Tutorial: Charge and Heat transport in mesoscopic conductors: How to build an engine

Andrew N. Jordan

SPICE conference on Quantum thermodynamics and transport, May 8-11, 2018

Outline

- Motivation
- History
- Fundamental Concepts
- Example mesoscopic engines – design principles
- Experiments!
- Outlook: Moving to fully quantum engines

The Kavli Institute for Theoretical Physics
University of California, Santa Barbara

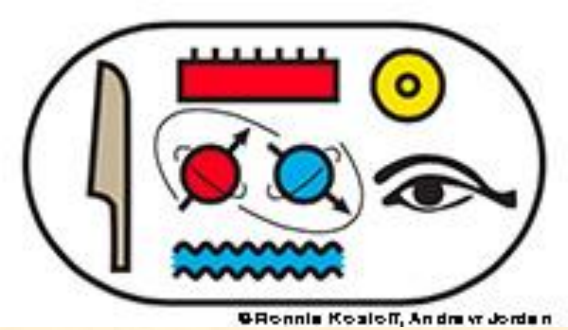
UNIVERSITY of ROCHESTER

Summer working vacation, 5/29-7/20

Thermodynamics of quantum systems: Measurement, engines, and control

Coordinators: Janet Anders, Gabriele De Chiara, Andrew N. Jordan, and Ronnie Kosloff

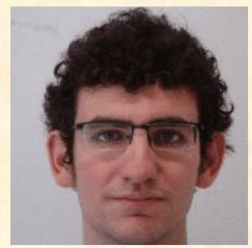
An associated conference will be held from June 25-29, 2018.



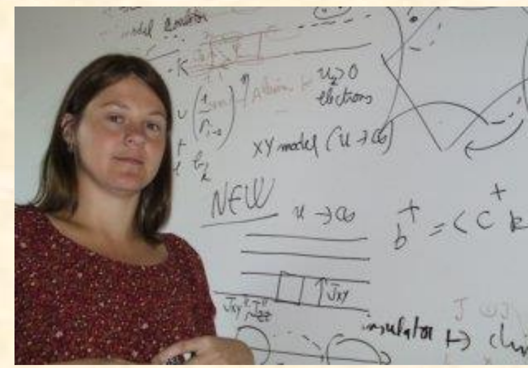
UNIVERSITY of ROCHESTER

Thanks to my collaborators

A new Velázquez?

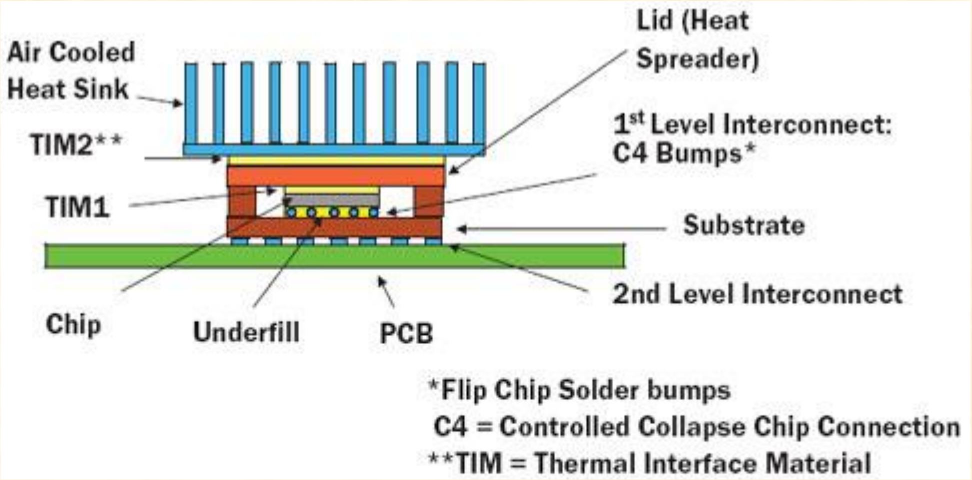


Cyril Elouard
Rafa Sanchez
Bjorn Sothmann
Markus Büttiker
Karyn LeHur
Yunjin Choi



Heat as a nuisance

"Packaging Challenges For High Heat Flux Devices"



The electronics industry is investing more and more space to dissipating heat from its chips. **It can't throw it away fast enough!**

From:
Electronics Cooling Magazine – Focused on Thermal Management, TIMs, Fans, Heat Sinks, CFD Software, LEDs/Lighting
Dedicated to Thermal Management in the Electronics Industry

Figure 1. Diagram of a flip-chip IC in a high-performance package with attached heat sink. Figure 1 depicts a typical configuration for a flip-chip processor attached to an external heat sink, which is usually air cooled. The temperature of the chip depends upon both the package and the heat sink thermal performance. This article will focus primarily on the thermal performance of the package.

The main heat flow path from the chip to air is: Chip => TIM1 => Lid => TIM2 => Heat sink => Air.

From a physics perspective, why not use this with a heat Engine?

Burn coal – it will warm up a room.

…or burn coal and turn the heat into work with an engine.

Harvesting energy

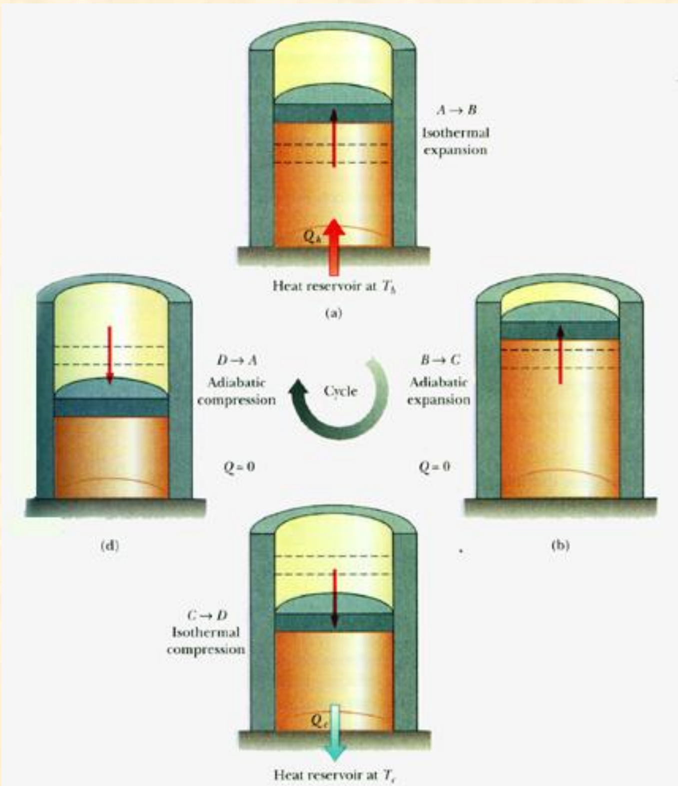
Use your laptop – it will warm up your lap.

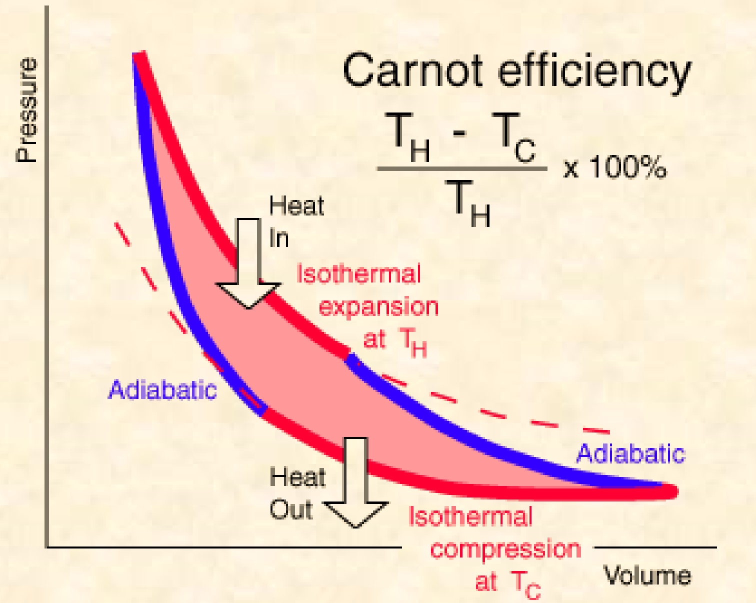
….Or use your laptop and harvest the energy to generate electricity and lower the laptop's consumption.

This is what the proposed nanoengines would do.

Heat Engine: any process that converts heat to electrical power or usable work.

Heat Engines



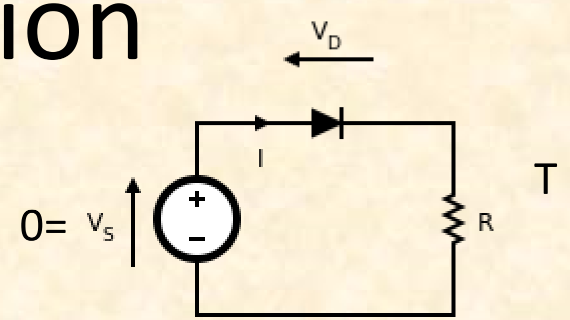


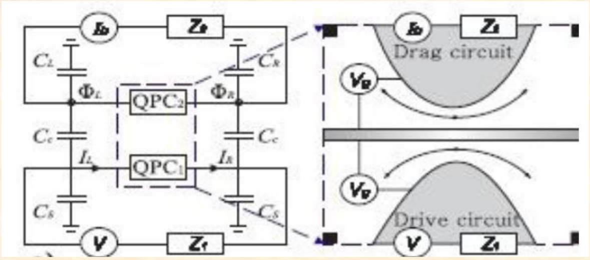
Works between hot and cold temperature reservoirs. E.g. T_room = 300K, T_hot=330K, efficiency = 30/300 = .1 = 10%

Heat Engine: any process that converts heat to electrical power or usable work.

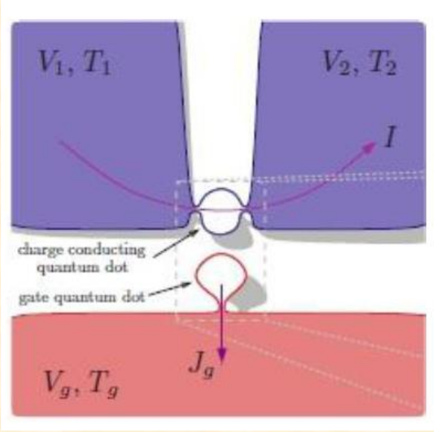
UNIVERSITY of ROCHESTER

Historical motivation





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



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

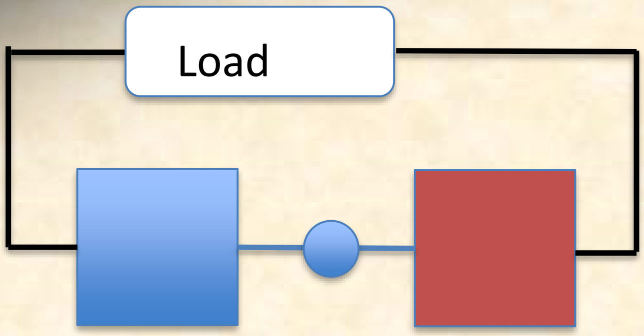
In 1950 Leon Brillouin asked why a circuit containing a resistor and diode could not rectify its own thermal rectifications.

