Engineered quantum systems.

G J Milburn

Centre for Engineered Quantum Systems, The University of Queensland

Taipei, June 2011.

Engineered quantum systems?

Superconducting qubits and microwave resonators.

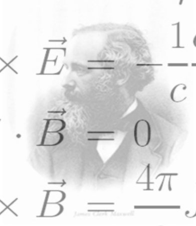
Entanglement via continuous measurement and feedback

Nanomechanical resonators

Enhanced energy transport due to vibrational modes.

Engineered quantum systems?

James Clerk Maxwell, 150 years on.

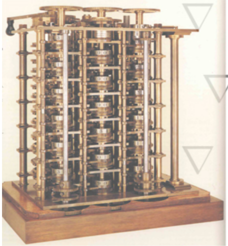


$$\nabla \cdot \vec{E} = 4\pi\rho$$

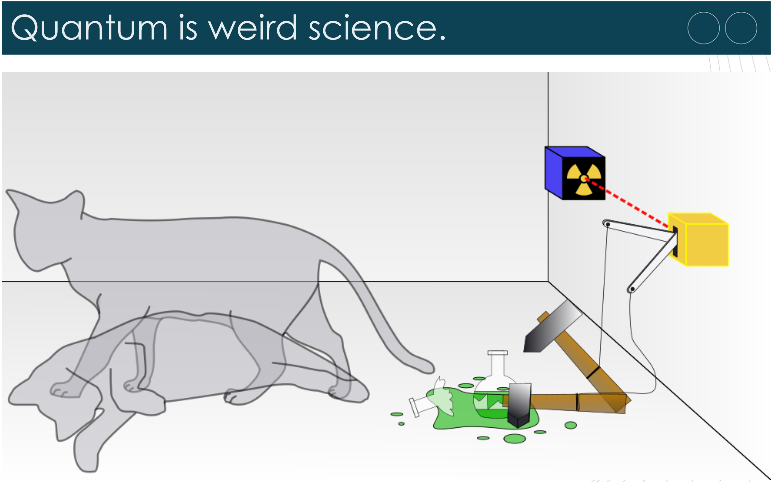
$$\nabla \times \vec{E} = -\frac{1}{c}\frac{\partial \vec{B}}{\partial t}$$

$$\nabla \cdot \vec{B} = 0$$

$$\nabla \times \vec{B} = \frac{4\pi}{c}\vec{J} + \frac{1}{c}\frac{\partial \vec{E}}{\partial t}$$



Engineered quantum systems?



Wikipedia

Engineered quantum systems?

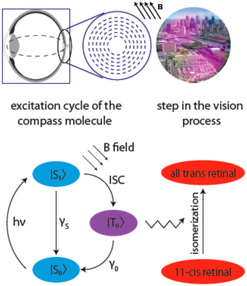
The World is Quantum

AVIAN NAVIGATION EXPLOITS THE QUANTUM WORLD

The quantum chemistry of a light sensitive molecule in the retina has a rate that depends on the orientation with respect to the Earth's magnetic field.

For experts: single to triplet conversion with a long lived charge separated state.

a)



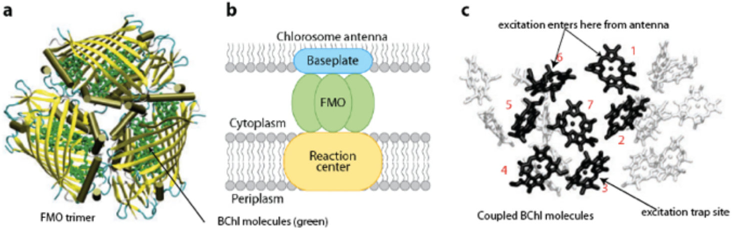
b)

A new model for magnetoreception , Stoneham et al 2010

Engineered quantum systems?

The World is Quantum

PHOTOSYNTHESIS EXPLOITS THE QUANTUM WORLD



Fast efficient transfer of energy through the system requires quantum effects.

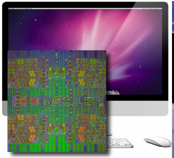
Engineered quantum systems?

Quantum Principles

Quantisation (energy levels) … semiconductors

Tunneling … scanning tunneling microscope

Uncertainty principle … quantum cryptography




Engineered quantum systems?

Quantum Principles

Quantisation (energy levels) … semiconductors

Tunneling … scanning tunneling microscope

Uncertainty principle … quantum cryptography

- Superposition (coherence)
- Entanglement

→ Engineered Quantum Systems

Engineered quantum systems?

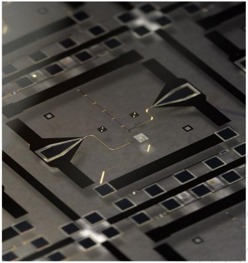
The largest engineered quantum system — *LIGO*

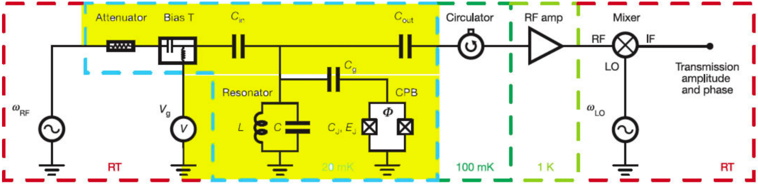
... engineering the Heisenberg uncertainty principle

Engineered quantum systems?

