Thermodynamic Computing

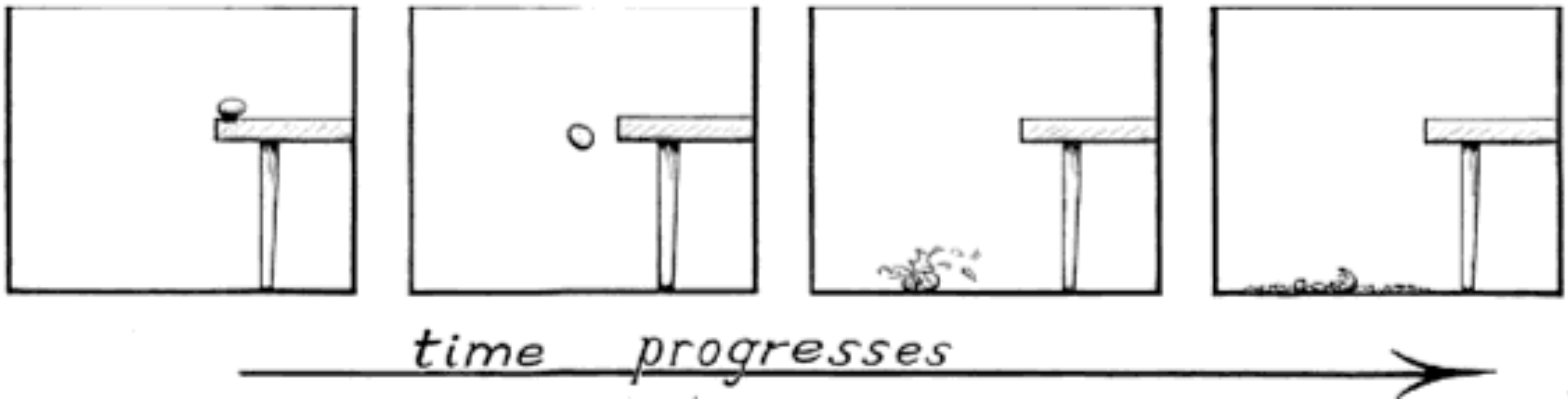
Forward Through Backwards Time by RocketBoom

The 2nd Law of Thermodynamics

Clausius inequality (1865)

$$\Delta S_{\text{total}} \geq 0$$

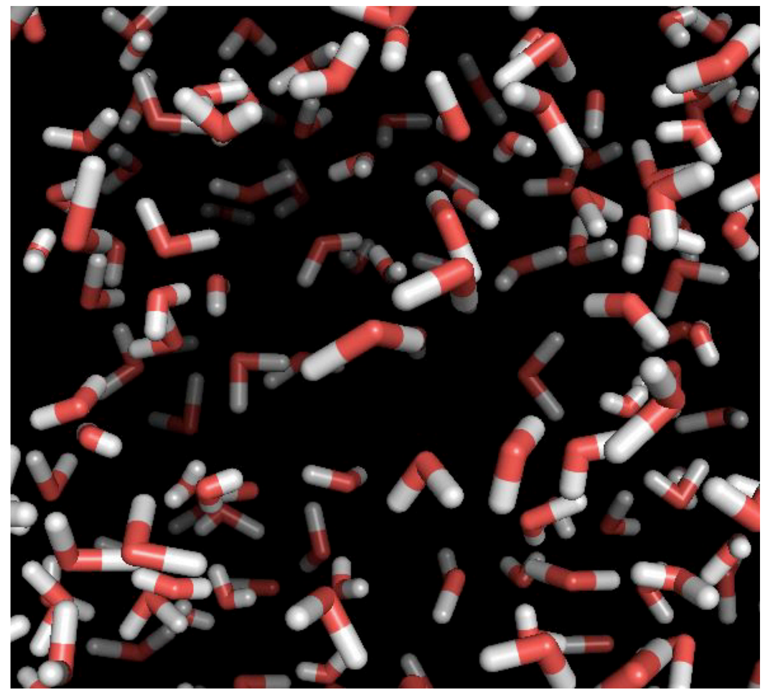
Total Entropy increases as time progresses



Cycles of time R.Penrose (2010)

Once or twice I have been provoked and asked the company how many of them could describe the Second Law of Thermodynamics. The response was cold. It was also negative. Yet I was asking something which is about the scientific equivalent of "Have you read a work of Shakespeare's?"
-- C. P. Snow

