IQC

University of Waterloo

NMR Quantum Information Processing: Successes and Challenges

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Quantum Information Science in Canada

IQC Institute *for* Quantum Computing

University of Waterloo

CIFAR Canadian Institute for Advanced Research

Goal: Investigate fundamental questions in Quantum Information

Fellows

- Prof R. Laflamme (Director and Ivey Fellow)
- Prof G. Brassard (Montréal)
- Prof R. Cleve (IQC and PI)
- Prof A. Steinberg (Toronto)
- Prof C. Crépeau (McGill)
- Dr D. Gottesman (Perimeter)
- Prof J. Watrous (IQC),

Associates

Dr S. Aaronson (MIT), Dr T. Jennewein (Vienna), Prof B. Sanders (Calgary), Dr B. Terhal (IBM)

Scholars

Dr A. Ambainis (IQC), Dr A. Blais (Sherbrooke), Dr J. Emerson (IQC), Dr P. Hayden (McGill), Dr P. Hoyer (Calgary), Dr D. Leung (IQC), Dr A. Lvovsky (Calgary), Dr M. Mosca (IQC and PI), Dr A. Nayak (IQC and PI), Dr M. Pioro-Ladrière (Sherbrooke), Dr R. Raussendorf (UBC), Dr A. Tapp (Montréal), Dr G. Weihs (IQC).

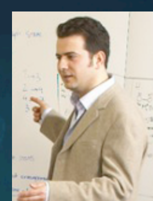
QuantumWorks

A research network with academic, industry and government partners to develop quantum technologies and their applications with headquarters at the University of Waterloo.

www.quantumworks.ca

Academic Partners: Institute Partners: Industry Partners:

IQC's origin



Mission

Develop quantum information science and technology bringing together mathematicians, computer science, physicists, chemists and engineers.

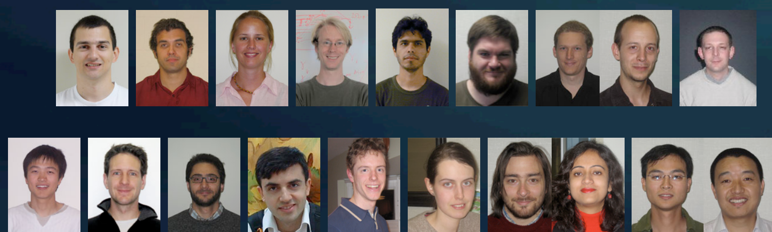
Strategic Objectives

1. Establish an international centre of excellence doing research at the highest level
2. Become an international magnet for students
3. Become a source of information, analysis and commentary on the state of quantum information processing

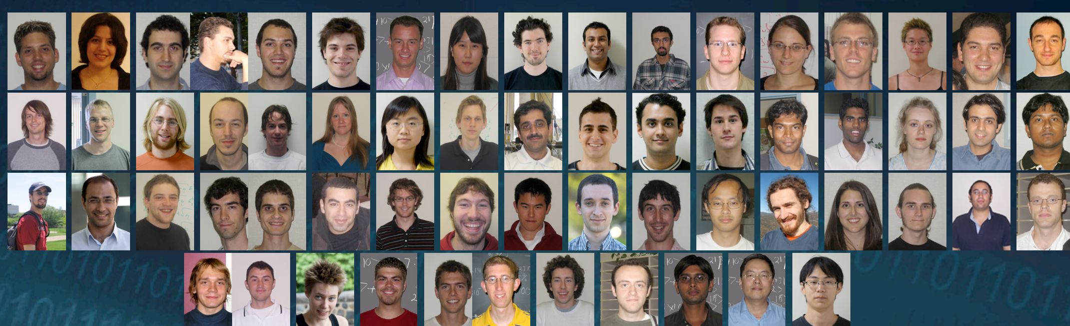
Brief history

- Institute founded in 2002
- Mike and Ophelia Lazaridis donate $50M
- 2005: UW commits to 30 faculty positions
- 2006: $50M Grant from Gov't of Ontario
- 2007: CFI/MRI approve $48M funding for fabrication facility
- 2009: $50M Grant from Gov't of Canada
- Other grants (ORDCF, ARO, CRC,CFI, NSERC, MITACS) $15M

