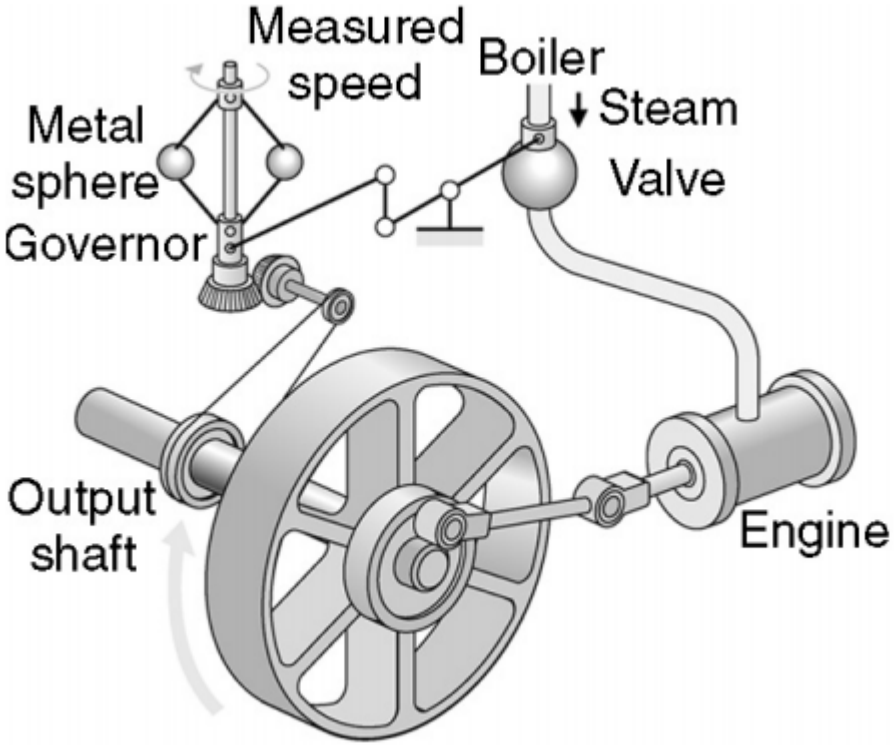
# feedback control: the *flyball governor*

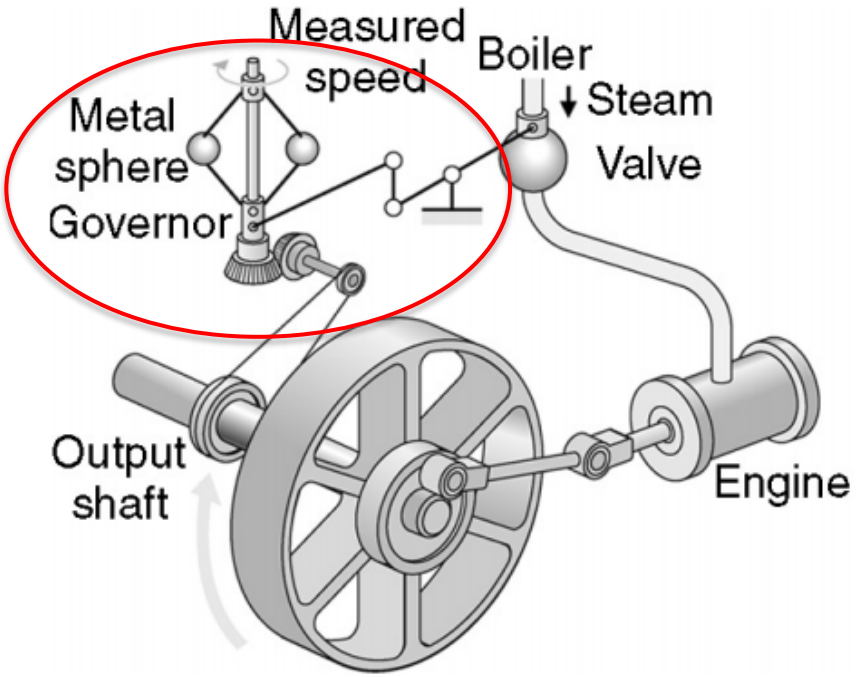
flyball governor (Boulton & Watt)