Thermodynamic Equilibrium: Future, past and present are indistinguishable



No change in entropy

What is Entropy?

$$S = \log\{\text{Number of configurations}\}$$

1 natural unit of entropy
equivalent to
1 kT of thermal energy

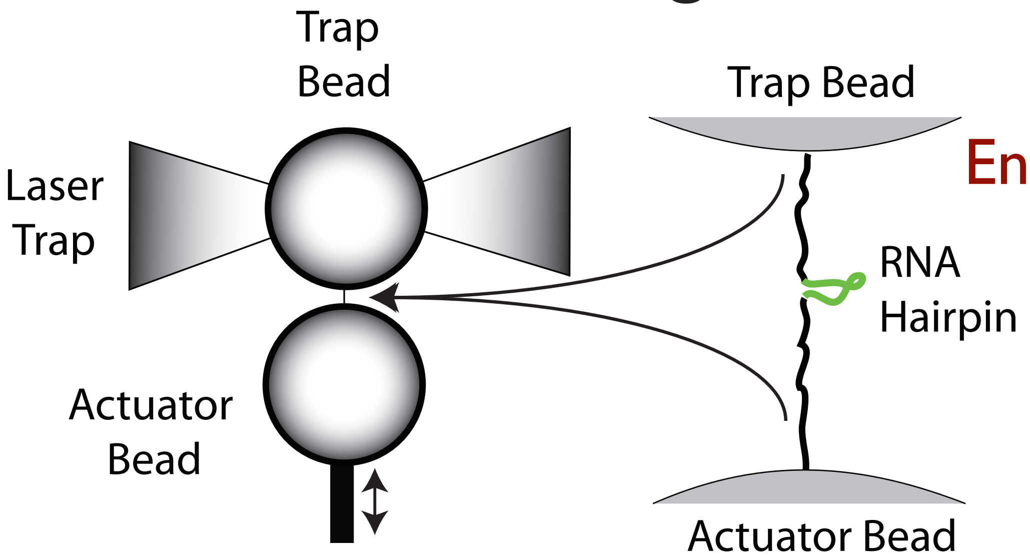
T : Temperature (ambient 300 Kelvin

k : Boltzmann's constant

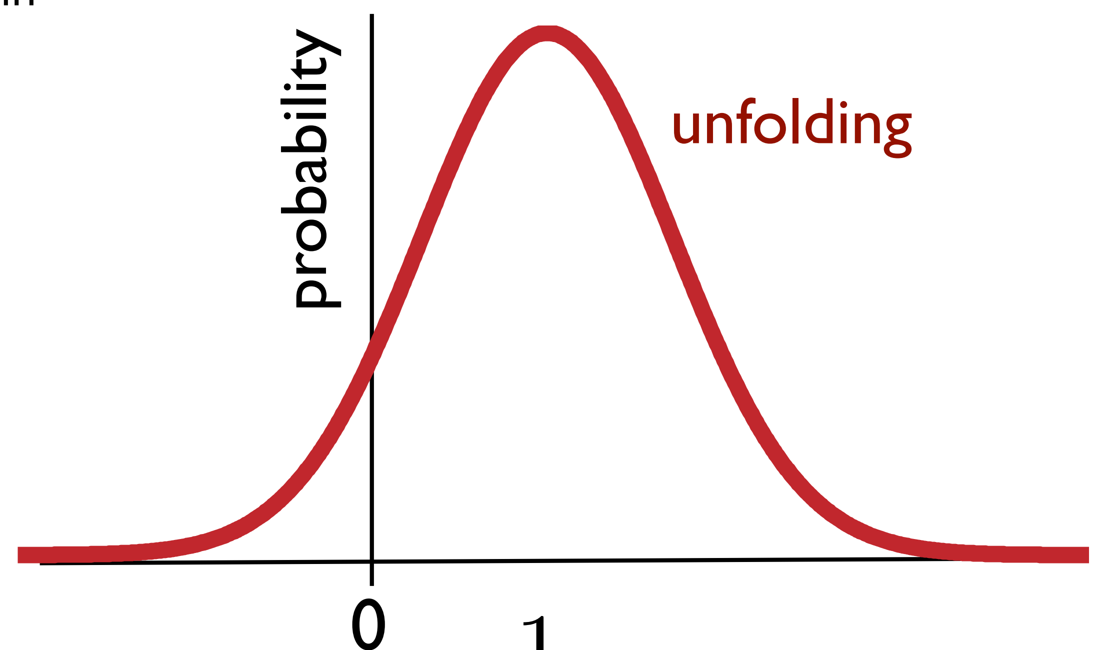
1 kT = 25 meV
= 2.5 kJ/mol

average kinetic energy = 1.5 kT

Unfolding of RNA hairpins. (circa 2000)