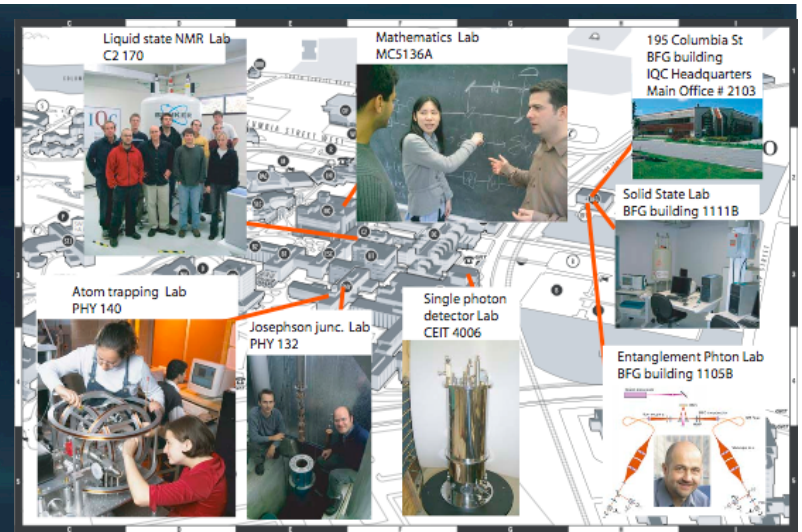
Faculty

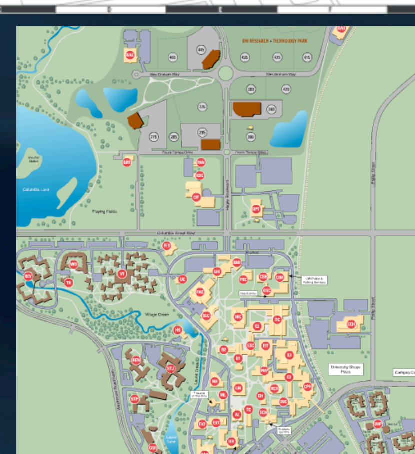


Post-Docs



Graduate Students





In 2008; 18 faculty,
21 pdfs, 64 students
Build to 30 faculty,
50 pdfs, 125 students

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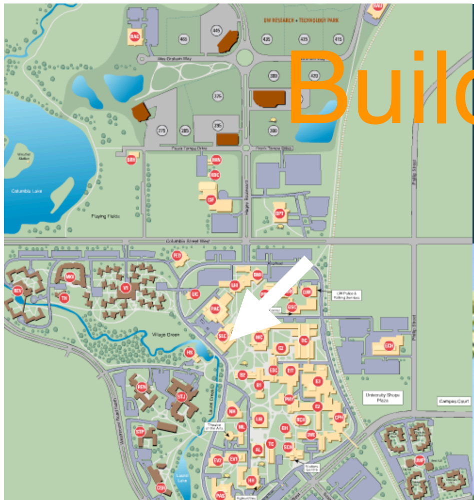
Building a World Class Facility



- Promote multi-disciplinary research
- 100 000 sq ft
- $80m
- next to 20 000 sq ft World Class Fab+Metrology

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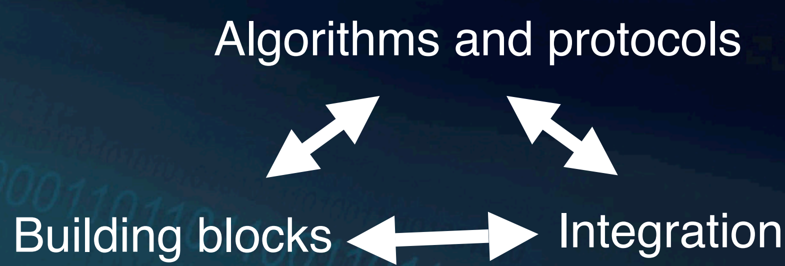
Research

Quantum Information Processing

Computation | **Communication**

	Q Com-puting	Q Com-munication
Theory	✓	✓
Experi-ment	✓	✓



Accuracy threshold theorem

- **Quantum error correction has been one the major achievement in QIP. Assumptions of the theorem:**

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

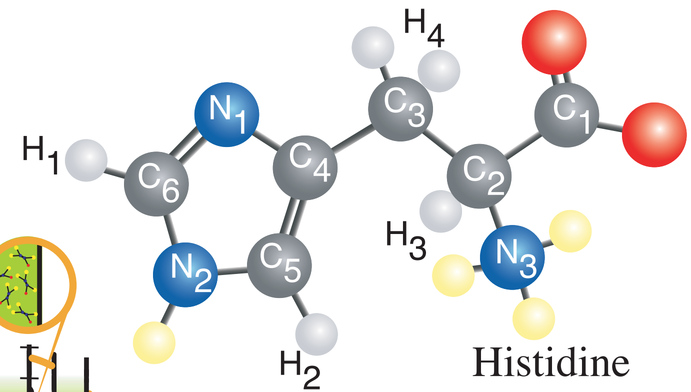
Liquid state NMR

Cory & Havel PNAS, 64, 1634, 1997

Gershenfeld & Chuang, Science 275, 350, 1997

Qubits/Control/Measurement/Noise

- **Larmor frequency:**
  $\omega_L = \mu_p B_0 = \sim$ 500 MHz
- **Single bit gate:** $H = \vec{\mu} \cdot \vec{B}$
  $\sim \omega_L Z^1 + \mu(B_x X + B_y Y)$
  $\sim$ 1/kHz $\sim$ ms
- **Two bit gate** $\sim$**10 ms:** $\vec{J}^1 \cdot \vec{J}^2$
  $H_{int} \sim J_{12} Z^1 Z^2$
- $T_2 \sim$ 1s ; $T_1 \sim 10s$



