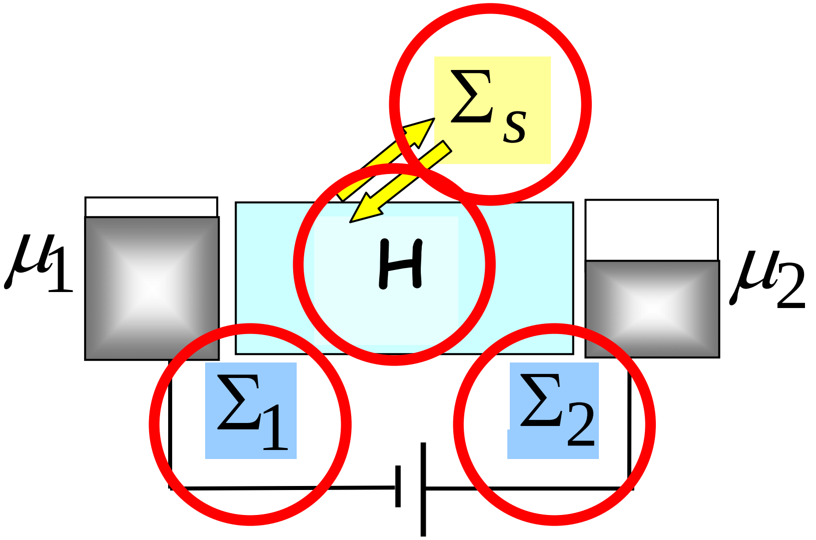
CQT, Lecture#1:

Nanodevices and Maxwell's Demon

Objective:
To illustrate the subtle interplay of dynamics and thermodynamics that distinguishes transport physics.

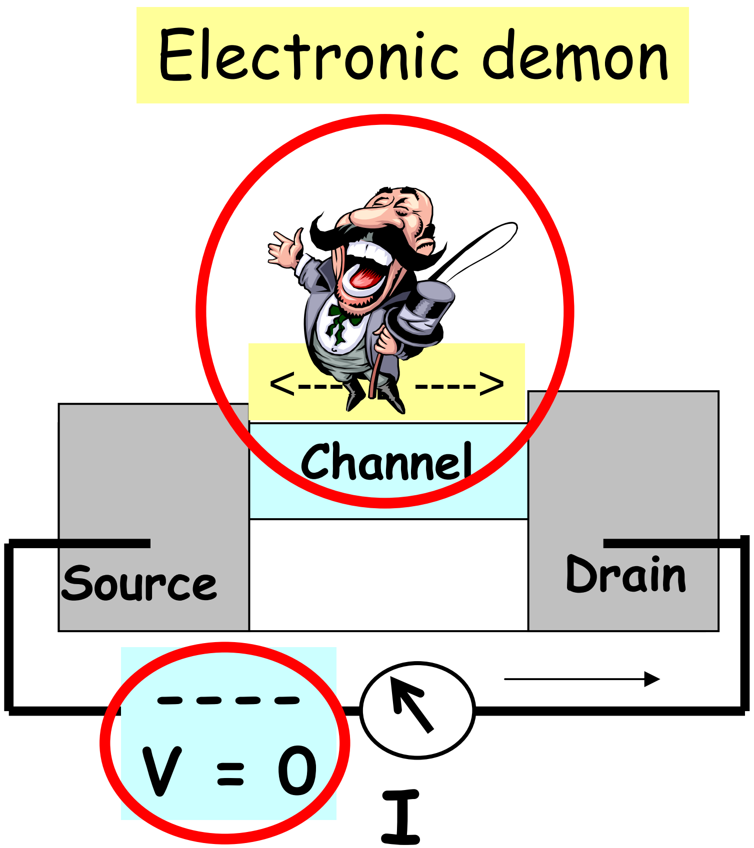
Reference:
S.Datta,"Nanodevices and Maxwell's demon", to appear in the Proceedings of the Third ASI International Workshop on Nano Science & Technology, Ed. Z.K.Tang, Taylor & Francis (2007).
http://arxiv.org/abs/0704.1623

