Dynamics of a Quantum System:

QM postulate: The time evolution of a state $|\psi\rangle$ of a closed quantum system is described by the **Schrödinger equation**

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

where H is the hermitian operator known as the **Hamiltonian** describing the closed system.

a **closed quantum system** does not interact with any other system

general solution:

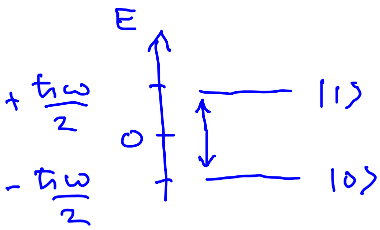
$$|\psi(t)\rangle = \exp\left[\frac{-iHt}{\hbar}\right]|\psi(0)\rangle$$

the **Hamiltonian**:

- H is hermitian and has a spectral decomposition
- with eigenvalues E
- and eigenvectors $|E\rangle$
- smallest value of E is the ground state energy with the eigenstate $|E\rangle$

$$H = \sum_E E\,|E\rangle\langle E|$$

example:



$$H = -\frac{\hbar\omega}{2} Z$$

$$H = -\frac{\hbar\omega}{2}\left(|0\rangle\langle 0| - |1\rangle\langle 1|\right)$$

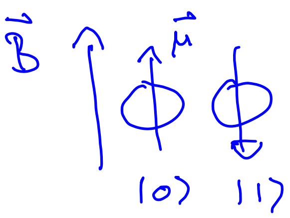
$$|\psi(0)\rangle = |0\rangle \longrightarrow |\psi(t)\rangle = e^{\frac{i\omega}{2}t}|0\rangle$$

$$|\psi(0)\rangle = |1\rangle \longrightarrow |\psi(t)\rangle = e^{-\frac{i\omega}{2}t}|1\rangle$$

$$|\psi(0)\rangle = \frac{1}{\sqrt{2}}\left(|0\rangle + |1\rangle\right)$$

$$= \frac{1}{\sqrt{2}}\cancel{e^{\frac{i\omega}{2}t}}\left(|0\rangle + e^{-i\omega t}|1\rangle\right)$$

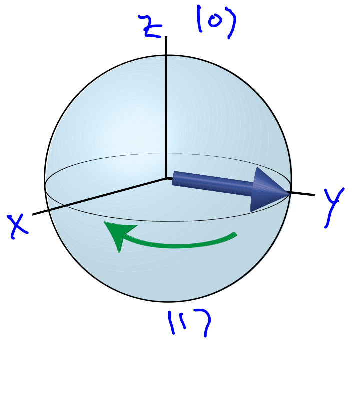
e.g. electron spin in a field:



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

$$\Longrightarrow \quad \theta = \frac{\pi}{2}, \quad \varphi = -\omega t$$

on the Bloch sphere:



this is a rotation around the equator with **Larmor precession frequency** ω

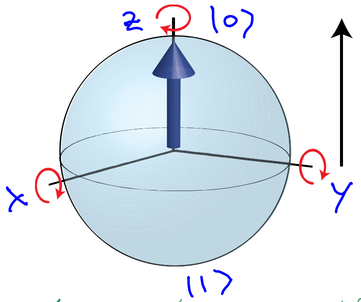
Rotation operators:

when exponentiated the Pauli matrices give rise to rotation matrices around the three orthogonal axis in 3-dimensional space.

$$R_x(\theta) = e^{-i\theta X/2} = \cos\frac{\theta}{2} I - i \sin\frac{\theta}{2} X = \begin{pmatrix} \cos\frac{\theta}{2} & -i\sin\frac{\theta}{2} \\ -i\sin\frac{\theta}{2} & \cos\frac{\theta}{2} \end{pmatrix}$$

$$R_y(\theta) = e^{-i\theta Y/2} = \cos\frac{\theta}{2} I - i \sin\frac{\theta}{2} Y = \begin{pmatrix} \cos\frac{\theta}{2} & -\sin\frac{\theta}{2} \\ \sin\frac{\theta}{2} & \cos\frac{\theta}{2} \end{pmatrix}$$

$$R_z(\theta) = e^{-i\theta Z/2} = \cos\frac{\theta}{2} I - i \sin\frac{\theta}{2} Z = \begin{pmatrix} e^{-i\theta/2} & 0 \\ 0 & e^{i\theta/2} \end{pmatrix}$$

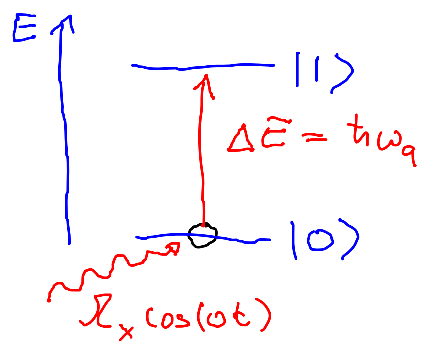


If the Pauli matrices X, Y or Z are present in the Hamiltonian of a system they will give rise to rotations of the qubit state vector around the respective axis.

exercise: convince yourself that the operators $R_{x,y,z}$ do perform rotations on the qubit state written in the Bloch sphere representation.

