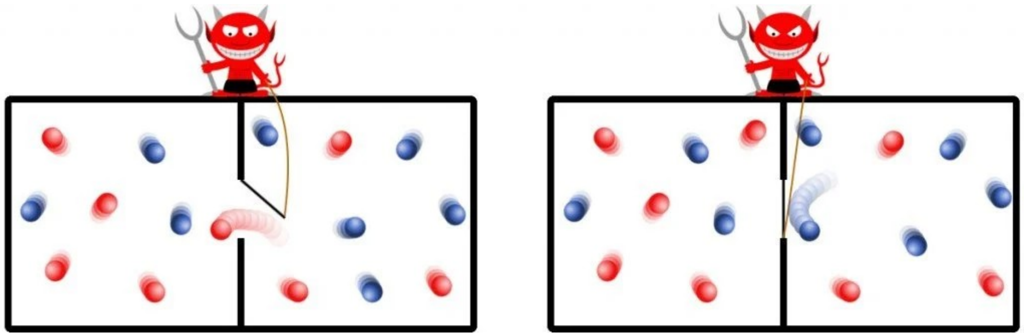
A Maxwell's demon that can work at macroscopic scales

Nahuel Freitas, Massimiliano Esposito

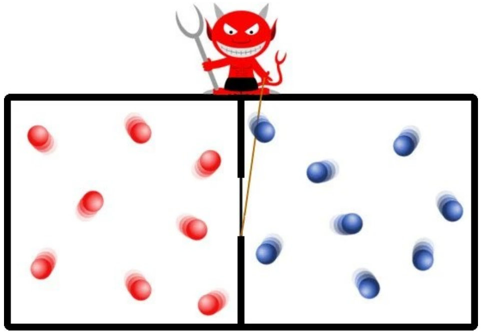
Phys. Rev. Lett. 129, 120602, 2022

YITP-YSF, August 2023

The basic idea of a Maxwell's demon



Thermal Equilibrium + Measurement and feedback control



Thermal gradient   Work extraction

Several implementations since 2007….

A molecular information ratchet

Viviana Serreli[1], Chin-Fa Lee[1], Euan R. Kay[1] & David A. Leigh[1]

Single-photon cooling at the limit of trap dynamics: Maxwell's demon near maximum efficiency

S Travis Bannerman[1], Gabriel N Price[1], Kirsten Viering[1] and Mark G Raizen

Experimental Observation of the Role of Mutual Information in the Nonequilibrium Dynamics of a Maxwell Demon

J. V. Koski, V. F. Maisi, T. Sagawa, and J. P. Pekola
Phys. Rev. Lett. **113**, 030601 – Published 14 July 2014

Observing a quantum Maxwell demon at work

Nathanaël Cottet, Sébastien Jezouin, Landry Bretheau, Philippe Campagne-Ibarcq, Quentin Ficheux, Janet Anders, Alexia Auffèves, Rémi Azouit, Pierre Rouchon, and Benjamin Huard -6 Authors Info & Affiliations

Experimental demonstration of information-to-energy conversion and validation of the generalized Jarzynski equality

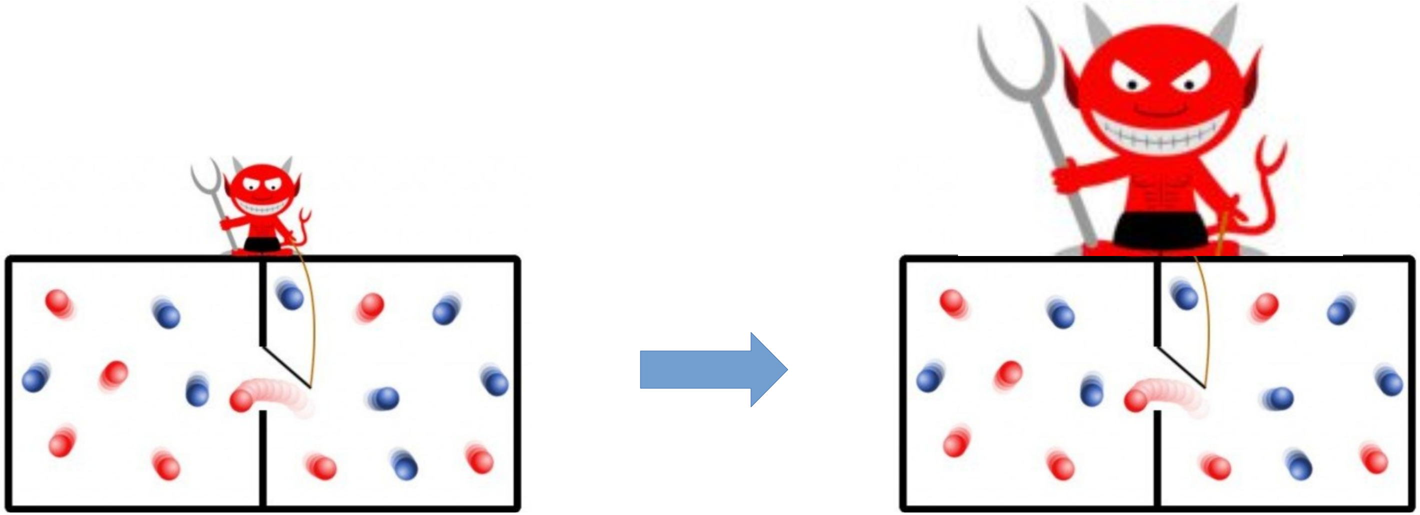
Shoichi Toyabe, Takahiro Sagawa, Masahito Ueda, Eiro Muneyuki & Masaki Sano

All these implementations work in microscopic regimes: single molecules, single atoms, single electrons, single photons …

"… a demon, according to the use of this word by Maxwell, is an intelligent being endowed with free-will and ***fine enough tactile and perception*** to give him the faculty of ***observing and influencing individual molecules*** of matter"

William Thomson, 1879

What happens if we scale up a Maxwell’s demon?

