Los Alamos
National Laboratory

Physical implementations for quantum information processing

Raymond Laflamme
qso.lanl.gov/~qc

(U of Waterloo & Perimeter Institute)

Reference: Fortschritte der Physik
Volume 48, Issue 9-11, 2000.
http://www3.interscience.wiley.com
also xxx.lan.gov/quant-ph

LDRD Laboratory-Directed Research and Development

ARDA

National Security Agency United States of America

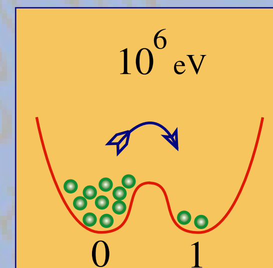
DARPA

United States Department of Energy
Science, Security and Energy: Powering the 21st Century

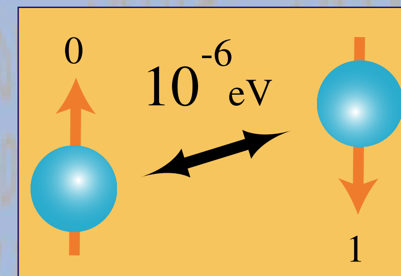
The fragility of quantum information

R. Landauer, PRSL 353, 367, 1995
W. G. Unruh, PRA 51 992, 1995
I. L. Chuang, R. L., P. Shor and
W. H. Zurek, Science 270, 1995

Today

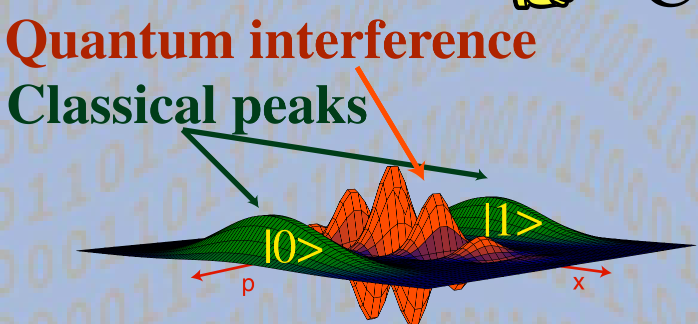


Quantum

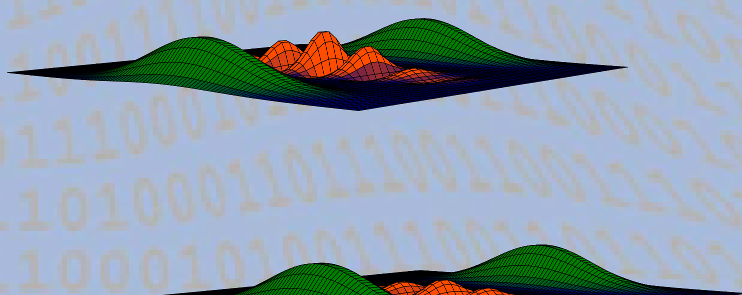


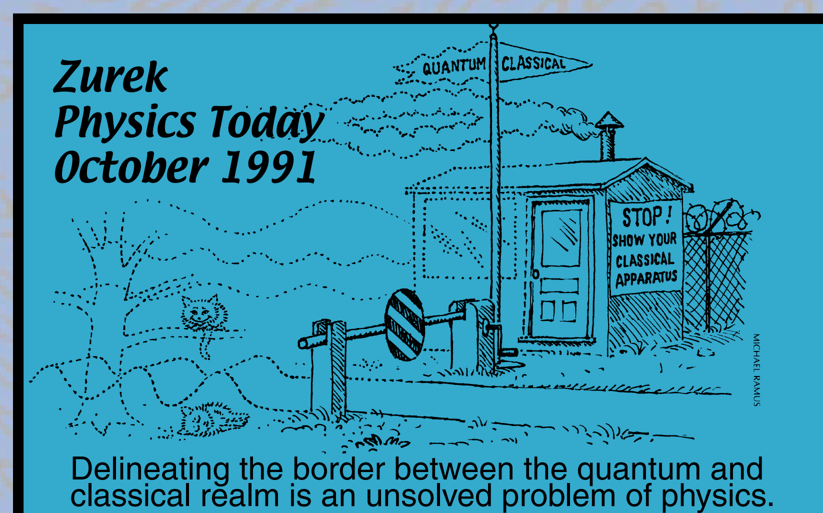
☞ Little energy

☞ Control of operations



☞ Quantum superpositions are extremely fragile





Error Correction and the Accuracy Threshold

A quantum computation can be as long as required with any desired accuracy as long as the noise level is below a threshold value

$$P < 10^{-6}$$

Knill et al.; Science, 279, 342, 1998

Kitaev, Russ. Math Survey 1997

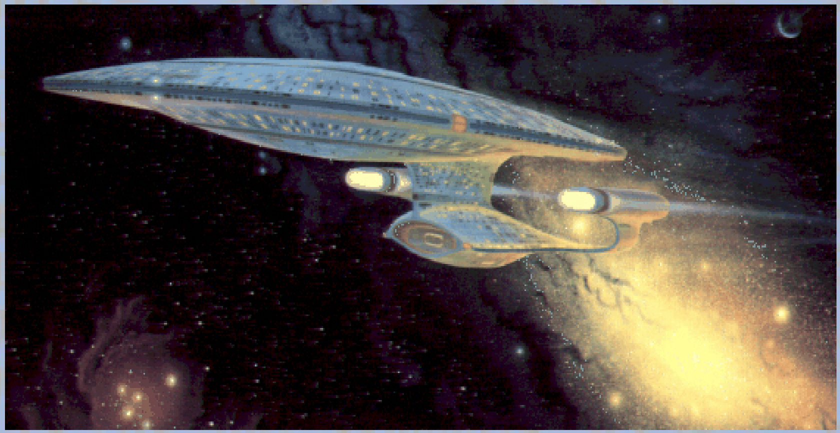
Aharonov & Ben Or, ACM press

Preskill, PRSL, 454, 257, 1998

Significance:

- -imperfections and imprecisions are not fundamental objections to quantum computation
- -it gives criteria for scalability
- -its requirements are a guide for experimentalists
- -it is a benchmark to compare different technologies

Theory



Experiment

Requirements for quantum computing

DiVincenzo Science 270, 255, 1995

Hilbert space

State preparation

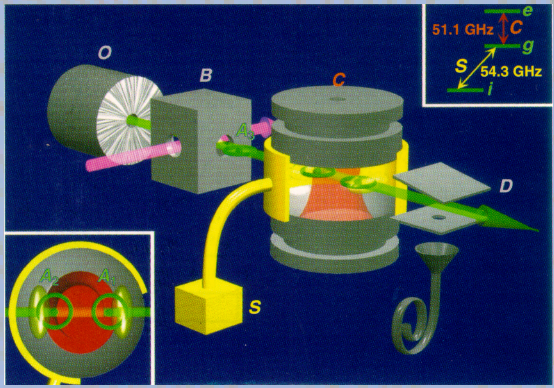
Controlled evolution

-unitary
-little decoherence

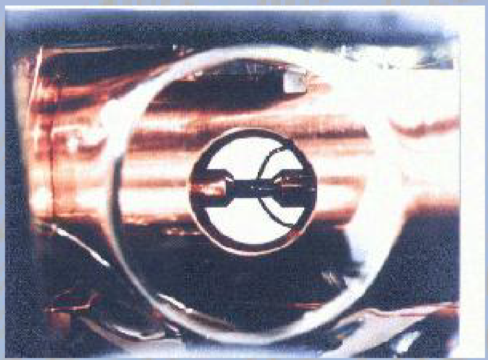
Single bit rotations +
control not is a universal set
Barenco & al. 96
Lloyd, 96
DiVincenzo 96

Measurements

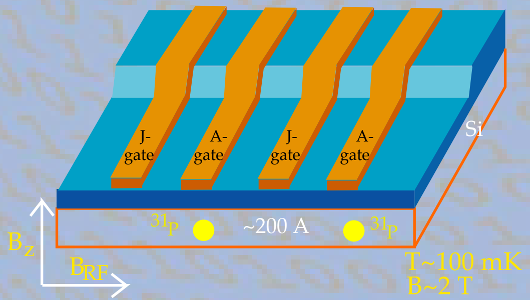
Devices for Quantum Information Processing

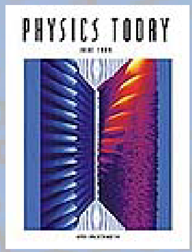


- Atom traps
- Cavity QED
- Electron floating on helium
- Electron trapped by surface acoustic waves
- Ion traps



- Nuclear Magnetic Resonance
- Quantum Optics
- Quantum dots
- Solid state
- Spintronics





- Superconducting Josephson junctions

Photonic QIPs

+

- quantum optics well developed
- photons are cheap
- room temperature
- long coherence time

TABLE I. Logic table for a Fredkin gate.

Input			Output		
c_i	a_i	b_i	c_o	b_o	a_o
0	0	0	0	0	0
0	0	1	0	0	1
0	1	0	0	1	0
0	1	1	0	1	1
1	0	0	1	0	0
1	0	1	1	1	0
1	1	0	1	0	1
1	1	1	1	1	1

Milburn,
PRL62,2124, 1989

VOLUME 62, NUMBER 18 PHYSICAL REV

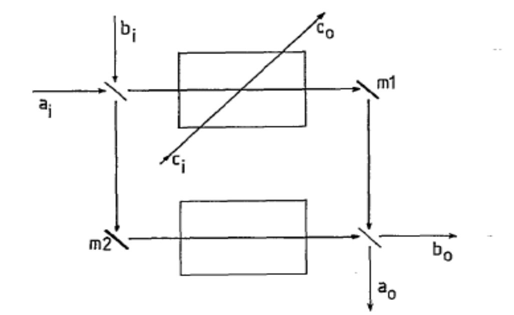


FIG. 1. Schematic outline of an optical system to realize a Fredkin gate. See text for details.

schematically in Fig. 1. Essentially it is a Mach-Zehnder interferometer. A substance with an intensity-dependent refractive index (optical Kerr effect[15]) is placed in both arms. In such a medium the field en-

-

- need non-linearity
- inefficient photon source/detector
- scalability

Qbit state

$$= \quad 01 \; + \quad 10$$

One bit gates

-phase shifter on the last mode => Z rotations

$$a_1 \qquad e^{i} \;\; a_1$$

-beam splitter => Y rotations

$$\begin{matrix} a_1 & & \cos\mu & \sin\mu & & a_1 \\ a_2 & & \sin\mu & \cos\mu & & a_2 \end{matrix}$$

