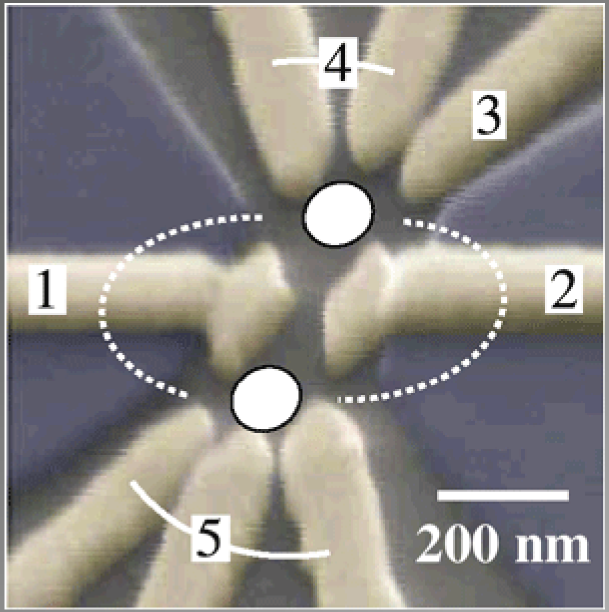
Solid State Qubits



http://www.wmi.badw.de/SFB631/tps/DQD2.gif

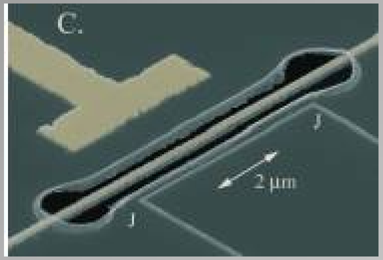
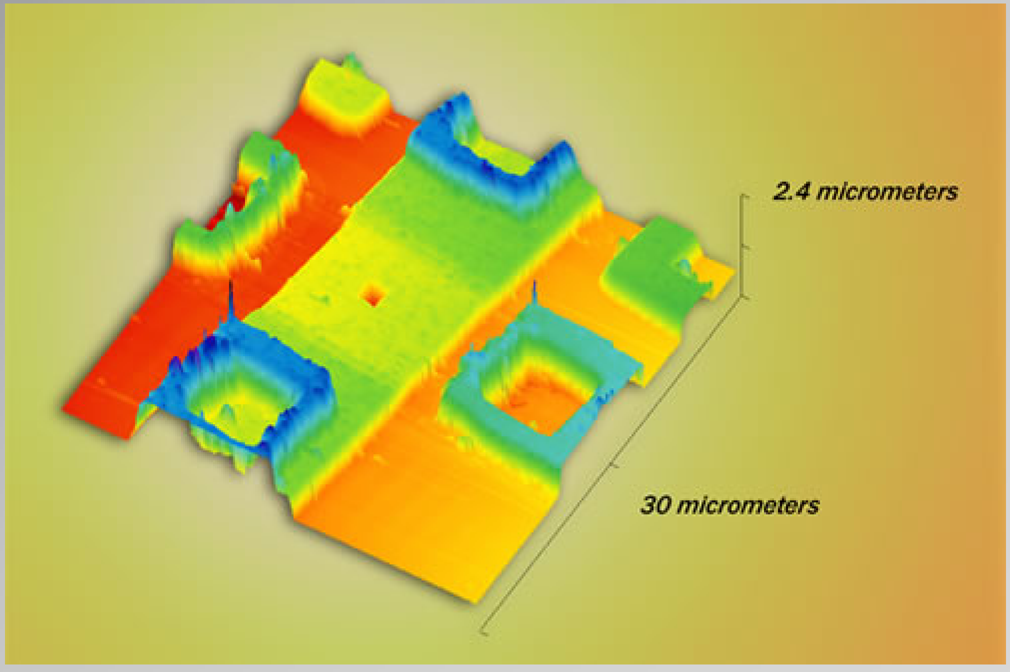