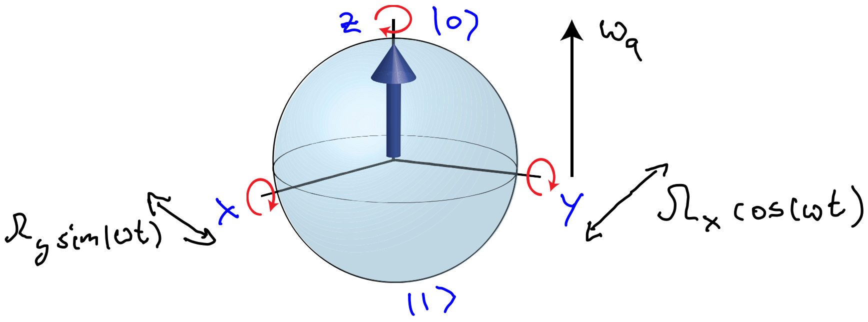
Control of Single Qubit States

by resonant irradiation:



qubit Hamiltonian with ac-drive:

$$H = \hbar\left[\frac{\omega_a}{2}\hat{Z} + \Omega_x\cos(\omega t)\,\hat{X} + \Omega_y \sin(\omega t)\,\hat{Y}\right]$$



ac-fields applied along the x and y components of the qubit state

Rotating Wave Approximation (RWA)

unitary transform:

$$H' = U H U^{\dagger} - i U \dot{U}^{-1}$$

with

$$U = e^{-i \frac{\omega}{2} t \hat{Z}}$$

result:

$$H' = \hbar \left[\frac{\omega_a - \omega}{2} \hat{Z} + \frac{\Omega_x}{2} \hat{X} \left(1 + e^{2 i \omega t}\right) + \frac{\Omega_y}{2} \hat{Y} \left(1 - e^{-2 i \omega t}\right) \right]$$

drop fast rotating terms (RWA):

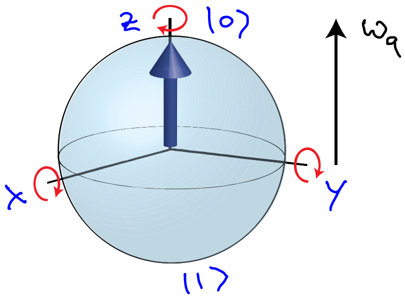
$$H' \approx \frac{\hbar}{2} \left[\Delta \hat{Z} + \Omega_x \hat{X} + \Omega_y \hat{Y} \right]$$

with detuning:

$$\Delta = \omega_a - \omega$$

I.e. irradiating the qubit with an ac-field with controlled amplitude and phase allows to realize arbitrary single qubit rotations.

preparation of qubit states:



initial state $|0\rangle$:

prepare excited state by rotating around x or y axis:

X_π pulse: $\Omega_x t = \pi$; $|0\rangle \; - \boxed{X_\pi} - \; |1\rangle$

Y_π pulse: $\Omega_y t = \pi$; $|0\rangle \; - \boxed{Y_\pi} - \; i|1\rangle$

preparation of a superposition state:

$X_{\pi/2}$ pulse: $\Omega_x t = \frac{\pi}{2}$ $\quad |0\rangle \; - \boxed{X_{\pi/2}} - \; \frac{|0\rangle + |1\rangle}{\sqrt{2}}$

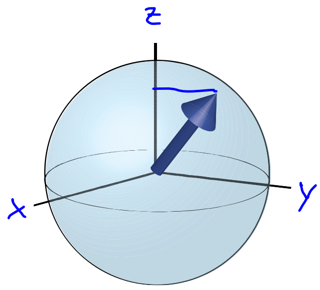
$Y_{\pi/2}$ pulse: $\Omega_y t = \frac{\pi}{2}$ $\quad |0\rangle \; - \boxed{Y_{\pi/2}} - \; \frac{|0\rangle + i|1\rangle}{\sqrt{2}}$

in fact such a pulse of chosen length and phase can prepare any single qubit state, i.e. any point on the Bloch sphere can be reached

Quantum Measurement

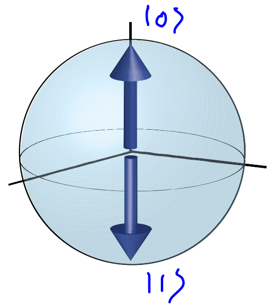
One way to determine the state of a qubit is to measure the projection of its state vector along a given axis, say the z-axis.

On the Bloch sphere this corresponds to the following operation:



After a projective measurement is completed the qubit will be in either one of its computational basis states.

In a repeated measurement the projected state will be measured with certainty.



QM postulate: **quantum measurement** is described by a set of operators $\{M_m\}$ acting on the state space of the system. The **probability** p **of a measurement result** m occurring when the state ψ is measured is

$$p(m) = \langle\psi| M_m^\dagger M_m |\psi\rangle$$

the **state of the system after the measurement** is

$$|\psi'\rangle = \frac{M_m |\psi\rangle}{\sqrt{p(m)}}$$

completeness: the sum over all measurement outcomes has to be unity

$$1 = \sum_m p(m) = \sum_m \langle\psi| M_m^\dagger M_m |\psi\rangle$$

example: projective measurement of a qubit in state ψ in its computational basis

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

measurement operators:

$$M_0 = |0\rangle\langle 0| = \begin{pmatrix} 1 & 0 \\ 0 & 0 \end{pmatrix} \; ; \; M_1 = |1\rangle\langle 1| = \begin{pmatrix} 0 & 0 \\ 0 & 1 \end{pmatrix}$$

measurement probabilities:

$$p(0) = \langle \psi | M_0^\dagger M_0 | \psi \rangle = \alpha^* \alpha \langle 0|0\rangle = |\alpha|^2$$
$$p(1) = \langle \psi | M_1^\dagger M_1 | \psi \rangle = \beta^* \beta \langle 1|1\rangle = |\beta|^2$$