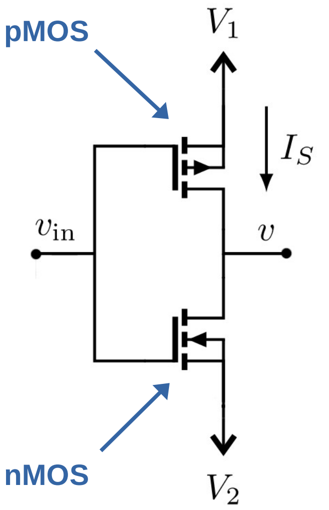


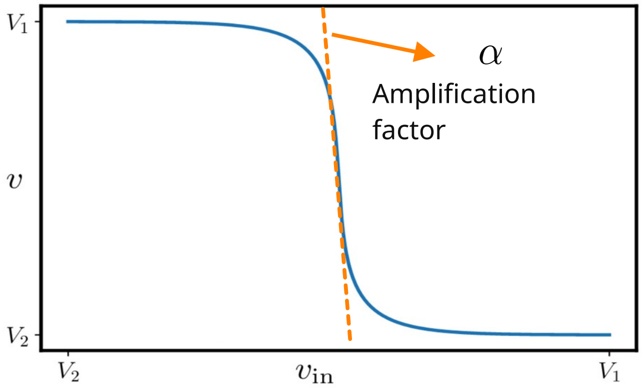
- If a Maxwell’s demon can only by microscopic, at which scale does it stop working?

- Can that be prevented in some way?

We will explore these questions in a model of an electronic Maxwell’s demon with a natural macroscopic limit

The CMOS inverter

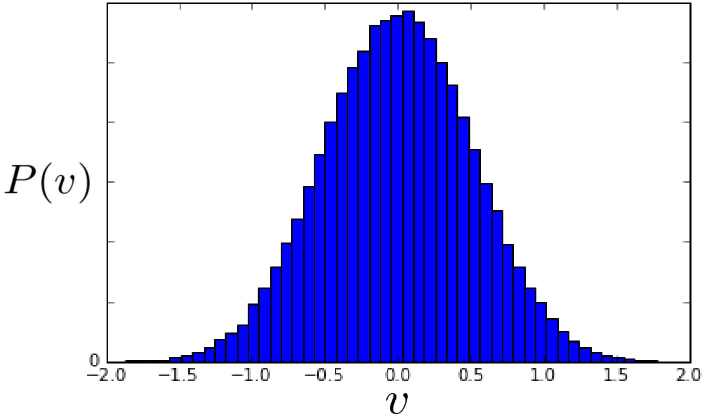




Can we revert the current?

We consider first the equilibrium case $V_1 = V_2 = 0$

$$P_{\text{eq}}(v) \propto e^{-E(v)/k_b T} \qquad E(v) = \frac{v^2}{2C}$$



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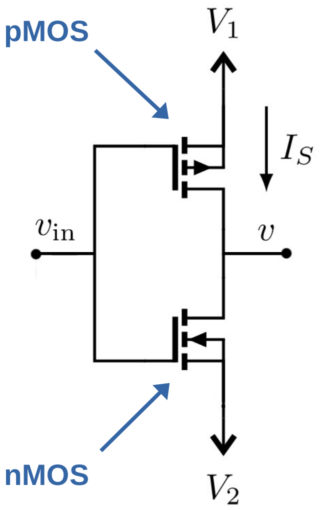