Histidine

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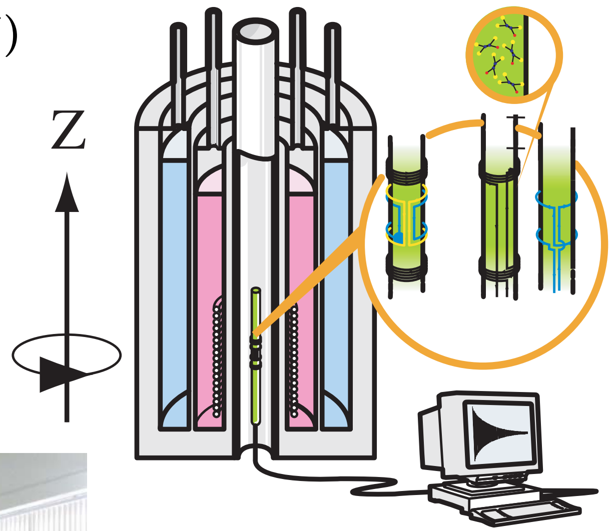
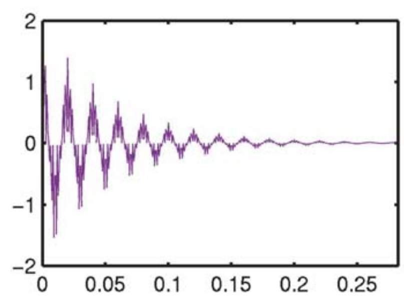
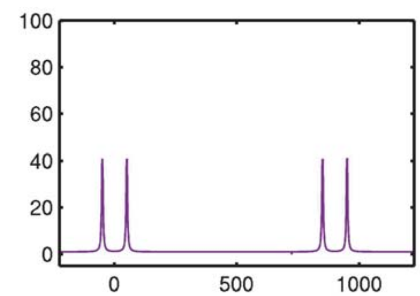


Bruker 700





Initial state in Liquid state NMR

We have highly mixed state at room temperature.

- **Making a "pseudo pure" state** (Cory et al. 1996, Gershenfeld et al. 1997)

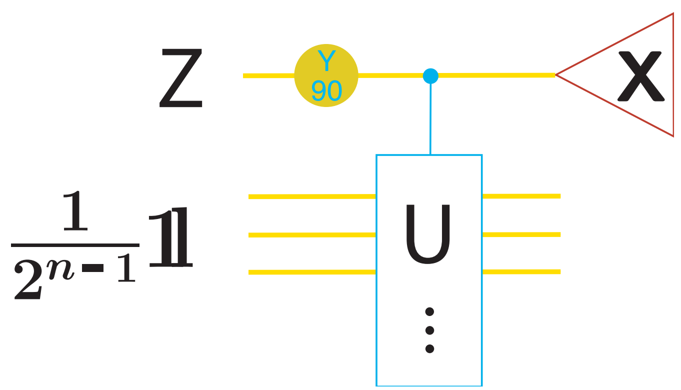
$$\rho = \frac{1}{Z}e^{-\beta H} \approx \frac{1}{Z}(\mathbb{1} - \beta H + \dots) \rightarrow \frac{1}{Z}(\mathbb{1} - \frac{\beta\omega n}{2^n}|\Psi\rangle\langle\Psi|) \; \textit{(not scalable)}$$

BUT: Schulman and Vazirani (STOC, 322, 1999): Algorithmic cooling (i.e. concentrate polarization of the qubits) is scalable.

- **The power of one bit of quantum information**

E. Knill& R.L. PRL81, 5672, 1998

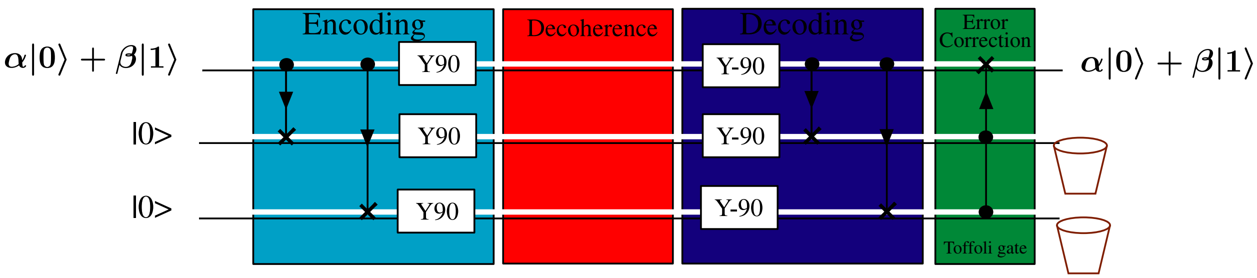
-Interpretation of tomography and spectroscopy as dual forms of quantum computation, Miquel, C. et al., Nature 418, 59-62, 2002.
-Characterization of complex quantum dynamics with a scalable NMR information processor Ryan, C, PRL 95, 250502, 2005.
-Estimating Jones polynomials is a complete problem for one clean qubit Shor, P. et a., QIC 8, 681, 2008.
-. . .

