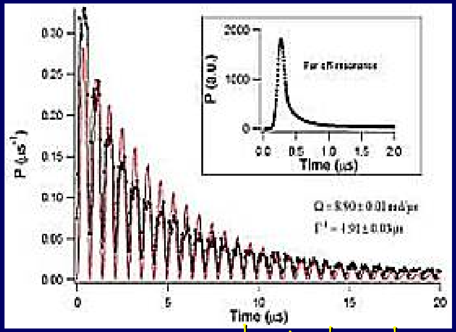
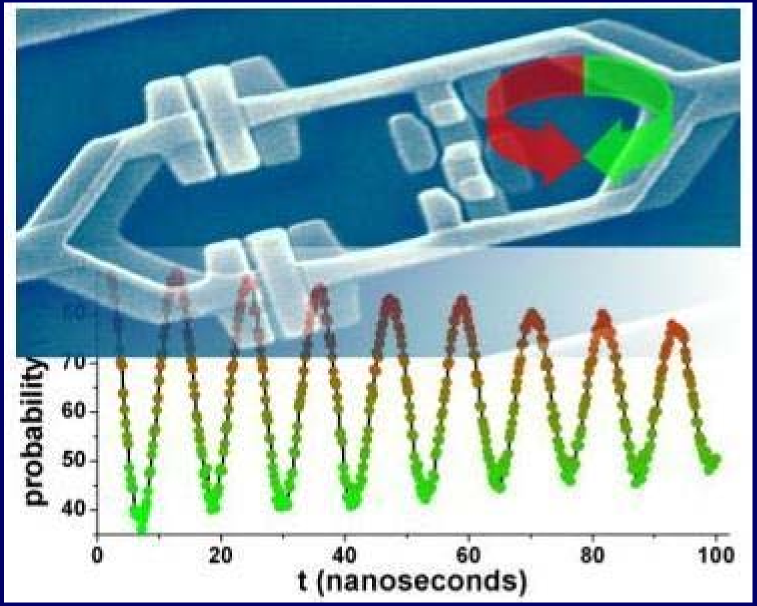
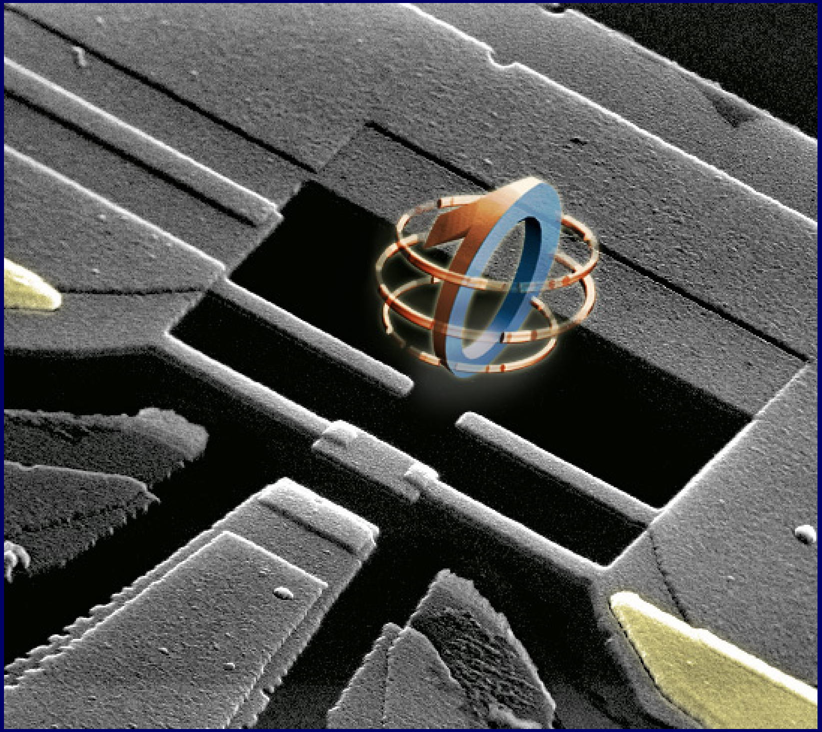
Superconductors - 1



www.physics.ku.edu



http://qt.tn.tudelft.nl/research/fluxqubit/qubit_rabi.jpg



http://www-drecam.cea.fr/

Superconducting qubits – a timeline

1911

Heike Kamerlingh Onnes
Superconductivity in Hg

1933

Walter Meissner
"Meissner effect"