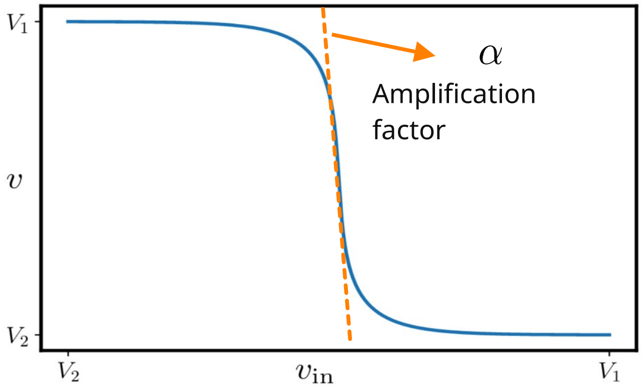

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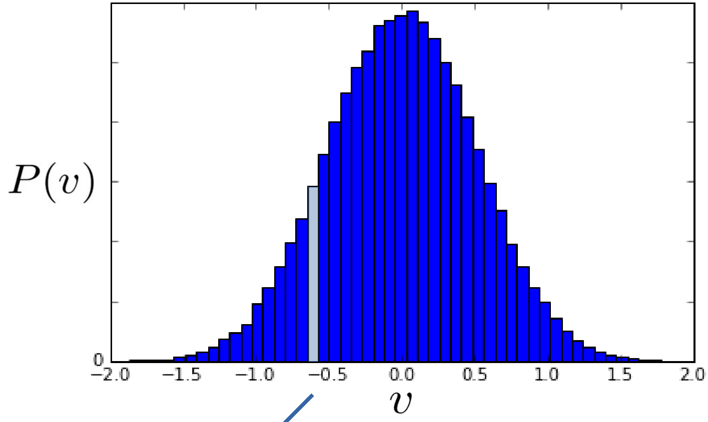
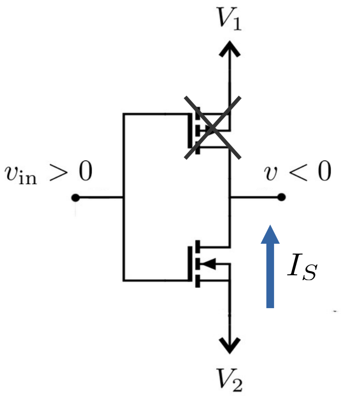
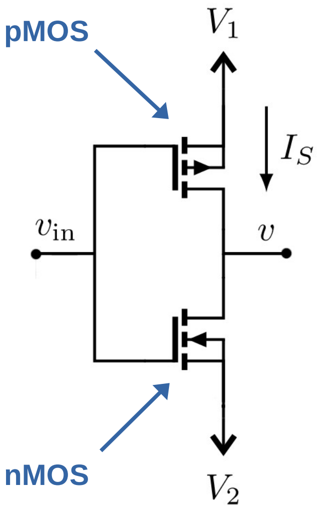
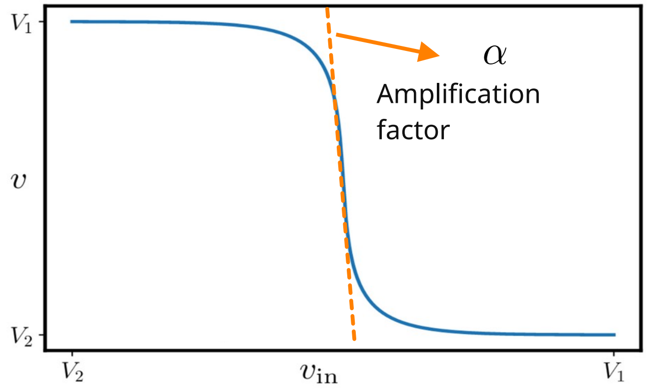




Feedback
$v_{\text{in}} = -\alpha' v$

The CMOS inverter





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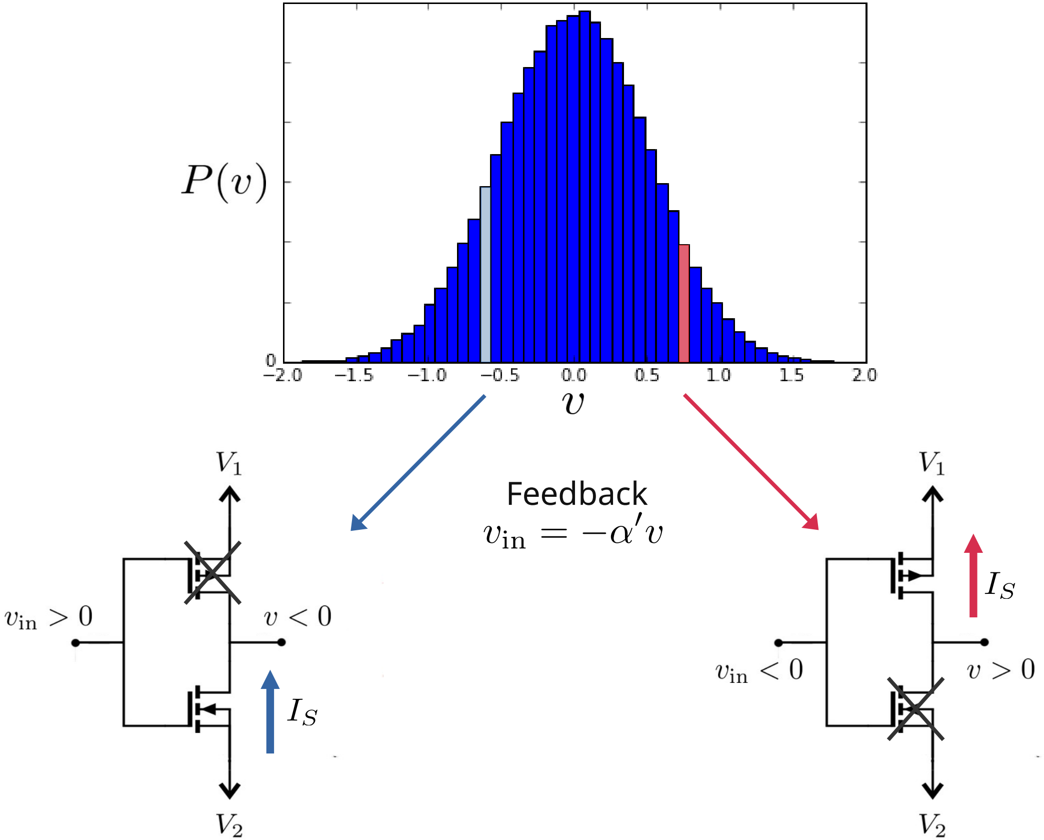
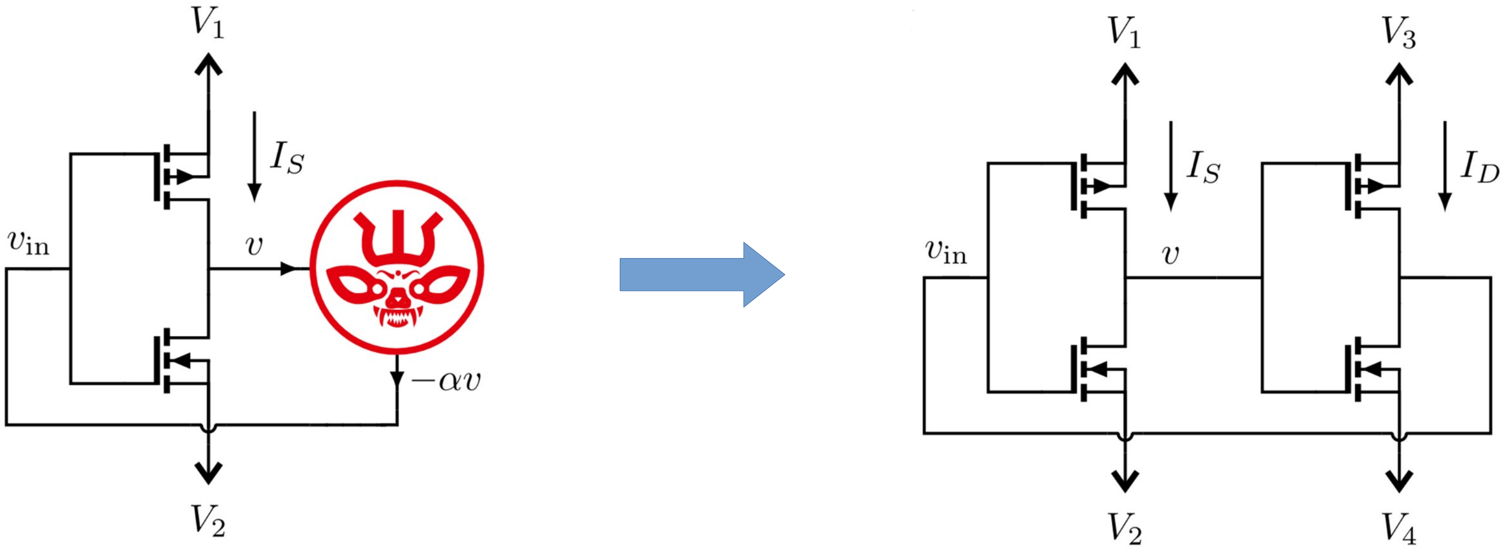


