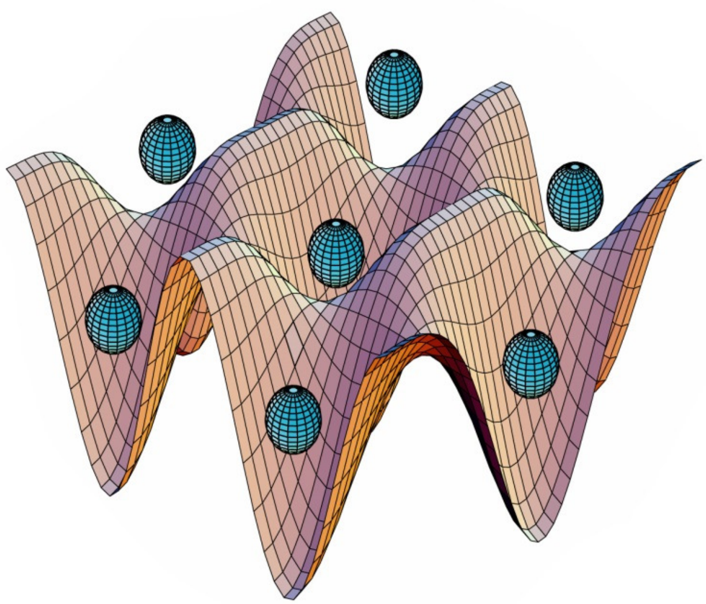
Quantum Computation with Neutral Atoms



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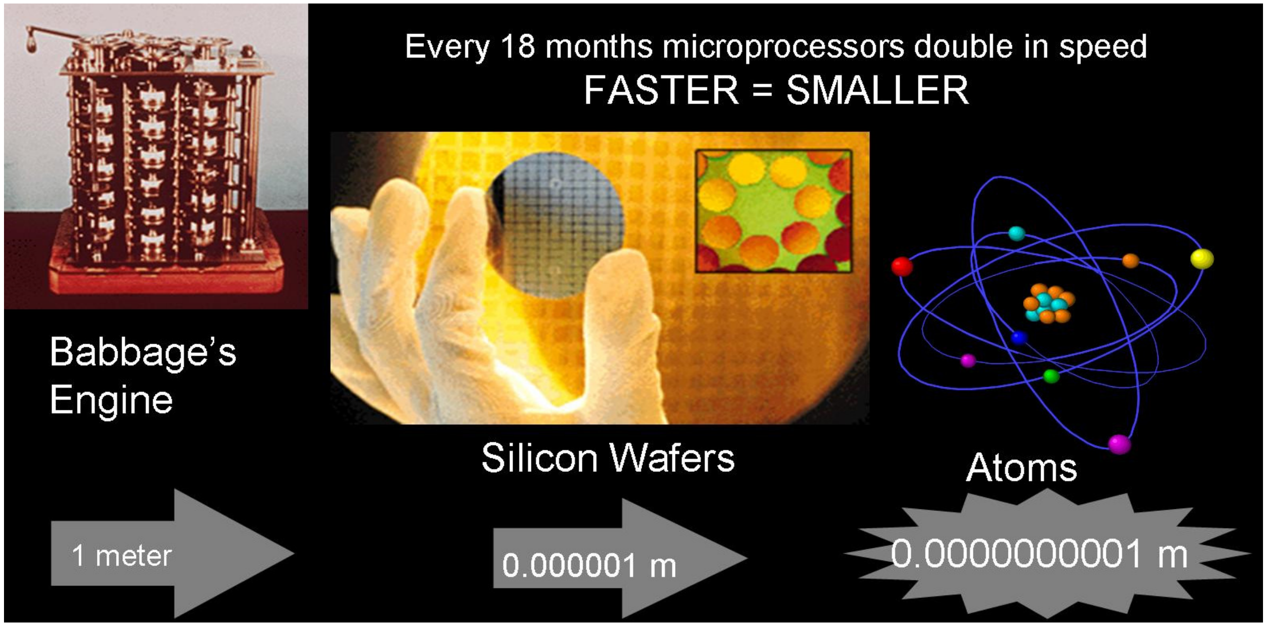
Why quantum information?

Information is physical!

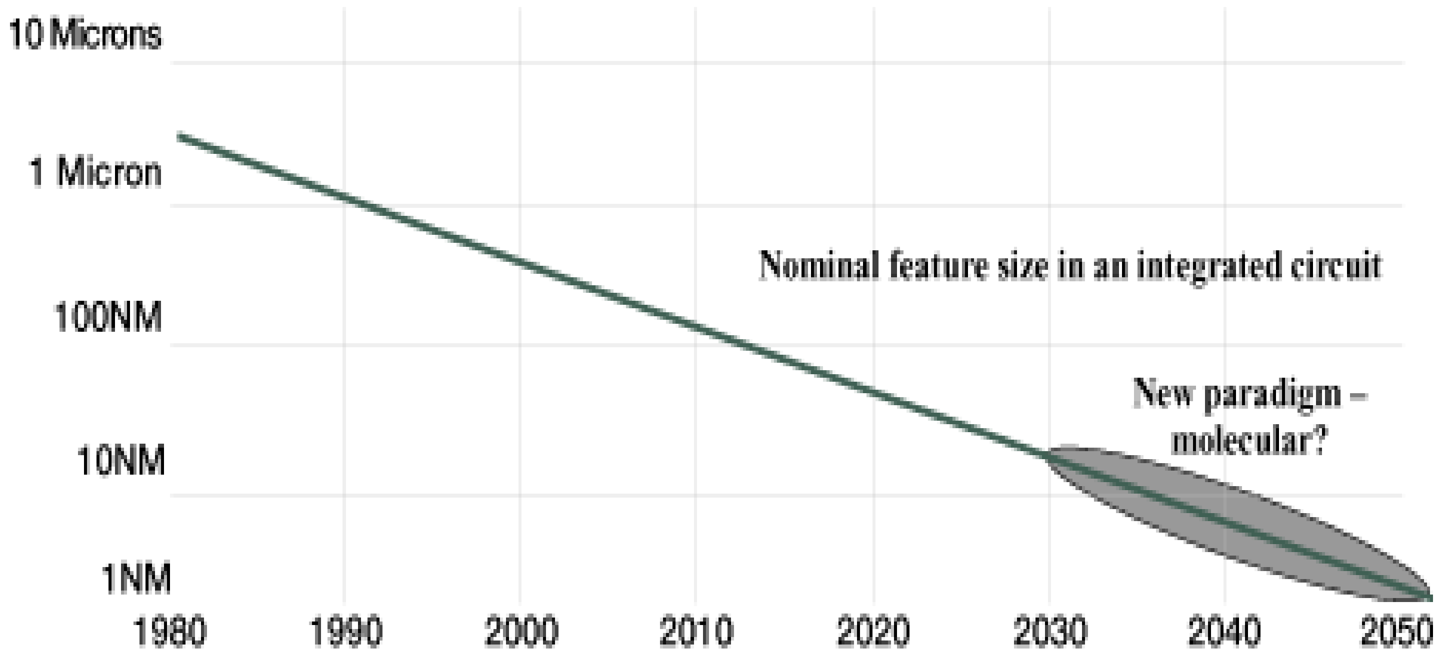
Any processing of information

is always performed by physical means

Bits of information obey laws of classical physics.



