Real Quantum Computers

Sources
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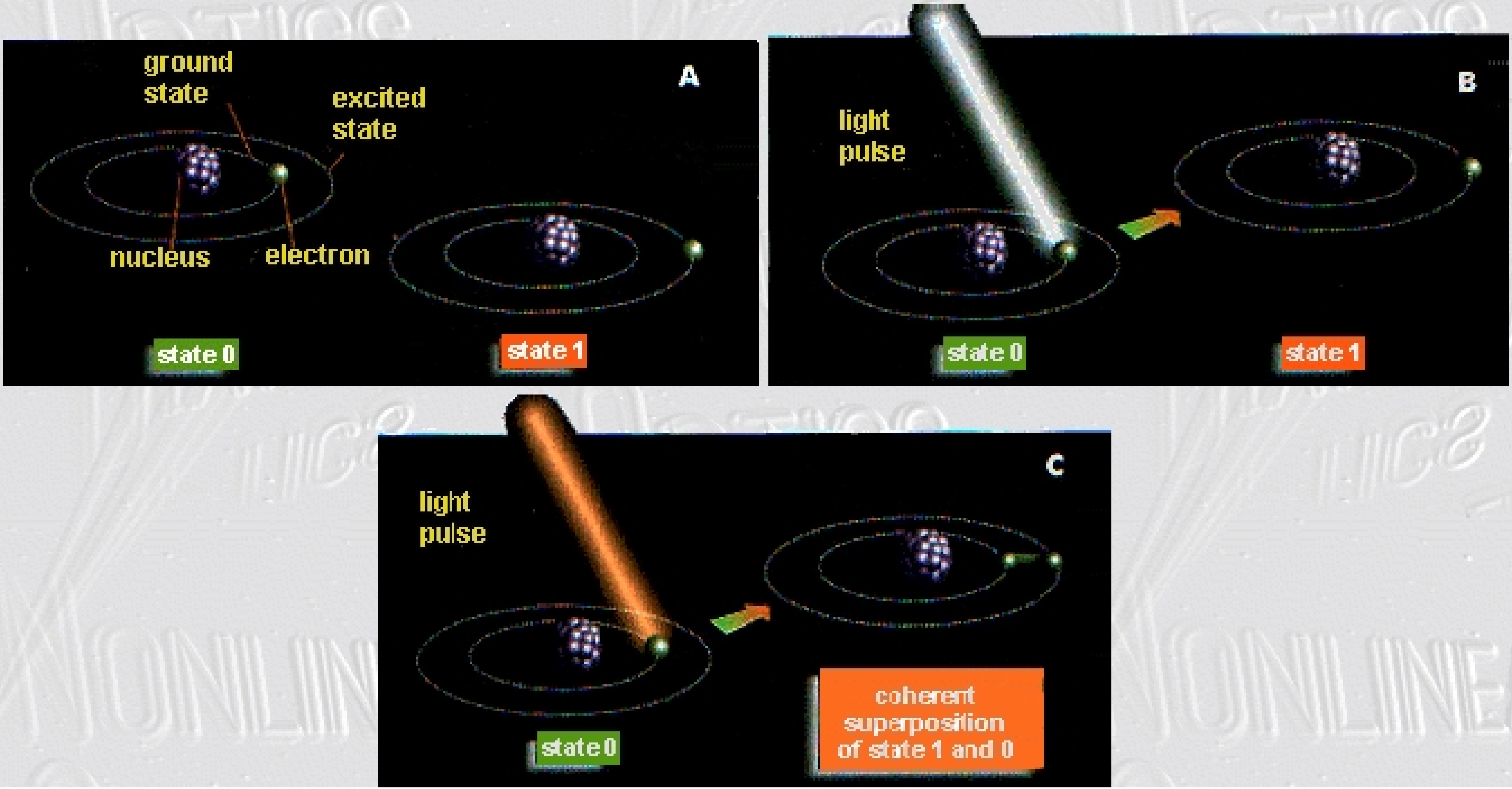
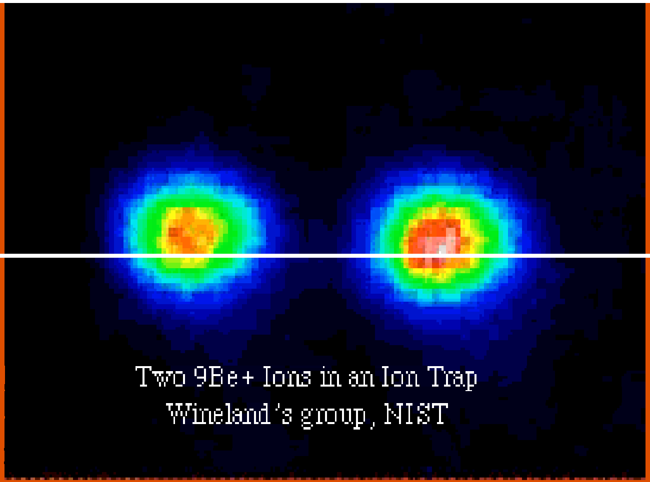
Outline

- Hurdles to building quantum computers
  - Decoherence
  - Error Correction
- Requirements for workable quantum computers
- NMR quantum computers
- Complete architecture proposal

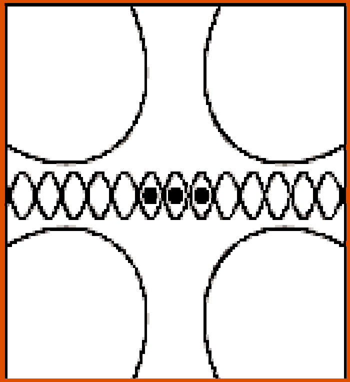
Two Level Atom as a qubit

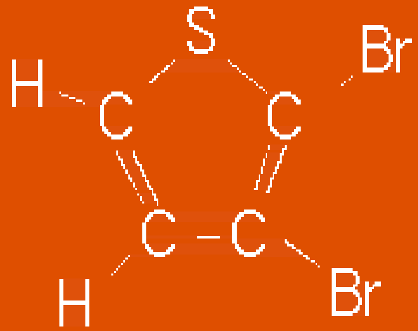


Physical implementation



- Ion traps, 2 & 3 qubit systems
- Nuclear spins in NMR devices, 4 (5?, 6?) qubits
- So far: very few qubits, impractical
- A lot of current research





•Two 9Be+ Ions in an Ion Trap
•Wineland's group, NIST

Main Contenders

- **1.** NMR (nuclear magnetic resonance), **invented in the 1940's and widely used in chemistry and medicine today**
- **2.** Ion traps - single atoms
- Optical lattices
- Quantum dots
- Electrons on liquid helium

etc.

Quantum Technology Requirements for Physical Implementation

Quantum Technology Requirements [Di Vicenzo '01]

- Scalable with well-characterized qubits
- Initializable to a pure state such as $|00\ldots0\rangle$
- Relatively long decoherence time
- "Universal" set of quantum gates
- Qubit-specific measurement capability
- Ability to faithfully communicate qubits

Decoherence

- Quantum computations rely on being able to operate on a set of qubits in an entangled/superimposed state
  - Allows computation on all possible inputs to a computation in parallel
- **Problem**: Interaction of qubits with environment affects their state, causing them to not be entangled/superimposed
  - Can partially address this by designing computer to **reduce interaction with environment**, but this may make it impractical (for example, running at very low temperatures)
- **General result:** a quantum computation can only proceed for a limited period of time **before a measurement** must be performed
  - Measurement forces the system into a more-stable classical state
  - Measurement destroys superposition
  - System limited by **ratio of** decoherence time to operation latency

Decoherence-related Figure of Merit

- precise control of quantum phenomena
- low noise = long decoherence time T
- fast coherent switching time t

Figure of merit D

$$D = \left(\frac{T}{t} \right)$$

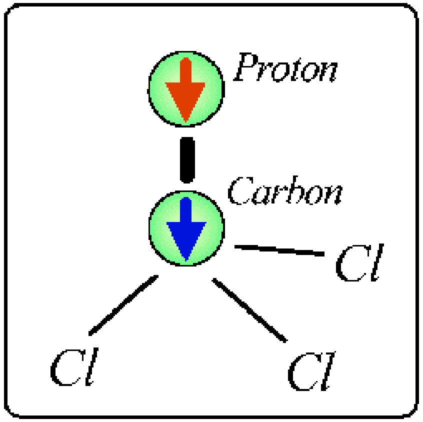
We want D as big as possible + quantum error correction

Using a single molecule?

- **A nearly ideal physical system that can be used as quantum computer is a single molecule, in which nuclear spins of individual atoms represent qubits.**
- **Using NMR techniques, these spins can be manipulated, initialized and measured.**

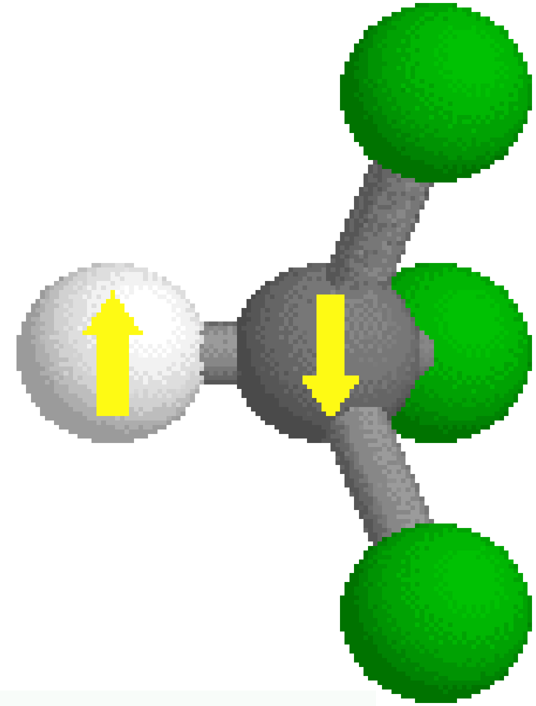
- **The quantum behavior of the spins can be exploited to perform quantum computation; for example, the carbon and hydrogen nuclei in a chloroform molecule (as shown) represent two qubits.**

Single molecule or ensamble?