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

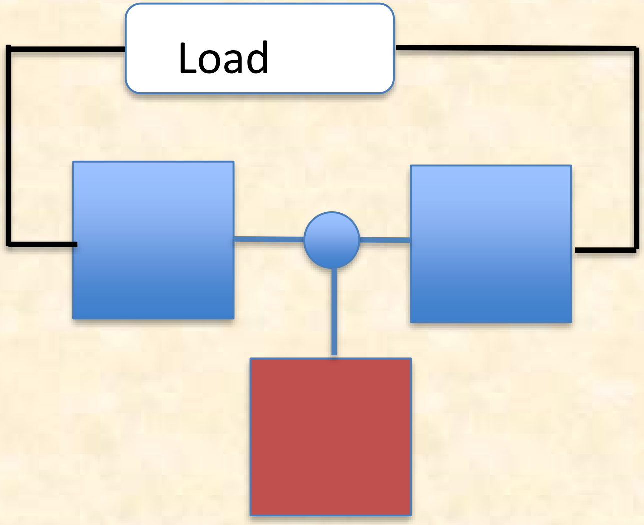
Recently, there have been interesting proposals made to miniaturize rectifiers to the single electron level, using Coulomb blockaded quantum dots.

While these can in principle reach ideal efficiencies, of the (typically) two or more tunneling processes involved give rise to expected current that are extremely small.

Geometry – two terminal or three terminal?



Carries both charge and heat currents.



Charge and heat currents are now separated – the load circuit is kept at the same temperature.

Review articles

Nanotechnology

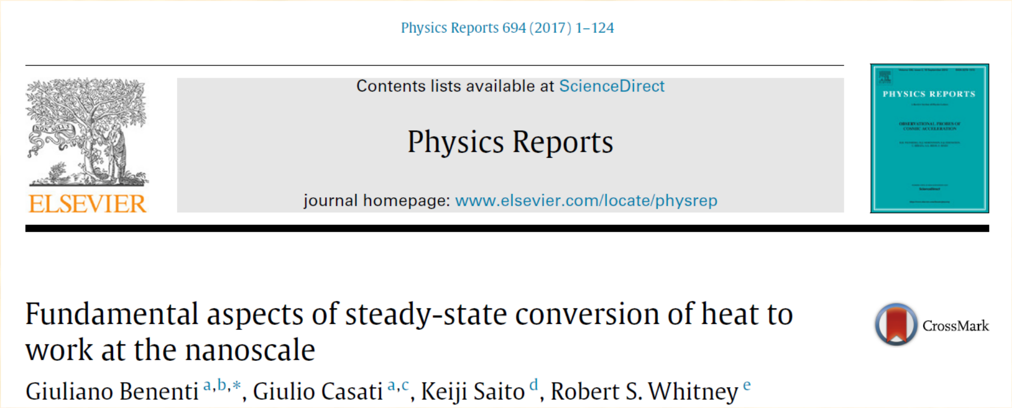
TOPICAL REVIEW

Thermoelectric energy harvesting with quantum dots

Björn Sothmann, Rafael Sánchez and ANJ

Published 30 December 2014 • © 2015 IOP Publishing Ltd

Nanotechnology, Volume 26, Number 3


Physics Reports 694 (2017) 1–124

Contents lists available at ScienceDirect

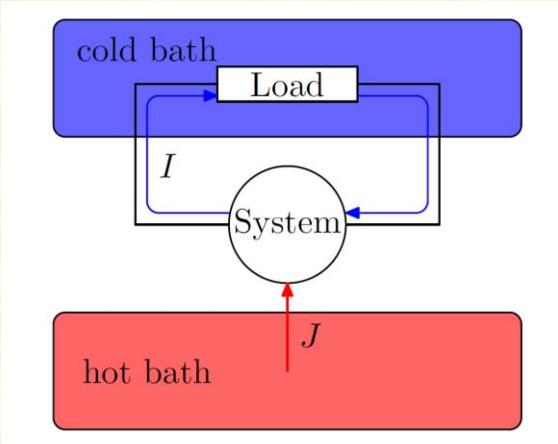
Physics Reports

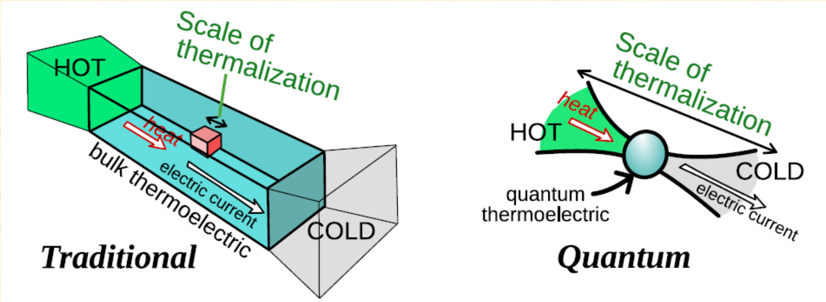
journal homepage: www.elsevier.com/locate/physrep

ELSEVIER

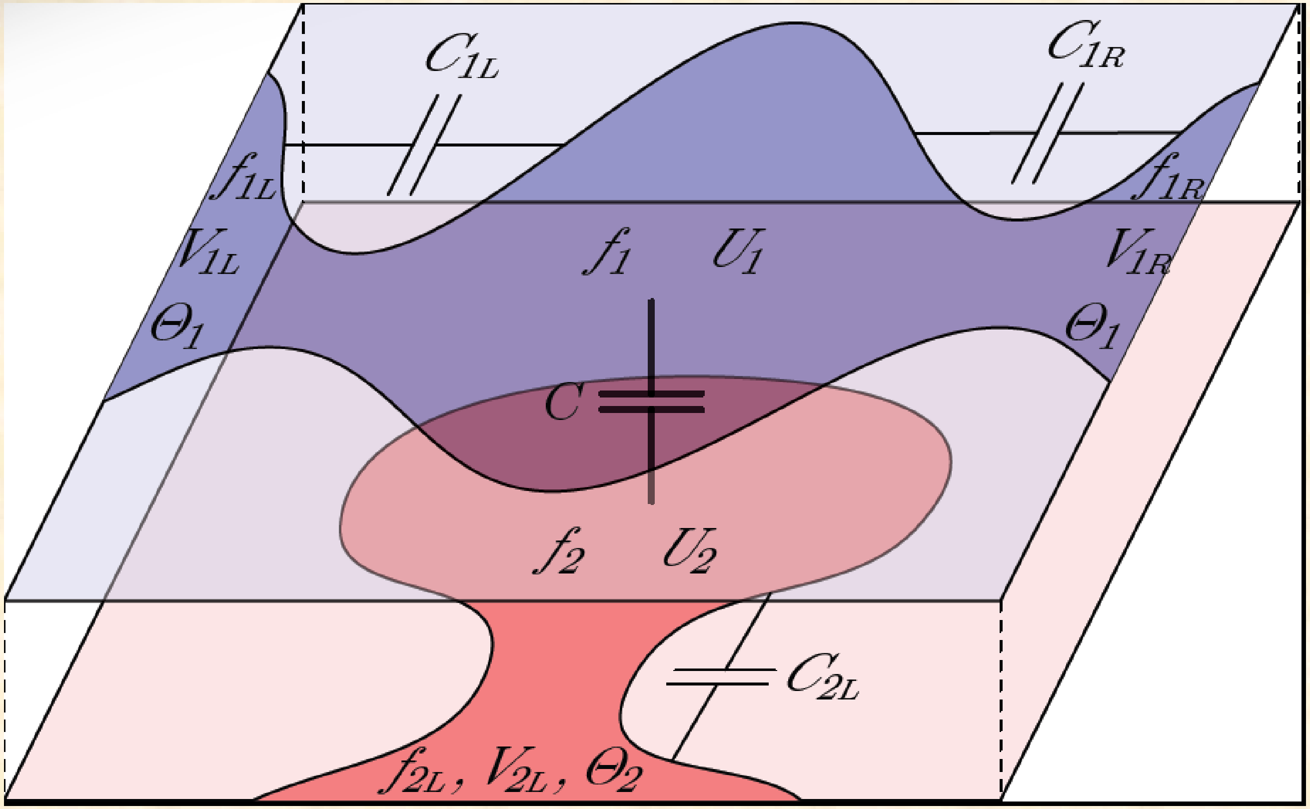
Fundamental aspects of steady-state conversion of heat to work at the nanoscale

Giuliano Benenti [a,b,*], Giulio Casati [a,c], Keiji Saito [d], Robert S. Whitney [e]





Geometry – open cavities



The upper (cold) cavity is connected to reservoirs by two leads, and is capacitively coupled to a lower (hot) cavity connected via a single lead to a separate reservoir.

UNIVERSITY of ROCHESTER

Rectification of electrical current requires three ingredients:

1. Different temperatures in upper and lower cavities.
2. Symmetry breaking between left and right leads.
3. Nonlinearity.

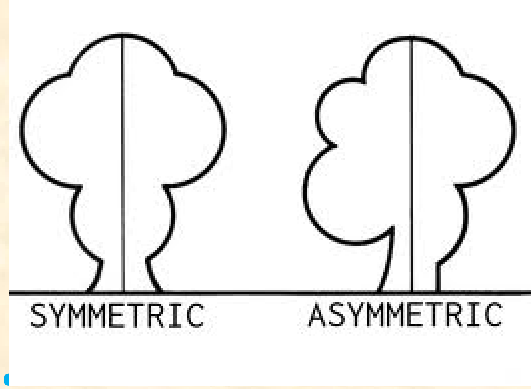
#1 Different temperatures required.

Suppose it were possible for some device we designed to rectify electrical current with no applied bias, and no temperature difference between the upper and lower cavity. Then, it would be possible to:

- Generate steady-state electrical current in global thermal equilibrium.
- Applying a small electrical voltage would then generate electrical power with only one heat reservoir, in violation of the second law of thermodynamics.
- Conservation of energy demands a net heat current passes between the cavities in global thermal equilibrium, tending to cool one cavity while heating the other without any input power, making a Maxwell demon.

L. Brillouin, Phys. Rev. **78**, 627 (1950)

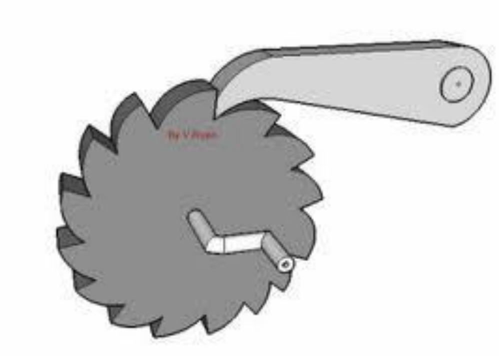
#2 Symmetry breaking between left and right leads.



Suppose it were possible to create a device where there was both a directed current created in the upper system, with a temperature difference between the two systems.