Why Quantum Computers?



Computer technology is making devices smaller and smaller…

…reaching a point where classical physics is no longer a suitable model for the laws of physics.

Bits & Qubits

Fundamental building blocks of classical computers:

BITS

STATE:
Definitely
0 or 1

Fundamental building blocks of quantum computers:

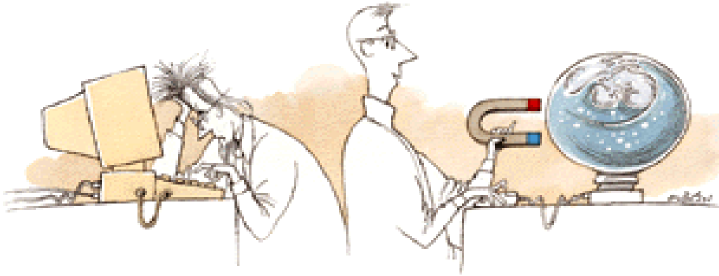
Quantum bits
or
QUBITS

Basis states: $|0\rangle$ and $|1\rangle$

Superposition:

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

Bits & Qubits



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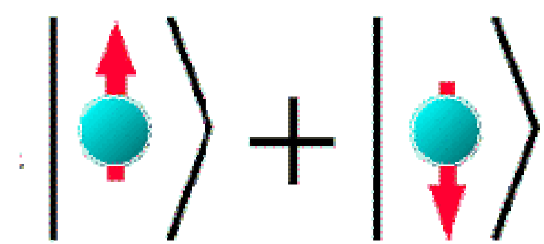
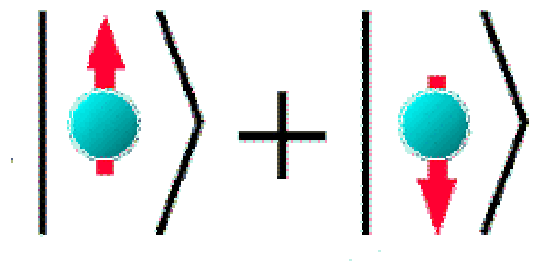
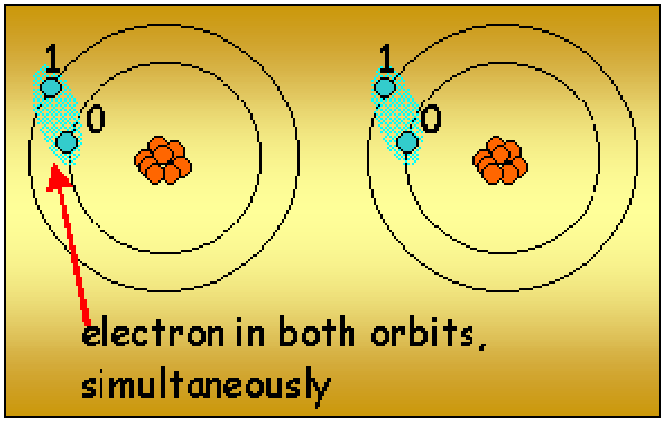
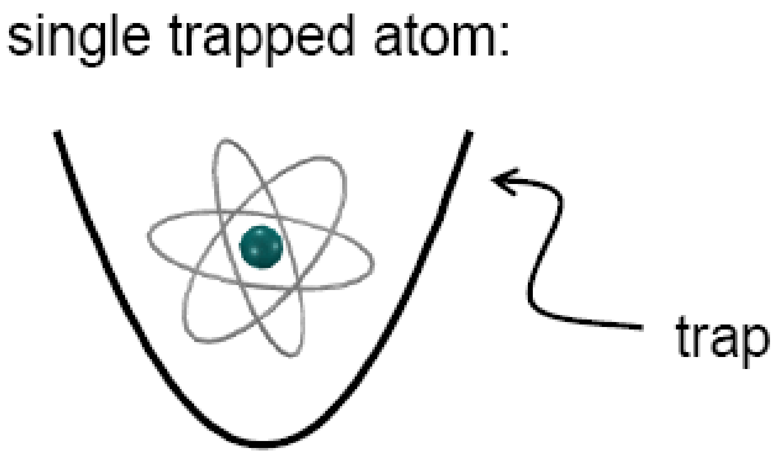
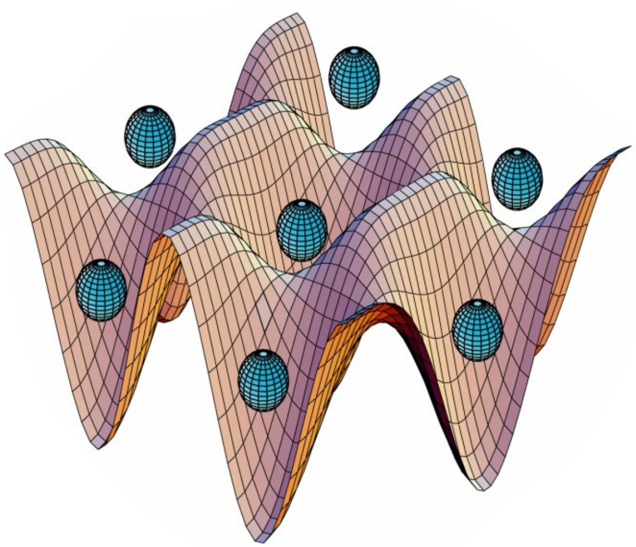