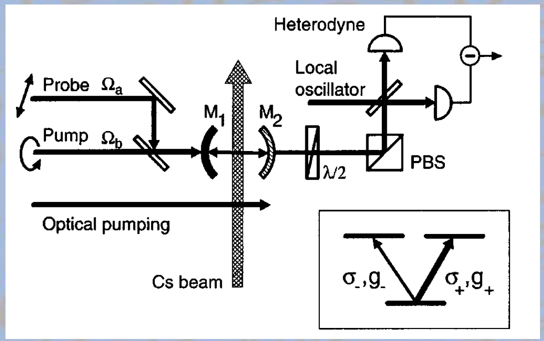
Two-bit gates kerr media

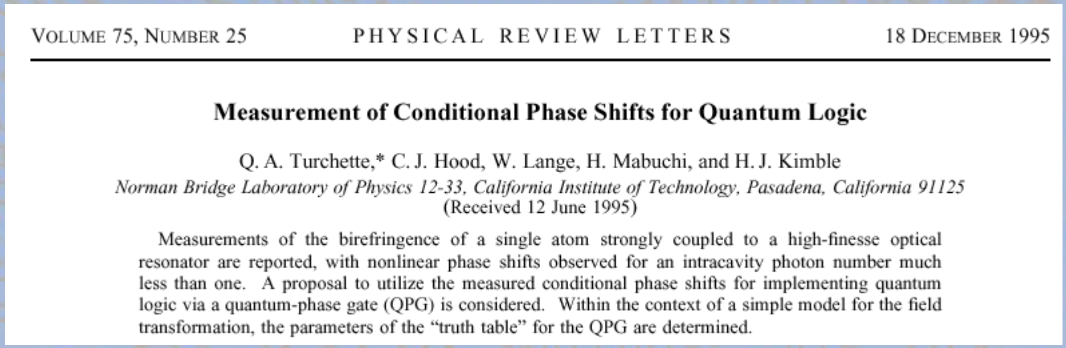
$$H_{Kerr} = \;\; a \; ab \;\; b$$

Groups:

Paris (Haroche)
Caltech (Kimble)
Georgia Tech (Chapman)

Cavity QED




VOLUME 75, NUMBER 25 PHYSICAL REVIEW LETTERS 18 DECEMBER 1995

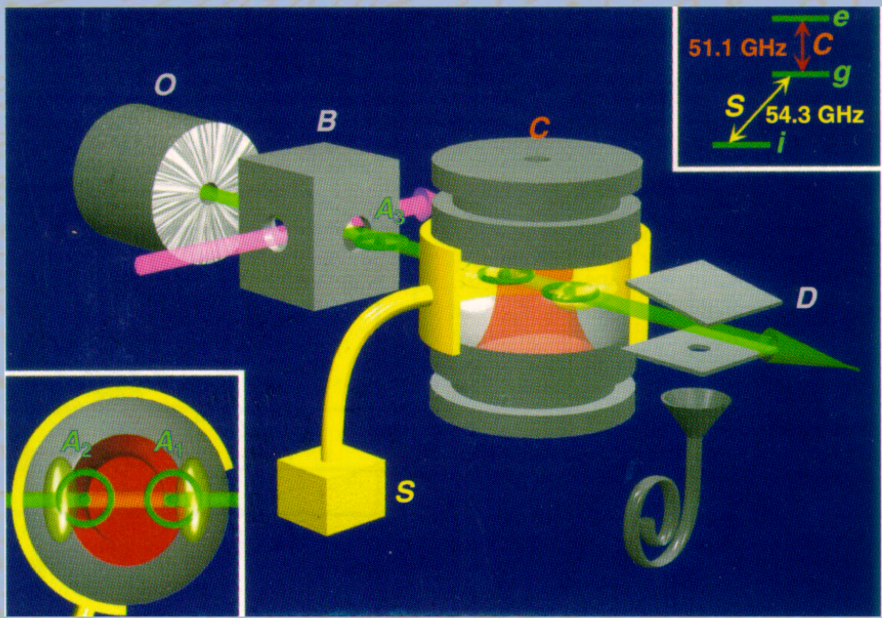
Measurement of Conditional Phase Shifts for Quantum Logic

Q. A. Turchette,* C. J. Hood, W. Lange, H. Mabuchi, and H. J. Kimble
Norman Bridge Laboratory of Physics 12-33, California Institute of Technology, Pasadena, California 91125
(Received 12 June 1995)

Measurements of the birefringence of a single atom strongly coupled to a high-finesse optical resonator are reported, with nonlinear phase shifts observed for an intracavity photon number much less than one. A proposal to utilize the measured conditional phase shifts for implementing quantum logic via a quantum-phase gate (QPG) is considered. Within the context of a simple model for the field transformation, the parameters of the "truth table" for the QPG are determined.