An *autonomous* demon



Entropy production rates (steady state)

System side: $\dot{\Sigma}_S = I_S(V_1 - V_2) = I_S \Delta V_S$

Demon side: $\dot{\Sigma}_D = I_S(V_3 - V_4) = I_D \Delta V_D$

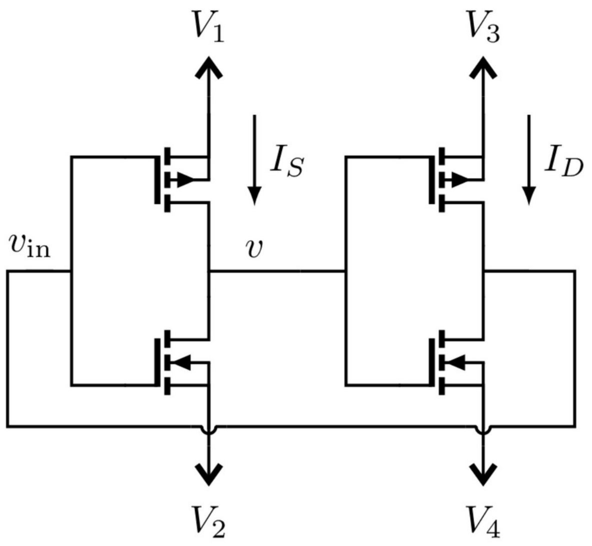
Total: $\dot{\Sigma} = \dot{\Sigma}_S + \dot{\Sigma}_D \geq 0$

Thermodynamic efficiency

If the demon can achieve rectification of the current through the system ($I_S < 0$)

$$\eta = -\frac{\dot{\Sigma}_S}{\dot{\Sigma}_D}$$

An *autonomous* demon



Deterministic treatment:

$$C\,d_t v = I_{\rm p}(v, v_{\rm in}; \Delta V_S) - I_{\rm n}(v, v_{\rm in}; \Delta V_S)$$

$$C\,d_t v_{\rm in} = I_{\rm p}(v_{\rm in}, v; \Delta V_D) - I_{\rm n}(v_{\rm in}, v; \Delta V_D)$$

$$I_{\rm p}(v, v_{\rm in}; \Delta V) = I_0 e^{(\Delta V/2 - v_{\rm in} - V_{\rm th})/n}\left(1 - e^{-(\Delta V/2 - v)}\right)$$

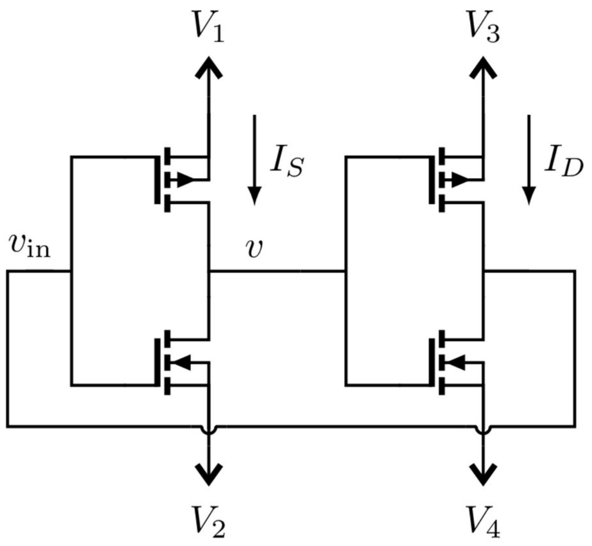
At steady state:

$$V_2 < v < v_1 \qquad\qquad I_S > 0$$
$$V_4 < v_{\rm in} < v_3 \quad\Longrightarrow\quad I_D > 0$$