Image courtesy of Keith Schwab

http://www.lbl.gov/Science-Articles/Archive/AFRD-quantum-logic.html



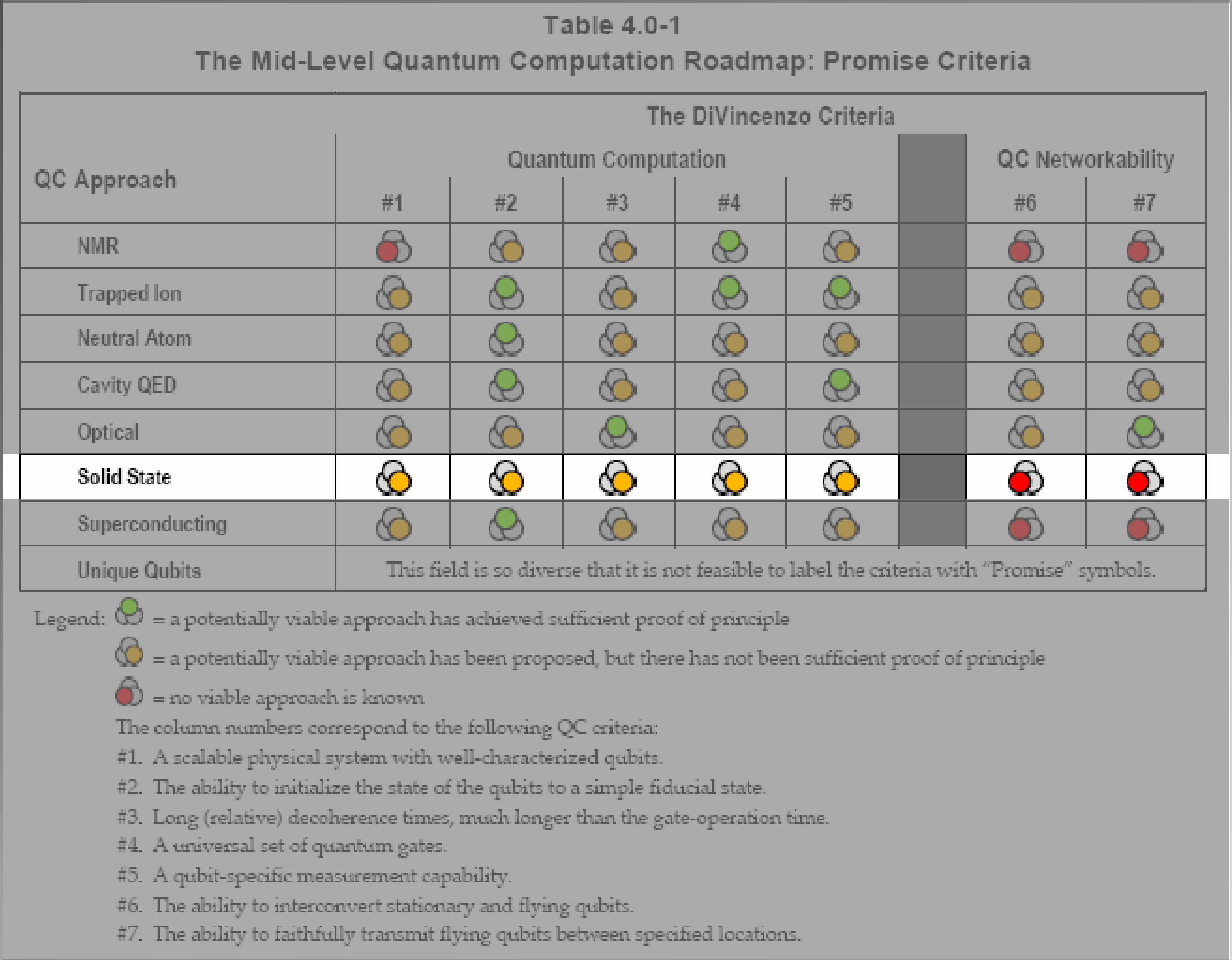


Table 4.0-1
The Mid-Level Quantum Computation Roadmap: Promise Criteria

QC Approach	The DiVincenzo Criteria						
	Quantum Computation					QC Networkability	
	#1	#2	#3	#4	#5	#6	#7
NMR	🔴	🟡	🟡	🟢	🟡	🔴	🔴
Trapped Ion	🟡	🟢	🟡	🟢	🟢	🟡	🟡
Neutral Atom	🟡	🟢	🟡	🟡	🟡	🟡	🟡
Cavity QED	🟡	🟢	🟡	🟡	🟢	🟡	🟡
Optical	🟡	🟡	🟢	🟡	🟡	🟡	🟢
Solid State	🟡	🟡	🟡	🟡	🟡	🔴	🔴
Superconducting	🟡	🟢	🟡	🟡	🟡	🔴	🔴
Unique Qubits	This field is so diverse that it is not feasible to label the criteria with "Promise" symbols.						