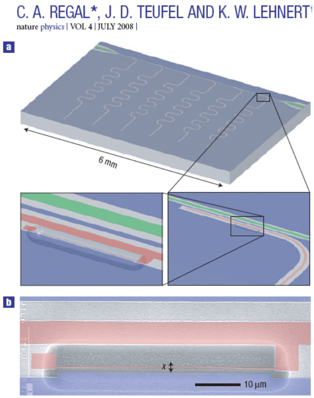
Example: quantum circuits

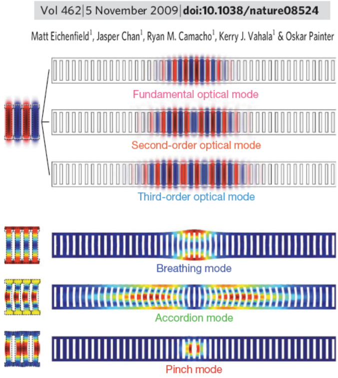
- Build circuits from superconductors
  - Current flows without resistance.
  - Engineer macroscopic quantum circuits.





Engineered quantum systems?

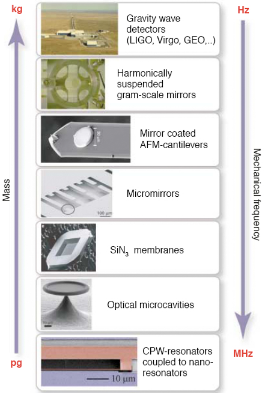




-Fabricated (artificial) devices that operate by the control of quantum coherence.
-Involves a very large number of atomic systems.
- Quantise a collective, macroscopic degree of freedom.

Engineered quantum systems?

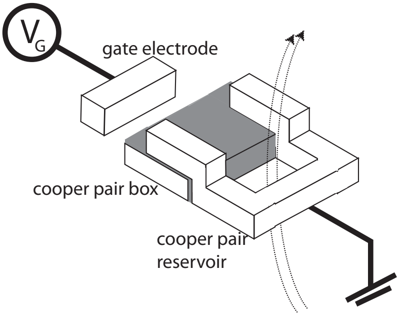
T. J. Kippenberg[1]*† and K. J. Vahala[2]*
29 AUGUST 2008 VOL 321 **SCIENCE**

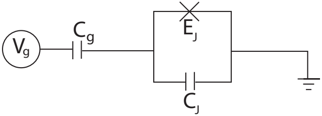


Engineered quantum systems ...
.... moving the quantum/classical border.

Superconducting qubits.

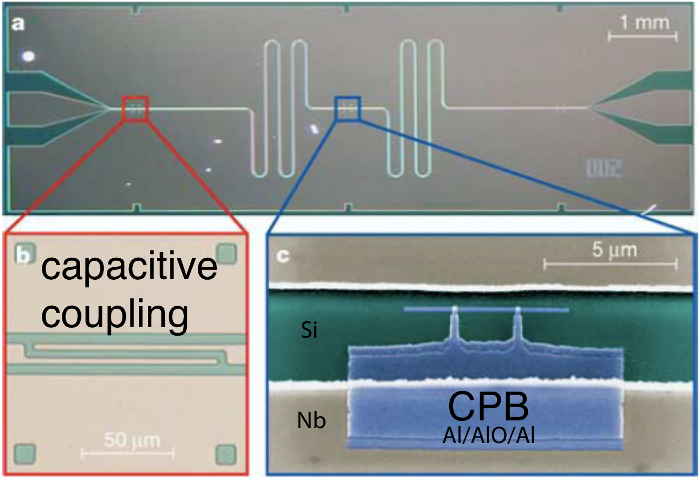
Copper pair box.





Split junction for control of $E_J(\phi_x)$.

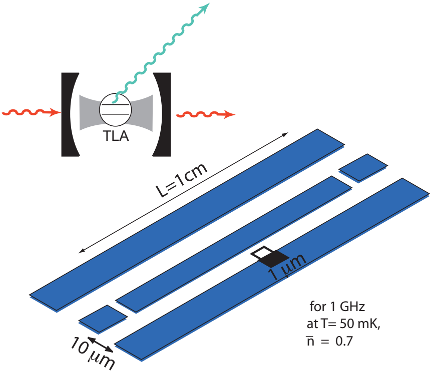
Superconducting coplanar cavities.



Wallraff et al., Nature (2004).

Superconducting circuit quantum electrodynamics.

Superconducting qubits in a transmission line.

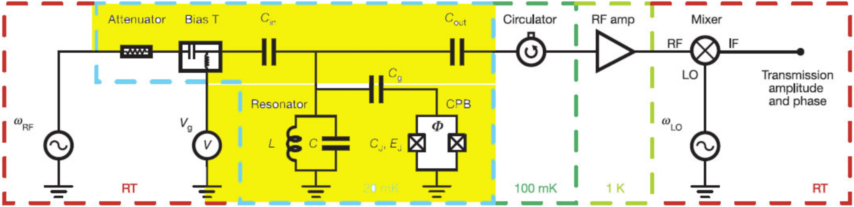


Girvin et al., (2003). and Blais, et al. (2004).

Quality factors vary:
$Q = 160$ at 5.19GHz (Schoelkopf, 2007),
$Q = 300,000$ at 3.29GHz (Wallraff, 2009).