No rectification is possible at the deterministic level

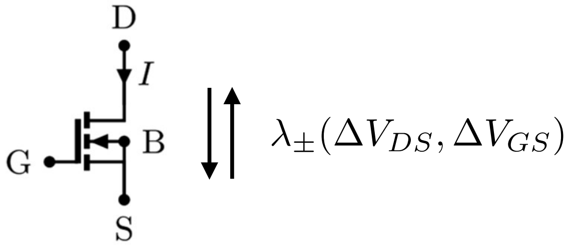
Also, the system becomes bistable for $\alpha^2 = \alpha_S \alpha_D > 1$ with $\alpha_{S/D} = e^{V_{S/D}/2} - 1$

An *autonomous* demon



Stochastic treatment:

Conduction through each transistor is modeled as a bidirectional jump process



The jump rates can be fully determined from the *I-V curve characterization* and the *local detailed balance conditions* (see *Freitas et. al. Phys. Rev. X 11, 031064*)

Master equation:

$$d_t P_t(\boldsymbol{v}) = \sum_{\rho} \lambda_\rho(\boldsymbol{v} - \boldsymbol{\Delta}_\rho v_e) P_t(\boldsymbol{v} - \boldsymbol{\Delta}_\rho v_e) - \lambda_\rho(\boldsymbol{v}) P_t(\boldsymbol{v})$$

$$\boldsymbol{v} = (v, v_{\text{in}})$$

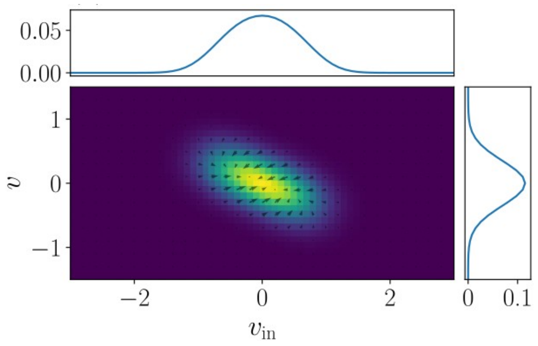
Circuit state

$$v_e = \frac{q_e}{C}$$

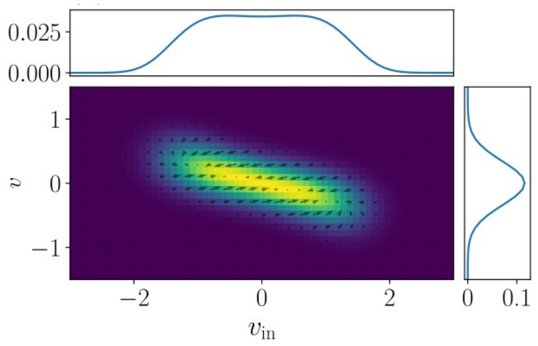
$$d_t P_t(\boldsymbol{v}) = \sum_\rho \lambda_\rho(\boldsymbol{v} - \boldsymbol{\Delta}_\rho v_e) P_t(\boldsymbol{v} - \boldsymbol{\Delta}_\rho v_e) - \lambda_\rho(\boldsymbol{v}) P_t(\boldsymbol{v})$$

<u>Steady states for:</u>

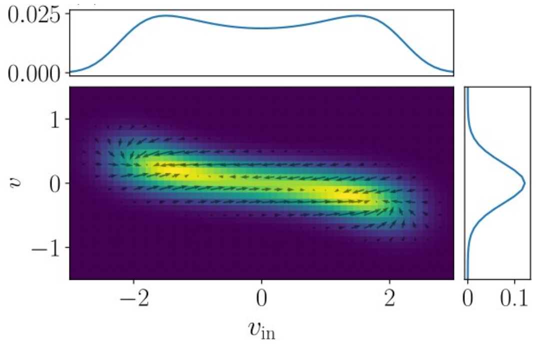
$\Delta V_S = 0.4$



$\Delta V_D = 2 \rightarrow \alpha^2 < 1$



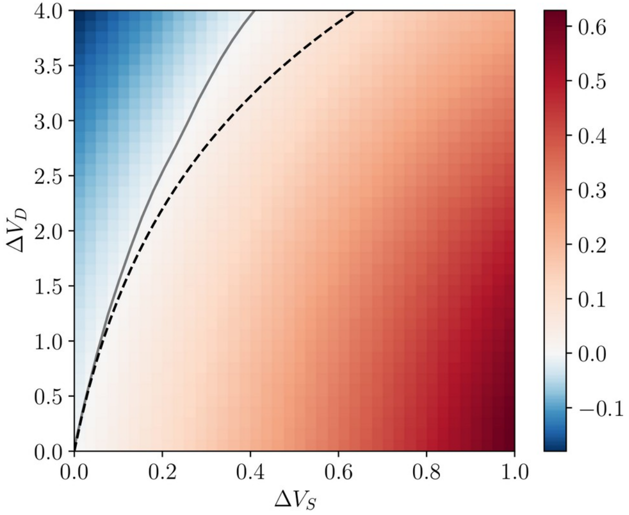
$\Delta V_D = 3.4 \rightarrow \alpha^2 = 1$