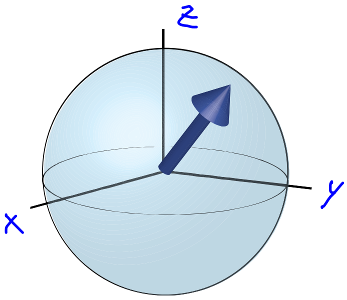
state after measurement:

$$\frac{M_0|\psi\rangle}{\sqrt{p(0)}} = \frac{\alpha|0\rangle}{\sqrt{|\alpha|^2}} = \frac{\alpha}{|\alpha|}|0\rangle$$

$$\frac{M_1|\psi\rangle}{\sqrt{p(1)}} = \frac{\beta|1\rangle}{\sqrt{|\beta|^2}} = \frac{\alpha}{|\alpha|}|1\rangle$$

measuring the state again after a first measurement yields the same state as the initial measurement with unit probability

information content in a single qubit:



- infinite number of qubit states
- but single measurement reveals only 0 or 1 with probabilities $|\alpha|^2$ or $|\beta|^2$
- measurement will collapse state vector on basis state
- to determine α and β an infinite number of measurements has to be made

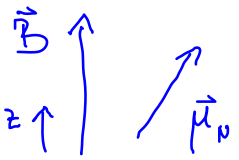
But, if not measured qubit contains 'hidden' information about α and β.

A Few Physical Realizations of Qubits

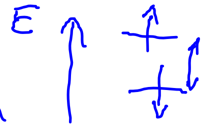
nuclear spins in molecules:

energy scales:
1 GHz ≈ 50 mK
1 GHz ≈ 4 μeV

- nuclear magnetic moment in external magnetic field

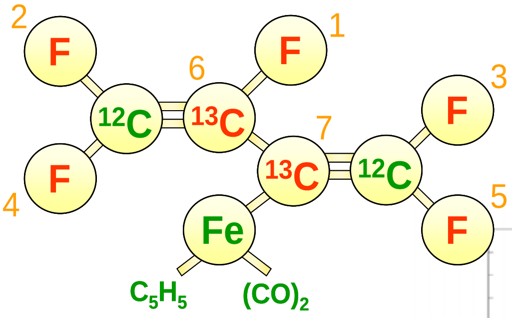


$$H_{int} = -\vec{\mu}_N \cdot \vec{B}_z$$
$$= -g \frac{e\hbar}{2m} B_z \frac{1}{2} \hat{z}$$

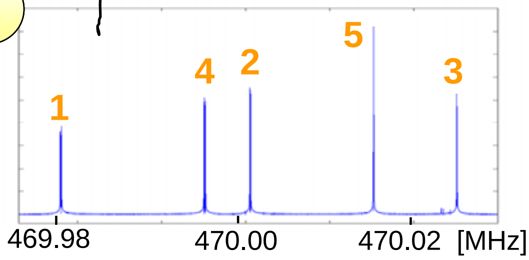


$\Delta E = g \mu_N B$
~ 450 MHz
~ 20 mK
~ 2 μeV

- solution of large number of molecules with nuclear spin



B ~ 10 T

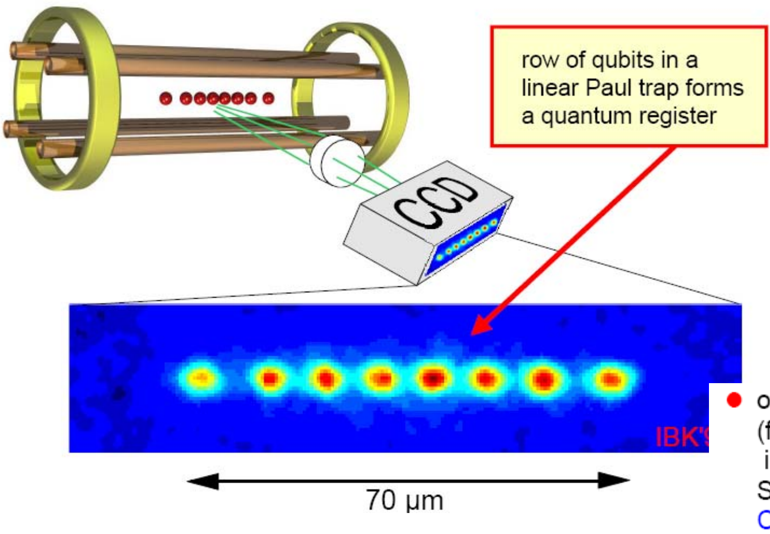


→ E

- distinct energies of different nuclei

figures from MIT group (www.mit.edu/~ichuang/)

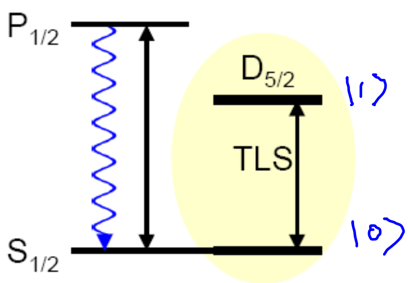
chain of **ions** in an ion trap:



