Title: Experimental Quantum Error Correction

Date: Aug 13, 2015 03:00 PM

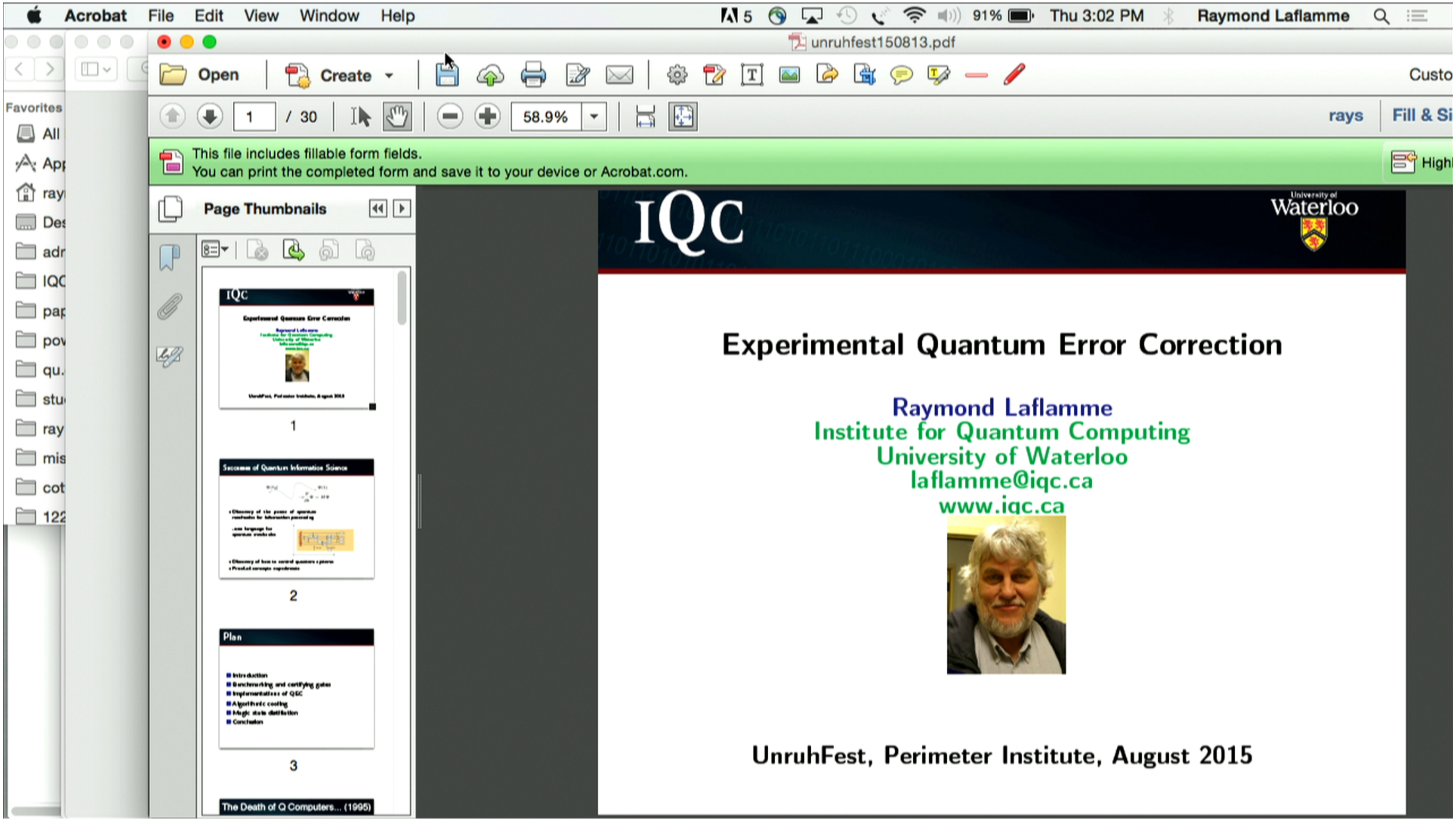
URL: http://pirsa.org/15080029

Abstract: The last decade has seen the impressive development of quantum information science, both in theory and in experiment. There are many measures that can be used to assess the achievements in the field: new algorithms, new applications and larger quantum processors, to name a few. The discovery of quantum algorithms has demonstrated the potential power of quantum information.

As pointed out by Bill some years ago, to realize this potential requires the ability to overcome the imprecision and imperfection inherent in physical systems.

Quantum error correction (QEC) has provided a solution, showing that errors can be corrected with a reasonable amount of resources as long as their rate is sufficiently small. Implementing QEC protocols remains one of the most important challenges in QIP.

In the experimental arena, the quest to build quantum processors that could outperform their classical counterparts has led to many blueprint proposals for potential devices based on NMR, electron spin resonance, ion traps, atom traps, optics, superconducting devices and nitrogen-vacancy centres, among others. Many have demonstrated not only the possibility of controlling quantum bits, but also the ability to do so in practice, showing the progression of quantum information science from the blackboard to the laboratory. My presentation will give an overview of some of the recent results in quantum information science on the way to implement quantum error correction. I will show how noise can be characterise efficiently when our goal is to find suitable quantum error correcting codes. I will show demonstrations of control to implement some quantum error correcting codes and finally how can noise be extracted through algorithmic cooling. I will comments on some challenges that need to be solved and a path towards implementing many round of quantum error correction.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Experimental Quantum Error Correction
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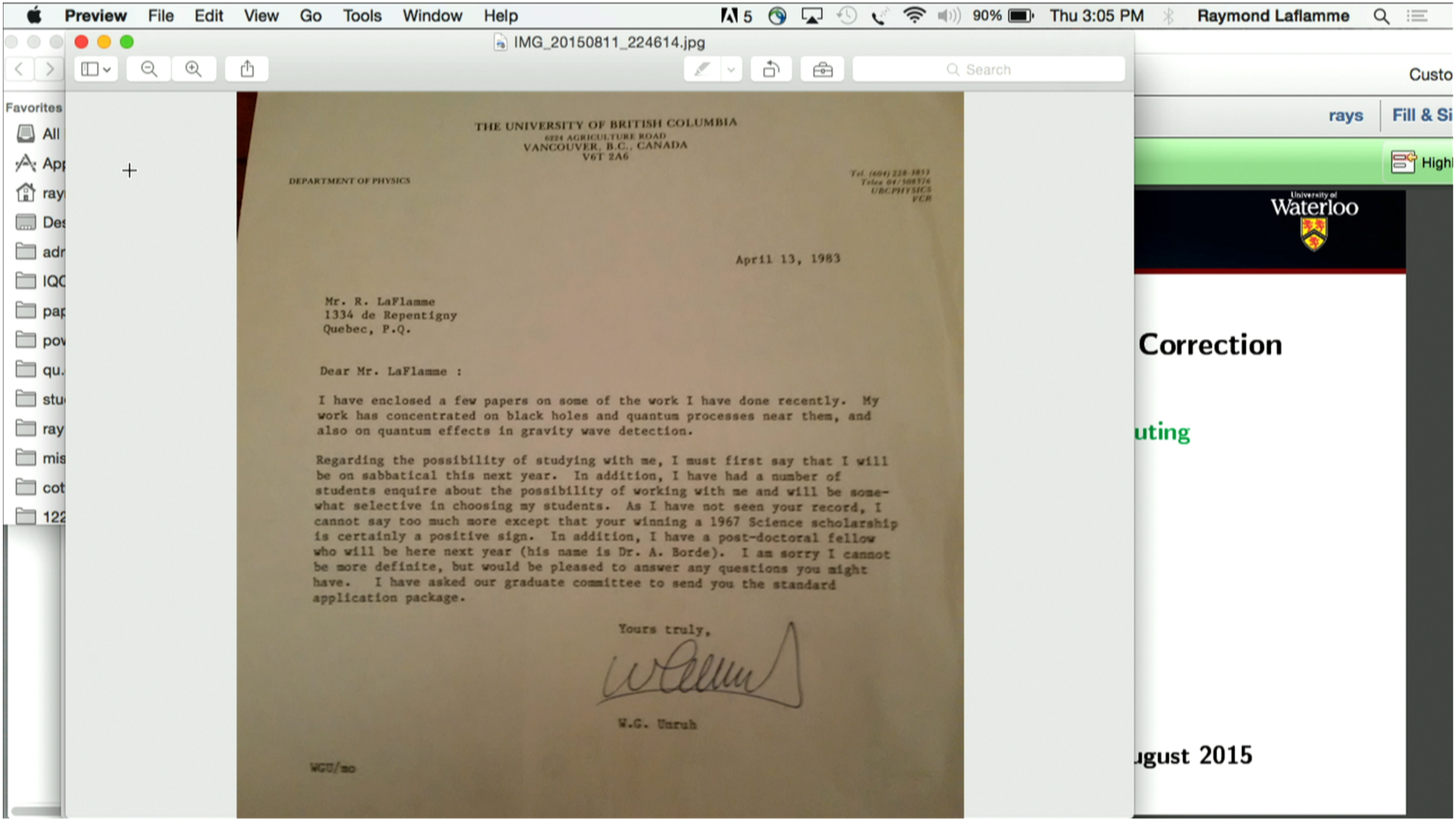
UnruhFest, Perimeter Institute, August 2015
Plan
The Death of Q Computers... (1995)



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April 13, 1983

Mr. R. LaFlamme
1334 de Repentigny
Quebec, P.Q.