$\Delta V_D = 5 \rightarrow \alpha^2 > 1$

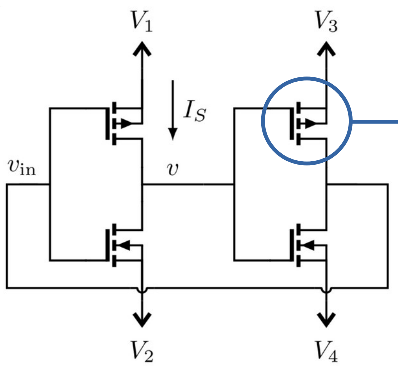
<u>Average current through the first inverter:</u>

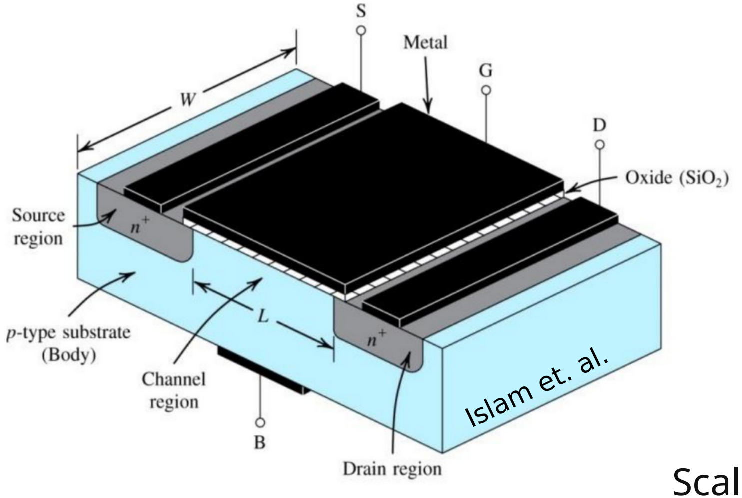
$$\langle I_S \rangle = q_e \sum_{\boldsymbol{v}} P_{\text{ss}}(\boldsymbol{v}) \left(\lambda_+^{\text{p/n}}(\boldsymbol{v}) - \lambda_-^{\text{p/n}}(\boldsymbol{v}) \right)$$



Rectification is possible if ΔV_D is high enough

The macroscopic limit





What happens if we increase the physical dimensions of the transistors?

Keeping L fixed and increasing W, we have:

$C \uparrow \Rightarrow v_e = q_e/C \downarrow$

$\langle I \rangle \uparrow \Rightarrow \lambda_\pm \uparrow$

Scale parameter

$$\Omega = v_e^{-1} \propto W$$

Rate function

$$P_t(\boldsymbol{v}) \asymp e^{-\Omega f(\boldsymbol{v},t)}$$

A *large deviations principle* is satisfied

Freitas, Delvenne, Esposito PRX 2021

Freitas, Proesmans, Esposito PRE 2022

Gopal, Esposito, Freitas PRB 2022

Freitas, Esposito Nat. Comm. 2022

The macroscopic limit

$$P_t(\boldsymbol{v}) \asymp e^{-\Omega f(\boldsymbol{v},t)}$$

$$d_t P_t(\boldsymbol{v}) = \sum_\rho \lambda_\rho(\boldsymbol{v} - \boldsymbol{\Delta}_\rho v_e) P_t(\boldsymbol{v} - \boldsymbol{\Delta}_\rho v_e) - \lambda_\rho(\boldsymbol{v}) P_t(\boldsymbol{v})$$

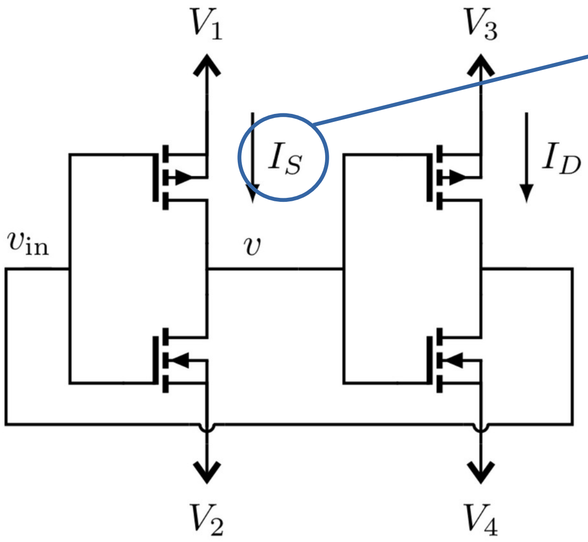
$$\Rightarrow$$

$$d_t f(\boldsymbol{v},t) = \sum_\rho \omega_\rho(\boldsymbol{v}) \left[1 - e^{\boldsymbol{\Delta}_\rho \cdot \nabla f(\boldsymbol{v},t)}\right]$$

- The minimum of $f(\boldsymbol{v},t)$ follows the deterministic dynamics
- A quadratic expansion around it gives us a Gaussian approximation, increasingly valid for larger Ω
- In the monostable phase, we obtain:

$$\langle I_S \rangle \simeq \frac{q_e}{2\tau_0} \left[\Delta V_S - v_e \left(e^{\Delta V_D/2} - 1\right)\right] + \mathcal{O}(\Delta V_S^2)$$