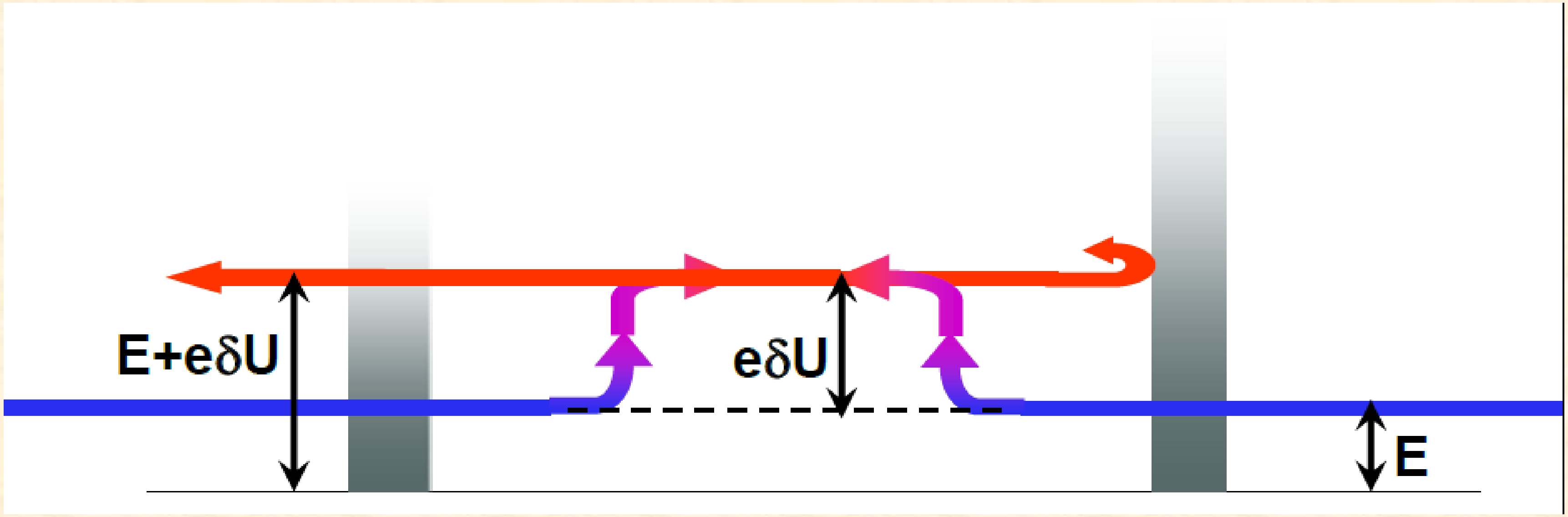
Then, there would be a heat current between the two systems, and it would be possible in principle for a steady-state electrical current to arise. However, if the upper system has inversion symmetry, then $I_{LR} = -I_{RL}$, and consequently, the net current must vanish. Thus, the symmetry must be broken.

However, even #1 and #2 are still not enough to generate a current in our system.



#3 Nonlinearity

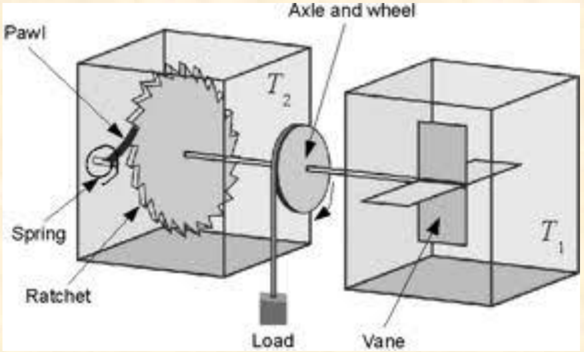
Rectification requires nonlinearity. In our model, it arises because in mesoscopic systems, the conductance (or transmission) of the contacts depends on the energy of the electrons that are transmitting through it.



As electrons in the cavity absorb energy $e\delta U$ from the fluctuating potential of the lower cavity, they experience different lead transmissions, generating the directed current in the system.

Results – rectification!

The net rectified current is a results of meetings conditions #1, #2, and #3. The upper cavity has temperature Θ_1 and the lower cavity has temperature Θ_2.



$$\langle I_{1\mathrm{L}} \rangle = \frac{\Lambda}{\tau_{RC}} k_{\mathrm{B}} (\Theta_1 - \Theta_2)$$

It is controlled by the asymmetry parameter Λ

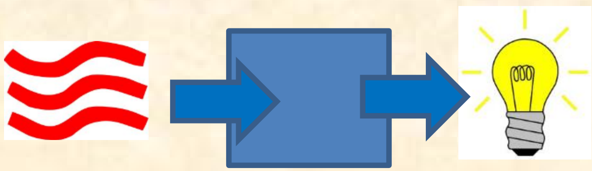
$$\Lambda = \frac{G'_{1\mathrm{L}} G_{1\mathrm{R}} - G'_{1\mathrm{R}} G_{1\mathrm{L}}}{G_{1\Sigma}^2}$$

(energy derivatives of the conductances)

τ_{RC} is an effective RC-time for the coupled cavities.

For realistic parameters $I \approx 0.1\, nA$

Results – apply electrical bias to generate power



$$J_H = \frac{1}{\tau_{RC}} k_{\rm B}(\Theta_1 - \Theta_2)$$

It the thermal heat current transferred between hot and cold cavities, which exists without the nonlinearity. Consequently, Λ controls the process of heat to charge conversion.

We apply a load across the cavity, generating a maximum power of:

G_1 is the total conductance of the upper cavity

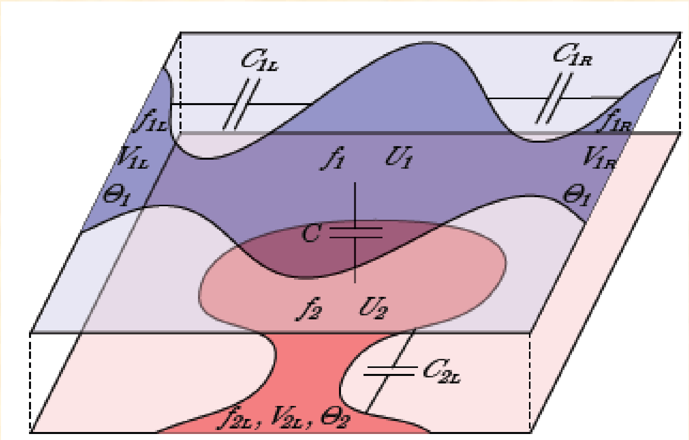
$$P_{\rm max} = \frac{G_1 \Lambda^2}{4\tau_{RC}^2} (k_{\rm B}(\Theta_1 - \Theta_2))^2$$

Thus, heat flows from the hot to the cold cavity, generating electrical power P_{max} with efficiency $\eta = P_{max}/J_H$

Results of this model

- Exactly solvable model of a mesoscopic heat engine.
- The device functions as a thermoelectric, transferring temperature differences into directed electrical current.
- Applying electrical bias generates back-flow of current, and useful electrical power.
- Maximal power is when the load is impedance-matched with the rectifying cavity.
- Efficiency is generally less than Carnot, this system can still give substantially larger currents than more efficient quantum dot (Coulomb blockade) proposals.
- Both energy conservation and the Onsager relations are satisfied.

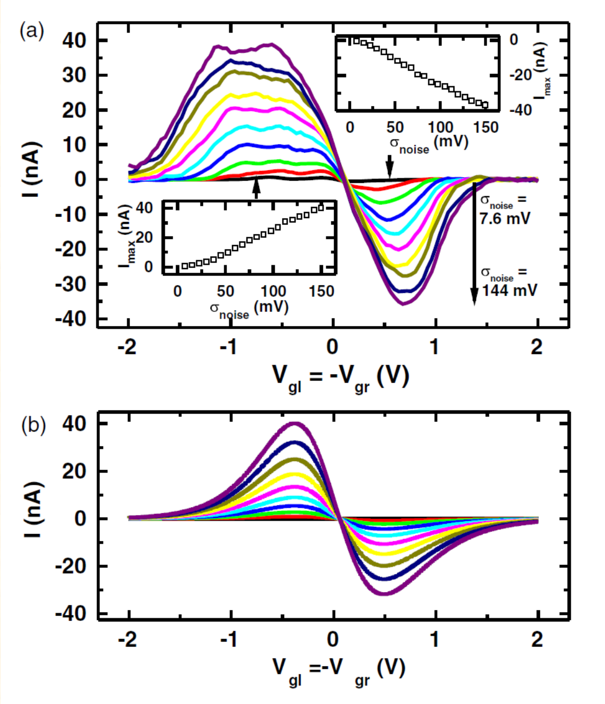
Phys. Rev. B 85, 205301 (2012), Björn Sothmann, Rafael Sánchez, ANJ, Markus Büttiker



Experiments!

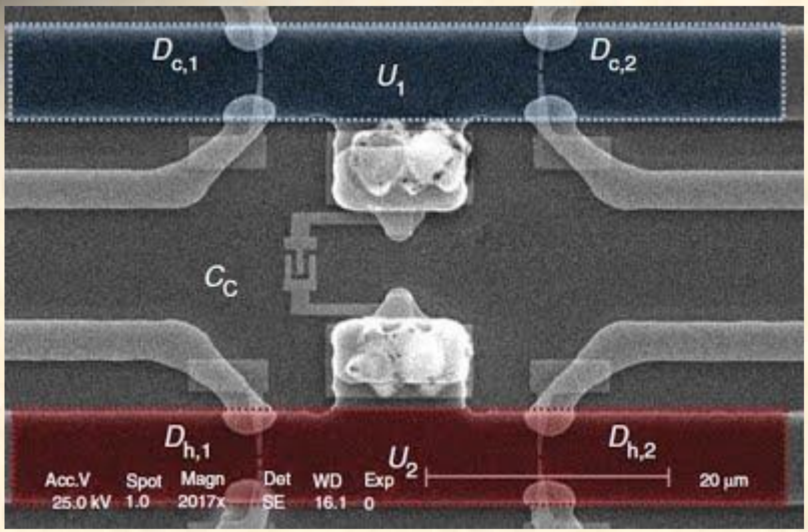
F. Hartmann, P. Pfeffer, S. Höfling, M. Kamp, and L. Worschech
Phys. Rev. Lett. **114**, 146805 – Published 10 April 2015

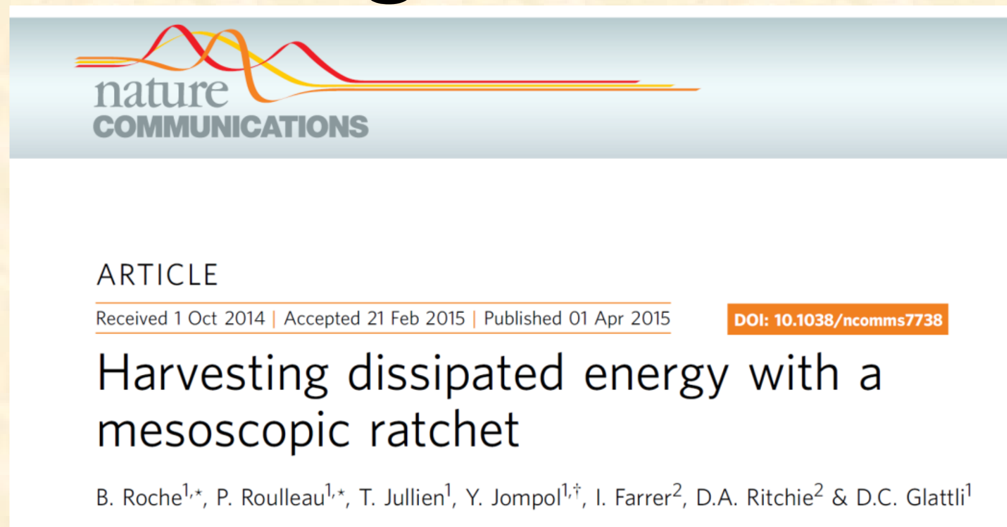
Wuerzburg group



The upper conductor has the energy-dependent transmissions, and playes the role of a ratchet and pawl in the nano-engine. The lower conductor displays excess noise, and gives thermal energy to the upper conductor, which rectifies it into a directed current.