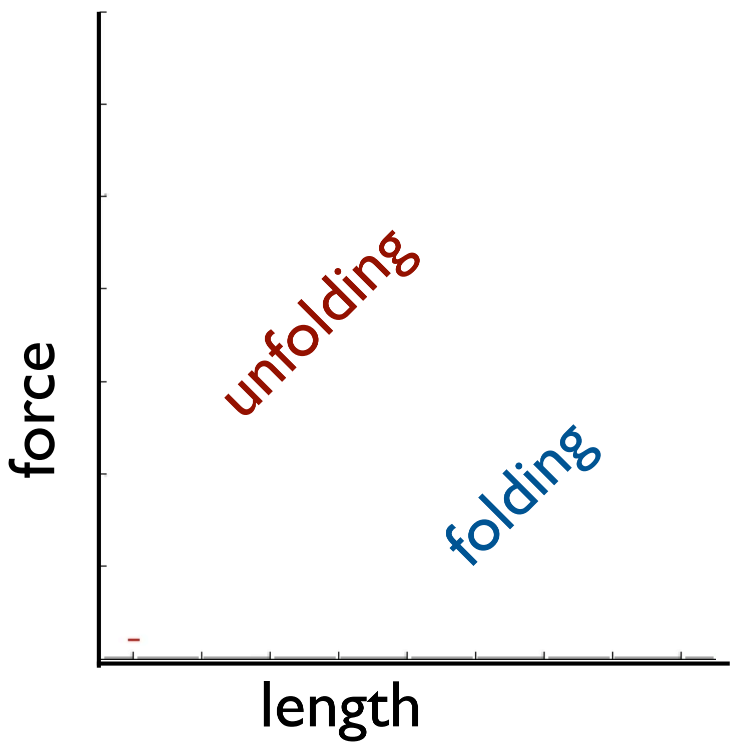


Entropy sometimes goes down!



$$\Delta S_{\text{total}} = \frac{1}{T}(W - \Delta F)$$

total entropy change — temperature — work — free energy change



The (improved) 2nd Law of Thermodynamics

Clausius inequality
(1865)

$$\langle \Delta S_{\rm total} \rangle \geq 0$$

equality only for
reversible process

Jarzynski identity
(1997)