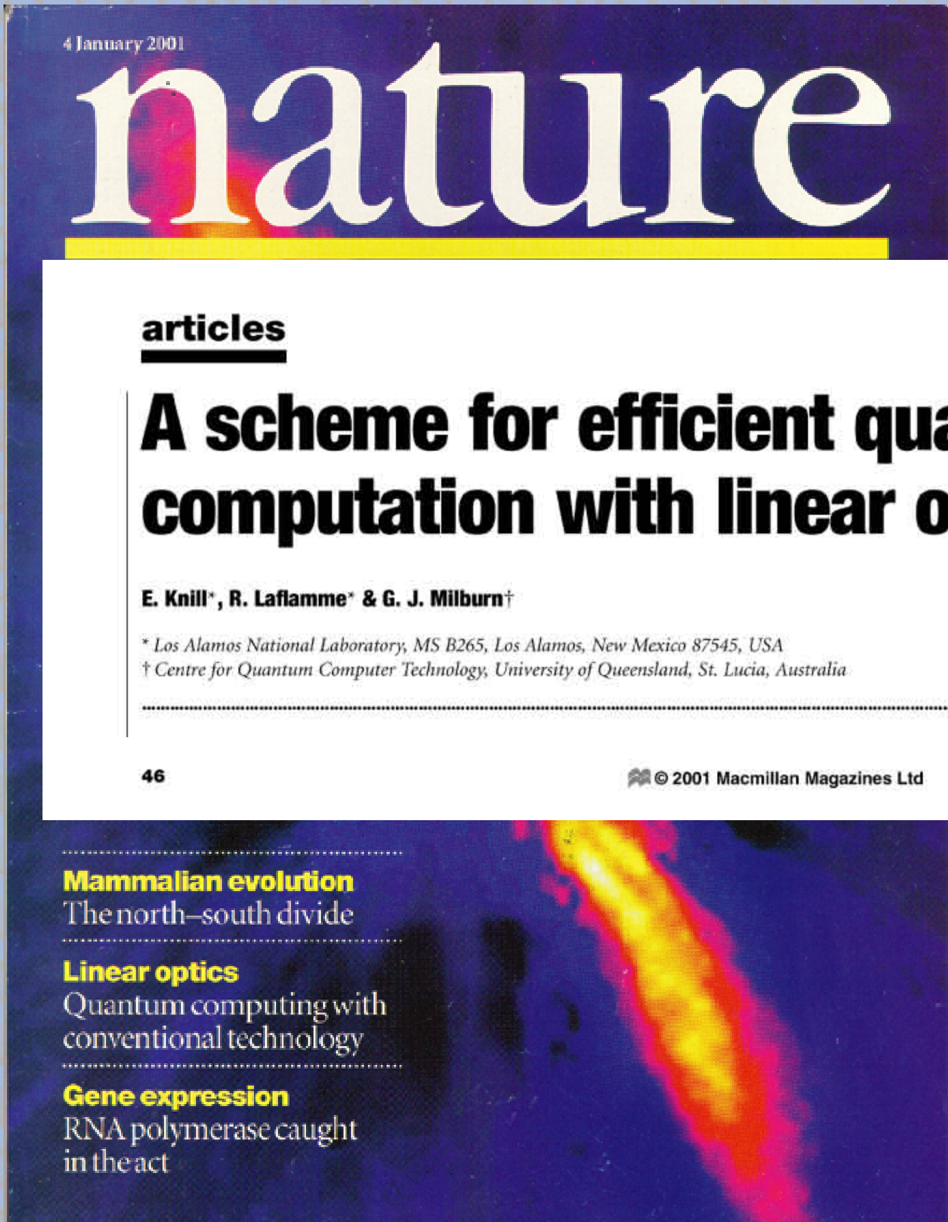
http://www.cco.caltech.edu/~qoptics/

Circular Rydberg: n =51 or 50 and l=|m|=n-1.
The quantum wavefunction is a very thin torus located around the classical orbit.



The Paris group's achievement
- quantum Rabi oscillations
- entaglement knitting
- quantum memory
- EPR atom pairs
- single photon QND detection
- Quantum phase gates

http://www.lkb.ens.fr/recherche/qedcav/english/rydberg/rydwelcome.html

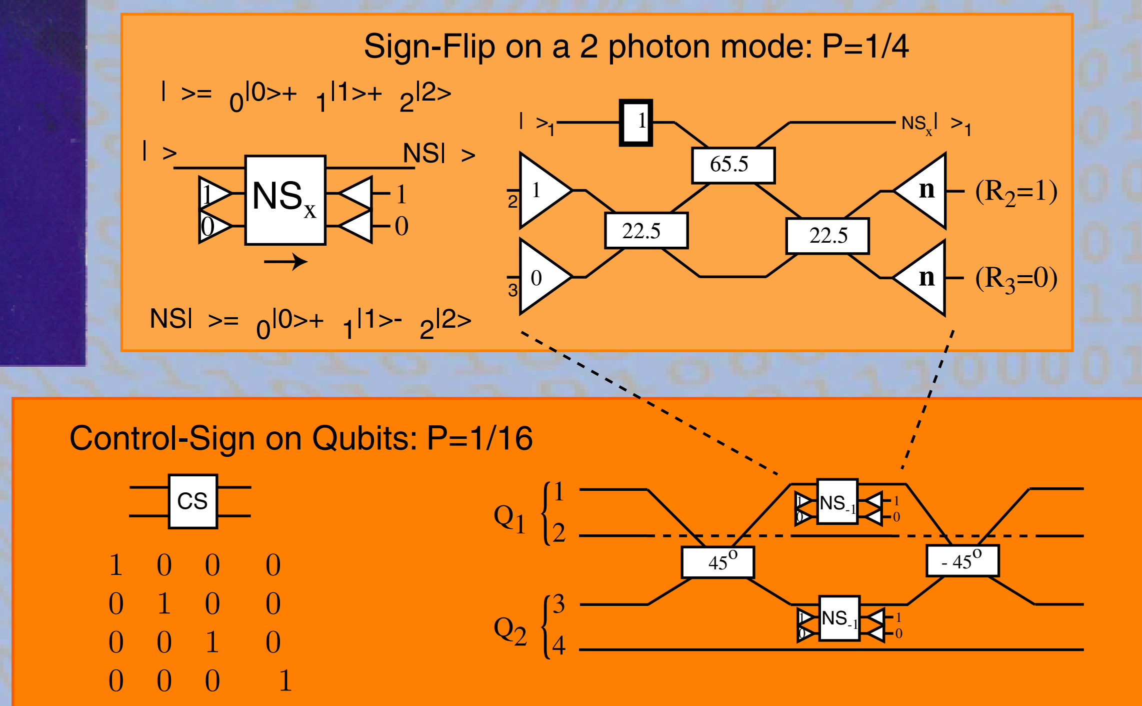


articles

A scheme for efficient quantum computation with linear optics

E. Knill*, R. Laflamme* & G. J. Milburn†

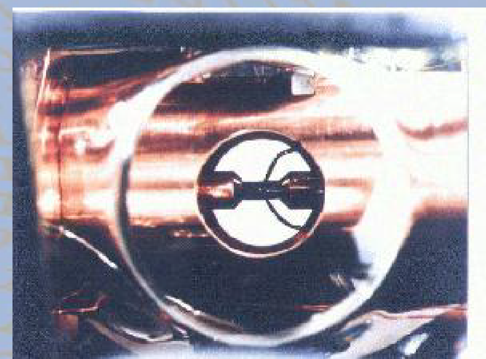
* *Los Alamos National Laboratory, MS B265, Los Alamos, New Mexico 87545, USA*
† *Centre for Quantum Computer Technology, University of Queensland, St. Lucia, Australia*