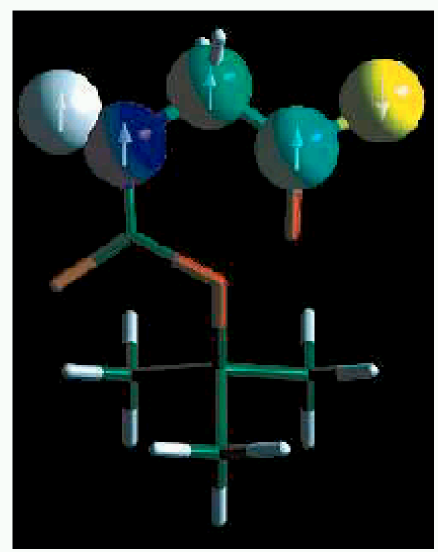
$|0\rangle |0\rangle$

NMR (Nuclear Magnetic Resonance)



- NMR was thought of in 1996
- Initial demonstrations of quantum algorithms have been performed using NMR quantum computing
  - 1997: Grover's quantum searching algorithm on a 2- qubit quantum computer
  - 2001: Shor's factorization algorithm on a 7- qubit quantum computer to factorize 15. Developed at IBM by Issac Chaung.
  - quantum search,
  - Deutsch
  - etc.

- Protons and Neutrons have spin.
  - In a normal atoms these spins cancel out.
  - In isotopes there are extra neutrons.
  - These extra neutrons create a net positive or negative spin in an atom.



A molecule containing 5 NMR spin qubits

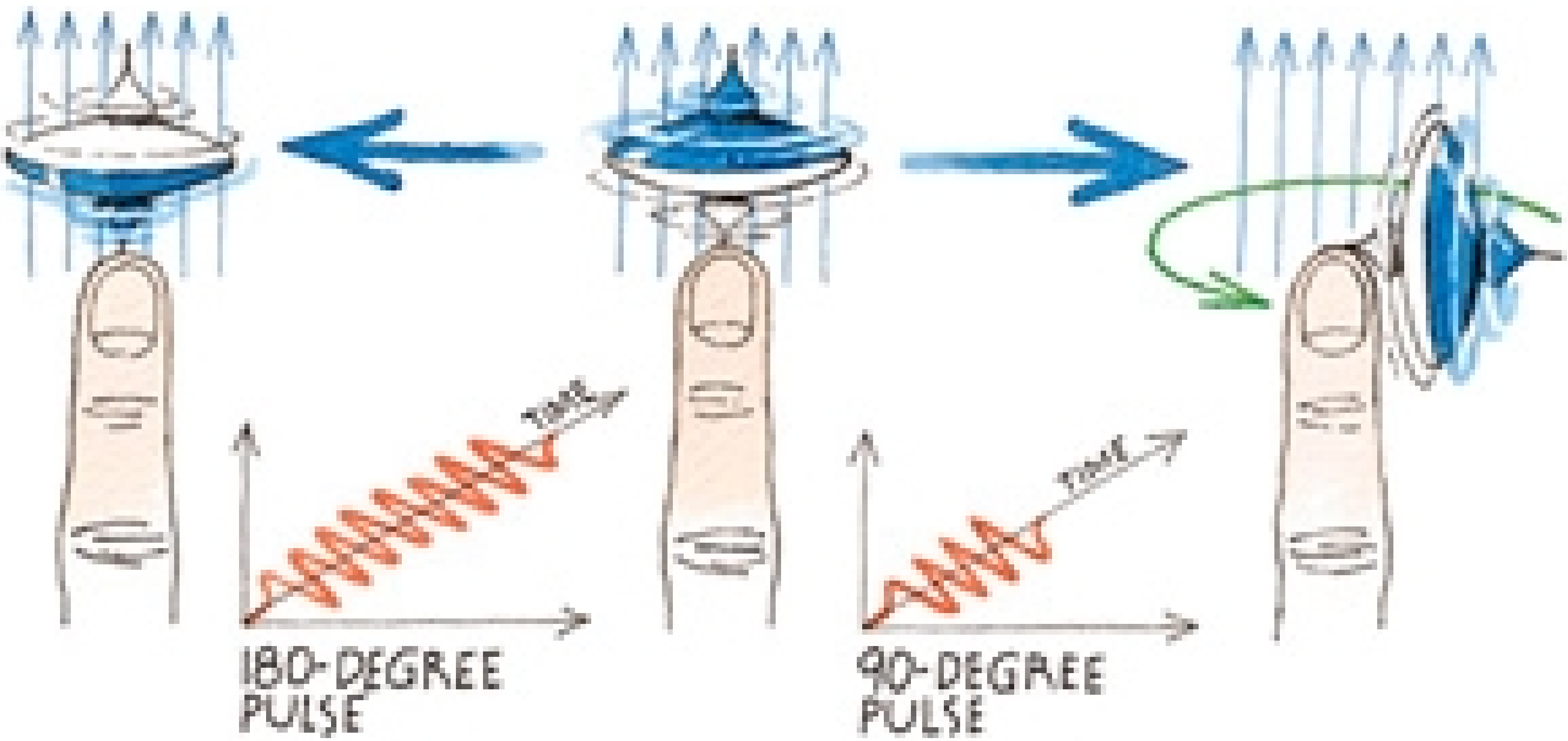
(Munich NMR QC group)

How to implement a logic operation NMR

- Lining up all the spins
  - A molecule is suspended in a solvent
  - The solvent is then put into a spectrometer’s main magnetic field.
  - This magnetic field aligns all the spins.
- Radio frequency pulse.
  - One of the atoms’ spins will flip or not flip depending on the spin of the other atoms.
- Multiple pulse sequences.
  - A quantum algorithm.

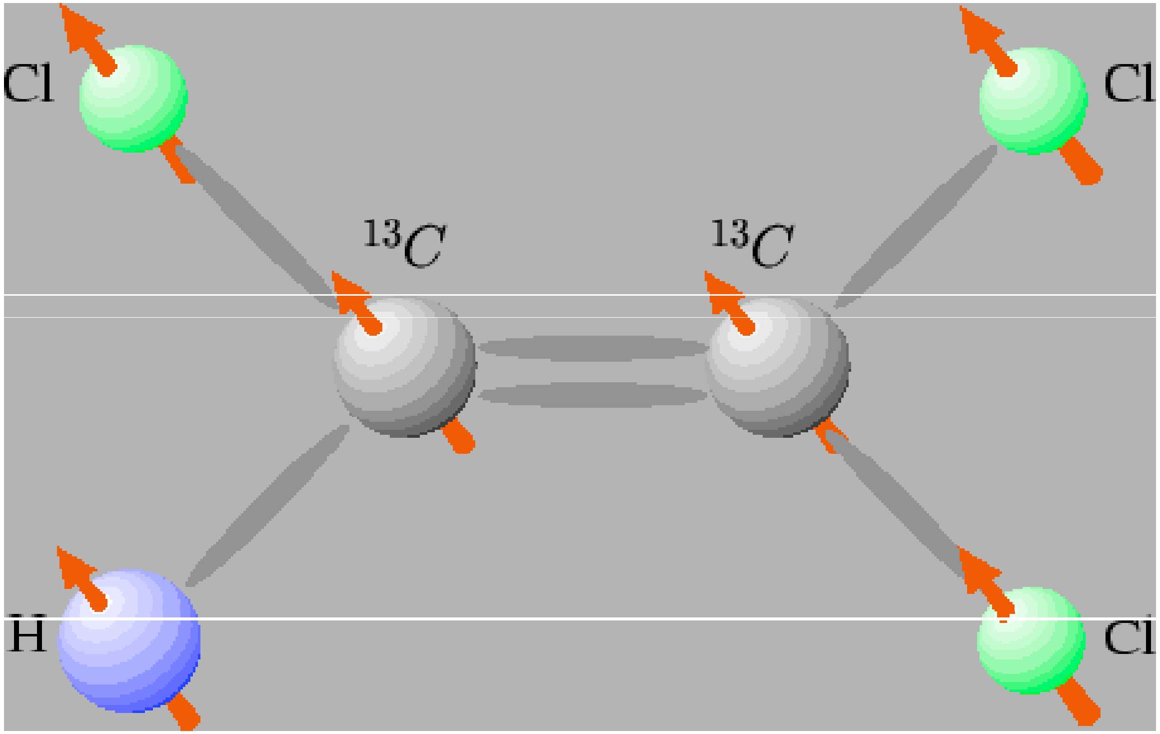
Current NMR Machine

Controlling spins



Example of radio frequencies interacting with spin.

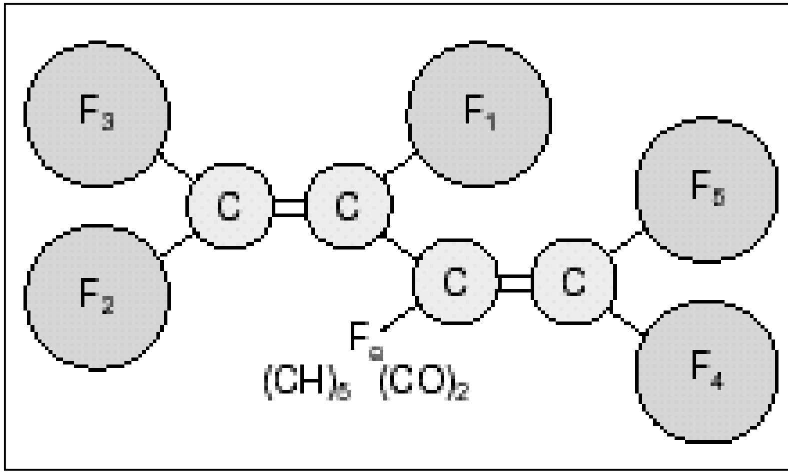
Protons and their Spins

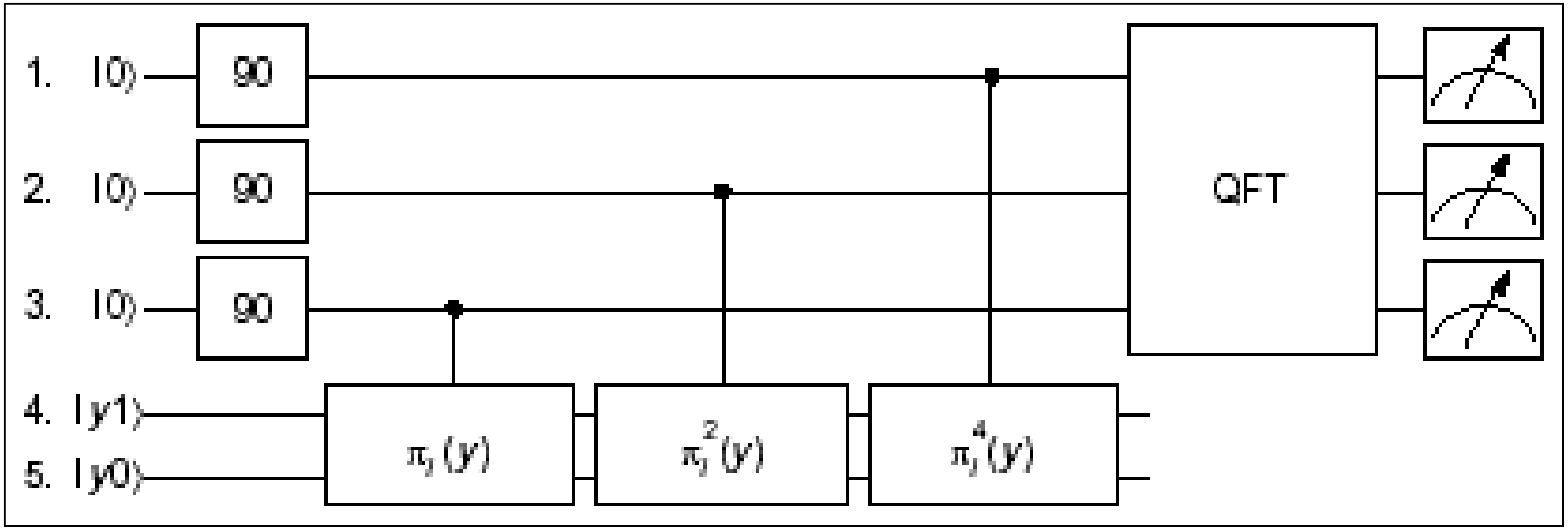


- Sample is placed in external magnetic field
  - Each proton's spin aligns with the field
- Can induce the spin direction to tip off-axis by RF pulses
  - Then the static field causes precession of the proton spins