Experiments - Again!





nature COMMUNICATIONS

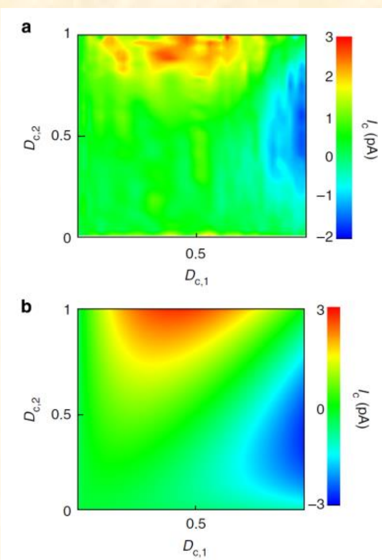
ARTICLE

Received 1 Oct 2014 | Accepted 21 Feb 2015 | Published 01 Apr 2015

DOI: 10.1038/ncomms7738

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]



Group of Christian Glattli, at the Service de Physique de l'Etat Condense at the CEA Saclay France

Color map of current as a function of QPC transmission of left and right leads.
Top: Experiment
Bottom: Theory

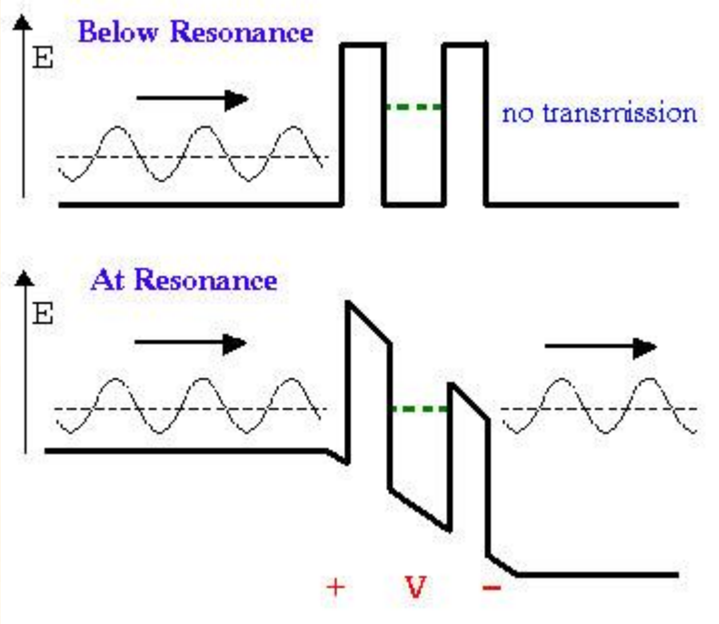
However … there are liabilities

- The rectification depends on energy-dependent nonlinearities in the transmission.
- In generic mesoscopic conductors, this is typically a 1 channel effect, on top of a N channel background.
- This typically leads to lower power that we would like, and lower effeciencies.

Is there a natural way to zoom in on just the single channel nonlinearity and make the more of that?

Yes!

Idea: Use resonant tunneling quantum dots



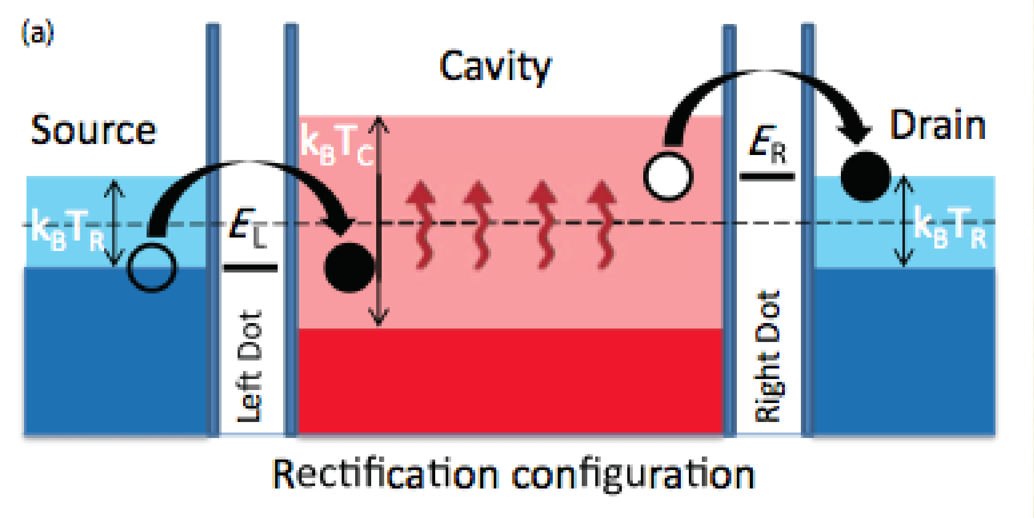
Have the property that transmission is forbidden unless the incident electron energy is on resonance with the quantum dot energies. In this case, transmission can be 1, otherwise it is 0.

Energy filters!

Mahan & Sofo, PNAS 1996

Next idea: 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.

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.

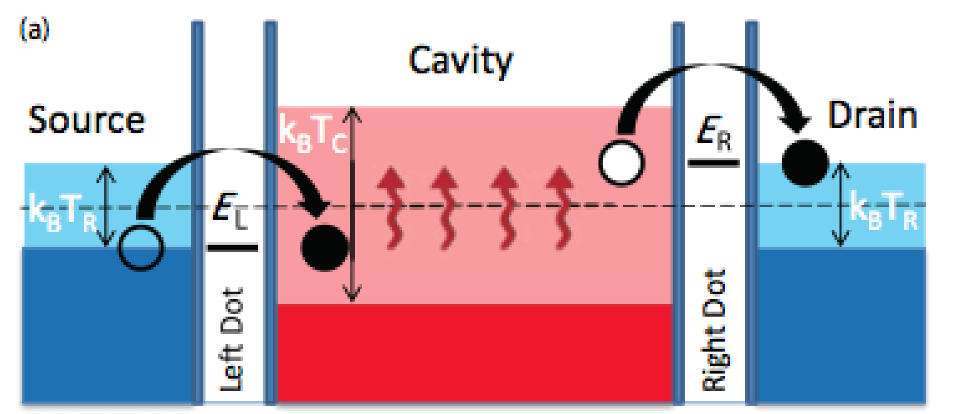
Consequently the charge and heat currents are proportional:

$I = \frac{e}{\Delta E} J$, 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

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:

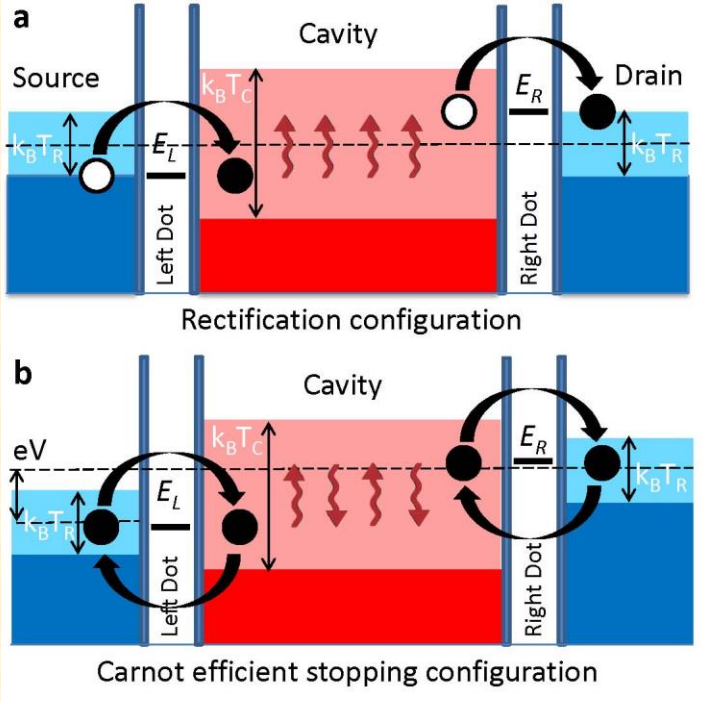
$$J = \frac{2\gamma\Delta E}{h}[f(\Delta E/2, T_{\rm C}) - f(\Delta E/2 - \mu/2, T_{\rm R})],$$

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 $\mu = \Delta E\ \eta_C$



Optimize power

UNIVERSITY of ROCHESTER

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

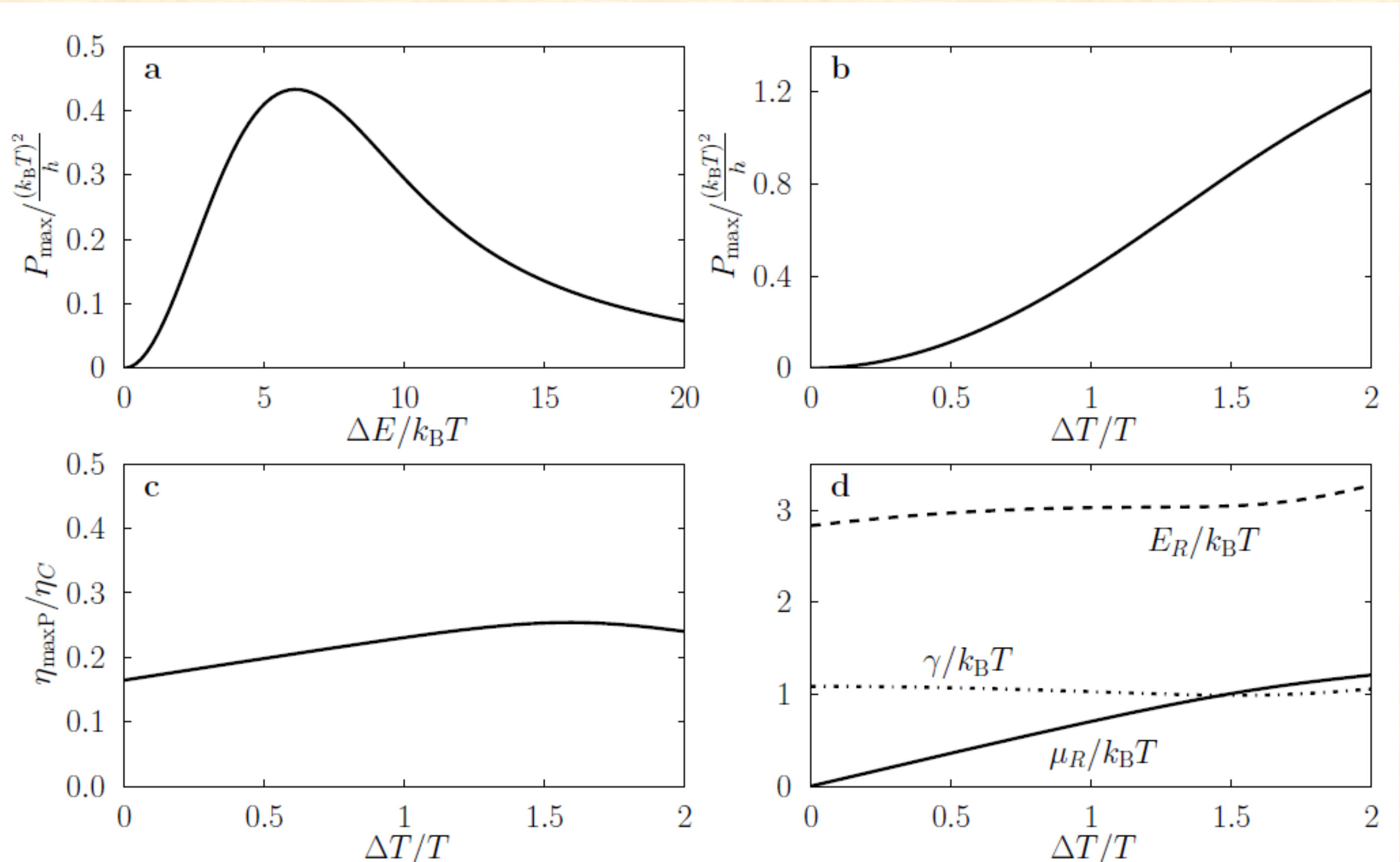
P_max ~ 0.1 pW at a temperature difference of 1K.