Qubit: any suitable two-level quantum system





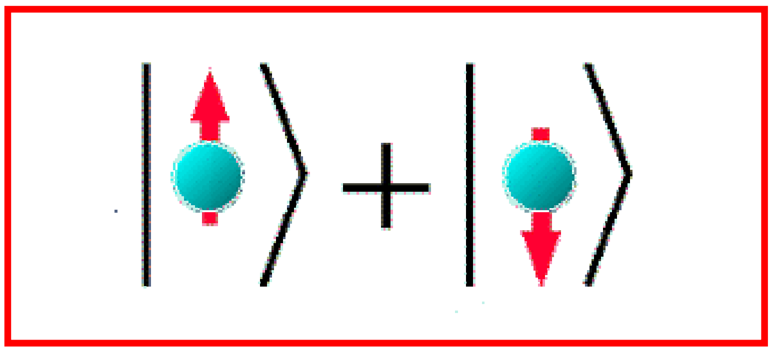




Bits & Qubits: primary differences

Superposition

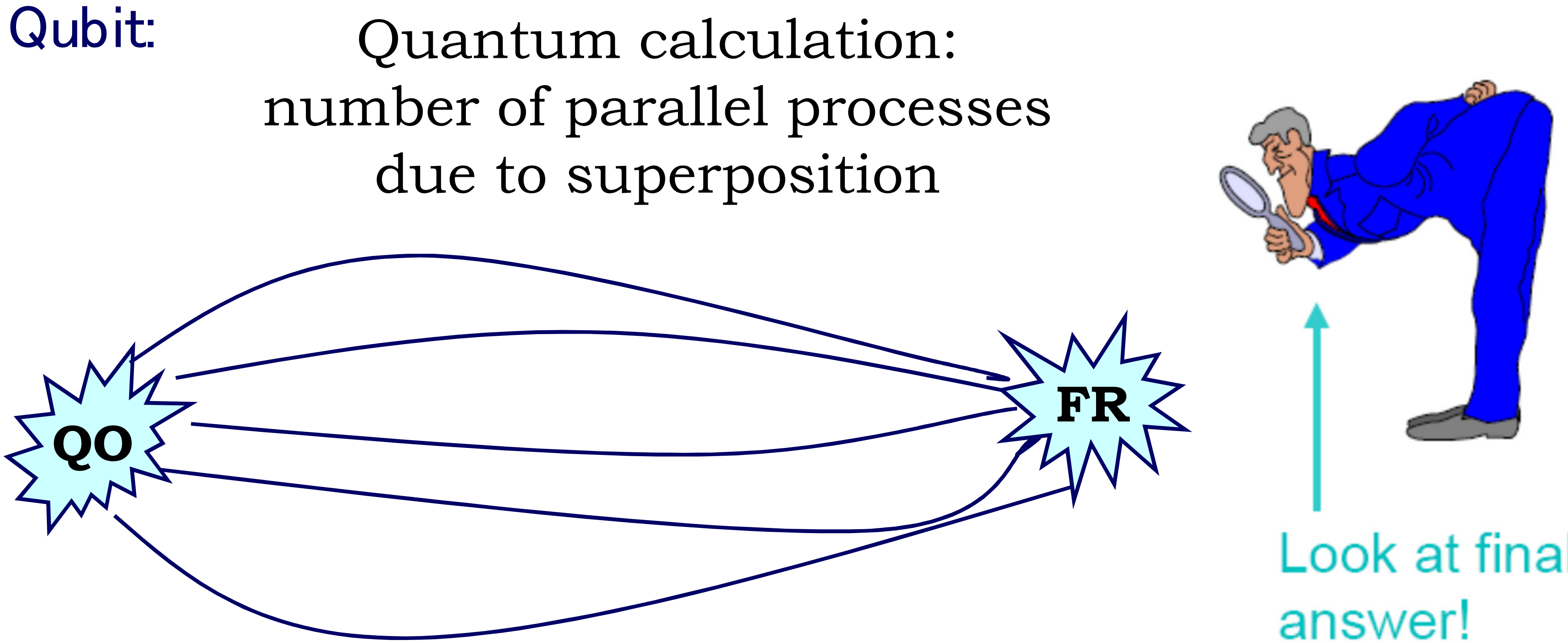
$$|\psi\rangle = \alpha|0\rangle + \beta|1\rangle$$



Bits & Qubits: primary differences

Measurement

- Classical bit: we can find out if it is in state 0 or 1 and the measurement will not change the state of the bit.
- Qubit:



Bits & Qubits: primary differences

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

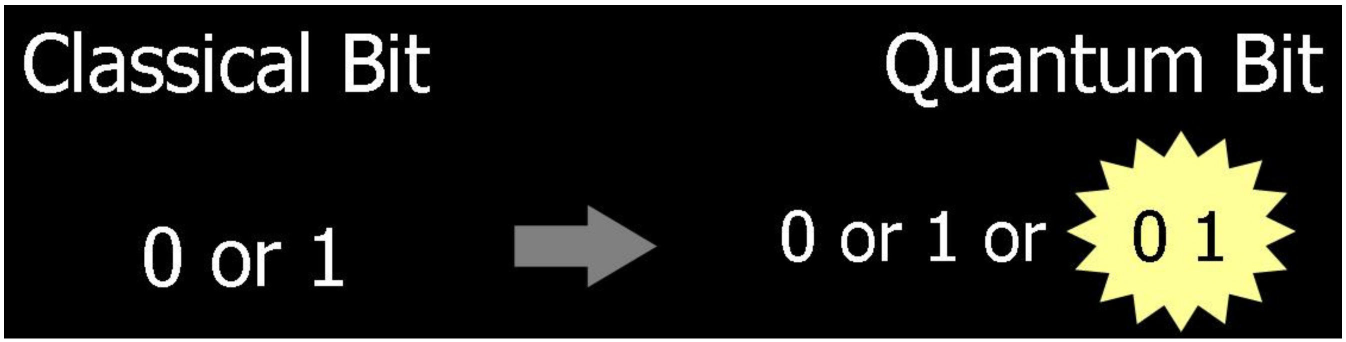
- Superposition
- Measurement
  - Classical bit: we can find out if it is in state 0 or 1 and the measurement will not change the state of the bit.
  - Qubit: we cannot just measure α and β and thus determine its state! We get either $|0\rangle$ or $|1\rangle$ with corresponding probabilities $|\alpha|^2$ and $|\beta|^2$.