Physical Implementation: NMR

- **Five-qubit** computer (contd.)
  - Molecule with 5 flourine atoms whose spins implement the qubits
  - Experimental 5-qubit circuit to find the **order of a permutation**

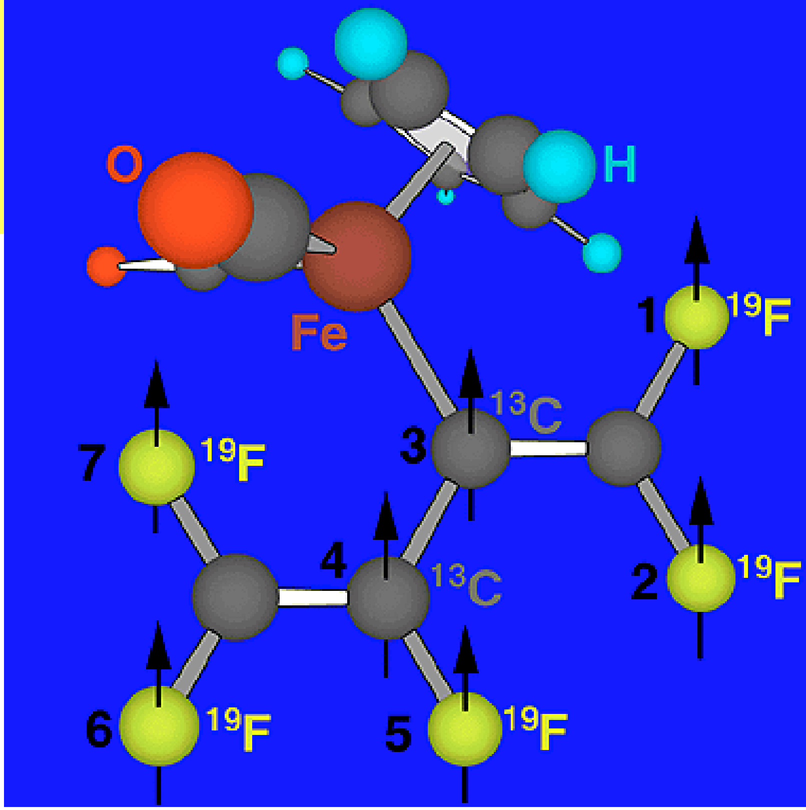




Spins and Coherence

- Most advanced demonstrated technology for quantum computation
- Use nuclei with spin ½ as qubits
  - Spin straight up = |0>
  - Spin straight down = |1>
  - Other directions indicate superpositions of |0> and |1>
  - **Long** coherence times (seconds)
    - Electron spins (alternate technology) have coherence times of nanoseconds
  - In a magnetic field, spin direction precesses about the field's axis at a rate that is proportional to the field strength

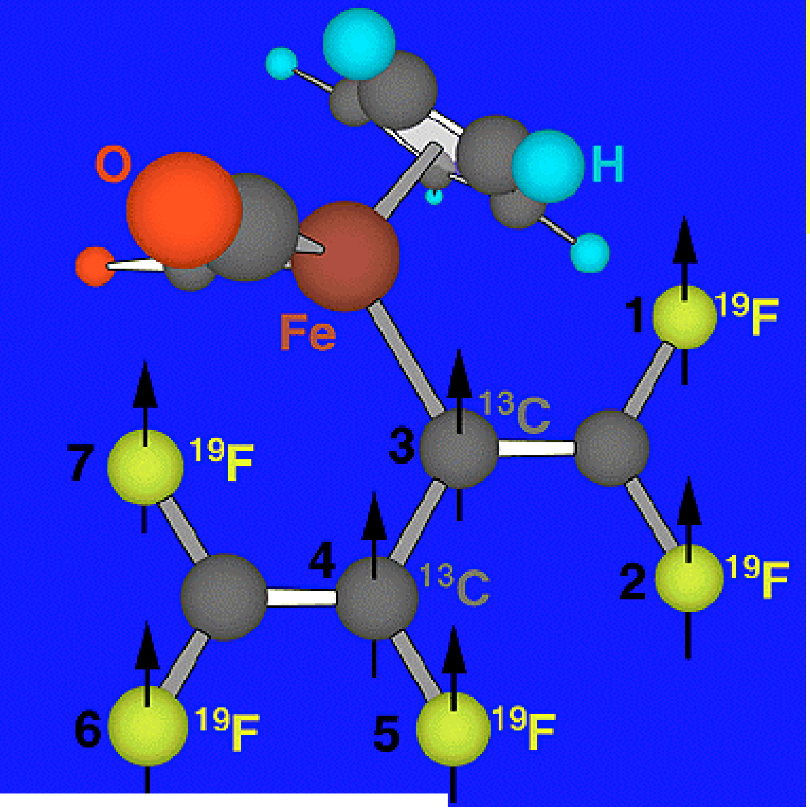
Inter-atomic bonds

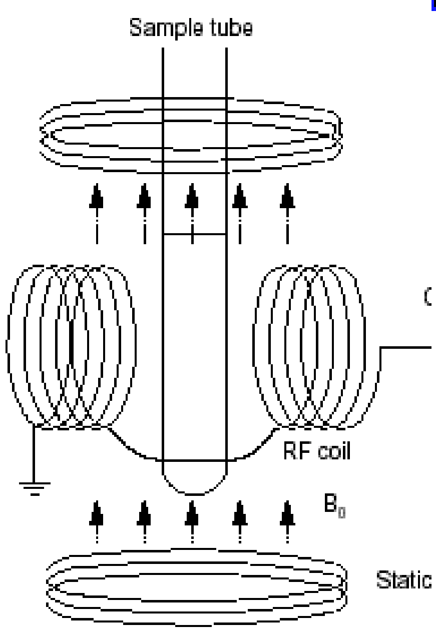


$C_{11}H_5F_5O_2Fe$

- Bond atoms that represent qubits into molecules
  - Inter-atomic bonds provide mechanism for different qubits to interact.
  - Each molecule becomes an n-qubit computing system
    - Can operate on multiple molecules in parallel to reduce errors
  - Asymmetry of molecule causes different atoms to precess at different frequencies
    - Individual addressability
  - **Interactions through chemical bonds allow multiple-qubit logic to be performed.**

- Each molecule is a „quantum computer“
- Each atom is a qubit.
- RF control and readout.



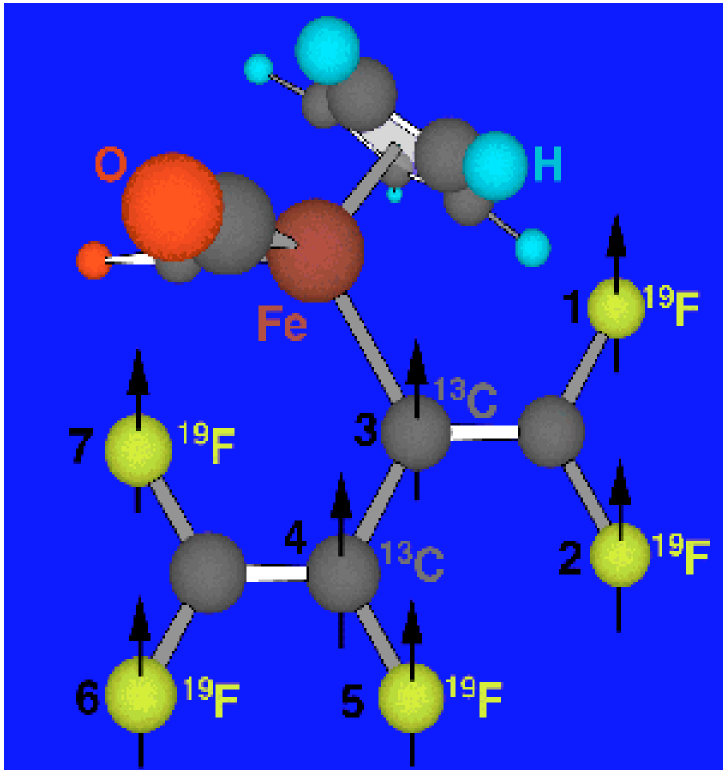


Electromagnetic Fields

– Radio energy applied perpendicular to magnetic field causes spins to rotate around axis of RF field if RF frequency is a resonant frequency of the precession frequency
  - Pulses of different durations cause different amounts of rotation
– Position of spin of atom A affects precession rate of nearby atom B by altering the magnetic field seen by B
– Differences between **precession frequencies** of different atoms in the molecule >> effect of nearby atom spins

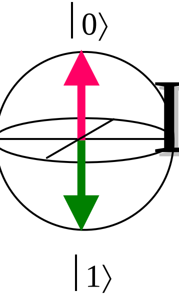
RF Pulses

- Several atoms' spins can be coupled chemically in a molecule
- However, they remain selectively addressable due to different resonant frequencies
- An RF pulse can rotate an atom's spin in a manner proportional to the amplitude and duration of the applied pulse
- A computation such as a gate/circuit operation consists of a sequence of carefully sized and separated RF pulses
- **Applying a radio-frequency pulse to the hydrogen nucleus addresses that qubit, and causes it to rotate from a |0> state to a superposition state.**