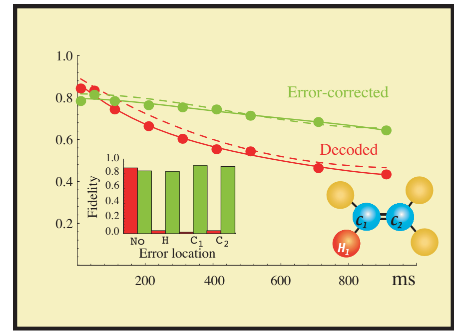


Quantum Control

Implementation of quantum error correction:

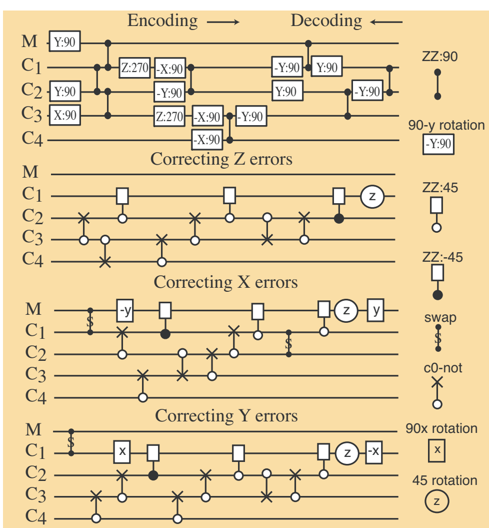
- **3 qubits or phase quantum error correcting code**



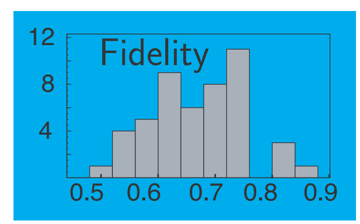


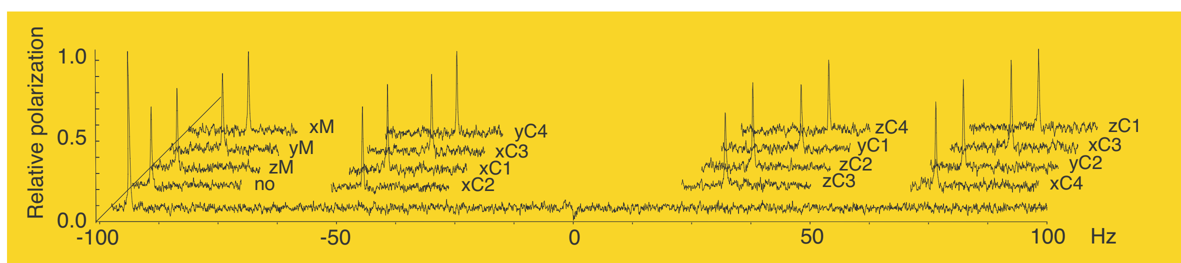
Cory et al., PRL 81, 2152, 1998

- **5 qubits quantum error correcting code**



Implementation of the 5 bit code with the stabilizer $Z^2Y^3Y^4X^5$, $Z^1Y^2Y^3X^4$, $Y^2Z^3Z^4Z^5$ and $X^1Z^2X^3Z^4$, including decoding and error correction for a basis of 1 qubit errors.



