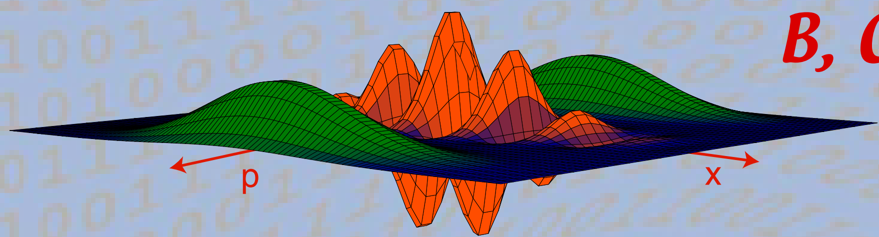
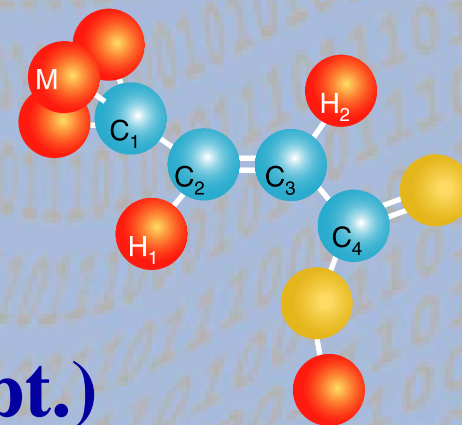
Los Alamos
National Laboratory

NMR Quantum Information Processing

B, CCS, T Divisions





Raymond Laflamme
(in U of Waterloo from Sept.)
http://qso.lanl.gov/qc

E. Knill, R. Martinez, W.H. Zurek,
D. Cory (MIT),

C. Negrevergene (LANL), M. Nielsen (Caltech), L. Viola (LANL)

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

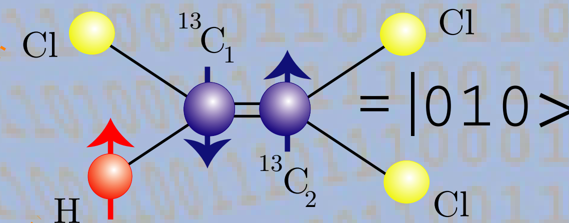
QIP NMR experiments

# 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

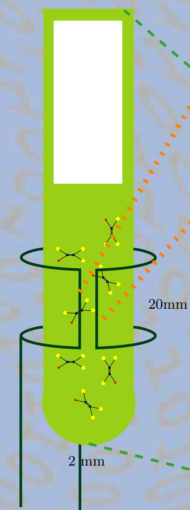
Liquid State NMR

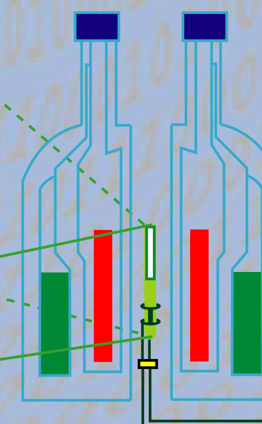
Cory & Havel PNAS, 64, 1634, 1997
Gershenfeld & Chuang, Science 275, 350, 1997

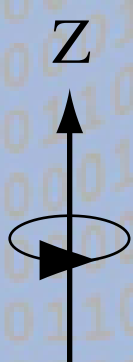
- -Larmor Frequency~ 500MHz
- -Single bit gate: 1/ ~ms
- -Two qubit gate: ~ 10ms
  - z^1 z^2 interaction
- -T2 ~ 1s
- -T1 ~ 5-30s
- - $=e^{-}$ H ~ 1- H