CNOT gate and machine language

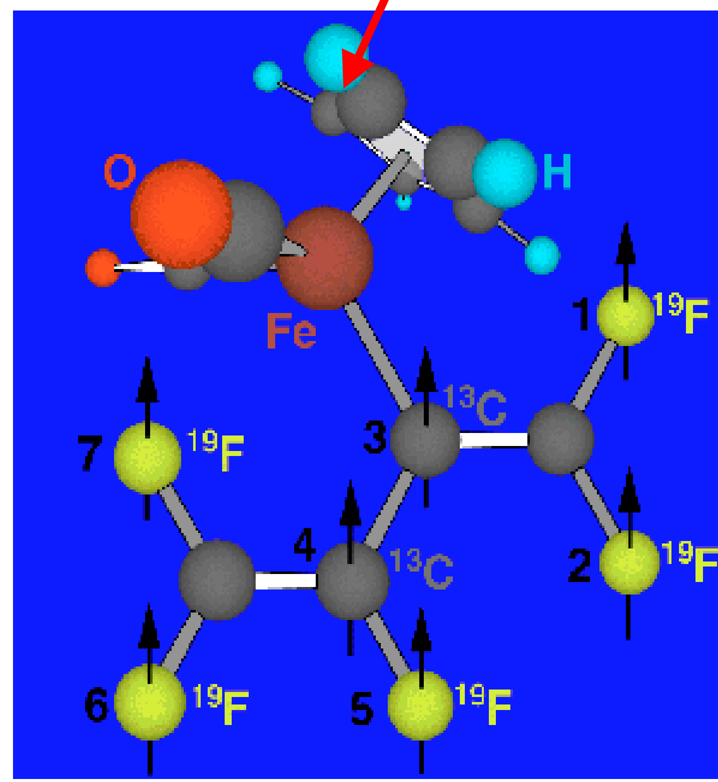
- Can flip state of bit with appropriately-timed RF pulse, or set into superposition with shorter pulse
- Can create multi-input gates by sending pulses at the frequency that the atom will precess at if appropriate other bits are in a given state.
  - CNOT operation
- CNOT operation + set of operations on individual qubits = universal set of gates
- "Machine language" is now set of frequency of RF pulses, duration of pulses, and time between pulses
- Read state out by rotating qubit spins into horizontal plane, sensing the time-varying magnetic field they create as they precess



Liquid State NMR Ensemble Computers

- **nucleus with quantum "spin"**
- **like a tiny bar magnet.**
- **Spin up/down = |0⟩/|1⟩.**

- Nuclei possess a magnetic moment
  - They respond to and can be detected by thei magnetic fields
- Single nuclei impossible to detect directly
  - If many are available they can be observed as an ensemble
- **Liquid state NMR**
  - → Nuclei belong to atoms forming a molecule
  - → Many molecules are dissolved in a liquid

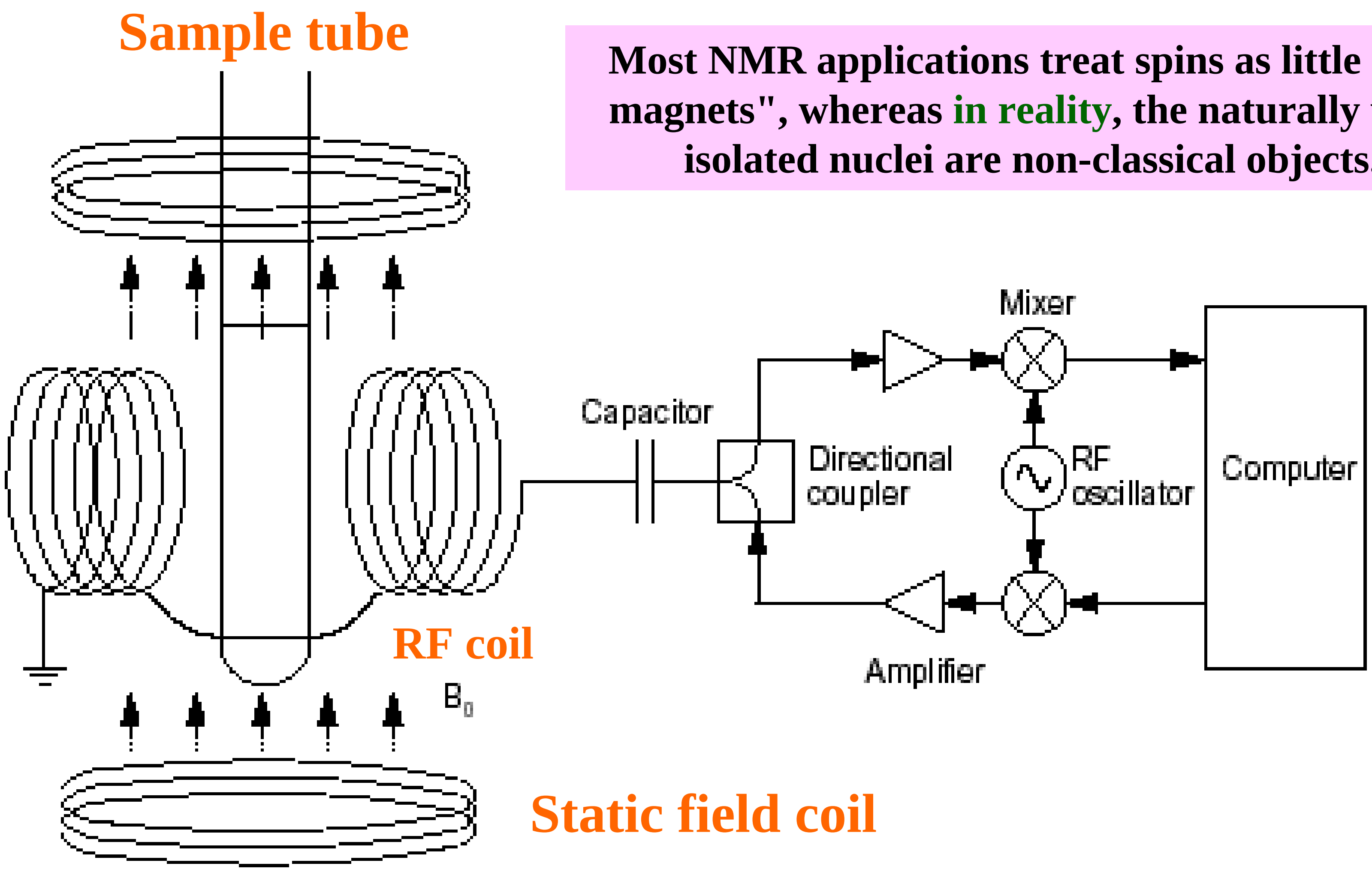


Many molecules (e..g, 10^{18}) can be combined in liquid solution to form a same-state ensemble of macroscopic and manageable size
All of **Di Vicenzo's criteria** can be met, except that scalability
seems to be limited to 20–30 qubits?

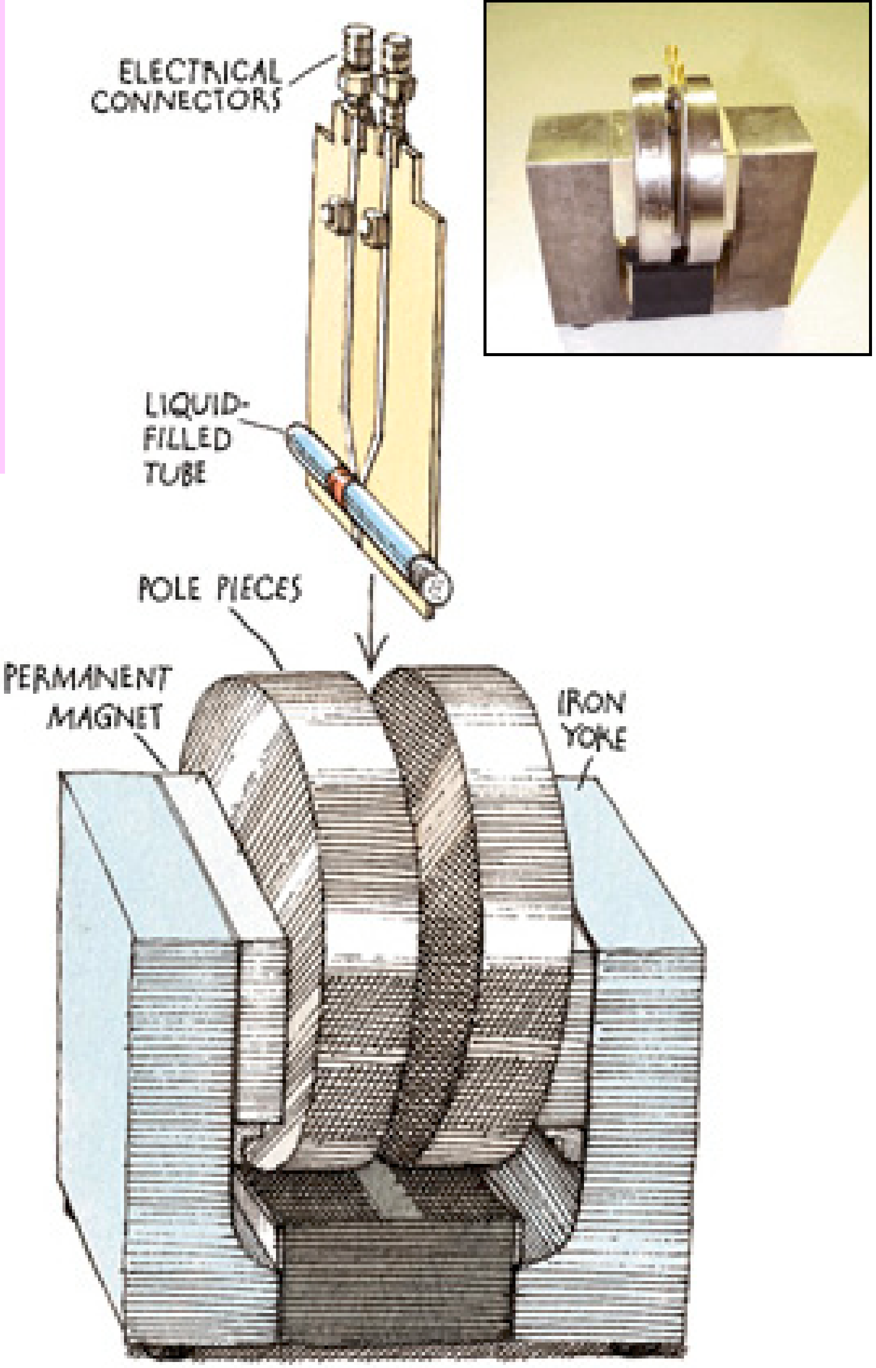
RF Coils and Static Field Coils

- Five-qubit NMR computer [Steffen et al. 2001]

Most NMR applications treat spins as little "bar magnets", whereas in reality, the naturally well-isolated nuclei are non-classical objects.