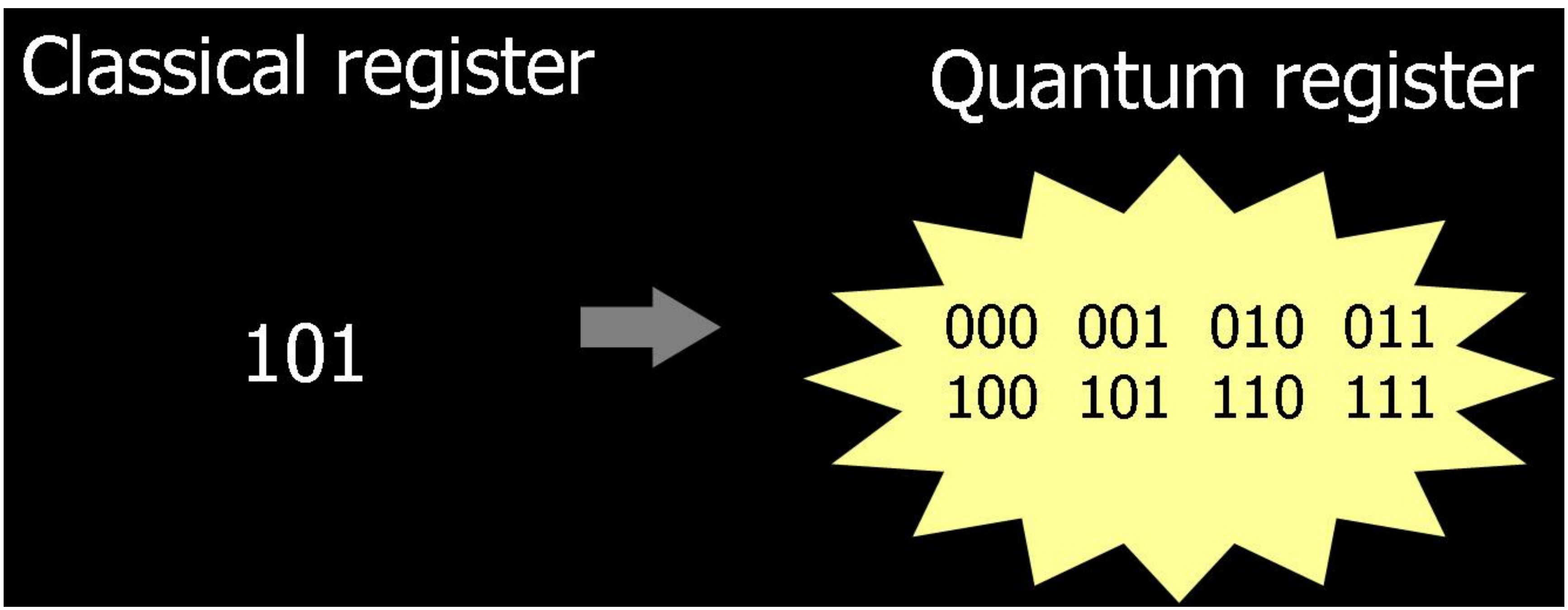
$$|\alpha|^2 + |\beta|^2 = 1$$

  - The measurement changes the state of the qubit!

Hilbert space is a big place!
- Carlton Caves

Multiple qubits





Hilbert space is a big place!

- Carlton Caves

Multiple qubits

- Two bits with states 0 and 1 form four definite states 00, 01, 10, and 11.
- Two qubits: can be in superposition of four computational basis set states.

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

2 qubits	4 amplitudes
3 qubits	8 amplitudes
10 qubits	1024 amplitudes
20 qubits	1 048 576 amplitudes
30 qubits	1 073 741 824 amplitudes
500 qubits	More amplitudes than our estimate of number of atoms in the Universe!!!

Entanglement

$$|\psi\rangle = \frac{|00\rangle + |11\rangle}{\sqrt{2}}$$

Results of the measurement

First	qubit	0	1
Second	qubit	0	1

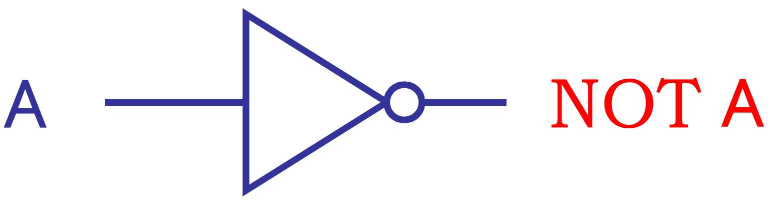
$$|\psi\rangle \neq |\alpha\rangle \otimes |\beta\rangle \longrightarrow$$

Entangled states

Quantum logic gates

Logic gates

Classical NOT gate



A	NOT A
0	1
1	0

The only non-trivial single bit gate

Quantum NOT gate (X gate)

$$\alpha|0\rangle + \beta|1\rangle \;—\boxed{X}—\; \alpha|1\rangle + \beta|0\rangle$$

Matrix form representation

$$X = \begin{bmatrix} 0 & 1 \\ 1 & 0 \end{bmatrix}$$

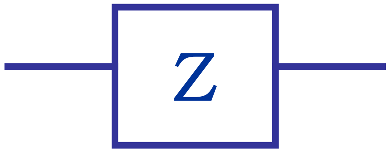
$$X \begin{bmatrix} \alpha \\ \beta \end{bmatrix} = \begin{bmatrix} \beta \\ \alpha \end{bmatrix}$$

More single qubit gates

Any unitary matrix U will produce a quantum gate!

$$Z = \begin{bmatrix} 1 & 0 \\ 0 & -1 \end{bmatrix}$$

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



$$\alpha|0\rangle - \beta|1\rangle$$

Hadamard gate:

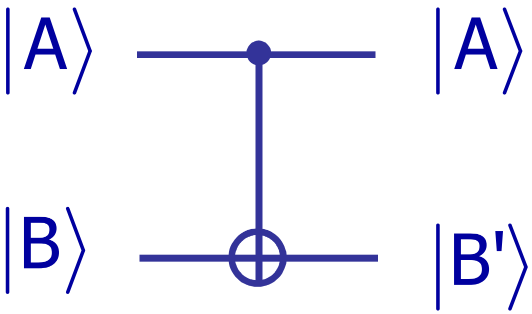
$$H = \frac{1}{\sqrt{2}}\begin{bmatrix} 1 & 1 \\ 1 & -1 \end{bmatrix}$$

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

$$\alpha\frac{|0\rangle + |1\rangle}{\sqrt{2}} + \beta\frac{|0\rangle - |1\rangle}{\sqrt{2}}$$

Two-qubit gates

Quantum CNOT gate



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

WE NEED TO BE ABLE TO MAKE ONLY ONE TWO-QUBIT GATE!

Back to the real world:

What do we need to build a quantum computer?

- **Qubits** which retain their properties.

  Scalable array of qubits.

- **Initialization:** ability to prepare one certain state repeatedly on demand. Need continuous supply of $|0\rangle$.

- **Universal set of quantum gates.** A system in which qubits can be made to evolve as desired.

- **Long relevant decoherence times.**

- Ability to efficiently **read out the result.**

Real world strategy

"…If X is very hard it can be substituted with more of Y.

Of course, in many cases both X and Y are beyond the present experimental state of the art …"

David P. DiVincenzo

The physical implementation of quantum computation.