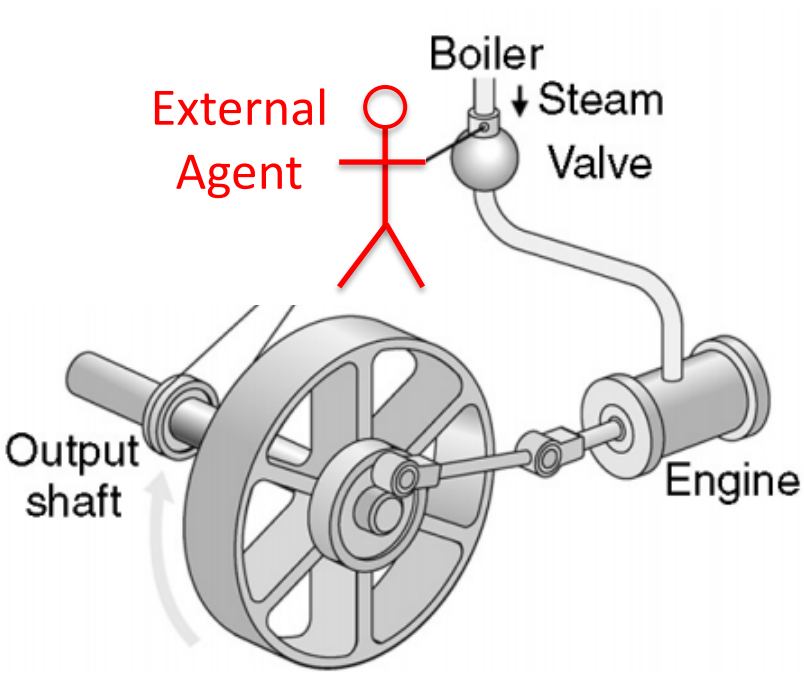
Science Museum, London




Dorf & Bishop, *Modern Control Systems*

# *autonomous* and *non-autonomous* feedback control

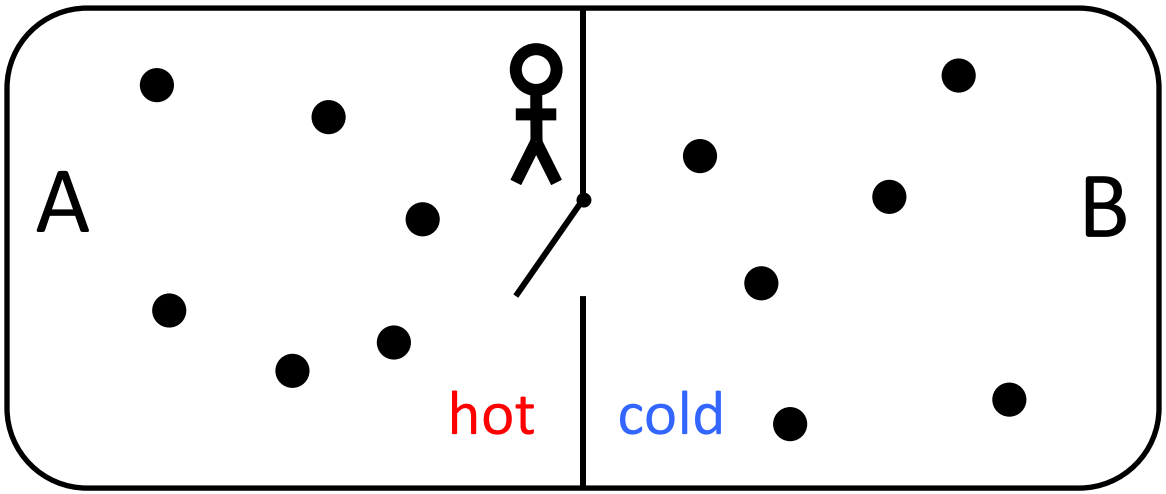



now consider feedback control **at the nanoscale**

… where *fluctuations* and *information* become important

# Maxwell's demon

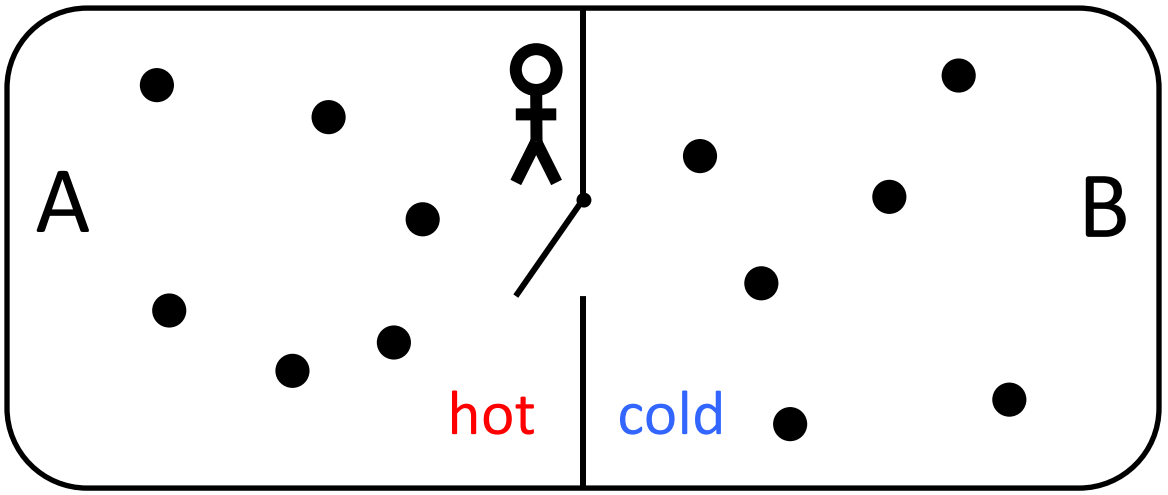



"… the energy in A is increased and that in B diminished; that is, the hot system has got hotter and the cold colder and yet no work has been done, only the intelligence of a very observant and neat-fingered being has been employed"