- optical transition frequencies (forbidden transitions, intercombination lines)
S – D transitions in alkaline earths: Ca^+, Sr^+, Ba^+, Ra^+, (Yb^+, Hg^+) etc.

qubit states are implemented as long lived electronic states of atoms

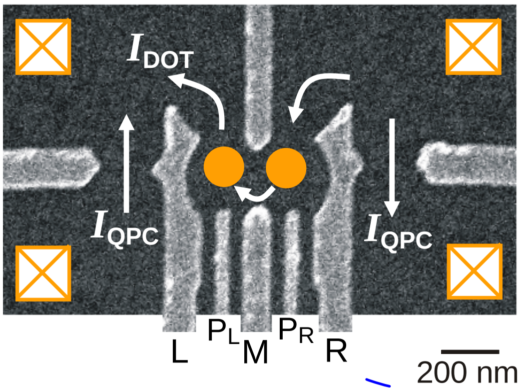
ΔE ~ 400 THz
~ 20 kK
~ 2 eV
↑
$10^6 \times \Delta E$ for nuclei



figures from Innsbruck group (http://heart-c704.uibk.ac.at/)

electrons in quantum dots:

- double quantum dot
- control individual electrons

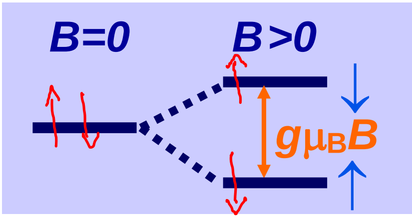


figures from Delft group
(http://qt.tn.tudelft.nl/)

NTT

GaAs/AlGaAs heterostructure
2DEG 90 nm deep
$n_s = 2.9 \times 10^{11}\ \mathrm{cm}^{-2}$

- spin states of electrons as qubit states
- interaction with external magnetic field B



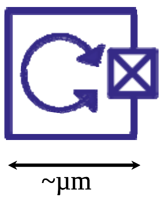
$B \sim 100\ \mathrm{mT}$

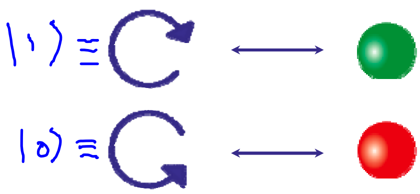
$$\Delta E \sim 450\ \mathrm{MHz} \sim 20\ \mathrm{mK} \sim 2\ \mu\mathrm{eV}$$

superconducting circuits:

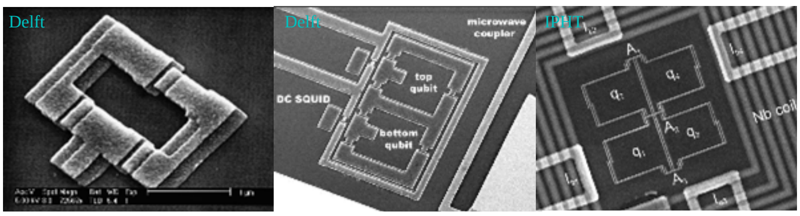
- qubits made from circuit elements

- circulating currents are qubit states



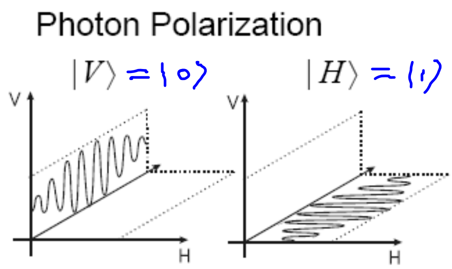


- made from sub-micron scale superconducting inductors and capacitors



$$\Delta E \sim 10\ \mathrm{GHz} \sim 500\ \mathrm{mK} \sim 40\ \mu\mathrm{eV}$$

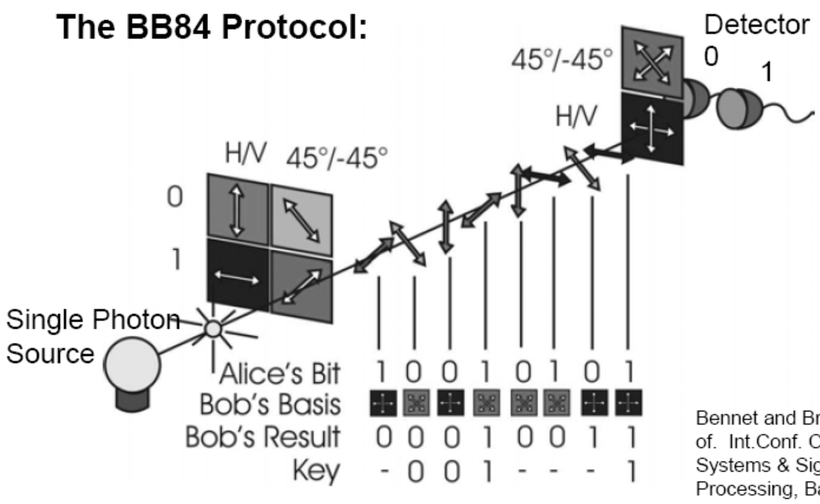
polarization states of photons:



- qubit states corresponding to different polarizations of a single photon (in the visible frequency range)

- are used in quantum cryptography and for quantum communication

- photons are also used in the one-way quantum computer



Bennet and Brassard Proc of. Int.Conf. Computers, Systems & Signal Processing, Bangalore India 175 (1984)