$$\left\langle e^{-\Delta S_{\rm total}} \right\rangle = 1$$

equality far-from-equilibrium

$$\Delta S_{\rm total} = \frac{1}{T}(W - \Delta F)$$

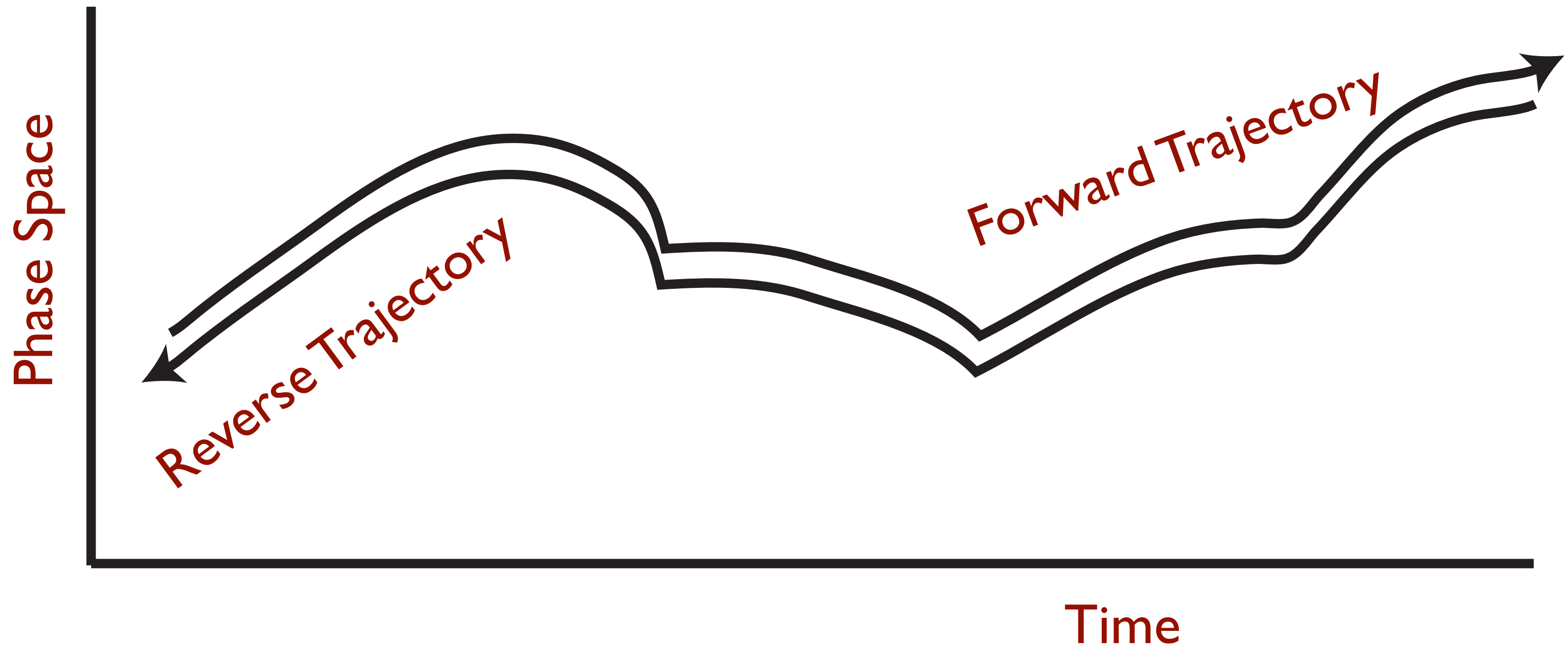
Fluctuation Theorems:
Dissipation breaks time-reversal symmetry

$$\frac{P[\text{trajectory}]}{P[\text{time reversed trajectory}]} = e^{\text{dissipation}} = e^{\beta W - \beta \Delta F}$$

Work (W)

Free Energy Change (ΔF)

Inverse Temperature (β)



What have we learned?

$$\langle e^{-\Delta S_{\mathrm{total}}} \rangle = 1$$

- There are exact, general relations valid far-from-equilibrium
- *Trajectories* are the primary objects (rather than *states*)
- The fluctuations matter
- Entropy change breaks time *quantitatively* reversal symmetry
- Directly relevant at small dissipation
- Information and entropy are related:
  Information flow is as important as work and heat flow.