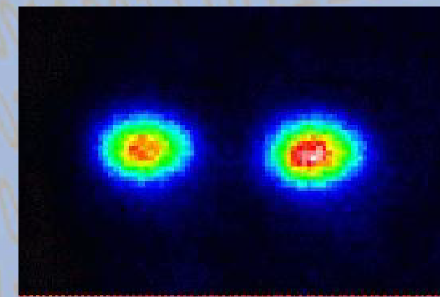


Groups:
NIST (Wineland)
Ann Arbour (Monroe)
Innsbruck (Blatt)
Oxford (Steane)
LANL (Hughes)
Munich (Walther)
IBM (DeVoe)

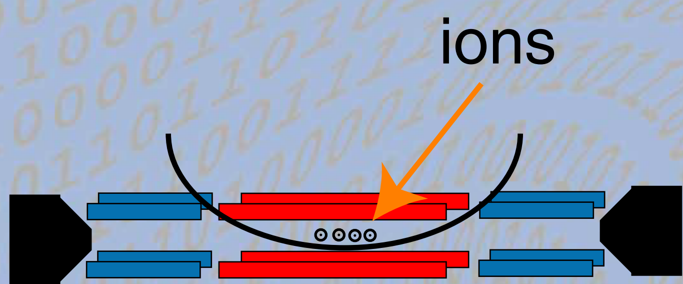
QIP using Ion traps

Cirac & Zoller PRL,1995

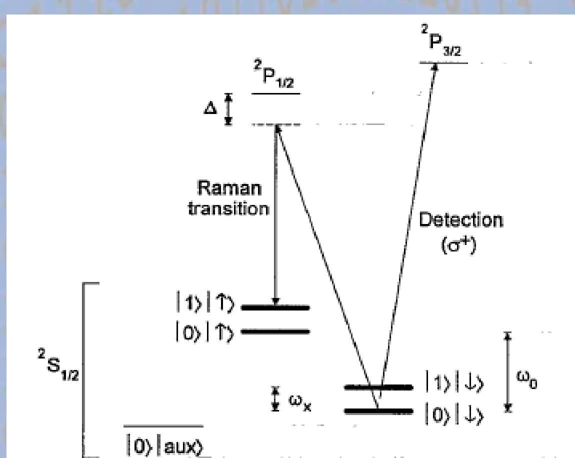




Paul Trap at NIST and 2 Be ions
http://www.boulder.nist.gov/timefreq/ion/



Plusses and minuses of ion traps
-demonstration of manipulations of up to 4 qubits
-decoherence time > operation time
-possible combination with cavities => photon
Minuses
-uncontrolled heating, limits # of ops
-increased complexity of cooling with #of qubits
-difficulty to address different qubits independently
-linear trap no parrallel ops

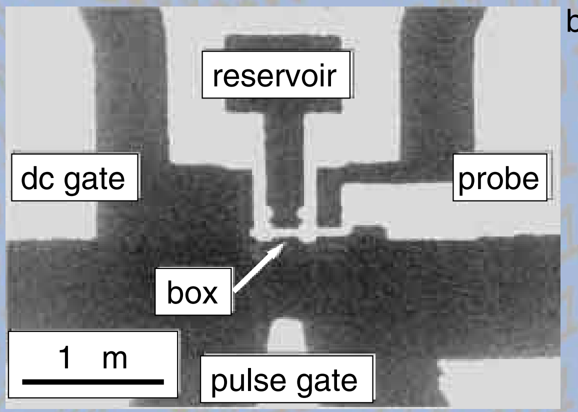


http://mste.laser.physik.uni-muenchen.de/lg/lgtop.html
http://heart-c704.uibk.ac.at/
http://p23.lanl.gov/Quantum/
http://www.qubit.org/research/IonTrap/

Groups:

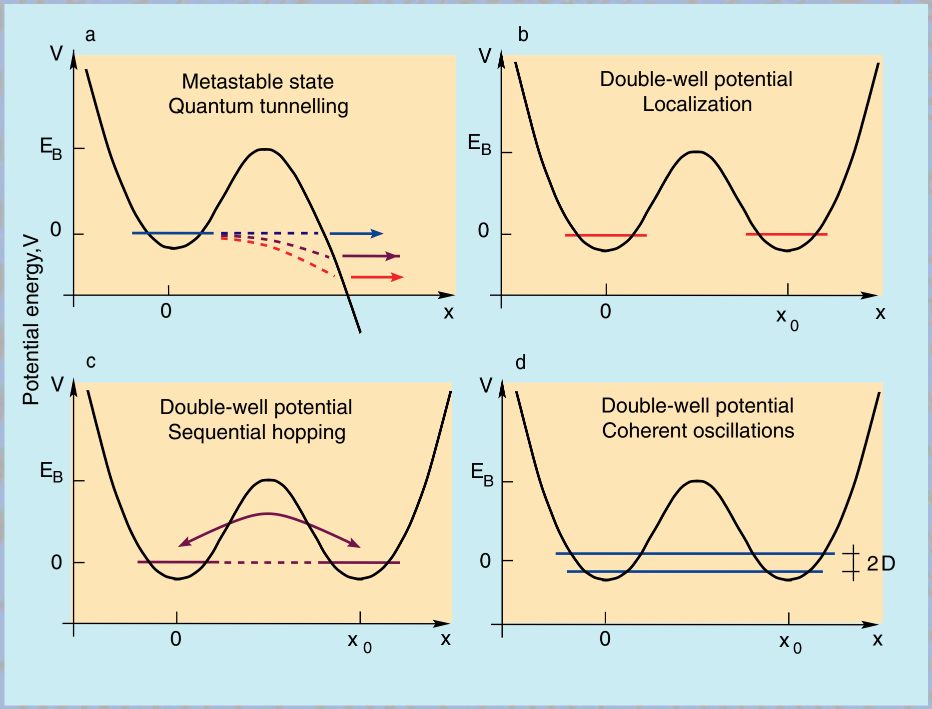
Delft (Mooij)
Stony Brook (Friedman)
Paris (Devoret)
(Nakamura)