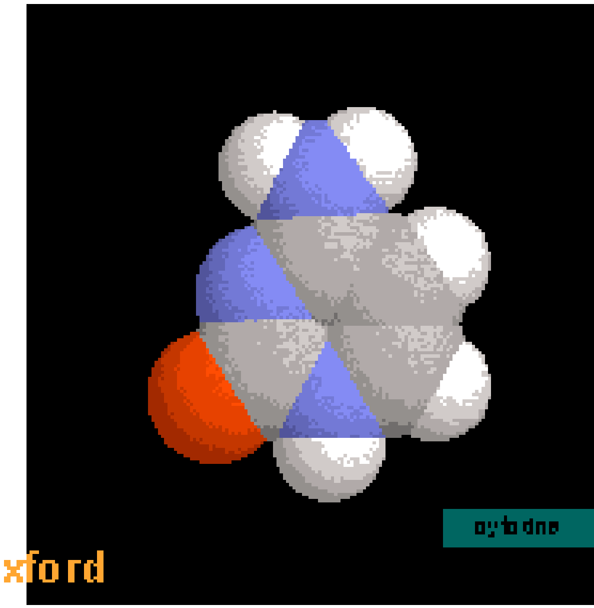


NMR in the works



- Currently NMR machines 3 and 7 qubit machines.
- Development by IBM to create a 10 qubit machine is in the works.
- There is also development of small, room temperature NMR machines for more practical uses.

Advantages of NMR



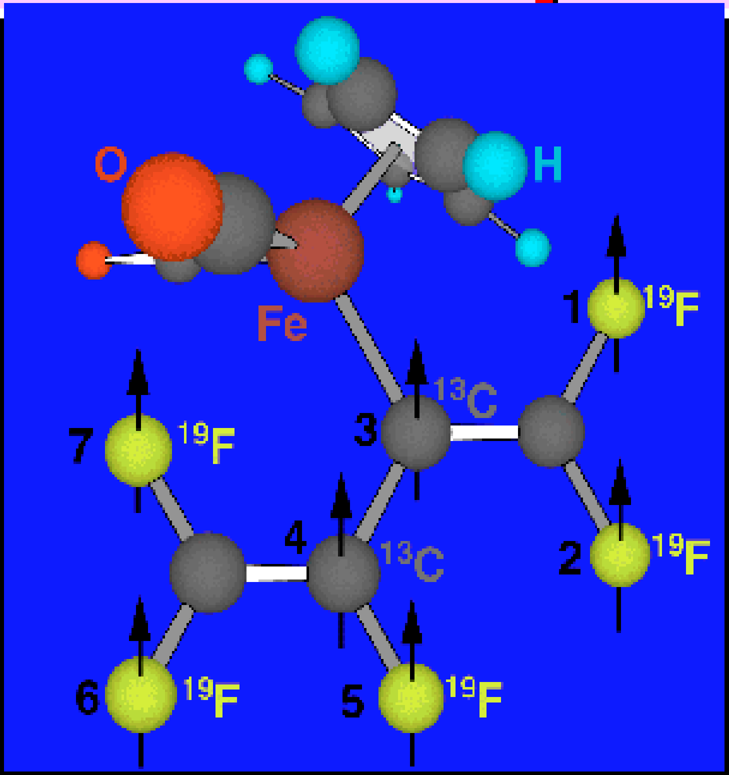
- Nucleus is naturally protected from outside interference.
  - Once the spins are lined up they will stay in the proper order for a long time.
- Nuclear qubits already exist in nature.
- Technology for manipulating these qubits already exists.
  - Hospital magnetic resonance imaging.

Disadvantages of NMR

- Very large in size.
    - Many are 10 feet tall.
  - NMR quantum computing demonstrates the principle, but cannot "scale up" beyond a few qubits
  - New scalable architectures (e. g., silicon- based, photonic) are necessary to perform useful computations
- Standard QC is based on pure states
  - In NMR single spins are too weak to measure

  →Must consider ensembles
- QC measurements are usually projective
  - In NMR get the average over all molecules
  - Suffices for QC
- Tendency for spins to align with field is weak
  - Even at equilibrium, most spins are random
  - Overcome by method of pseudo-pure states

Example: 7- Qubit Q-Computer by IBM



Alanine, an amino acid.

From IBM research news

- Could be Most advanced model of QC
- Finding the factors of the number 15 with Shor's algorithm
- Nuclei of five fluorine and two carbon atoms interacting with each other
- Programmed by RF pulses
- Detected by NMR technique

Experimental Realization of Shor's Factoring Algorithm[‡]

M. Steffen[1,2], L.M.K. Vandersypen[1,2], G. Breyta[1], C.S. Yannoni[1], M. Sherwood[1], I.L.Chuang[1,3]

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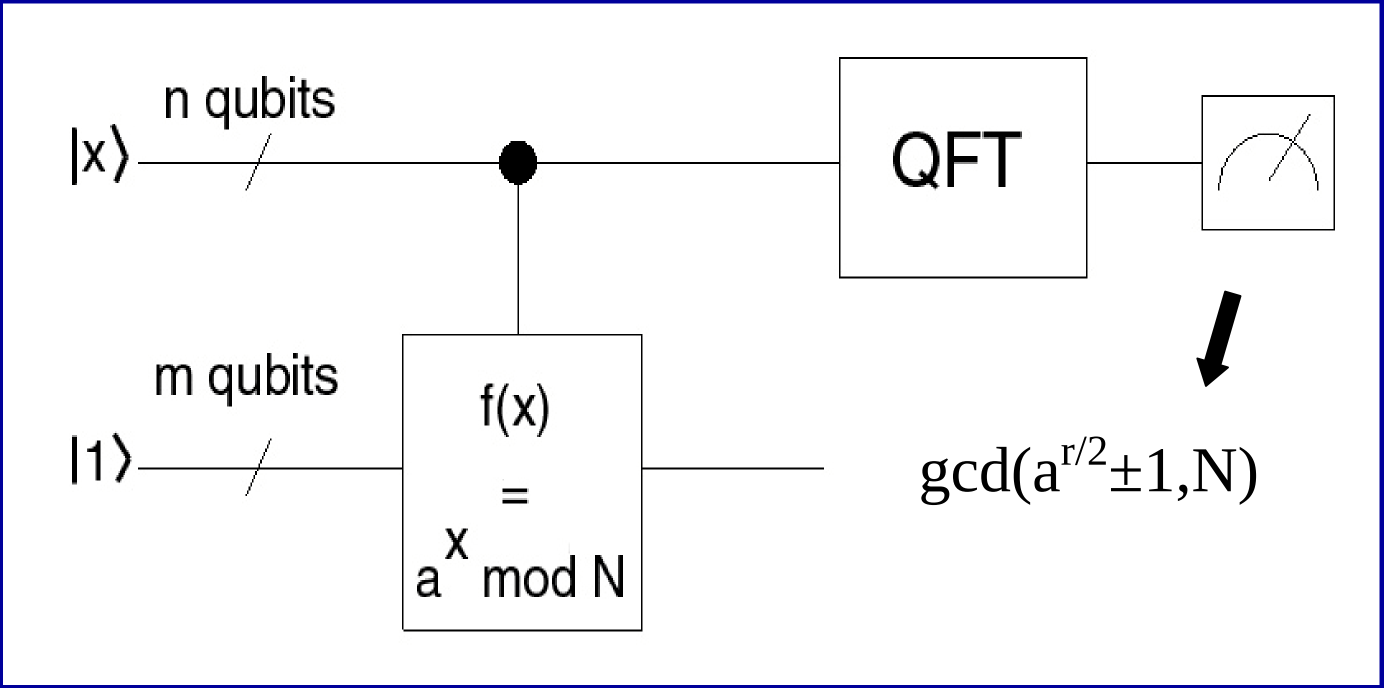
[3] MIT Media Laboratory, Cambridge, MA 02139

[‡]Vandersypen L.M.K, et al, *Nature*, v.414, pp. 883 – 887 (2001)

Shor's Factoring Algorithm

Quantum circuit to factor an integer N



Implemented for the case N = 15 -- expect 3 and 5

Factoring N = 15

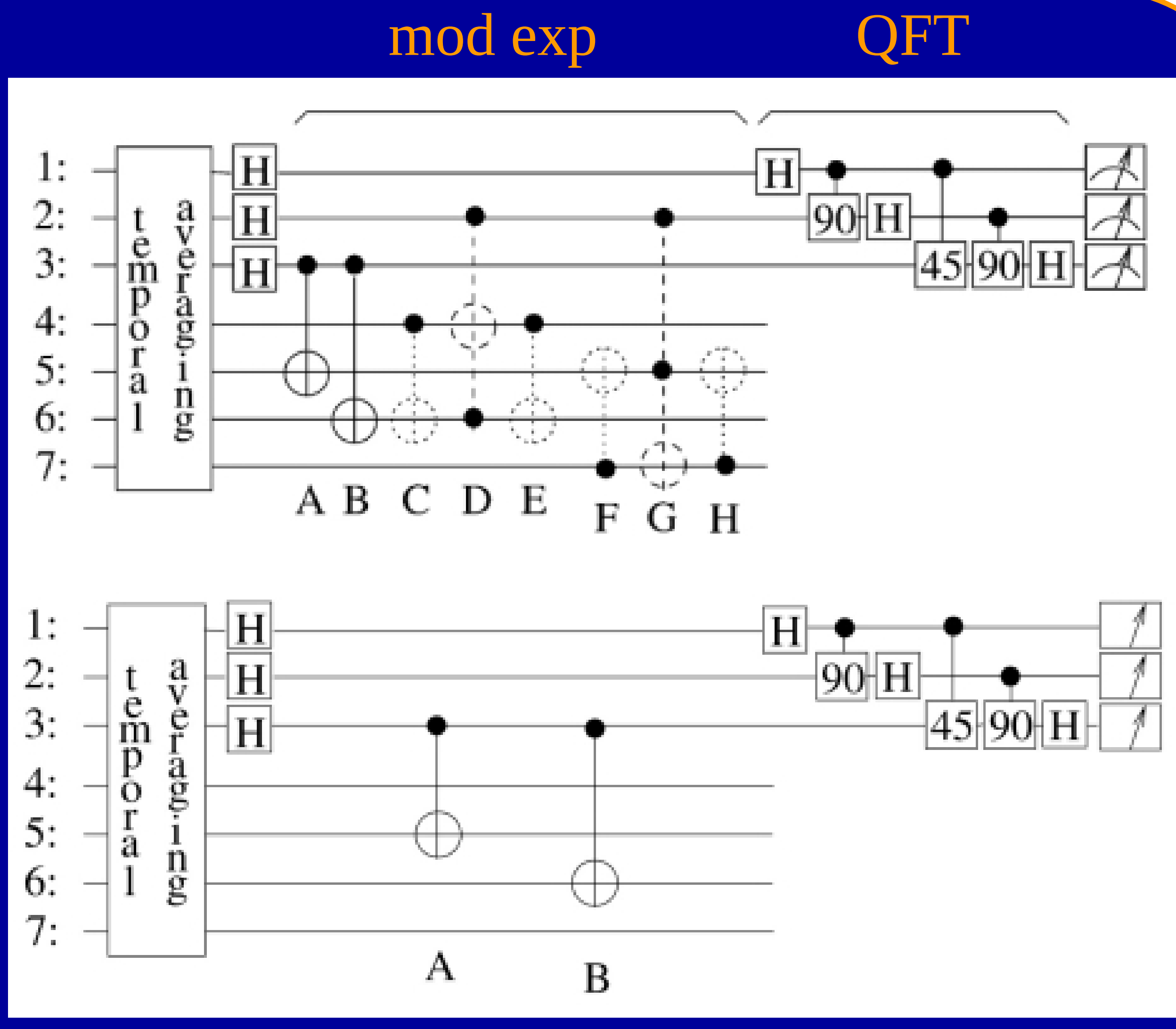
Challenging experiment:

- synthesis of suitable 7 qubit molecule
- requires interaction between almost all pairs of qubits
- coherent control over qubits

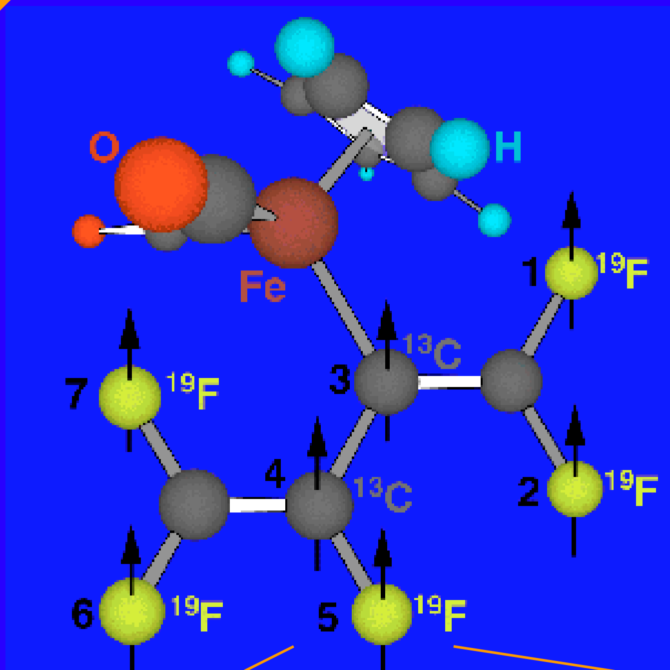
Factoring N = 15

a = 7
‘hard case’

a = 11
‘easy case’

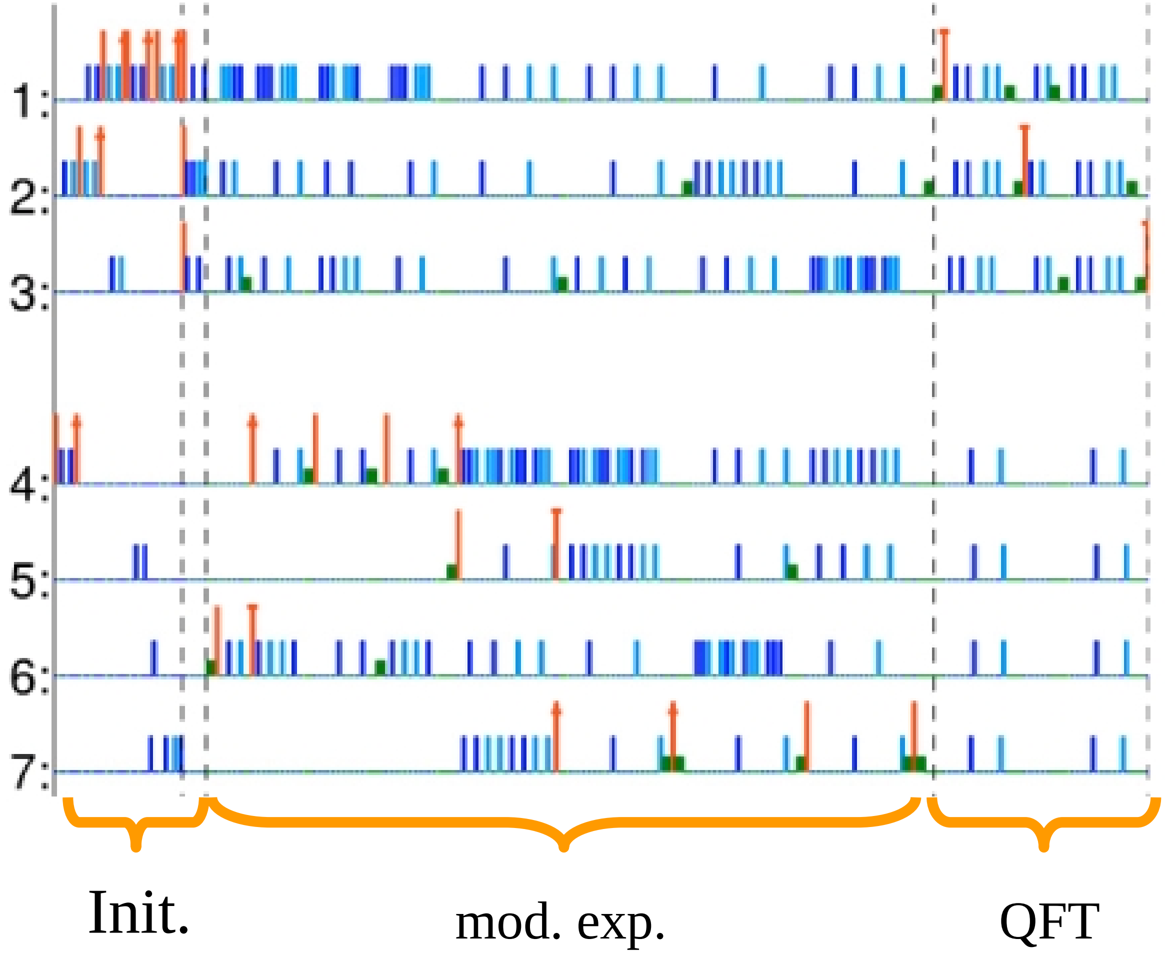


The molecule



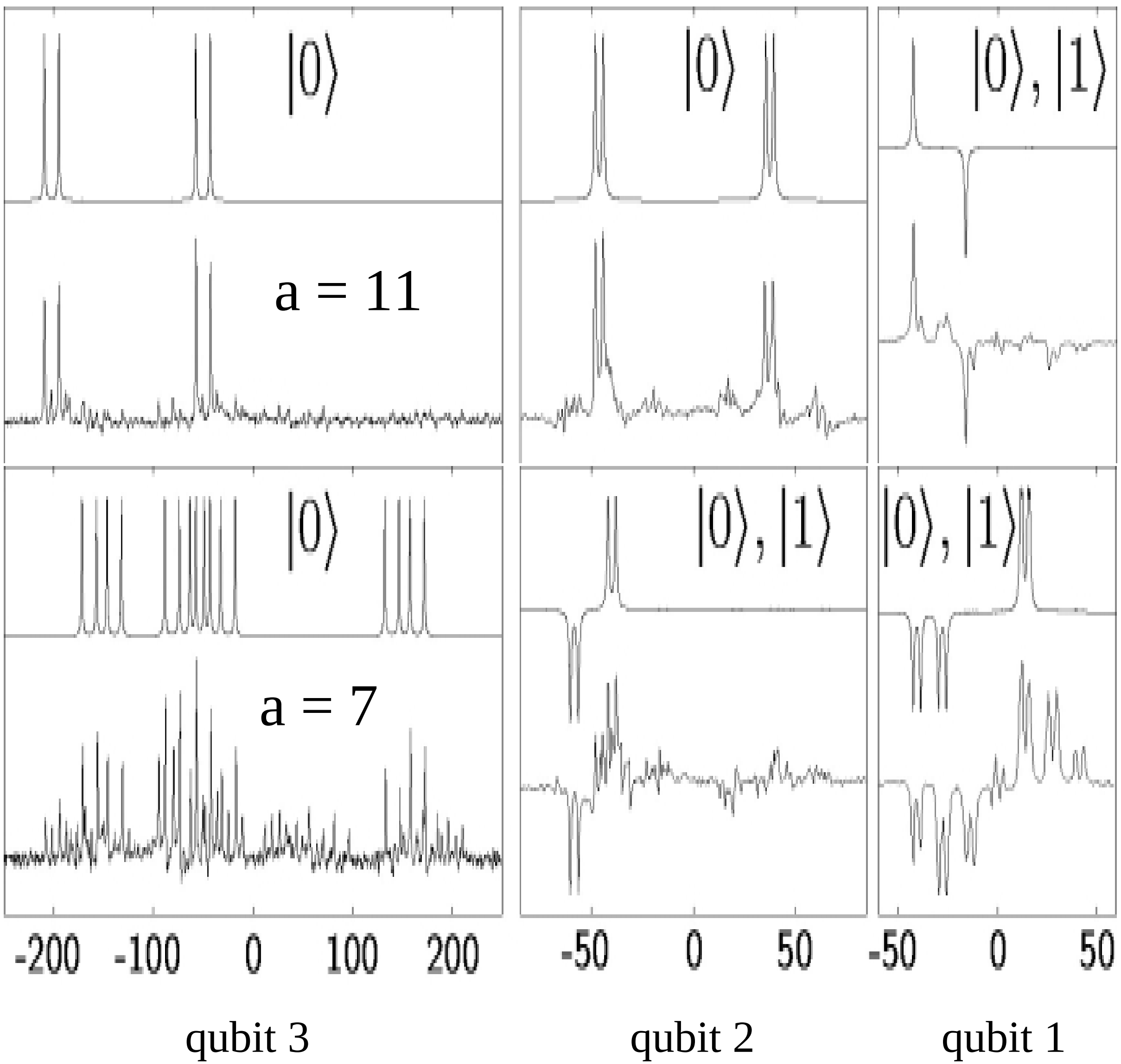
i	$\omega_i/2$	$T_{1,i}$	$T_{2,i}$	J_{7i}	J_{6i}	J_{5i}	J_{4i}	J_{3i}	J_{2i}
1	−22052.0	5.0	1.3	−221.0	37.7	6.6	−114.3	14.5	25.16
2	489.5	13.7	1.8	18.6	−3.9	2.5	79.9	3.9	
3	25088.3	3.0	2.5	1.0	−13.5	41.6	12.9		
4	−4918.7	10.0	1.7	54.1	−5.7	2.1			
5	15186.6	2.8	1.8	19.4	59.5				
6	−4519.1	45.4	2.0	68.9					
7	4244.3	31.6	2.0						