Legend: 🟢 = a potentially viable approach has achieved sufficient proof of principle

🟡 = a potentially viable approach has been proposed, but there has not been sufficient proof of principle

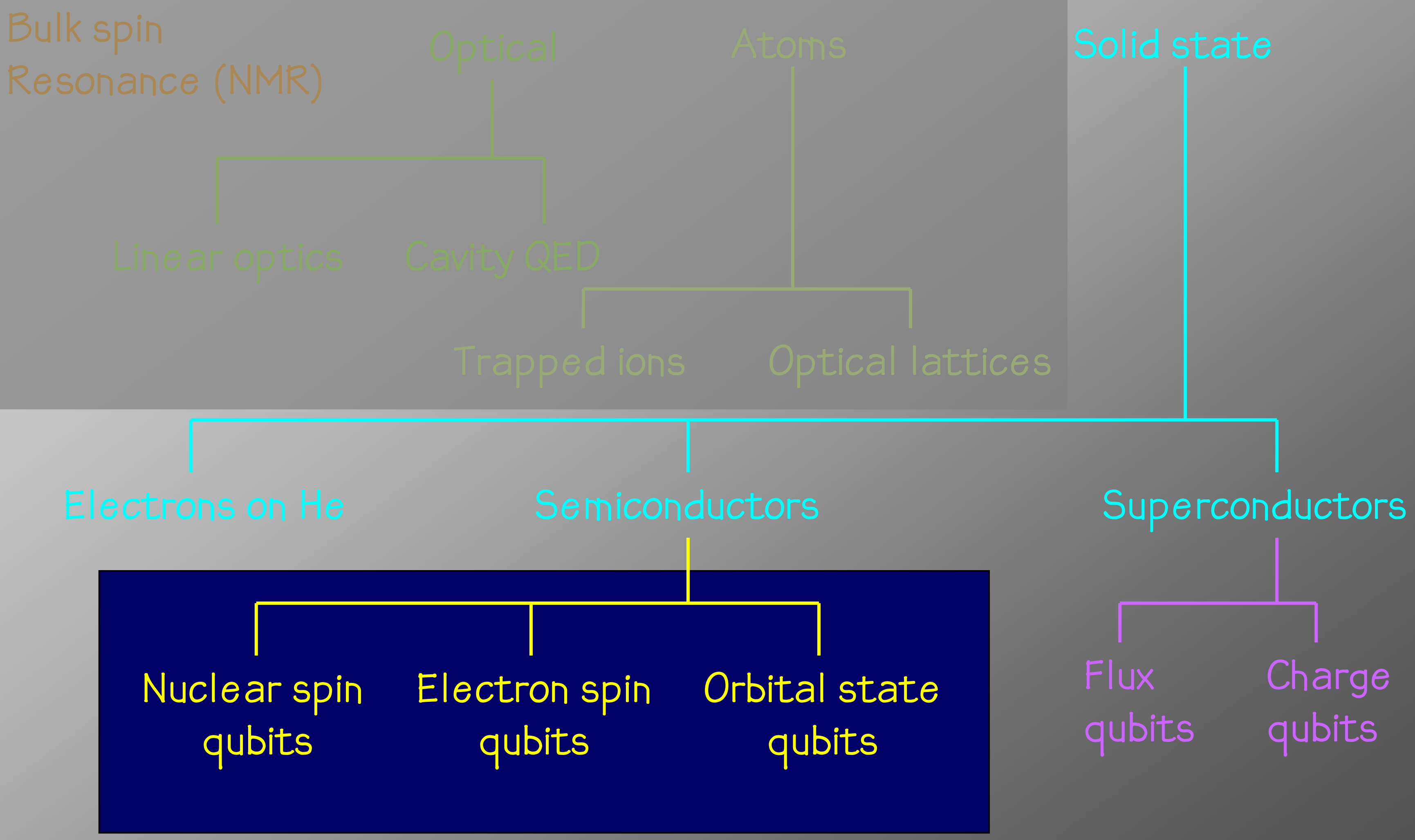
🔴 = no viable approach is known

The column numbers correspond to the following QC criteria:

#1. A scalable physical system with well-characterized qubits.
#2. The ability to initialize the state of the qubits to a simple fiducial state.
#3. Long (relative) decoherence times, much longer than the gate-operation time.
#4. A universal set of quantum gates.
#5. A qubit-specific measurement capability.
#6. The ability to interconvert stationary and flying qubits.
#7. The ability to faithfully transmit flying qubits between specified locations.

http://qist.lanl.gov/qcomp_map.shtml

QC implementation proposals



Bulk spin
Resonance (NMR)

Optical

Atoms

Solid state

Linear optics

Cavity QED

Trapped ions

Optical lattices

Electrons on He

Semiconductors

Superconductors

Nuclear spin qubits

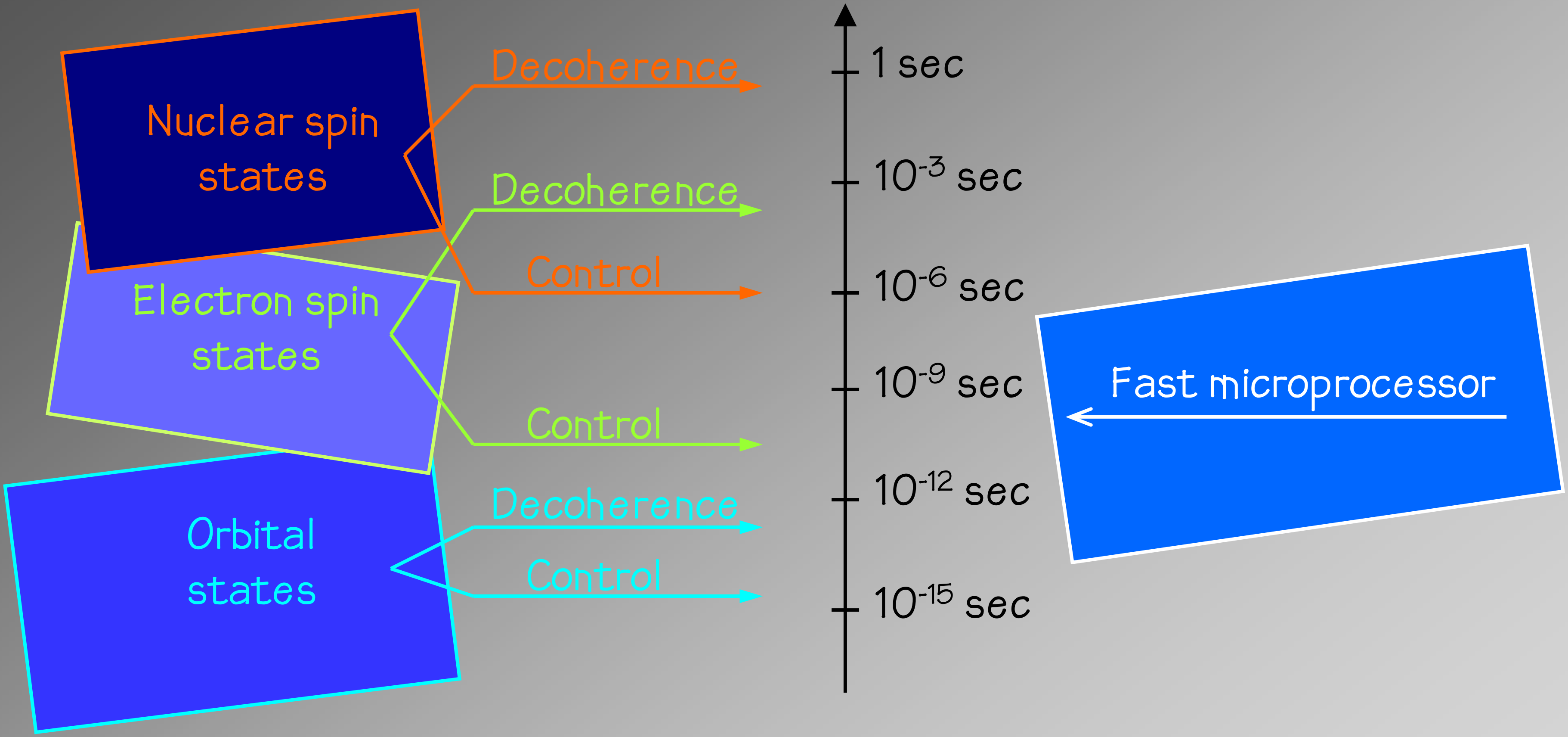
Electron spin qubits

Orbital state qubits

Flux qubits

Charge qubits

Semiconductor qubits: time scales



Nuclear spin states

Decoherence

Control

Electron spin states

Decoherence

Control

Orbital states

Decoherence

Control

1 sec

10^{-3} sec

