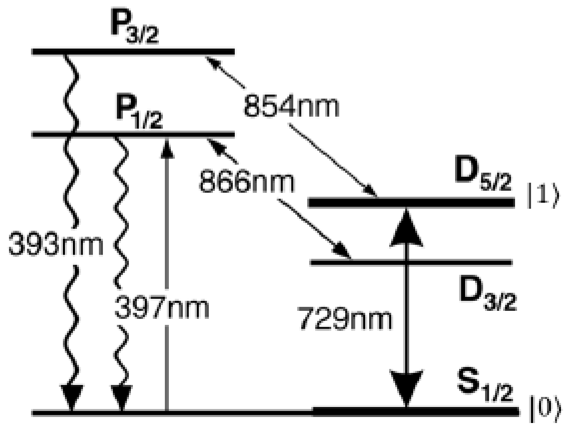
Quantum Computers - implementations

- Spin qubits (compatible with Si processing!)
- Optical traps (Most stable!)
- Superconducting Qubits (Most qubits!)
- Majorna Zero Modes – Topological Qubits (Most difficult to understand. Best?)

Ion Trap – Optical Qubits



↔
10μm



Atomic Ions trapped in RF/DC field
Laser cooling
Strongly isolated from environment
+Very long decoherance T1 times (s-years(!!)
-Scalability?
-Geometry?

Qubit Operation
B-field + 729 nm laser – excite between $|0\rangle$ and $|1\rangle$

Multi-qubit operation motivated through phonons

Readout – 397nm (and 866nm) laser
Scattered light only if atom in state $|0\rangle$

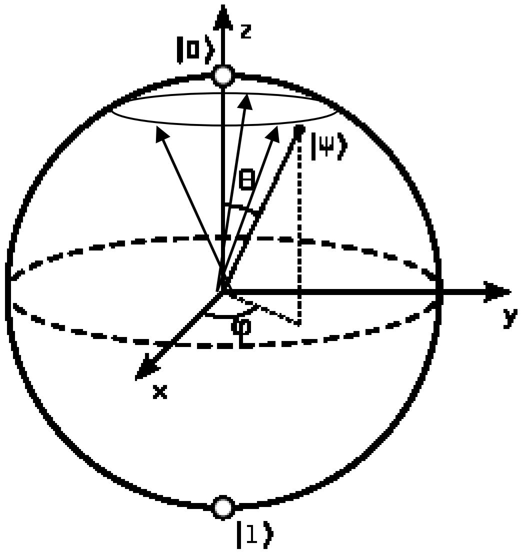
Spin Qubits

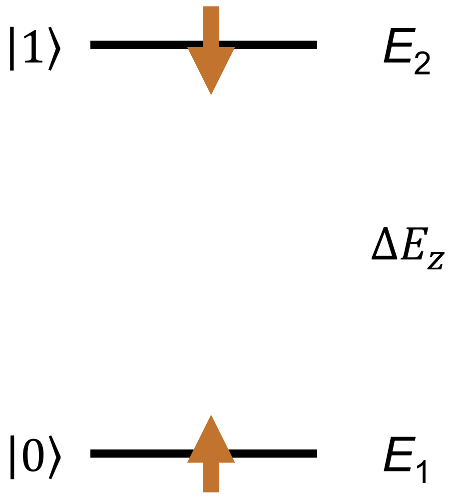
Single ½ spin in B-field

Two energy eigenstates
– Spin up and spin down

Energy split is small

B=1T (InAs, g^*=-10)
gives $\Delta E_z = 0.5\ meV$





$$\Delta E_z = g^* \mu_b B$$

Thermal energy (~kT/q) should be smaller then this value

T=300K - 25 meV
T=1K – 0.08 meV

We need to operate our qubits at cryogenic temperature!

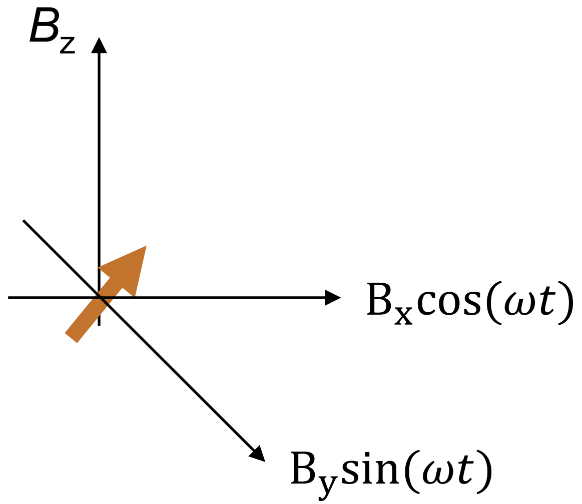
Spin Qubits Manipulation

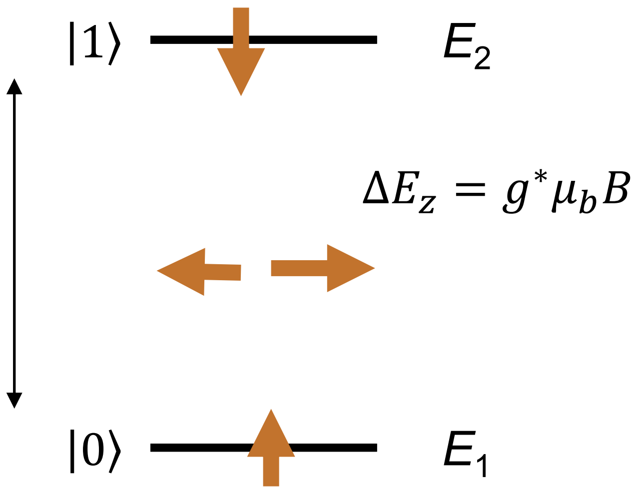
By applying a varying RF magnetic field in x-y direction

Also works for field in x direction *only* – have to use pulses.

Spin position can be controllable shifted

Resonance – only effective is RF frequencies close to energy difference are effective in rotating the spin!