J.C. Maxwell, letter to P.G. Tait, Dec. 11, 1867

**non-autonomous** feedback control

# Maxwell's demon



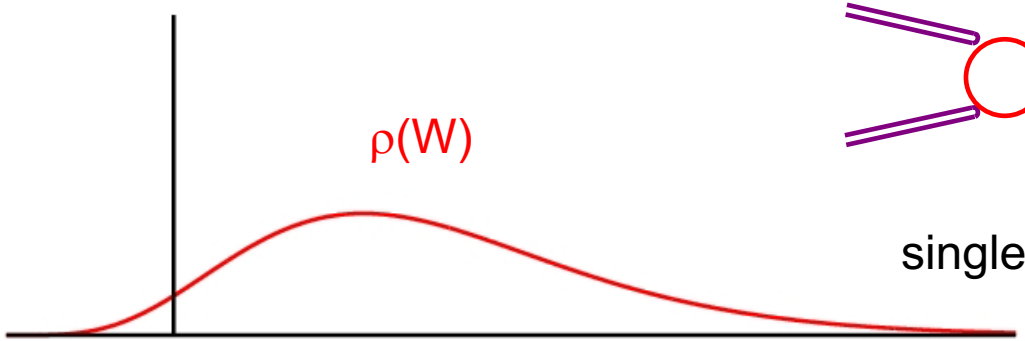

Intuition: more information ➔ greater ability to violate 2nd law

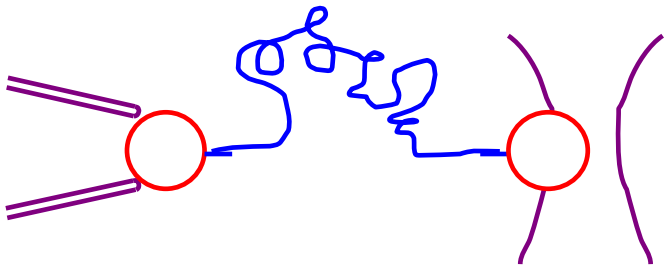
*Can this be quantified?*

**non-autonomous** feedback control

# Second Law of Thermodynamics

*… without feedback control*



single-molecule stretching

$$\langle W \rangle \geq \Delta F$$

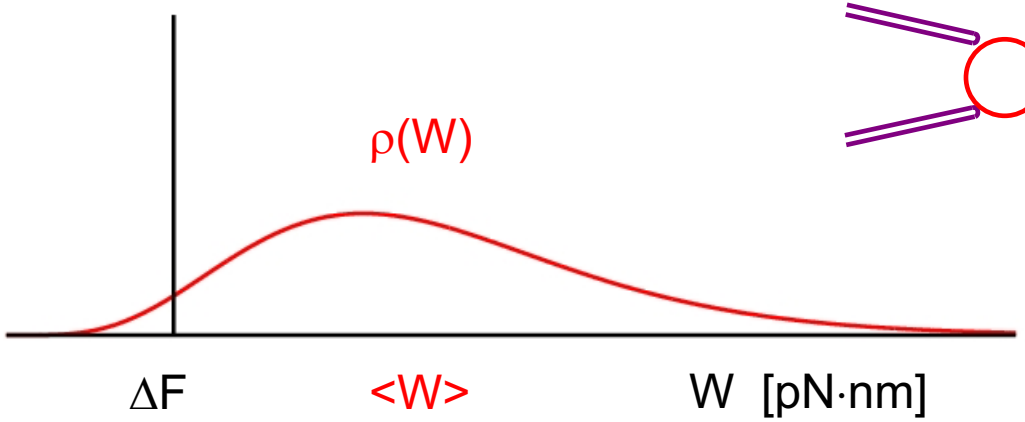
Second law of thermodynamics

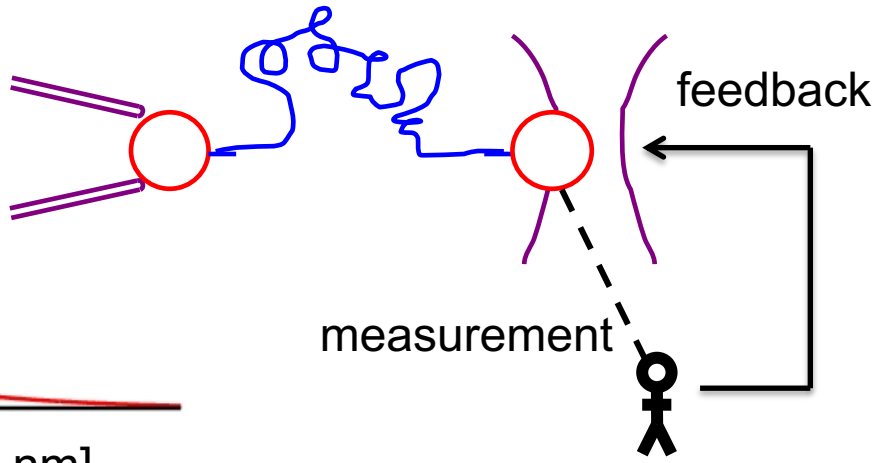
$$\left\langle e^{-\beta W} \right\rangle = e^{-\beta \Delta F}$$

CJ, *PRL* **78**, 2690 (1997)