Experimental proposals

- Liquid state NMR
- Trapped ions
- Cavity QED
- **Trapped atoms**
- Solid state schemes
- And other ones …

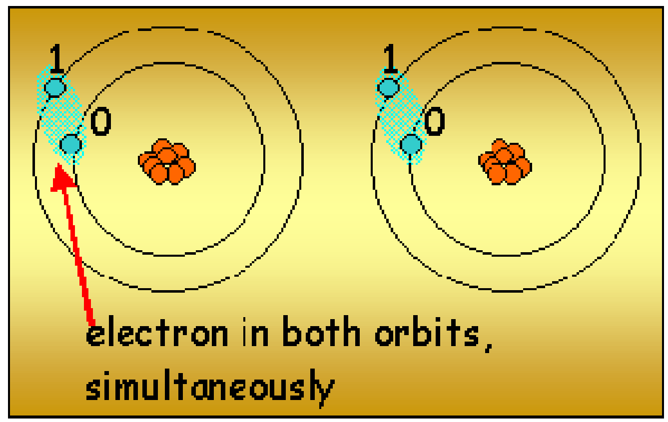
1. A scalable physical system with well characterized qubits: memory

(a) Internal atomic state qubits:

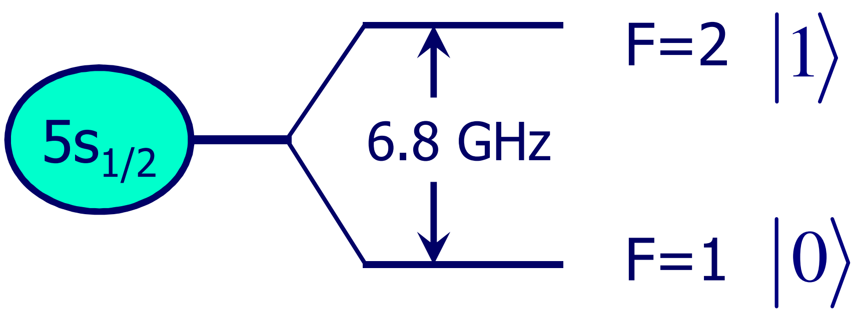
ground hyperfine states of neutral trapped atoms

well characterized

Very long lived!



M_F=-2,-1,0,1,2



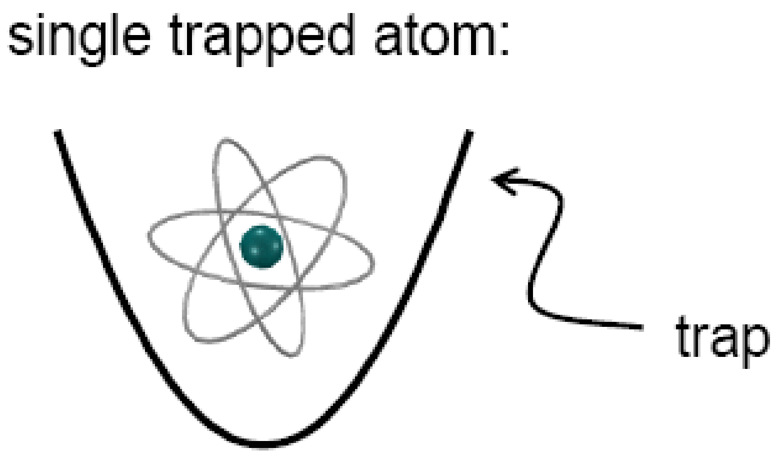
^{87}Rb: Nuclear spin I=3/2

M_F=-1,0,1

1. A scalable physical system with well characterized qubits: memory

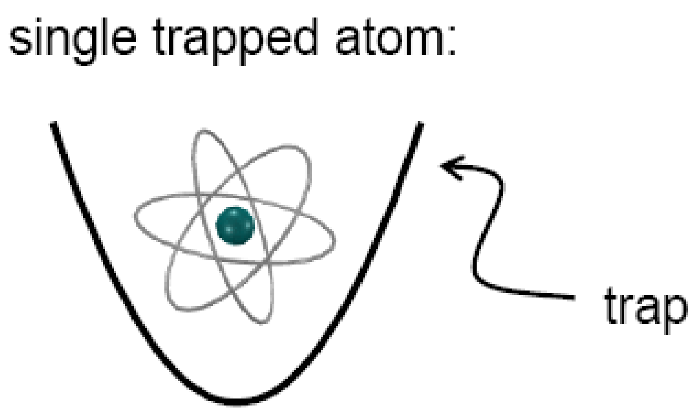
(b) Motional qubits : quantized levels in the trapping potential also well characterized

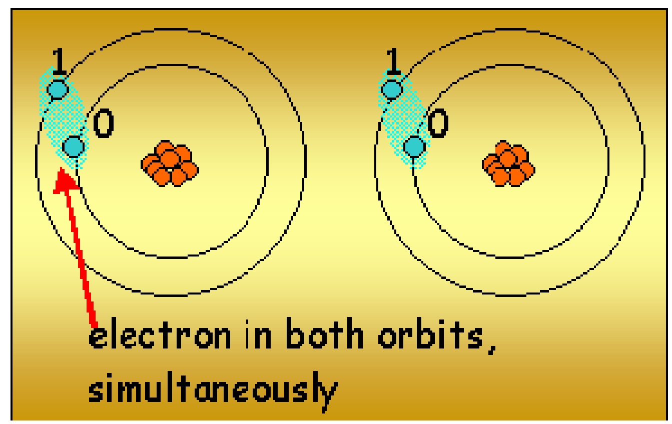
http://www.colorado.edu/physics/2000/index.pl



1. A scalable physical system with well characterized qubits: memory

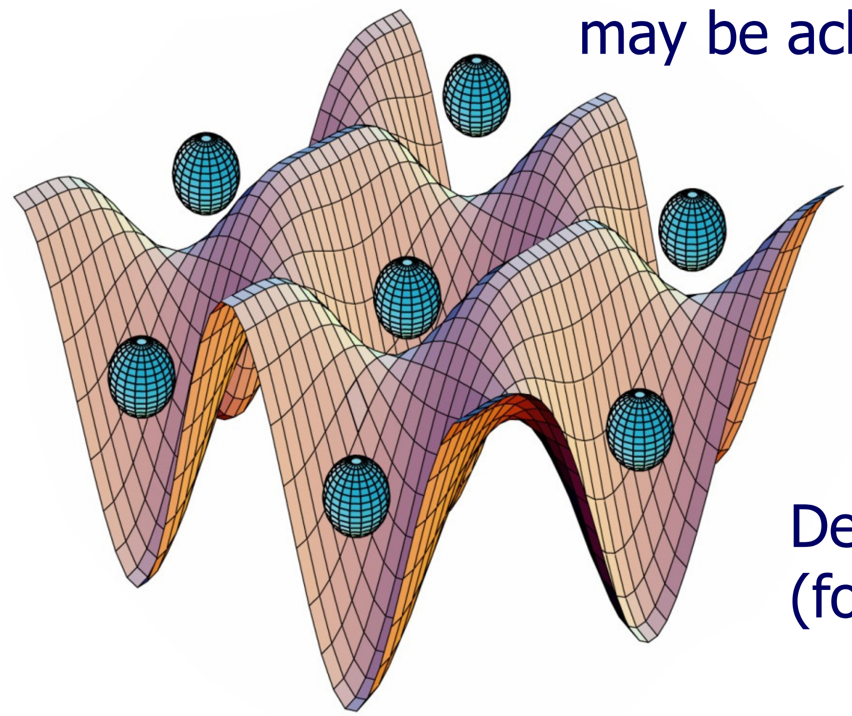
(a) Internal atomic state qubits
(b) Motional qubits





Advantages: very long decoherence times!
Internal states are well understood: atomic spectroscopy & atomic clocks.

