Performance of shortcut-to-adiabaticity quantum engines

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Sales of inefficient vacuum cleaners banned
By ***Euronews*** · last updated: 01/09/2017

Powerful vacuum cleaners are to be banned from today after the European Union introduced new rules which aim to improve energy efficiency across the continent.

'Widespread misconception'

The European Environment Bureau (EEB) said: "Power doesn't always equal performance, though the misconception has become widespread."

"Some efficient models maintained high standards of dust pick-up while using significantly less energy - due to design innovation."

From **BBC News** 01/09/2017

Outline

1. Motivation
   - Introduction
   - Downscaling engines
2. Four-stroke Otto engine
3. Shortcut-to-adiabaticity engine
   - Fast and efficient engines
   - Generic bounds on quantum machines

Introduction

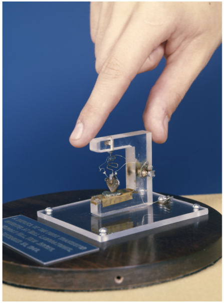
Miniaturization:

is about building smaller devices — Drexler 1981

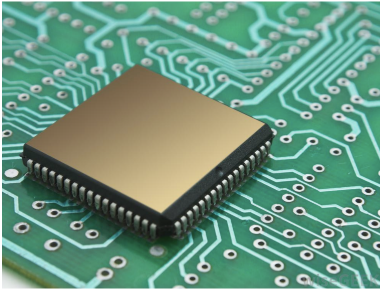
→ fundamental limit = atomic structure of matter

Transistor:

1947



Today



Introduction

Mobile phone:

1973/1983

Today

➔ weight 1.1kg, 30min talk time, 10h charge time, price 4000$

Introduction

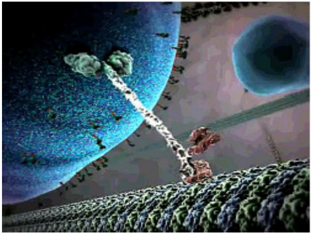
"There is plenty of room at the bottom": Feynman 1959

"Consider any machine – for example, an automobile – and ask about the problems of making an infinitesimal machine like it"

Two basic strategies:

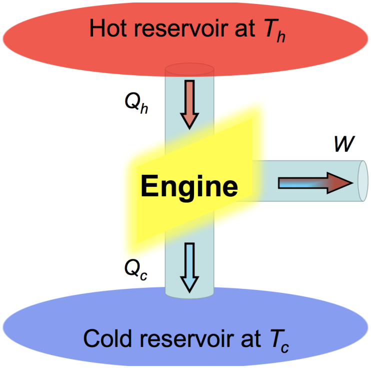
Follow engineers

Follow nature



Macroscopic heat engine

$\rightarrow$ convert thermal energy into mechanical work = motion



Carnot efficiency:

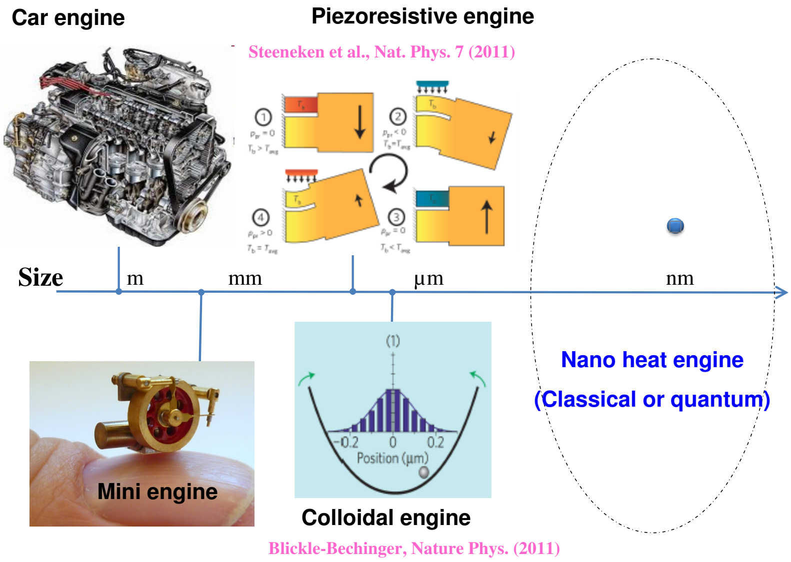
$$\eta = \frac{\text{Work produced}}{\text{Heat absorbed}} \leq 1 - \frac{\beta_h}{\beta_c} = 1 - \frac{T_c}{T_h}$$