Circuit QED.

Effective Quantisation via equivalent circuit



Wallraff *Nature*, (2004).

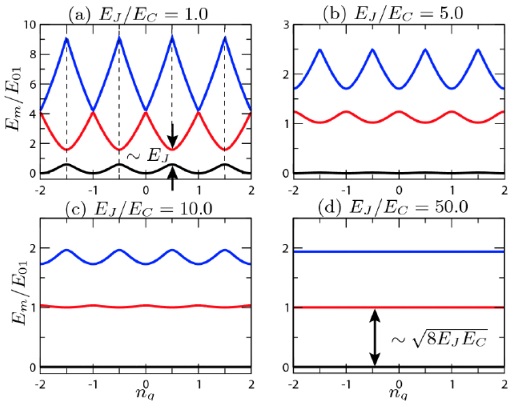
The CPB Hamiltonian.

$$H = 4E_c \sum_N (N - n_g(t))^2 |N\rangle\langle N| - \frac{E_J}{2} \sum_N |N\rangle\langle N+1| + |N+1\rangle\langle N|$$

$$\begin{aligned} E_C &= \frac{e^2}{2C_\Sigma} \\ n_g(t) &= \frac{C_g V_g(t)}{2e} \end{aligned}$$

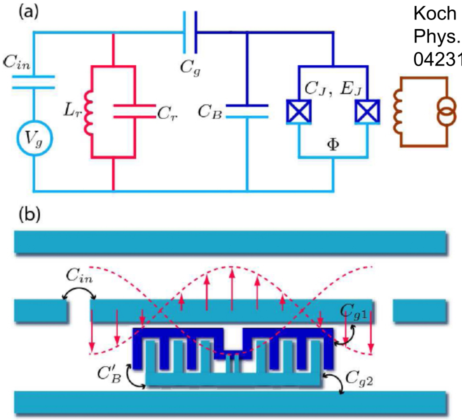
$$V_g(t) = V_g^{(0)} + \hat{v}(t)$$

The Hamiltonian



Koch et al.,
Phys. Rev. A 76,
042319 (2007).

The Hamiltonian



Koch et al.,
Phys. Rev. A 76,
042319 (2007).

The Hamiltonian

Work in subspace, $N = 0, 1$.

$$H = H_{CPB} - 4E_C \delta\hat{n}_g(t)(1 - 2n_g^{(0)} - \bar{\sigma}_z)$$

$$H_{CPB} = -2E_C(1 - 2n_g^{(0)})\bar{\sigma}_z - \frac{E_J}{2}\bar{\sigma}_x$$

$$\bar{\sigma}_z = |0\rangle\langle 0| - |1\rangle\langle 1|, \quad \bar{\sigma}_x = |1\rangle\langle 0| + |0\rangle\langle 1|$$

$$\delta\hat{n}_g(t) \approx \frac{C_g}{2e}\hat{v}(t)$$

write

$$\hat{v}(t) = V_{rms}^0(a + a^\dagger)$$

The Hamiltonian

$$H = \hbar\omega_c a^\dagger a + \frac{\hbar\epsilon}{2}\bar{\sigma}_z - \frac{\hbar\Delta}{2}\bar{\sigma}_x - \hbar g(a + a^\dagger)\bar{\sigma}_z$$

$\hbar\omega_c a^\dagger a$: cavity field

$$\left.\begin{array}{lcl} \hbar\epsilon & = & -2E_C(1 - 2n_g^{(0)}) \\ \hbar\Delta & = & \frac{E_J\cos(\phi_e)}{2} \end{array}\right\}\text{controlled independently}$$

$$\hbar g \approx \beta V_{rms}^0 \left(\frac{E_J}{4E_C}\right)^{1/4}$$

Circuit QED

Rotating wave approximation: *Jaynes-Cummings*.

Diagonalise H_{CPB}

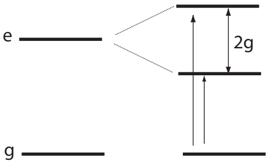
$$H = \hbar\omega_c a^\dagger a + \frac{\hbar\Omega}{2}\sigma_z - \hbar g(a\sigma_+ + a^\dagger\sigma_-)$$

$$\Omega = \sqrt{\Delta^2 + \epsilon^2}$$

Vacuum Rabi splitting

Vacuum Rabi splitting.

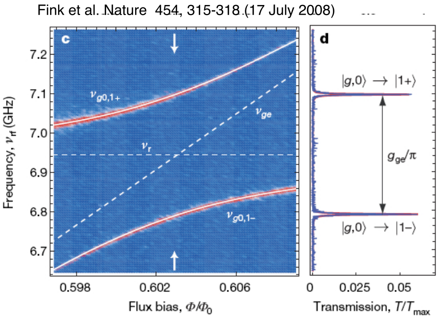
$$\Omega = \omega_c \ : \quad (|1, g\rangle \quad |0, e\rangle) \quad \text{degenerate}$$



Probe the transmission of a weak coherent signal as the qubit is detuned.

Vacuum Rabi splitting

Walraff group: Fink et al., Nature 454, 315 (2008) .



Coupling strength: $g/2\pi \sim 154$MHz.

Measurement in circuit QED.