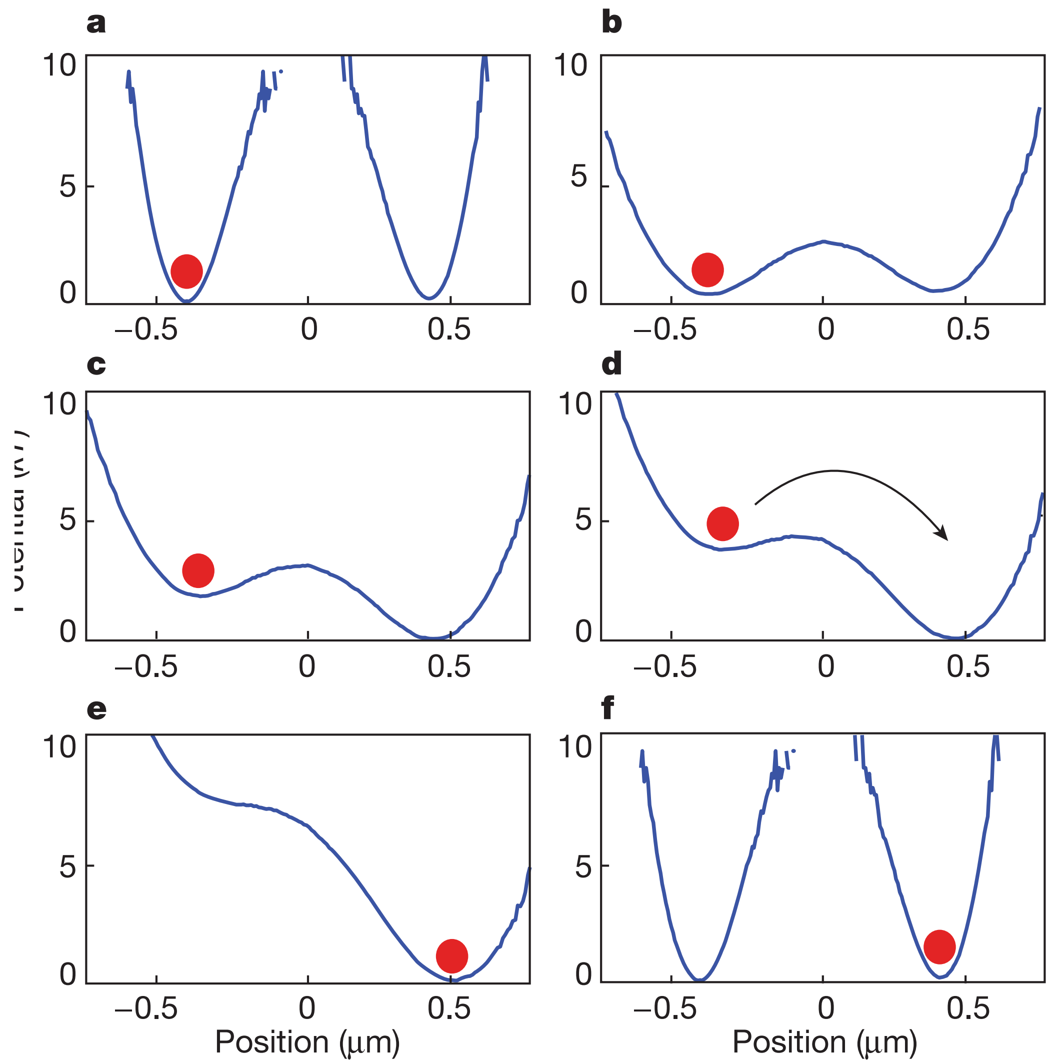
Experimental verification of Landauer's principle linking information and thermodynamics (2012)

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

Erasing 1 bit of information requires at least ln 2 kT energy

Thermodynamic entropy and Shannon information are related

Bits are *physical*



Non-equilibrium Theory of erasure see: Esposito (2011)

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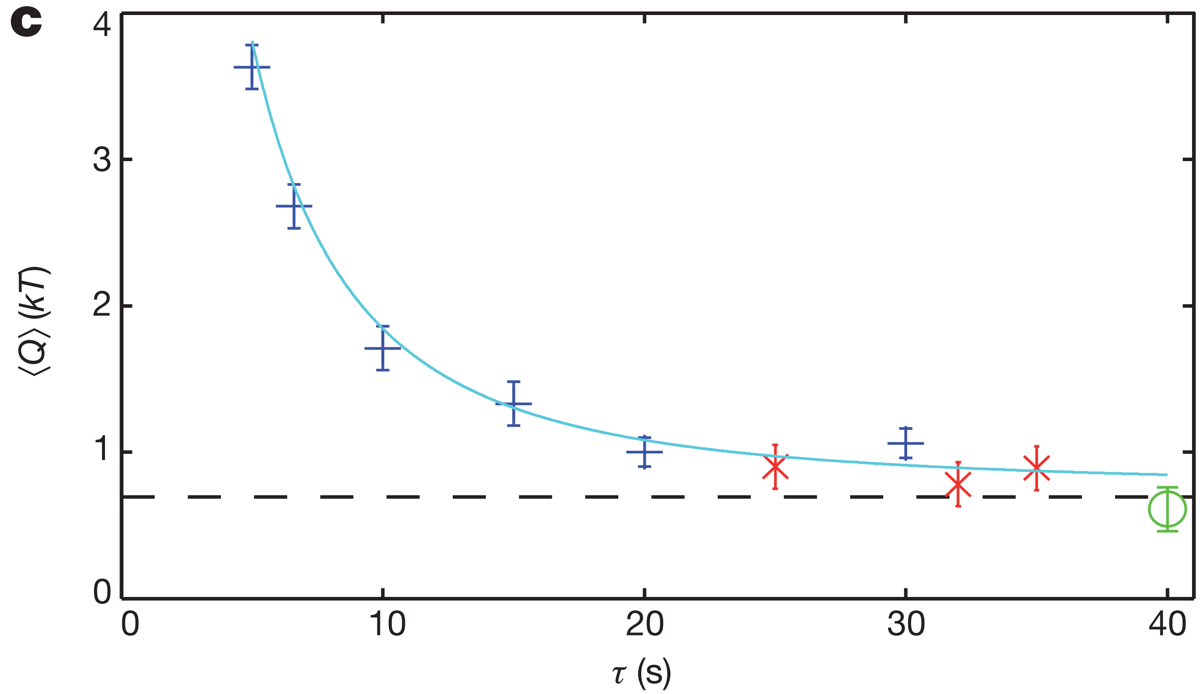
Average heat