1957

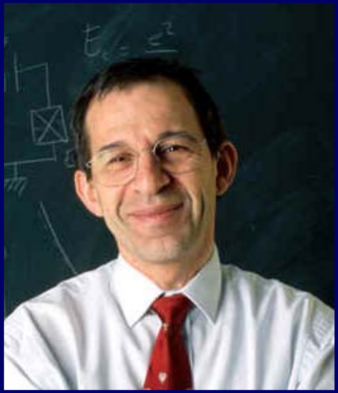
Bardeen, Cooper, Schrieffer
Theory of Superconductivity

1962

Supercurrent
through a non-
superconducting
gap

1997

Schnirman et al. – theoretical
proposal for JJ qubits



1998

Devoret group (Saclay)
first Cooper Pair Box qubit

1999

Nakamura, Tsai (NEC)
Rabi oscillations in CPB

2000

Lukens, Han (SUNY SB)
Flux qubit

2002

Martinis (NIST)
phase qubit

2006

Martinis (UCSB)
two-qubit gate (87% fidelity)

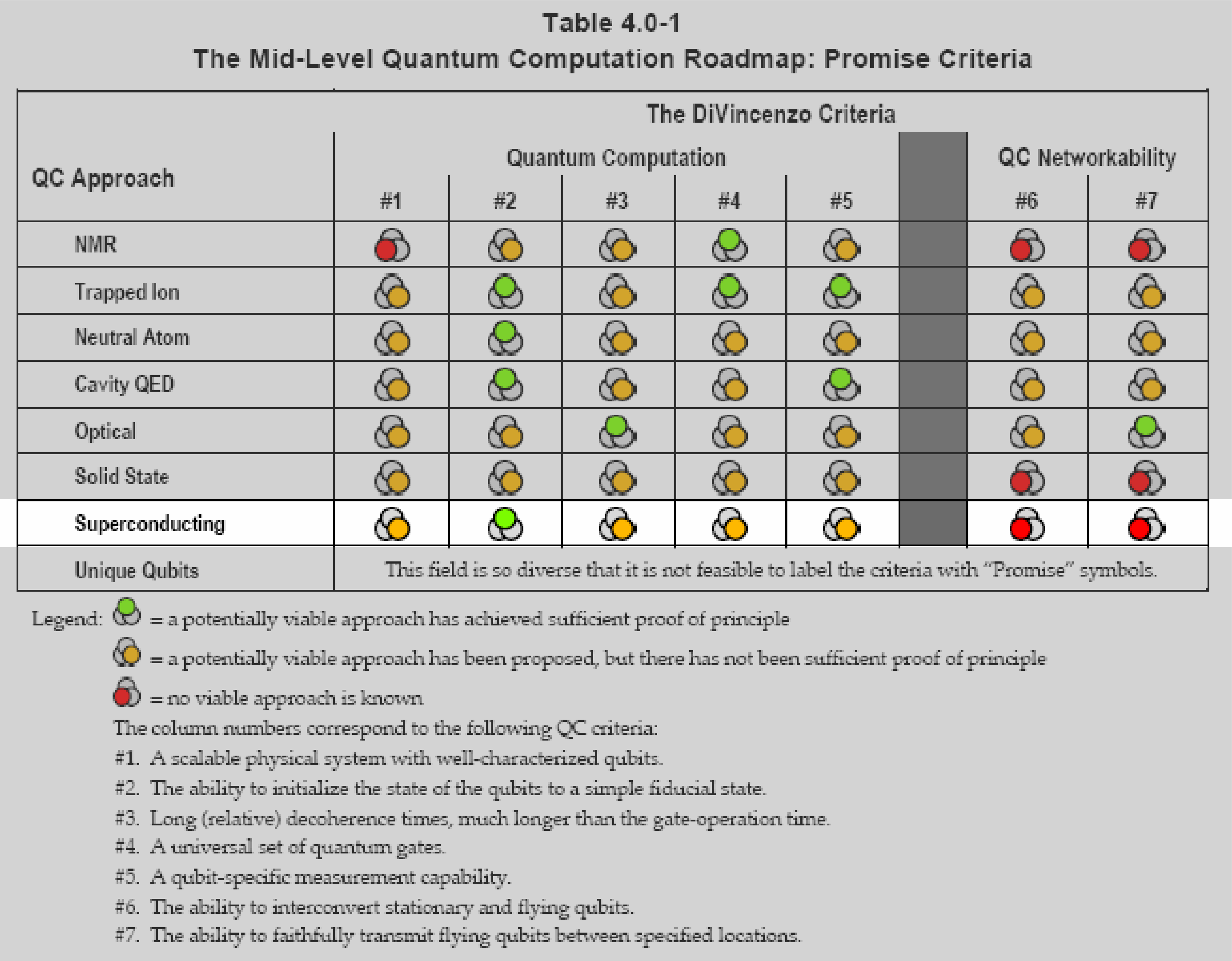


Table 4.0-1

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.

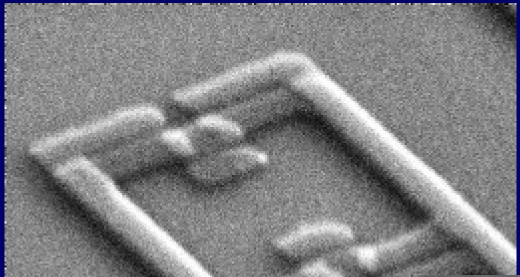
#5. A qubit-specific measurement capability.

#6. The ability to interconvert stationary and flying qubits.