$$\Delta T = T_{\mathrm{C}} - T_{\mathrm{R}}$$

$$T = (T_{\mathrm{C}} + T_{\mathrm{R}})/2$$

Choose

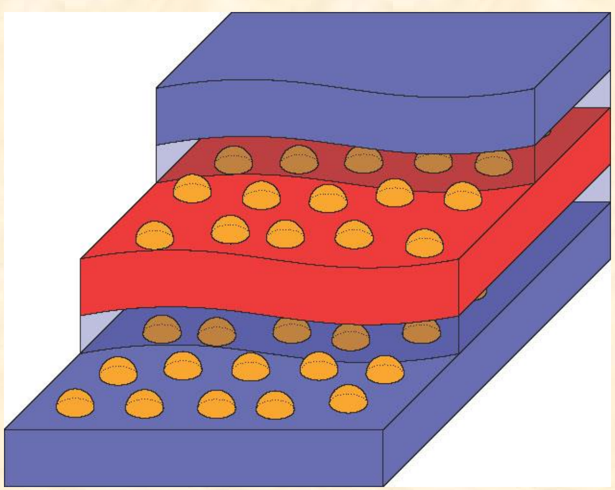
$$\gamma = k_B T$$
$$\Delta E = 6\, k_B T$$

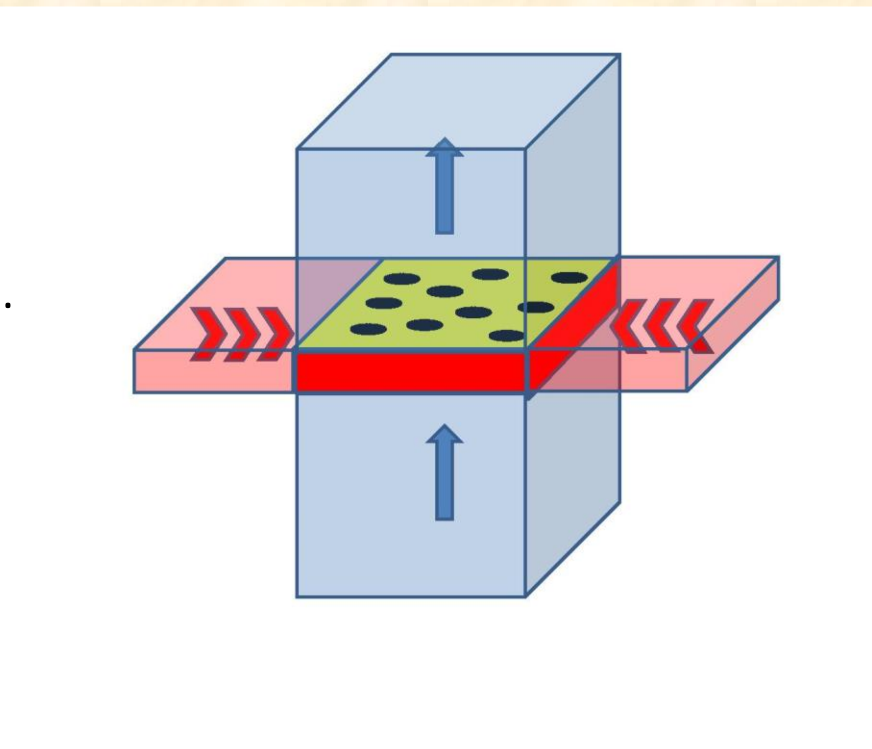


Scaling up

UNIVERSITY of ROCHESTER

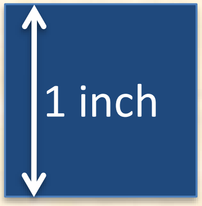
One can fabricate an entire plane of repeated nano-engines in parallel in order to scale the power. For such a repeated array of cavities and quantum dots, one can connect all the cavities to make a single engine. The two boundary layers consist of planes of quantum dots, so electrons can only penetrate through them. These layers sandwich a hot interior region and separate it from the left and right cold exterior contacts. The sandwich engine fabricated with self-assembled quantum dots tolerates variations in width and fluctuations in energy levels.



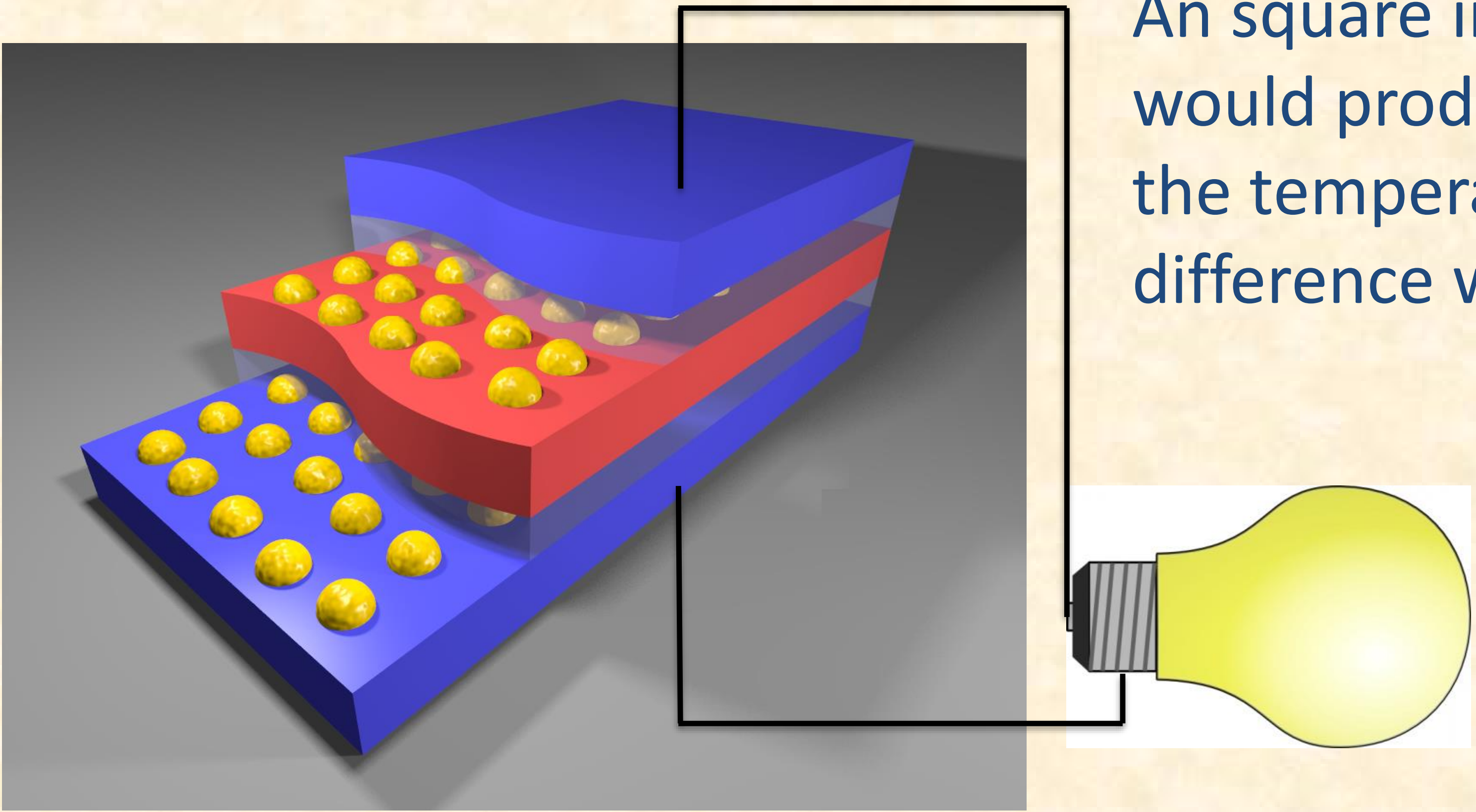


“Swiss Cheese Sandwich” arrangement:

We show the thermoelectric properties are robust to fluctuations in size of quantum dots.

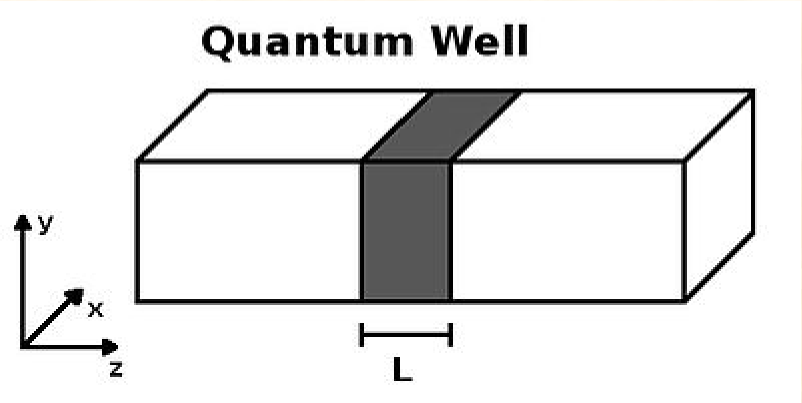


An square inch array would produce 1 Watt if the temperature difference was 1 degree.

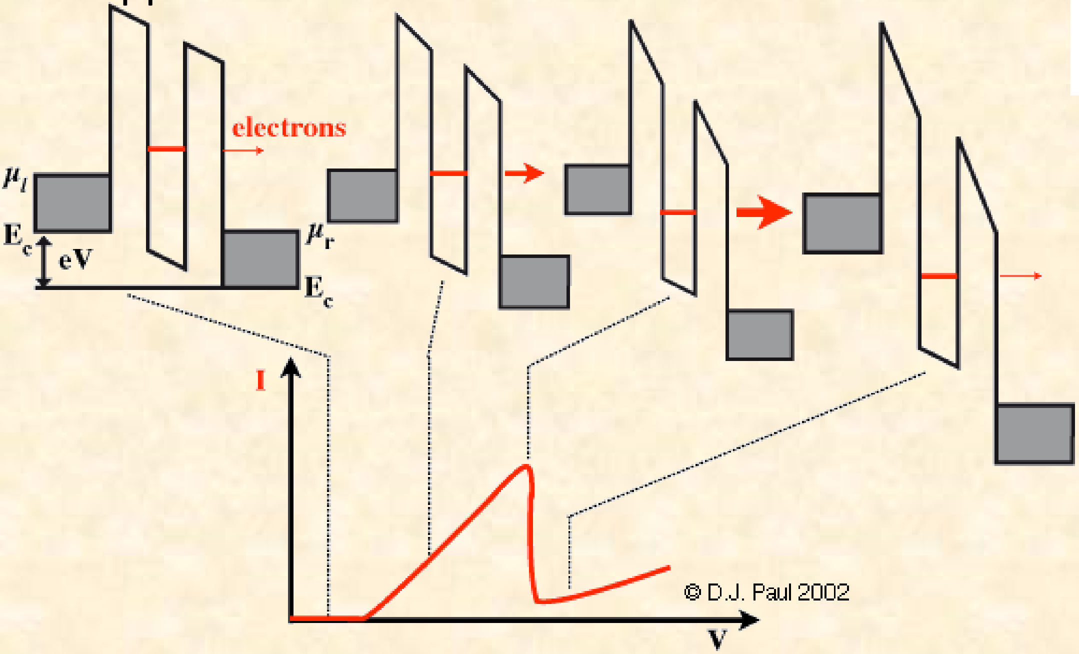


Another idea: Resonant quantum wells

Particle in a box confinement in 1 dimension,
free particles in the perpendicular dimensions.
Easier to fabricate.