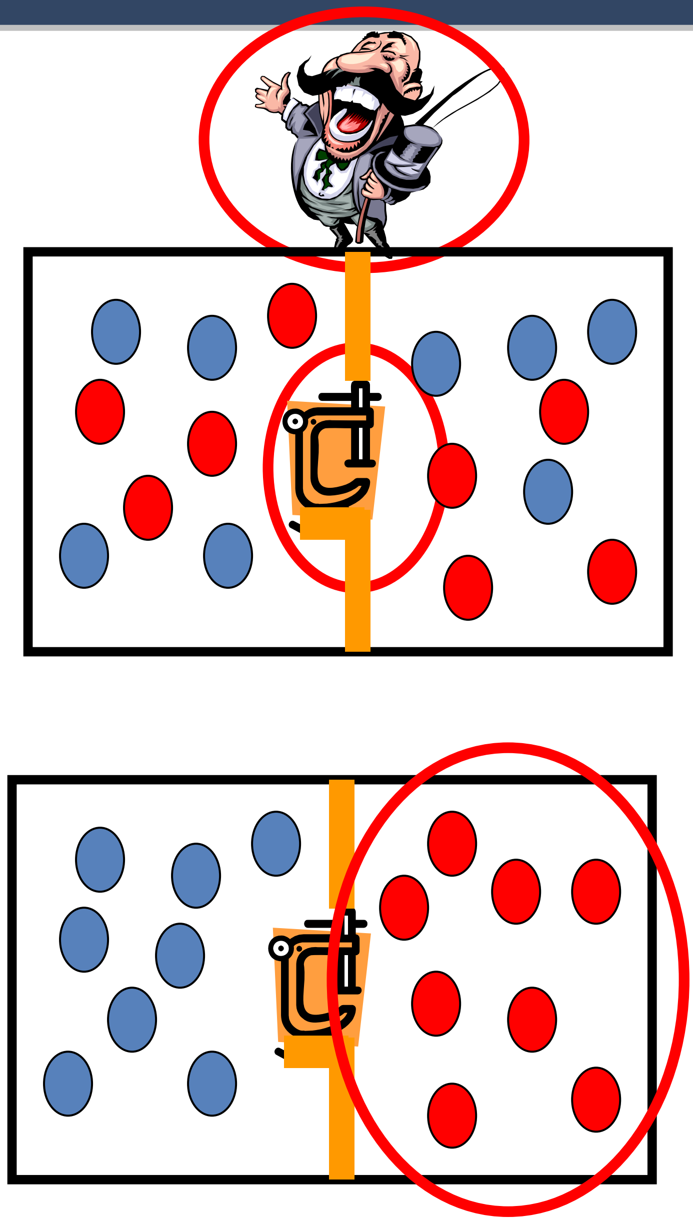
Unified Model for Quantum Transport Far from Equilibrium



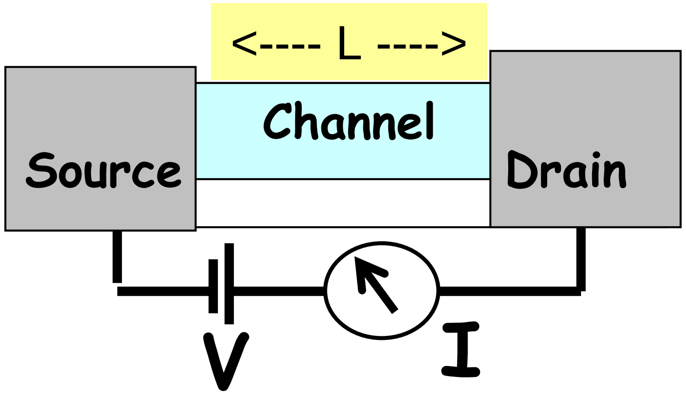
"QTAT"
Datta, Quantum Transport: Atom to Transistor, Cambridge (2005)

Maxwell's demon





Top-down view



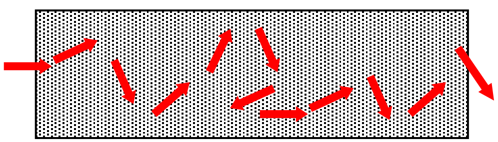
V = I R or I = V G

Conductance, G = 1/R

$$G = \sigma A / L$$

Conductivity

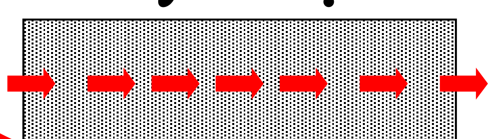
$$\sigma = q^2 n \tau / m$$

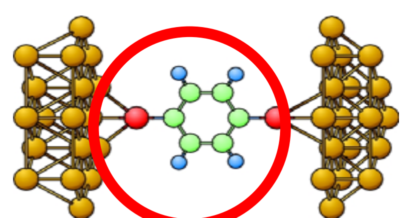


CHANNEL

m = ? n = ?

$\tau = ?$





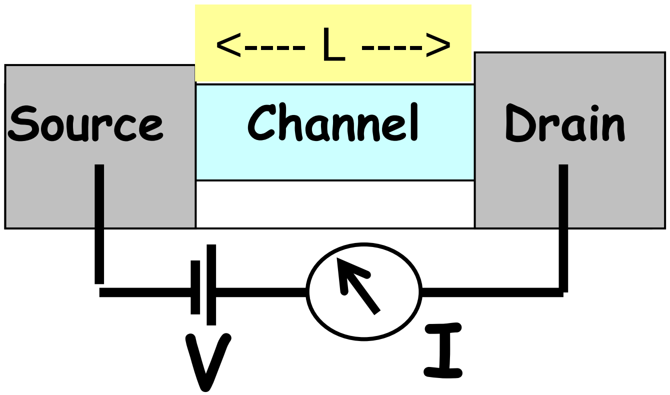
"Very complicated"

Bottom-up View

"Top"