Pulse Sequence



~ 300 RF pulses || ~ 750 ms duration

Results: Spectra



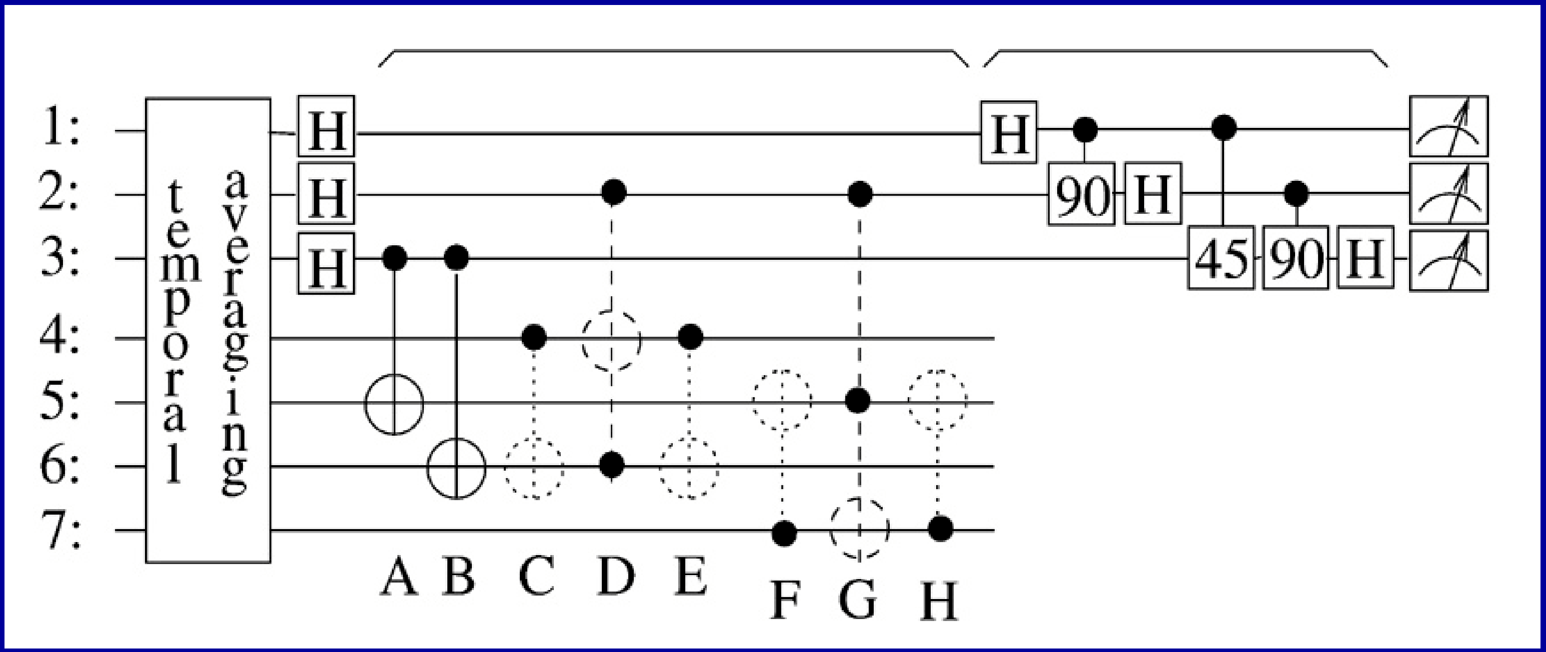
Mixture of $|0\rangle, |4\rangle$
$2^3/4 = r = 2$
$\gcd(11^{2/2} \pm 1, 15) = 3, 5$

$15 = 3 \cdot 5$

Mixture of $|0\rangle, |2\rangle, |4\rangle, |6\rangle$
$2^3/2 = r = 4$
$\gcd(7^{4/2} \pm 1, 15) = 3, 5$

Results: Circuit Simplifications

‘Peephole’ optimization



- control of C is $|0\rangle$
- control of F is $|1\rangle$
- E and H inconsequential to outcome
- targets of D and G in computational basis

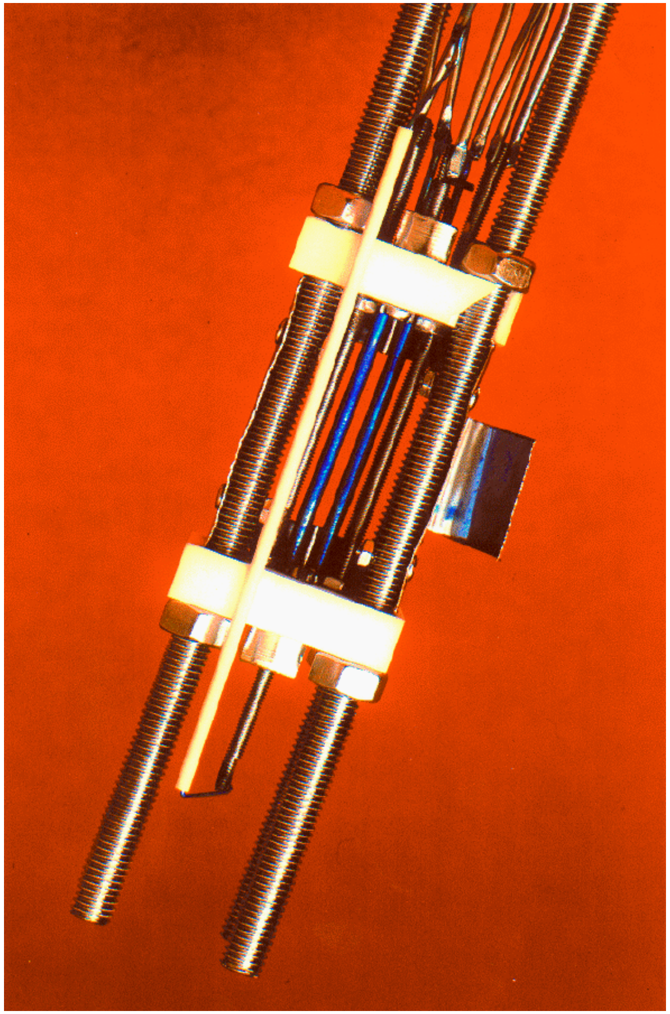
Results of Chuang's Work

- First experimental demonstration of Shor's factoring algorithm
- Methods for circuit simplifications
- Used NMR technology to implement the core of Shor's algorithm on permutations of a four-element set.

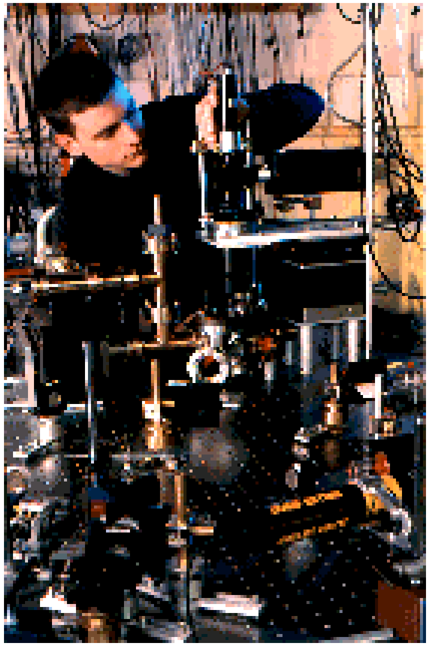
Duration: 50-500ms, depending on permutation

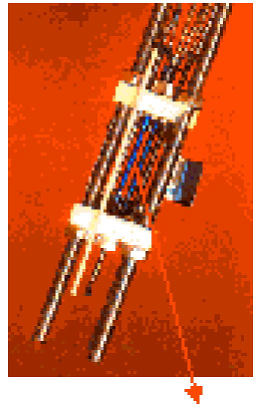
Linear ion trap

- Ions in a radio frequency trap interact by exchanging vibrational excitations. Each ion can be controlled by a polarized, properly focused laser beam.
- Picture shows the electrode structure.
- The electrode is 1mm thick.