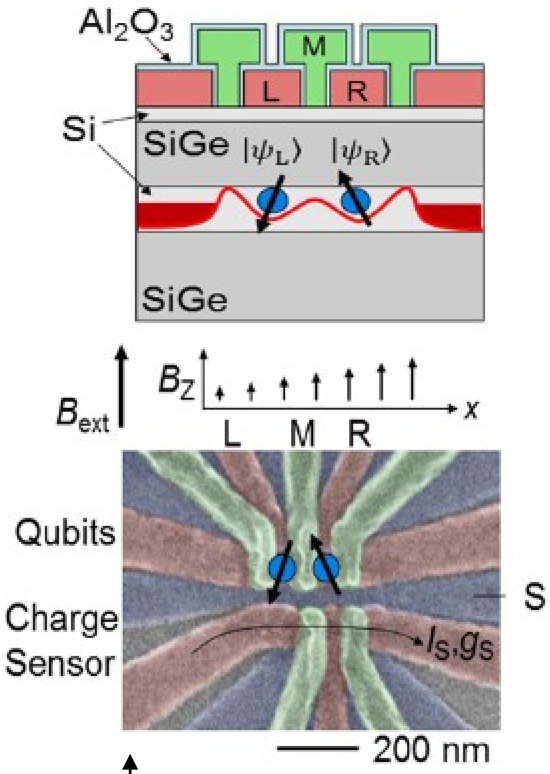




→ Can access different qubits by global B-field. Single qbit control!

$$\hbar\omega = \Delta E_z = g^* \mu_b B$$

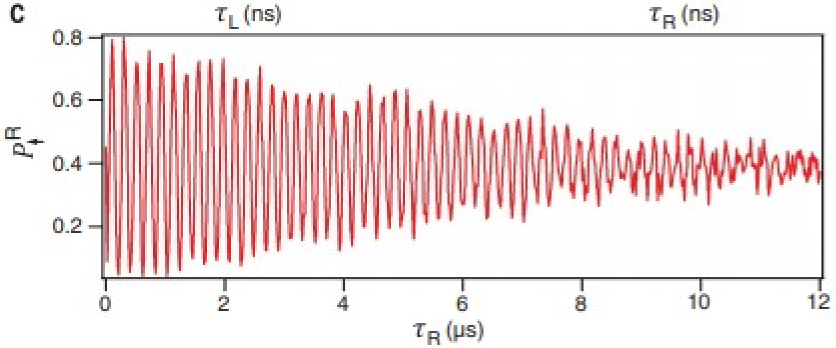
Spin Qubit Implementation



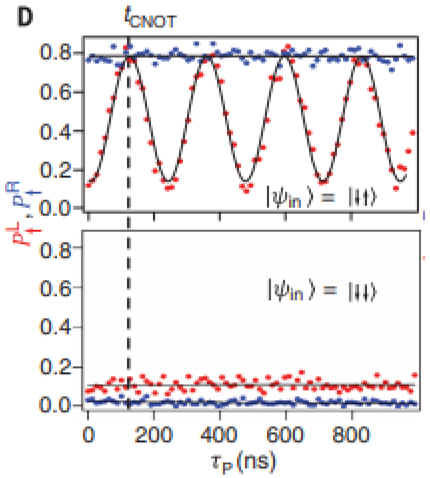
Single Electron Transistor – can localize single electron in each gate

Applying RF B-field – rotates spin. Qbit control!

Si qubit



Rabi oscillation – rotate the spin between up and down.
Spin relaxation time T1 - μS range



$$H = -JS_1 \cdot S_2$$

Two nearby spins will influence each other through exchange mechanism – can build CNOT gates!

Charge sensor (Spin detector)

Decoherence

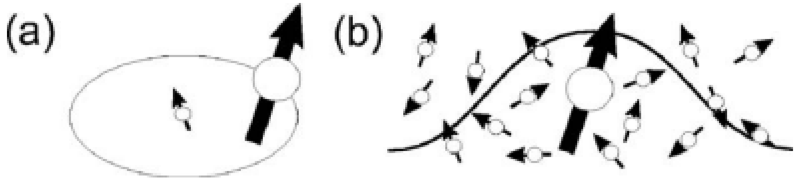


FIG. 24. One-electron spin interacts with (a) a single nuclear spin in an atom and vs (b) many nuclear spins in a semiconductor quantum dot.

Single Electron will interact with a background of many nuclear spins

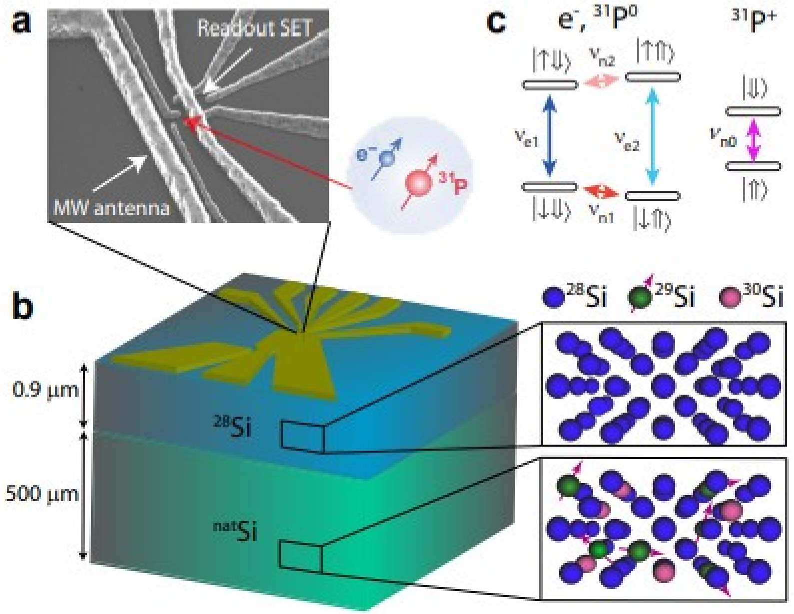
These are randomly distributed in the material
nS-μS decoherence time

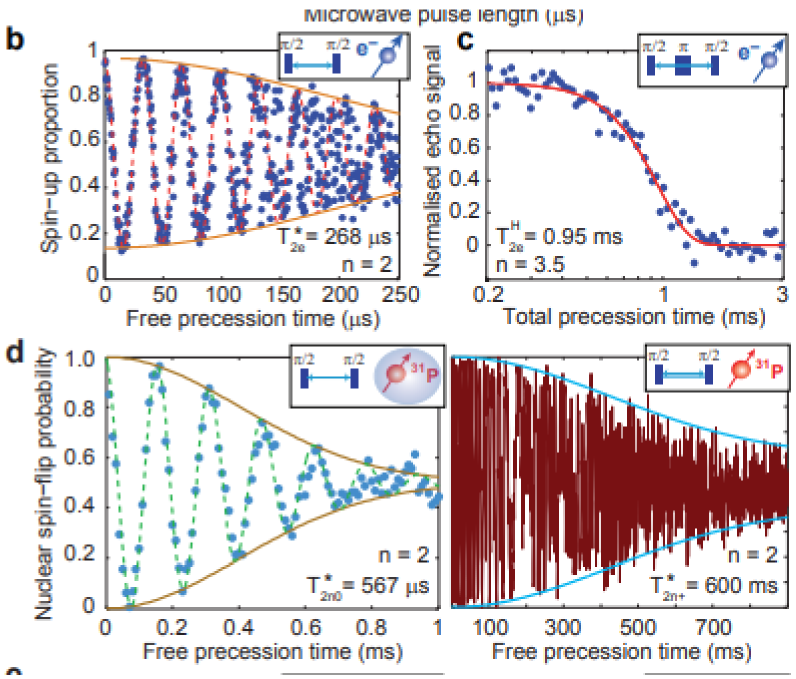
Electron moving in a electric field will experience a magnetic field. This leads to spin-orbit-interaction. Electrical noise (and phonons!) can thus couple to a spin.
Spin-orbit-interaction is stronger for heavy elements (III-Vs)