10^{-6} sec

10^{-9} sec

10^{-12} sec

10^{-15} sec

Fast microprocessor

The figure of merit is the ratio of coherence time and control time.

But: if these times are too fast, good control is difficult.

"Charge qubits" and "spin qubits"

The qubits levels can be formed by either the energy levels of an electron in a potential well (such as a quantum dot or an impurity ion) or by the spin states of the electron (or the nucleus).

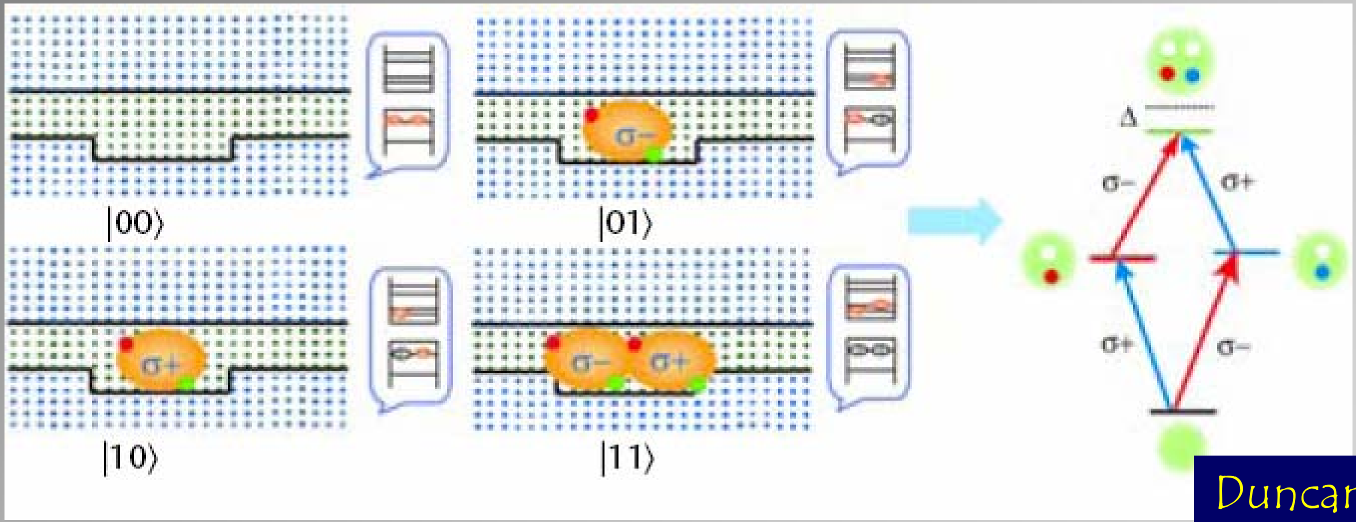
The former are examples of charge qubits. The charge qubits have high energy splitting, and can be manipulated by applying potentials to control electrodes. However, charge qubits states are readily affected by various sources of noise (thermal, electronic, acoustic) present in the semiconductor material.

The spin qubits are better isolated from the environment. Spin degree of freedom couples to higher order fluctuations of electric and magnetic fields. Being a plus, this, unfortunately, makes it harder to control spins.