Superconducting devices

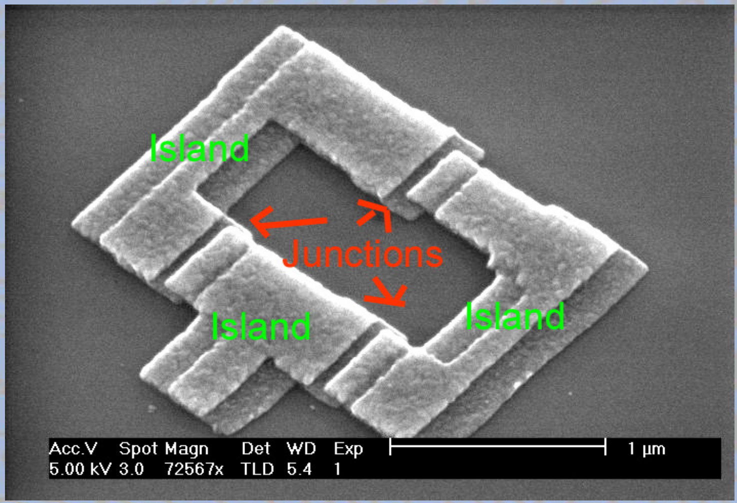


NATURE | VOL 398 | 29 APRIL 1999 | www.nature.com

Flux or charge qubits?



Friedman et al. NATURE | VOL 406 | 6 JULY 2000 | www.nature.com



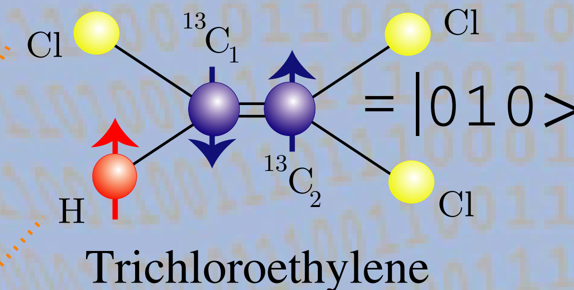
http://vortex.tn.tudelft.nl/~junctions/

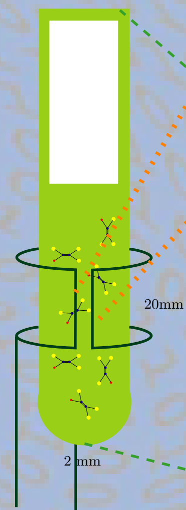
Science

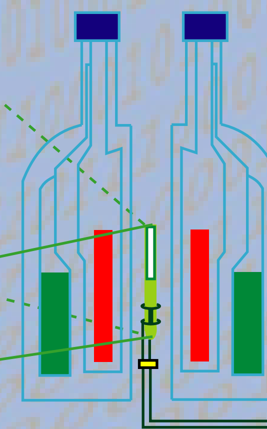
Liquid State NMR

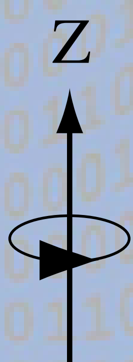
Cory & Havel PNAS, 64, 1634, 1997
Gershenfeld & Chuang, Science 275, 350, 1997

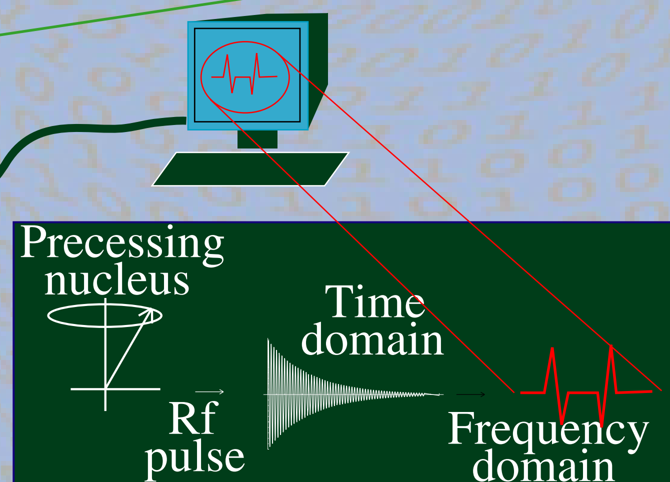
- -Larmor Frequency~ 500MHz
- -Single bit gate: 1/   ~ms
- -Two qubit gate: ~ 10ms
  - z^1 z^2 interaction
- -T2 ~ 1s
- -T1 ~ 5-30s
- - =e$^-$ H ~ 1- H