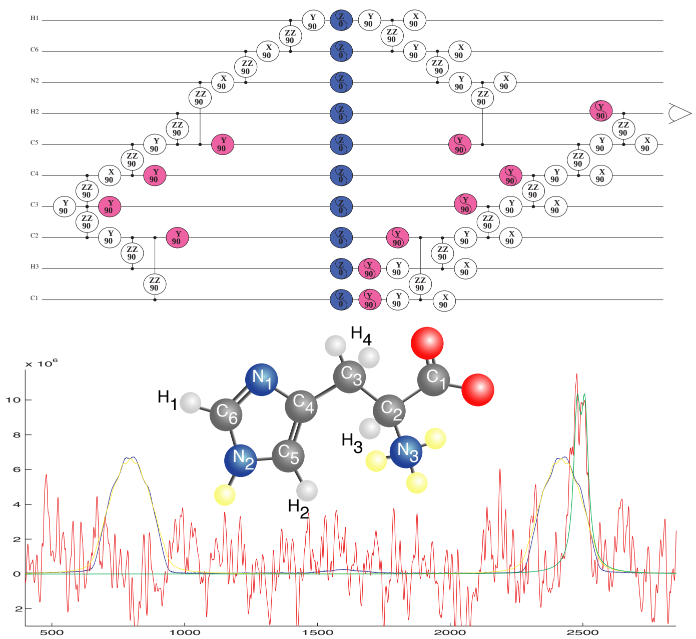


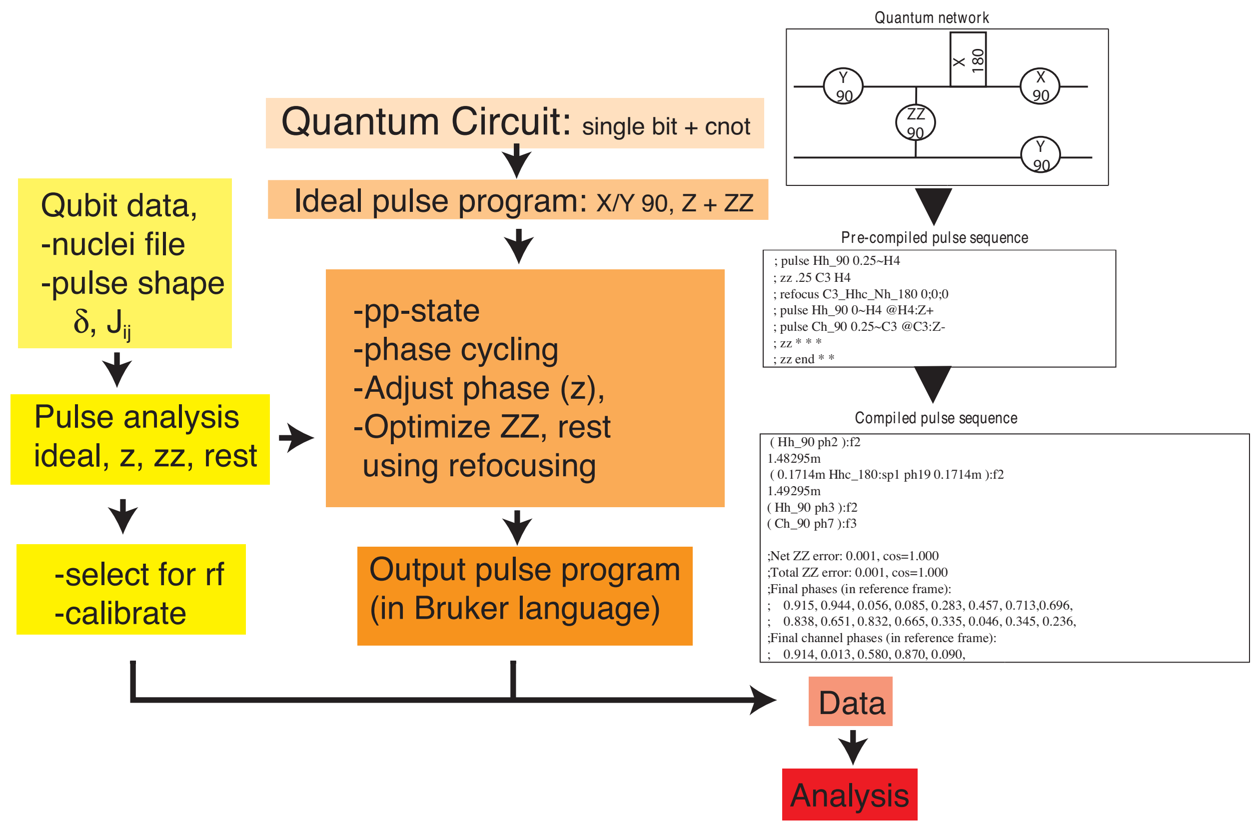
Knill et al. PRL 86, 5811 (2001)

Controlling larger Hilbert space

Controlling a dozen quantum bits

-need to use methods to minimize errors, compilers, grape pulses, refocussing etc.

