Survey of nanoscale quantum engines: thermal control, stochastic cycles, and measurement

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KITP program:
Energy and Information Transport in Non-Equilibrium Quantum Systems

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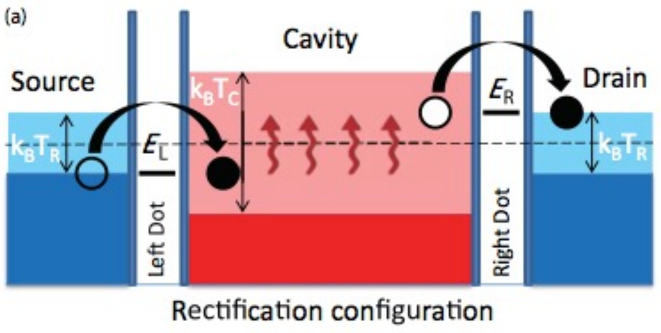
U.S. DEPARTMENT OF ENERGY | Office of Science

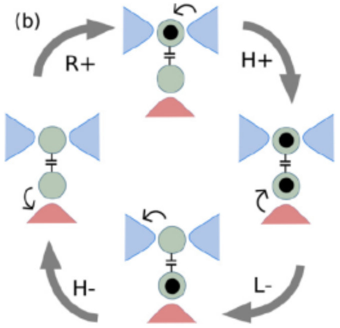
Plug for Quantum Studies submissions

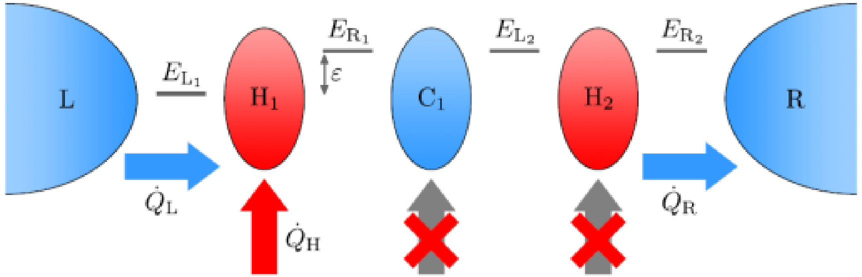
- Journal dedicated to quantum physics
- Quantum Thermodynamics contributions welcome

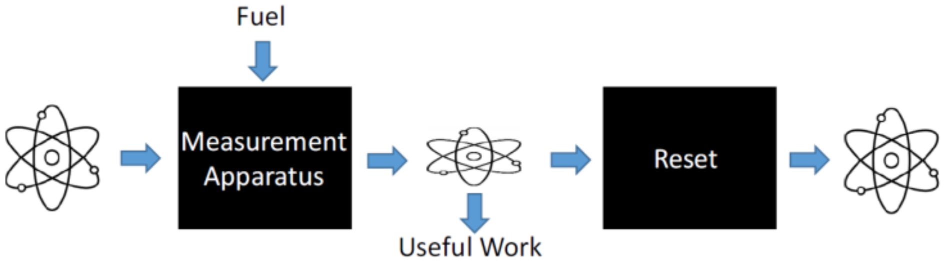
Talk Outline

- Thermal engines
- Stochastic cycles
- Thermal control
- Measurement as a new quantum resource









Thanks to my collaborators on these projects!

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Rafa Sánchez
(Madrid) and
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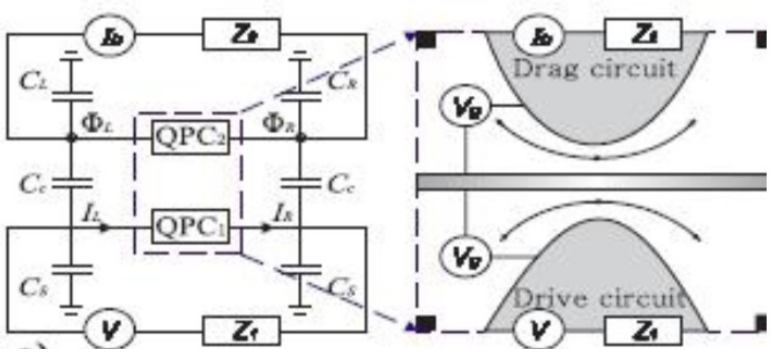
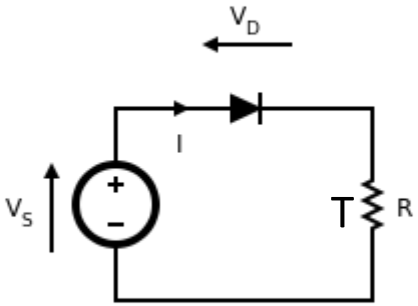
Historical motivation



A. Levchenko and A. Kamenev, PRL 101, 216806 (2008)

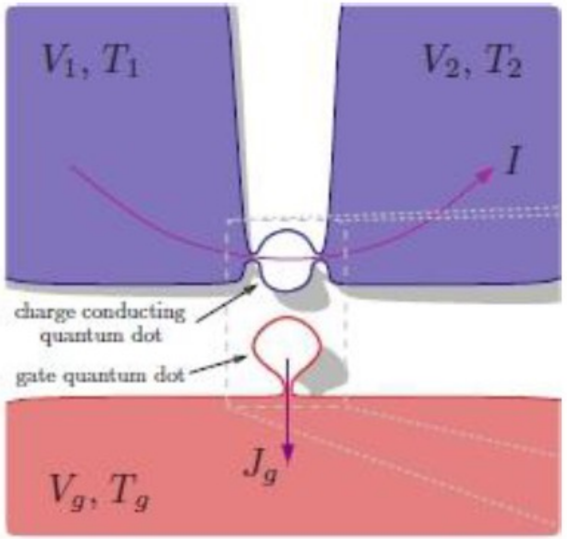


In 1950 Leon Brillouin asked why a circuit containing a resistor and diode could not **rectify** its own **thermal fluctuations**. If possible, this would violate the second law of thermodynamics.

In mesoscopic physics, from the 1990s on, scientists have been increasingly interested in designing thermoelectric devices.

Recently, there have been interesting proposals and experiments made to miniaturize rectifiers to the single electron level.

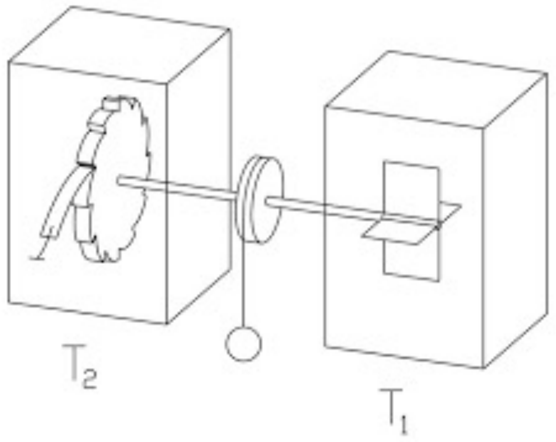
While these can in principle reach ideal efficiencies, the resulting currents and power is extremely small.



R. Sanchez and M. Buttiker, PRB 83, 085428 (2011)

Rectification of electrical current requires three ingredients:

1. Different temperatures in the system.
2. Symmetry breaking between left and right leads.
3. Nonlinearity.

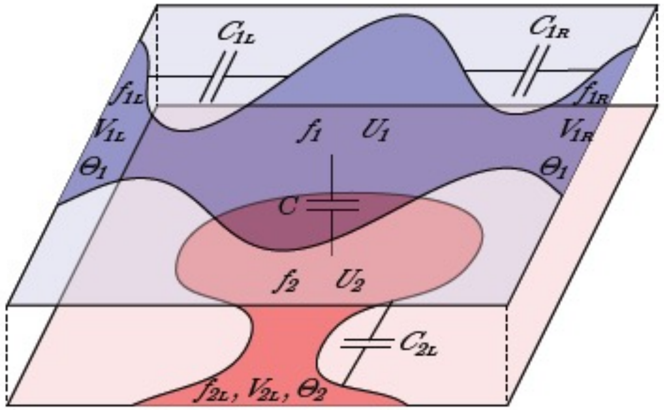


Mesoscopic conductor thermoelectrics

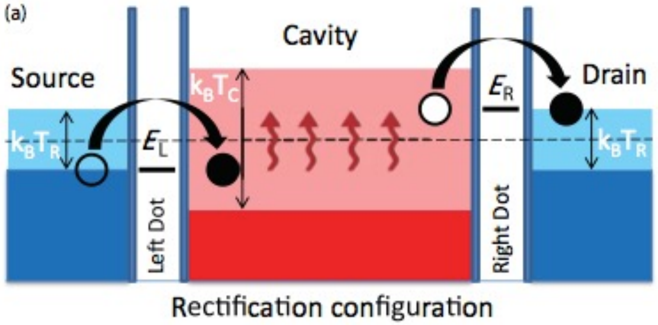
- Introduce energy filtering to give energy-dependent transmission
- Break symmetry with either spatial asymmetry or magnetic field
- Apply both thermal and electrical bias

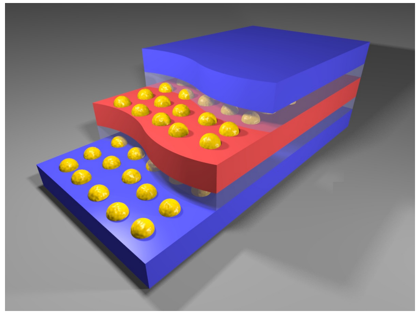
Fundamental Goal: Design new thermal devices on the nanoscale: Heat engines, energy harvesters, refrigerators, heat diodes, etc.

Chaotic cavities, resonant tunneling dots and well and superlattices

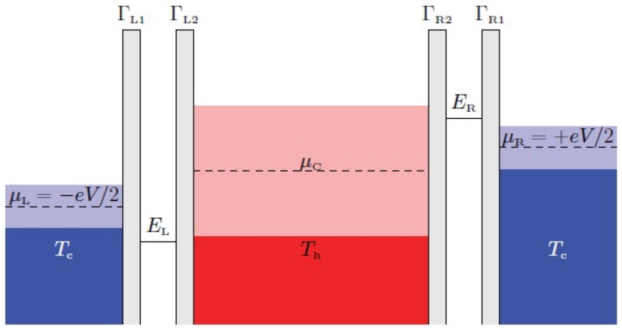


Phys. Rev. B 85, 205301 (2012), Björn Sothmann, Rafael Sánchez, ANJ, Markus Büttiker

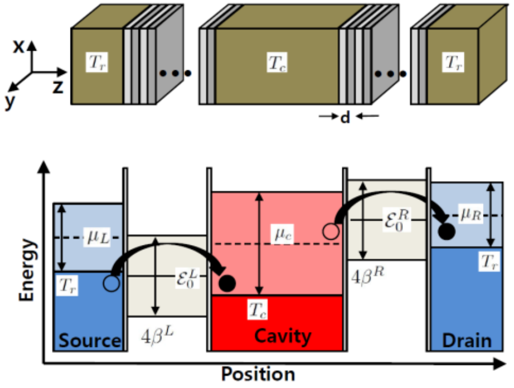




AN Jordan, B Sothmann, R Sánchez, M Büttiker
Physical Review B, 2013

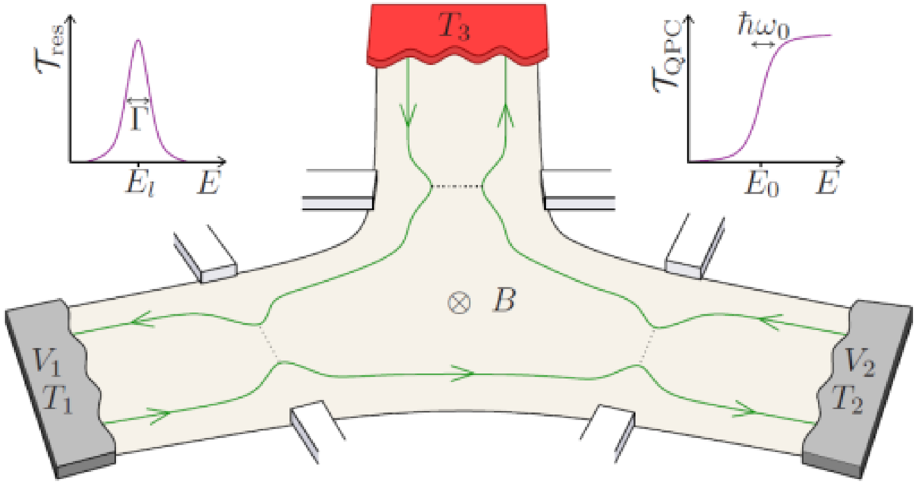


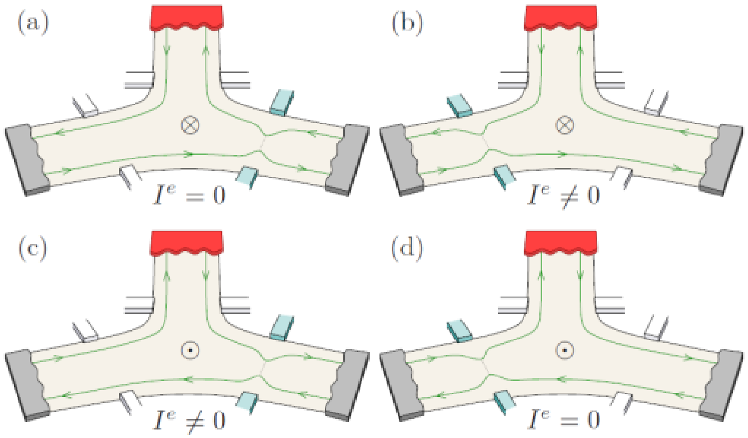
ANJ, Sothmann, Sanchez, and Buttiker,
New Journal of Physics, 2013.