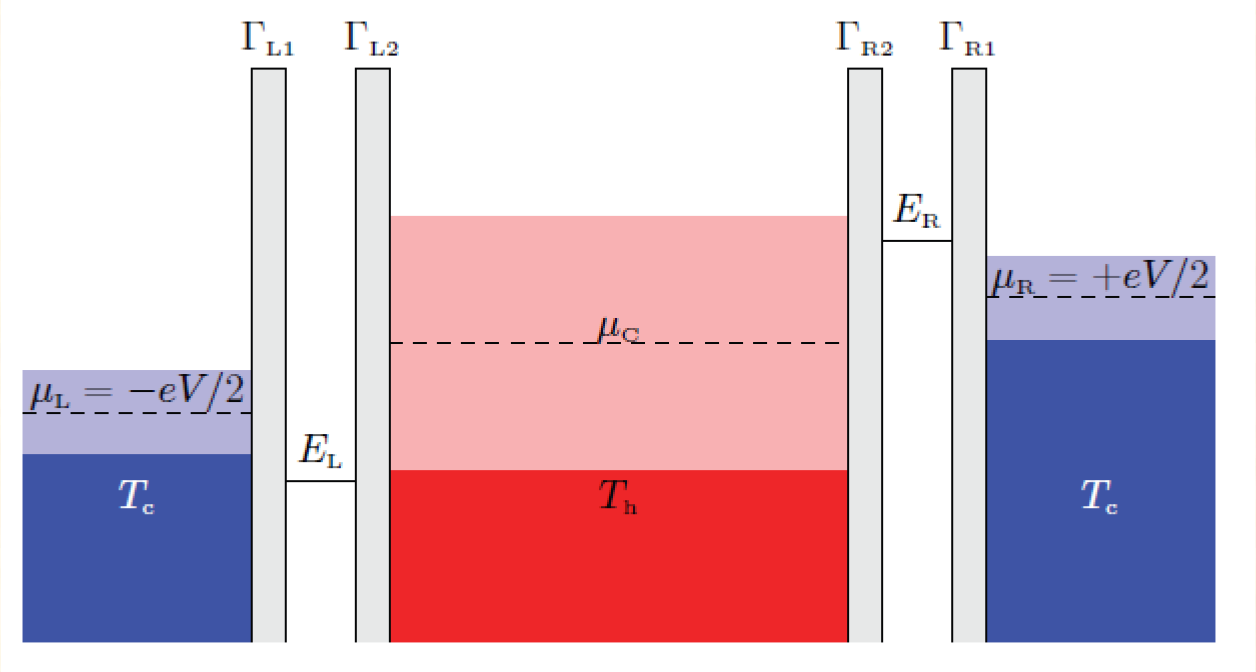
Application as a tunnel diode:



e.g.
AlAs-GaAa-AlAs
Or
GaN-InGaN-GaN

Take two Resonant wells in series

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



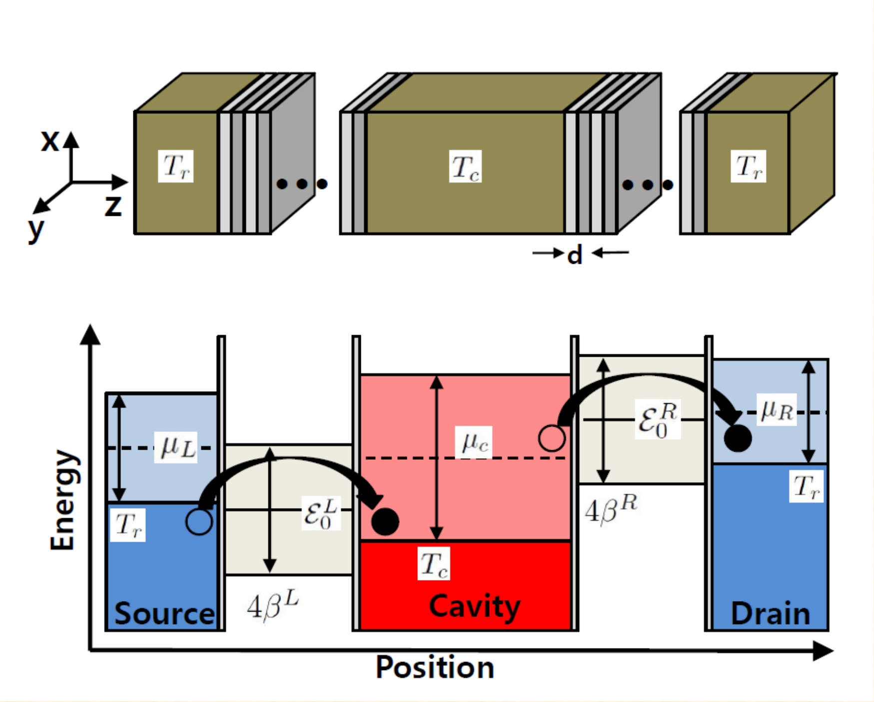
Unlike quantum dots, the transmission now has a `turn on' feature at the resonant energy, rather than a sharp level. Can reach ~7% of the Carnot efficiency at max power. The power is still high, at ~0.2 W/cm^2 for a 1K temperature difference.

Can generalize this idea to superlattices

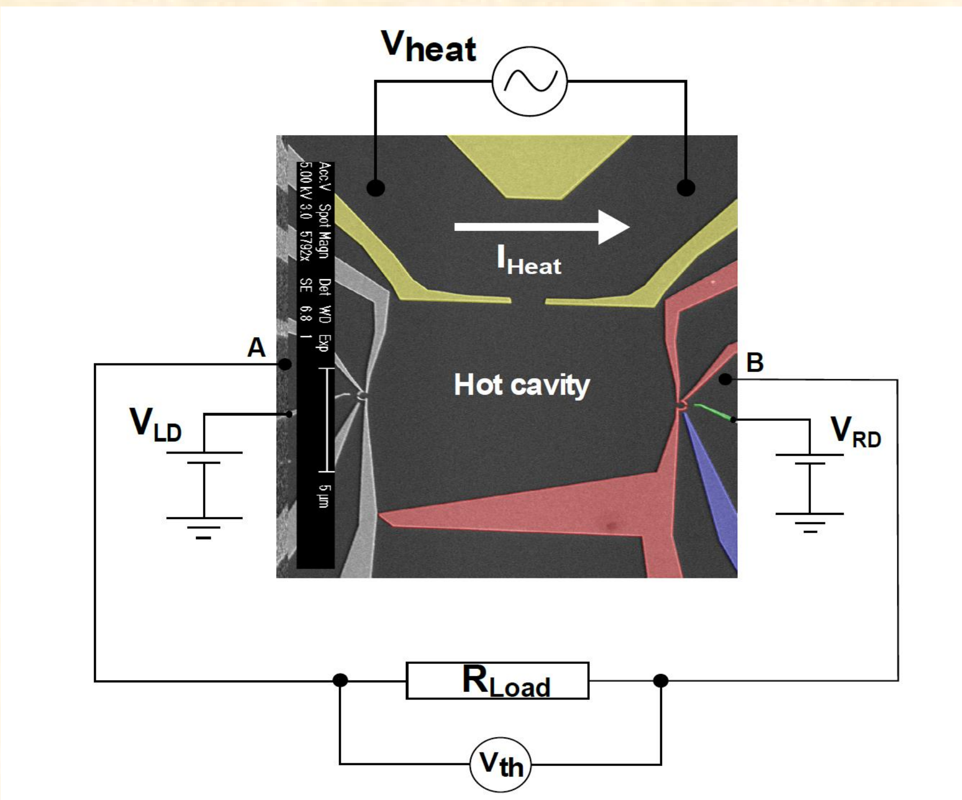
Yunjin Choi and ANJ,
Physica E 74, 465
(2015)

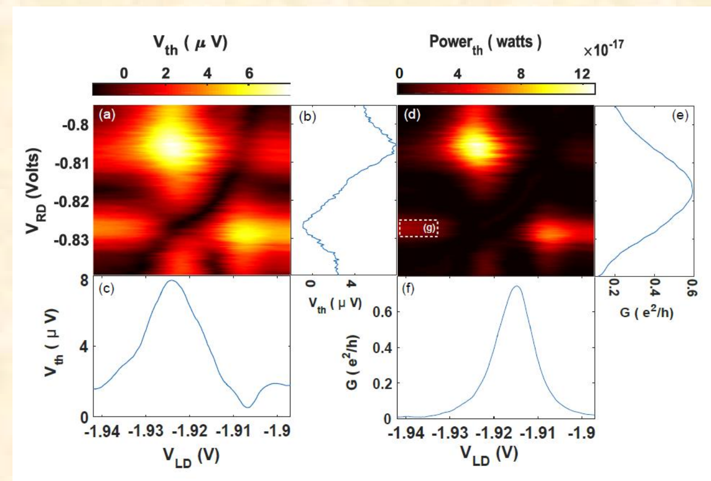
Periodicity in the superlattice opens
up a band gap in the transmission, which
Can be used to tailor the filtering and
Measurement power.

Helps with phonons, too.



Unpublished experiment! – Charles Smith group, Cambridge, UK





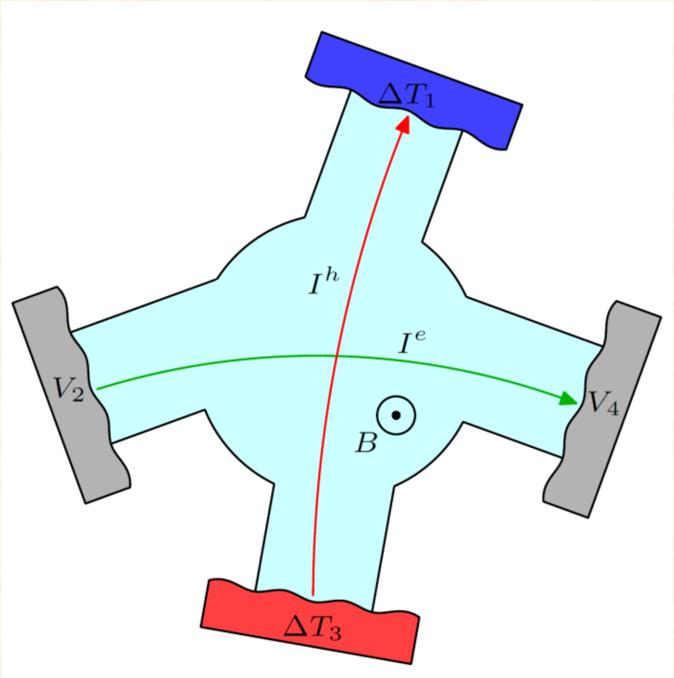
The thermal voltage V and power across the device, as a function of left and right plunger gates measured whilst an AC current, is applied to the heating channel.