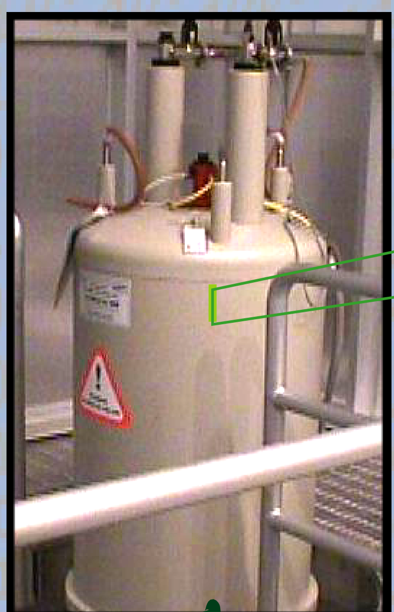


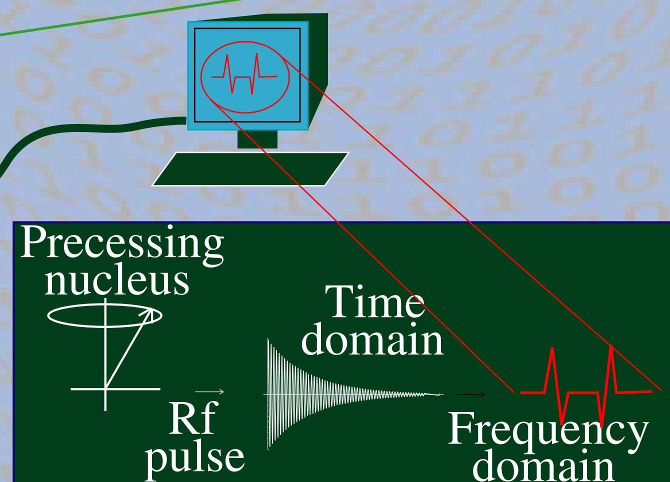
Trichloroethylene



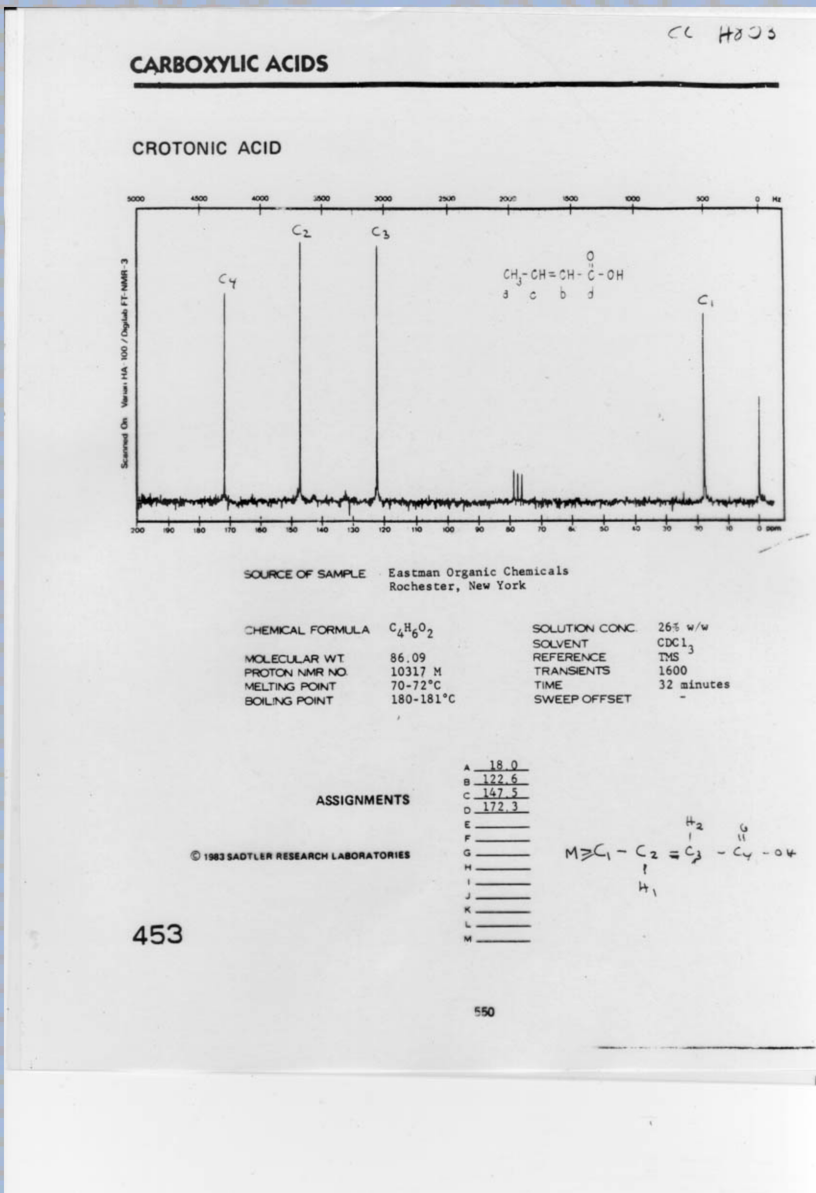





Bruker DRX-500



Choosing a molecule


CC H8O3

CARBOXYLIC ACIDS

CROTONIC ACID

SOURCE OF SAMPLE	Eastman Organic Chemicals Rochester, New York		
CHEMICAL FORMULA	$C_4H_6O_2$	SOLUTION CONC.	26% w/w
MOLECULAR WT	86.09	SOLVENT	$CDCl_3$
PROTON NMR NO.	10317 M	REFERENCE	TMS
MELTING POINT	70-72°C	TRANSIENTS	1600
BOILING POINT	180-181°C	TIME	32 minutes
		SWEEP OFFSET	-

ASSIGNMENTS

A 18.0
B 122.6
C 147.5
D 172.3
E
F
G
H
I
J
K
L
M

453

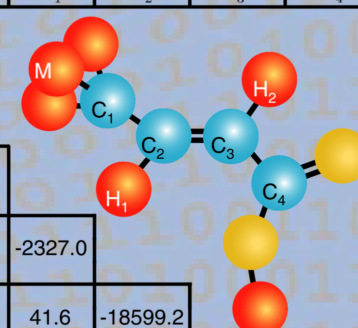
550

- different chemical shifts
- large decoherence times
- strong couplings

Rudy Martinez, B-2

Stable Isotope Laboratory at Los Alamos

	M	H_1	H_2	C_1	C_2	C_3	C_4
M	-969.4						
H_1	6.9	-3560.3					
H_2	-1.7	15.5	-2938.2				
C_1	127.5	3.8	6.2	-2327.0			