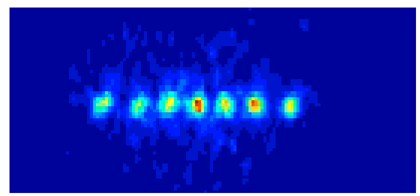


Linear ion trap

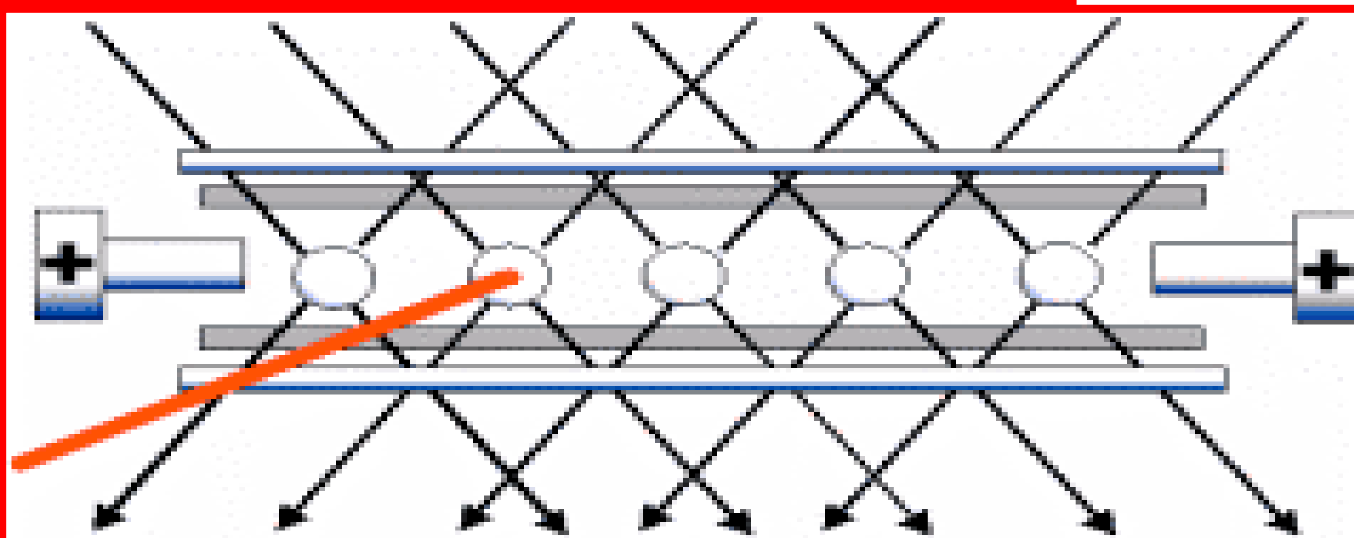




Ion trap
© CQC Oxford

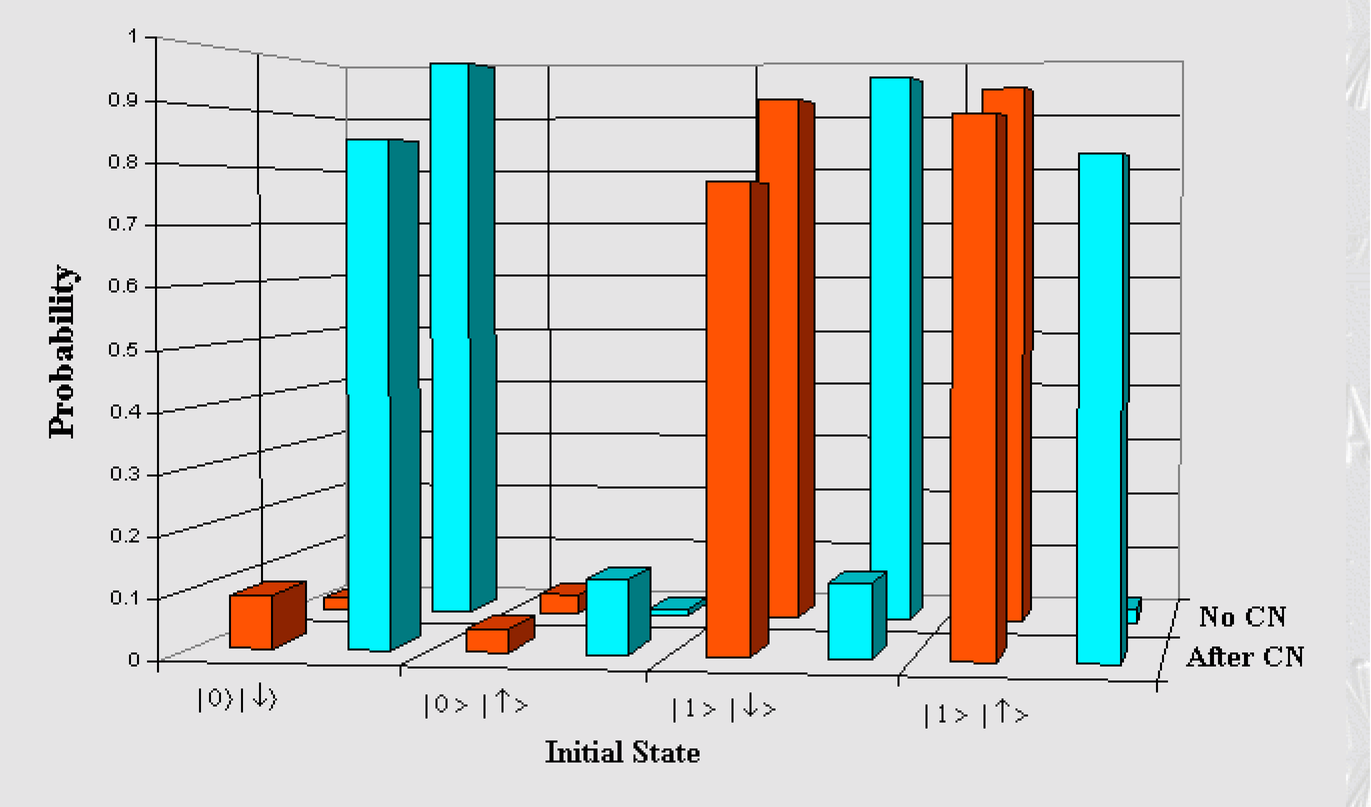


7 trapped ions © R. Blatt, Innsbruck



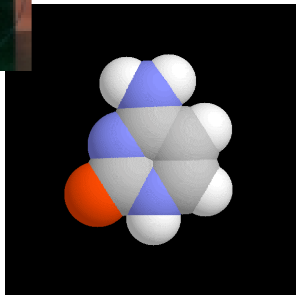
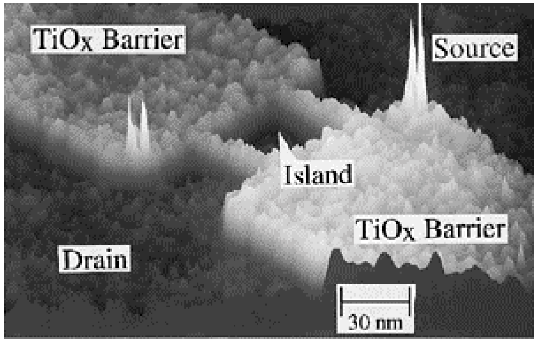
Linear ion trap

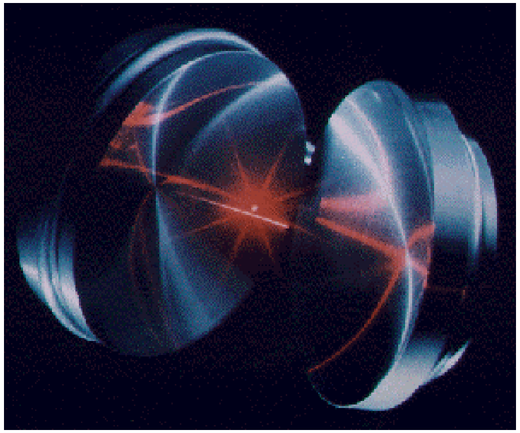
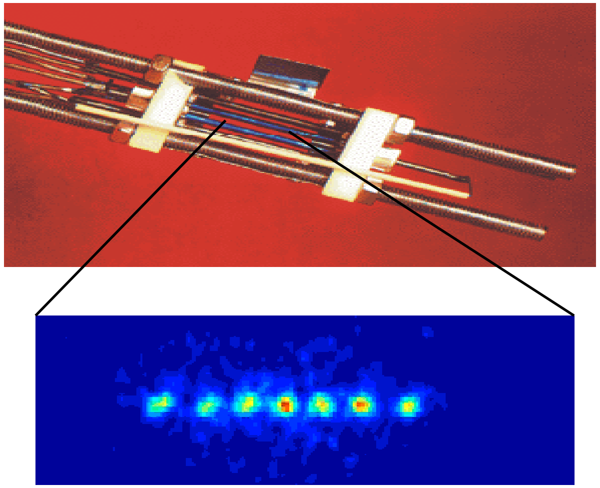
Quantum CNOT gate on beril ion in the trap



What about scaling?

- 1-7 qubits using NMR technology
- 1-2 qubits using ion traps
- 1-2 qubits using various other quantum technologies
- Scaling is very hard!
- Is the problem technical or fundamental?

Technical or Fundamental?

- Noise, “decoherence”, imprecision are detrimental
- Similar problems exist in “classical” systems
- Theory of linear error correction and fault tolerant computing can be generalised to the quantum setting (Shor, Steane, etc.)
- Using “reasonable” physical models, there exist fault-tolerant schemes for scalable quantum computing

Quantum Circuits

Quantum **Error-Correction** Circuit

- Problem: State $|\xi\rangle = a|0\rangle + b\,|1\rangle$ is degraded by noise

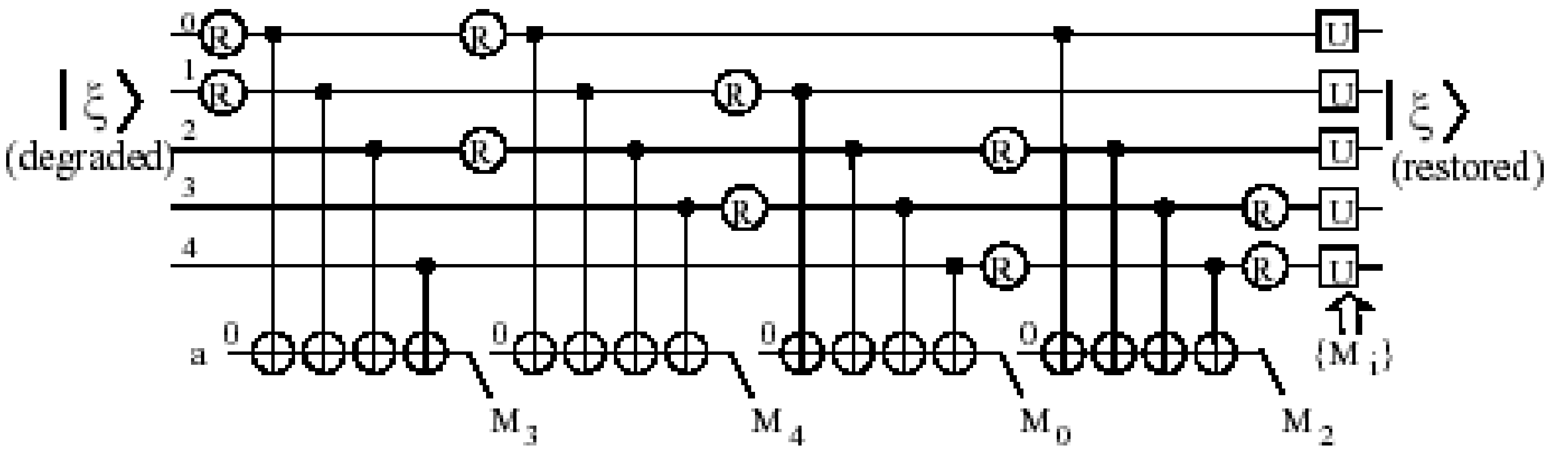
- Solution Encode in a suitable EC code such as the 5-bit code:

$|0\rangle = |00000\rangle + |11000\rangle + |01100\rangle + |00110\rangle + |00011\rangle + |10001\rangle$

$- |10100\rangle - |01010\rangle - |00000\rangle - |10010\rangle - |01001\rangle$

$- |11110\rangle - |01111\rangle - |10111\rangle - |11011\rangle - |11101\rangle$

$|1\rangle = |11111\rangle + |00111\rangle + |10011\rangle + \ldots$



Summary

- Quantum Computers are a natural generalisation of “classical” computers
- Quantum algorithms: Factoring, Discrete log, Hidden Subgroup, Hidden Affine Functions, Searching, Counting
- Small implementations exist
- Scaling is difficult, but *seems* to be a technological (not fundamental) problem

References

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- 2: Hey, Anthony; Possible Technologies for Quantum Computers; May 1998; http://www.ecs.soton.ac.uk/~ajgh/quantrep.html
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