Yunjin Choi and ANJ,
Physica E 74, 465 (2015)

Quantum Hall heat engines

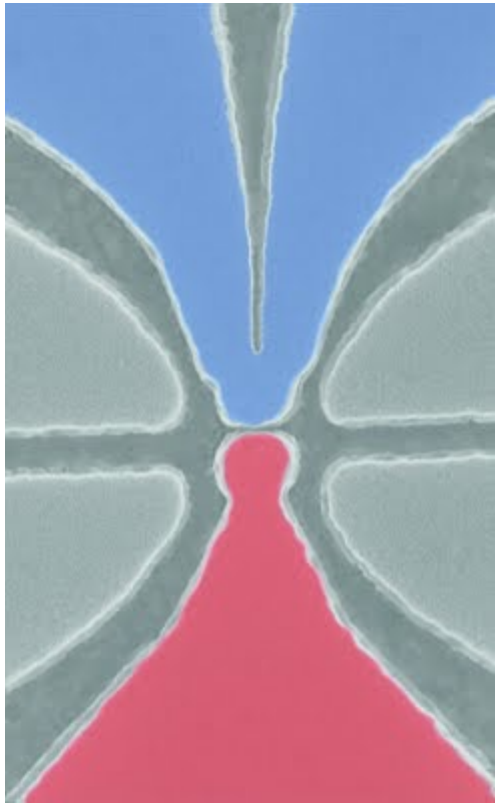




Rafael Sánchez, Björn Sothmann, ANJ
Phys. Rev. Lett. 114, 146801 (2015)

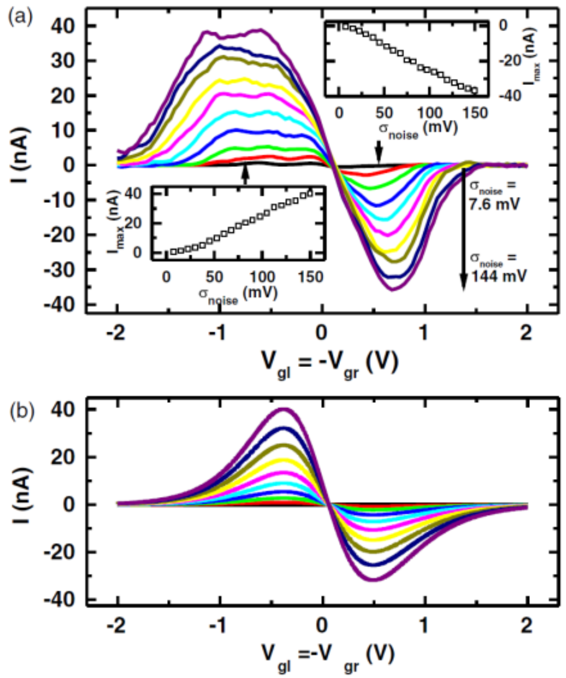
The chirality of the electron motion and the three terminal geometry allows novel thermoelectricity where one can have a Peltier effect and no Seebeck effect, and visa versa.

Some nice experiments on quantum thermal machines:



F. Hartmann, P. Pfeffer, S. Höfling, M. Kamp, and L. Worschech
Phys. Rev. Lett. **114**, 146805 – Published 10 April 2015

Wuerzburg group



nature COMMUNICATIONS

ARTICLE

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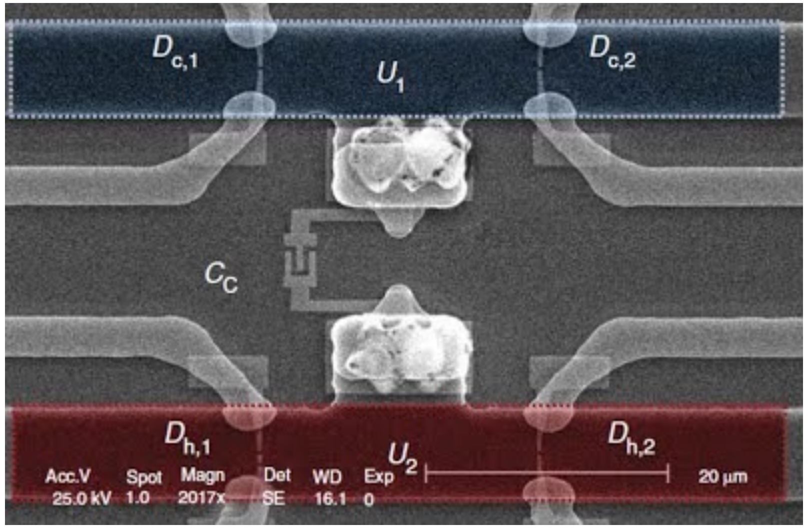
Harvesting dissipated energy with a mesoscopic ratchet

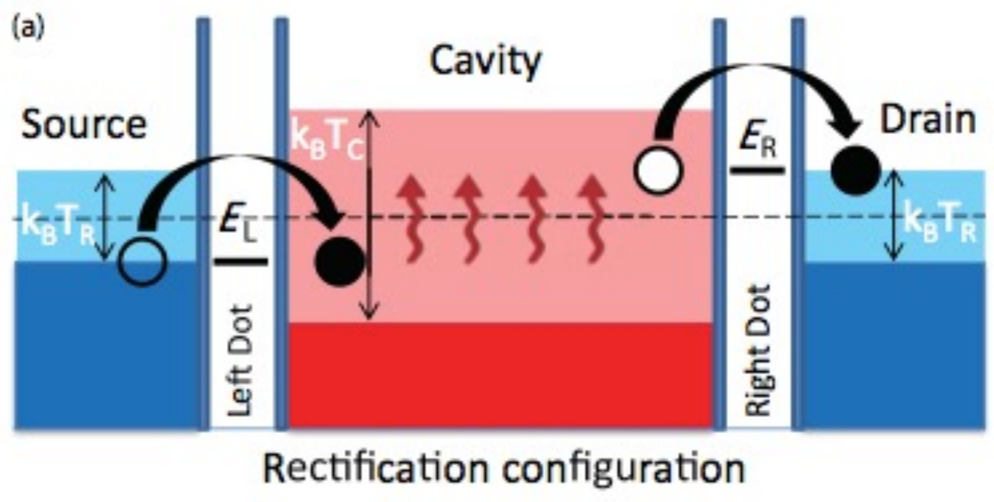
B. Roche[1,*], P. Roulleau[1,*], T. Jullien[1], Y. Jompol[1,†], I. Farrer[2], D.A. Ritchie[2] & D.C. Glattli[1]



Resonant tunneling quantum dot engine

Nanoengine that uses two quantum dots, so electrons *resonantly tunnel*.

Hot cavity is kept in thermal equilibrium with energy source.



Electrons start at a cold contact, enter a hot cavity at one energy E_L, take energy away from the hot cavity, and exit at a higher energy E_R into the opposite cold contact, generating an electrical current.

Resonant tunneling quantum dot engine

Model details:

- Each dot has Lorentzian transmission profile.
- We impose conservation of average energy and charge.
- We assume the central cavity is in thermal equilibrium with hot energy source.

We define the *energy gain* as $\Delta E = E_R - E_L$.

In order to transfer an electron from the right to left contact in the steady state, each electron must gain energy ΔE.

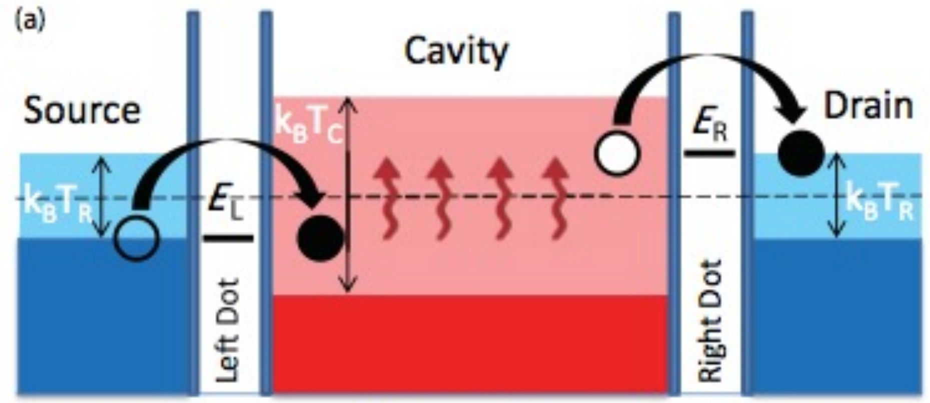
Consequently the charge and heat currents are proportional:

$I = \frac{e}{\Delta E} J$, where I is the electrical current and J is the heat current.

This is true regardless of the left and right chemical potentials, μ_L, μ_R.

Therefore, the thermodynamic efficiency is simply:

$$\eta = \frac{\mu_L - \mu_R}{\Delta E}$$



Rectification configuration

Resonant tunneling quantum dot engine

In the limit when the level width γ is smaller than the other energy scales in the problem, we have a simple result for the heat current:

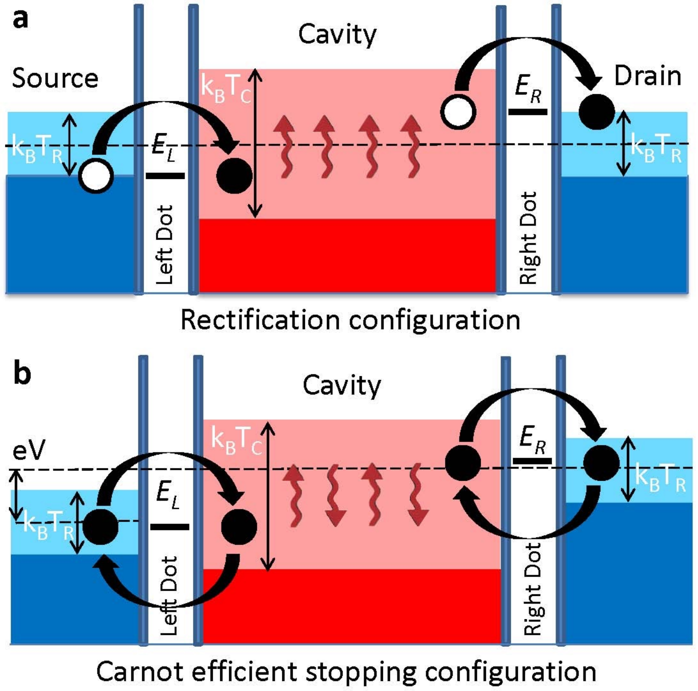
$$J = \frac{2\gamma \Delta E}{h}[f(\Delta E/2, T_{\rm C}) - f(\Delta E/2 - \mu/2, T_{\rm R})],$$

Here, h = Planck's constant, f = Fermi function, and T_C, T_R are the cavity and reservoir temperatures.

$$\mu_{R,L} = \pm\mu/2 + (E_L + E_R)/2$$

When a load is placed across the circuit, a back-flow of current occurs. When the rectified current matches the back-flow current, the output power is zero (I=J=0), but the system reaches the **Carnot efficiency** and is reversible.

This happens when $\mu = \Delta E\, \eta_C$



Resonant tunneling quantum dot engine

Optimize power

Broadening the resonant levels allows electron backflow to the left, decreasing efficiency, however, it also allows more electrons through, creating more power.

P_max ~ 0.1 pW at a temperature difference of 1K.