C_2	-7.1	156.0	-0.7	41.6	-18599.2		
C_3	6.6	-1.8	162.9	1.6	69.7	-15412.8	
C_4	-0.9	6.5	3.3	7.1	1.4	72.4	-21685.1



Quantum Gates in NMR

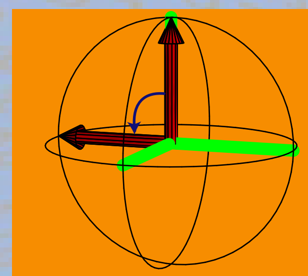
1 bit gates

Rotation around x/y axis: e.g. around x

Rotation around z axis:

hard pusle: 10 s;

soft pulse 1/



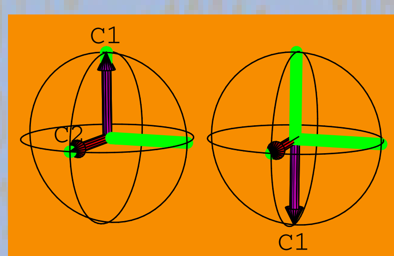
$$e^{\quad i\mu X} = \mathbb{1}\cos\mu \quad iX\sin\mu :$$

$$Z \qquad Z\cos\mu \quad Y\sin\mu$$

$$Y \qquad Y\cos\mu + Z\sin\mu$$

2 bit gates

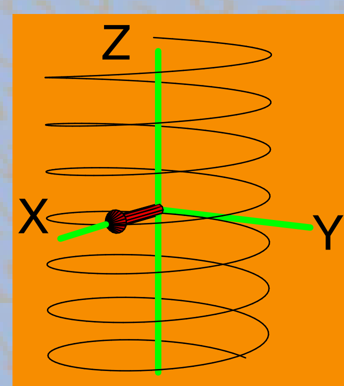
J coupling ~ 100 Hz



$$e^{\quad i \quad ZZ} = \mathbb{1}\cos \qquad iZZ\sin \quad :$$

$$X\mathbb{1} \qquad X\mathbb{1}\cos\mu + YZ\sin\mu$$

Gradient field



$$I_+ = X + iY \qquad e^{i\pi \quad z} I_+$$

State Preparation

$$\Omega = \frac{1}{2^n} e \quad H$$

- Computational cooling

  (DiVincenzo/ Knill/ Schulman & Vazirani: quant-ph9804060)