Two Qubits:

2 classical bits with states:

bit 1	bit 2
0	0
0	1
1	0
1	1

- 2^n different states (here $n=2$)
- but only one is realized at any given time

2 qubits with quantum states:

qubit 1 qubit 2

$|00\rangle$
$|01\rangle$
$|10\rangle$
$|11\rangle$

- 2^n basis states ($n=2$)
- can be realized simultaneously
- quantum parallelism

2^n complex coefficients describe quantum state

$$|\psi\rangle = \alpha_{00}|00\rangle + \alpha_{01}|01\rangle + \alpha_{10}|10\rangle + \alpha_{11}|11\rangle$$

normalization condition $$\sum_{ij} |\alpha_{ij}|^2 = 1$$

Composite quantum systems

QM postulate: The state space of a composite systems is the tensor product of the state spaces of the component physical systems. If the component systems have states ψ_i the composite system state is

$$|\psi\rangle = |\psi_1\rangle \otimes |\psi_2\rangle \otimes \dots \otimes |\psi_n\rangle$$

This is a product state of the individual systems.

example:

$$|\psi_1\rangle = \alpha_1 |0\rangle + \beta_1 |1\rangle$$
$$|\psi_2\rangle = \alpha_2 |0\rangle + \beta_2 |1\rangle$$

$$\rightarrow \quad |\psi\rangle = |\psi_1\rangle \otimes |\psi_2\rangle = |\psi_1 \psi_2\rangle$$
$$= \alpha_1\alpha_2 |00\rangle + \alpha_1\beta_2 |01\rangle + \beta_1\alpha_2 |10\rangle + \beta_1\beta_2 |11\rangle$$

exercise: Write down the state vector (matrix representation) of two qubits, i.e. the tensor product, in the computational basis. Write down the basis vectors of the composite system.

there is no generalization of Bloch sphere picture to many qubits

Information content in multiple qubits

- 2^n complex coefficients describe state of a composite quantum system with n qubits!
- Imagine to have 500 qubits, then 2^{500} complex coefficients describe their state.
- How to store this state. 2^{500} is larger than the number of atoms in the universe. It is impossible in classical bits. This is also why it is hard to simulate quantum systems on classical computers.
- A quantum computer would be much more efficient than a classical computer at simulating quantum systems.
- Make use of the information that can be stored in qubits for quantum information processing!

Operators on composite systems:

Let A and B be operators on the component systems described by state vectors $|a\rangle$ and $|b\rangle$. Then the operator acting on the composite system is written as

$$A \otimes B \left(|a\rangle \otimes |b\rangle \right) = A|a\rangle \otimes B|b\rangle$$

tensor product in matrix representation (example for 2D Hilbert spaces):

$$A \otimes B = \begin{pmatrix} A_{11} B & A_{12} B \\ A_{21} B & A_{22} B \end{pmatrix}$$

$$|a\rangle \otimes |b\rangle = \begin{pmatrix} a_1 |b\rangle \\ a_2 |b\rangle \end{pmatrix} = \begin{pmatrix} a_1 b_1 \\ a_1 b_2 \\ a_2 b_1 \\ a_2 b_2 \end{pmatrix}$$

Entanglement:

Definition: An **entangled state** of a composite system is a state that cannot be written as a product state of the component systems.

example: an entangled 2-qubit state (one of the Bell states)

$$|\psi\rangle = \frac{1}{\sqrt{2}} \left(|00\rangle + |11\rangle \right)$$

What is special about this state? Try to write it as a product state!

$$|\psi_1\rangle = \alpha_1 |0\rangle + \beta_1 |1\rangle \; ; \; |\psi_2\rangle = \alpha_2 |0\rangle + \beta_2 |1\rangle$$

$$|\psi_1 \psi_2\rangle = \alpha_1 \alpha_2 |00\rangle + \alpha_1 \beta_2 |01\rangle + \beta_1 \alpha_2 |10\rangle + \beta_1 \beta_2 |11\rangle$$

$$|\psi\rangle \stackrel{!}{=} |\psi_1 \psi_2\rangle \Rightarrow \alpha_1 \alpha_2 = \frac{1}{\sqrt{2}} \wedge \beta_1 \beta_2 = \frac{1}{\sqrt{2}} \Rightarrow \alpha_1 \beta_2 \neq 0$$

$$\wedge\, \alpha_2 \beta_1 \neq 0 \, !$$

It is not possible! This state is special, it is entangled!

Measurement of single qubits in an entangled state:

$$|\psi\rangle = \frac{1}{\sqrt{2}}\left(|00\rangle + |11\rangle\right)$$

measurement of first qubit:

$$p_1(0) = \langle\psi|(M_0 \otimes I)^\dagger (M_0 \otimes I)|\psi\rangle = \frac{1}{\sqrt{2}} \langle 00| \frac{1}{\sqrt{2}} |00\rangle = \frac{1}{2}$$

post measurement state:

$$|\psi'\rangle = \frac{(M_0 \otimes I)|\psi\rangle}{\sqrt{p_1(0)}} = \frac{\frac{1}{\sqrt{2}}|00\rangle}{\frac{1}{\sqrt{2}}} = |00\rangle$$

measurement of qubit two will then result with certainty in the same result:

$$p_2(0) = \langle\psi'|(I \otimes M_0)^\dagger (I \otimes M_0)|\psi'\rangle = 1$$

The two measurement results are **correlated**! Correlations in quantum systems can be stronger than correlations in classical systems. This can be generally proven using the **Bell inequalities** which will be discussed later. Make use of such correlations as a **resource** for information processing, for example in **super dense coding** and **teleportation**.