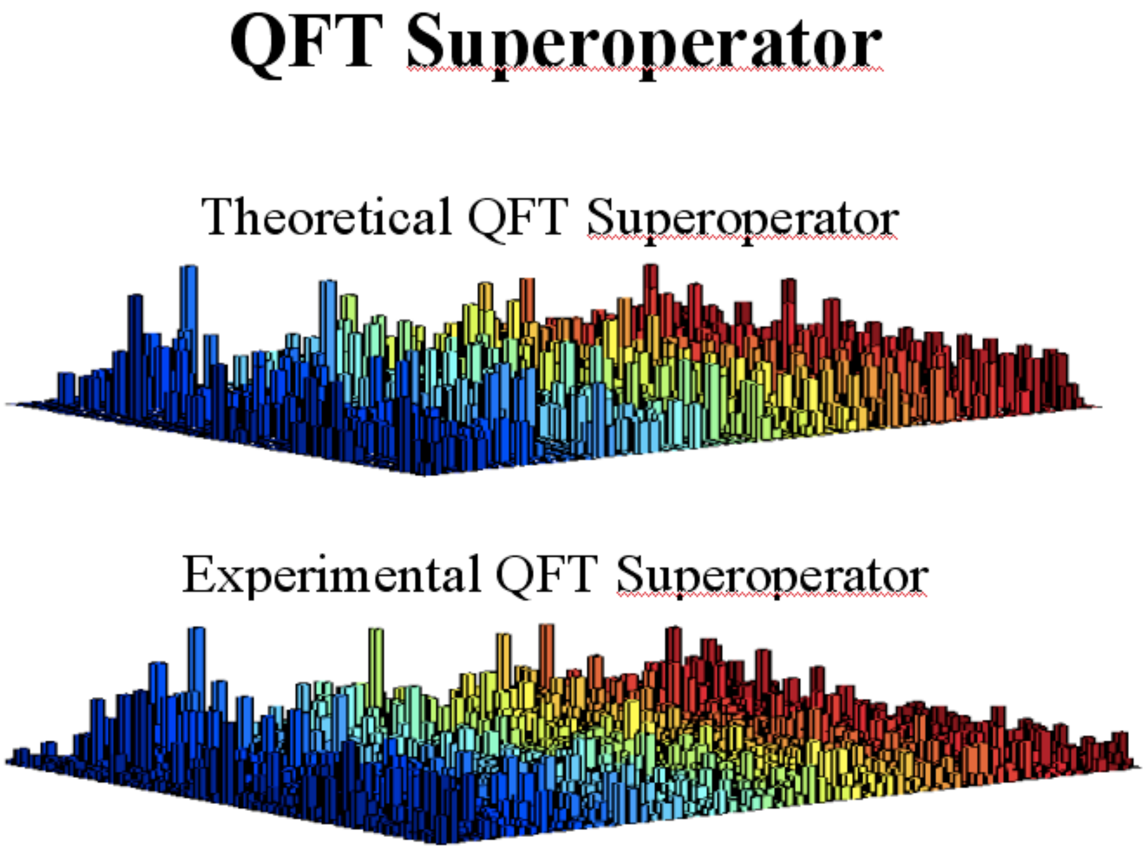




C. Negregrne et al. PRL 96, 170501 (2006)
Ryan et al., PRA78, 012328, 2008

Characterising noise in QIPs

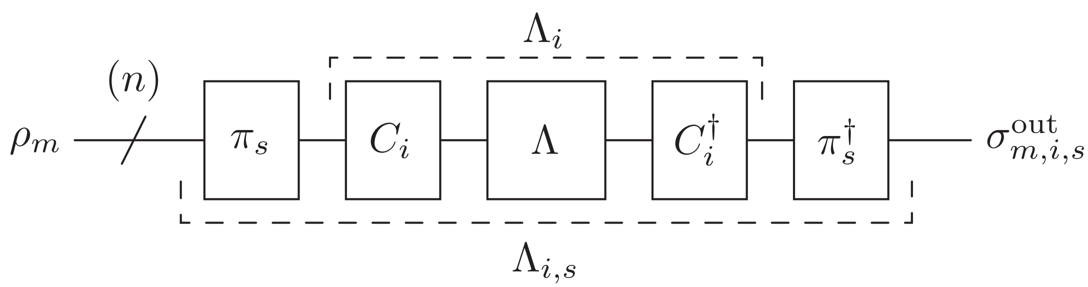
Can do process tomography, give all noise parameters, but scale as 4^{2n}, already for 3 qubits the tasks is daunting.



Cory et al. JCP121, 6114, 2004

Instead can we get a few parameters that are useful? Coarse grain the parameters and ask questions relevant to quantum error correction, porbability to get zero (P_0), one (P_1), two errors,..., independently of the type (X, Y, Z) and which qubits are affected.

- **Average the noise by randomising each qubits over $SU(2)$ using 2-design techniques**
- **Randomise qubits**
- **Use sampling of randomising operators Chernoff bound**



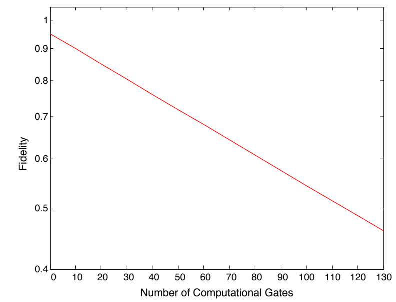
Start with the state $|00\ldots0\rangle$ and measure the numbers of bits flips, and repeat, and estimate the P_i.

#	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	$0.84\ ^{+0.01}_{-0.01}$	$0.15\ ^{+0.02}_{-0.03}$	$0.01\ ^{+0.03}_{-0.01}$	$0.00\ ^{+0.02}$

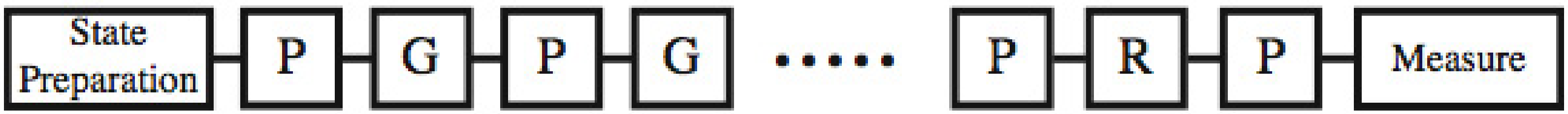
Emerson, et al. Science 317, 1893, 2007

Benchmarking

Estimate the accuracy of gates such that:



- **Device indepedent**
- **Independent of state prep and measurement**
- **Characterised by one parameter (strength of the depolarised noise)**



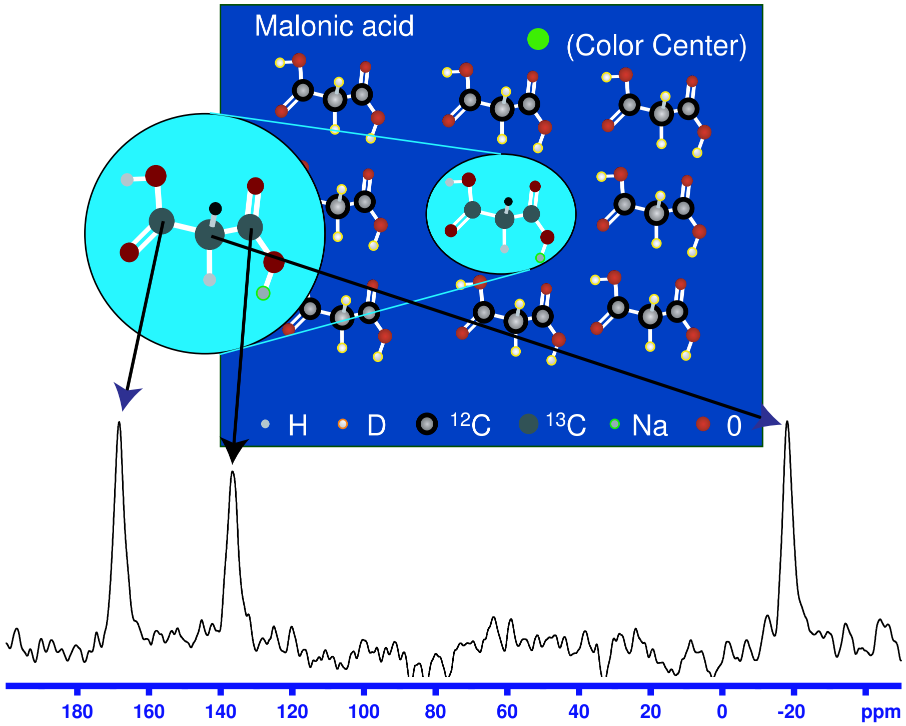
G gates - Clifford group generators, P gates - Pauli gates, R gate - recovery operation

	liquid-state NMR	**ion traps**	**superconducting qubits**
single-qubit	$1.3 \pm 0.1 \times 10^{-4}$ [1]	$4.82 \pm 0.02 \times 10^{-3}$ [2]	$1.1 \pm 0.3 \times 10^{-2}$ [3]
multi-qubit	$4.7 \pm 0.3 \times 10^{-3}$ [1]	$99.3\%^{*}$ [4]	$55\%^{*}$ [5]

[1] C.A.Ryan, M. Laforest and R. Laflamme. Randomized benchmarking of single- and multi-qubit control in liquid-state NMR quantum information processing. New Journal of Physics 11: 013034 (2009).
[2] E. Knill et al. Randomized benchmarking of quantum gates. Physical Review A 77: 012307 (2008).
[3] J.M. Chow et al. Randomized benchmarking and process tomography for gate errors in a solid-state qubit. arXiv:0811.4387 (2008).
[4] J. Benhelm, G. Kirchmair, C.F. Roos and R. Blatt. Towards fault-tolerant quantum computing with trapped ions. Nature Physics 4: 463 (2008).
[5] S. Filipp et al. Two-Qubit State Tomography using a Joint Dispersive Read-Out. arXiv:0812.2485 (2008).

Solid state NMR

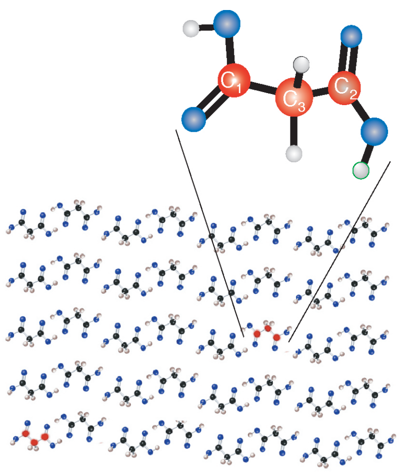
- **Stronger couplings**
- **Higher polarization**
- **Lower decoherence**
- **Control between the processors'qubits and the bath**