- Pseudo pure states

  Havel & Cory 1996
  Gershenfeld & Chuang 1996

$$\frac{1}{2^n}(I \quad H + \quad)$$

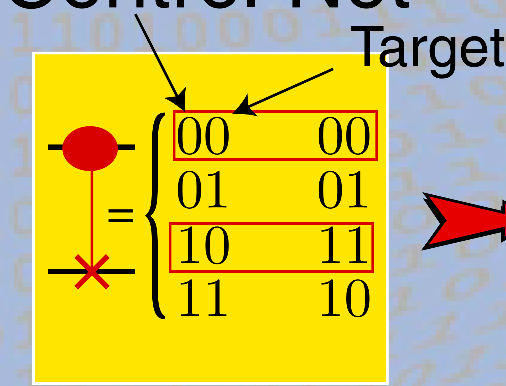
$$\Omega \quad \frac{1}{2^n} I +$$

- 1 Pseudo pure qubit

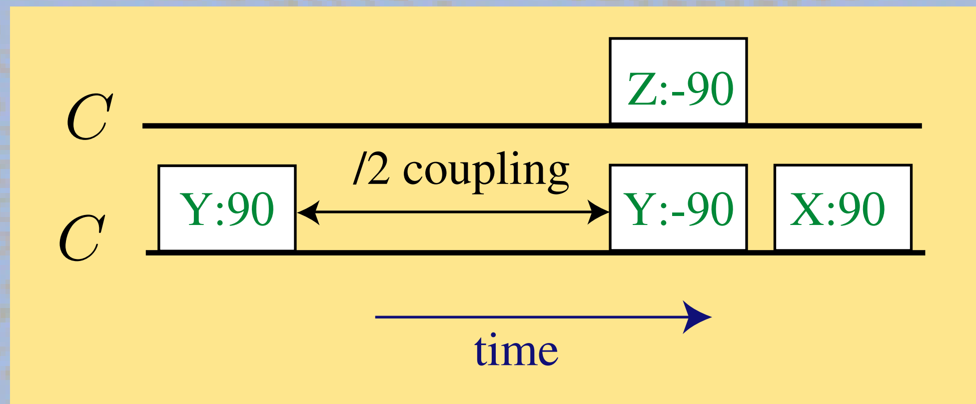
  Knill & Laflamme, PRL 81, 5672, 1998

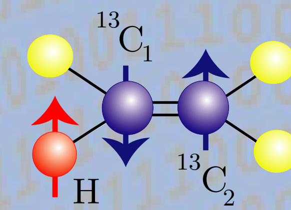
From quantum algorithms to machine language

Control-Not



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

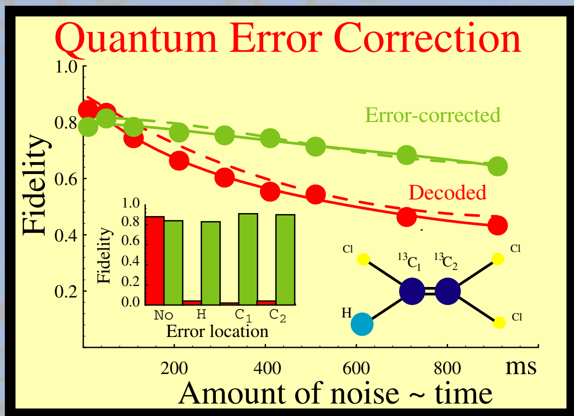
```
1 ze
2 lhold LOCKH_OFF

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

  lhold LOCKH_ON

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

  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
```

Experiments

NMR-GHZ, R.L., E. Knill, W.H. Zurek,
P. Catasti, S. Vellupillai,
Proc.Roy.SocA356, 1941, 1998.