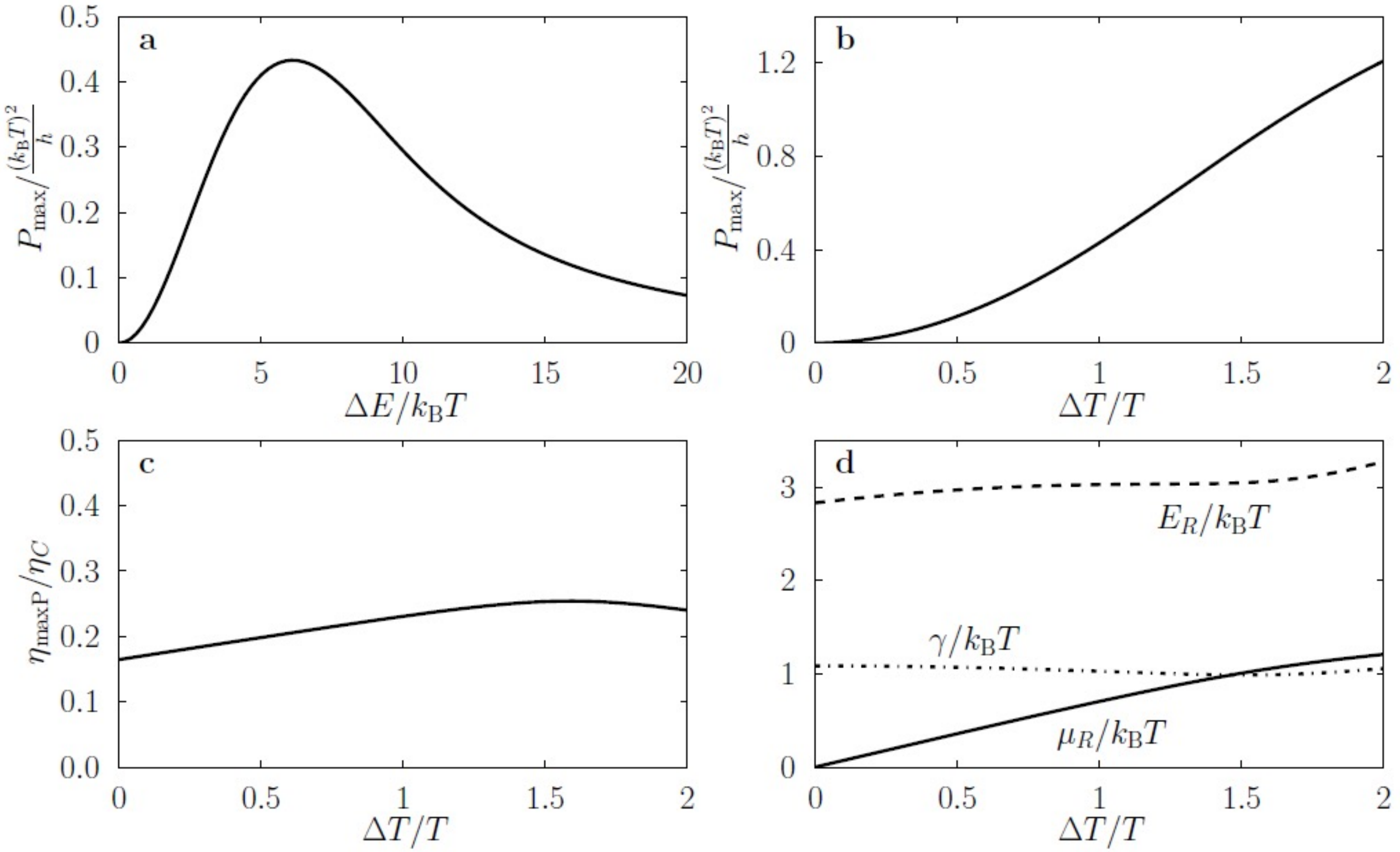
$$\Delta T = T_C - T_R$$

$$T = (T_C + T_R)/2$$

Choose

$$\gamma = k_B T$$

$$\Delta E = 6\, k_B T$$



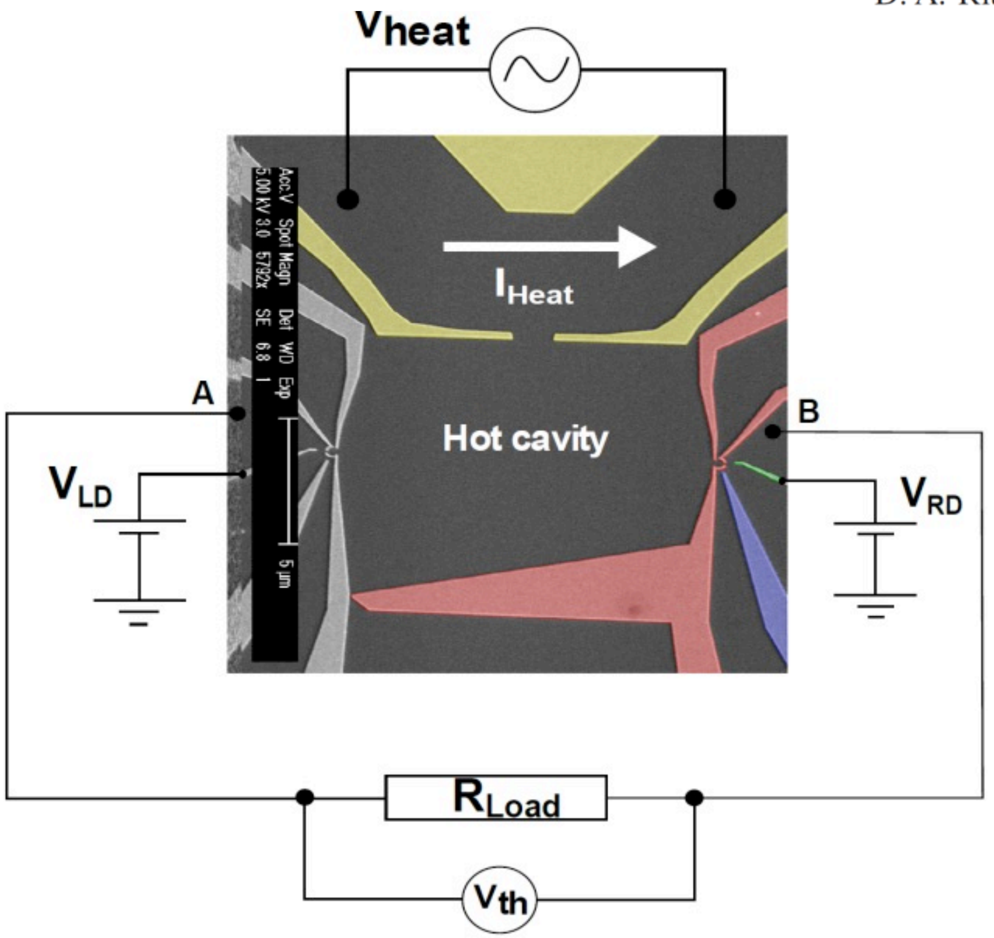
Resonant tunneling quantum dot engine

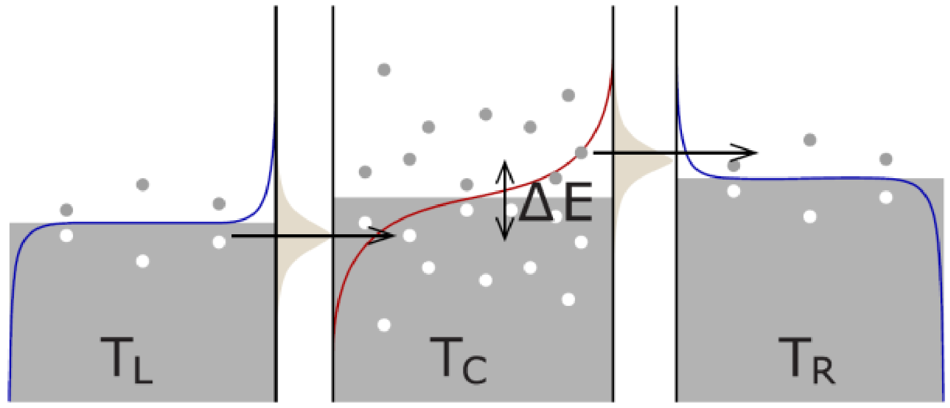
PHYSICAL REVIEW LETTERS **123**, 117701 (2019)

Editors' Suggestion

Experimental Realization of a Quantum Dot Energy Harvester

G. Jaliel,[1,*] R. K. Puddy,[1] R. Sánchez,[2] A. N. Jordan,[3] B. Sothmann,[4] I. Farrer,[5] J. P. Griffiths,[1] D. A. Ritchie,[1] and C. G. Smith[1]



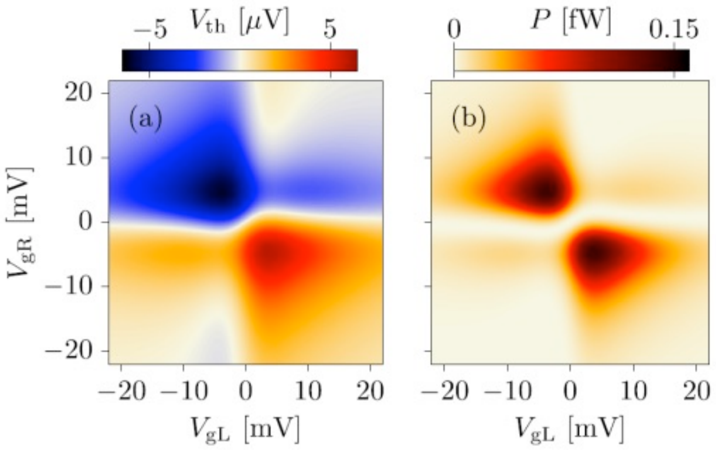


Charles Smith group, Cambridge, UK

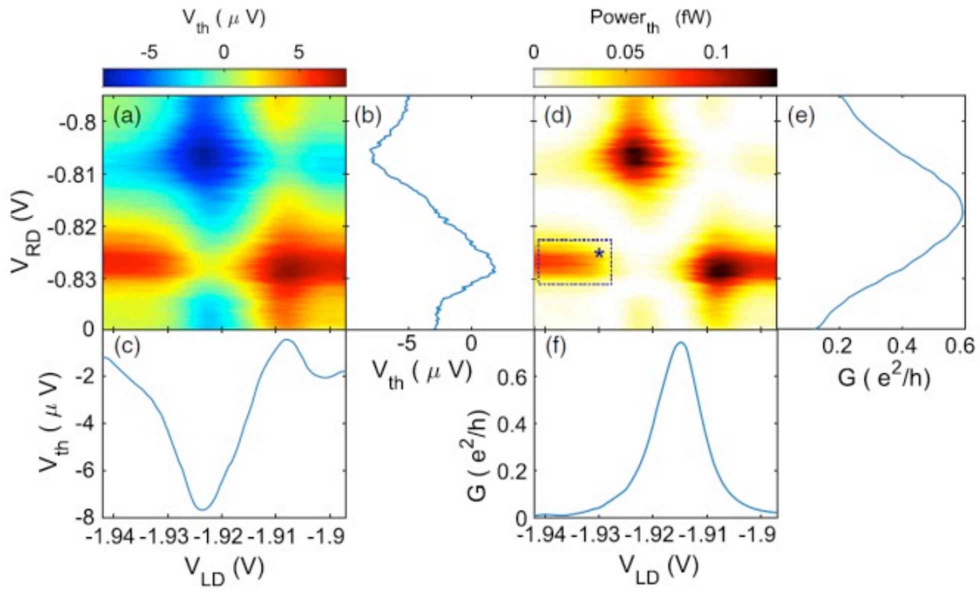
Resonant tunneling quantum dot engine

Experiment – Charles Smith group, Cambridge, UK

Theory



Experiment

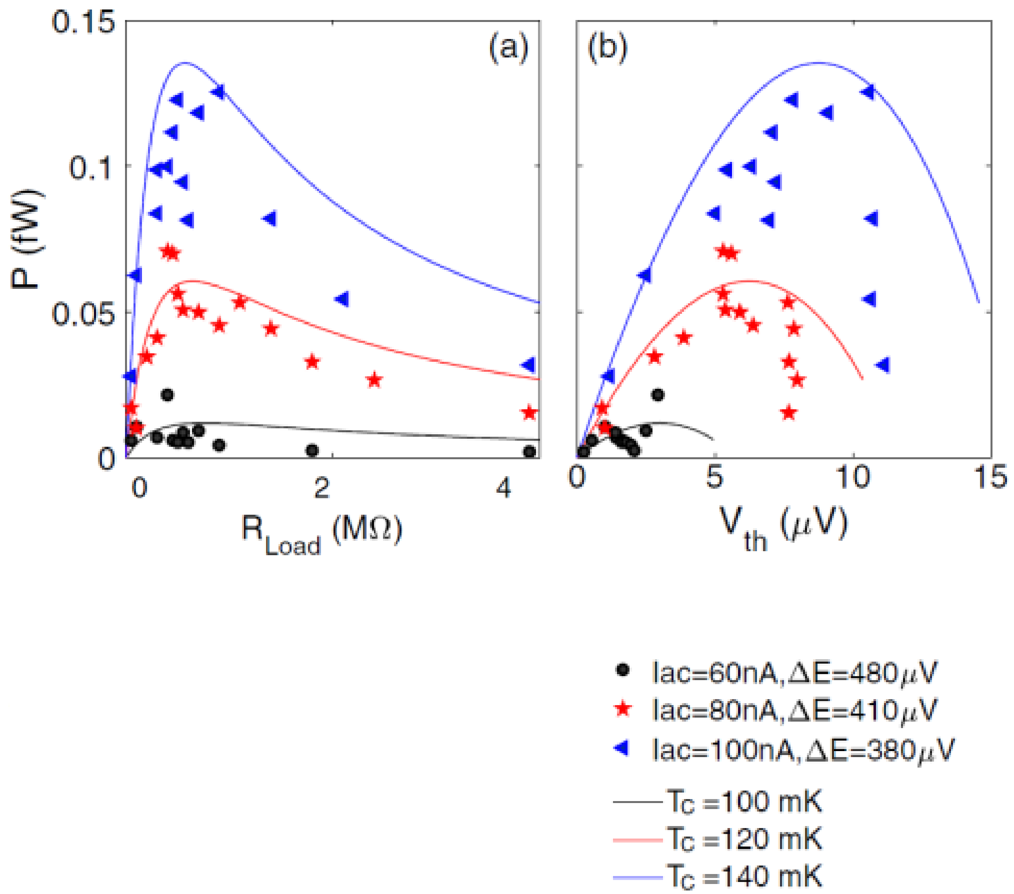


The thermal voltage V and power across the device, as a function of left and right plunger gates measured whilst an AC current, is applied to the heating channel.

Resonant tunneling quantum dot engine

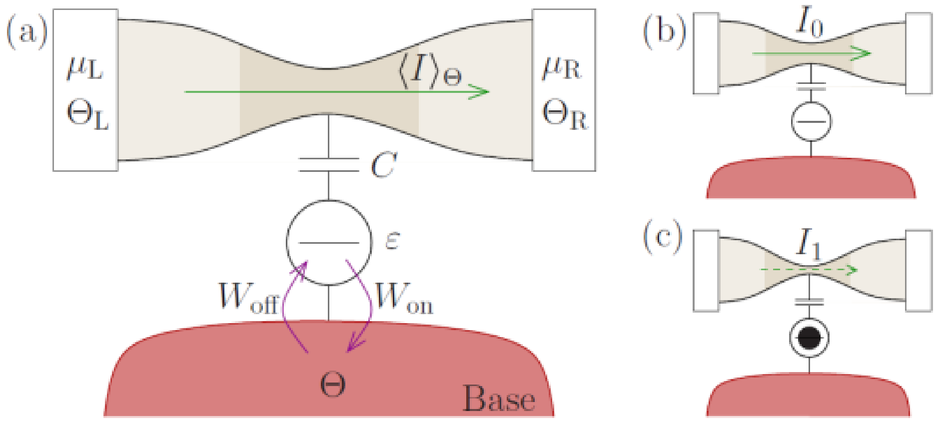
Charles Smith group, Cambridge, UK

Engine characteristics. Panel (a) depicts the maximum thermal power from the measurements with different loading resistance, whilst applying AC current 60 nA, 80 nA and 100 nA on the heating channel. Panel (b) shows the thermal power and its relative thermal voltage.