No efficient microwave photon counters exist,

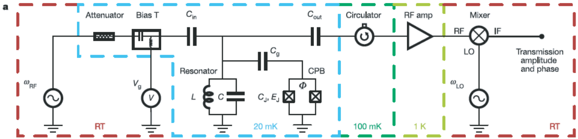
$$\frac{E_\mu}{E_{vis}} \sim 10^{-5}$$

Measurement in circuit QED.

No efficient microwave photon counters exist,

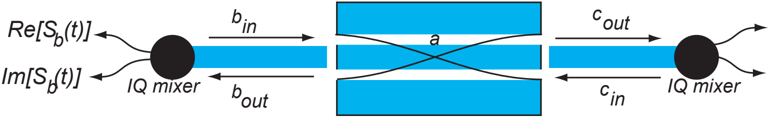
$$\frac{E_\mu}{E_{vis}} \sim 10^{-5}$$

Directly measure voltages:



Use electronic mixers (not beam splitters) for heterodyne/homodyne detection.

Measurement in circuit QED.



$$b_{out} = \sqrt{\kappa_b}\, a - b_{in} \qquad\qquad c_{out} = \sqrt{\kappa_c}\, a - c_{in}$$

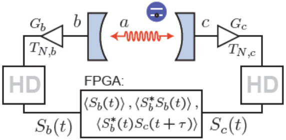
Stochastic current is conditioned on the quantum sate of the cavity field

$$S_b(t) = g_b \langle a \rangle_c + \eta(t)$$

where $\eta(t)$ is a noise term.

Measurement in circuit QED.

Example: *Measurements of the Correlation Function of a Microwave Frequency Single Photon Source*, Bozyigit et al. arXiv:1004.3987

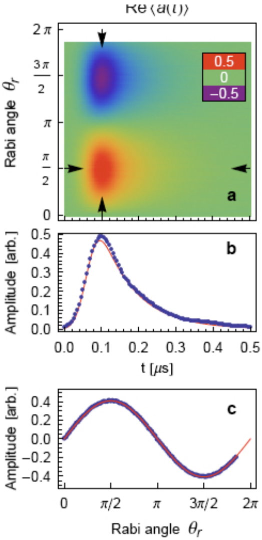


Note, measurements are made on both ends of the cavity.

Prepare (via qubit coherent control) a single photon state $\cos\theta_r|0\rangle + \sin\theta_r|1\rangle$ in the cavity.

$$S_b(t) \propto \langle a(t)\rangle = \sin\theta_r$$

Measurement in circuit QED.

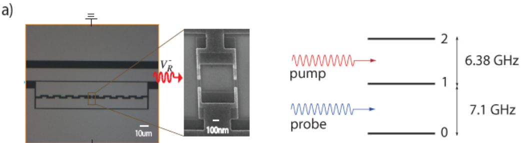


Measurements of the Correlation Function of a Microwave Frequency Single Photon Source
Bozyigit, et al
1002.3738

Transmon nonlinear microwave optics.

Switching a single microwave photon.

Delsing group: Hoi et al., arXiv:1103.1782v1



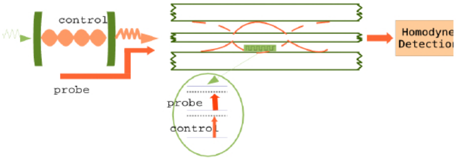
Hoi et al.

Pump-off: probe is reflected.
Pump-on: probe is transmitted.

Switch a single-photon signal from an input port to either of two output ports with an on-off ratio of 90%

Transmon as a single photon detector.

Bixuan Fan, Tom Stace, GJM and Goran Johansson (Chalmers):



Can we detect a single photon control by a phase shift on the probe?

Prepare a single photon in the source cavity at $t = 0$, and look at time resolved homodyne signal.

Transmon as a single photon detector.

Bixuan Fan, Tom Stace, GJM and Goran Johansson (Chalmers):

$$\begin{aligned}\dot{\rho} &= i[\rho, H_s] + \gamma_1\mathcal{D}[\hat{a}_c] + \gamma_2\mathcal{D}[\hat{\sigma}_{01}] + \gamma_3\mathcal{D}[\hat{\sigma}_{12}] \\ &- \sqrt{\gamma_1\gamma_2}([\hat{\sigma}_{10}, \hat{a}_c\rho] + [\rho\hat{a}_c^\dagger, \hat{\sigma}_{01}])\end{aligned}$$

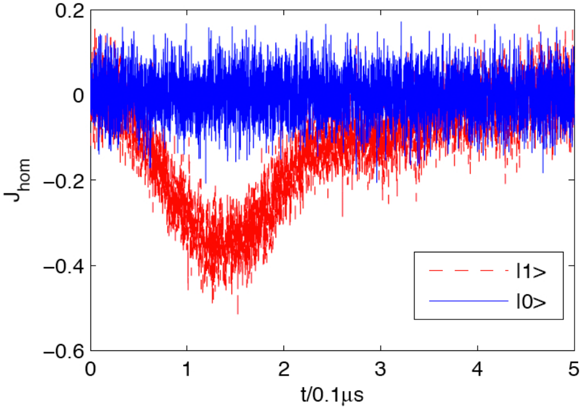
$$H_s = \Delta_{2p}\hat{\sigma}_{22} + \Delta_{1c}\hat{\sigma}_{11} + g_2\beta(\hat{\sigma}_{12} + \hat{\sigma}_{21})$$