Erasure time

But: Thermodynamically reversible computation requires Carnot limit, i.e. infinity long time

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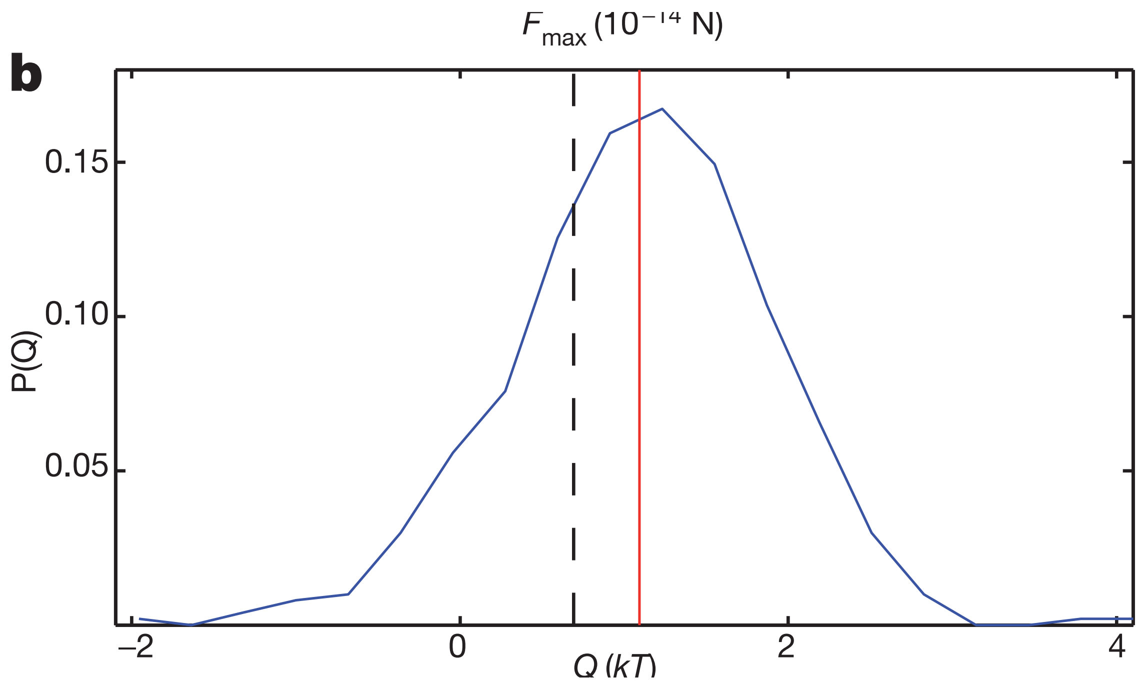
P(Heat)