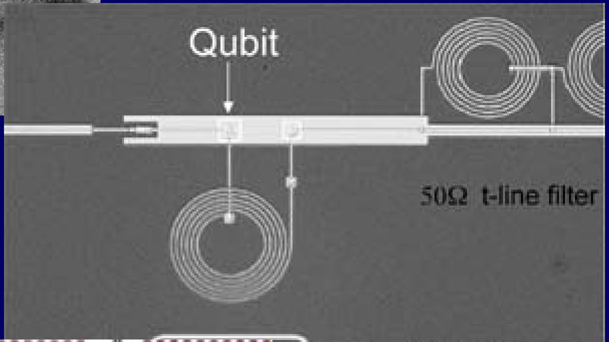
#7. The ability to faithfully transmit flying qubits between specified locations.

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

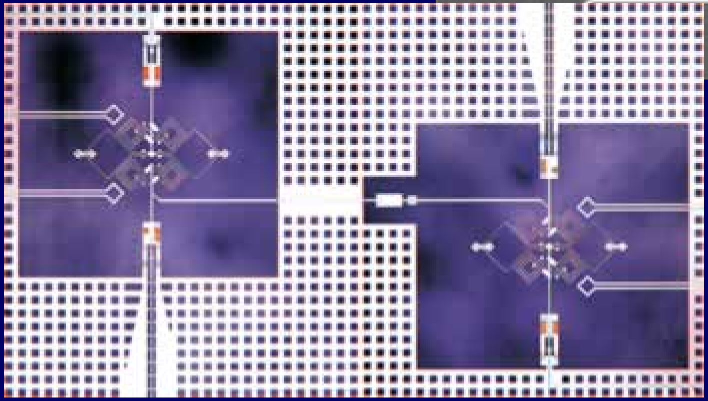
"Scalable physical system with well-characterized qubits"



The system is physical – it is a microfabricated device with wires, capacitors and such



The system is in principle quite scalable. Multiple copies of a qubit can be easily fabricated using the same lithography, etc.



But: the qubits can never be made perfectly identical (unlike atoms). Each qubit will have slightly different energy levels; qubits must be characterized individually.