Dear Mr. LaFlamme :

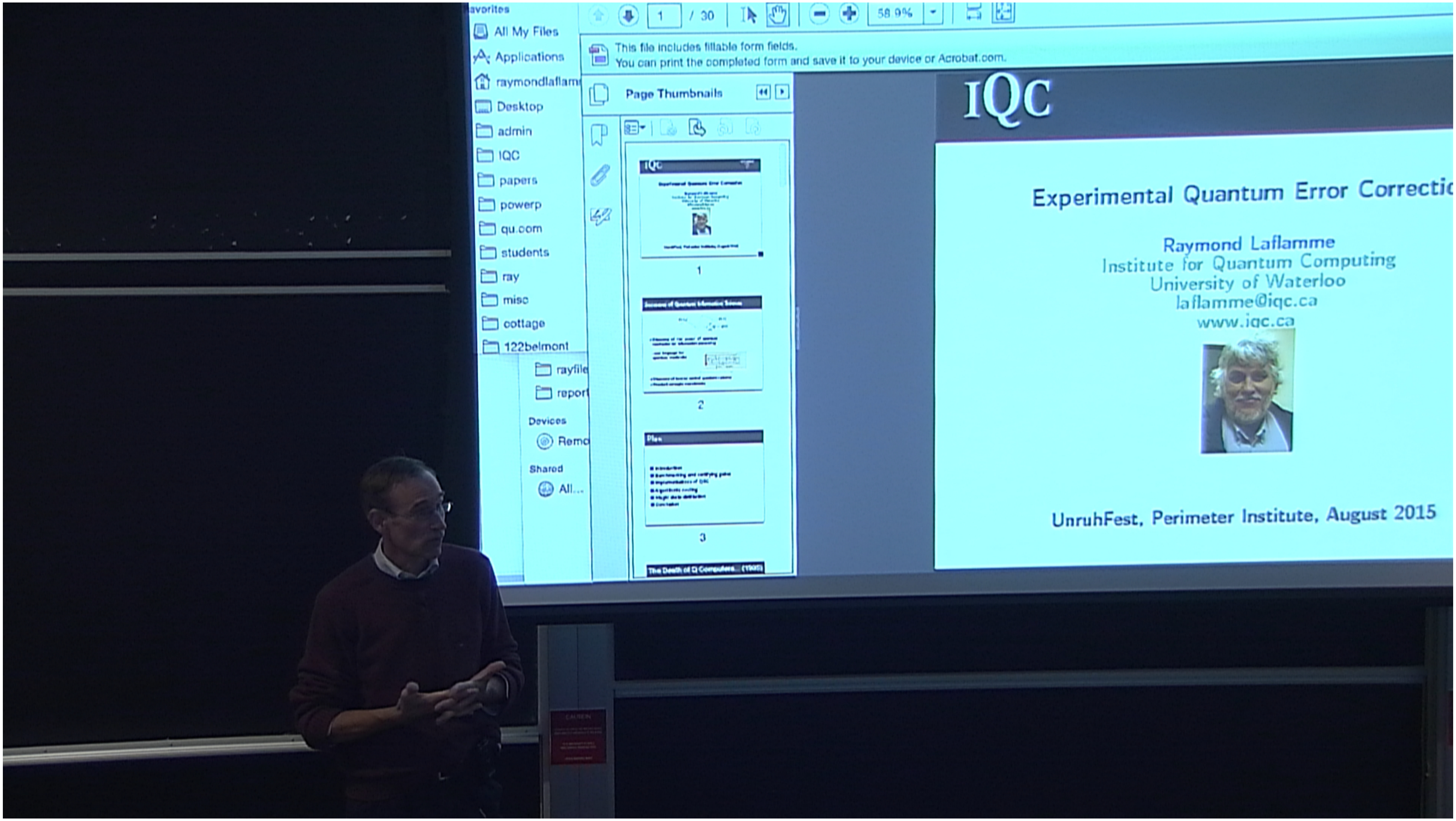
I have enclosed a few papers on some of the work I have done recently. My work has concentrated on black holes and quantum processes near them, and also on quantum effects in gravity wave detection.

Regarding the possibility of studying with me, I must first say that I will be on sabbatical this next year. In addition, I have had a number of students enquire about the possibility of working with me and will be somewhat selective in choosing my students. As I have not seen your record, I cannot say too much more except that your winning a 1967 Science scholarship is certainly a positive sign. In addition, I have a post-doctoral fellow who will be here next year (his name is Dr. A. Borde). I am sorry I cannot be more definite, but would be pleased to answer any questions you might have. I have asked our graduate committee to send you the standard application package.

Yours truly,

W.G. Unruh

WGU/mo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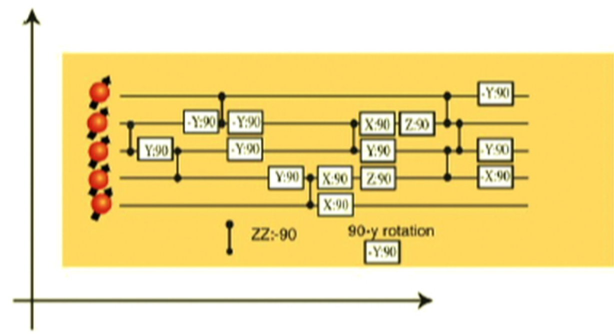
Successes of Quantum Information Science

$$-i\frac{\partial}{\partial t}\Psi = H\Psi$$

- Discovery of the power of quantum mechanics for information processing

-new language for quantum mechanics



- Discovery of how to control quantum systems
- Proof-of-concepts experiments

The Death of Q Computers... (1995)

a large number of states is important), not only must the coupling be small, but the time taken in the quantum calculation must be less than the thermal time scale $\hbar/k_BT$. For longer times the condition on the strength of the coupling to the external world becomes much more stringent.

Abstract—Adventurous technological proposals are subject to inadequate critical assessment. It is the proponents who organize meetings and special issues. Optical logic, mesoscopic switching devices and quantum parallelism are used to illustrate this problem.

Index Terms—Technology assessment, optical logic, mesoscopic devices, quantum parallelism.

PHYSICAL REVIEW A VOLUME 51, NUMBER 2 FEBRUARY 1995

Maintaining coherence in quantum computers

W. G. Unruh*
Canadian Institute for Advanced Research, Cosmology Program, Department of Physics, University of British Columbia, Vancouver, Canada V6T 1Z1
(Received 10 June 1994)

The effects of the inevitable coupling to external degrees of freedom of a quantum computer are examined. It is found that for quantum calculations (in which the maintenance of coherence over a large number of states is important), not only must the coupling be small, but the time taken in the quantum calculation must be less than the thermal time scale $\hbar/k_BT$. For longer times the condition on the strength of the coupling to the external world becomes much more stringent.

If the probability of doing a gate has success $(1-p)$,
the probability of doing successfully n
decrease exponentially as $(1-p)^n$

Threshold theorem

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

$$P < 10^{-6,-5,-4,-3,-2,\dots}$$

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

Kitaev, Russ. Math Survey 1997

Aharonov & Ben Or, ACM press

Preskill, PRSL, 454, 257, 1998

...

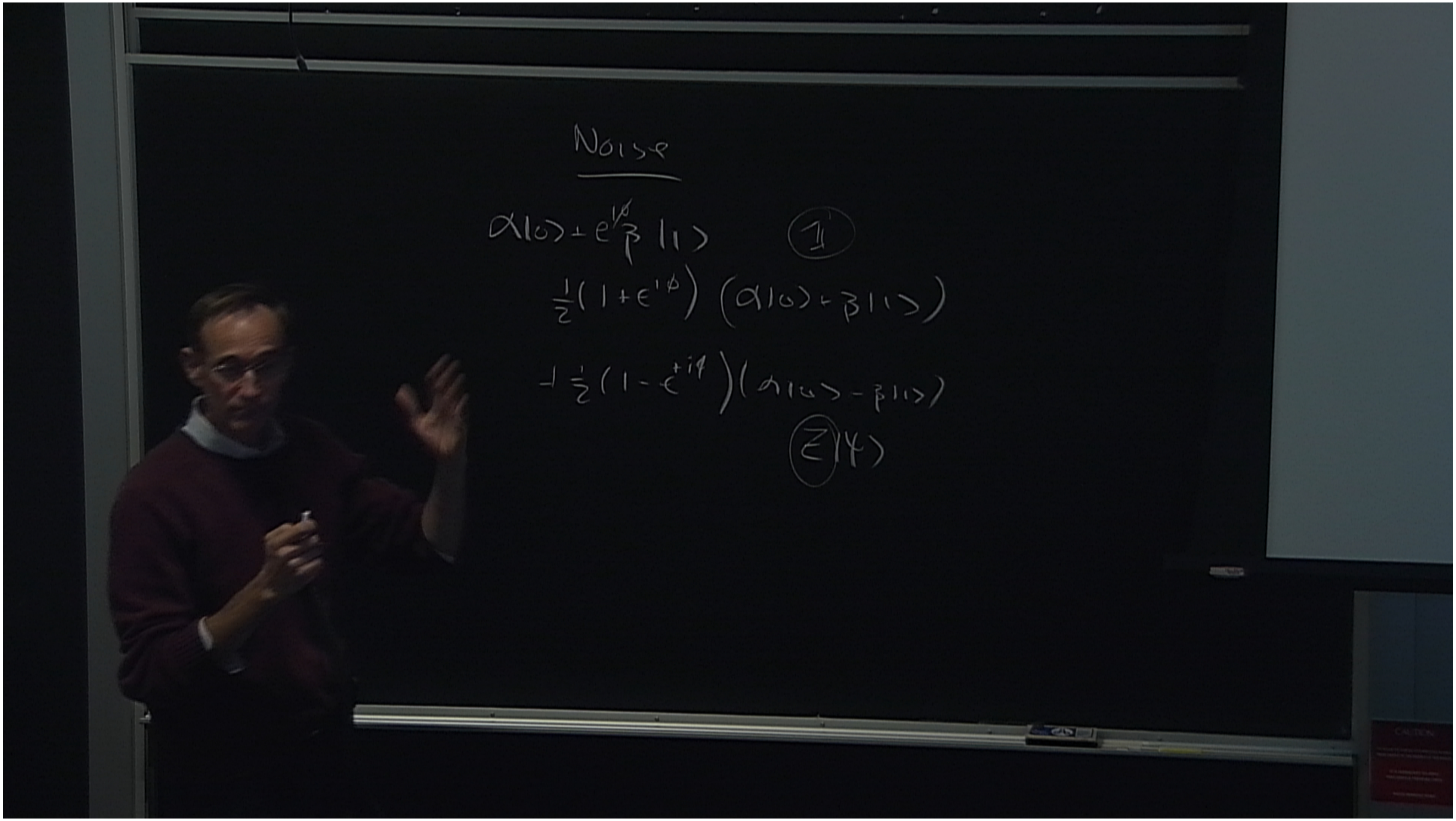
Significance:

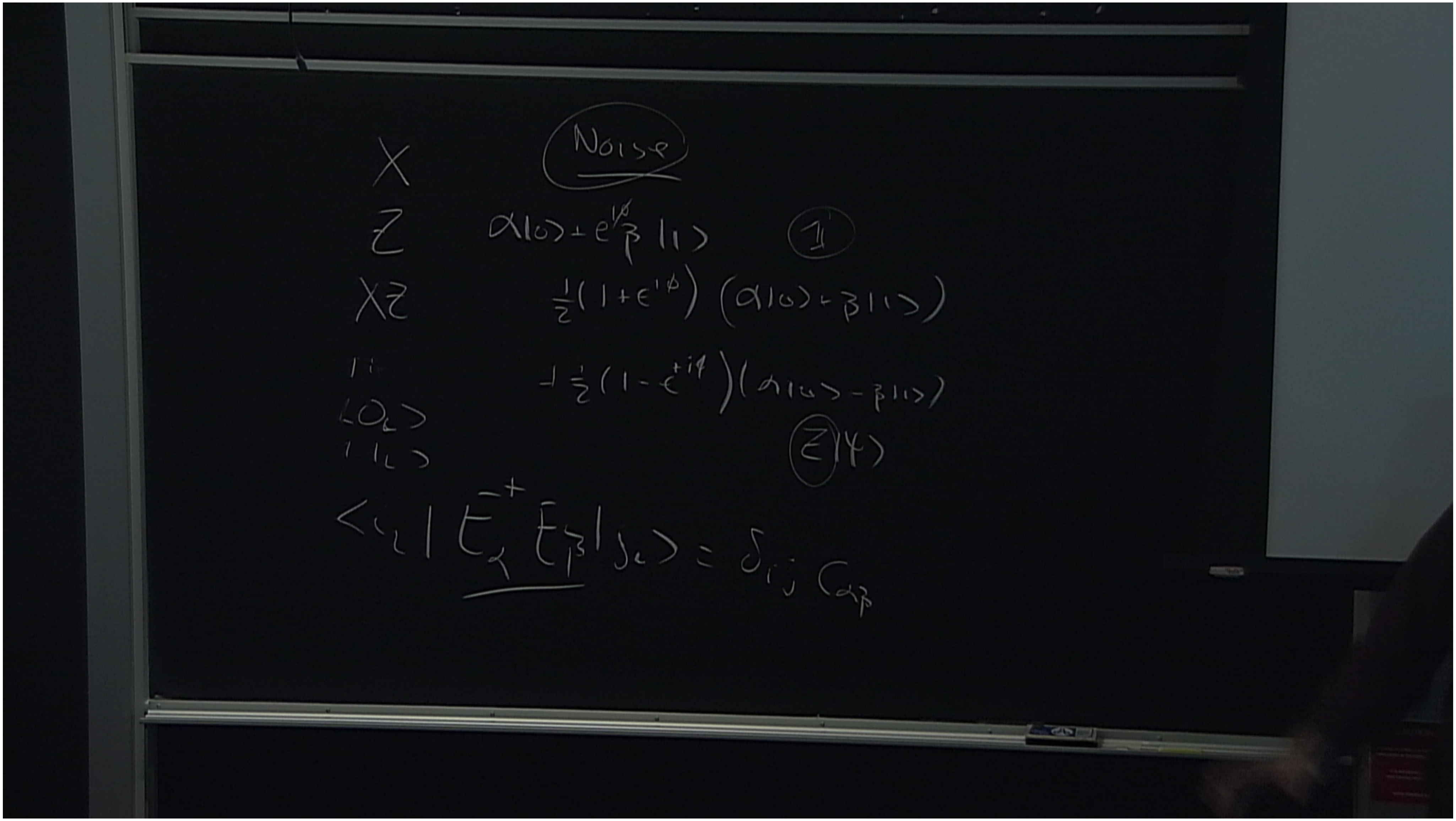
-imperfections and imprecisions are not fundamental objections to quantum computation

-it gives criteria for scalability

-its requirements are a guide for experimentalists

-it is a benchmark to compare different technologies


Noise
$\alpha|0\rangle + e^{i\phi}\beta|1\rangle$
I
$\frac{1}{2}(1+e^{i\phi})(\alpha|0\rangle+\beta|1\rangle)$
$+\frac{1}{2}(1-e^{+i\phi})(\alpha|0\rangle-\beta|1\rangle)$
$Z|\psi\rangle$


Noise
X
Z
$\alpha|0\rangle + e^{i\phi}\beta|1\rangle$
1
XZ
$\frac{1}{2}(1+e^{i\phi})(\alpha|0\rangle+\beta|1\rangle)$
$+\frac{1}{2}(1-e^{i\phi})(\alpha|0\rangle-\beta|1\rangle)$
$\langle O_L\rangle$
$|1_L\rangle$
$Z|\psi\rangle$
$\langle i_L|E_\alpha^\dagger E_\beta|j_L\rangle = \delta_{ij}C_{\alpha\beta}$

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Ingredients for FTQEC

- **Parallel operations**
- **Good quantum control**
- **Ability to extract entropy**
- **Knowledge of the noise**
  - No lost of qubits
  - Independent or quasi independent errors
  - Depolarising model
  - Memory and gate errors
  - ...

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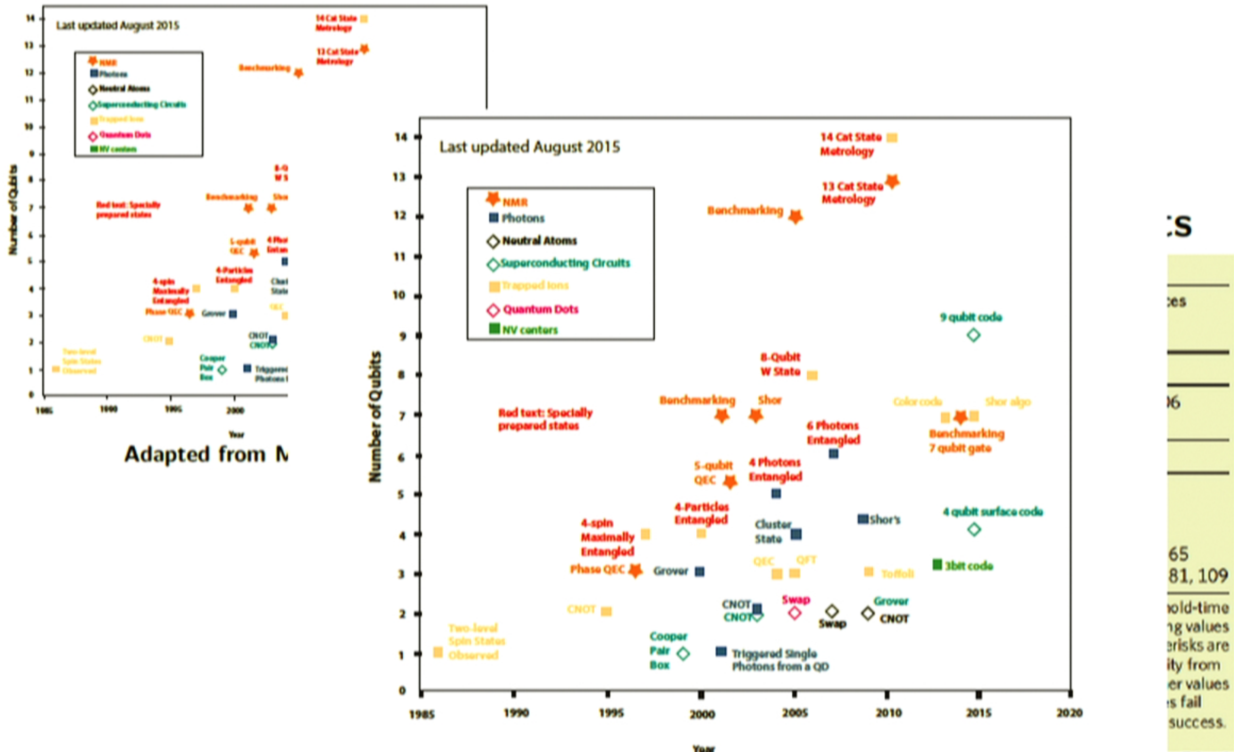
and lots of qubits...