(James Watt 1783: $\eta \sim 5 - 7$ %)

$\rightarrow$ maximum efficiency

Today's gasoline engines: $\eta \sim 25 - 30$ %

Downscaling of heat engines

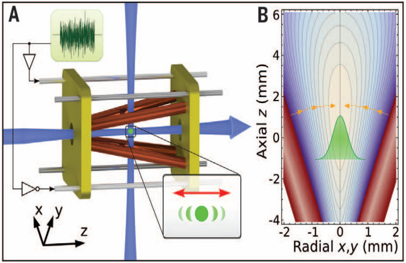


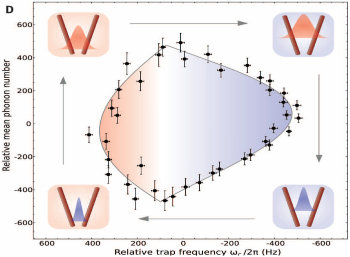
Single atom heat engine

Rossnagel et al., Science 352, 325 (2016)

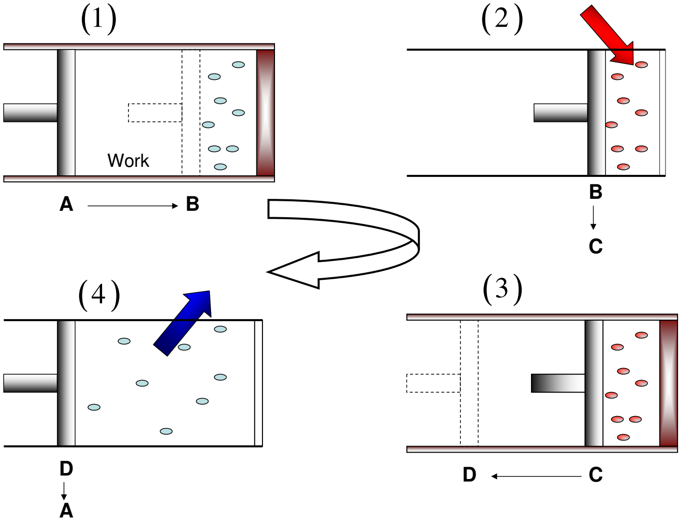
Reservoir engineering:

- Cold reservoir: laser (Doppler) cooling (always on)
- Hot reservoir: electrode noise (switched on/off)