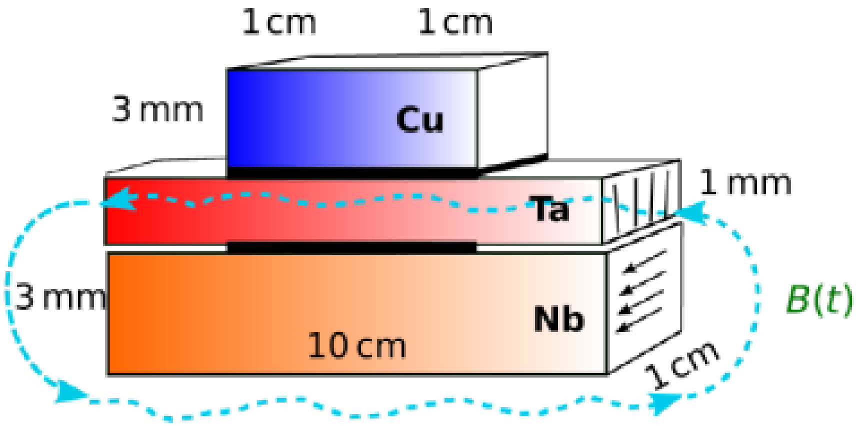
Quantum thermal machines created at the last KITP program!

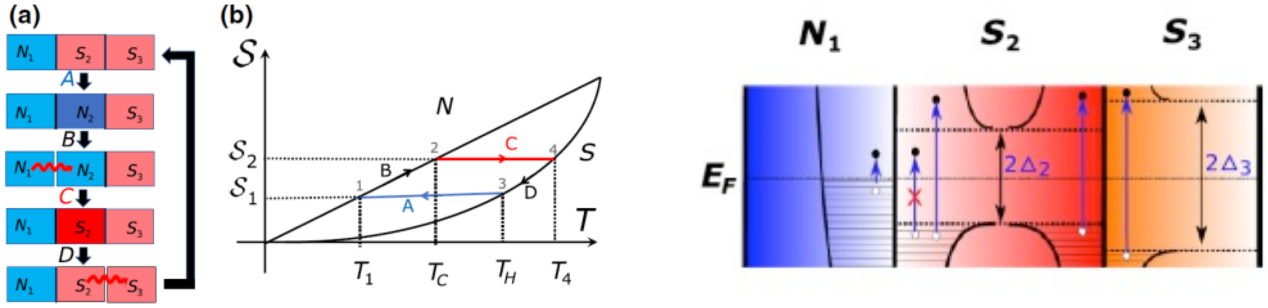
Single electron thermometer and thermoelectric transistor



Jing Yang, Cyril Elouard, Janine Splettstoesser, Björn Sothmann, Rafael Sánchez, and ANJ
PRB (2017)

Superconducting refrigerator





Sreenath K. Manikandan, Francesco Giazotto, and ANJ
PR Appl. 2019

Stochastic Cycles in thermal machines

Motivation: At the last KIPT meeting, we had a fight with Robert Alicki.

Claim: No steady-state thermoelectric engine can exist without self-oscillation.

Self-oscillation is a spontaneous process where a system exhibits periodic behavior despite no cyclic driving.

R. Alicki, Thermoelectric generators as self-oscillating heat engines, J. Phys. A: Math. Theor. **49**, 085001 (2016).

Stochastic Cycles in thermal machines

RA argues there is a contradiction:

A system must have **cyclic motion** to produce work, but the engines I have been talking about go to a **steady-state**. This means such a system cannot perform useful work.

Our resolution: Cycles? – Yes. Periodicity? – Not necessarily. This lead to a nice work investigating the stochastic nature of the cycles of these thermoelectric engines.

PHYSICAL REVIEW B **103**, 075404 (2021)

Stochastic thermodynamic cycles of a mesoscopic thermoelectric engine

R. David Mayrhofer,[1] Cyril Elouard,[1,*] Janine Splettstoesser,[2] and Andrew N. Jordan[1,3]

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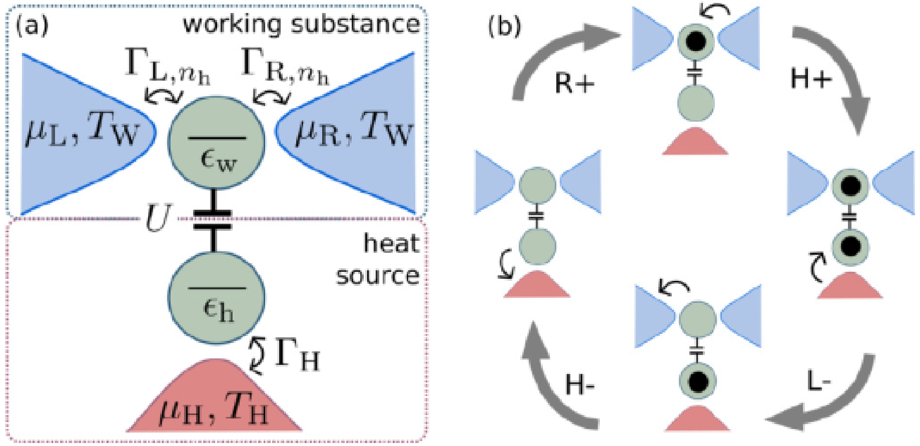
Stochastic Cycles in thermal machines



$$\dot{\rho}(t) = \mathcal{W}\rho(t),$$

$$\mathcal{W} = \begin{pmatrix} -W_0^+ & W_{\mathrm{H},0}^- & W_{\mathrm{W},0}^- & 0 \\ W_{\mathrm{H},0}^+ & -W_{\mathrm{W},1}^+ - W_{\mathrm{H},0}^- & 0 & W_{\mathrm{W},1}^- \\ W_{\mathrm{W},0}^+ & 0 & -W_{\mathrm{W},0}^- - W_{\mathrm{H},1}^+ & W_{\mathrm{H},1}^- \\ 0 & W_{\mathrm{W},1}^+ & W_{\mathrm{H},1}^+ & -W_1^- \end{pmatrix}$$

$$\rho(t) = (p_{00}, p_{01}, p_{10}, p_{11})^{\mathsf{T}}.$$

4 possibilities exist: Each dot is empty or filled.

$$W_{\alpha,n_{\overline{j_\alpha}}}^+ = \Gamma_{\alpha,n_{\overline{j_\alpha}}} f_\alpha(\epsilon_{j_\alpha} + U n_{\overline{j_\alpha}}),$$

$$W_{\alpha,n_{\overline{j_\alpha}}}^- = \Gamma_{\alpha,n_{\overline{j_\alpha}}}(1 - f_\alpha(\epsilon_{j_\alpha} + U n_{\overline{j_\alpha}})).$$

Transition rates depend on tunneling rates, Fermi occupation, and charging energy, U.

Stochastic Cycles in thermal machines

$$\mathcal{A} = \frac{\Gamma_{R,0}\Gamma_{L,1} - \Gamma_{R,1}\Gamma_{L,0}}{(\Gamma_{L,0} + \Gamma_{R,0})(\Gamma_{L,1} + \Gamma_{R,1})} \to 1$$

In order to generate work – that is, drive a current against a bias, the asymmetry A should be nonzero, and ideally as large as possible. The efficiency hits Carnot when A=1.

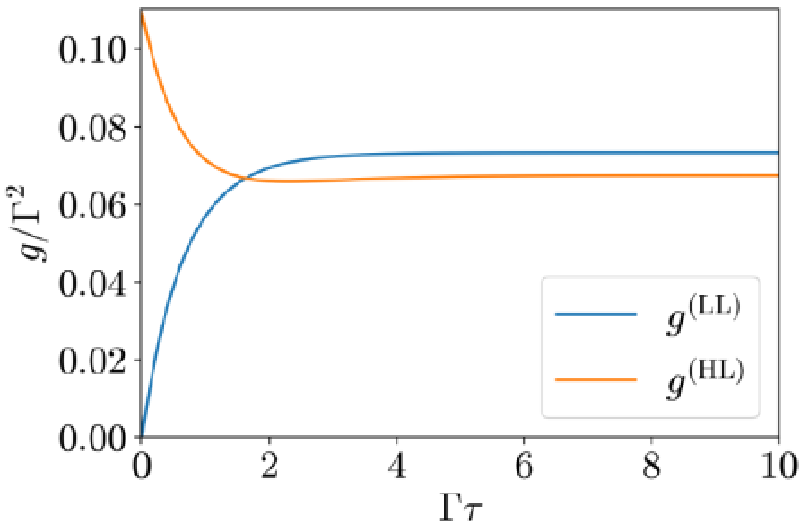
Could self-oscillations be hiding somewhere?

Check – The dynamics of the average occupations of each dot – N_h, N_w – their dynamical equations take the form of driven, coupled oscillators:

$$\ddot{N}_w + \kappa\dot{N}_w + \omega^2 N_w = -AN_h + B,$$
$$\dot{N}_h + \Gamma_H N_h = -CN_w + D.$$

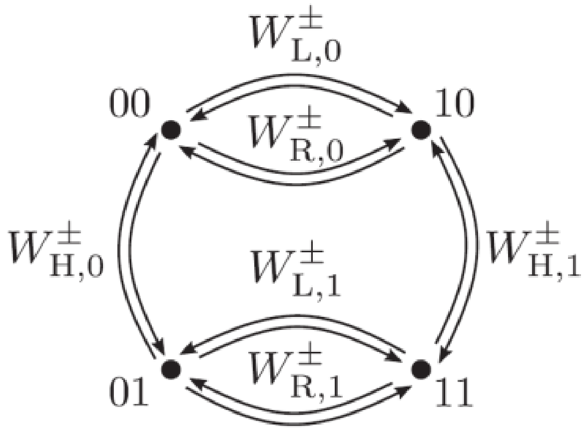
However, for our parameters, the system is always in the **over-damped** regime, **so no oscillations are present.**

Correlation functions also reveal no oscillations:



This leads us to a trajectory-based analysis

Cycle	Jumps	$\delta n_{\rm L}(\mathcal{C})$	$Q_{\rm H}(\mathcal{C})$	$\delta\sigma(\mathcal{C})$
$\mathcal{C}_1$	$L_+H_+R_-H_-$	-1	U	$(\beta_{\rm W}-\beta_{\rm H})U+\beta_{\rm W}\Delta\mu$
$\mathcal{C}_2$	$R_+H_+R_-H_-$	0	U	$(\beta_{\rm W}-\beta_{\rm H})U$
$\mathcal{C}_3$	$L_+H_+L_-H_-$	0	U	$(\beta_{\rm W}-\beta_{\rm H})U$
$\mathcal{C}_4$	$R_+H_+L_-H_-$	1	U	$(\beta_{\rm W}-\beta_{\rm H})U-\beta_{\rm W}\Delta\mu$
$\mathcal{C}_5$	$H_+L_+R_-H_-$	-1	0	$\beta_{\rm W}\Delta\mu$
$\mathcal{C}_6$	L_+R_-	-1	0	$\beta_{\rm W}\Delta\mu$



Markov chain

We can categorize the fundamental cycles in the system, along with their entropy production, $\delta\sigma$, amount of charge transported (from left), and heat provided by the hot reservoir, Q_H

The theory of stochastic thermodynamics can then be applied to calculate the cycle statistics and quantities such as the rectified current from a cycle perspective. Applying large deviation theory,

$$\mathcal{I}_\gamma = \frac{1}{\tau}\sum_{\mathcal{C}\in\text{cycles}} N_{\mathcal{C}}(\gamma)\delta n_{\rm L}(\mathcal{C}) + \frac{\delta n_{\rm L}(\tilde{\gamma})}{\tau}. \qquad \mathcal{I}_\gamma \underset{\Gamma\tau\to\infty}{\sim} \bar{I}_{\rm L}, \quad \sum_{\mathcal{C}\in\text{cycles}} j_{\mathcal{C}}(\gamma)\delta n_{\rm L}(\mathcal{C}),$$

j is the probability rate of cycle C in a long trajectory.

If you know the cycle statistics, then you know all

- Cycle resolved entropy production also obeys a fluctuation theorem, related to Crook's theorem.

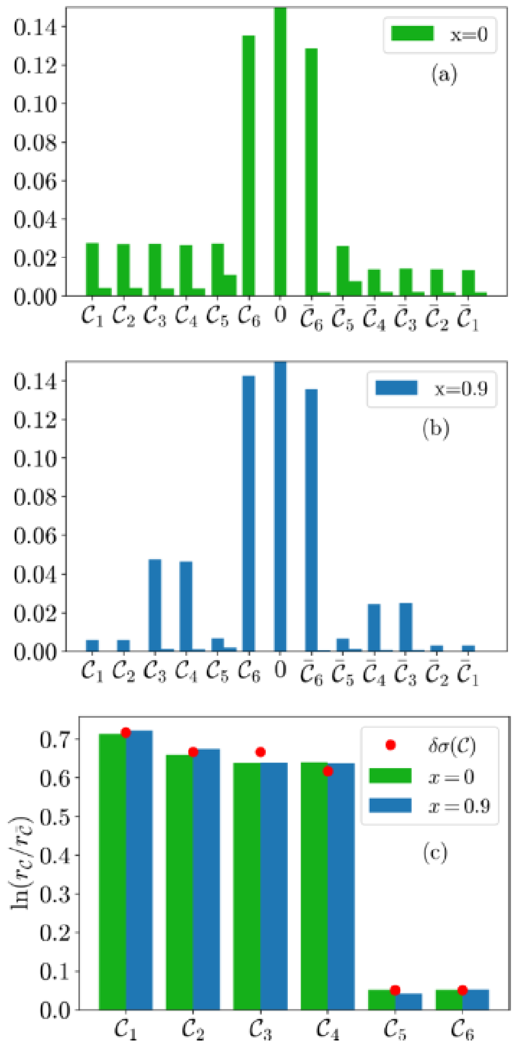
$$\langle e^{-\delta\sigma} \rangle = 1,$$

- Cycle correlations functions also show no oscillations.