Progress in experimental QIP

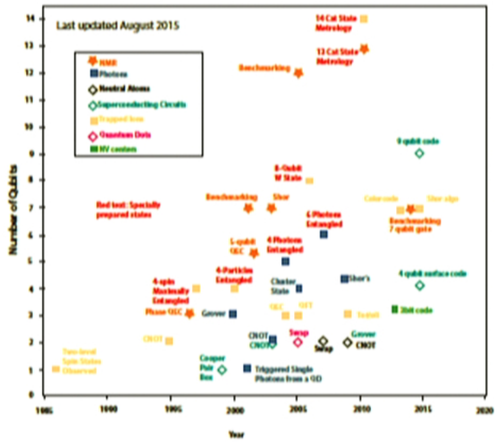
- # of qubits vs time



Ladd, T. D., et al., Nature, 464(7285), 45–53, 2010

Progress in experimental QIP

- **# of qubits vs time**



Adapted from Michael Mandelberg

- **Increasing control of qubits**

Table 1 | Current performance of various qubits

Type of qubit	T_2	Benchmarking (%)		References
		One qubit	Two qubits	
Infrared photon	0.1 ms	0.016	1	20
Trapped ion	15 s	0.48†	0.7*	104–106
Trapped neutral atom	3 s	5		107
Liquid molecule nuclear spins	2 s	0.01†	0.47†	108
e^- spin in GaAs quantum dot	3 μs	5		43, 57
e^- spins bound to ^{31}P:^{28}Si	0.6 s	5		49
^{29}Si nuclear spins in ^{28}Si	25 s	5		50
NV centre in diamond	2 ms	2	5	60, 61, 65
Superconducting circuit	4 μs	0.7†	10*	73, 79, 81, 109

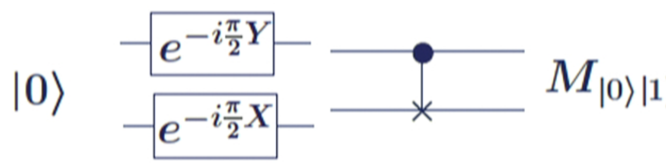
Measured T_2 times are shown, except for photons where T_2 is replaced by twice the hold-time (comparable to T_1) of a telecommunication-wavelength photon in fibre. Benchmarking values show approximate error rates for single or multi-qubit gates. Values marked with asterisks are found by quantum process or state tomography, and give the departure of the fidelity from 100%. Values marked with daggers are found with randomized benchmarking[110]. Other values are rough experimental gate error estimates. In the case of photons, two-qubit gates fail frequently but success is heralded; error rates shown are conditional on a heralded success. NV, nitrogen vacancy.

Ladd, T. D., et al., Nature, 464(7285), 45–53, 2010

Characterising noise

Usually we think of the circcuit model: Prepare a state, compute, measure

Other possibility is to use only generators of the Clifford group (generated by Hadamard, Phase gate and CNOT), with state preparation and measuremen in the computational basis:



and include the preparation of the magic state

$$\rho = \frac{1}{2}\mathbb{1} + \frac{1}{\sqrt{3}}(X + Y + Z)$$

Characterising noise for QIPs

How do we learn about the noise model?

- Assume first only for memory
- Focus on applying QEC
- Want to be efficient

1) Full process tomography

Kraus operators

tensor product of Pauli Matrices

$$\rho_f = \sum_j A_j \rho_i A_j^\dagger = \sum_{kl} \chi_{kl} P_k \rho_i P_l = \Big(\overset{\sim 4^{2n}}{\cdots}\Big)\rho_i$$

2) Can we get instead coarse grained values of the quantum process such as probability of 0 error (P_0), 1 error (P_1), 2 errors(P_2),... independent of which qubit is affected and the particular error (i.e. X/Y/Z).

- do process tomography and coarse grain $\longrightarrow$ not efficient
- find an efficient protocol, coarse graining $\Longrightarrow$ symmetrise

Characterising noise for QIPs

Coarse graining $\Longrightarrow$ imposing a symmetry

- **error independent of a particular qubit use permutations:** π_s
- **average over $X/Y/Z$ $\rightarrow$ "twirl" average over $SU(2)^{\otimes n}$**

$$\rho_f = \sum_{kl} \chi_{kl} \int d\mu(U) U^\dagger P_k U \rho_i U^\dagger P_l^\dagger U$$

$$\Downarrow \qquad \text{"2-design"}$$

$$\rho_f = \sum_{kl} \chi_{kl} \sum_{\alpha} C_\alpha^\dagger P_k C_\alpha \rho_i C_\alpha^\dagger P_l^\dagger C_\alpha$$

where C_α belongs to the Clifford group $\sim \mathcal{SP}$ with
$\mathcal{P} = \{\mathbb{1}, X, Y, Z\}$, $\mathcal{S} = \{e^{-i\frac{\pi}{4}X}, e^{-i\frac{\pi}{4}Y}, e^{-i\frac{\pi}{4}Z}\}$

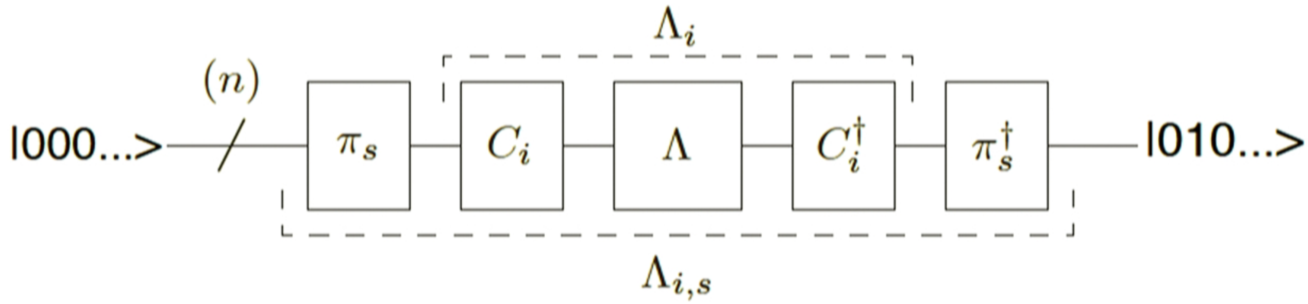
$$\Downarrow \qquad \text{"Chernoff-bound"}$$

$$\rho_f \approx \sum_{kl} \chi_{kl} \sum_{\alpha} C_\alpha^\dagger P_k C_\alpha \rho_i C_\alpha^\dagger P_l^\dagger C_\alpha$$

DiVincenzo et al., 2002, IEEE Trans. Inform. Theory 48, 580
Dankert, C., et al., PRA 80, 012304, 2009.

Characterising noise protocol

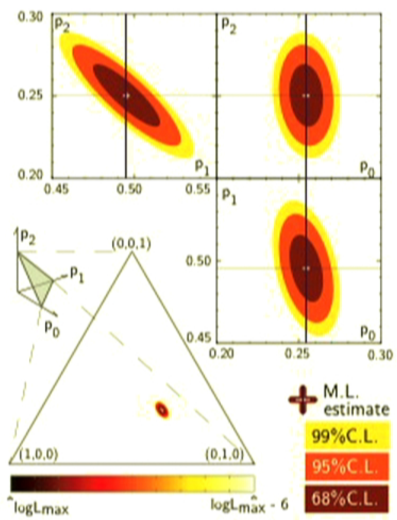
- **start with the state $|000\dots\rangle$,**
- **implement the symmetrisation group and the Clifford group**
- **measure how many bits have been flipped.**
- **Repeat $\longrightarrow P_0, P_1, \dots$**

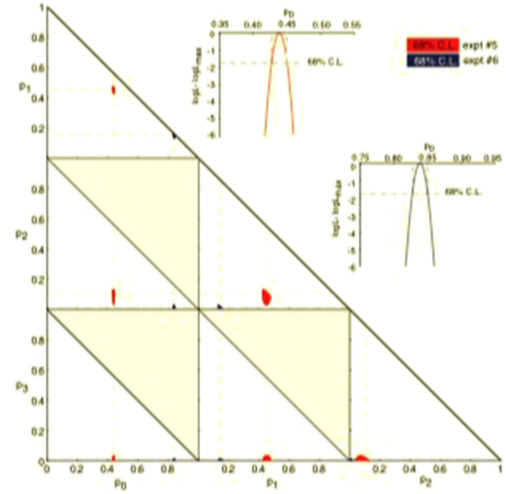


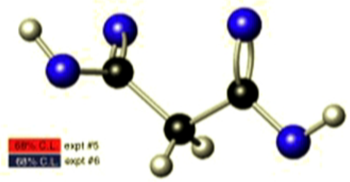
see Emerson et al. Science 317, 1893, 2007