Spin qubits
Materials with no nuclear spin
- Si^{29}
- C^{12}

Light elements (C, Si – low SOI)

Spin Qubit Si^{29}, Si^{29}-P





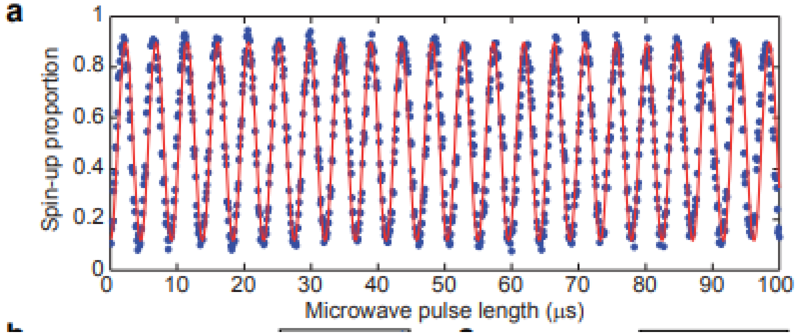
Electron quantum dot
Spin qubit
T2=268 μS

Electron – Donor
Qubit T2=567 μS

Nuclear Spin Qubit
T2= 0.6S

This can be increased to $T_2 = 30S$ (!!) using pulse focusing techniques!

Electron Spin



T1 >> 100 μS (!!)

Spin Qubit Implementation

Spin qubit summary

+Can be made with standard Silicon Technology (!!)

+Small – 10 – 100 nm size

+Long decoherance times can be demonstrated

+CNOT gate

+ GHz resonance frequencies - fast

- Sensitive to single atomic defects – difficult to control
- How to couple many qubits?

Currently - at a single qubit / single gate stage.

Superconducting Qbits

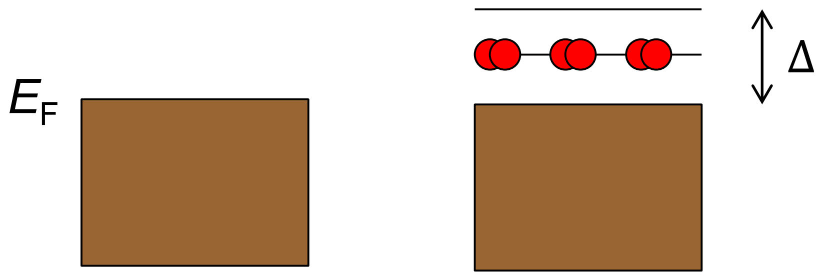
Superconducting Qbits

- Some metals becoms superconducting at low T

Al – T_C=1.12K
Nb – T_C= 9K

Again – we need to operate qubits at mK temperatures!

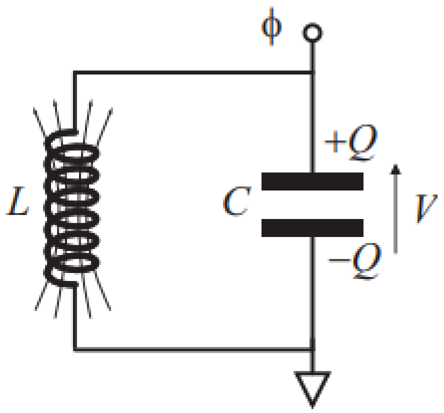
- **Zero resistivity**
  - Induced current decay over very long times (millions of years..)
- **BCS Theory**
  - Electrons form Cooper pairs (↑+↓)
  - Energy-gap around the Fermi energy
  - Can move through the metal without any resistance



$$\psi(x) = \sqrt{n_s(x)}e^{j(\phi(x))}$$

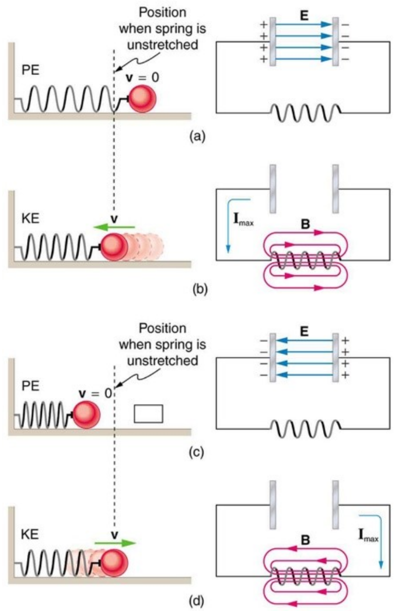
- **Macroscopic wavefunction**
  - n_s – Cooper pair concentration
  - ϕ– global phase

Quantum LC-circuit



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

Energy oscillates between capacitor and inductor

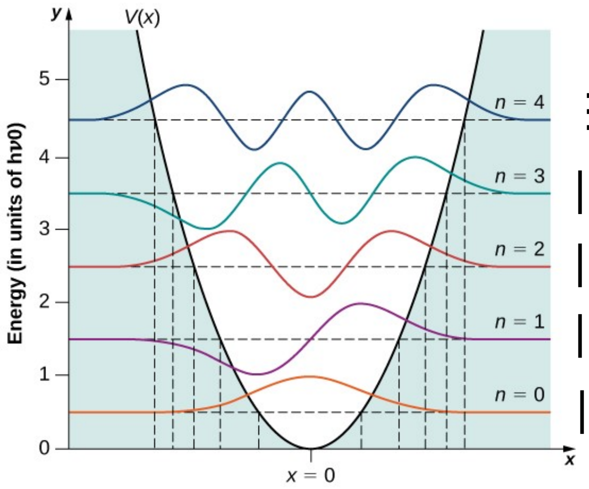


Stored energy in *C* Stored energy in *L*

$$H = \frac{1}{2C}Q^2 + \frac{1}{2L}\phi^2 \qquad [Q,\phi] = -i\hbar$$

$$H = \frac{1}{2m^*}p^2 + \frac{1}{2}m^*\omega^2x^2 \quad [p,x] = -i\hbar$$

The quantum version of the LC-circuit behaves as an Harmonic Oscillator!



$\vdots$

$|3\rangle$

$|2\rangle$

$|1\rangle$

$|0\rangle$

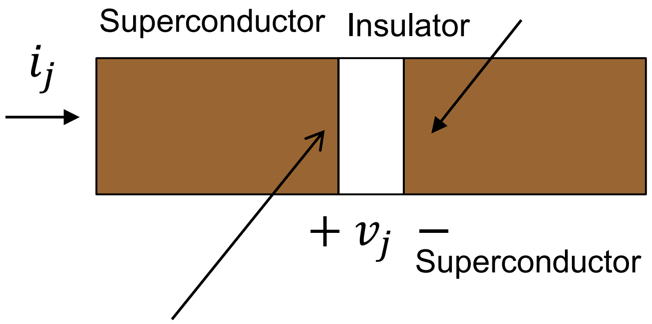
Equi-distant energy separation between energy levels

$$\Delta E = \hbar\omega$$

Not a two-level system!