# Second Law of Thermodynamics

*… with feedback control*




I = information gained

$$\langle W \rangle \geq \Delta F - k_B T \langle I \rangle$$

Sagawa & Ueda, *PRL* **100**, 080403 (2008)

$$\left\langle e^{-\beta W - I} \right\rangle = e^{-\beta \Delta F}$$

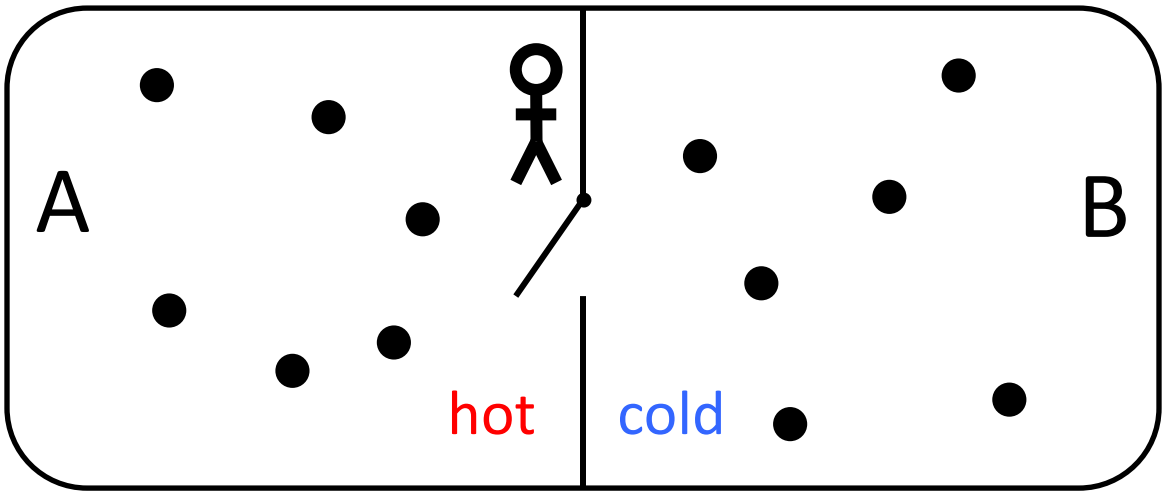
Sagawa & Ueda, *PRL* **104**, 090602 (2010)

experiment:

Koski *et al*, *PRL* **113**, 030601 (2014)

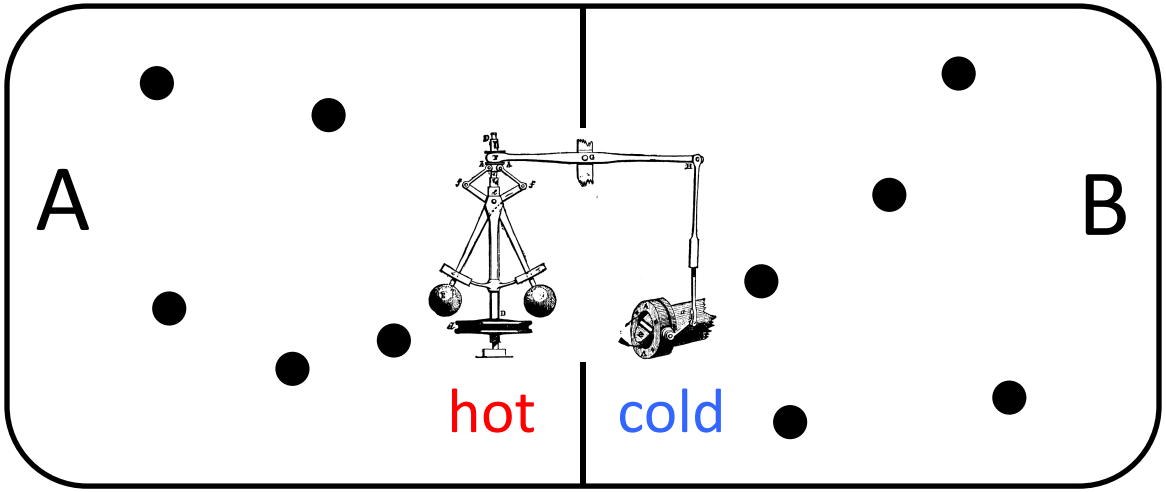
[ Toyabe *et al, Nature Phys* ***6***, 988 (2010) ]