Examples of charge and spin qubits

A single electron-hole pair (exciton) in a quantum dot can serve as a charge qubits. Presence (absence) of an exciton corresponds to qubit state |1> (|0>). Excitons can be created optically by ultrafast laser pulses; controlling the pulse parameters allows creating excitonic superposition states.

By doping a quantum dot with a single electron, a spin qubit can be realized based on the spin states of the single electron. Operations on the spin qubit are performed by creating a "trion" (a charged exciton made of the original electron and an exciton).



Duncan Steel (U. Mich.)

"Scalable physical system with well-characterized qubits"

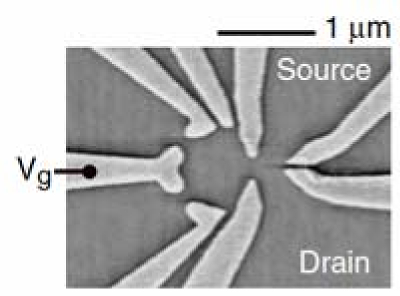
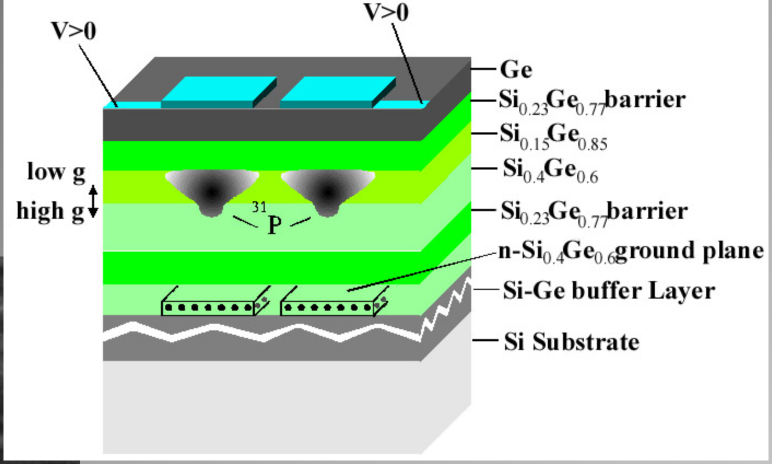
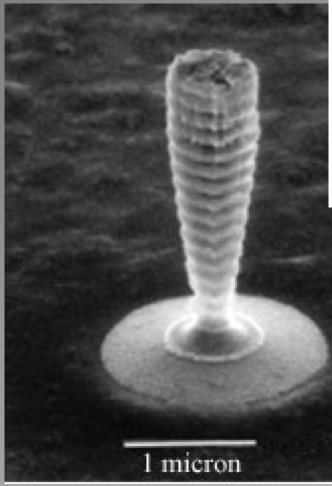


Image courtesy of Charlie Marcus

The qubits are microfabricated devices, just like the superconducting qubits are.



Scalability seems straightforward. After all, we are dealing with semiconductor chips!