Scaling analysis



$$\langle I_S \rangle \simeq \frac{q_e}{2\tau_0}\left[\Delta V_S - v_e \underbrace{\left(e^{\Delta V_D/2} - 1\right)}_{\alpha_D}\right] + \mathcal{O}(\Delta V_S^2)$$

Rectification ($\langle I_S \rangle < 0$) is possible only if:

$$\Omega = v_e^{-1} < \frac{\alpha_D}{\Delta V_S} \equiv \Omega_{\max} \longrightarrow$$ Maximum scale

Or equivalently if:

$$\Delta V_D^* = 2\log(1 + \Delta V_S / v_e) \propto 2\log(\Omega) \longrightarrow$$ Minimum powering voltage

For fixed α^2:

$$\langle I_S \rangle \simeq \frac{q_e}{2\tau_0}\left[\Delta V_S - v_e \frac{\alpha^2}{\left(e^{\Delta V_S/2} - 1\right)}\right] + \mathcal{O}(\Delta V_S^2)$$

We choose $\Delta V_S = c v_e$

and $\Delta V_D = 2\log(1 + 2\alpha^2 / c v_e)$

$\Rightarrow$

$$T\dot{\Sigma}_S = \Delta V_S \langle I_S \rangle \sim -\alpha^2 \quad \text{for} \quad v_e \to 0$$

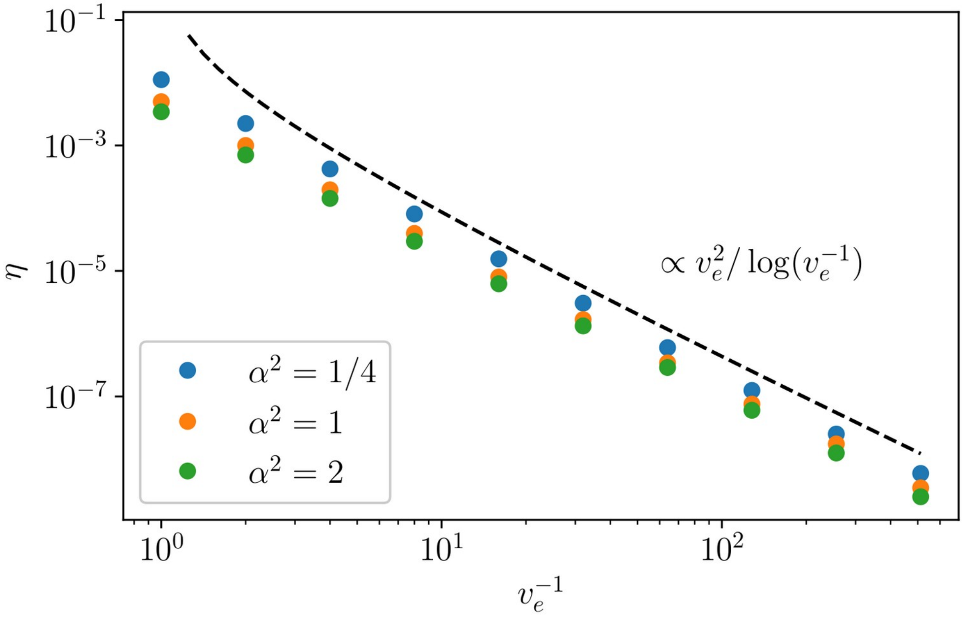
and

$$T\dot{\Sigma}_D = \Delta V_D \langle I_D \rangle \sim \log(v_e^{-1})/v_e^2 \quad \text{for} \quad v_e \to 0$$

Scaling analysis

Then, the thermodynamic efficiency scales as

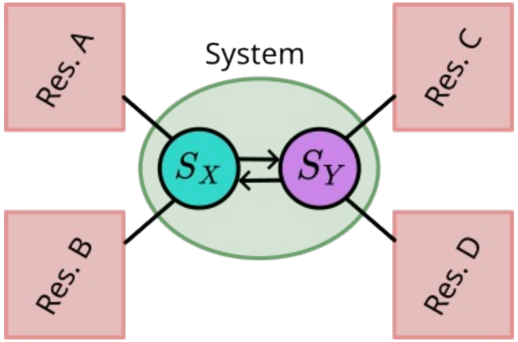
$$\eta \sim v_e^2 / \log(v_e^{-1}) = 1/(\log(\Omega)\Omega^2)$$

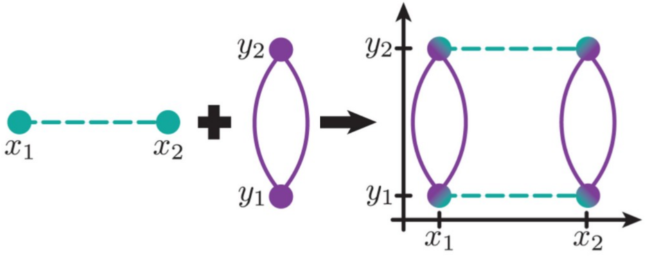


- For fixed powering, the demon stops working above a maximum scale
- If the powering is scaled appropriately, the demon continues to work but with decreasing efficiency