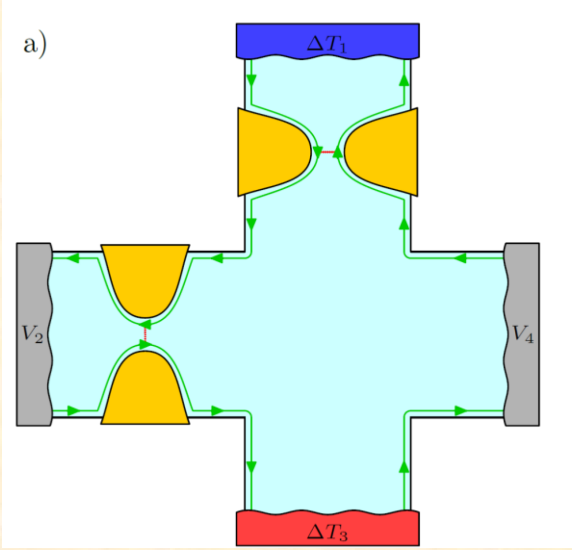
New directions: Quantum Nernst Engine

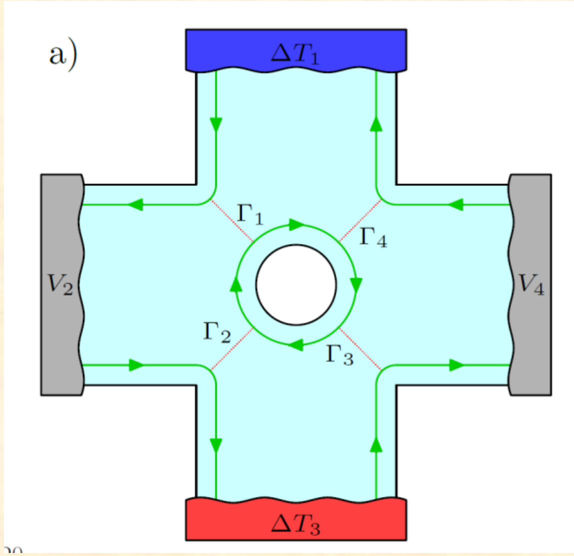
A Nernst engine is made with a magnetic field applied perpendicular to a two-dimensional conductor. A temperature bias along the sample will then give rise to a charge current perpendicular to both the temperature gradient and the magnetic field.

Sothmann, Sánchez, ANJ, Europhys. Lett. 107, 47003 (2014)

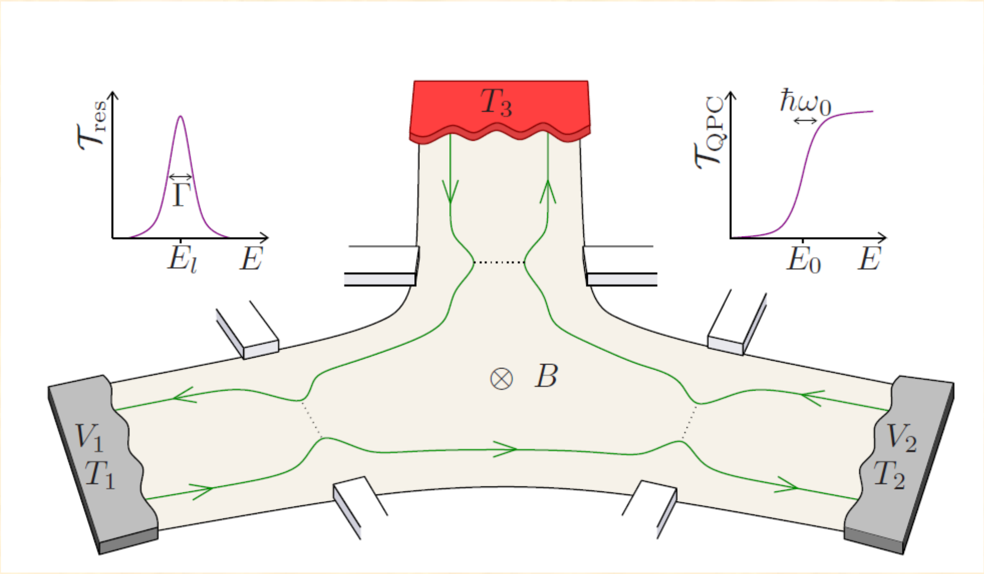
See also Stark J., Brandner K., Saito K. and Seifert U., Phys. Rev. Lett., 112 (2014) 140601.

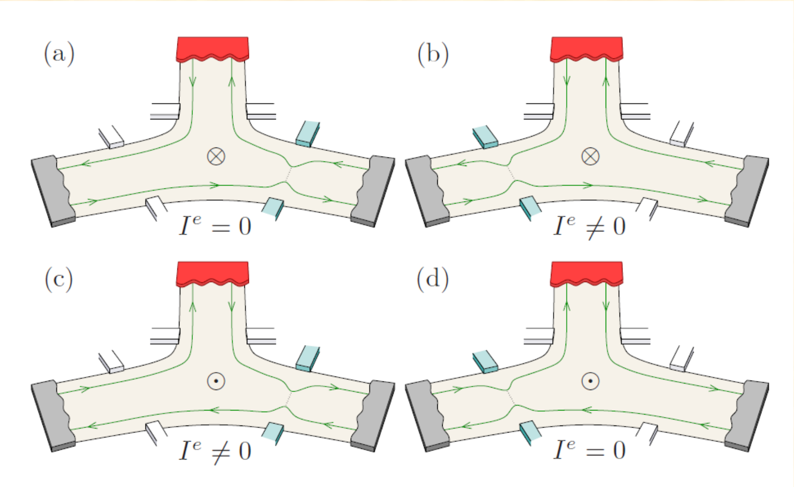






New directions: Quantum Hall heat engines





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

We show that if only one of the QPCs (either lead 1 or 2) is pinched off partly, then heating lead 3 to a higher temperature can lead to an electrical current between leads 1 and 2 (Seebeck effect), but this depends on which of the QPCs is pinched - pinching QPC 1 gives a Seebeck effect, but pinching QPC 2 does not. This is because of the chirality of the electron motion. Further - applying electrical voltage between leads 1 and 2 leads to a heat current flowing into lead 3 (the Peltier effect), or not, but in the **opposite** configurations discussed above.

Chiral motion of the electrons divorces Peltier from Seebeck.

$$\begin{pmatrix} I^e \\ I_3^h \end{pmatrix} = \begin{pmatrix} \mathcal{L}_{eV} & \mathcal{L}_{eT} \\ \mathcal{L}_{hV} & \mathcal{L}_{hT} \end{pmatrix} \begin{pmatrix} F_1^V - F_2^V \\ F_3^T \end{pmatrix}$$

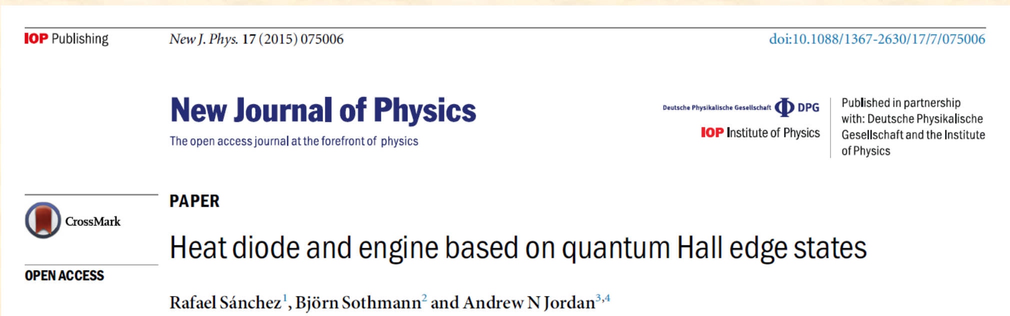
We can physically understand why this effect occurs, because in the case where there is no Seebeck effect, the hot terminal 3 creates electron-hole excitations, which have energy. However, these are charge-neutral excitations, and if QPC 1 is open, they are all absorbed in lead 1, giving heat, but no current. On the other hand, if QPC 1 is pinched, this leads to the high energy ones (electrons) being transmitted into lead 1, and the low energy ones (holes) reflected into lead 2, giving rise to a charge current.

Chiral motion of the electrons divorces Peltier from Seebeck.

Consider now no temperature difference on lead 3, but a voltage bias on lead 2. If we now pinch QPC 1 but not QPC 2 (where there was a Seebeck effect), the electrons leaving QPC 2 now all enter lead 3, and all leave lead 3 with the same energy distribution, since it is assumed to be a voltage probe. Since the probe is at the same temperature as lead 2, there is no loss or gain of energy - so there is no Peltier effect. In the case where we pinch QPC 2 but not QPC 1 (where there was no Seebeck effect), we now have the case where the high energy electrons are transmitted to lead 3, and the low energy one are reflected back to lead 2. Since lead 3 is at the same temperature as lead 2 (the voltage probe), it reshuffles the electrons to a thermal distribution at its temperature, which involves taking some energy from the electrons, and therefore producing a heat current (giving a Peltier effect). A similar story works if we voltage bias lead 1 instead.

Onsager still has something important to tell us: In a fixed geometry (say QPC 1 pinched, and QPC 2 open), we can exchange Seebeck for Peltier by flipping the magnetic field direction!

Can also use this geometry as a heat diode


IOP Publishing   New J. Phys. 17 (2015) 075006   doi:10.1088/1367-2630/17/7/075006

New Journal of Physics
The open access journal at the forefront of physics

Deutsche Physikalische Gesellschaft DPG
IOP Institute of Physics
Published in partnership with: Deutsche Physikalische Gesellschaft and the Institute of Physics

CrossMark

OPEN ACCESS

PAPER

Heat diode and engine based on quantum Hall edge states

Rafael Sánchez[1], Björn Sothmann[2] and Andrew N Jordan[3,4]

$$\mathcal{R}_{ij} = \frac{\mathcal{L}_{ij}^{hT}}{\mathcal{L}_{ji}^{hT}}$$

New J. Phys. 17, 075006 (2015)

The effect of chirality is not only restricted to the propagation of charge. It also affects the heat currents. This effect is parametrized by the heat rectification coefficient