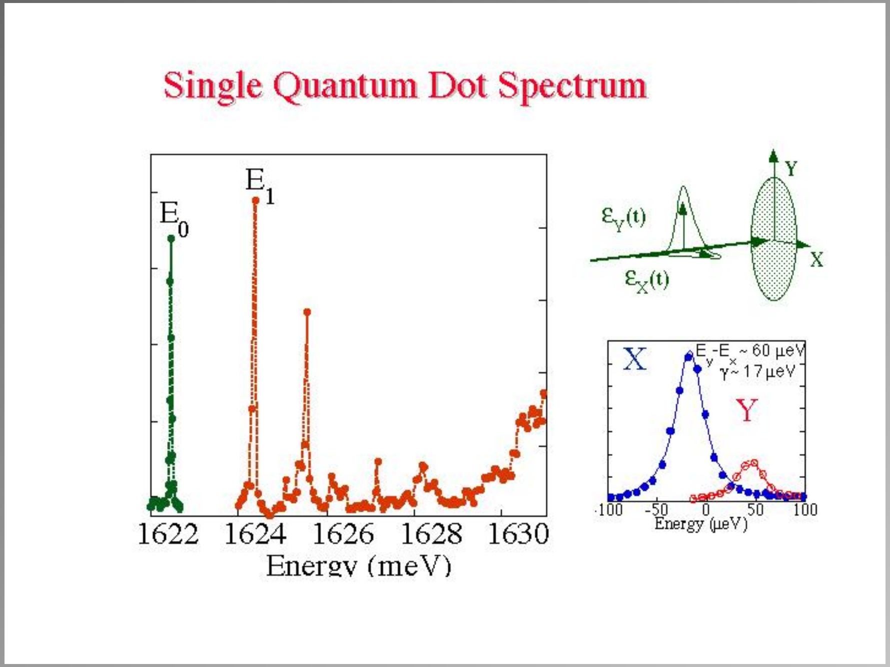


Yoshi Yamamoto, Stanford

But, as with any fabricated qubits, not two qubits are alike. Each qubit would have to be individually characterized.

"ability to initialize qubit state"

Qubit initialization relies on cooling the qubits down well below the energy splitting between the ground and the excited states. As with the JJ qubits, the Boltzmann distribution gives high probability of occupying the ground state if the temperature is low enough.



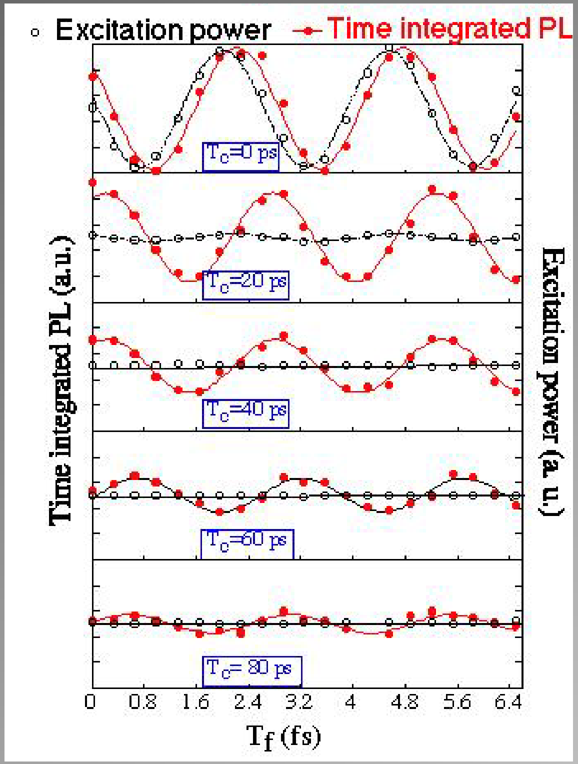
Single Quantum Dot Spectrum

For the spin-based qubits, large magnetic fields (several Tesla) are applied to produce the energy level splitting and to initialize the qubits.

As the energy gaps are generally speaking larger than in the JJ qubits, higher operation temperatures are possible, as high as liquid helium at 4.2 K.

"(relative) long coherence times"

Spin qubits have significantly longer relaxation times than do charge qubits. For example, nuclear spin relaxation times for P donors in Si are measured in hours at LHe temperatures.



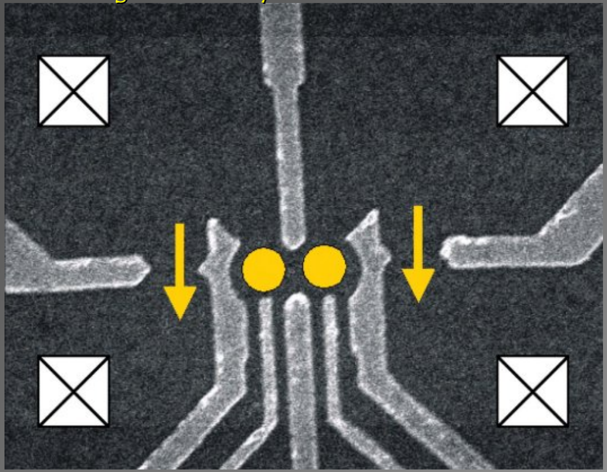
Duncan Steel (U. Mich.)

Relaxation times, however, are not necessarily the same as coherence times.