Scaling Laws for Information Flows

A bipartite system: *Horowtiz and Esposito, PRX, 2014*





The usual 2nd Law applies to the full system:

$$d_t S - \dot{\Sigma} \geq 0$$

But not to each subsystem:

$$d_t S_X - \dot{\Sigma}_X \ngeq 0$$

Editors' Suggestion

Information flows in macroscopic Maxwell's demons

Nahuel Freitas and Massimiliano Esposito
Phys. Rev. E **107**, 014136 – Published 26 January 2023

However, the local 2nd Laws can be generalized to:

$$d_t S_X - \dot{\Sigma}_X - k_b \dot{I}_X \geq 0$$
$$d_t S_Y - \dot{\Sigma}_Y - k_b \dot{I}_Y \geq 0$$

$$d_t I(X;Y) = \dot{I}_X + \dot{I}_Y$$

Information Flows

We can define detailed efficiencies for system and demon:

$$\eta_S = -\frac{\dot{\Sigma}_X}{\dot{I}} \leq 1 \qquad \eta_D = -\frac{\dot{\Sigma}_Y}{\dot{I}} \leq 1$$

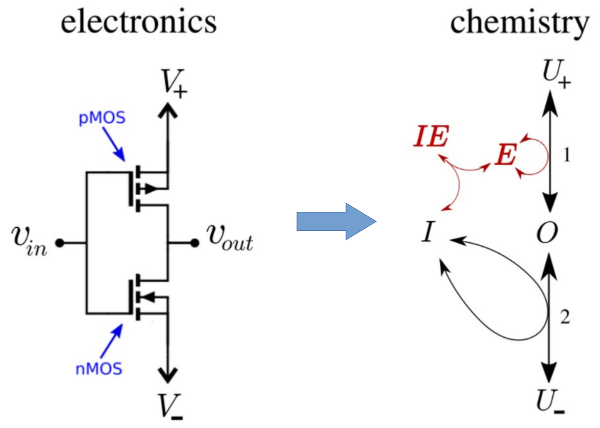
Now, in the scaling limit where $P_{\rm ss}(x,y) \propto e^{-\Omega f(x,y)}$

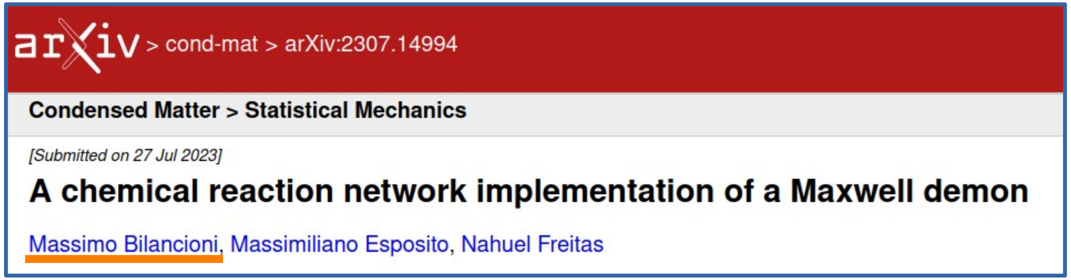
$\dot{\Sigma}_X$, $\dot{\Sigma}_Y$ are ***extensive***

$\dot{I}$ is ***intensive***

→ Everything else fixed, Σ_X must become positive above some value of Ω

A chemical Maxwell's Demon



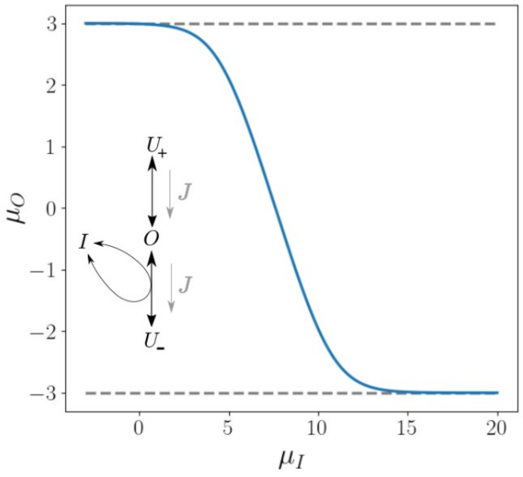

arXiv > cond-mat > arXiv:2307.14994

Condensed Matter > Statistical Mechanics

[Submitted on 27 Jul 2023]

A chemical reaction network implementation of a Maxwell demon

Massimo Bilancioni, Massimiliano Esposito, Nahuel Freitas



- The same design can be carried on to chemical reaction networks
- However, the response of the chemical inverter is bounded:

$$\alpha = \left| \frac{d\mu_O}{d\mu_I} \right| \leq n \tanh\left(\Delta\mu/4\right) \leq n$$

Owen, Gingrich, Horowitz PRX 2020

- Thus, the chemical demon does not survive the macroscopic limit

Final comments

- Previous proposals of macroscopic Maxwell's demons

The Szilard engine revisited: Entropy, macroscopic randomness, and symmetry breaking phase transitions

Cite as: Chaos **11**, 725 (2001); https://doi.org/10.1063/1.1388006
Submitted: 02 January 2001 • Accepted: 29 May 2001 • Published Online: 31 August 2001

Juan M. R. Parrondo

- Uses symmetry breaking in phase transitions to transfer information from micro to macro scales
- Non-autonomous
- Work extraction limited by $kT\log(2)$ per cycle

- Breaking the link between the macro limit and deterministic dynamics

  - If thermodynamic resources are invested to amplify thermal fluctuations, they can be transferred to macroscopic scales.
  - For this to happen, those resources must be scale-dependent.
  - **Fluctuations can survive the macroscopic limit in non-equilibrium settings**