"ability to initialize qubit state"

Qubits are initialized by cooling to low temperatures (mK) in a dilution refrigerator. This is how:

Energy splittings between qubit states are of the order of $f = 1 - 10$ GHz (which corresponds to $T = hf/k_B = 50 - 500$ mK)

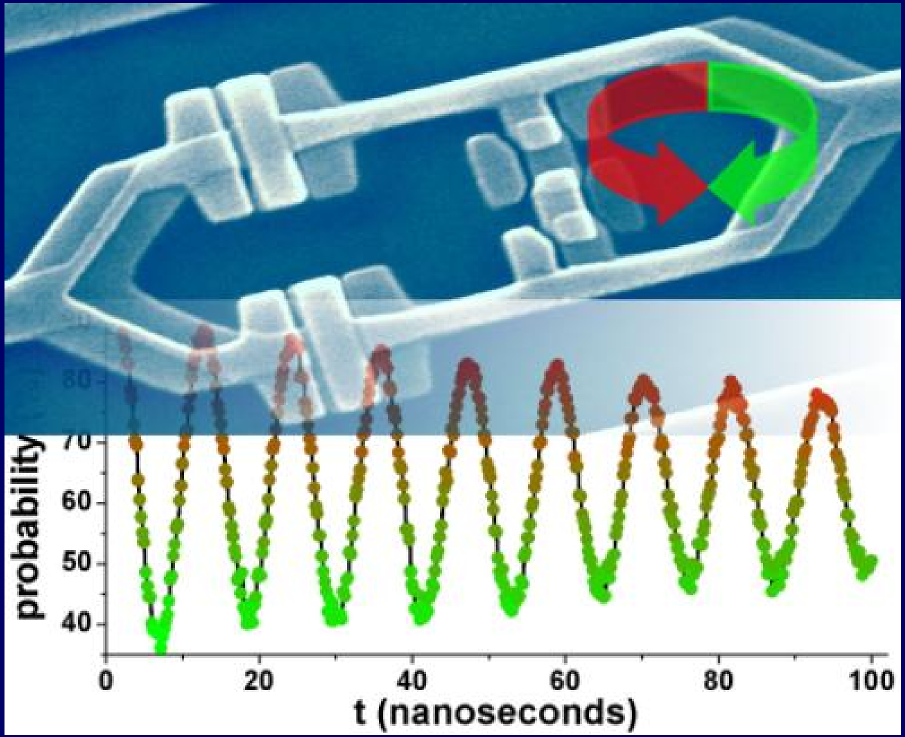
If the system is cooled down to $T_0 = 10$ mK, the ground state occupancy is, according to Boltzmann distribution:

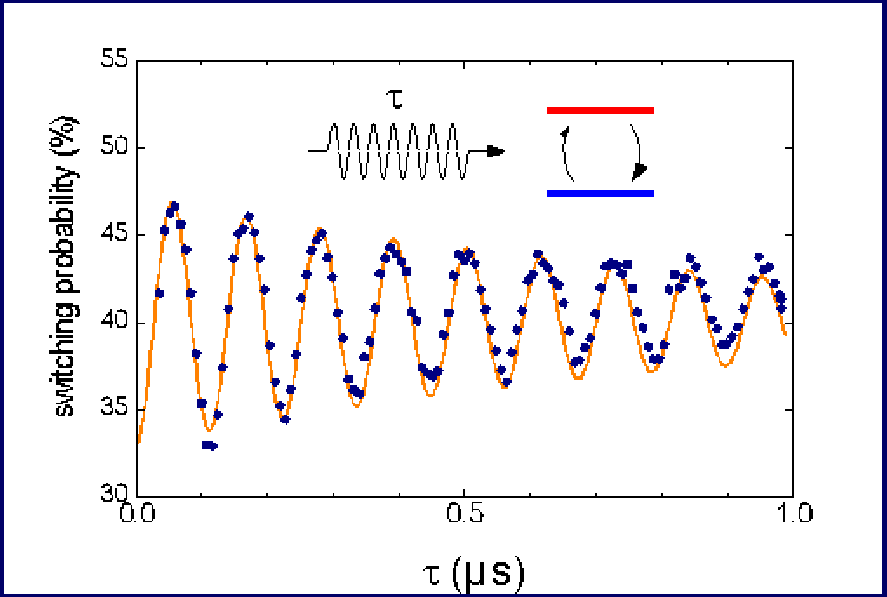
$$P_{|0\rangle} = \exp(-hf/k_B T_0) = 0.82 - 0.98$$

Lower temperature dilution refrigerators mean better qubit initialization!