Conditional homodyne current

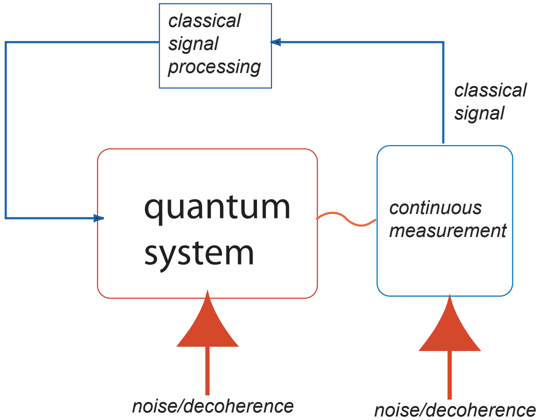
$$J_{hom}(t) = i\gamma_3\eta\,\langle\hat{\sigma}_{12} - \hat{\sigma}_{21}\rangle_J(t) + \sqrt{\gamma_3\eta}\xi(t)$$

Transmon as a single photon detector.

Bixuan Fan, Tom Stace, GJM and Goran Johansson (Chalmers):



Quantum feedback.



see H M Wiseman and GJM, *Quantum measurement and control*, CUP, 2010

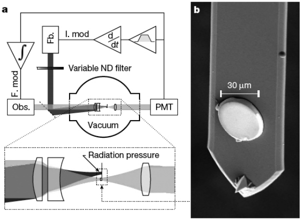
Feedback control, with measurement.

Feedback cooling of an optomechanical resonator.

Sub-kelvin optical cooling of a micromechanical resonator

Dustin Kleckner[1] & Dirk Bouwmeester[1]

nature Vol 444|2 November 2006|doi:10.1038/nature05231



but not quantum noise limited...

Entangling two SC qubits by feedback.

Usually create *entangled state* of two qubits via unitary control:

$$|0\rangle|0\rangle \rightarrow |0\rangle|1\rangle + |1\rangle|0\rangle$$

Enable:

- violation of Bell inequality
- quantum teleportation
- quantum cryptography
- quantum computing

In superconducting circuits:
Matthias Steffen, et al. Science **313**, 1423 (2006);

Entangling two SC qubits by feedback.

Dispersive limit: $\delta = \omega_c - \omega_q \gg g \sim 10\text{MHz}$

Effective Hamiltonian in the interaction picture.

$$H_I = \chi a^\dagger a(|1\rangle\langle 1| - |0\rangle\langle 0|) \equiv \chi a^\dagger a \sigma_z$$

Conditional frequency shift of cavity.

Entangling two SC qubits by feedback.

*Sarovar, Goan, Spiller , GJM, Phys. Rev. A, 72, 062327 (2005)**
Two CPB qubits, dispersive limit.

$$H_I = 2\chi J_z a^\dagger a + \chi(\sigma_1^+\sigma_2^- + \sigma_2^-\sigma_1^+)$$

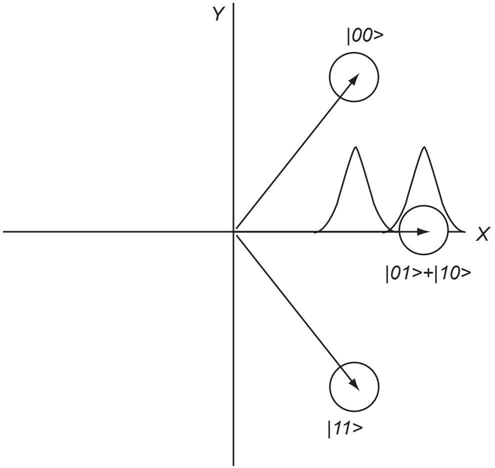
where $J_z = \sigma_{z1} + \sigma_{z2}$.

$$\begin{aligned} & e^{-i\theta J_z a^\dagger a}(|00> + |01> + |10> + |11>)|\alpha\rangle \\ = \quad & |00\rangle|\alpha e^{i\theta}\rangle + |11\rangle|\alpha e^{-i\theta}\rangle + (|10\rangle + |01\rangle)|\alpha\rangle \end{aligned}$$

Measure phase of field by homodyne detection.

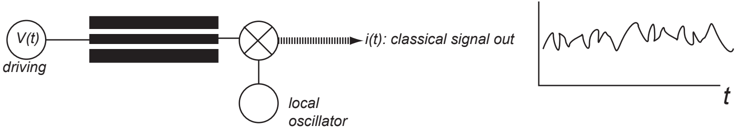
* See also "Tunable joint measurements in the dispersive regime of cavity QED", Lalumière, Gambetta, Blais arXiv:0911.5322

Entangling two SC qubits by feedback.



Nemoto & Munro. PRL 2004.

Continuous conditional evolution.



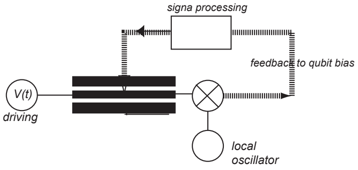
The homodyne current for *quantum limited detection* obeys

$$dI(t) = \kappa\langle a + a^\dagger\rangle + \sqrt{\kappa}dW(t)$$

Assume the only source of noise in the signal comes from the quantum source.

What is the conditional state of the source, conditioned on a particular current history, $i(t)$.