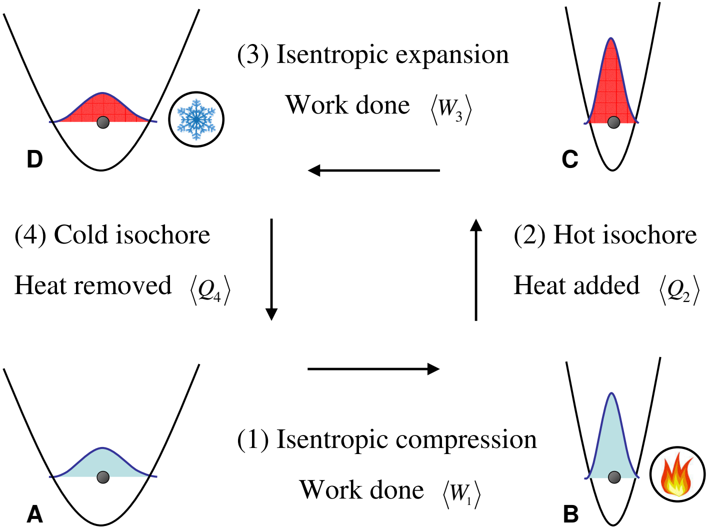




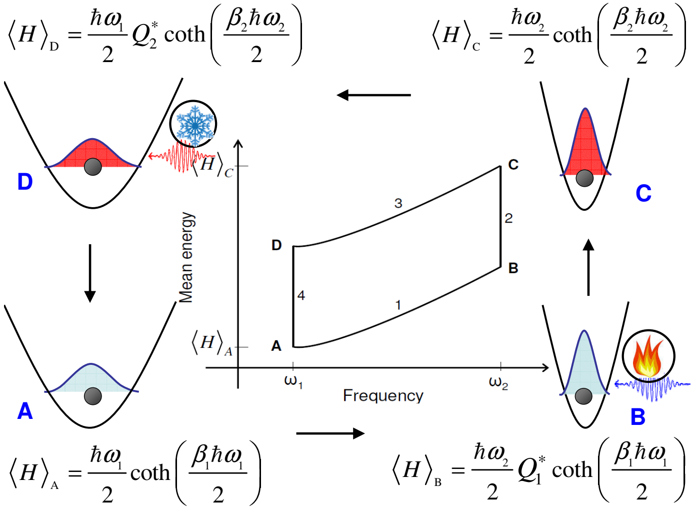
Classical four-stroke heat engine



Quantum Otto heat engine



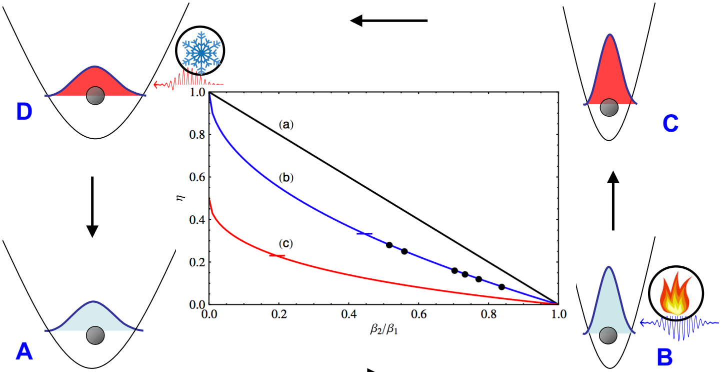
Quantum Otto heat engine: theory



Quantum Otto heat engine

Abah et al, PRL **112**, 030602 (2012)

$$\langle H \rangle_D = \frac{\hbar\omega_1}{2} Q_2^* \coth\left(\frac{\beta_2\hbar\omega_2}{2}\right) \qquad \langle H \rangle_C = \frac{\hbar\omega_2}{2} \coth\left(\frac{\beta_2\hbar\omega_2}{2}\right)$$



$$\langle H \rangle_A = \frac{\hbar\omega_1}{2} \coth\left(\frac{\beta_1\hbar\omega_1}{2}\right) \qquad \langle H \rangle_B = \frac{\hbar\omega_2}{2} Q_1^* \coth\left(\frac{\beta_1\hbar\omega_1}{2}\right)$$

Question How can we speed up the heat engine?

National waiters day

- gadgets – shoes, tray, ...
- optimal protocol

More bang for your buck:
Super-adiabatic quantum engines

A. del Campo[1,2], J. Goold[3] & M. Paternostro[4]

Scientific Report 4 : 6208 (2014)

Waiters race, fast service is a priority!

Shortcut-to-adiabaticity (STA)

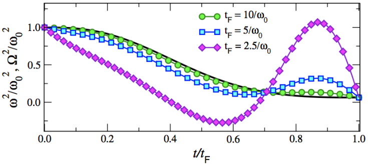
... inducing a "fast motion video of the adiabatic dynamics."