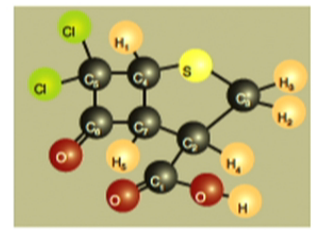
Experimental result

Noise Characterization - NMR results







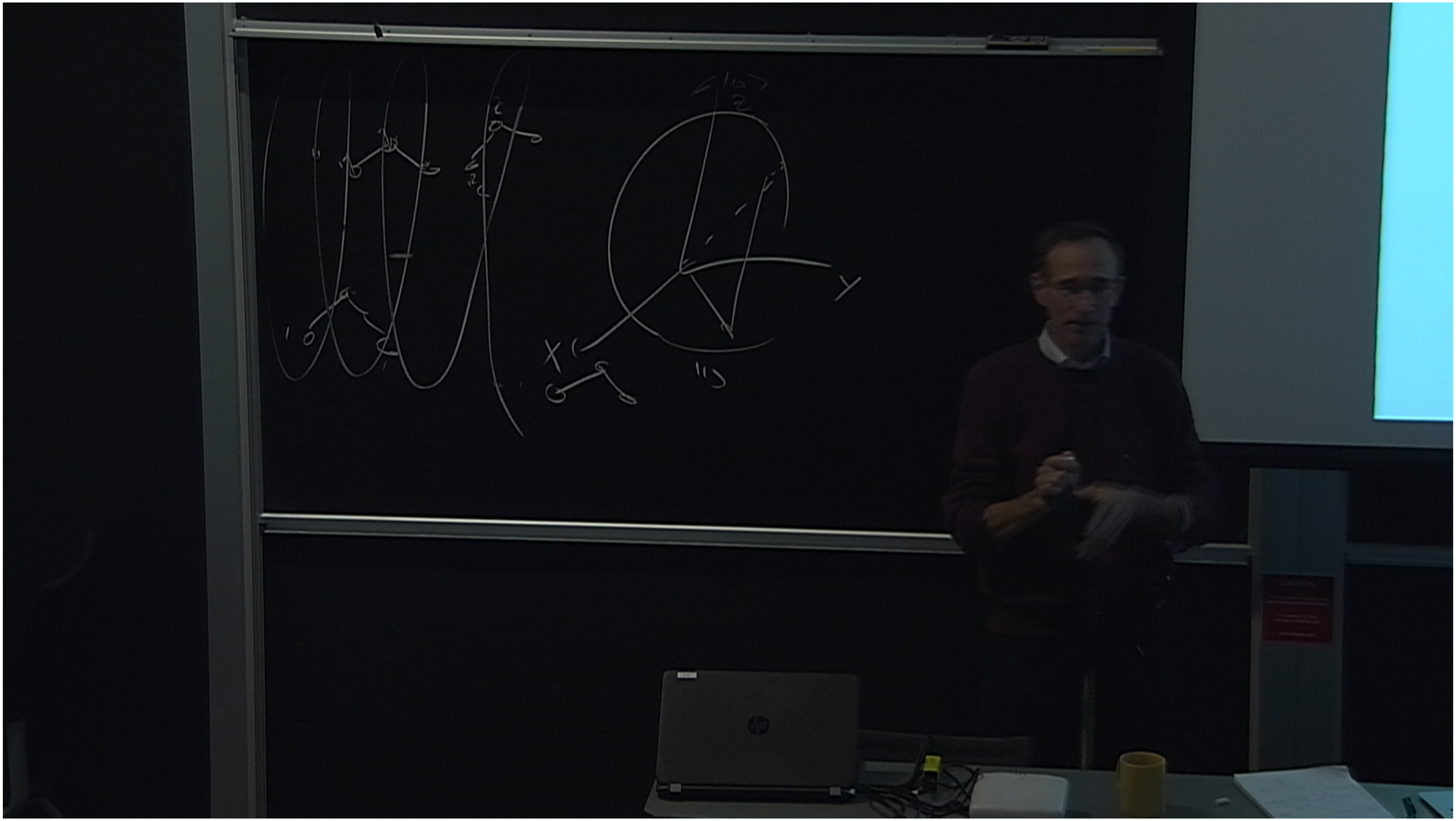


1

#	Map Description	Krauss operators (A_k)	k_m	p_0	p_1	p_2	p_3
1	Engineered: $\mathbf{p} = [0,1,0]$.	$\frac{1}{\sqrt{2}}\{Z_1, Z_2\}$	288	$0.000\ ^{+0.004}$	$0.991\ ^{+0.009}_{-0.015}$	$0.009\ ^{+0.017}_{-0.009}$	-
2	Engineered: $\mathbf{p} = [0,0,1]$.	$\{Z_1 Z_2\}$	288	$0.001\ ^{+0.006}_{-0.001}$	$0.004\ ^{+0.011}_{-0.004}$	$0.996\ ^{+0.004}_{-0.011}$	-
3	Engineered: $\mathbf{p} = [1/4, 1/2, 1/4]$.	$\{exp[i\frac{\pi}{4}(Z_1 + Z_2)]\}$	288	$0.254\ ^{+0.010}_{-0.010}$	$0.495\ ^{+0.021}_{-0.020}$	$0.250\ ^{+0.019}_{-0.019}$	-
4	Engineered: $\mathbf{p} = [0,1,0,0]$.	$\frac{1}{\sqrt{3}}\{Z_1, Z_2, Z_3\}$	432	$0.01\ ^{+0.01}_{-0.01}$	$0.99\ ^{+0.01}_{-0.03}$	$0.01\ ^{+0.02}_{-0.01}$	$0.00\ ^{+0.01}$
5	Natural noise (a)	unknown	432	$0.44\ ^{+0.01}_{-0.02}$	$0.45\ ^{+0.03}_{-0.03}$	$0.10\ ^{+0.04}_{-0.08}$	$0.01\ ^{+0.03}_{-0.01}$
6	Natural noise (b)	unknown	432	$0.84\ ^{+0.01}_{-0.01}$	$0.15\ ^{+0.02}_{-0.03}$	$0.01\ ^{+0.03}_{-0.01}$	$0.00\ ^{+0.02}$

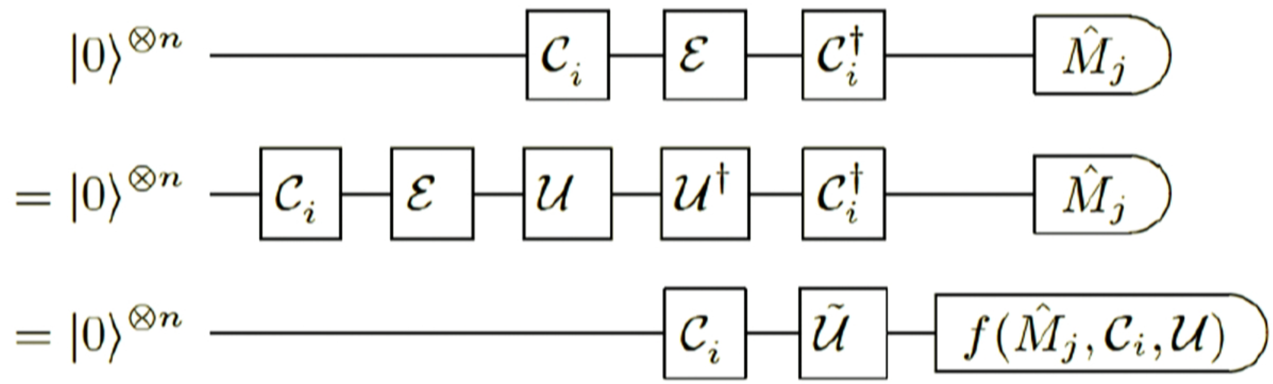
TABLE I: Summary of experimental results.

Emerson, RL et al., Science 317, 1893, 2007



Errors in Clifford gates

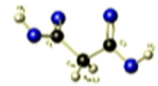
Adapt the idea to benchmark Clifford gates



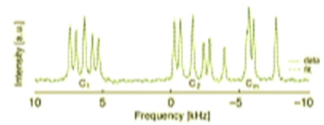
$f(\hat{M}_j, \mathcal{C}_i, \mathcal{U})$ is a measurement in a different classical basis we can then find $P_0, P_1, \ldots$ in the gate $\mathcal{U}$.

Errors in Clifford gates

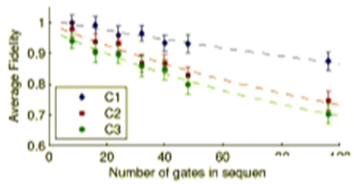
Use malonic acid in solid state



kHz	C_1	C_2	C_m
C_1	6.380	0.297	0.780
C_2	-0.025	-1.533	1.050
C_m	0.071	0.042	-5.650

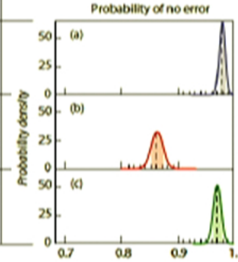


One qubit can be benchmarked using the Knill procedure:

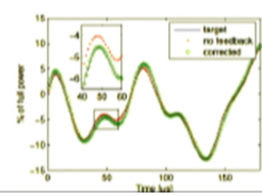


and Clifford gates using the new procedure

	Target	Experiment	w	k_w	λ_w	F
a		prep	1	6	0.967 ± 0.010	$0.983^{+0.007}_{-0.006}$
			2	21	1.000 ± 0.009	
			3	7	0.978 ± 0.017	
b		prep, unrectified pulse	1	8	0.848 ± 0.022	$0.863^{+0.013}_{-0.012}$
			2	21	0.883 ± 0.017	
			3	8	0.799 ± 0.023	
c		prep, rectified pulse	1	6	0.959 ± 0.014	$0.973^{+0.009}_{-0.008}$
			2	21	0.989 ± 0.013	
			3	8	0.964 ± 0.016	