Example: hyperfine state qubits in atoms. There, relaxation times are of the order eternity. The **actual achieved and measured** coherence times are of the order of minutes…

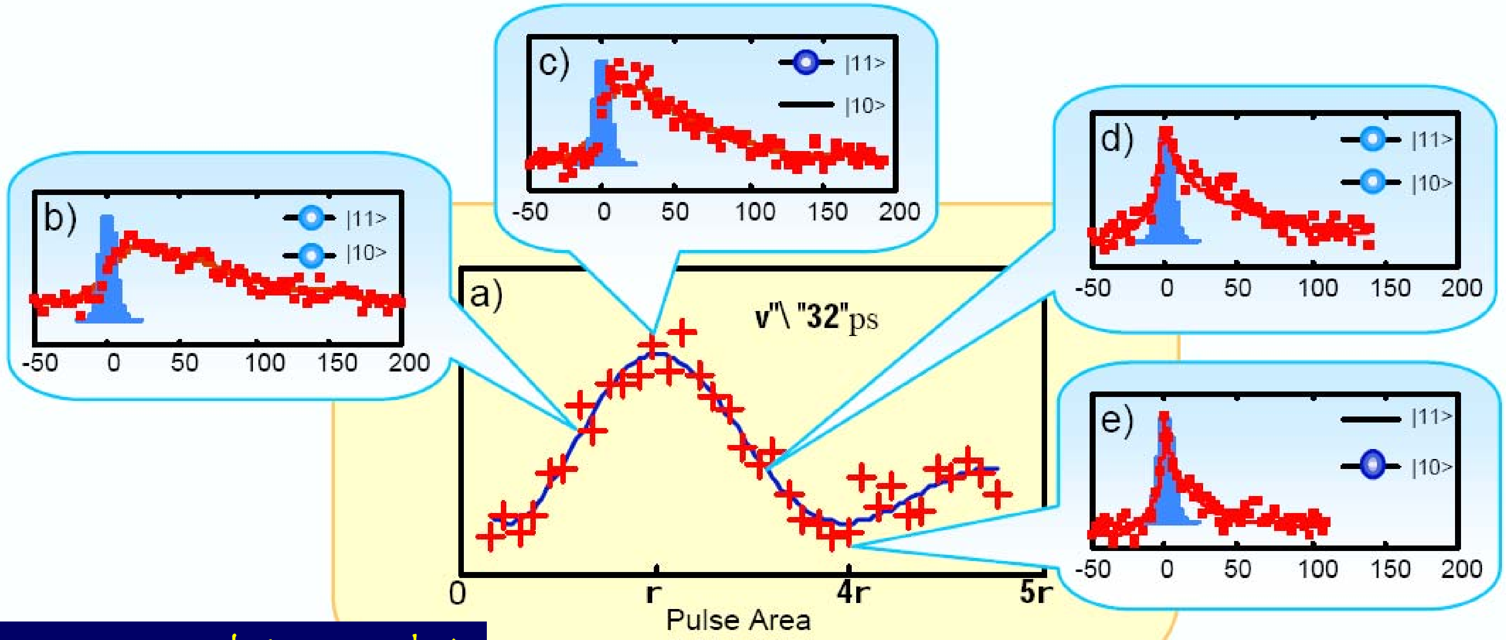
"universal set of quantum gates"

Image courtesy of Charlie Marcus



Single qubit and multiple qubit operations depend on the actual system:

- In optically-excited quantum dots, operations are performed by ultrafast (ps and fs) laser pulses.
- Phosphor in Silicon is driven by electrodes in the immediate vicinity of the qubit



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"qubit-specific measurement"

Single-electron transistors (for P in Si, etc.)

Optical spectroscopy (for optically excited QDs)

Nanomechaical devices???

For many systems (like spins in Si) measurement remains a challenge.

Semiconsuctor qubits – pros and cons

- Straightforward fabrication*
- Easy scaling
- LHe operation (not a dilution fridge)
- Computers are made of silicon, darn it!
- Coupling to flying qubits seems possible

- Noise in the environment seems unavoidable – decoherence may be a roadblock
- *Fabrication very demanding (purity, precision, etc.)
- Measurement??? Gates???