The relative occurrence of different cycles for different values of rate asymmetry

$$\Gamma_{\alpha,n} = (1 - x\delta_{\alpha,\mathrm{R}}\delta_{n,1})\Gamma .$$

Entropy production is related to the relative occurrence of the forward and backward cycle.



Summery of main points on this topic

- Deeper insight can be given to thermal machines by going to a trajectory-based description.

- The basic work mechanics is indeed a closed cycle in the space of configurations of electrons on and off the quantum dots. This is similar to thermodynamic cycles in textbooks.

- However, the cycles are not periodic, they are stochastic in nature. We identify the important cycles leads to charge and energy transport through the system, producing work.

- Use of stochastic thermodynamics formalism, together with large deviation theory permits the calculation of the average current from this point of view, as well as allows to quantify the weight of the most important cycles.

Thermal Control

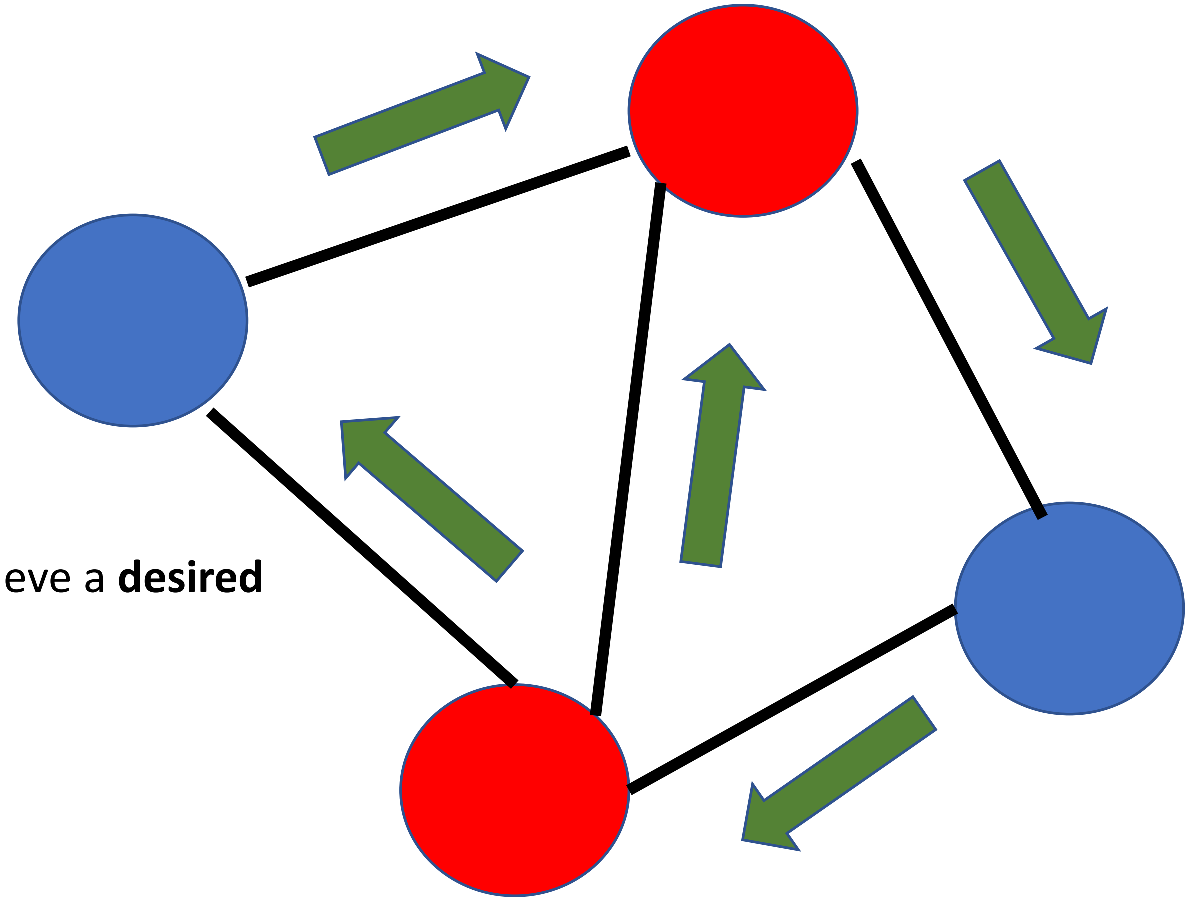
- What is it?

Consider a network of system, each
characterized by a temperature and connected.

The systems can exchange charge and heat.

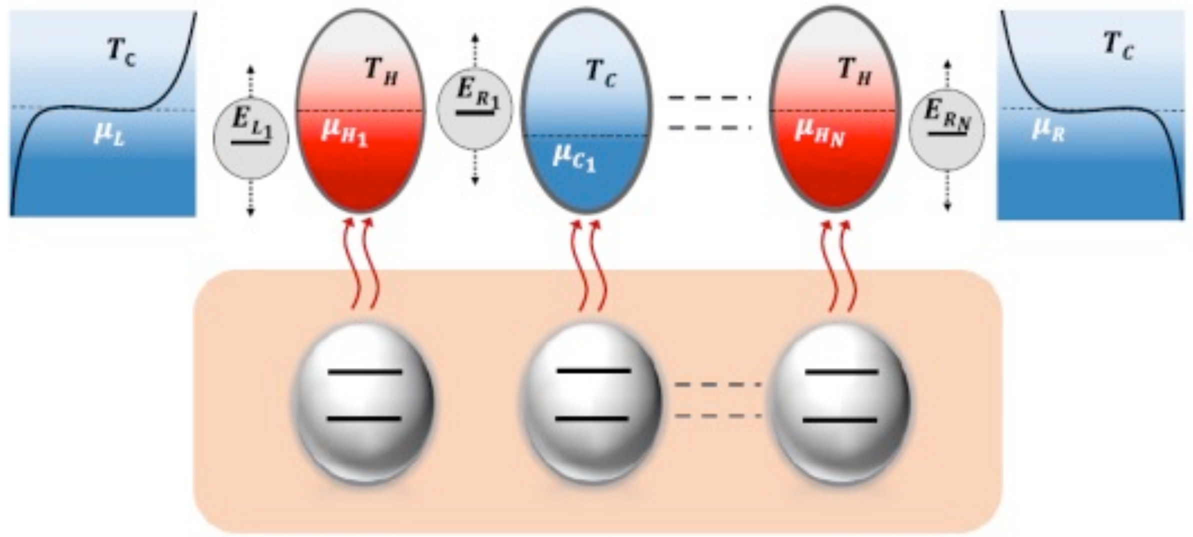
Can I **control** the properties of the connections, so I can achieve a **desired**
Set of heat currents in the system?

General principles: Charge and energy much be conserved.
I have to do work to achieve heat flow from cold to hot.



Thermal Control – in a chain of cavities

We consider a chain of cavities with alternating temperatures – each one of which is the earlier cavity, coupled by a resonant tunneling quantum dot.



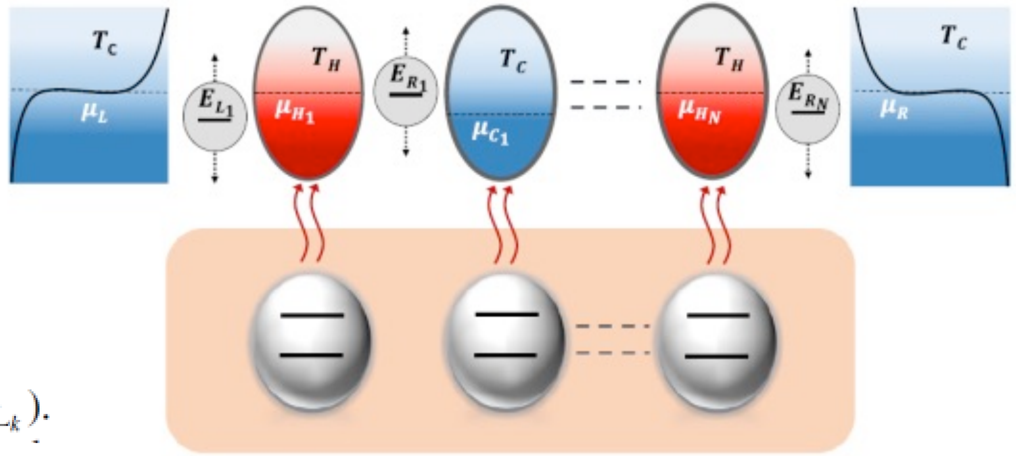
What is the control parameter? Here it is simply the position of the resonant energy level which can be tuned with a gate electrode, and costs no energy.

Challenge: Can we set up any desired set of heat currents in the system?

Thermal Control – in a chain of cavities

Yes, we have found an exact solution in the linear response regime.

Given fixed cavity temperatures, we can find the chemical potentials of each cavity, particle current across the chain.



$$\mu_{\mathrm{H}_k} = \left(\frac{T_{\mathrm{H}}}{T_{\mathrm{C}}} - 1\right)\left(\sum_{l=1}^{k-1} E_{\mathrm{R}_l} - \sum_{l=1}^{k} E_{\mathrm{L}_l} - \frac{(2k-1)\Delta}{2N}\right),$$

$$\mu_{\mathrm{C}_k} = \left(1 - \frac{T_{\mathrm{C}}}{T_{\mathrm{H}}}\right)\left(\sum_{l=1}^{k} (E_{\mathrm{R}_l} - E_{\mathrm{L}_l}) - \frac{k\Delta}{N}\right),$$

$$\Delta = \sum_{k=1}^{N} (E_{\mathrm{R}_k} - E_{\mathrm{L}_k}).$$

$$j = \frac{\gamma\Delta}{8N\hbar k_{\mathrm{B}}\Theta},$$

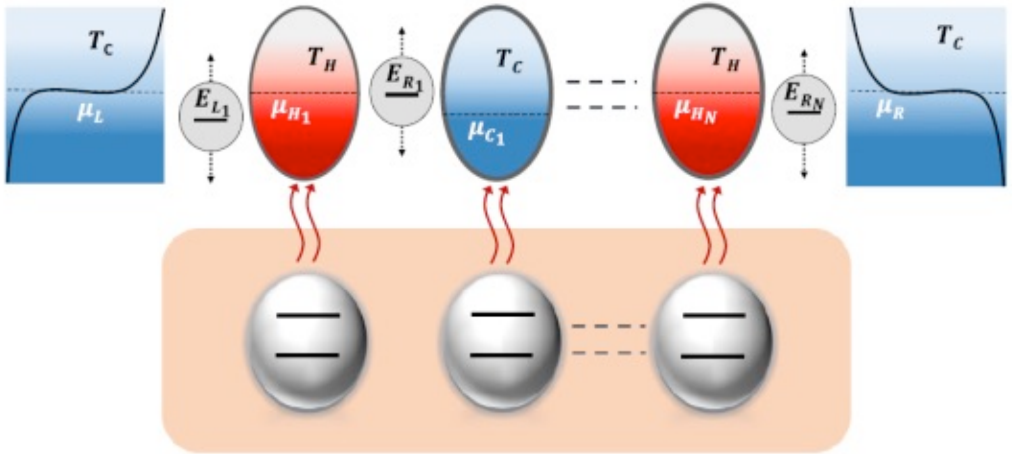
$$\Theta = 1/(T_{\mathrm{C}}^{-1} - T_{\mathrm{H}}^{-1})$$

Thermal Control – in a chain of cavities

The heat currents are.

$$\dot{Q}_{\mathrm{H}_k} = \frac{\gamma\Delta\left(E_{\mathrm{R}_k} - E_{\mathrm{L}_k}\right)}{8N\hbar k_{\mathrm{B}}\Theta},$$

$$\dot{Q}_{\mathrm{C}_k} = \frac{\gamma\Delta\left(E_{\mathrm{L}_{k+1}} - E_{\mathrm{R}_k}\right)}{8N\hbar k_{\mathrm{B}}\Theta}.$$