Feedback creation of entanglement.



Feedback homodyne current from SET to change bias conditions of the CPB.

Process signal by low-pass filter:

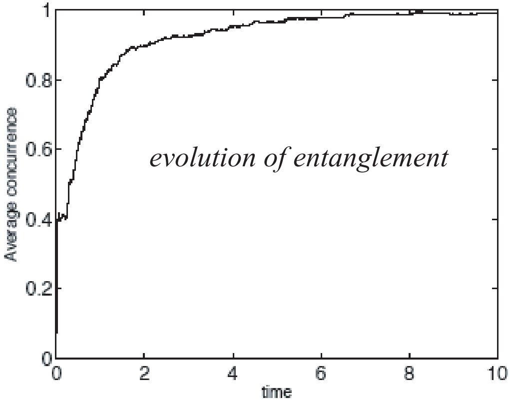
$$R(t) = \frac{1}{N} \int_{t-T}^{t} e^{-\gamma(t-t')} dI(t')$$

Add control Hamiltonian

$$H_{FB} = \lambda R(t)^3 (\sigma_{x1} + \sigma_{x2})$$

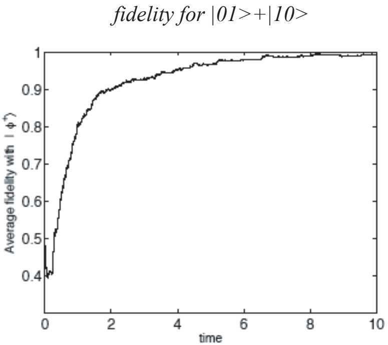
Feedback creation of entanglement.

$$d|\psi_c(t)\rangle = [-iH_I - iH_{FB}(t) - \kappa a^\dagger a]|\psi_c(t)\rangle dt + dI(t)\ a|\psi_c(t)\rangle$$



average over 300 trajectories.

Feedback creation of entanglement.

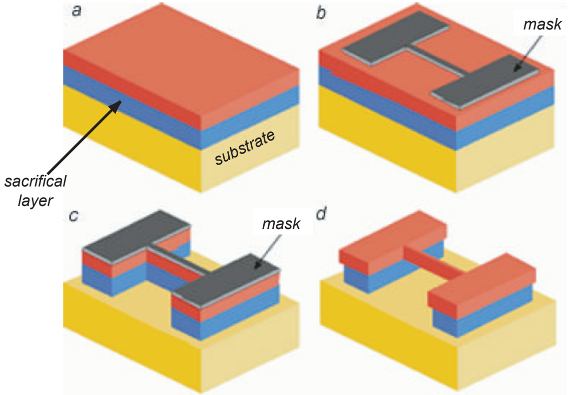


99% of trajectories converge to target state.

Sarovar et al., Phys. Rev. A 72, 062327 (2005)

Fabrication of nanomechanical systems.

How to make MEMS and NEMS



Roukes, Physics World, Feb, 2001.

Roukes, Physics World, 2001.

Quantum nanomechanical systems.

$$\hbar\nu > k_B T$$

Fundamental resonance frequency of a mechanical bar:

Table 1: Fundamental Frequency *vs.* Geometry for *SiC*, [Si], and (GaAs) Mechanical Resonators

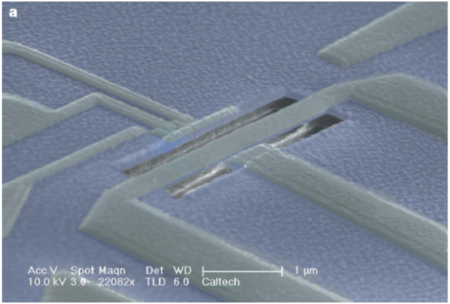
Boundary Conditions	**Resonator Dimensions** ($L \times w \times t$, *in* µ*m*)			
	$100 \times 3 \times 0.1$	$10 \times 0.2 \times 0.1$	$1 \times 0.05 \times 0.05$	$0.1 \times 0.01 \times 0.01$
Both Ends Clamped or Free	*120 KHz* [77] (42)	*12 MHz* [7.7] (4.2)	*590 MHz* [380] (205)	*12 GHz* [7.7] (4.2)
Both Ends Pinned	*53 KHz* [34] (18)	*5.3 MHz* [3.4] (1.8)	*260 MHz* [170] (92)	*5.3 GHz* [3.4] (1.8)
Cantilever	*19 KHz* [12] (6.5)	*1.9 MHz* [1.2] (0.65)	*93 MHz* [60] (32)	*1.9 GHz* [1.2] (0.65)

M.L. Roukes, "Nanoelectromechanical Systems", cond-mat/0008187

Roukes, 2000.

SC qubits + nanomechanics.

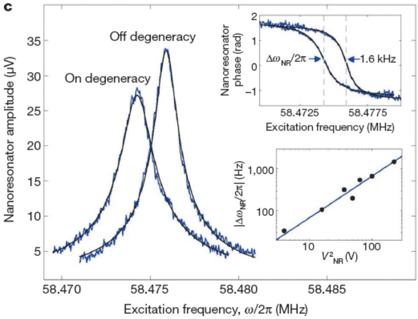
Nanomechanical measurements of a superconducting qubit



LaHaye, Suh, Echternach, Schwab & Roukes, *Nature, (2009)*

SC qubits + nanomechanics.