Effective Hamiltonian: $H_{\text{eff}}(t) = H_0(t) + H^i_{\text{STA}}(t)$

$H^i_{\text{STA}}(t)$ - STA driving Hamiltonian and $i = (1, 3)$ - compression/expansion steps

➔ fast and reduces irreversible losses

$$\omega(0) = \omega_i, \quad \dot{\omega}(0) = 0, \quad \ddot{\omega}(0) = 0,$$
$$\omega(\tau) = \omega_f, \quad \dot{\omega}(\tau) = 0, \quad \ddot{\omega}(\tau) = 0,$$



For harmonic oscillator:

LCD technique

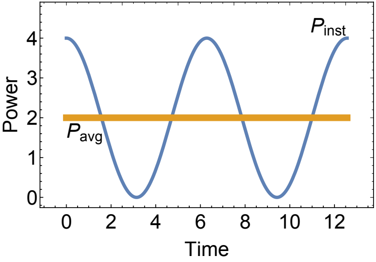
$$H_{\text{STA}} = \frac{m}{2}\left(\Omega_t^2 - \omega_t^2\right)x^2$$
$$= \frac{m}{2}\left(-\frac{3\dot{\omega}_t^2}{4\omega_t^2} + \frac{\ddot{\omega}_t}{2\omega_t}\right)x^2$$

Demirplak and Rice, JPC A **107**, 9937 (2003)
Berry, JPA **42**, 365303 (2009)
Chen et al, PRL **109**, 100403 (2010)
del Campo, PRL **111**, 100502 (2013)

Energetic cost of the shortcut driving

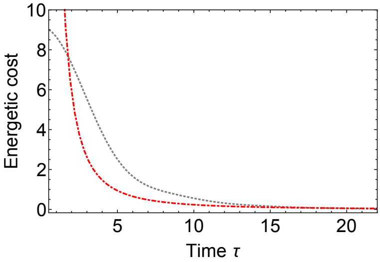
Elementary power analysis

$$P_{inst} = 2 + 2\cos\omega t$$



$$P_{avg} = (1/T)\int_0^T P_{inst}\,dt$$

Abah and Lutz, EPL **118**, 40005 (2017)



Cost of the driving:

$$\langle H^i_{\rm STA}\rangle_\tau = (1/\tau)\int_0^\tau dt \langle H^i_{\rm SA}(t)\rangle$$

Nonadiabatic work (friction):

$$\langle W_i\rangle_{\rm NA} = \langle W_i\rangle - \langle W_i\rangle_{\rm AD}$$

- the actual and the adiabatic work

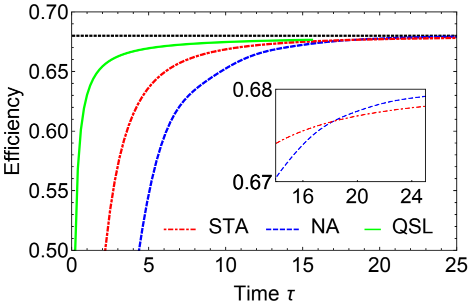
Performance of STA quantum engines

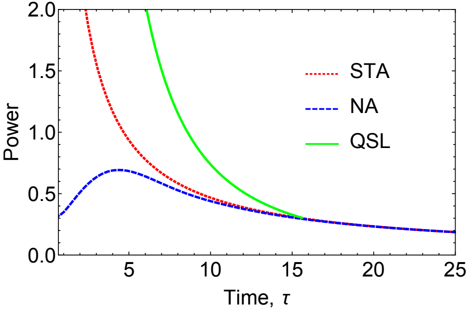
Efficiency:

$$\eta_{\mathsf{STA}} = \frac{\text{energy output}}{\text{energy input}} = \frac{-(\langle W_1\rangle_{\mathsf{STA}} + \langle W_3\rangle_{\mathsf{STA}})}{\langle Q_2\rangle + \left\langle H^1_{\mathrm{STA}}\right\rangle_\tau + \left\langle H^3_{\mathrm{STA}}\right\rangle_\tau}$$

Power:

$$P_{\mathsf{STA}} = \frac{\text{energy output}}{\text{Cycle time}} = -\frac{\langle W_1\rangle_{\mathsf{STA}} + \langle W_3\rangle_{\mathsf{STA}}}{\tau_{\mathsf{cycle}}}.$$





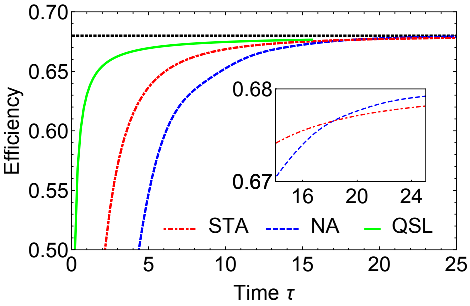
Generic bounds: quantum speed limit (QSL)