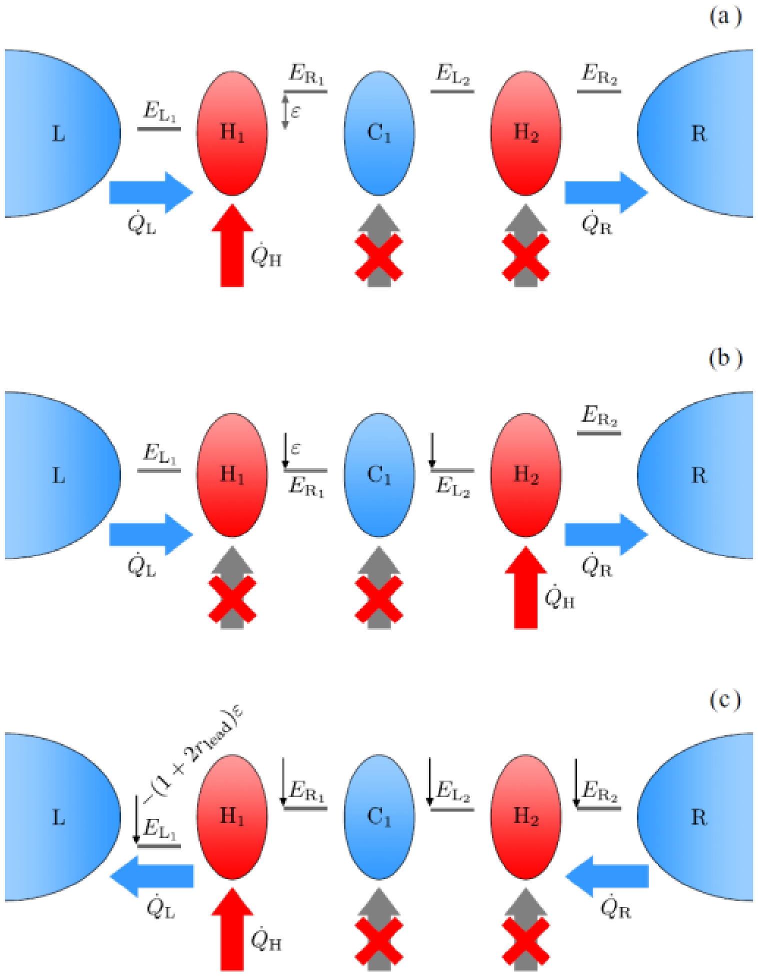
These can be inverted to solve the thermal control problem, given a set of desired heat currents in the system:

$$E_{\mathrm{L}_k} = \pm\sqrt{\frac{8\hbar k_{\mathrm{B}}\Theta}{\gamma\langle\dot{Q}_{\mathrm{H}}\rangle}\left(\dot{Q}_{\mathrm{L}} + \sum_{l=1}^{k-1}(\dot{Q}_{\mathrm{H}_l} + \dot{Q}_{\mathrm{C}_l})\right)},$$

$$E_{\mathrm{R}_k} = \pm\sqrt{\frac{8\hbar k_{\mathrm{B}}\Theta}{\gamma\langle\dot{Q}_{\mathrm{H}}\rangle}\left(\dot{Q}_{\mathrm{L}} + \sum_{l=1}^{k}\dot{Q}_{\mathrm{H}_l} + \sum_{l=1}^{k-1}\dot{Q}_{\mathrm{C}_l}\right)},$$

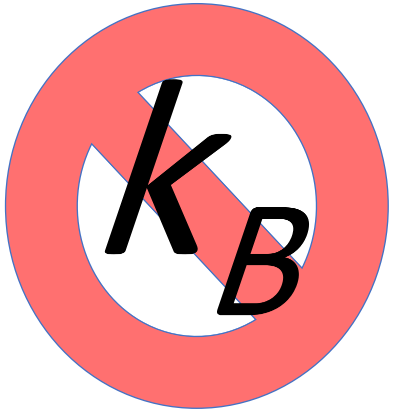
Thermal Control – examples

Heat can be drawn at will from different reservoirs by changing the placement of the resonant levels.



New challenge!

Can I design a fully quantum engine that operates with no work done by the system Hamiltonian? Do away with thermal baths as much as we can.



Quantum measurement powered engines

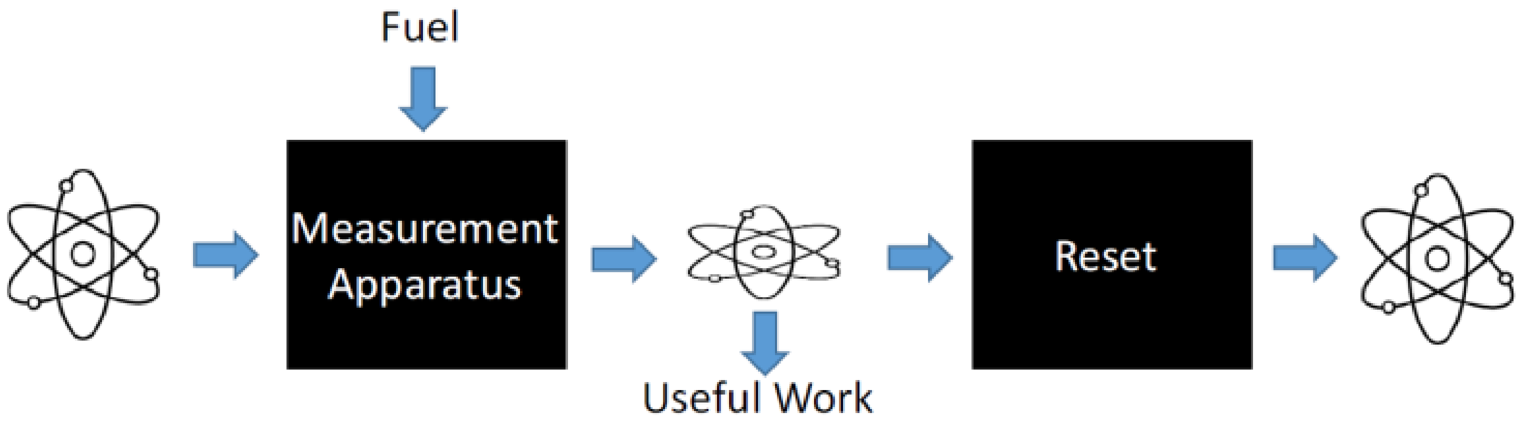
Measurement may *randomly perturb* the state of a quantum particle.

Point of view of thermodynamics *Energetics*

Measurement may *randomly change* the energy of a quantum particle.

- We can consider this stochastic energy exchange as *analogous* to heat
  “Quantum Heat” – Alexia Auffeves.
- We can further design engines to extract this energy as useful work

Quantum measurement powered engines



Simplest Example: Qubit

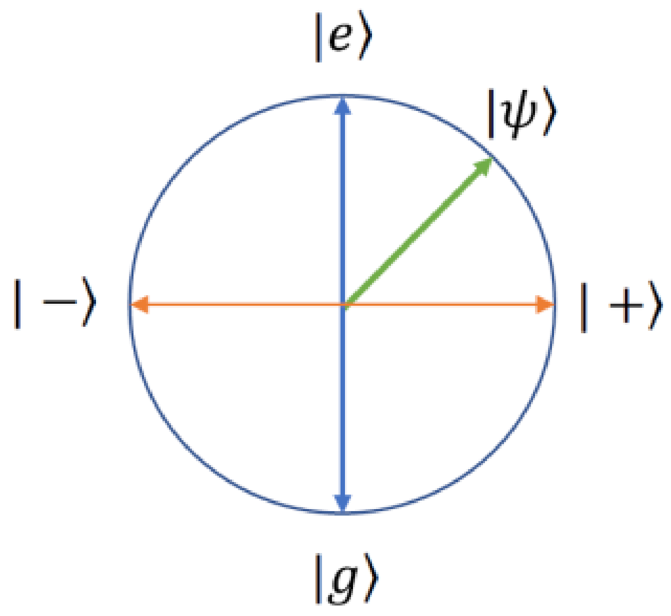
$$H = \frac{\epsilon}{2}(|e\rangle\langle e| - |g\rangle\langle g|),$$

Measurements in the e, g basis leave the average energy of the qubit unchanged (measurement basis commutes with the Hamiltonian).

Measurements in (say) the +,- basis do not commute with the Hamiltonian, so an engine cycle can be arranged:

1) Prepare state ψ
2) Measure in +, - basis (average energy changes)
3) Reset state conditionally with control pulse
4) Repeat.

Simple example, let ψ be the ground state; either measurement option raises the energy of the qubit, which can then be extracted with a coherent control tone.



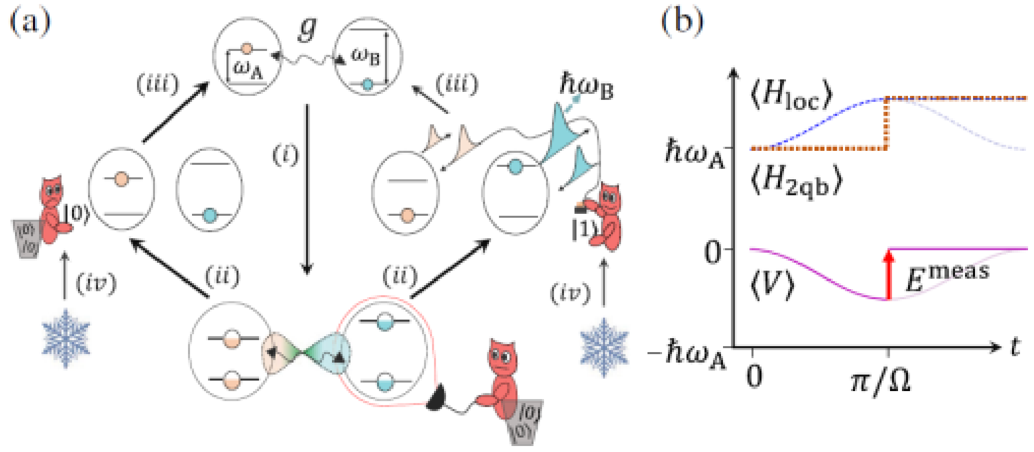
Some subtilities:

a) Control pulse is different depending on measurement outcome.
b) Memory erasure should be accounted for (a la Landauer, Bennet, etc.)
c) Zeno limit with no feedback if ψ rotated just energetically below +.

Elouard, C., Herrera-Martí, D., Huard, B., Auffèves, A, PRL (2017).

Next simple Example: 2 Qubits

With two qubits, entanglement can be created with an interaction between the two. If the qubits are detuned, the excitation of one is incompletely transferred to the other. If we make local measurements, the other qubit can be found in an energy higher than what we started with, and can be extracted. This makes an entanglement powered engine.



PHYSICAL REVIEW LETTERS **126,** 120605 (2021)

Editors' Suggestion

Two-Qubit Engine Fueled by Entanglement and Local Measurements

Léa Bresque,[1] Patrice A. Camati,[1] Spencer Rogers,[2] Kater Murch,[3] Andrew N. Jordan,[2,4] and Alexia Auffèves[1,*]

PHYSICAL REVIEW LETTERS **120,** 260601 (2018)

Efficient Quantum Measurement Engines

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Science NOW

Quantum measurements could power a tiny, hyperefficient engine | Science

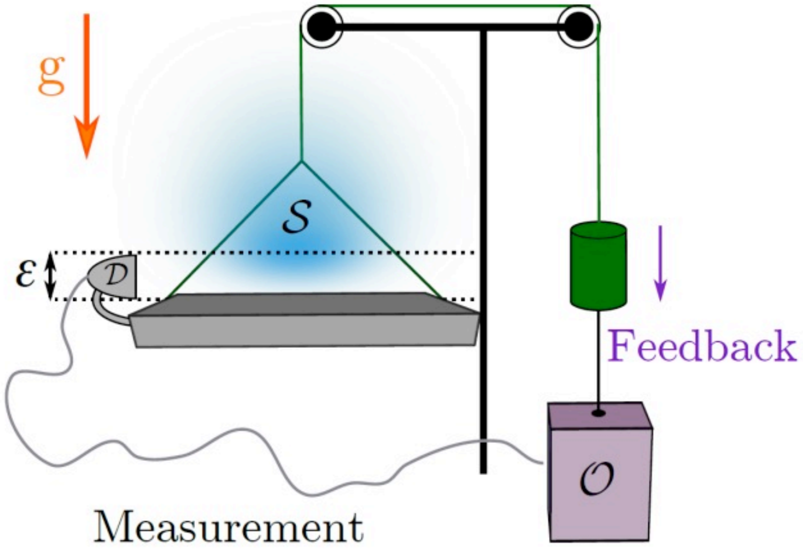
Science/AAAS, 10 Jul 2018

You can't measure an atom without disturbing it, at least according to quantum mechanics.

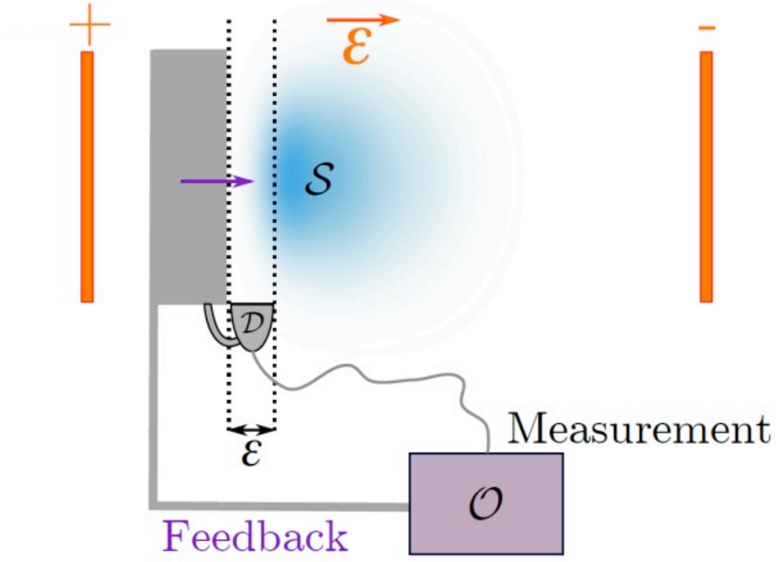
Basic idea: Use quantum measurement as a source of energy to drive an engine.