Josephson Junction

$$\psi(x_2) = \sqrt{n_s(x_2)}e^{j(\phi(x_2))}$$



$$\psi(x_1) = \sqrt{n_s(x_1)}e^{j(\phi(x_1))}$$

$$\begin{cases} i_j(t) = I_0 \sin(\delta) \\ v_J(t) = \dfrac{\hbar}{e}\dfrac{d\delta(t)}{dt} = \dfrac{d\phi}{dt} \end{cases}$$

δ is the phase difference between the two superconductors.

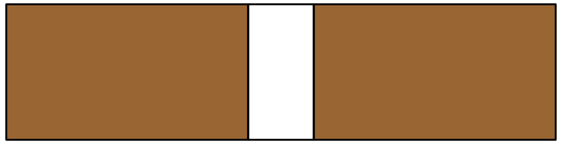
$$\frac{di_j}{dt} = I_0 \cos(\delta)\frac{d\delta}{dt} \qquad \frac{d\delta}{dt} = \frac{di_j}{dt}\frac{1}{\mathrm{I}_0 \cos(\delta)} \qquad v_j(t) = \frac{e}{\hbar}\frac{1}{\mathrm{I}_0\cos(\delta)}\frac{di_j}{dt}$$

$$v_L = L\frac{di}{dt}$$ Ordinary inductor

- A JJ-junction will act as a **non-linear inductor**
- *L* increases when the stored flux increases
- This will lead to *anharmonicity*

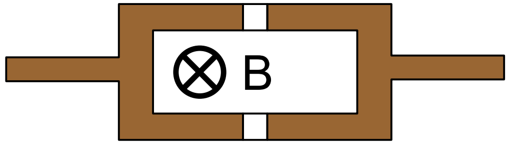
  LC oscillator with different energies

Tunable Josephson Junction - SQUID



$i_j(t) = I_0 \sin(\delta)$

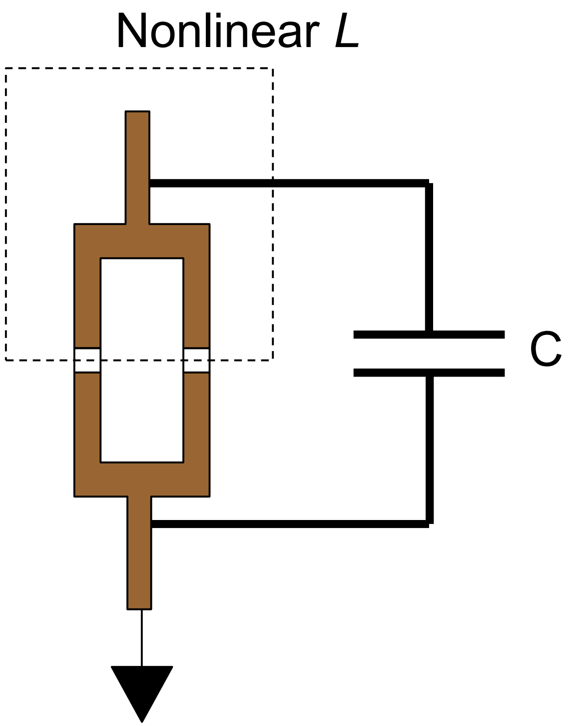
I_0 depends on how well the wave function overlaps in the insulating region. Can be difficult to control.



Solution – connect two JJ and apply an magnetic field. This can be shown to change $I_o \rightarrow I_0 \cos(kB)$. A local B-field can be created by running a DC-current through a conductor

We get a JJ-junction which can be tuned to adjust the non-linear L!

Superconducting Qubit

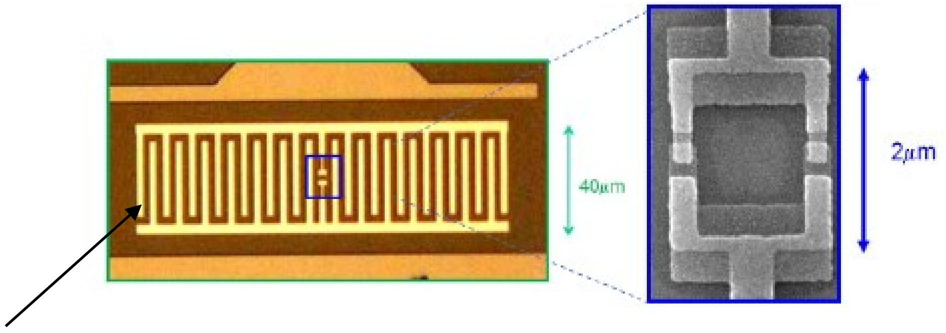


This forms an isolated island for charges ‘Coper-pair box’

Sensitive to charge fluctuations & electrical noise

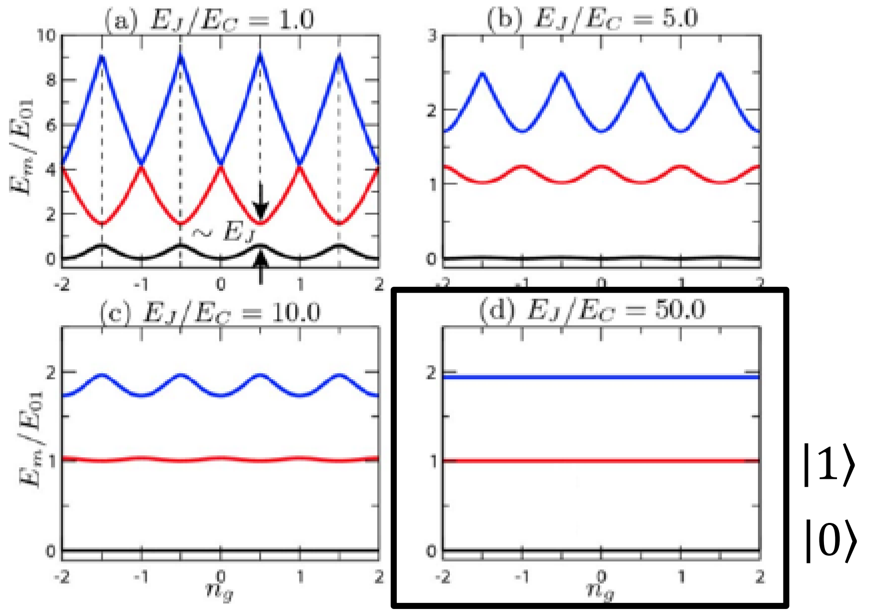
Solution – make C large!
Variation in charge on the box – small change in energy
Insensitive to charge noise – longer coherence time!