Two Qubit Quantum Logic Gates

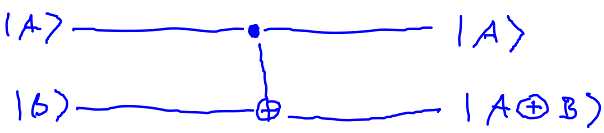
The **controlled NOT gate** (CNOT):

function:

$$|00\rangle \rightarrow |00\rangle$$
$$|01\rangle \rightarrow |01\rangle$$
$$|10\rangle \rightarrow |11\rangle$$
$$|11\rangle \rightarrow |10\rangle$$

$$|A,B\rangle \rightarrow |A, A \oplus B\rangle$$ addition mod 2 of basis states

CNOT circuit:



control qubit

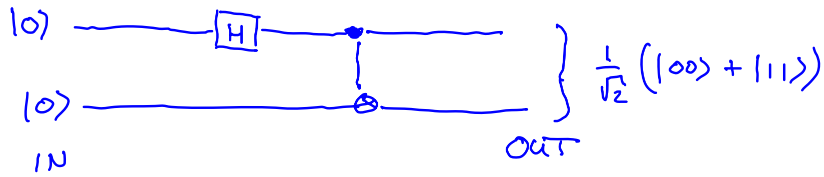
target qubit

comparison with classical gates:

- XOR is not reversible
- CNOT is reversible (unitary)

universality of controlled NOT:
Any multi qubit logic gate can be composed of CNOT gates and single qubit gates X,Y,Z.

application of CNOT: **generation of entangled states (Bell states):**



$$|00\rangle \xrightarrow{H_1} \frac{1}{\sqrt{2}}(|00\rangle + |10\rangle) \xrightarrow{CNOT} \frac{1}{\sqrt{2}}(|00\rangle + |11\rangle)$$

$$|01\rangle \xrightarrow{H_1} \frac{1}{\sqrt{2}}(|01\rangle + |11\rangle) \xrightarrow{CNOT} \frac{1}{\sqrt{2}}(|01\rangle + |10\rangle)$$

$$|10\rangle \xrightarrow{H_1} \frac{1}{\sqrt{2}}(|00\rangle - |10\rangle) \xrightarrow{CNOT} \frac{1}{\sqrt{2}}(|00\rangle - |11\rangle)$$

$$|11\rangle \xrightarrow{H_1} \frac{1}{\sqrt{2}}(|01\rangle - |11\rangle) \xrightarrow{CNOT} \frac{1}{\sqrt{2}}(|01\rangle - |10\rangle)$$

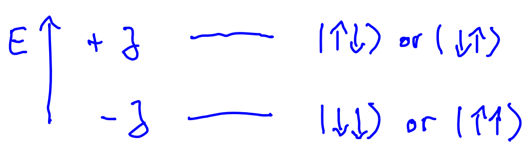
exercise: Write down the unitary matrix representations of the CNOT in the computational basis with qubit 1 being the control qubit. Write down the matrix in the same basis with qubit 2 being the control bit.

Implementation of CNOT:

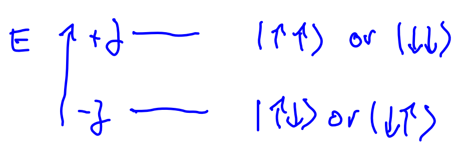
Ising interaction: $H = -\sum_{ij} J_{ij}\, \hat{z}_i \hat{z}_j$ pair wise spin interaction

generic two-qubit interaction: $H = -J\, \hat{z}_1 \hat{z}_2$

J > 0: ferromagnetic coupling



J < 0: anti-ferrom. coupling



2-qubit unitary evolution: $C(\gamma) = e^{-i\frac{\gamma}{2}\hat{z}_1\hat{z}_2}$

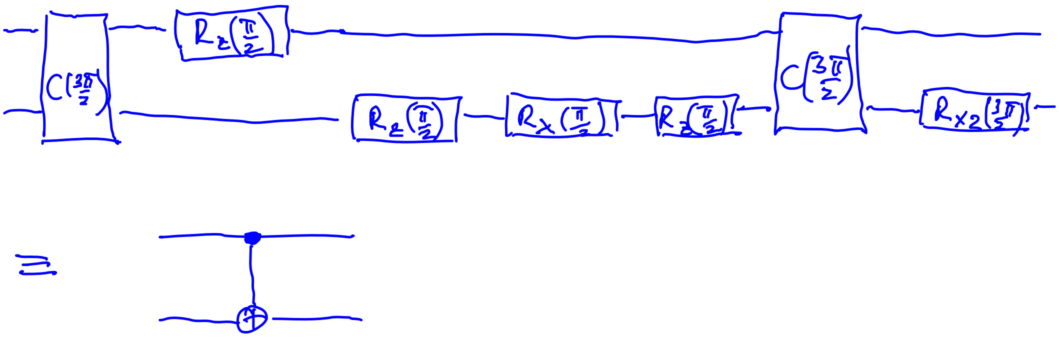
BUT this does not realize a CNOT gate yet. Additionally, single qubit operations on each of the qubits are required to realize a CNOT gate.