Elementary Quantum Engines

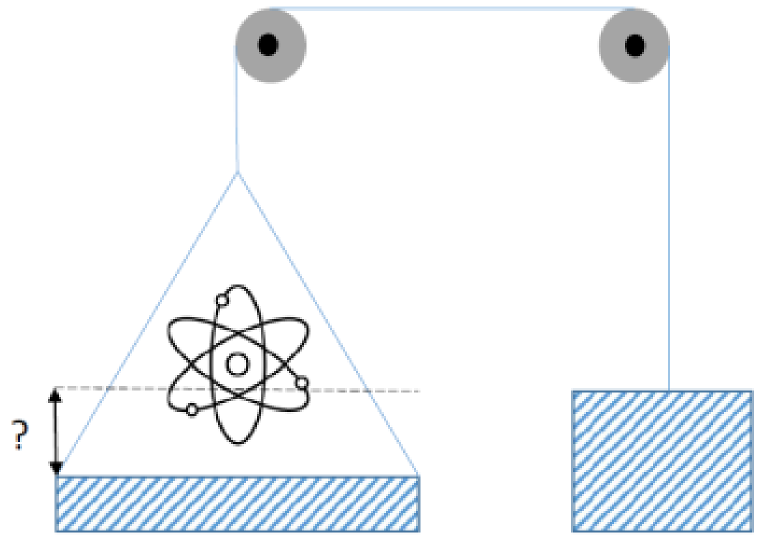
Single atom elevator



Single electron battery

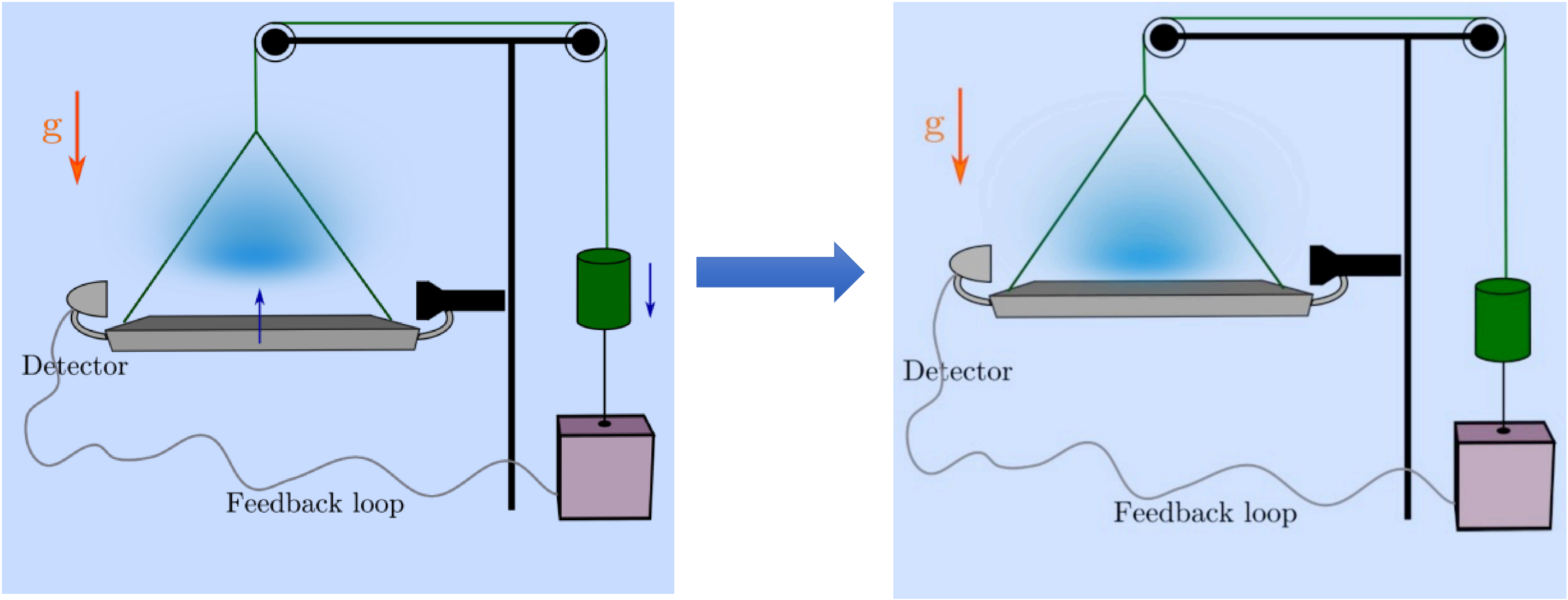


Quantum Measurement Elevator



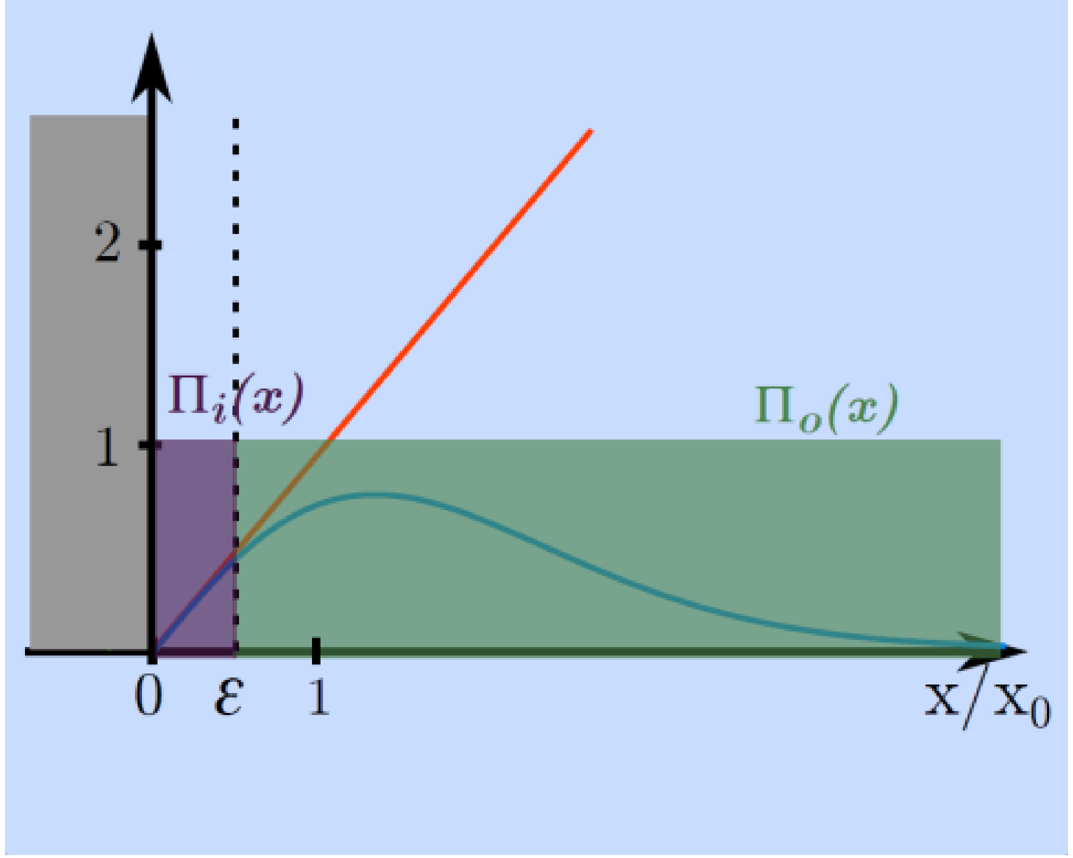
Can we use information about where the atom is to design an engine?

Quantum Measurement Elevator



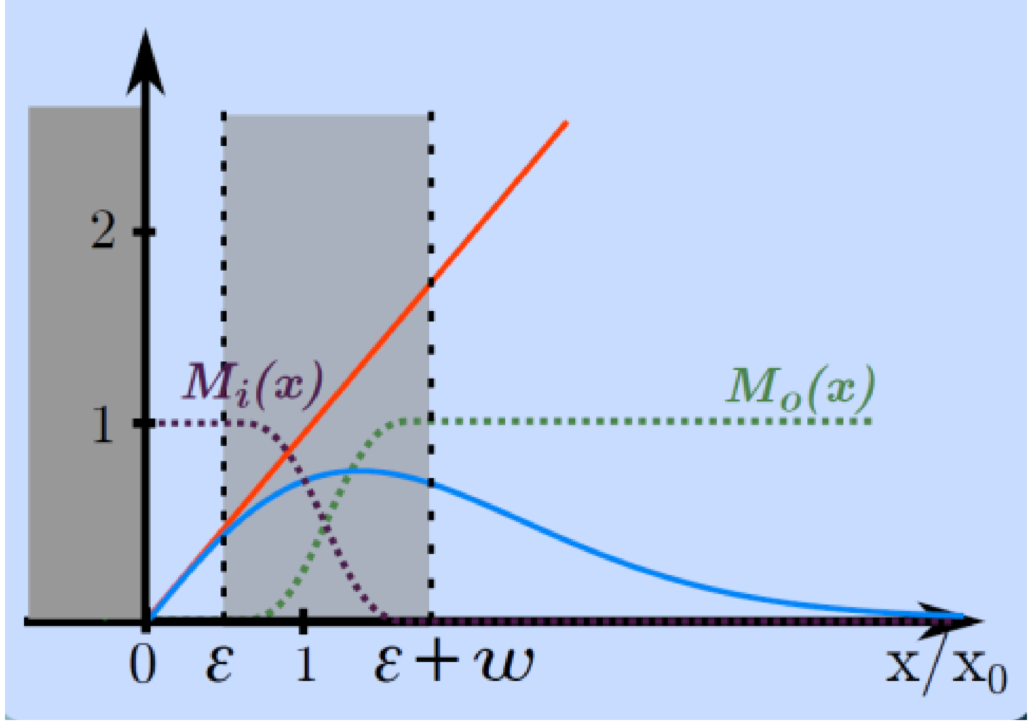
Same situation as at the beginning but the atom is now higher.
Work has been extracted !

Suppose we make a sharp inside/outside measurement....



The collapsed wavefunction has a sharp edge → Energy cost diverges

Soften the measurement



→ Requires a smooth transition in region $[\epsilon, \epsilon + w]$

Generalized position measurement

$$M_o(x) = \begin{cases} 0, & x/x_0 < \varepsilon, \\ \sin[\pi(x/x_0 - \varepsilon)/2w], & \varepsilon < x/x_0 < \varepsilon + w, \\ 1, & x/x_0 > \varepsilon + w. \end{cases}$$