Nanomechanical resonator is driven capacitively
Qubit is driven by microwaves,

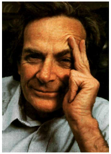


Measure resonator frequency shift as charge (ϵ) and tunneling (Δ) bias of qubit are changed.

Engineered Quantum Systems for simulation.

Synthetic Quantum Systems & Simulation

Program



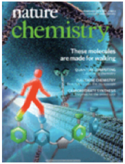
Richard Feynman

Simulating physics with computers,
Int. J. Theoretical Physics (1982)

equations $\propto$ e$^{\text{particles}}$

Seth Lloyd

Universal quantum simulators,
Science (1996)

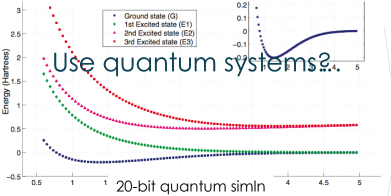


QT Lab, EQuS

Towards quantum chemistry on
a quantum computer
Nature Chemistry (2010)

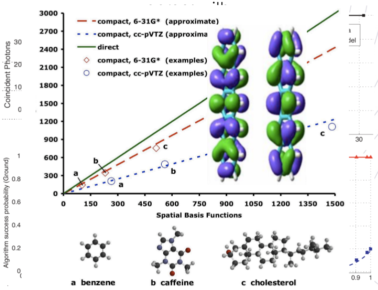
Editors choice for best paper

Exploiting the quantum advantage



Use quantum systems?..

20-bit quantum simln

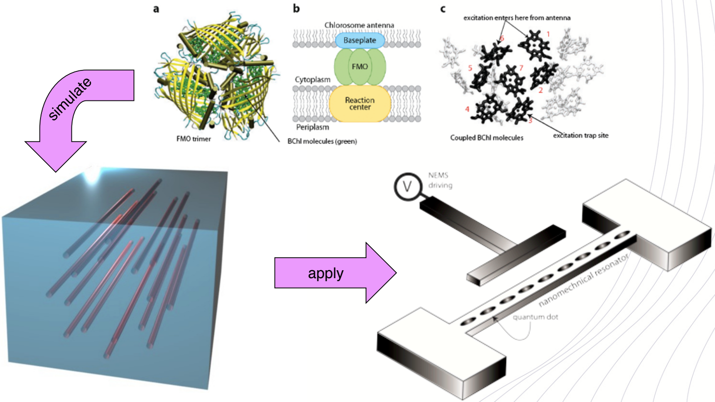


Engineered Quantum Systems for simulation.

Synthetic Quantum Systems & Simulation

Program

Harnessing the quantum advantage

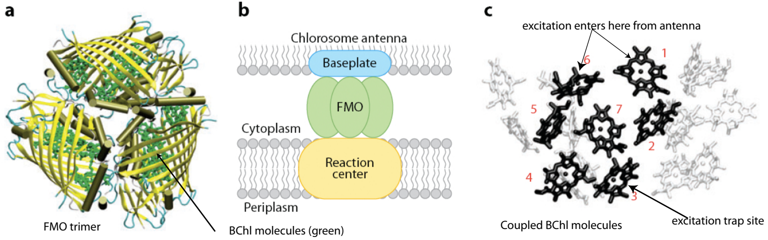


Key Outcome: *Experimentally simulate photosynthetic energy transfer using a 3D quantum walk. Use lessons learned to design new light-harvesters.*

Enhanced energy transport due to vibrational modes.

Energy transport through coupled chromophores in various photosynthetic systems is fast and largely coherent.

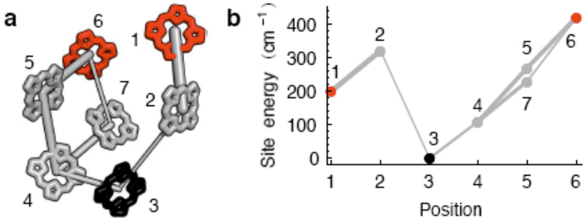
Fenna-Matthews-Olson (FMO) complex.



Dynamics of Light Harvesting in Photosynthesis, Cheng and Fleming, Annu Rev Phys Chem (2009).

Enhanced energy transport due to vibrational modes.

Fenna-Matthews-Olson (FMO) complex.



Hoyer, Sarovar and Whaley, arXiv:0910.1847

both site energies and dipole couplings are disordered.

Enhanced energy transport due to vibrational modes.

Coherence and rapid transport results from complex interplay between dipole coupling of chromopores and vibrational motion of the protein cage.