1. A scalable physical system with well characterized qubits



Optical lattices: loading of one atom per site may be achieved using Mott insulator transition.

Scalability: the properties of optical lattice system do not change in the principal way when the size of the system is increased.

Designer lattices may be created (for example with every third site loaded).

Advantages: inherent scalability and parallelism.
Potential problems: individual addressing.

2: Initialization

Internal state preparation: putting atoms in the ground hyperfine state

Very well understood (optical pumping technique is in use since 1950)

Very reliable (>0.9999 population may be achieved)

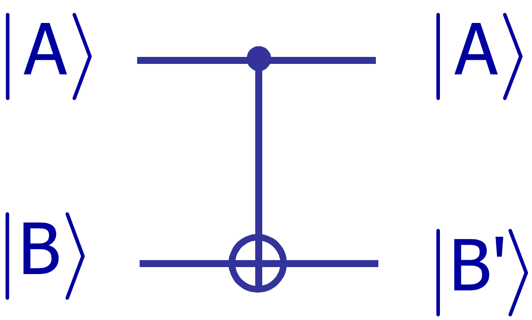
Motional states may be cooled to motional ground states (>95%)

Loading with one atom per site: Mott insulator transition and other schemes.

Zero's may be supplied during the computation (providing individual or array addressing).

3: A universal set of quantum gates

CNOT



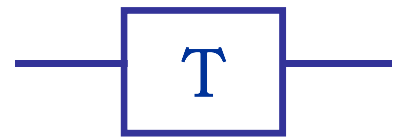
$\lvert AB\rangle$	$\lvert AB'\rangle$
$\lvert 00\rangle$	$\lvert 00\rangle$
$\lvert 01\rangle$	$\lvert 01\rangle$
$\lvert 10\rangle$	$\lvert 11\rangle$
$\lvert 11\rangle$	$\lvert 10\rangle$

Hadamard gate:

$\lvert A\rangle$	$\lvert A'\rangle$
$\lvert 0\rangle$	$\frac{\lvert 0\rangle + \lvert 1\rangle}{\sqrt{2}}$
$\lvert 1\rangle$	$\frac{\lvert 0\rangle - \lvert 1\rangle}{\sqrt{2}}$

$$H = (X + Z)/\sqrt{2}$$

$\pi/8$ gate:



$$T = \begin{bmatrix} 1 & 0 \\ 0 & e^{i\pi/4} \end{bmatrix}$$

Phase gate S:

$$S = \begin{bmatrix} 1 & 0 \\ 0 & i \end{bmatrix}$$

$$S = T^2$$

3: A universal set of quantum gates

1. Single-qubit rotations: well understood and had been carried out in atomic spectroscopy since 1940's.

2. Two-qubit gates: none currently implemented (conditional logic was demonstrated)

Proposed interactions for two-qubit gates:

(a) Electric-dipole interactions between atoms
(b) Ground-state elastic collisions
(c) Magnetic dipole interactions

Only one gate proposal does not involve moving atoms (Rydberg gate).

Advantages: possible parallel operations
Disadvantages: decoherence issues during gate operations

Two-qubit quantum gates

(a) Electric-dipole interactions between atoms

Brennen et al. PRL 82, 1060 (1999), PRA 61, 062309 (2000),

Pairs of atoms are brought to occupy the same site in far-off-resonance optical lattice by varying polarization of the trapping laser.
Two "types" of atoms: trapped in σ+ and σ- polarized wells.
Near-resonant electric-dipole is induced by auxiliary laser (depending on the atomic state).

Brennen, Deutch, and Willaims PRA 65, 022313 (2002)

Deterministic entanglement of pairs of atoms trapped in optical lattice is achieved by coupling to excited state molecular hyperfine potentials.

Two-qubit quantum gates

(a) Electric-dipole interactions between atoms … cont.

Jaksch et al., Phys. Rev. Lett. 85, 2208 (2000)
Gate operations are mediated by excitation of Rydberg states

(b) Ground-state elastic collisions

Calarco et al. Phys. Rev. A 61, 022304 (2000)
Cold collisions between atoms conditional on internal states.
Cold collisions between atoms conditional on motional-state tunneling.

(c) Magnetic-dipole interactions between pairs of atoms

Rydberg gate scheme

Gate operations are mediated by excitation of Rydberg states
Jaksch et al., Phys. Rev. Lett. 85, 2208 (2000)

Why Rydberg gate?

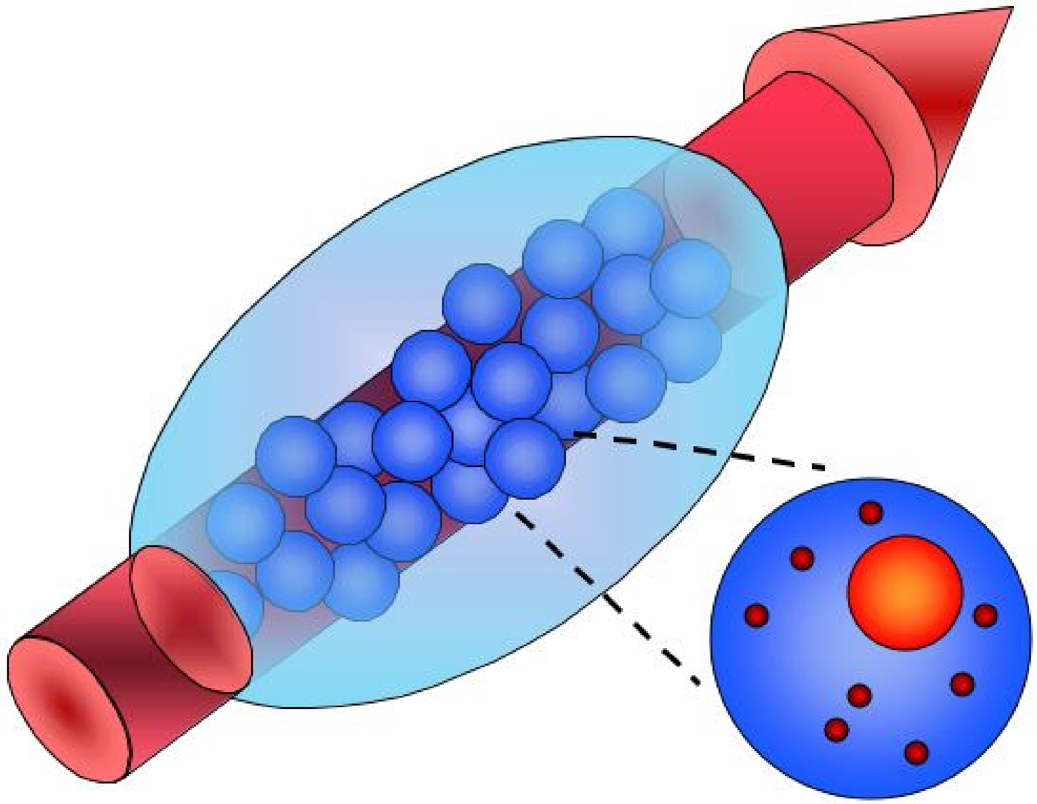
Rydberg gate scheme

Gate operations are mediated by excitation of Rydberg states
Jaksch et al., Phys. Rev. Lett. 85, 2208 (2000)

Do not need to move atoms!