Transmon Qubit



C

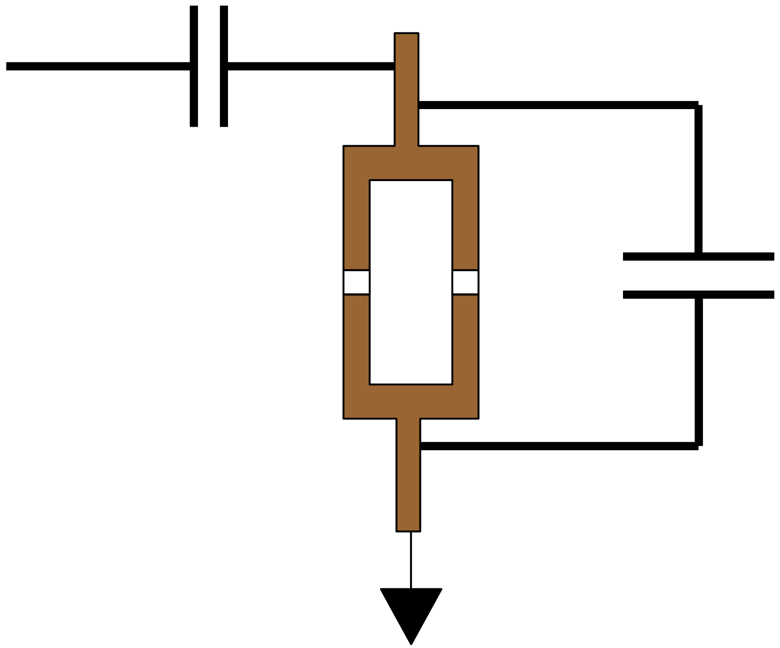
JJ Junction



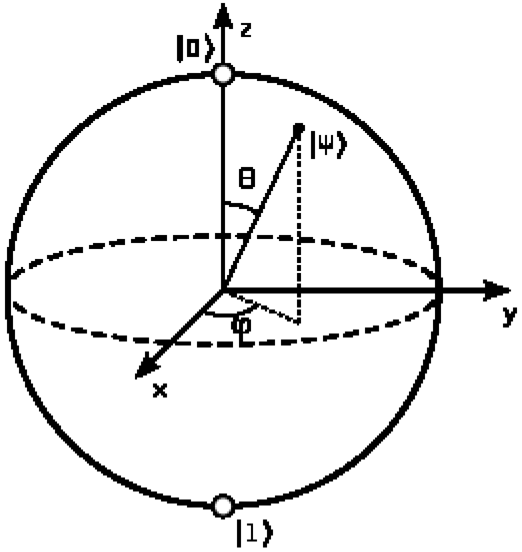
Transmission Line Shunted Plasma Oscillation Qubit

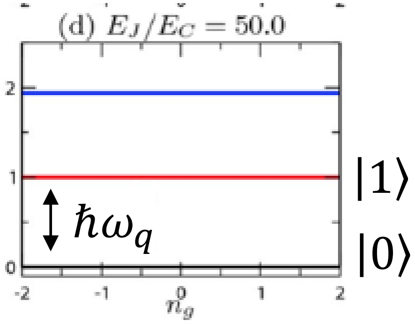
Superconducting Qubit Control

$v_{app}(t) = A cos(\omega_d - \phi)$



Capacitviely couple a RF signal to the transmon



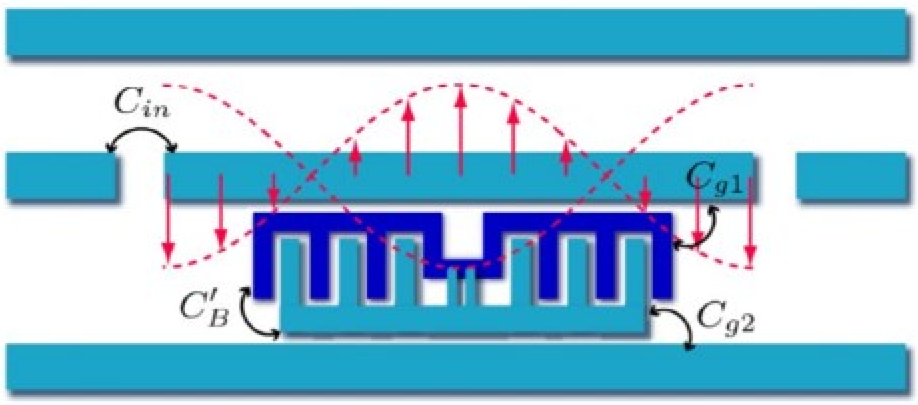


- Frequency difference - $\omega_q - \omega_d$ rotation around z-axis
- Phase difference – rotation around x and y axis

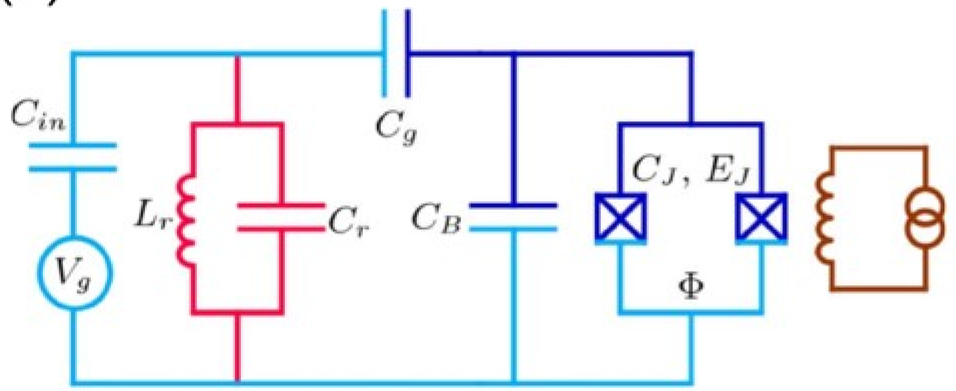
- Full control over Qbit states!