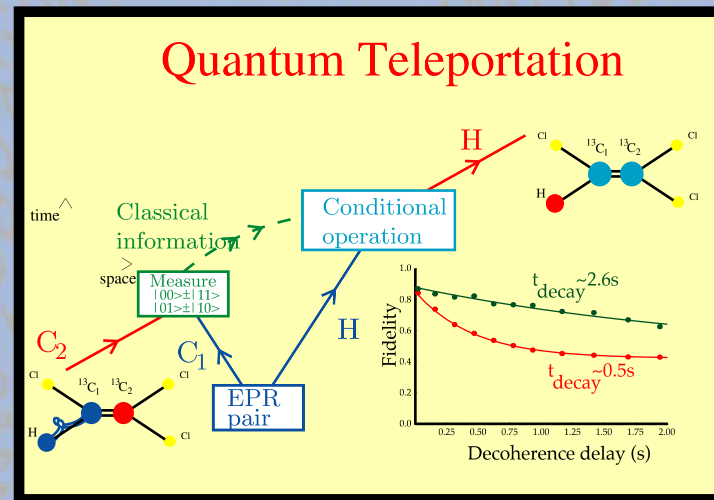
with MIT



SCIENCE

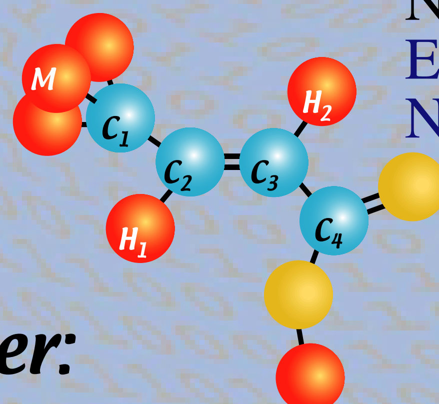
Top 10 breakthroughs of the year; Science 282, 2156, 1998

Experimental Quantum Error Correction: D. G. Cory,
M. D. Price, W. Maas, E. Knill,
R. Laflamme, W. H. Zurek,
T. F. Havel and S. S. Somaroo.
PRL 81, 2152, 1998



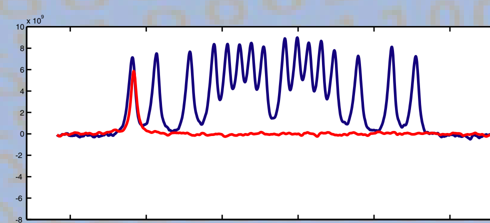
Complete quantum teleportation using NMR: M. Nielsen,
E. Knill, R. Laflamme
Nature 396, 52, 1998