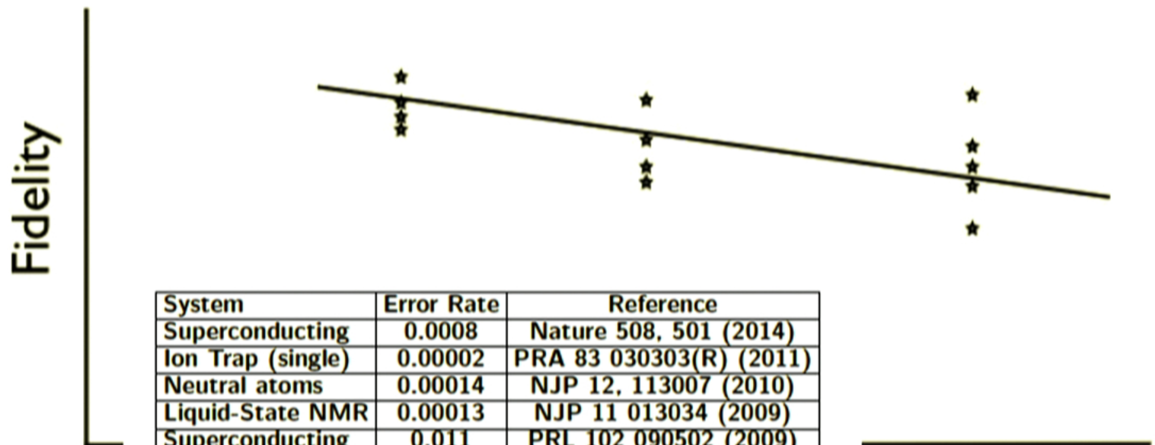


Note: the difference between b) and c) is improving the pulse ("fixing")



Moussa, Silva, Laflamme PRL 109, 100503 (2012)

Benchmarking gates



System	Error Rate	Reference
Superconducting	0.0008	Nature 508, 501 (2014)
Ion Trap (single)	0.00002	PRA 83 030303(R) (2011)
Neutral atoms	0.00014	NJP 12, 113007 (2010)
Liquid-State NMR	0.00013	NJP 11 013034 (2009)
Superconducting	0.011	PRL 102 090502 (2009)
Ion Trap (crystal)	0.0008	QIC 9 920 (2009)
Ion Trap (single)	0.00482	PRA 77 012307 (2008)
ESR	0.007	Laflamme/Morton

Benchmarking gate

Two qubit comparison
Summary table

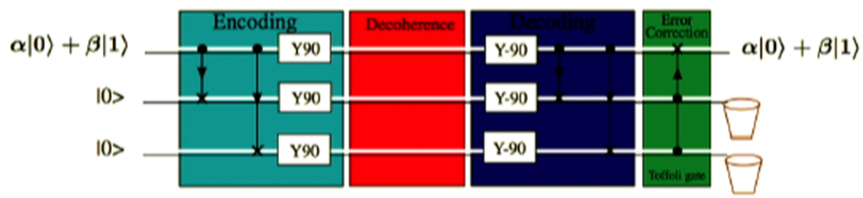
System	Error Rate	Reference
Superconducting	0.006	Nature 508, 501 (2014)
Ion Trap	0.069/0.162	PRL 108, 260503 (2012)
Liquid-State NMR	0.005	NJP 11 013034 (2009)
Neutral Atoms	0.27	PRL 104, 010503 (2010)
Ion trap	0.007	Nat. Phys. 4 463 (2008)
NV centre	0.11	Science 320 1326 (2008)
ESR	0.05	Nature 455 1085 (2008)
Linear Optics	0.10	PRL 93 080502 (2004)

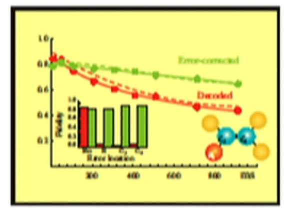
QEC Experimental implementation

VOLUME 81, NUMBER 10 PHYSICAL REVIEW LETTERS 7 SEPTEMBER 1998

Experimental Quantum Error Correction

D. G. Cory,[1] M. D. Price,[2] W. Maas,[3] E. Knill,[4] R. Laflamme,[4] W. H. Zurek,[4] T. F. Havel,[5] and S. S. Somaroo[5]





(Error rate $\epsilon \rightarrow c\epsilon^2$)

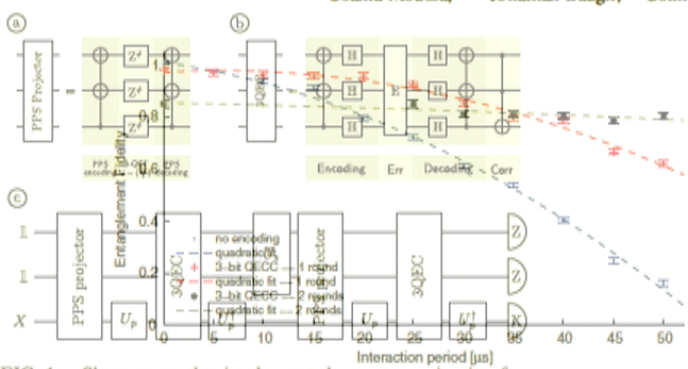
1998:
T2: H= 3s , C1=1.1s, C2=0.6s
DE: $0.85 - 1.10t + O(t^2)$
EC: $0.79 - 0.09t + O(t^2)$

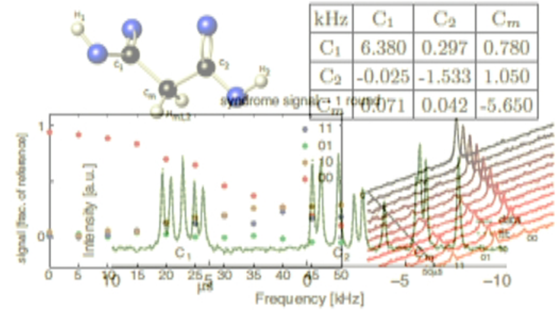
2011: (J. Zhang, et al R.L., PRA 84, 034303, 2011)
T2: H= 1.7s , C1=1.18s, C2=0.45s
DE: $0.99 - 0.436t + O(t^2))$
EC: $0.98 - 0.017t + O(t^2)$

PRL **107,** 160501 (2011) PHYSICAL REVIEW LETTERS week ending 14 OCTOBER 2011

Demonstration of Sufficient Control for Two Rounds of Quantum Error Correction in a Solid State Ensemble Quantum Information Processor

Osama Moussa,[1,2,*] Jonathan Baugh,[1,3] Colm A. Ryan,[1,2] and Raymond Laflamme[1,2,4]





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C_2	-0.025	-1.533	1.050
C_m	0.071	0.042	-5.650

FIG. 1. Shown are the implemented quantum circuits for: (a) labeled-PPS preparation procedure: a 3QCF is conjugated by a unitary operation that encodes (and decodes) the labeled pseudopure state $|00\rangle\langle 00|X$ in the triple quantum coherence $|000\rangle\langle 111| + |111\rangle\langle 000|$; (b) the implemented quantum circuit of a 3-qubit QECC, showing the encoding, decoding, and error-correction steps. The top two qubits are initialized to the $|00\rangle$ state, and the bottom qubit carries the information to be encoded. After the decoding and correction operations, the bottom qubit is restored to its initial state, while the top two qubits carry information about which error had occurred; and (c) the procedure for two rounds: U_p prepares X, Y, or Z inputs, and $U_s = \{II, XI, IX, XX\}$ toggles between the different syndrome subspaces; i.e., the experiment is repeated 4 times, cycling through the different U_s, and then the results are added, similar to a standard phase cycling procedure.

FIG. 4 (color online). Summary of experimental results for the *partial decoupling* map; the system evolves under the natural Hamiltonian as well as 70 kHz decoupling fields that partially modulate the heteronuclear interactions (between the carbons and protons). Shown (on left) are the single-qubit entanglement fidelities in the cases where no encoding is employed (blue dots), or one round of the 3-bit code (red crosses), or two rounds of the 3-bit code (black asterisks), where the interaction period is split to two equal intervals. The dashed lines are quadratic fits to the data and are included to guide the eye. Also shown (on right) is the signal after one round of error correction as distributed over the various error-syndrome subspaces. In this case, the dominant errors are phase flips on the top and bottom qubits, which are encoded on C_1 and C_m, respectively.

FIG. 2. Malonic acid ($C_3H_4O_4$) molecule and Hamiltonian parameters (all values in kHz). Elements along the diagonal represent chemical shifts, ω_i, with respect to the transmitter frequency ($\sum_i \pi\omega_i Z_i$). Above the diagonal are dipolar coupling constants ($\sum_{i<j} \pi D_{i,j}(2Z_iZ_j - X_iX_j - Y_iY_j)$), and below the diagonal are J coupling constants ($\sum_{i<j} \frac{\pi}{2} J_{i,j}(Z_iZ_j + X_iX_j + Y_iY_j)$). An accurate natural Hamiltonian is necessary for high fidelity control and is obtained from precise spectral fitting of (also shown) a proton-decoupled ^{13}C spectrum following polarization-transfer from the abundant protons. The central peak in each quintuplet is due to natural abundance ^{13}C nuclei present in the crystal at $\sim 1\%$. (for more details see [7, 10] and references therein.)