# Maxwell's demon




**non-autonomous** feedback control

# Maxwell's gadget



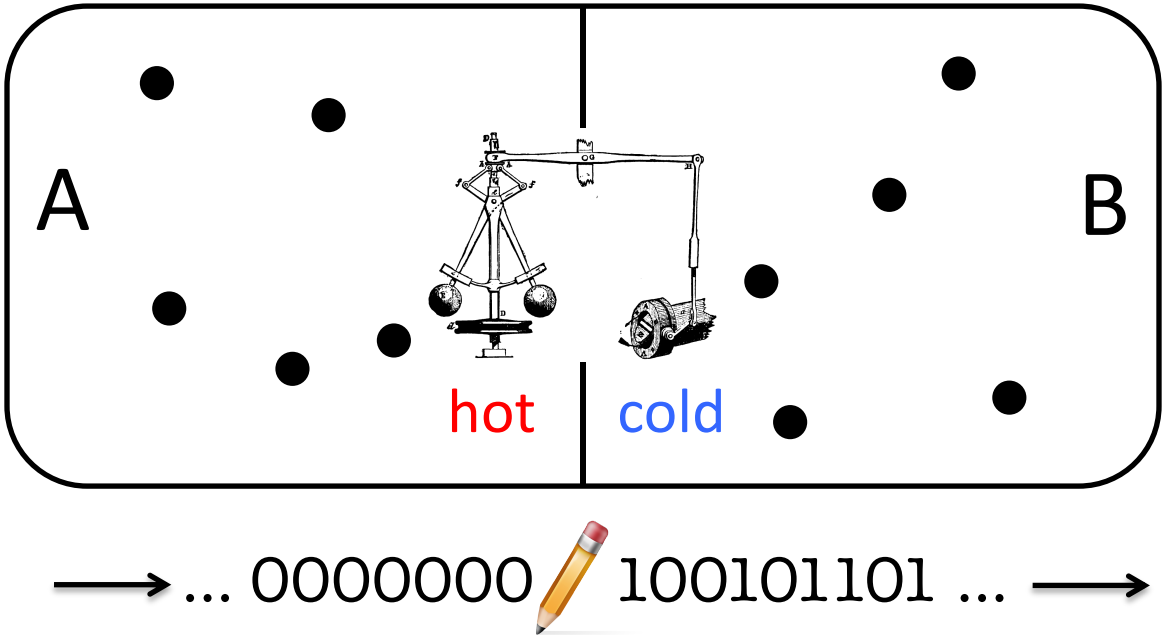

**autonomous** feedback control

*Is a "mechanical" Maxwell demon possible?*

M. Smoluchowski, *Phys Z* **13**, 1069 (1912)
R.P. Feynman, *Lectures*

**no!**

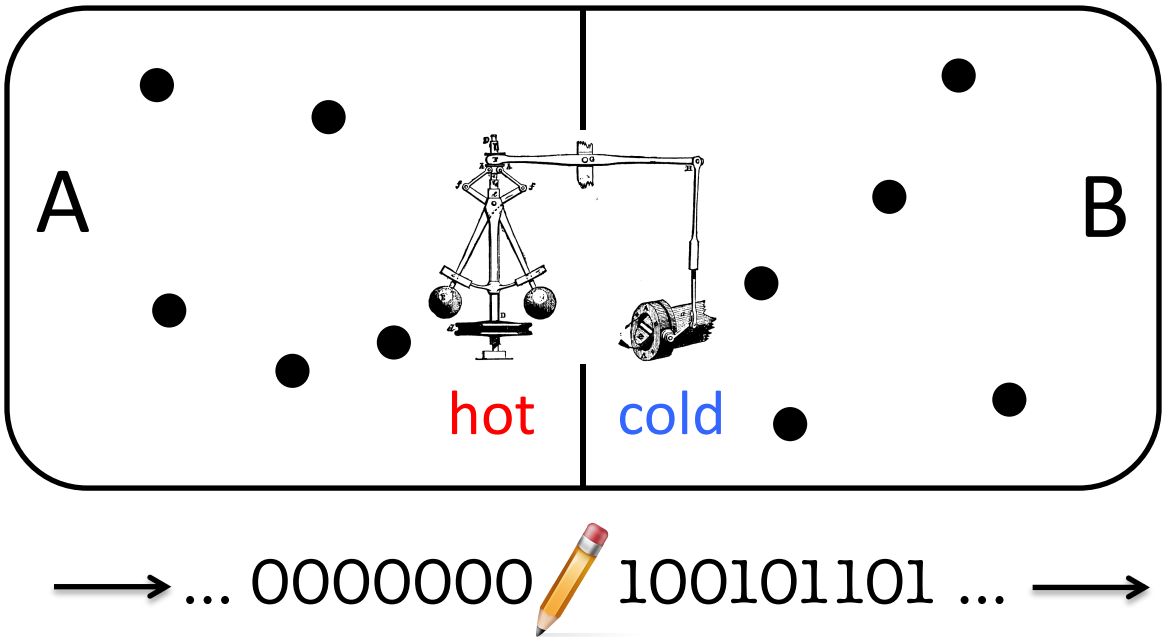
# Maxwell's gadget




*Is a "mechanical" Maxwell demon possible?*

R. Landauer, *IBM J Res Dev* **5**, 183 (1961)
O. Penrose, *Foundations of Statistical Mechanics* (1970) **yes, *but* ...**
C.H. Bennett, *Int J Theor Physics* **21**, 905 (1982)

# Maxwell's gadget




In principle a mechanical device can achieve the same outcome as Maxwell's demon, but only at the cost of *writing information*.