- ω_q is in the GHz range – nS time / operation

Superconducting Qubit Resonator

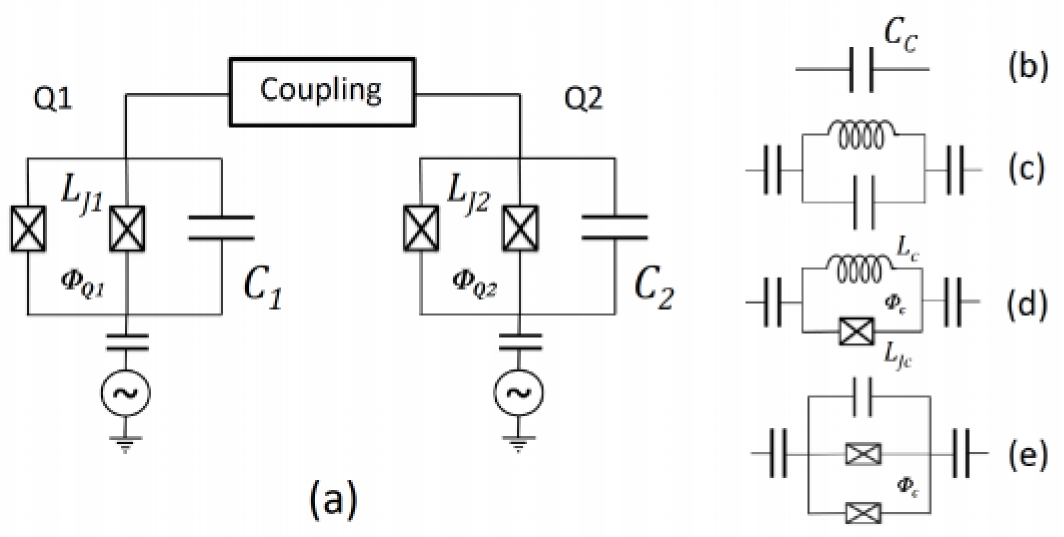


(d)



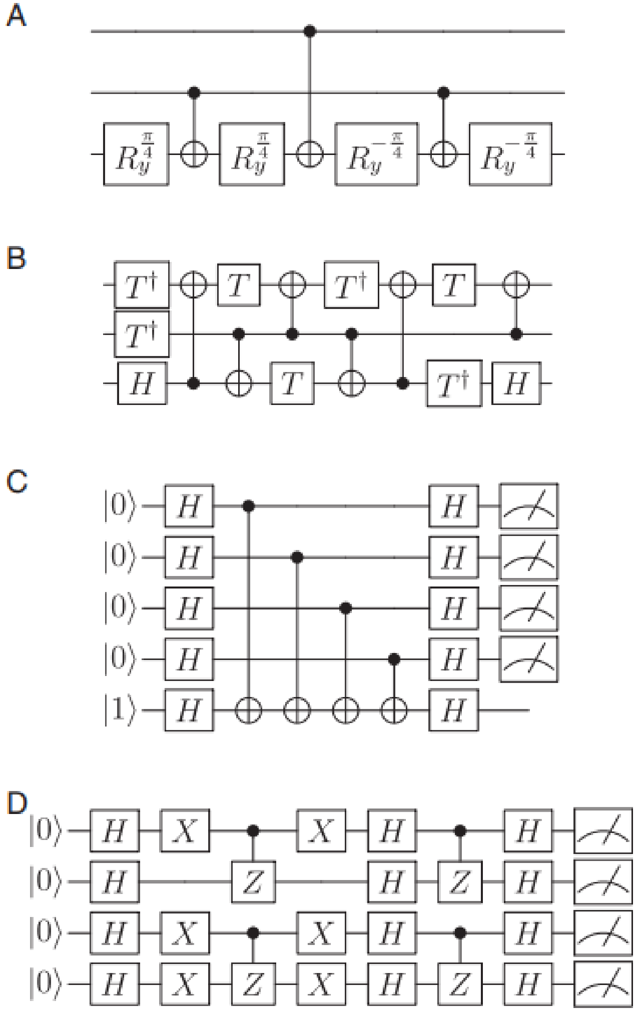
- We integrate the qubit in a section of a microwave resonator
- The qbit will slightly shift the resonance frequency of the resonator depending on the qbit state ($|0\rangle$ $|1\rangle$).
- By measuring the resonance frequency of the resonator ω_r we can perform a measurement on the qbit!
- By applying RF pulses at the qbit resonance frequency ω_q we can manipulate the qbit state

2-Qubit Gates



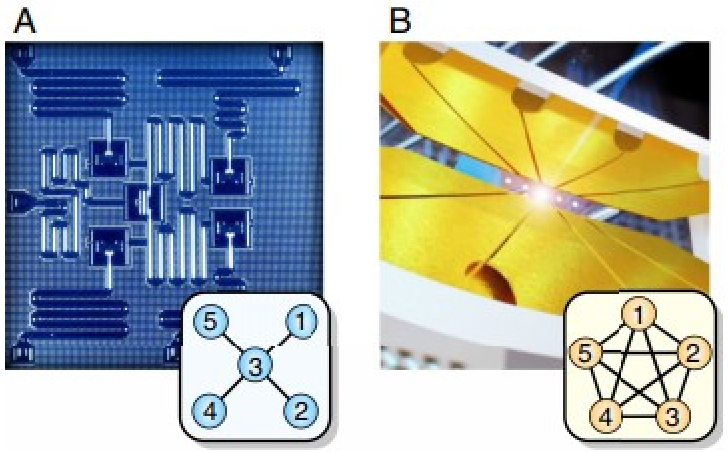
- Qbit interaction is possible by coupling different qubits together
- This can be tunable through coupling via a DC SQUID
- CPHASE/CNOT qubit control can be implemented

Superconducting Qubit Control



Transmon

Ion Trap



Current state-of-the-art

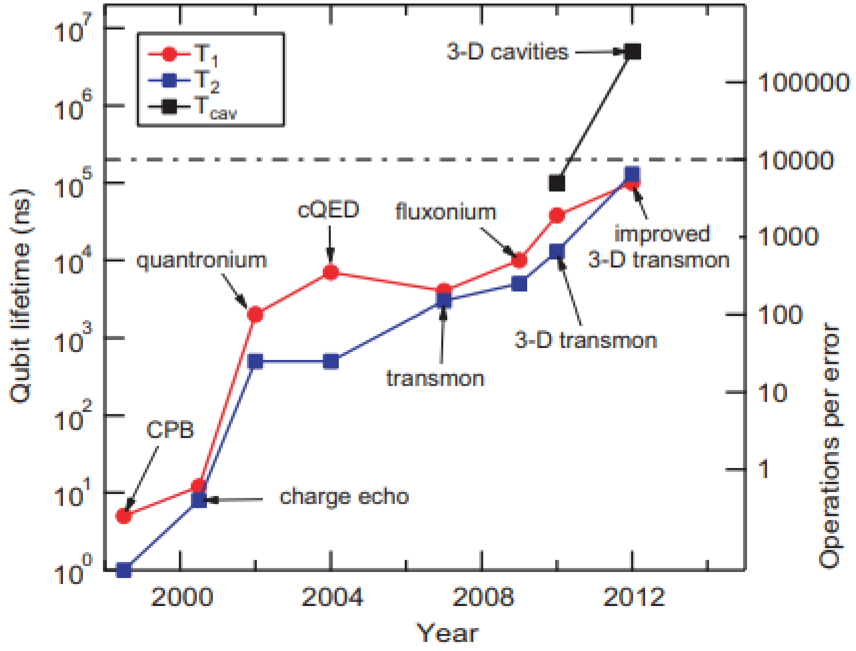
Google Bristlecone – 72 qubits

Table 2. Summary of the achieved success probabilities for the implemented circuits, in percentages

Connectivity	Star shaped			Fully connected		
Hardware	Superconducting			Ion trap		
Success probability/%	Obs	Rand	Sys	Obs	Rand	Sys
Margolus	74.1(7)	82	75	90.1(2)	91	81
Toffoli	52.6(8)	78	59	85.0(2)	89	78
Bernstein–Vazirani	72.8(5)	80	74	85.1(1)	90	77
Hidden shift	35.1(6)	75	52	77.1(2)	86	57

Superconducting qubits – reasonable advanced circuits
50-75% success rate

Superconducting Qubit Control



Sources of Decoherance

- Emission of photon
- Critical current flucutations (I_0 in JJ)
- Dielectric losses
- Quasi-particle tunneling

- Charge noise

Decoherence Times in the 10-100 µS time range.