PRL 107, 160501 (2011) PHYSICAL REVIEW LETTERS week ending 14 OCTOBER 2011

Demonstration of Sufficient Control for Two Rounds of Quantum Error Correction in a Solid State Ensemble Quantum Information Processor

Osama Moussa,[1,2,*] Jonathan Baugh,[1,3] Colm A. Ryan,[1,2] and Raymond Laflamme[1,2,4]

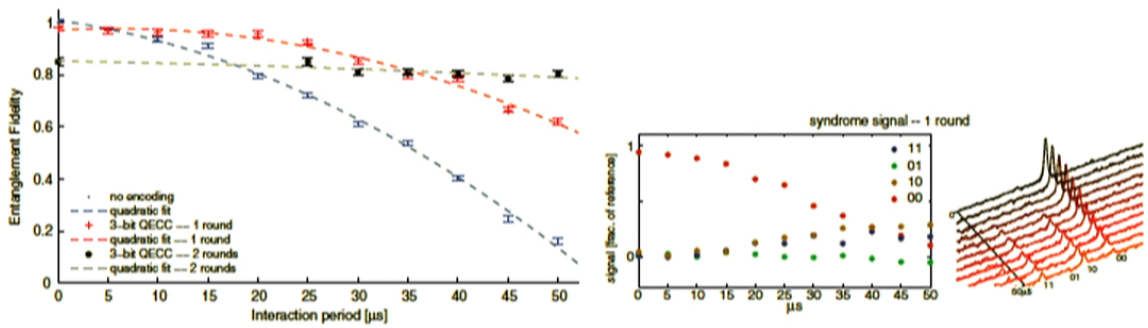
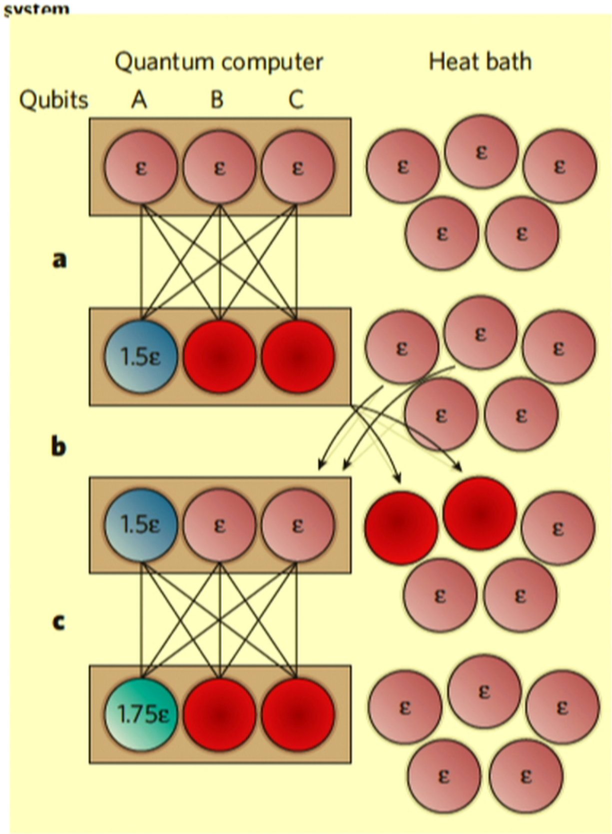


FIG. 4 (color online). Summary of experimental results for the *partial decoupling* map: the system evolves under the natural Hamiltonian as well as 70 kHz decoupling fields that partially modulate the heteronuclear interactions (between the carbons and protons). Shown (on left) are the single-qubit entanglement fidelities in the cases where no encoding is employed (blue dots); or one round of the 3-bit code (red crosses); or two rounds of the 3-bit code (black asterisks), where the interaction interval is split to two equal intervals. The dashed lines are quadratic fits to the data and are included to guide the eye. Also shown (on right) is the signal after one round of error correction as distributed over the various error-syndrome subspaces. In this case, the dominant errors are phase flips on the top and bottom qubits, which are encoded on C_1 and C_m, respectively.

Algorithmic cooling with a heat bath

Energy and disorder of a 3 qubit system (at equilibrium)

$|000\rangle \rightarrow (1\text{-}p)^3$
$|001\rangle \rightarrow p(1\text{-}p)^2$
$|010\rangle \rightarrow p(1\text{-}p)^2$
$|011\rangle \rightarrow p^2(1-p)$
$|100\rangle \rightarrow p(1\text{-}p)^2$
$|101\rangle \rightarrow p^2(1-p)$
$|110\rangle \rightarrow p^2(1-p)$
$|111\rangle \rightarrow p^3$



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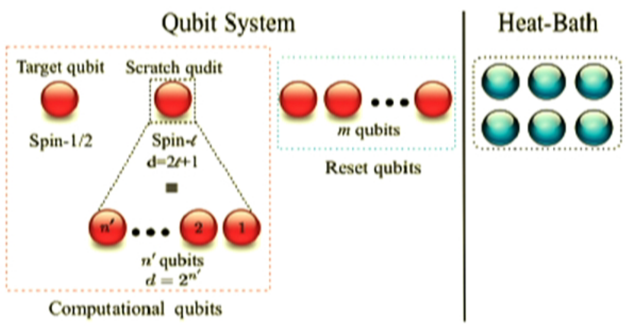
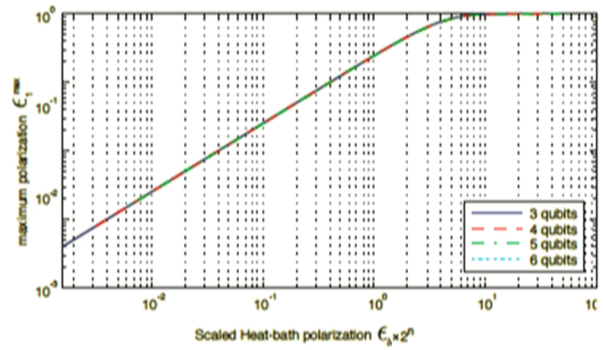
Algorithmic cooling with a heat bath

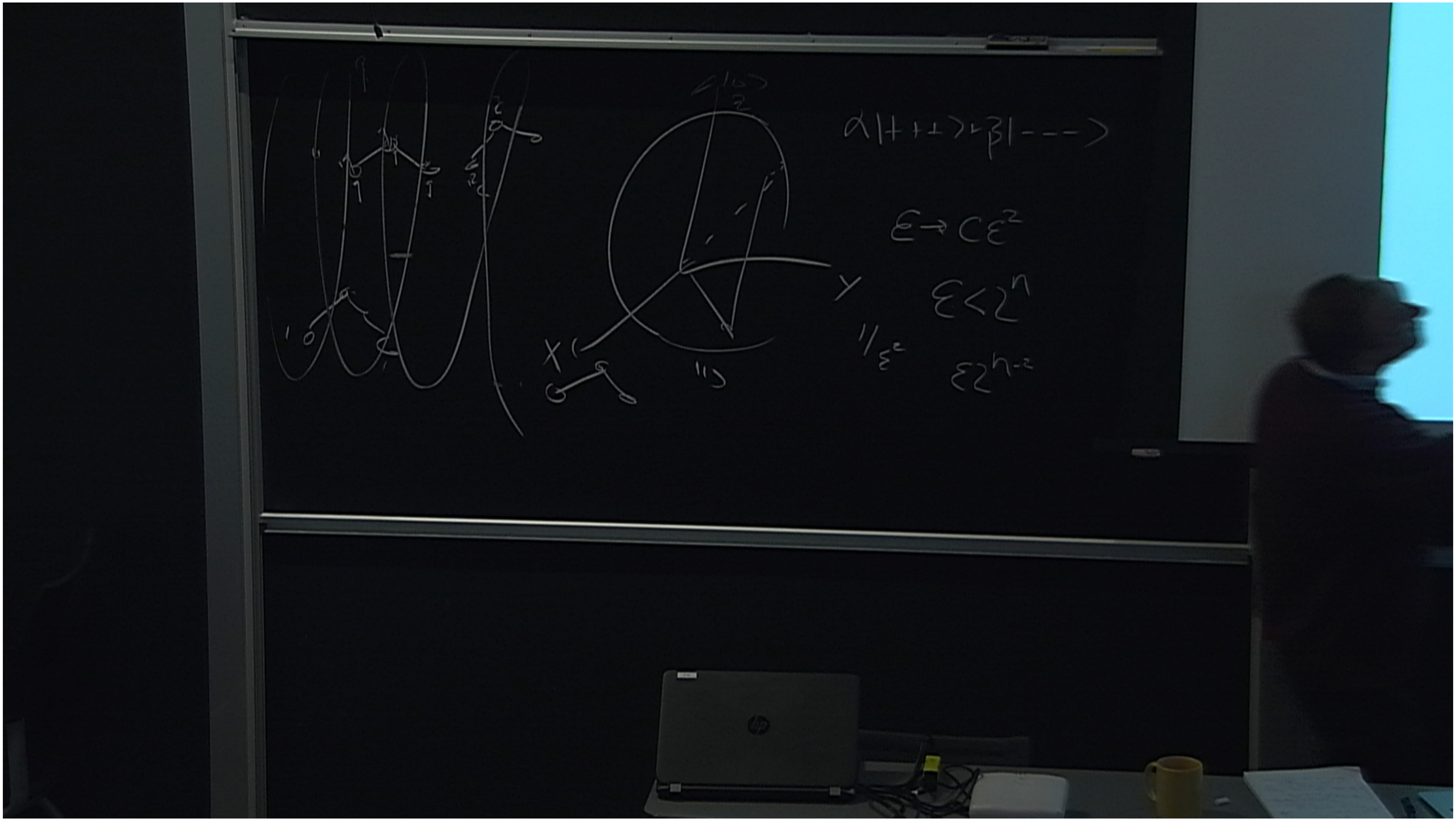


Moussa, MSc thesis 2005

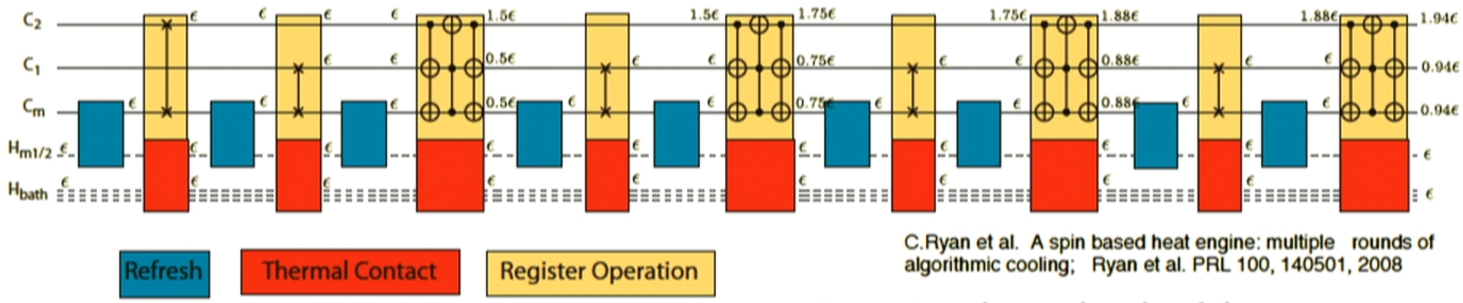


$$\epsilon_{1}^{\infty} = \frac{(1+\epsilon_b)^{md} - (1-\epsilon_b)^{md}}{(1+\epsilon_b)^{md} + (1-\epsilon_b)^{md}}.$$