Conversely, the *erasure* of information carries an inherent thermodynamic penalty of $k_B T \ln(2)$ per bit. (*Landauer's Principle*)

Bérut *et al*, *Nature* **483**, 187 (2012)
Jun *et al*, *PRL* **113**, 190601 (2014)

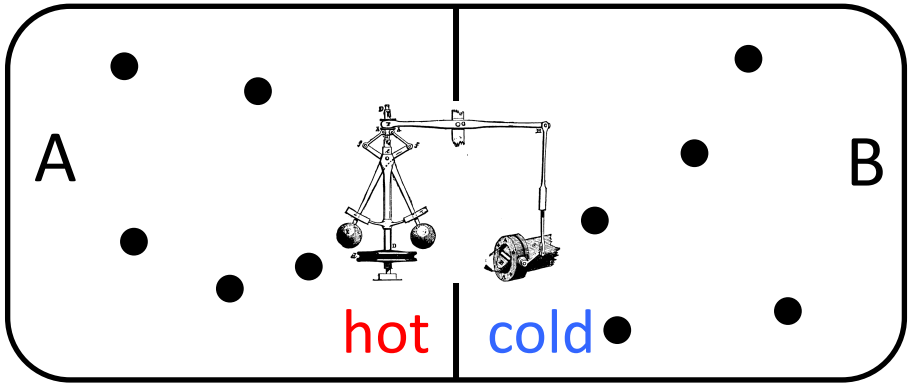
# Autonomous demons

H.T. Quan *et al*, *PRL* **97**, 180402 (2006)
D. Mandal and C. Jarzynski, *PNAS* **109**, 11641 (2012)
T. Sagawa and M. Ueda, *PRL* **109**, 180602 (2012)
P. Strasberg *et al*, *PRL* **110**, 040601 (2012)
J.M. Horowitz, T. Sagawa and J.M.R. Parrondo *PRL* **111**, 010602 (2013)
A.C. Barato and U. Seifert, *EPL* **101**, 60001 (2013)
D. Mandal, H.T. Quan and C. Jarzynski, *PRL* **111**, 030602 (2013)
S. Deffner, *PRE* **88**, 062128 (2013)
Z. Lu, D. Mandal and C. Jarzynski, *Phys Today* **67**, 60 (2014)

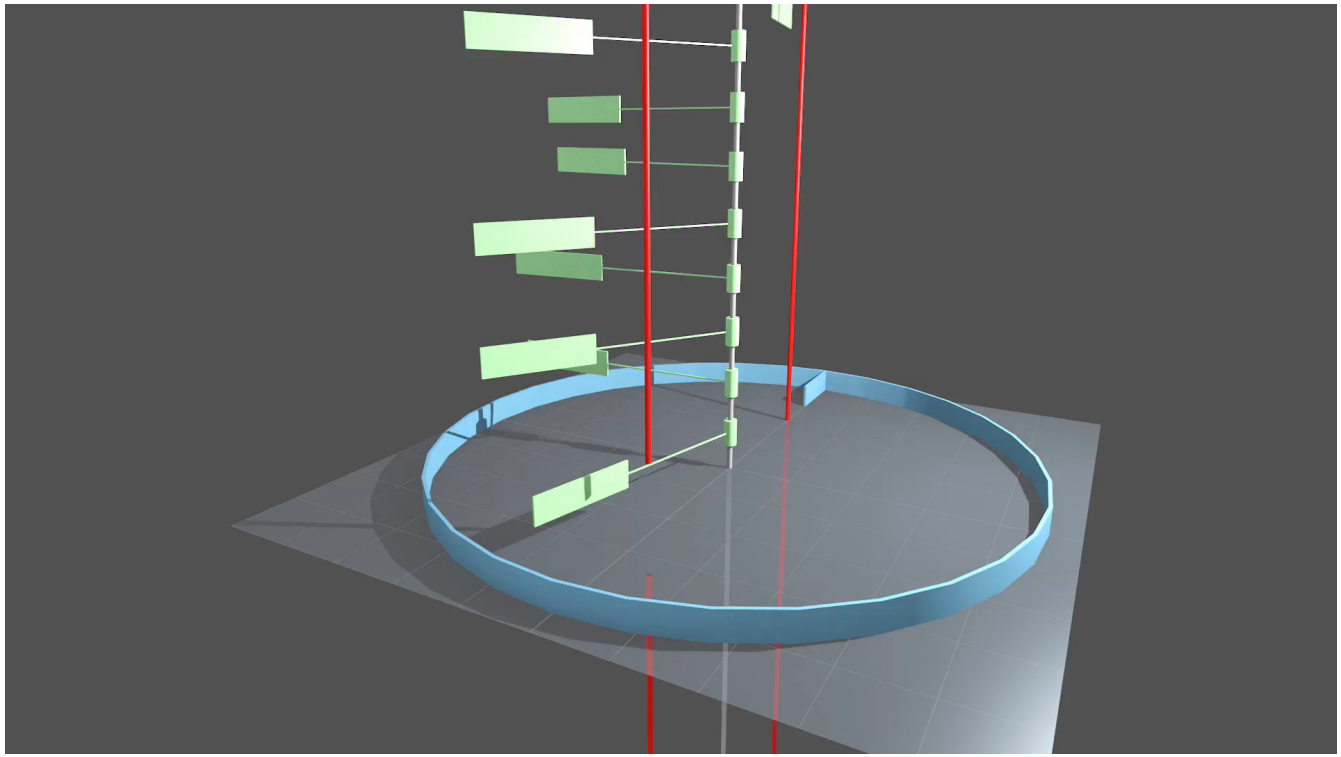
Gedankenengineering:

Design a mechanical gadget that …

(1) systematically withdraws energy from a single thermal reservoir,
(2) delivers that energy to raise a mass against gravity, and
(3) records information in a memory register.