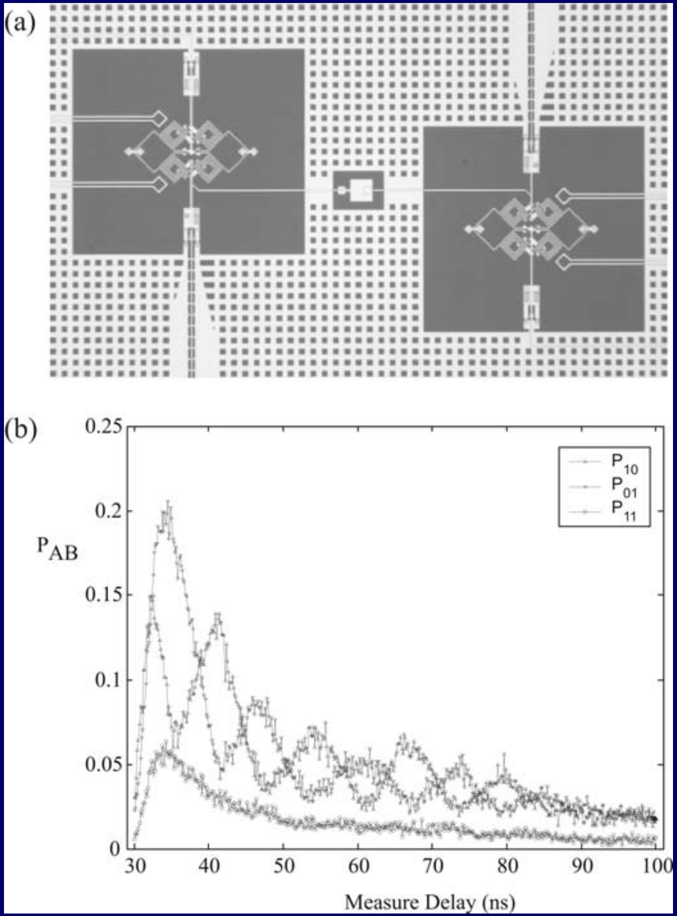
"(relative) long coherence times"

Coherence times from a fraction of a nanosecond (charge qubits) to tens of nanoseconds (flux) to microseconds ("quantronium"). Correspond to about 10 – 1000 operations before decoherence. Many sources of noise (it's solid state!)





"universal set of quantum gates"



Single qubit gates: applying microwaves (1 – 10 GHz) for a prescribed period of time.

Two-qubit gates: via capacitive or inductive coupling of qubits.

Science ***313***, *1432 (2006)* – entanglement of two phase qubits (Martinis' group – UCSB)

"qubit-specific measurement"

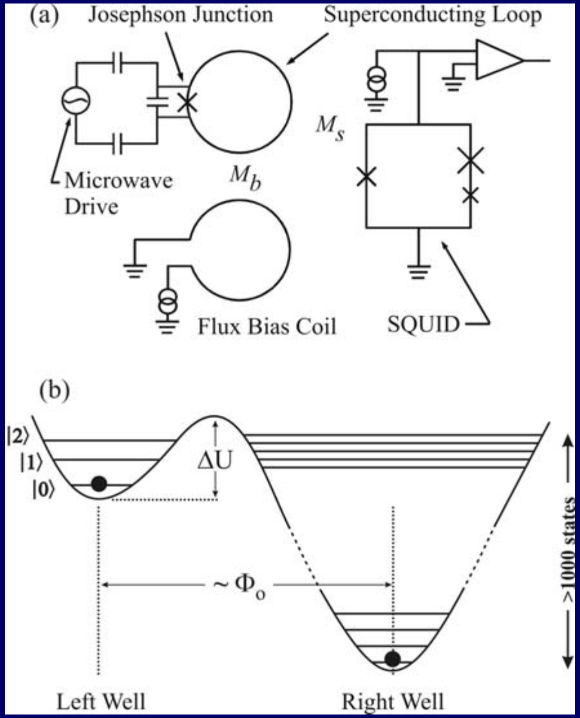
Measurement depends on the type of qubit.

Charge qubit readout: bifurcation amplifier with bimodal response corresponding to the state of the qubit.

Flux and phase qubits readout: built-in DC-SQUID that detects the change of flux.