N Rodriguez-Briones,RL PRL to appear


α|+++⟩+β|---⟩
ε→cε²
ε<2ⁿ
1/ε²
ε2ⁿ⁻²
X
Y

Multiple Rounds of Algorithmic Cooling



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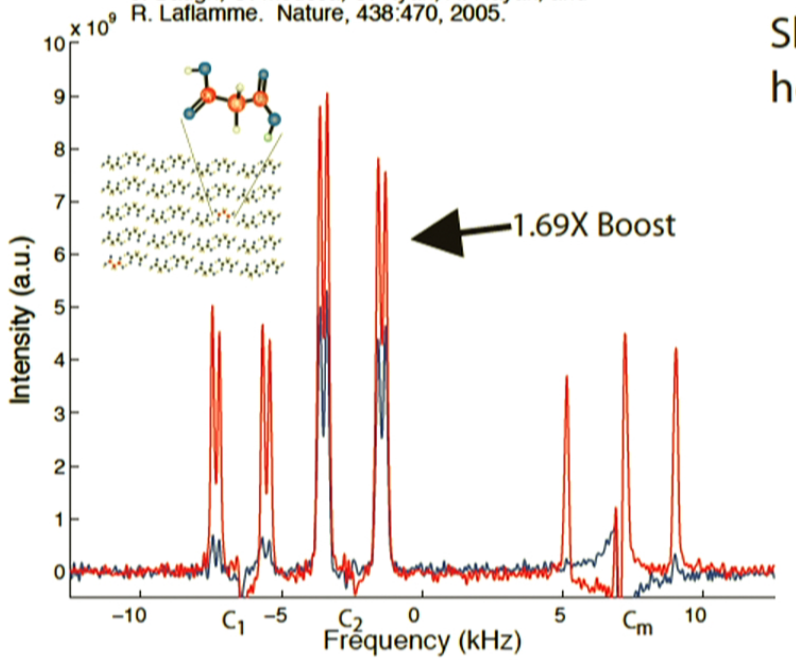


- By using heat-bath able to surpass Shannon/Soresnsen bound of 1.5X heat-bath polarization

Polarization Boost w.r.t. heat-bath

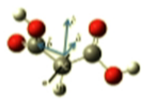
Compression Step	C_2	C_1	C_m
1	1.39	0.47	0.49
2	1.56	0.68	0.71
3	1.64	0.76	0.79
4	1.69	0.79	0.84

Irradiated malonic acid

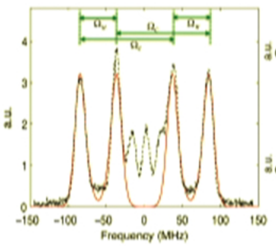
PRL 107, 170503 (2011) Selected for a Viewpoint in *Physics* PHYSICAL REVIEW LETTERS week ending 21 OCTOBER 2011

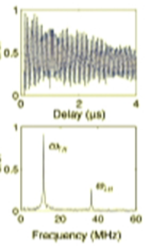
Coherent Control of Two Nuclear Spins Using the Anisotropic Hyperfine Interaction

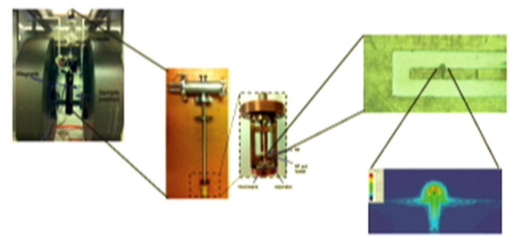
Yingjie Zhang,[1,2] Colm A. Ryan,[1,2] Raymond Laflamme,[1,2,3] and Jonathan Baugh[1,2,4,*]

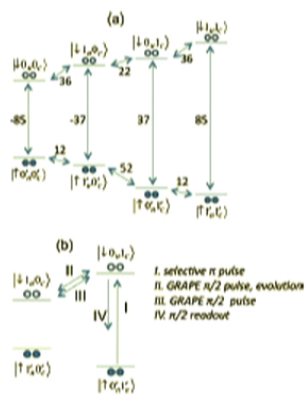


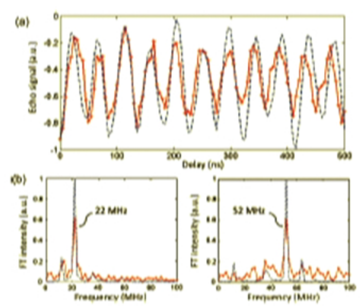
	e	^1H	^{13}C	T_1	T_2
e	93187.5	-42.30 (A)	93.83 (A)	38	2.3
^1H	20.00 (B)	-13.90	–	–	9.5 (T_2^*)
^{13}C	79.20 (B)	–	-8.53	–	–







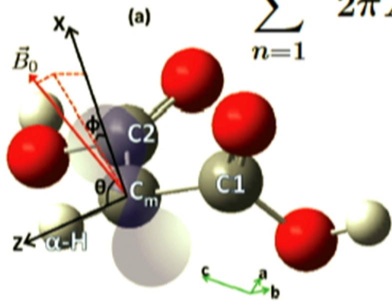


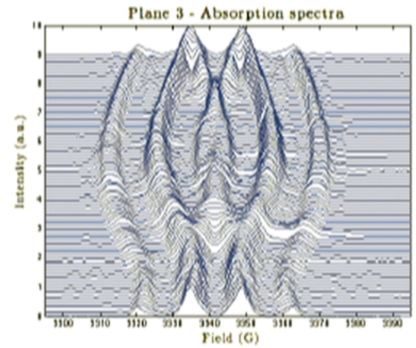


Cooling with the help of e^-

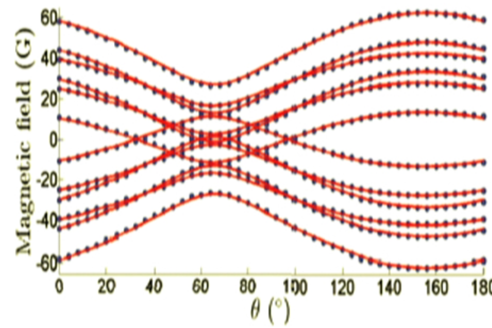
DK Park, G Feng, R Rahimi, St Labruyere, T Shibata, S Nakazawa, K Sato, T Takui, R Laflamme and J. Baugh. Quantum Information Processing 14, 2435, 2015.

$$\hat{\mathcal{H}} = \mu_B g_{\alpha\beta} B_{0\alpha} \hat{S}_\beta + \sum_{n=1}^{K} 2\pi A^n_{\alpha\beta} \hat{S}_\alpha \hat{I}^n_\beta - \gamma_n \hat{I}^n_\alpha B_{0\alpha}$$





		Direction cosines to $\mathbf{A}^H$ principal axis		
		X	Y	Z
g_{xx}	2.00250 ± 0.00038	-0.1657	0.9779	0.1272
g_{yy}	2.00373 ± 0.00037	-0.9811	-0.1766	0.0797
g_{zz}	2.00417 ± 0.00036	0.1004	-0.1115	0.9887
A^H_{xx}	-26.6 ± 2.8	1	0	0
A^H_{yy}	-56.0 ± 0.7	0	1	0
A^H_{zz}	-91.5 ± 0.6	0	0	1
A^{Cm}_{xx}	24.5 ± 1.0	0.0696	-0.0019	0.9976
A^{Cm}_{yy}	43.0 ± 1.3	0.9962	0.0530	-0.0694
A^{Cm}_{zz}	212.3 ± 0.6	-0.0528	0.9986	0.0056
$A^{C_{1,2}}_{xx}$	-36.1 ± 0.3	0.0627	0.0082	0.9980
$A^{C_{1,2}}_{yy}$	-39.3 ± 0.3	0.9805	-0.1870	-0.0601
$A^{C_{1,2}}_{zz}$	-40.6 ± 0.3	0.1862	0.9823	-0.0198



Conclusion

In order to implement quantum error correction, we will need

- Good knowledge of the noise
- Good quantum control
- Ability to extract entropy
- Parallel operations

Recent experiments have demonstrated these elements individually but we need to pull them together.

It is only the beginning of experimental QEC.