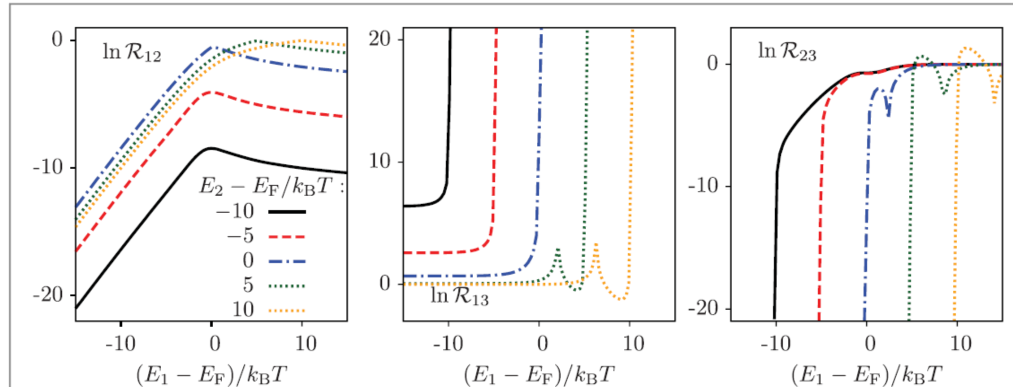
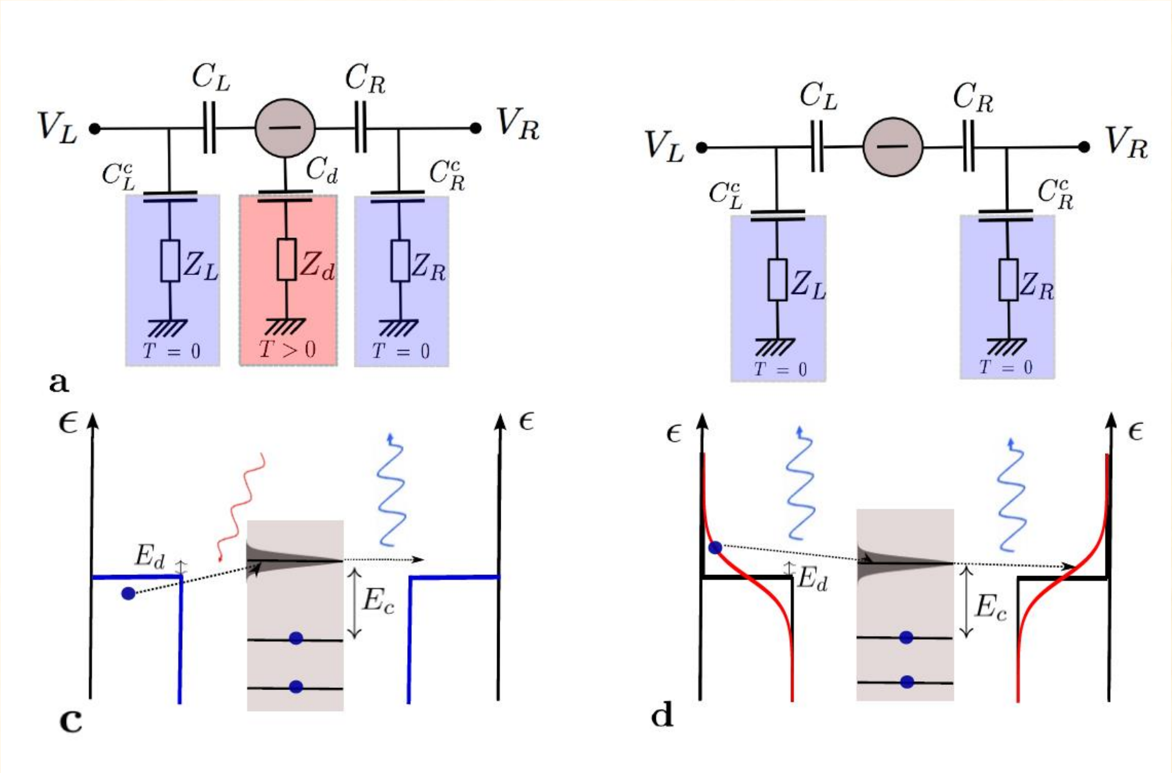


Figure 3. Heat rectification coefficient $\ln \mathcal{R}_{ij}$ corresponding to the configuration of figure 2. As the energy E_1 is becomes positive and larger than $k_B T$, the contact 1 gets closed. The different curves correspond to different positions of the contact in terminal 2. The longitudinal coefficient $\mathcal{R}_{12}$ is exponentially suppressed when junction 1 is open. The crossed coefficients $\mathcal{R}_{13}$ and $\mathcal{R}_{23}$ show divergences when one of the corresponding coefficients changes sign.

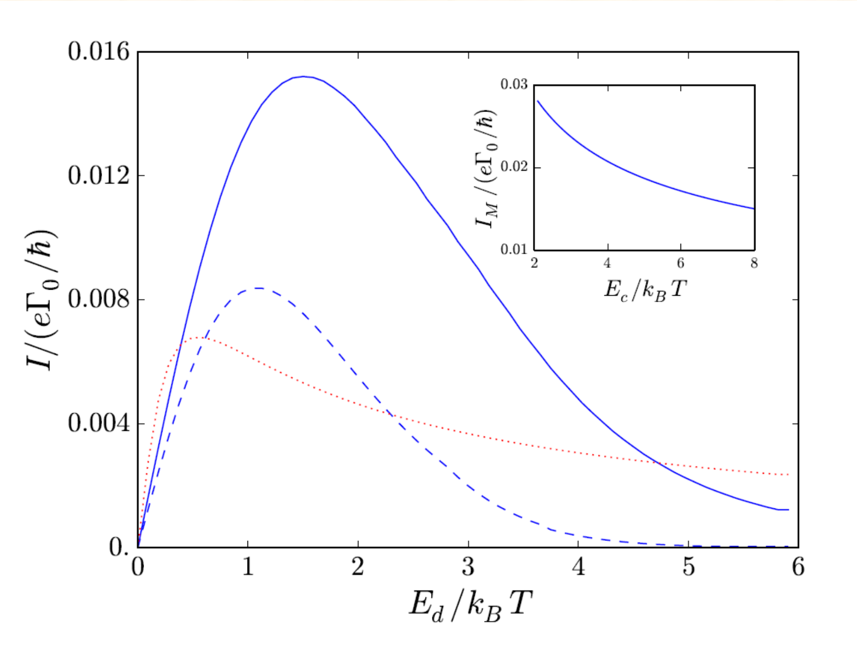
New directions: Using the electromagnetic environment



Loic Henriet, ANJ, Karyn Le Hur
Phys. Rev. B 92, 125306 (2015)

See also: T. Ruokola and T. Ojanen, Phys. Rev. B 86, 035454 (2012).

Rossello, R. Lopez, and R. Sanchez, Phys. Rev. B 95, 235404 (2017)



UNIVERSITY *of* ROCHESTER

Loic Henriet, ANJ, Karyn Le Hur
Phys. Rev. B 92, 125306 (2015)

P(E) theory approach using a quantum electromagnetic environment.

Rectified current as a function of quantum dot energy level, divided by the temperature of the leads (Fig. 1b).

Sequential limit:

$$\alpha_l = R_q/R_l \gg 1$$

$$I = e\,\frac{T_{+,L}(E_d)T_{+,R}(E_d) - T_{-,L}(E_d)T_{-,R}(E_d)}{T_{+,L}(E_d) + T_{+,R}(E_d) + T_{-,L}(E_d) + T_{-,R}(E_d)}$$

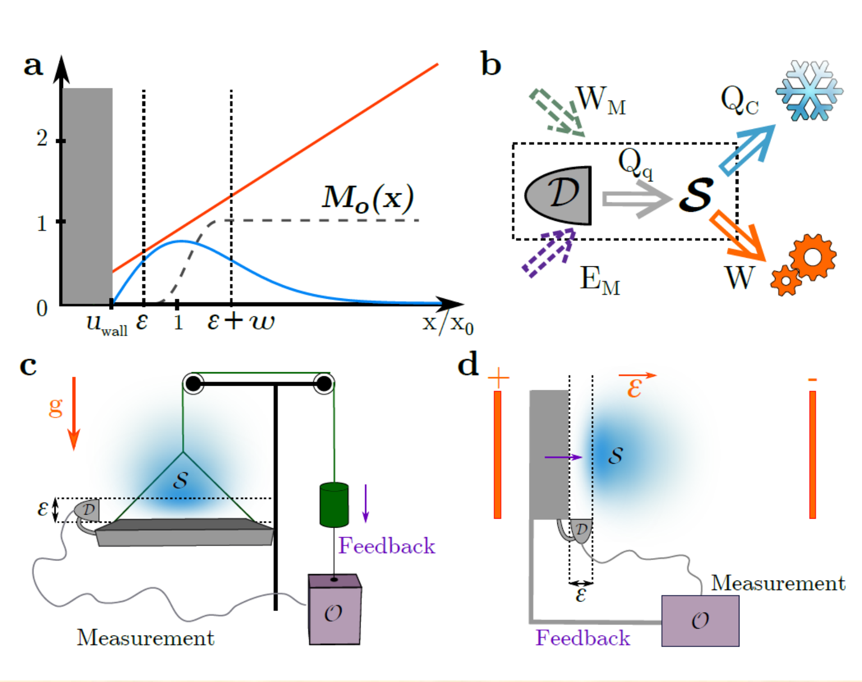
$$T_{\pm,L}(\Omega) = -T_{0,L}e^{-\frac{2\gamma_e}{\alpha_L}}\left(\frac{\pi k_BT}{\alpha_L E_c}\right)^{\frac{2}{\alpha_L}}\mathrm{Li}_{\frac{2}{\alpha_L}}\left(-e^{\frac{\mp\Omega\pm\mu/2}{k_BT}}\right)$$

$$T_{\pm,R}(\Omega) = -T_{0,R}e^{-\frac{2\gamma_e}{\alpha_R}}\left(\frac{\pi k_BT}{\alpha_R E_c}\right)^{\frac{2}{\alpha_R}}\mathrm{Li}_{\frac{2}{\alpha_R}}\left(-e^{\frac{\pm\Omega\pm\mu/2}{k_BT}}\right),$$

Moving away from thermal resources…..

Can I design a fully quantum engine that operates with no work done by the system Hamiltonian?

Quantum measurement as a pseudo-thermal resource: a single-atom elevator and a single-electron battery



Efficient Quantum Measurement Engines
Cyril Elouard, ANJ, arXiv:1801.03979

Despite the stochastic nature of the quantum measurement process, unit thermodynamic efficiency is possible with feedback!

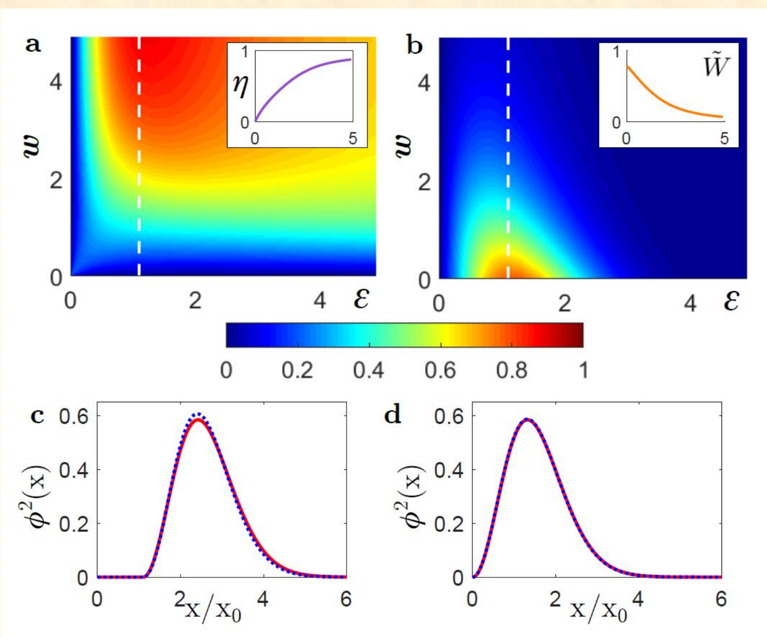
Quantum measurement Engines: results

Three stroke engine cycle, starting from the ground state:

1) Make a generalized position measurement.
2) Move the wall, or not, depending on result.
3) Wait to reset the ground state.

Efficient Quantum Measurement Engines
Cyril Elouard, ANJ, arXiv:1801.03979

Efficiency Work



See also: C. Elouard, D. Herrera-Mart, B. Huard, and A. Aueves, Phys. Rev. Lett. 118, 260603 (2017).

Designer measurements:

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

Measurement operator to tell if the particle is near the wall, or not.

Conclusions and Outlook

- Proposed method to harvest energy from the nanoscale up to the macro scale.
- High efficiency, high power system (for mesoscopic systems!) using resonant tunneling quantum dots and wells as energy filters.
- Proposed scalable, practical version with self-assembled quantum dots. No moving parts.
- Even easier to make with quantum wells.
- Could be used to harvest waste energy from electronics for longer battery life, or the powering of auxiliary system.
- New thermoelectric fundamental physics using Quantum Hall, vacuum fluctuations, and quantum measurement