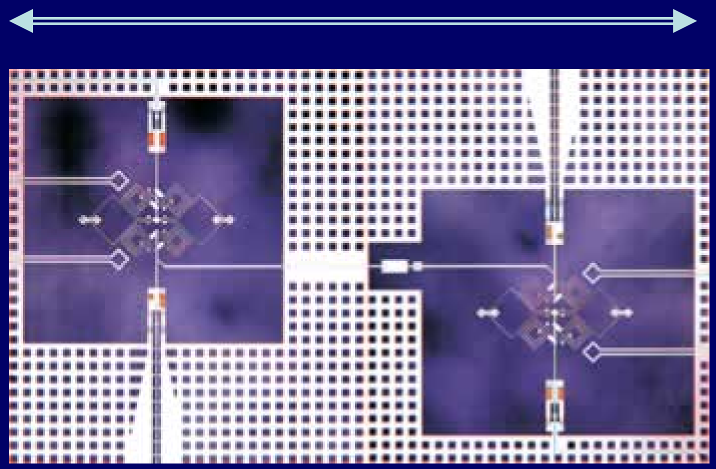
UCSB

Martinis' qubit: a large JJ phase qubit

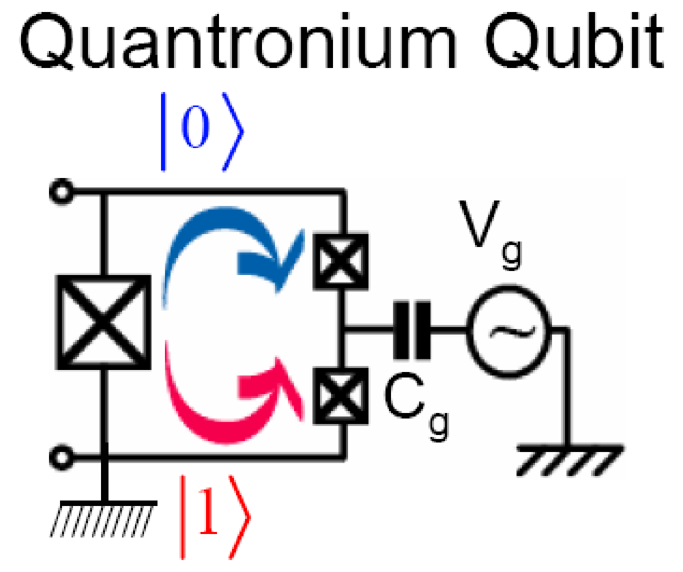


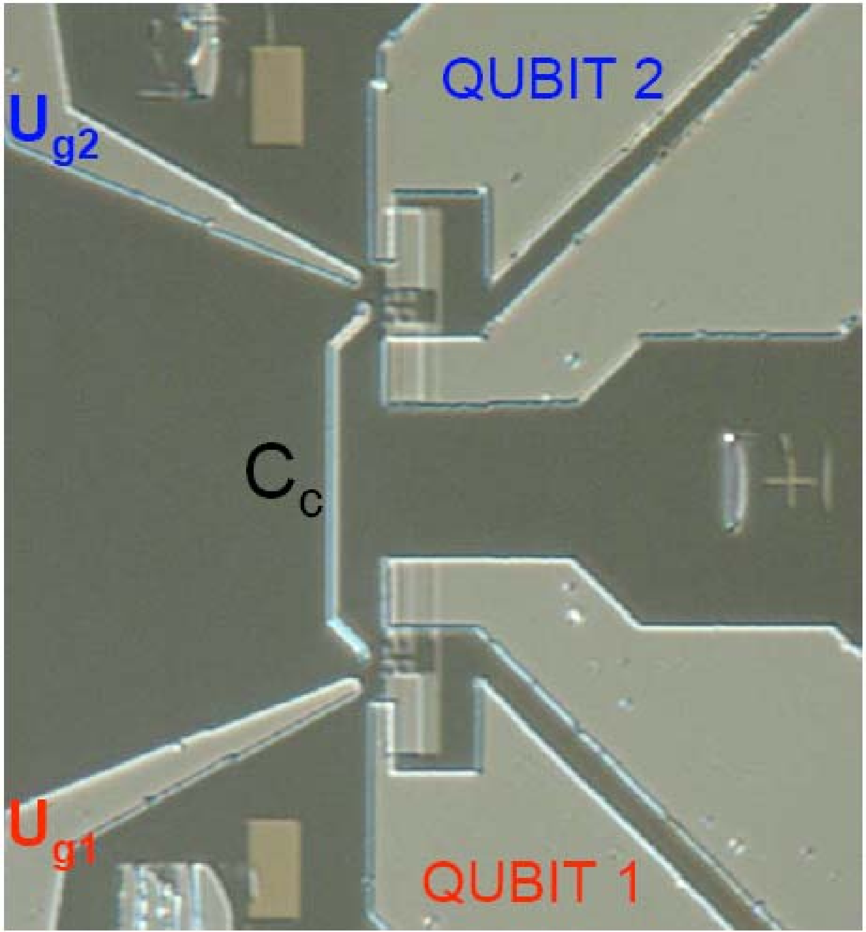
- 95% readout fidelity
- 67% Rabi oscillation contrast
- 87% entangled state (corrected) fidelity