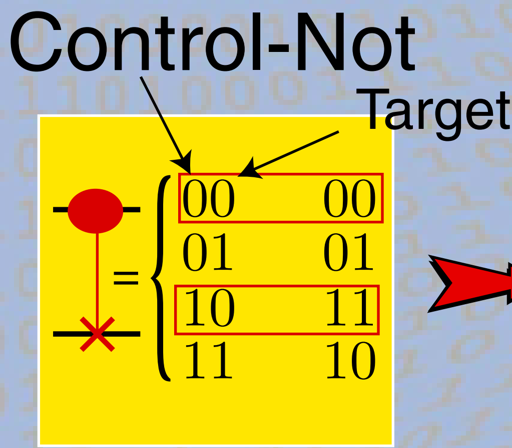




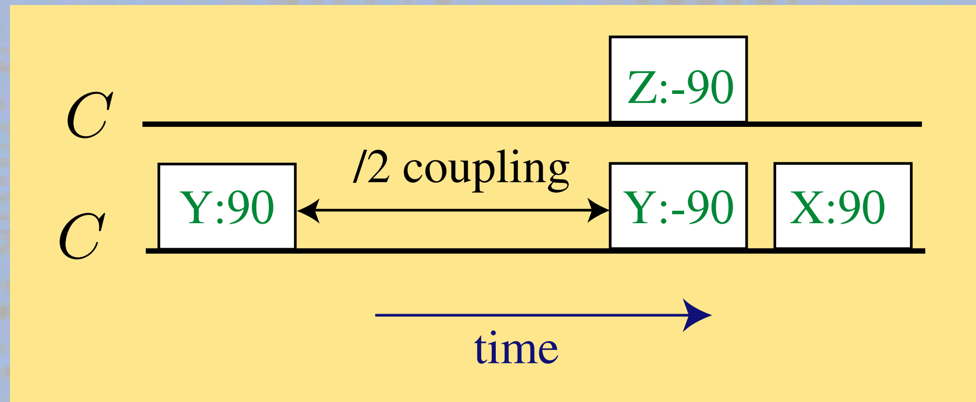
QIP NMR experiments

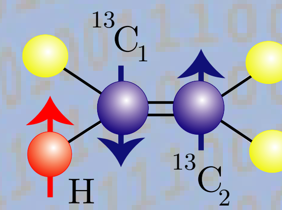
# of qubits	Algorithms	Year	Reference
2	Gates	1996	MIT, Stanford, NC, Oxford
	Database Search	1998	Oxford, IBM
	Deutsch-Josza	1998	Oxford, IBM
	Quantum Simulation	1999	MIT/LANL
	Quantum Fourier Transform	1998	MIT, CAS
	Dense Coding	1998	CAS
	Quantum Detecting Code	1999	IBM
3	GHZ state	1997	LANL, MIT
	Quantum Error Correction	1997	MIT/LANL
	Quantum Teleportation	1997	LANL
	Deutsch-Josza	1998	KAIST, India
	Quantum Simulation	1999	MIT/LANL
	Quantum Fourier Transform	1998	MIT
	Quantum Eraser	1998	MIT
4	C^3-not Gate	1999	MIT
5	Deutsch-Josza	1999	Frankfurt
	Order finding	2000	IBM
	Quantum Error Correction	2001	LANL
6	Decoupling	1998	Cambridge
7	Benchmark	2000	LANL

From quantum algorithms to machine language



Quantum circuit





Pre-compiler (Optimizer)

```
;; Debug to track down error sources by doing partial error correction.

#define C1obs
;!$watch{H1} = 1;
;!$watch{H2} = 1;
#include "c1pp.h"

;> $locRng = 5; $locStp = 2;


 ; erate .1
;;<
;;> $locRng = 5; $locS

 ; pulse noop @M:Z-
;;;
;;Correction steps
;;;

 ;;cnot C1->C2

 ; pulse C2_90 .
 ; zz .25 C1 C2
 ; zpulse M:.75;
 ; pulse C2_90 .
 ; pulse C2_90 .
 ; refocus C1C2_

 ;; delay end .0

;<


#include "crot_def.
```

```
; pulse C2_90 .25
; zz .25 C1 C2
; zpulse C1:.75;C2:
; pulse C2_90 .75
; pulse C2_90 .0
refocus C1C2_180
```

Bruker (machine) language

```
1 ze
2 lhold LOCKH_OFF

  d1
  1u reset:f1
  1u reset:f2
  1m

  lhold LOCKH_ON

  ;Initial virtual 180s
 ;Time: 0.000e+00 seco

  8u
  3u
  ( C2_90:sp9 ph13
  3u
  3u ipp13

  0.71365m

  8u
  8u
 (C2_90:sp9 ph
  6u ipp15 ipp
  8u
 (C2_90:sp9 ph
  6u ipp15 ipp


  3u fq1:f2
  3u fq2:f1

  go=2 ph0:r

  100m

  lhold LOCKH_OFF
```