CNOT realization with the Ising-type interaction:

CNOT - unitary:

$$C_{NOT} = e^{-i\frac{3\pi}{4}} R_{x2}\left(\tfrac{3\pi}{2}\right) C\left(\tfrac{3\pi}{2}\right) R_{z2}\left(\tfrac{\pi}{2}\right) R_{x2}\left(\tfrac{\pi}{2}\right) R_{z2}\left(\tfrac{\pi}{2}\right) R_{z1}\left(\tfrac{\pi}{2}\right) C\left(\tfrac{3\pi}{2}\right)$$

circuit representation:



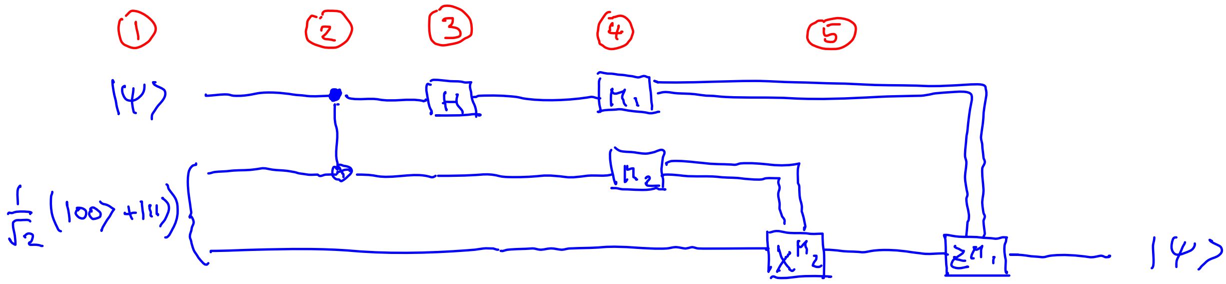
Any physical two-qubit interaction that can produce entanglement can be turned into a universal two-qubit gate (such as the CNOT gate) when it is augmented by arbitrary single qubit operations. [Bremner et al., PRL **89**, 247902 (2002)]

Quantum Teleportation:

Task: Alice wants to transfer an unknown quantum state ψ to Bob only using **one entangled pair** of qubits and **classical information** as a resource.

note:
- Alice does not know the state to be transmitted
- Even if she knew it the classical amount of information that she would need to send would be infinite.

The **teleportation circuit**:



original article:

Teleporting an unknown quantum state via dual classical and Einstein-Podolsky-Rosen channels
Charles H. Bennett, Gilles Brassard, Claude Crépeau, Richard Jozsa, Asher Peres, and William K. Wootters
Phys. Rev. Lett. **70**, 1895 (1993) [PROLA Link]

How does it work?

(1) $$|\psi\rangle \otimes \frac{1}{\sqrt{2}}\left(|00\rangle + |11\rangle\right) = \frac{1}{\sqrt{2}}\left(\alpha|000\rangle + \alpha|011\rangle + \beta|100\rangle + \beta|111\rangle\right)$$

CNOT between qubit to be teleported and one bit of the entangled pair:

(2) $$\xrightarrow{CNOT_{12}} \frac{1}{\sqrt{2}}\left(\alpha|000\rangle + \alpha|011\rangle + \beta|110\rangle + \beta|101\rangle\right)$$

Hadamard on qubit to be teleported:

(3) $$\xrightarrow{H_1} \frac{1}{2}\Big[\left(|00\rangle(\alpha|0\rangle + \beta|1\rangle)\right) + |10\rangle(\alpha|0\rangle - \beta|1\rangle) + |01\rangle(\alpha|1\rangle + \beta|0\rangle) + |11\rangle(\alpha|1\rangle - \beta|0\rangle)\Big]$$

measurement of qubit 1 and 2, classical information transfer and single bit manipulation on target qubit 3:

(4) $\xrightarrow{M_1 \otimes M_2}$ (5)

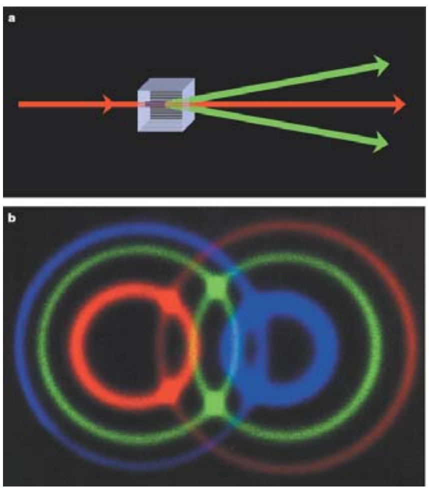
$$p_{00} = \frac{1}{4} \; ; \; |\psi_3\rangle = \alpha|0\rangle + \beta|1\rangle \xrightarrow{I} |\psi\rangle$$