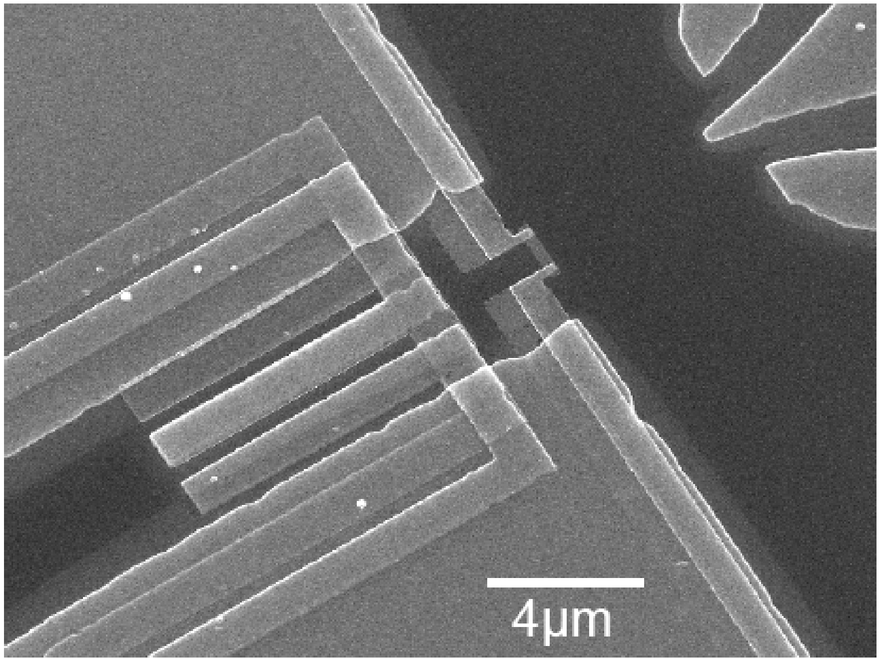
~1.3 mm



Devoret's qubit: the "quantronium"







Superconducting qubits - pros and cons

- Cleanest of all solid state qubits.
- Fabrication fairly straightforward, uses standard microfab techniques
- Gate times of the order of ns (doable!)
- Scaling seems straightforward

- Need dilution refrigerators (and not just for noise reduction)
- Initialization will always be limited by Boltzmann factor
- No simple way to couple to flying qubits (RF photons not good)
- Longer coherence needed, may be impossible

Superconducting qubits – what can we expect in near term?

- More research aimed at identifying and quantifying the major source(s) of decoherence.