FAST!

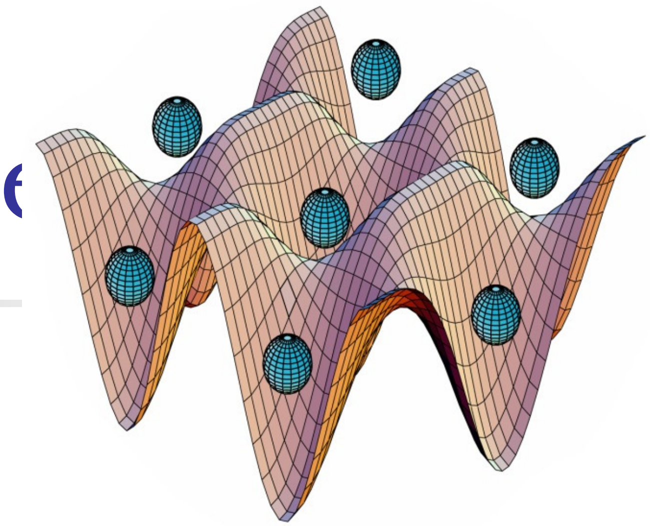
Local blockade of Rydberg excitations



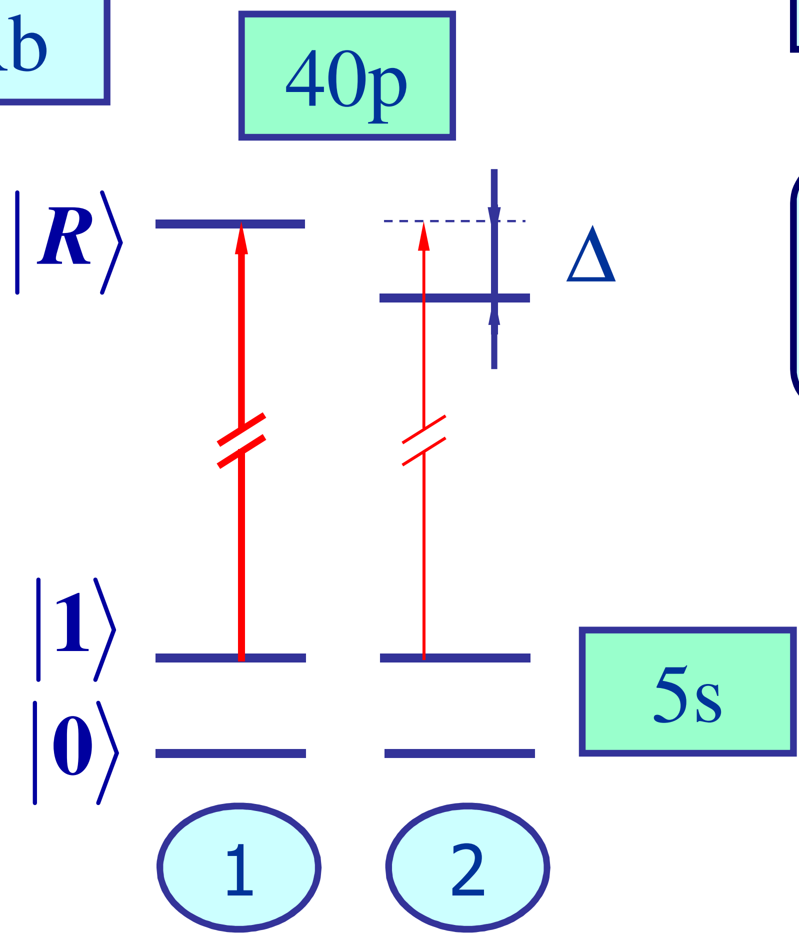
Excitations to Rydberg states are suppressed due to a dipole-dipole interaction or van der Waals interaction

http://www.physics.uconn.edu/~rcote/

Rydberg gate scheme



Rb



FAST!

Apply a series of laser pulses to realize the following logic gate:

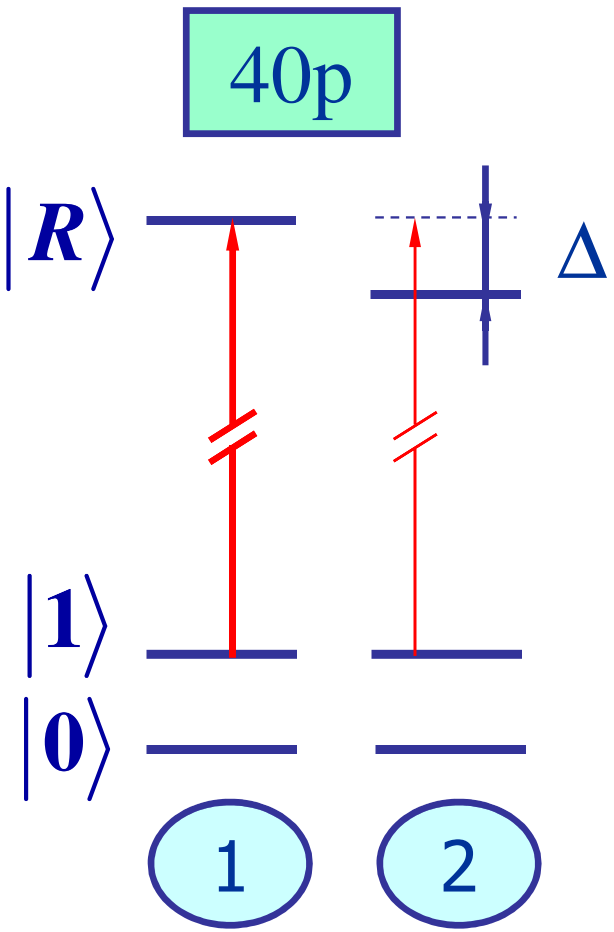
$$
\begin{aligned}
|00\rangle &\rightarrow |00\rangle \\
|10\rangle &\rightarrow |01\rangle \\
|01\rangle &\rightarrow |10\rangle \\
|11\rangle &\rightarrow -|11\rangle
\end{aligned}
$$

Jaksch et al., Phys. Rev. Lett. 85, 2208 (2000)