A
B
hot
cold

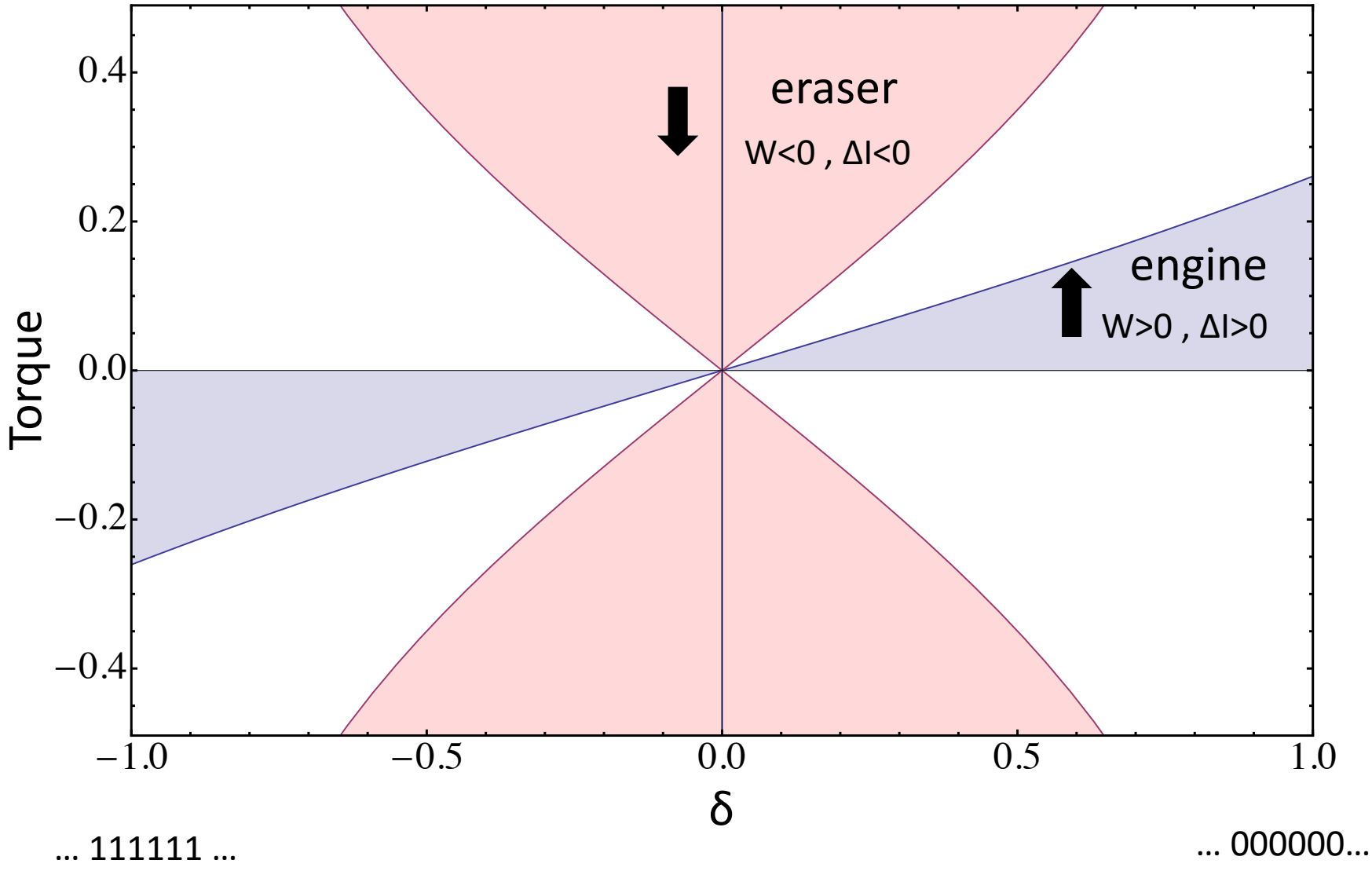

... 0000000 100101101 ...