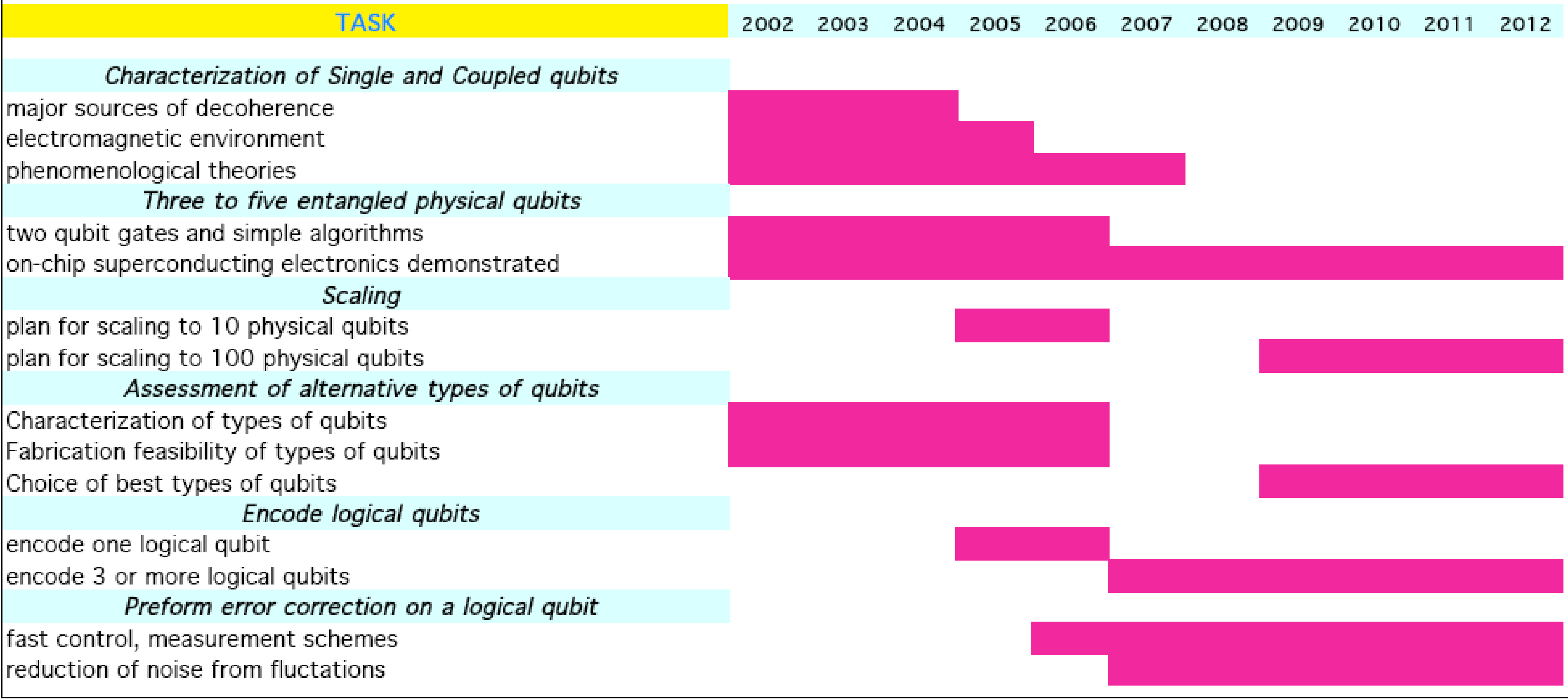
- Improved control of the electromagnetic environment – sources, wires, capacitors, amplifiers.

- Entanglement demonstrations in other types of SC qubits.

- Integration of the qubit manipulation electronics (on the same chip as the qubits themselves).

Superconducting Quantum Computing
Road Map

TIME LINES



TASK	2002	2003	2004	2005	2006	2007	2008	2009	2010	2011	2012
Characterization of Single and Coupled qubits											
major sources of decoherence	■	■	■								
electromagnetic environment	■	■	■	■							
phenomenological theories	■	■	■	■	■	■					
Three to five entangled physical qubits											
two qubit gates and simple algorithms	■	■	■	■	■						
on-chip superconducting electronics demonstrated	■	■	■	■	■	■	■	■	■	■	■
Scaling											
plan for scaling to 10 physical qubits				■	■						
plan for scaling to 100 physical qubits								■	■	■	■
Assessment of alternative types of qubits											
Characterization of types of qubits	■	■	■	■	■						
Fabrication feasibility of types of qubits	■	■	■	■	■						
Choice of best types of qubits								■	■	■	■
Encode logical qubits											
encode one logical qubit				■	■						
encode 3 or more logical qubits						■	■	■	■	■	■
Preform error correction on a logical qubit											
fast control, measurement schemes					■	■	■	■	■	■	■
reduction of noise from fluctations						■	■	■	■	■	■