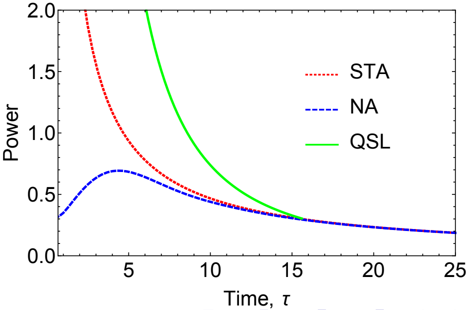
Quantum: limits the speed of evolution of a system — Anandan and Aharonov, PRL (1990)

QSL time: $\tau_{\text{QSL}} = \frac{\hbar \mathcal{L}(\rho_i,\rho_f)}{\langle H_{\text{STA}} \rangle_\tau} \leq \tau$ — $\mathcal{L}(\rho_i, \rho_f)$ - the Bures angle between density operators

Efficiency: $\eta_{\text{STA}} \leq \eta_{\text{STA}}^{\text{QSL}} = -\frac{\langle W_1 \rangle_{\text{AD}} + \langle W_3 \rangle_{\text{AD}}}{\langle Q_2 \rangle + \hbar(\mathcal{L}_1 + \mathcal{L}_3)/\tau}$

Power: $P_{\text{STA}} \leq P_{\text{STA}}^{\text{QSL}} = -\frac{\langle W_1 \rangle_{\text{AD}} + \langle W_3 \rangle_{\text{AD}}}{\tau^1_{\text{QSL}} + \tau^3_{\text{QSL}}}$ — Abah and Lutz, EPL 118, 40005 (2017)

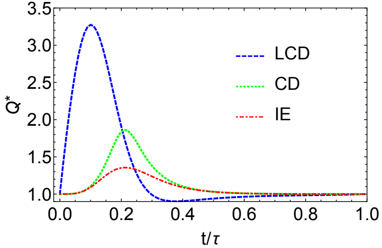




Fast and efficient quantum engines

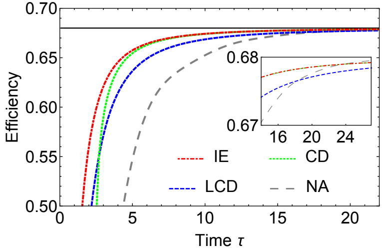
Question: Is it true for every shortcut-to-adiabaticity protocol?

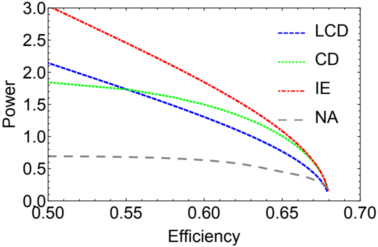
Abah and Lutz, arXiv. 1707.09963 (2017)



Q^* - Adiabaticity parameter

LCD - local counterdiabatic driving
CD - counterdiabatic driving
IE - inverse engineering
NA - nonadiabatic driving





➔ simultaneous increase of efficiency and power for fast cycles

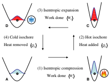
Take-Home message

- STA engine are energy efficient machines
  - ➔ outperform their convention counterpart
- Quantum speed limit impose bounds to performance
  - ➔ fundamental limit for quantum machines
  - ➔ tighter than the second law of thermodynamics
- Power doesn't always equal performance
  - ➔ overall efficiency is important quantity

References

⋆ *Energy efficient quantum machines*
O. Abah and E. Lutz

EPL (Europhys. Lett.) **118**, 40005 (2017)



Physicists investigate fundamental limits of quantum engines
(Phys.org)—Quantum engines are known to operate differently than—and in some cases, outperform—their classical counterparts.

⋆ *Performance of shortcut-to-adiabaticity quantum engines*
O. Abah and E. Lutz

arxiv: 1707.09963 (2017)

⋆ *Shortcut-to-adiabaticity quantum refrigerator*
O. Abah, M. Paternostro, and E. Lutz

(*to appear soon*)

Thanksforyourattention!!