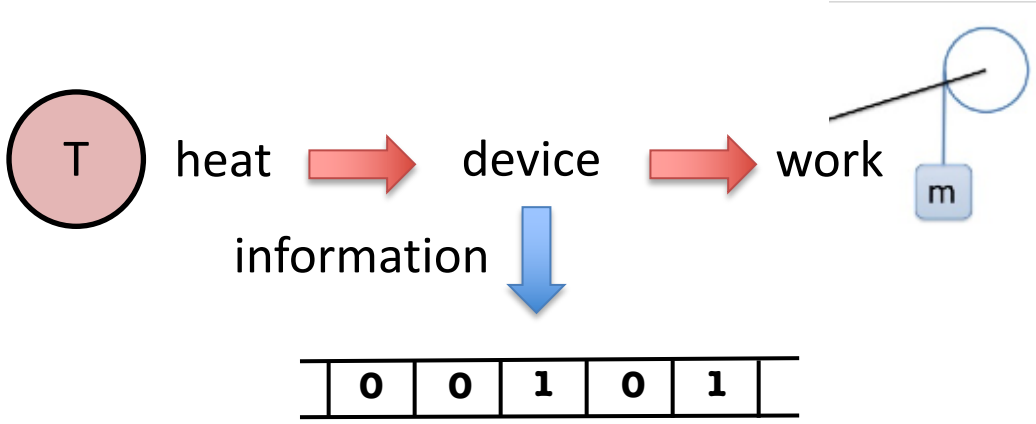
# Phase diagram

$W$ = work delivered to raise mass against gravity

$\Delta I$ = change in Shannon entropy of bit stream



# Second law of thermodynamics



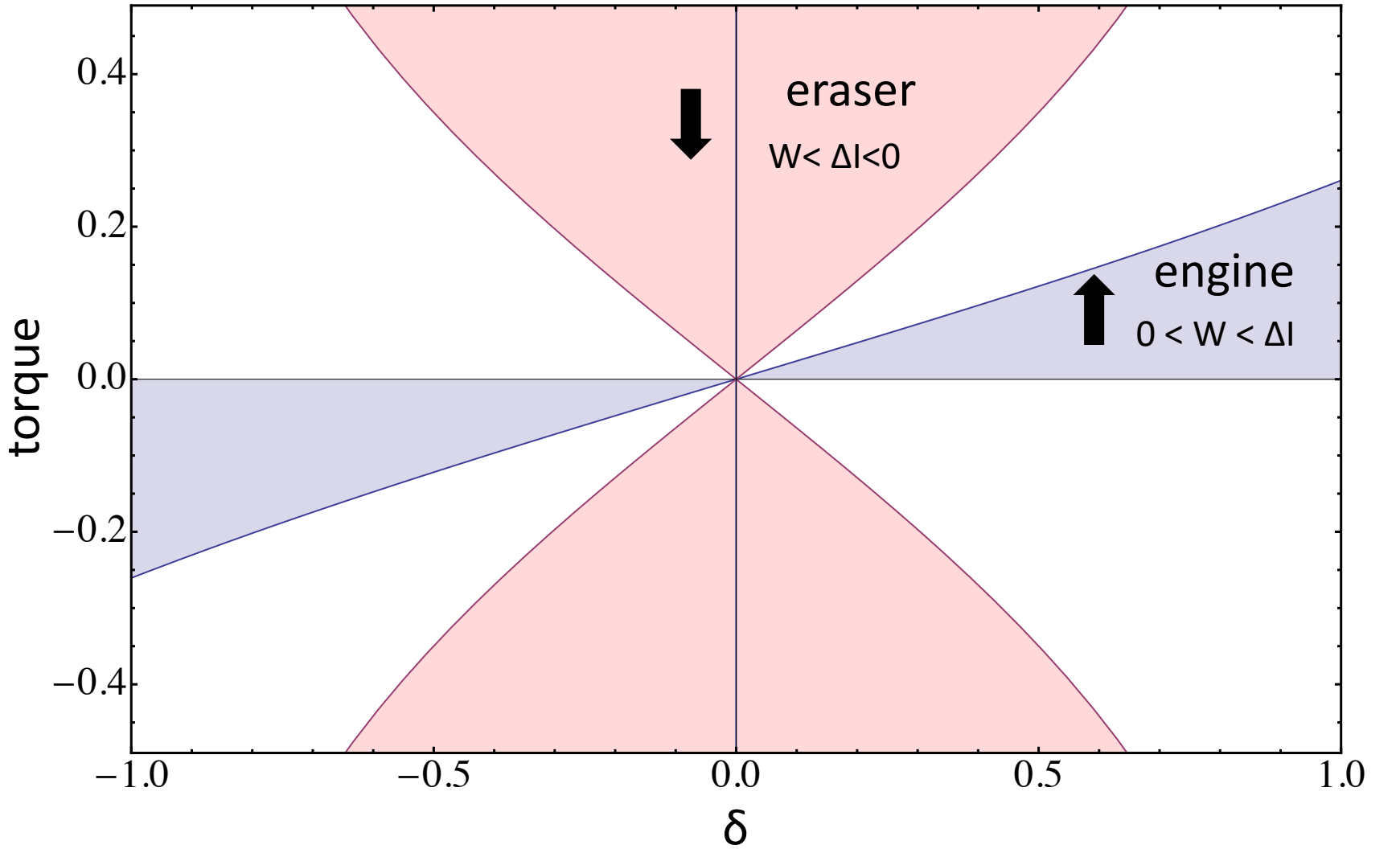

$$\Delta S(\text{device}) = 0$$
$$\Delta S(\text{heat reservoir}) = -W/T$$
$$\Delta S(\text{mass}) = 0$$
$$\Delta S(\text{memory register}) = \Delta I$$

$$\boxed{W \leq T\,\Delta I}$$

Hamiltonian approach: S. Deffner & C. Jarzynski, *Phys Rev X* **3**, 041003 (2013)
Stochastic approach: A. C. Barato & U. Seifert, *Phys Rev Lett* **112**, 090601 (2014)

# Second law of thermodynamics

$W \leq \Delta I$ (T=1)



LETTER

doi:10.1038/nature10872

# Experimental verification of Landauer's principle linking information and thermodynamics

Antoine Bérut[1], Artak Arakelyan[1], Artyom Petrosyan[1], Sergio Ciliberto[1], Raoul Dillenschneider[2] & Eric Lutz[3]†

*Nature* **483**, 187 (2012)