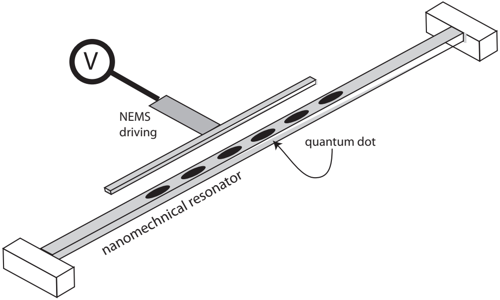
A. Olaya-Castro, C. F. Lee, F. F. Olsen, and N. F. Johnson, Phys. Rev. B 78, 085115 (2008).
M. Mohseni, P. Rebentrost, S. Lloyd, and A. Aspuru-Guzik, J. Chem. Phys. 129, 174106 (2008).
M. B. Plenio and S. F. Huelga, New J. Phys. 10, 113019 (2008).
P. Rebentrost1, M. Mohseni, I. Kassal, S. Lloyd, and A. Aspuru-Guzik, New J. of Phys. 11, 033003 (2009).
M. Sarovar, A. Ishizaki, G. R. Fleming, and K. B. Whaley, arXiv:0905.3787v1 (2009)
S. Hoyer, M, Sarovar, and K. B. Whaley, arXiv:0910.1847v1 (2009)
P. Rebentrost, M. Mohseni,and A. Aspuru-Guzik, J. Phys. Chem. B 113, 9942 (2009).
F. Caruso, A. W. Chin, A. Datta, S. F. Huelga, and M. B. Plenio, J. of Chem. Phys. 131, 105106 (2009).
J. Eckel, J. H. Reina, and M. Thorwart, New J. of Phys. 11, 085001 (2009).

and many others...

phonon baths seen by each chromophore are NOT independent.

Enhanced energy transport due to vibrational modes.

A simple nanomechanical model:



Coupled exciton quantum dots in a coherently driven NEMS.

F. Semiao, K. Furuya and GJM, New J. Phys. 12 083033 (2010).

Enhanced energy transport due to vibrational modes.

Quantum dot Hamiltonian

$$H_N = \sum_{j=1}^{N} \frac{\omega_j}{2}\sigma_z^j + \sum_{j}^{N} \lambda_j(\sigma_+^j \sigma_-^{j+1} + \sigma_-^{j+1}\sigma_+^j)$$

with $\sigma_z = |e\rangle\langle e| - |g\rangle\langle g|$

Enhanced energy transport due to vibrational modes.

Quantum dot Hamiltonian

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with $\sigma_z = |e\rangle\langle e| - |g\rangle\langle g|$ Add vibrational Hamiltonian

$$H_{NV} = H_N + \nu \hat{a}^\dagger \hat{a} + \varepsilon(a^\dagger e^{-i\nu t} + a e^{i\nu t}) + \hat{q}\sum_{j=1}^{N} g_j \sigma_z^j$$

Enhanced energy transport due to vibrational modes.

Quantum dot Hamiltonian

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Dynamics includes damping of vibrational motion

$$\frac{d\zeta}{dt} = -i[H_{NV}, \zeta] + \gamma(\bar{n}+1)\mathcal{D}[a]\zeta + \gamma\bar{n}\mathcal{D}[a^\dagger]\zeta$$

Enhanced energy transport due to vibrational modes.

- Work in the single excitation sector
- Adiabatically eliminate vibrational motion.
- Inject an excitation at site 1
- Absorb excitation at site N

Compute the average absorption probability, the *efficiency*, to time t

Enhanced energy transport due to vibrational modes.

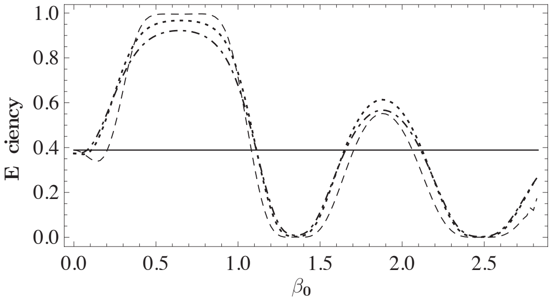


Figure: Efficiency as a function of β_0 for an integration time $t = 3000\lambda$. The network frequencies are $\omega_3 = 1.0$ and $\omega_1 = \omega_2 = \omega_4 = \omega_5 = \omega_6 = 0$, the couplings between chromophores and vibration mode $g_3 = 1.5$ and $g_1 = g_2 = g_4 = g_5 = g_6 = 0.5$, decay constant to the sink $\kappa = 0.2$, mean number of thermal phonons $\bar{n} = 5$, and inter-chromophore coupling $\lambda = 0.1$. The different curves correspond to γ equal to 1.1×10^5 (dashed), 1.1×10^3 (dotted) and 5.5×10^2 (dot-dashed).

Enhanced energy transport due to vibrational modes.

Special driving amplitudes?

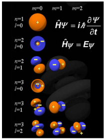
Go to an interaction picture at time-dependent on-site energies

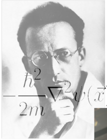
$$H_I(t) = \lambda \sum_{n=-\infty}^{n=\infty} \sum_{j=1}^{N} [(i)^{-n} J_n(4\Delta g_j \beta q_0/\nu)) e^{i(\Delta\omega_j - n\nu)t} e^{4i\Delta g_j \beta q_0/\nu} \sigma_+^j \sigma_-^{j+1} + h.c.].$$

$\Delta\omega_j = \omega_j - \omega_{j+1}$ site-disorder,
$\Delta g_j = g_j - g_{j+1}$ coupling disorder

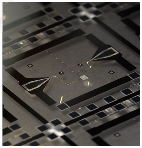
resonances at $\Delta\omega_j - n\nu$, with strength given by the Bessel function.

No disorder, no resonances!





$$i\hbar\frac{\partial\psi(\vec{x})}{\partial t} = -\frac{\hbar^2}{2m}\nabla^2\psi(\vec{x}) + V(\vec{x})\psi(\vec{x})$$



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Thanks

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The Swedish Foundation for International Cooperation in Research and Higher Education