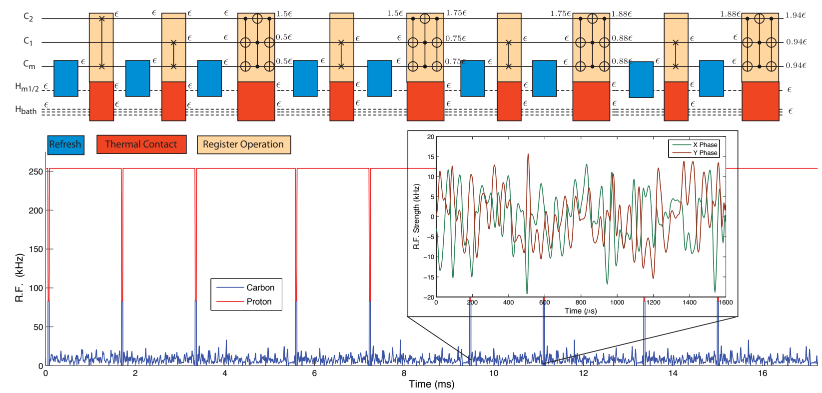


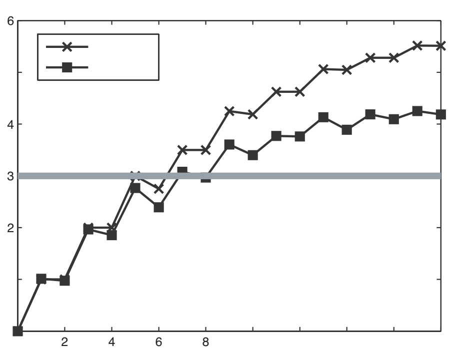
Algorithmic cooling

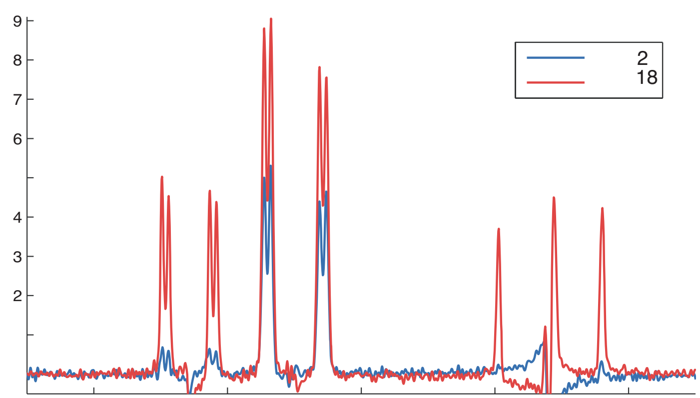
L. J. Schulman and U. V. Vazirani, in STOC 99: p.322, 1999
L. J. Schulman, et al., PRL 94, 120501, 2005

Compressing the purity into a smaller number of qubits, thermalize the hot qubits with a bath using solid state NMR









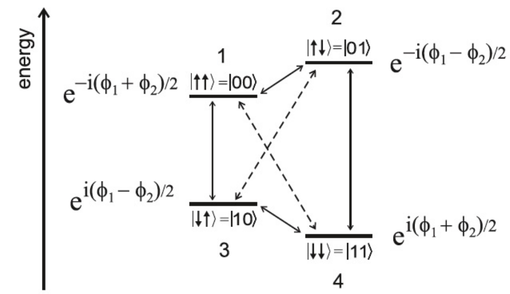
Compression Step	C_2	C_1	C_m
1	1.39	0.47	0.49
2	1.56	0.68	0.71
3	1.64	0.76	0.79
4	1.69	0.79	0.84

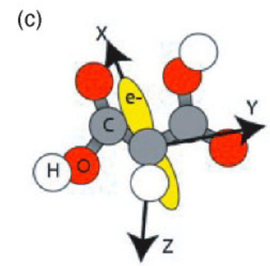
Baugh et al. Nature 438, 470, 2005
Ryan et al. PRL 100, 140501, 2008

Solid state NMR and ESR

Going towards hybrid systems

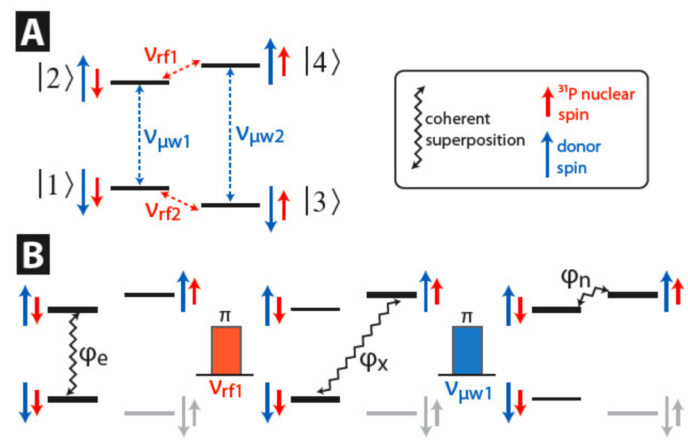
- Mehring et al. 2002:coherent transfer between nuclei and electron spin in malonic acid and $^{15}N@C60$





- Cory et al. universal control of the nuclei via anisotropic hyperfine interactions

- Morton et al. (Oxford) using ^{31}P in ^{28}Si, tomography of states



- Lukin ...