nature



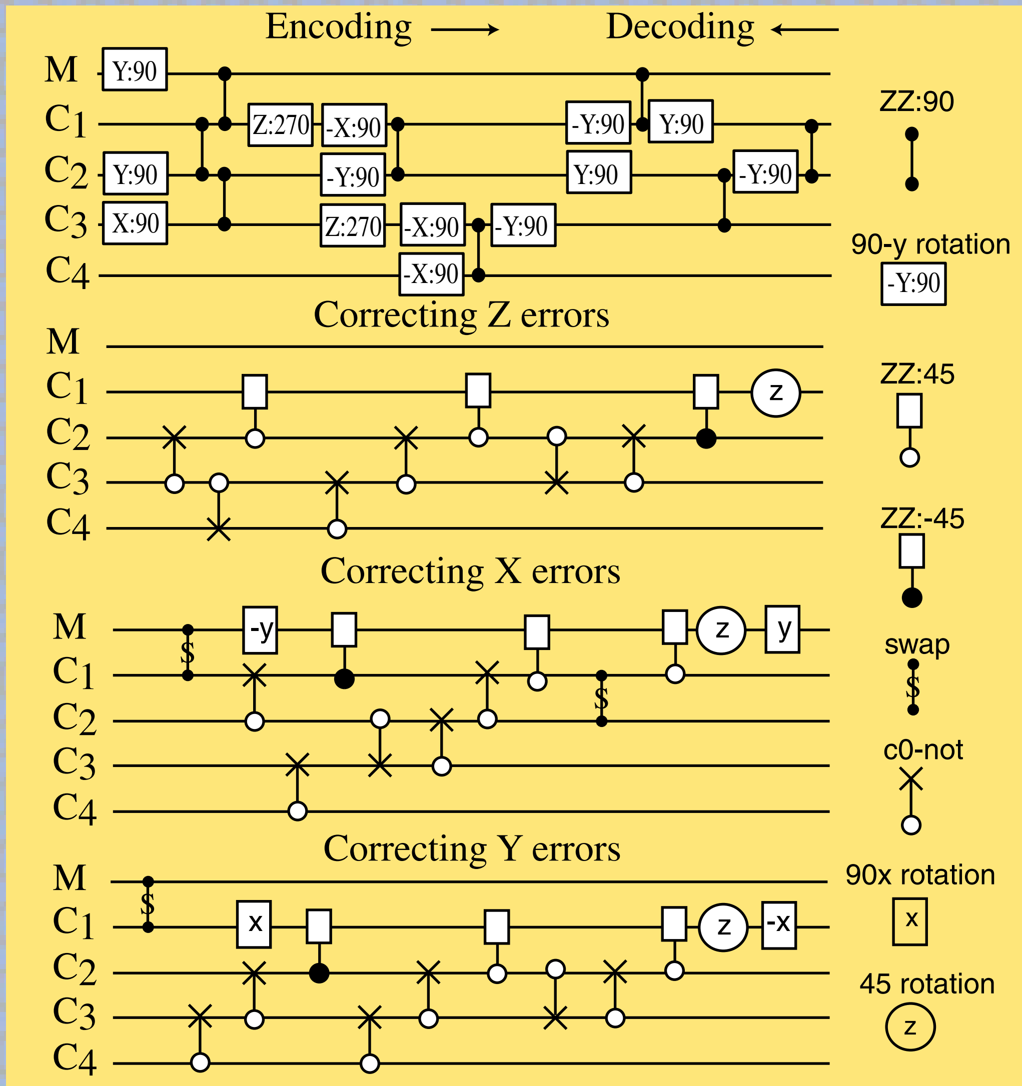
nature

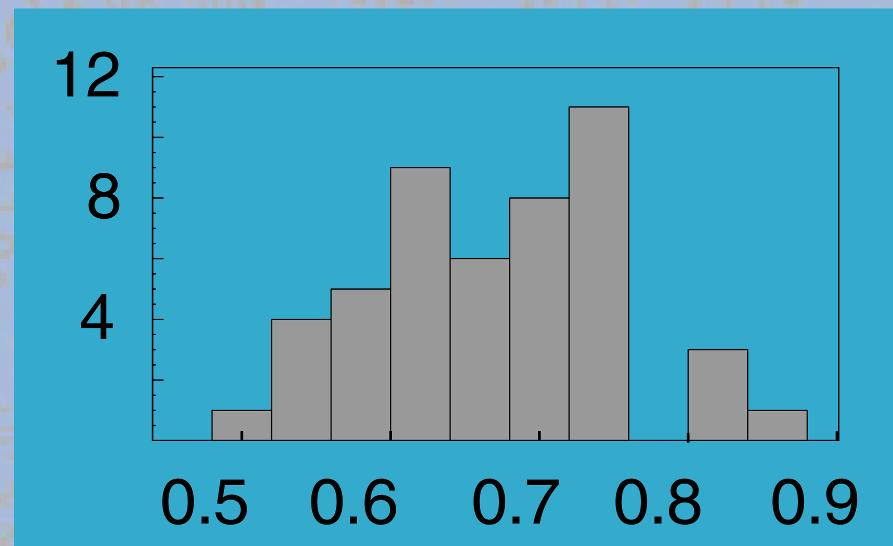
A 7 bit quantum computer:

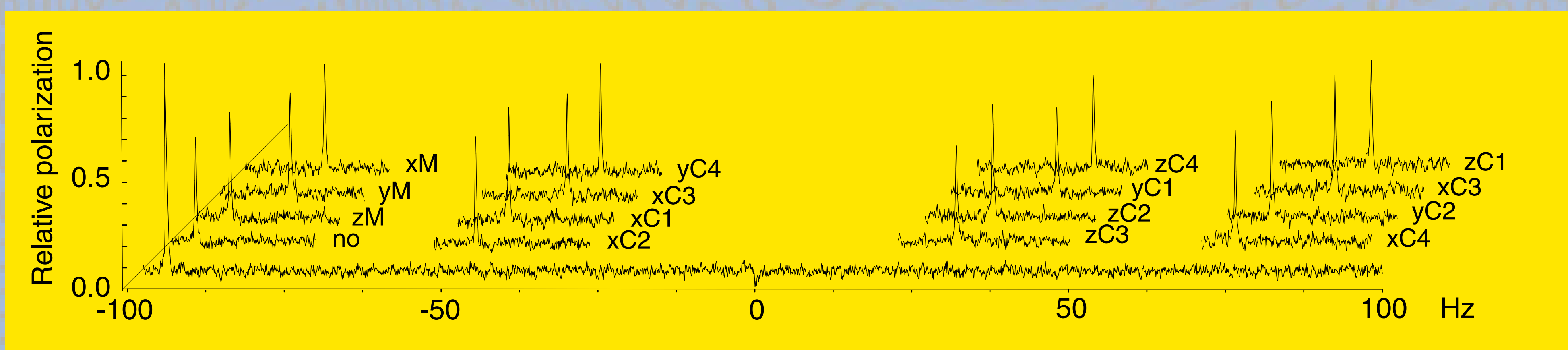


An algorithmic benchmark for quantum information processing,
E. Knill, R. L., R. Martinez, C.-H. Tseng, Nature 404, 368-370, 2000

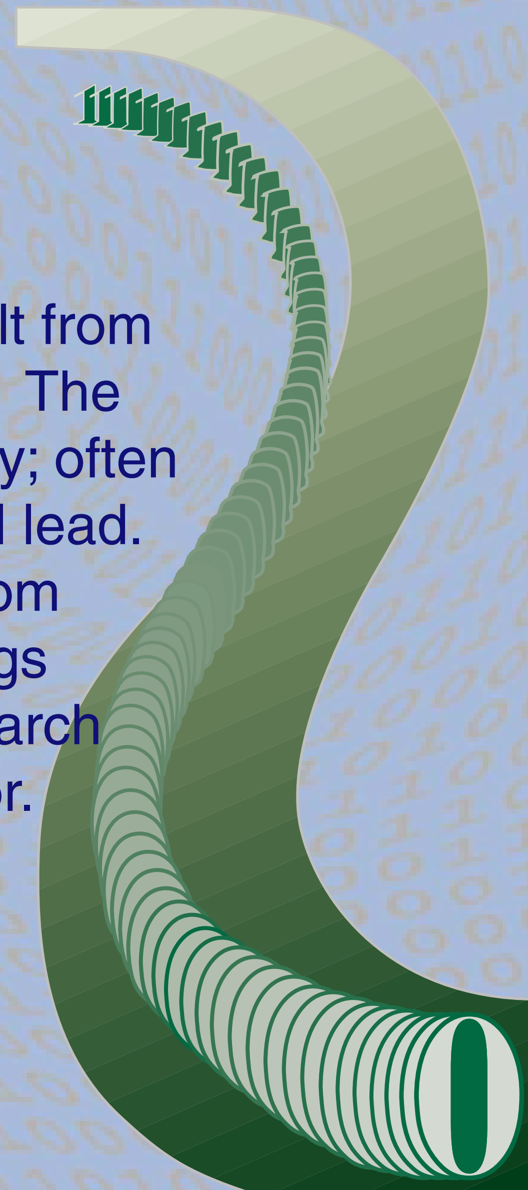
The perfect 5 bit quantum error correcting code







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.