Heat

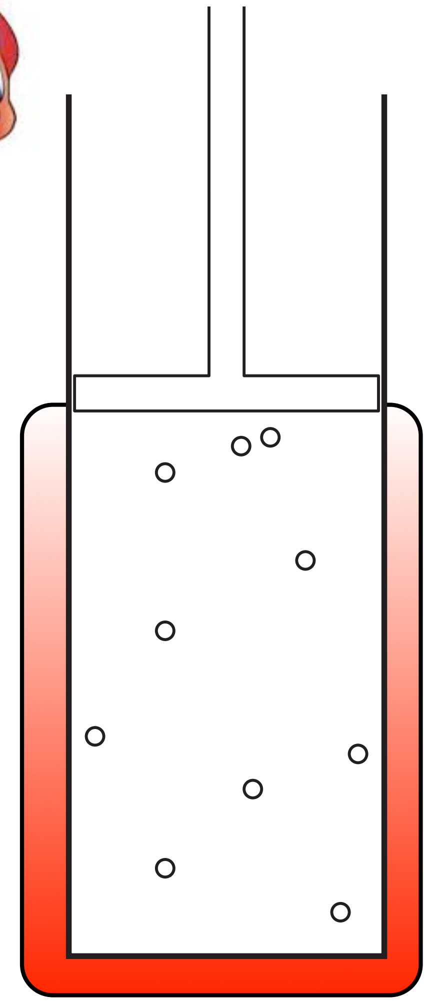
Fluctuations matter!

Tradeoff between error, time, and energy

Research Highlights

Feedback Fluctuation Theorems (c2010)

$$\left\langle e^{-\frac{1}{T}(W-\Delta F)-I} \right\rangle = 1$$



Demon-system information

Sagawa & Ueda (2008)
Horowitz & Vaikuntanathan (2010)

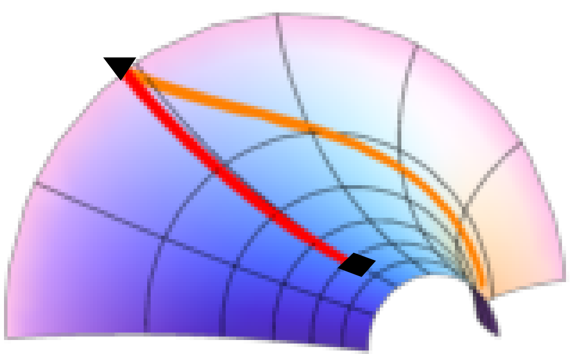
Research Highlights

Thermodynamics of Prediction

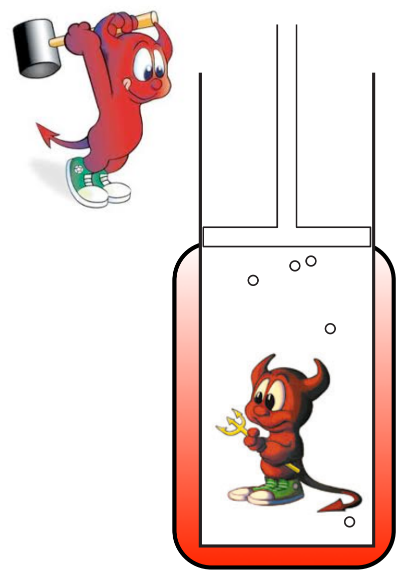
Still, Sivak, Bell, Crooks (2012)

Research Highlights 1/2

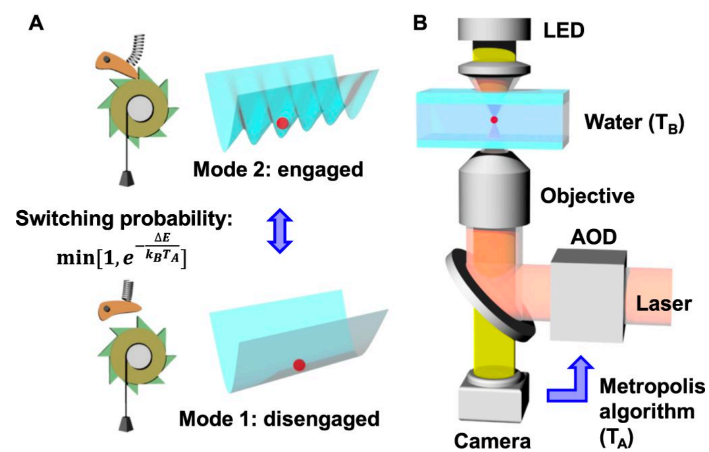
Optimal thermodynamic control



Coupled Systems



Experiments



Feynman's ratchet

Bang et al (2018)

Research Highlights 2/2

time-dissipation-error tradeoff

Lahiri, Sohl-Dickstein, Ganguli (2016)

Thermodynamics uncertainty realtions

T. R. Gingrich, J. M. Horowitz, N. Perunov and J. L. England (2015)

Self-organization and the generation of complexity