Rydberg gate scheme

Rb

5s



$$
\begin{array}{ccccccc}
 & \pi[1] & & 2\pi[2] & & \pi[1] & \\
|00\rangle & \rightarrow & |00\rangle & \rightarrow & |00\rangle & \rightarrow & |00\rangle \\
|01\rangle & \rightarrow & |01\rangle & \rightarrow & -|01\rangle & \rightarrow & -|01\rangle \\
|10\rangle & \rightarrow & |R0\rangle & \rightarrow & |R0\rangle & \rightarrow & -|10\rangle \\
|11\rangle & \rightarrow & |R1\rangle & \rightarrow & |R1\rangle & \rightarrow & -|11\rangle
\end{array}
$$

Decoherence

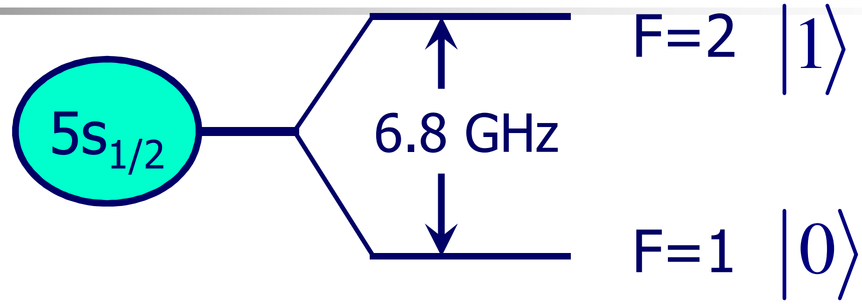
- One of the decoherence sources: motional heating. Results from atom “seeing” different lattice in ground and Rydberg states.
- Solution: choose the lattice photon frequency ω to match frequency-dependent polarizability $\alpha(\omega)$ of the ground and Rydberg states.
- Error correction: possible but error rate has to be really small ($< 10^{-4}$).

Other decoherence sources

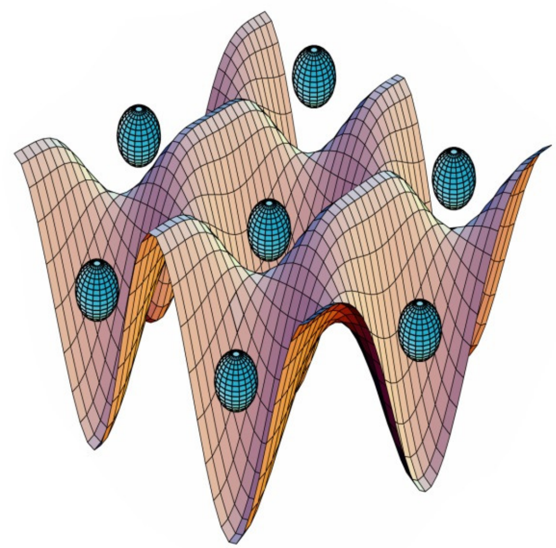
- Photoionization
- Spontaneous emission
- Transitions induced by black-body radiation
- Laser beam intensity stability
- Pulse timing stability
- Individual addressing accuracy

4. Long relevant decoherence times

Memory: long-lived states.



Fundamental decoherence mechanism for optically trapped qubits: photon scattering.



Decoherence during gate operations: a serious issue.

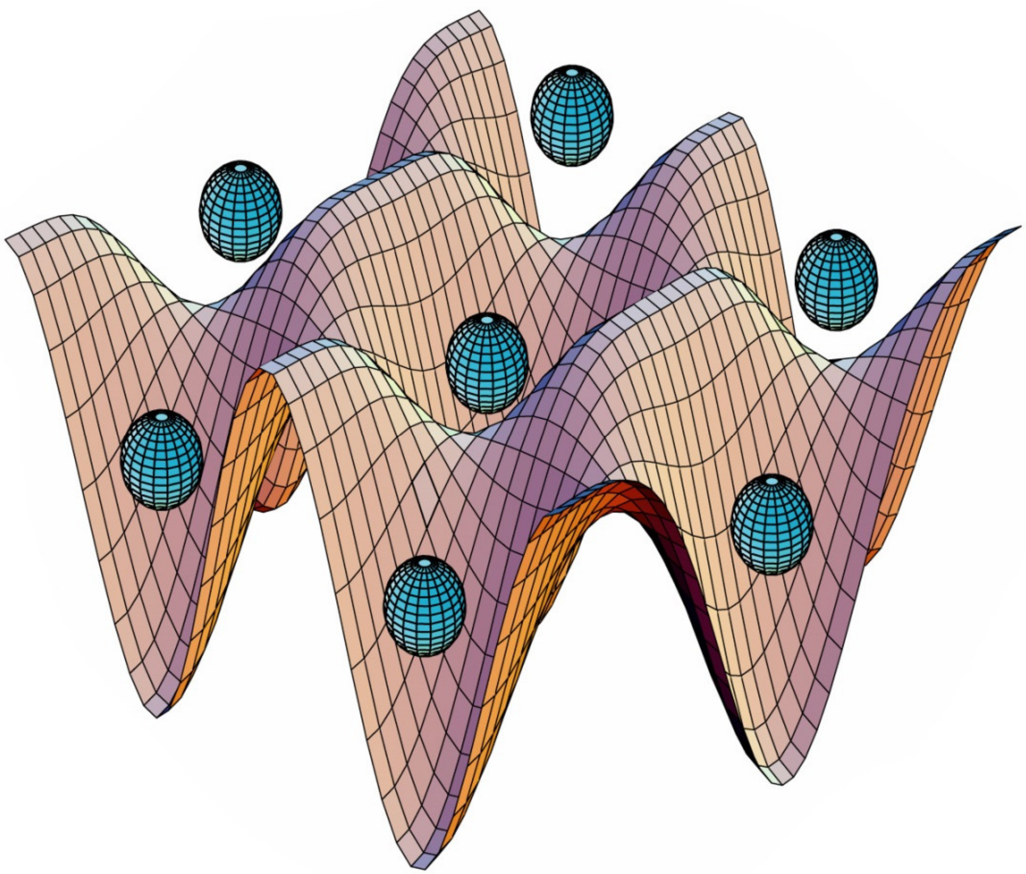
5: Reading out a result

“Quantum jump” method via cycling transitions.

Advantages: standard atomic physics technique, well understood and reliable.

Quantum computation with NEUTRAL ATOMS: ADVANTAGES

Scalability



Possible massive parallelism due to lattice geometry

Long decoherence times (weak coupling to the environment)

Availability of the controlled interactions

Well-developed experimental techniques for initialization, state manipulation, and readout

Accurate theoretical description of the system is possible.

Quantum computation with NEUTRAL ATOMS: PROBLEMS

Decoherence during the gate operations
(various sources)

Reliable lattice loading and individual addressing

QC architecture for lattice geometry:
Error-correcting codes and fault-tolerant computation,
how to run algorithms on neutral atom quantum computer.