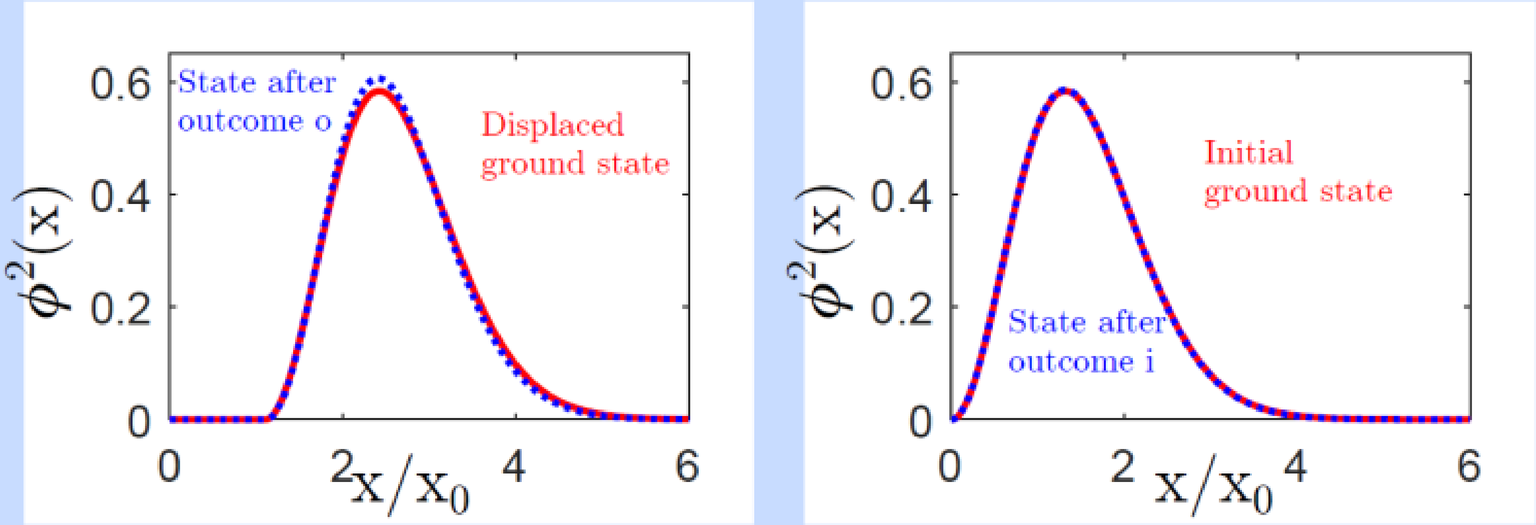
$$M_i(x) = \sqrt{1 - M_o(x)^2}$$

Designer Measurements

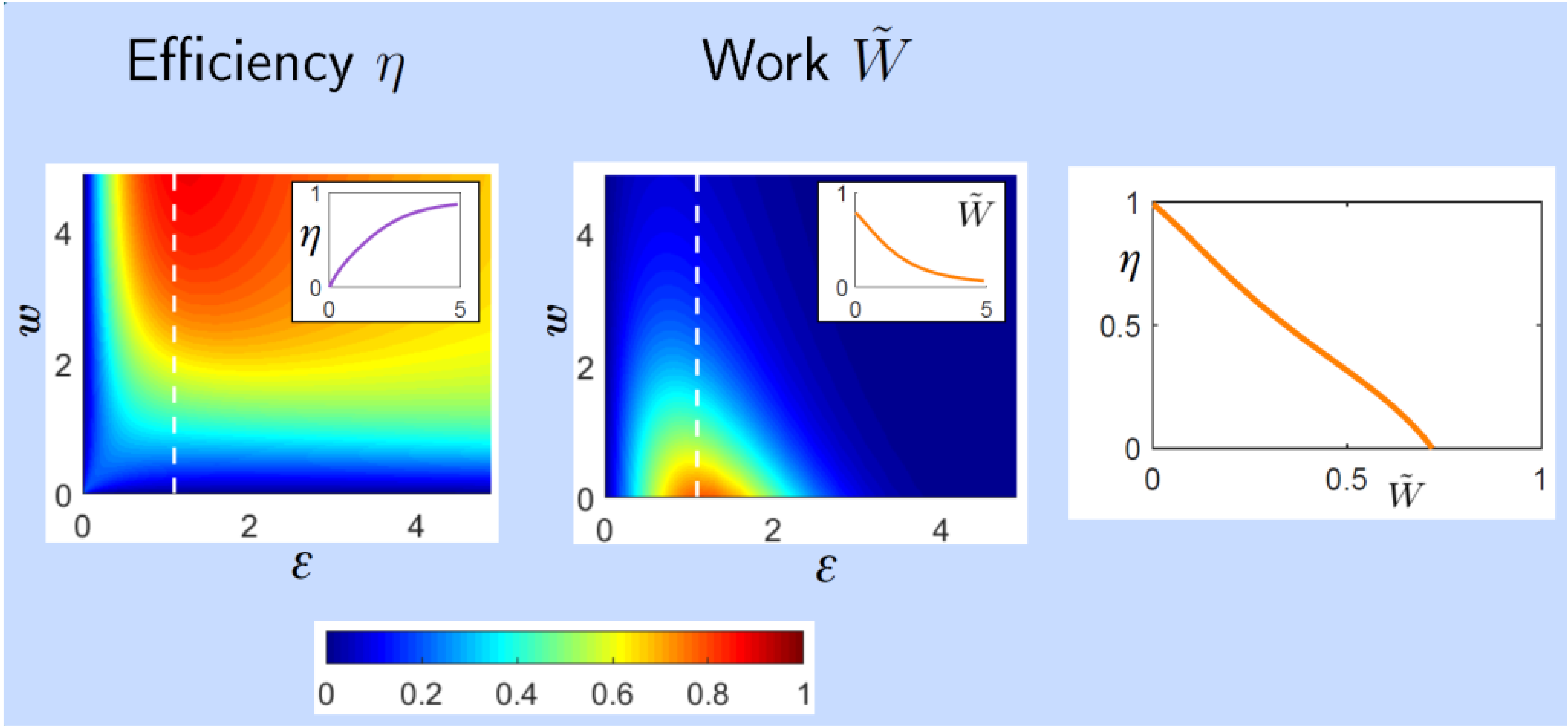
Conditions to have no relaxation needed

- The state after finding o is the new ground state corresponding to the shifted position of the wall
- The state after finding i is the initial ground state

Can be reached approximately for $\epsilon = \epsilon^* \simeq 1.1$ and $w >> 1$.



Performance tradeoff

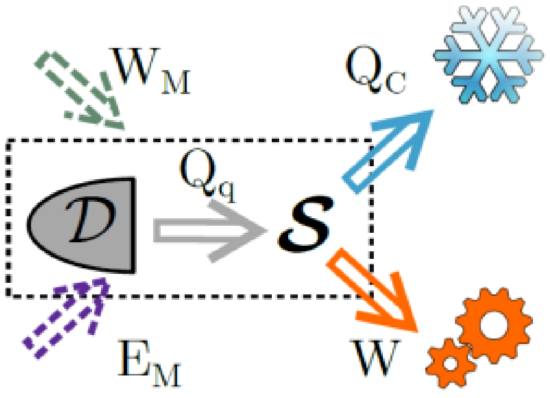


Possible realization of the measurement procedure

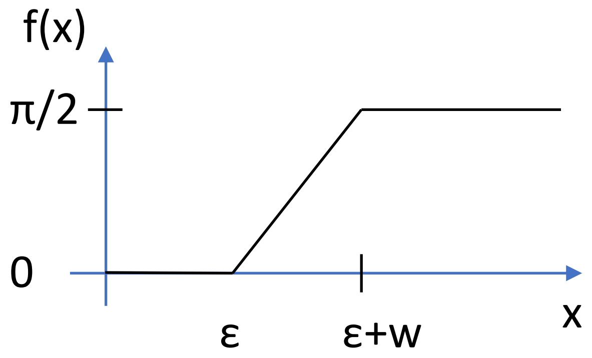
$$H_{int} = \hbar f(\hat{x})\sigma_y \delta(t),$$

Generates the entangled state:

$$|\Psi\rangle = |0\rangle \cos[f(\hat{x})]|\phi\rangle + |1\rangle \sin[f(\hat{x})]|\phi\rangle.$$



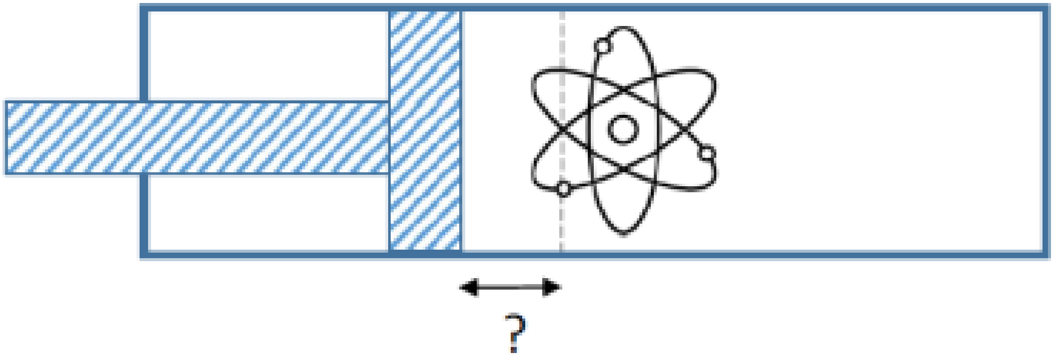
Let f(x) be a phase ramp, from 0 to π/2



Projection of spin on spin state 0 or 1 realizes the generalized measurement on the particle's position.

Energy analysis indicates that we must prepare the spin with initial energy E_o-E_i . Upon successful finding of the particle away from the barrier, that energy is transferred to this system. Therefore, we must **reenergize** the measuring spin after each cycle if the result is successful.

Another example: The atom and the piston

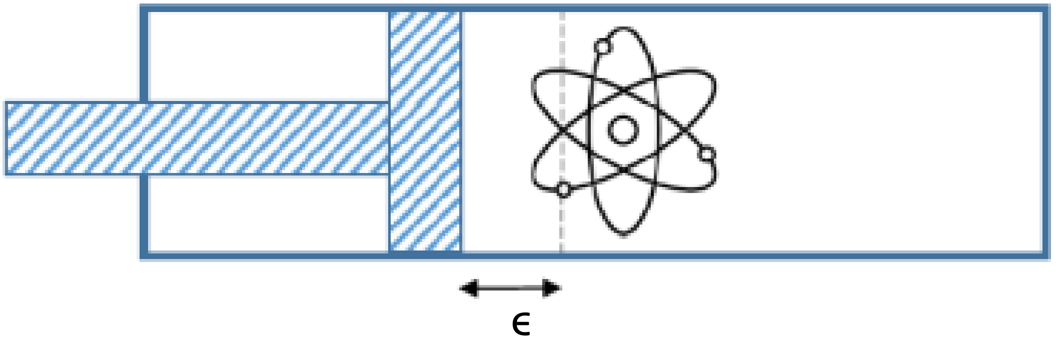


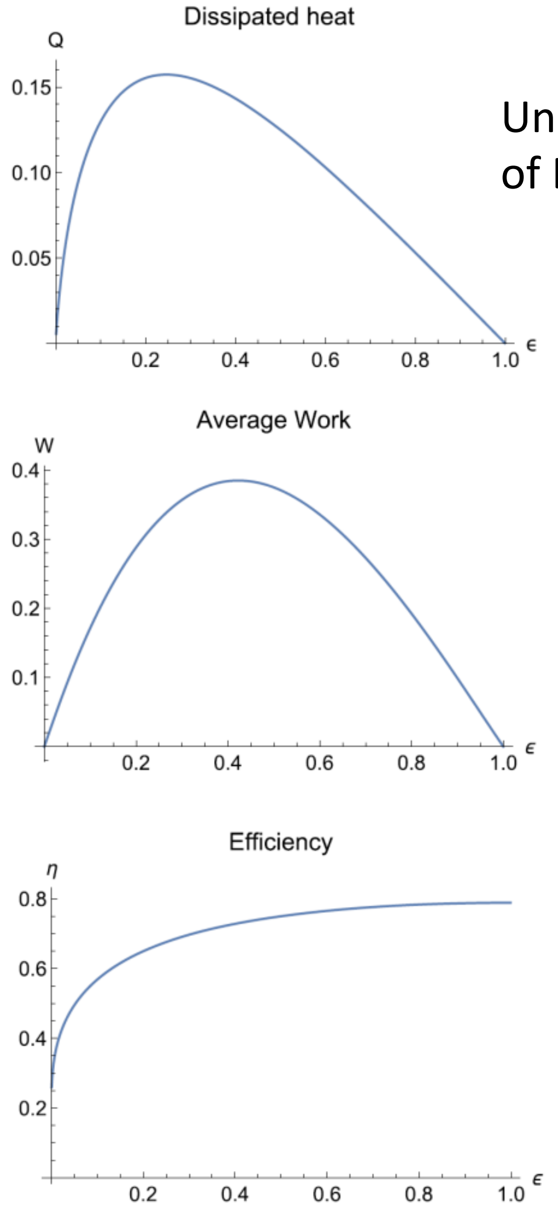
1) Prepare the system in its ground state.
2) Carry out a generalized measurement of the form discussed about.
3) (A) If the particle is found to be not close to the piston, insert the piston quickly, with no work done. Unlike before, we adiabatically allow the particle to push the piston out, doing useful work. (B) If the particle is close to the piston – wait.
4) When the piston is back in the original configuration, we then let the particle relax back to its ground state by exchanging energy with a zero temperature bath.

$$\psi_g(x) = \sqrt{\frac{2}{L}}\sin(\pi x/L),$$

$$E_g = \frac{\hbar^2\pi^2}{2mL^2}$$

Another example: The atom and the piston





Units of E_g

Can arrange the problem so all work is accomplished on the successful step, and all heat is generated in the failure step by measurement engineering.

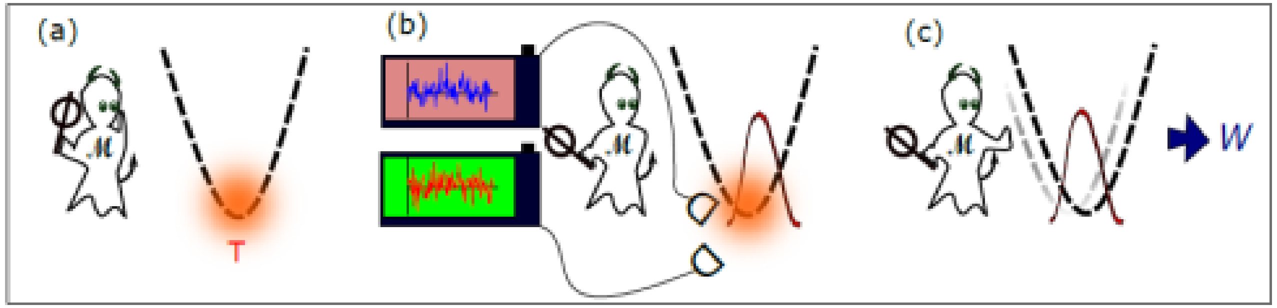
This doesn't lead to perfect efficiency, but interestingly the best efficiency is when you push the piston all the way in!

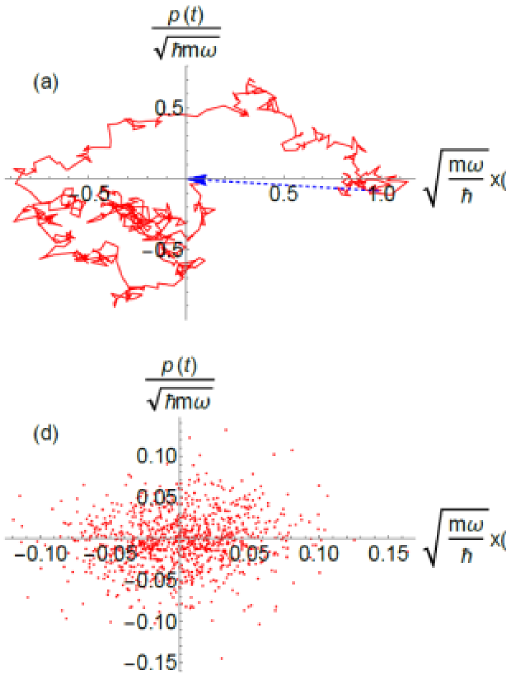
Last example: The harmonic oscillator

If we consider the harmonic oscillator in its ground state, we can make quantum limited measurements of the position and momentum of the oscillator jointly.

Provided the measurements are weak, this results in a displacement of the state in a stochastic way, adding a photon of noise.

By displacing the origin of the potential, that quantum of noise can be extracted, making a working system.





Efficiently Fuelling a Quantum Engine with Incompatible Measurements

Sreenath K. Manikandan,[1,2,3,*] Cyril Elouard,[1,4] Kater W. Murch,[5] Alexia Auffèves,[6] and Andrew N. Jordan[7,2,1]

arXiv:2107.13234

Conclusions

- Covered different types of heat engines / refrigerators in mesoscopic systems.
- Illustrated the alternative insights of using cycle analysis.
- Discussed thermal control
- New types of energetic resource in quantum engines - measurement