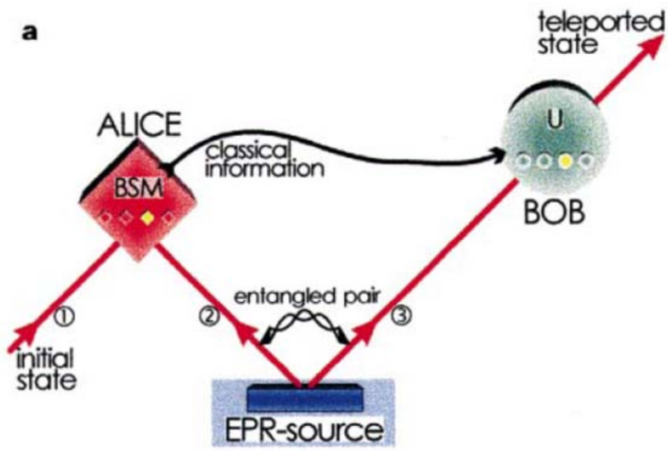
$$p_{10} = \frac{1}{4} \; ; \; |\psi_3\rangle = \alpha|0\rangle - \beta|1\rangle \xrightarrow{Z} |\psi\rangle$$

$$p_{01} = \frac{1}{4} \; ; \; |\psi_3\rangle = \alpha|1\rangle + \beta|0\rangle \xrightarrow{X} |\psi\rangle$$

$$p_{11} = \frac{1}{4} \; ; \; |\psi_3\rangle = \alpha|1\rangle - \beta|0\rangle \xrightarrow{XZ} |\psi\rangle$$

(One) Experimental Realization of Teleportation using Photon Polarization:





- parametric down conversion (PDC) source of entangled photons
- qubits are polarization encoded

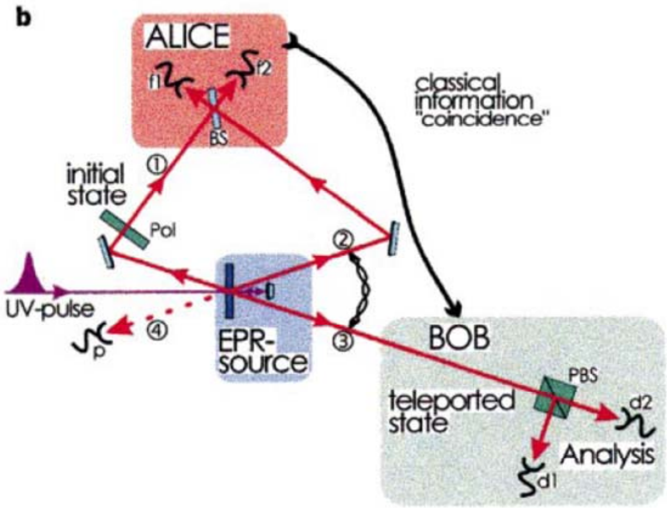
Experimental quantum teleportation
Dik Bouwmeester, Jian-Wei Pan, Klaus Mattle, Manfred Eibl, Harald Weinfurter, Anton Zeilinger
Nature 390, 575 - 579 (11 Dec 1997) Article
Abstract | Full Text | PDF | Rights and permissions | Save this link

Experimental Implementation

start with states

$$|\psi_1\rangle = \alpha\,|H\rangle + \beta\,|V\rangle$$

$$|\psi_{23}\rangle = \frac{1}{\sqrt{2}}\left(|HV\rangle - |VH\rangle\right)$$



combine photon to be teleported (1) and one photon of entangled pair (2) on a 50/50 beam splitter (BS) and measure (at Alice) resulting state in Bell basis.

analyze resulting teleported state of photon (3) using polarizing beam splitters (PBS) single photon detectors

- polarizing beam splitters (PBS) as detectors of teleported states

teleportation papers for you to present:

Experimental Realization of Teleporting an Unknown Pure Quantum State via Dual Classical and Einstein-Podolsky-Rosen Channels
D. Boschi, S. Branca, F. De Martini, L. Hardy, and S. Popescu
Phys. Rev. Lett. **80**, 1121 (1998) [PROLA Link]

Unconditional Quantum Teleportation
A. Furusawa, J. L. Sørensen, S. L. Braunstein, C. A. Fuchs, H. J. Kimble, and E. S. Polzik
Science 23 October 1998 282: 706-709 [DOI: 10.1126/science.282.5389.706] (in Research Articles)
Abstract » Full Text » PDF »

Complete quantum teleportation using nuclear magnetic resonance
M. A. Nielsen, E. Knill, R. Laflamme
Nature 396, 52 - 55 (05 Nov 1998) Letters to Editor
Abstract | Full Text | PDF | Rights and permissions | Save this link

Deterministic quantum teleportation of atomic qubits
M. D. Barrett, J. Chiaverini, T. Schaetz, J. Britton, W. M. Itano, J. D. Jost, E. Knill, C. Langer, D. Leibfried, R. Ozeri, D. J. Wineland
Nature 429, 737 - 739 (17 Jun 2004) Letters to Editor
Abstract | Full Text | PDF | Rights and permissions | Save this link

Deterministic quantum teleportation with atoms
M. Riebe, H. HÃ¤ffner, C. F. Roos, W. HÃ¤nsel, J. Benhelm, G. P. T. Lancaster, T. W. KÃ¶rber, C. Becher, F. Schmidt-Kaler, D. F. V. James, R. Blatt
Nature 429, 734 - 737 (17 Jun 2004) Letters to Editor
Abstract | Full Text | PDF | Rights and permissions | Save this link

Quantum teleportation between light and matter
Jacob F. Sherson, Hanna Krauter, Rasmus K. Olsson, Brian Julsgaard, Klemens Hammerer, Ignacio Cirac, Eugene S. Polzik
Nature 443, 557 - 560 (05 Oct 2006) Letters to Editor
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