Topological Qbits

- All qbits are sensitive to decoherence (nS-mS decoherence time)
- Local flucutations causes decoherance

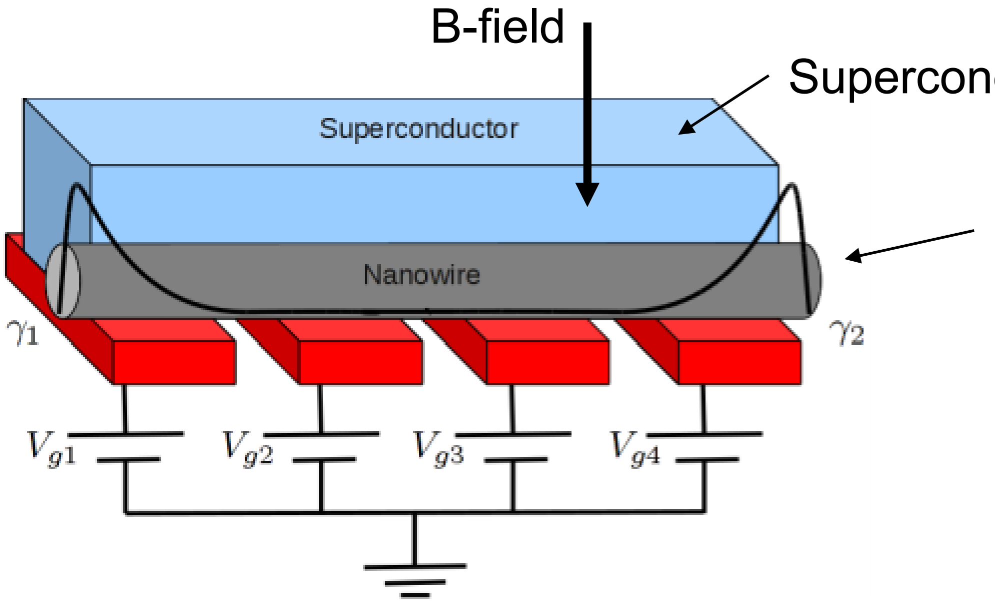
- Can we build a qubit which is insensitive towards local pertubations?
  - (*Microsoft thinks so!*)

- These are so called Majorana Fermions – 'Topological protected states'

- Should appear in a "p-type" superconductor
  - Cooper pairs with *same* spin
  - Can form at the edge of a p-type superconducting wire

- **p-type superconductors do not really exist….**

Majorana Zero Modes



Superconductor with epitaxial contact to nanowire

Nanowire (1D)with large spin-orbit interaction and large g-factor (InSb, InAs).

- Under ***very precise*** conditions we can then form Majorana Zeros Modes (Majorana Fermions) at the ends to the nanowire. (*Very low T, exact position of Fermi energy, high quality SC-N interface, thin SC…)*

- These are part of the same (quasi-)particle
- Highly non-local!
- To perturb the particle state one needs to perturb both ends of the wire – unlikely!

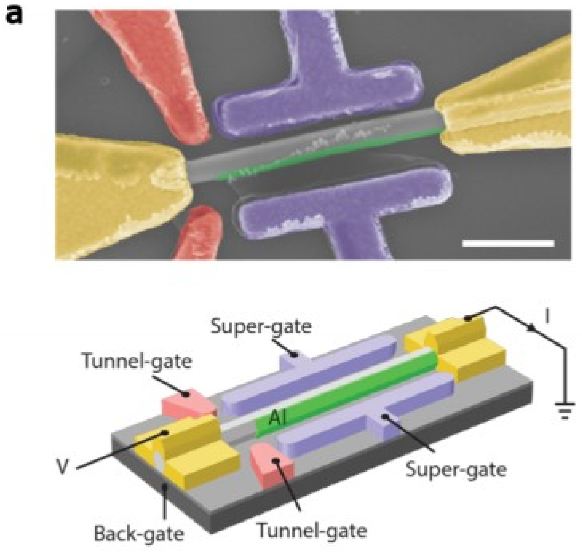
- 'Topological protected states'

- Potentially ***very long*** coherence times!

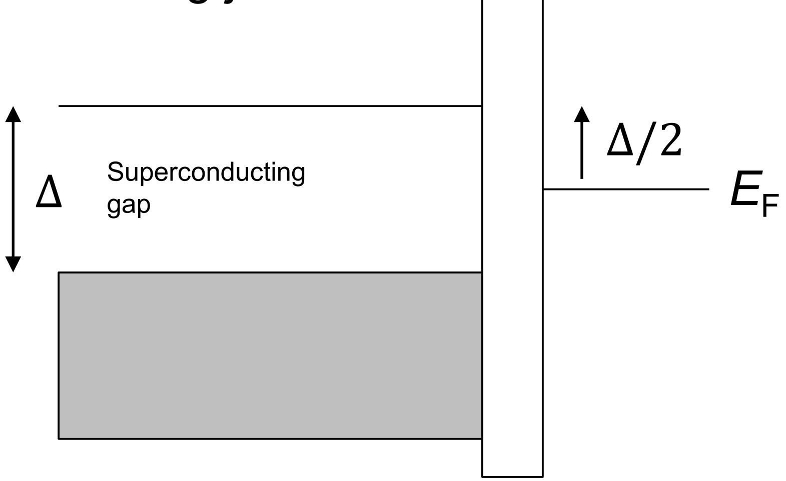
- The 1D nanowire will be spin polarized
- Superconductivity can be induced from the standard superconductor