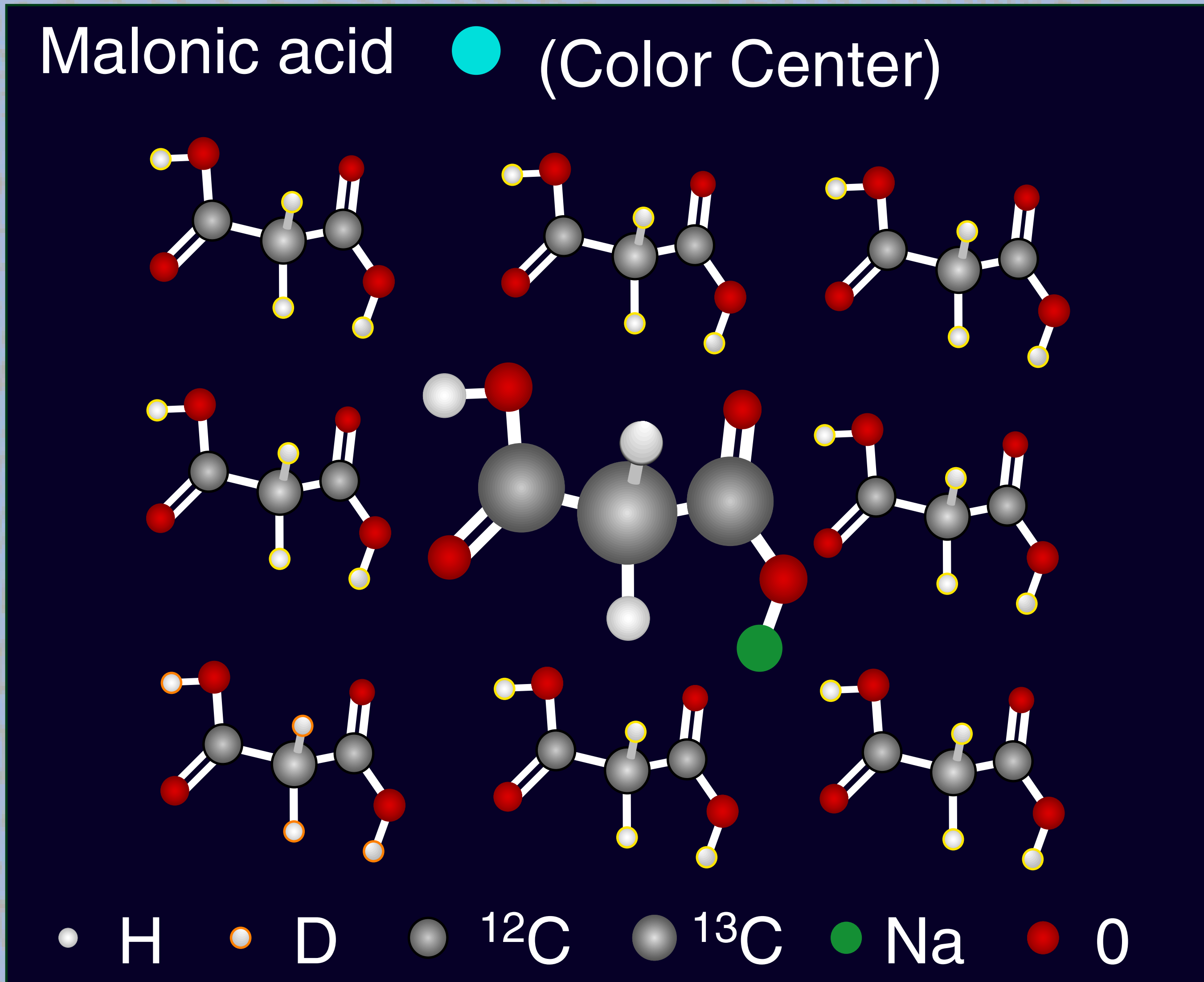
```
(C2_90:sp9 ph13 ):f1
 3u
 3u ipp13

 0.71365m

 8u
 8u
(C2_90:sp9 ph19):f1
 6u ipp15 ipp19
 8u
(C2_90:sp9 ph20):f1
 6u ipp15 ipp20
```

Next Generation of NMR QIP expts.

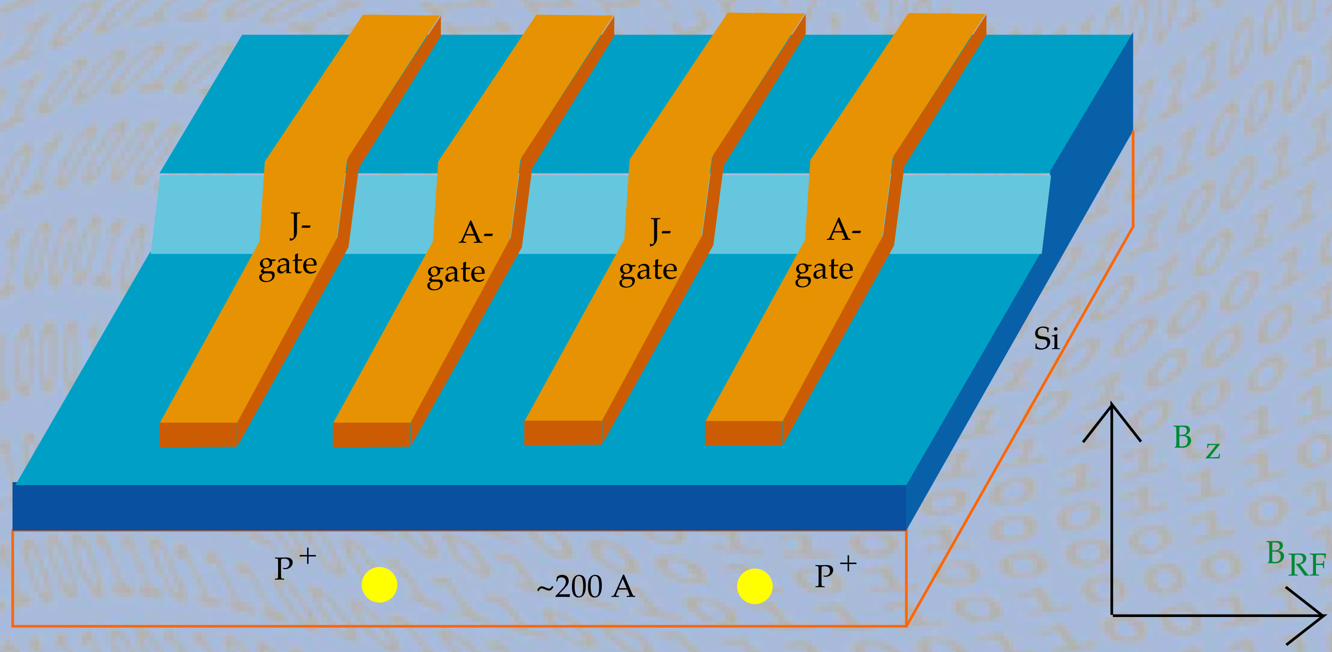
MIT & LANL



✶ Polarization ~1 ✶ Higher clock rate ✶ Eraseable register

Single Spin Solid-State NMR

Uof Maryland (Kane)
Sydney (Clark)
LANL (Hammel, Haley)
UCLA (Yablanovitch)



Conclusion

``Many of today's practical technologies result from basic science done years to decades before. The people involved, motivated mainly by curiosity; often have little idea as to where their research will lead. Our ability to forecast the practical payoffs from fundamental exploration of the nature of things (and, similarly, to know which of today's research avenues are technological dead ends) is poor. This springs from a simple truth: new ideas discovered in the process of research are really new."

Charles Townes

in How the Laser Happened.