- **The nanowire system approximates a p-type superconductor!**

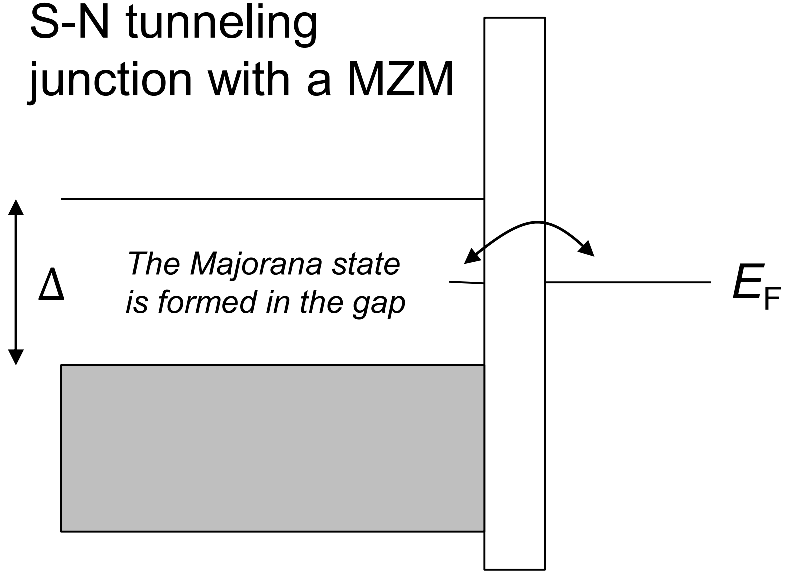
Majorana Zero Modes



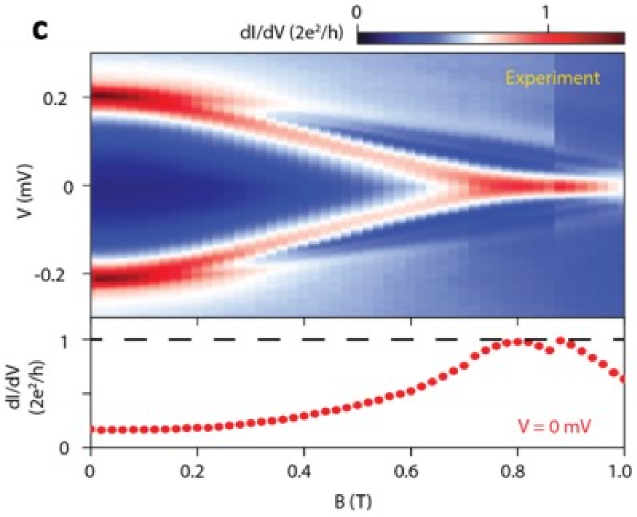
Ordinary S-N
tunneling junction



S-N tunneling
junction with a MZM



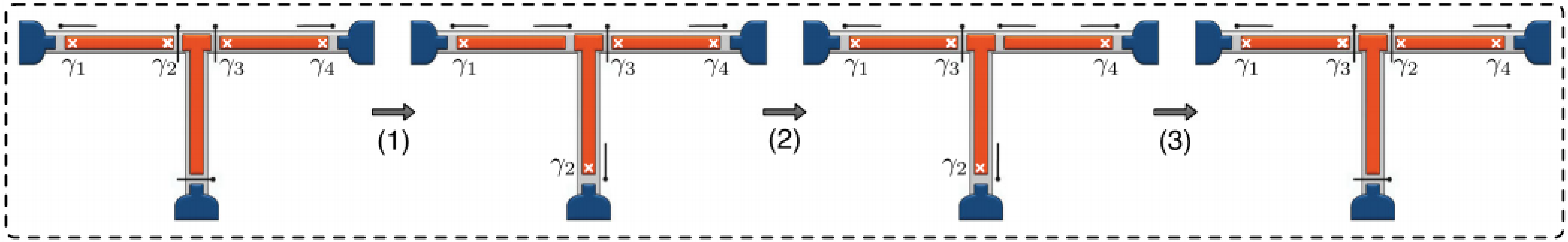
Need to apply $\Delta/2$ in V_{ds}
for a current to flow!



Zero Bias Peak
(Strong) indication that MZM have been formed

This is what has been experimentally
shown to far…

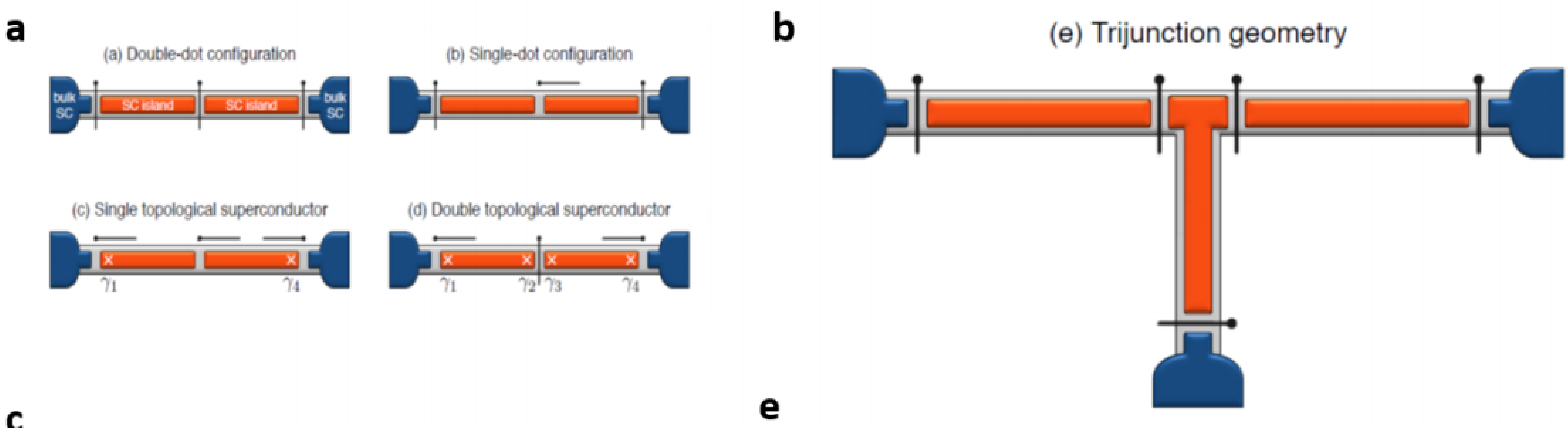
MZM qubit gates (?)

$B =$ 

- The MZM adhers show ‘non-abelian’ statistics
- Interchange of two particles change the particle state in a non-trivial way
  - i.e. not only a change of phase
- Apply network of wires and gates to move Majorana states around each other.
- Could implement some qubit gates.
- **This has never been demonstrated.**

It is not clear which is the best way to implement Qubit or Gates…

MZM qubit gates



- Measurement could be done by ‘fusing’ two states
- *Its own anti-particle – will annihilate*

- Nothing or creation of electron

- **This has also never been demonstrated.**

Quantum Computing Conclusions

- Quantum Computers CAN do SOME things much better then a classical computer will be able to.
- Some IMPORTANT problems can get an EXPONENTIAL speed up
- Qubits are DIFFICULT to build
- Quantum Gates are even HARDER to build
- **Plenty of very interesting and deep physics!**
- **Plenty of very interesting engineering challanges!**
- There are alot of large companies (Google, Microsoft, Intel, IBM) working hard on this!

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