Ohm's law

$$I = GV \quad , \quad G = \sigma A / L$$

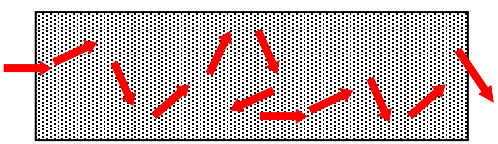


Escape rate

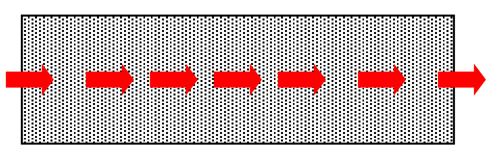
Density of states

$$G = (q^2/h) \; (\pi D \gamma)$$

$\gamma \equiv escape\ rate$



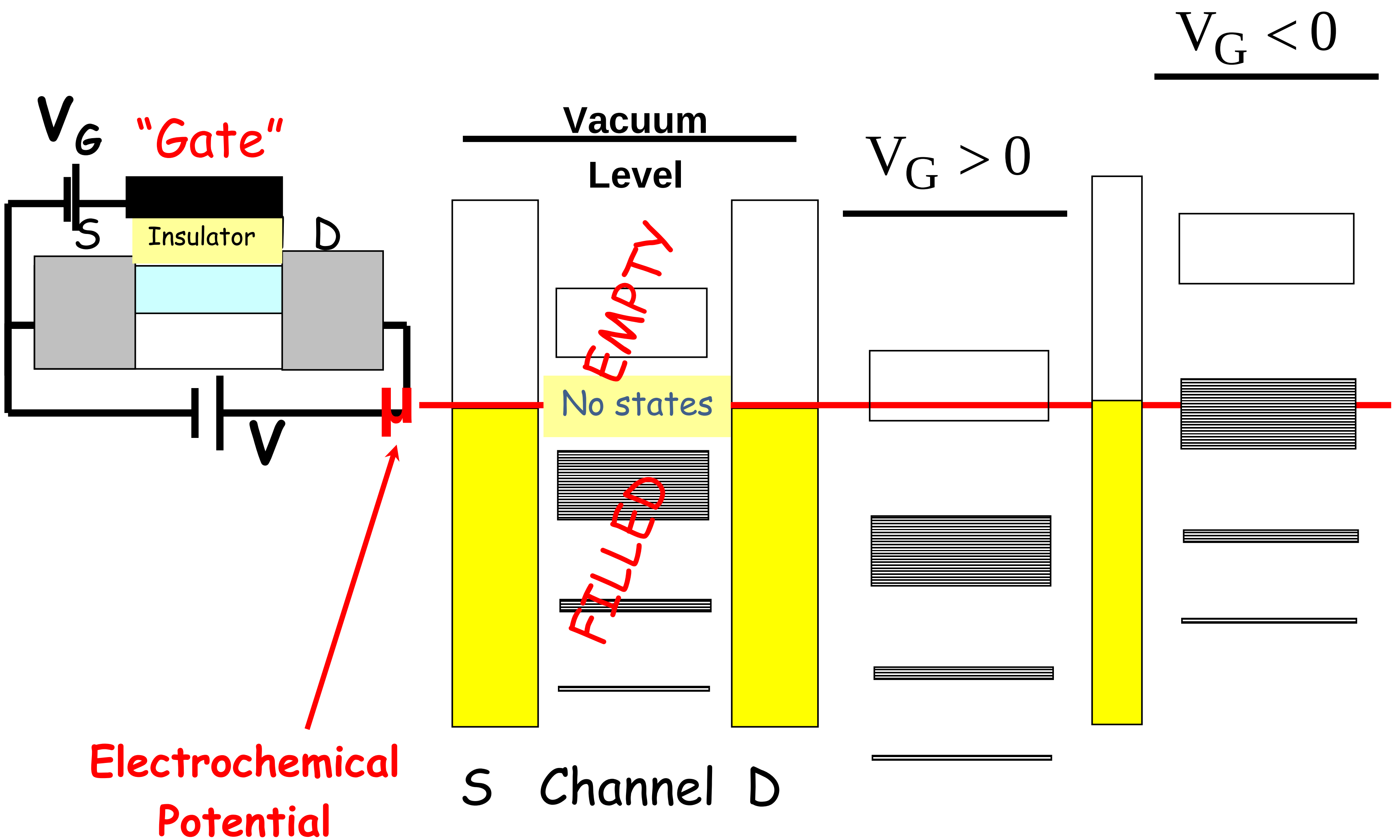
CHANNEL



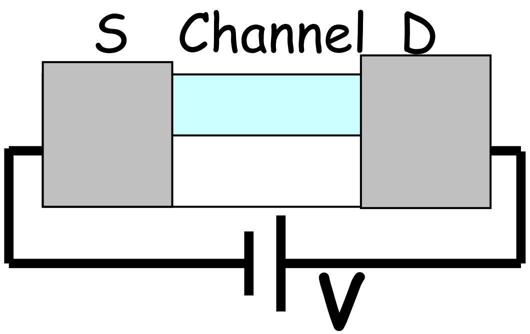
$$G = \underbrace{(q^2/h)}_{1/25.8\,K\Omega}$$

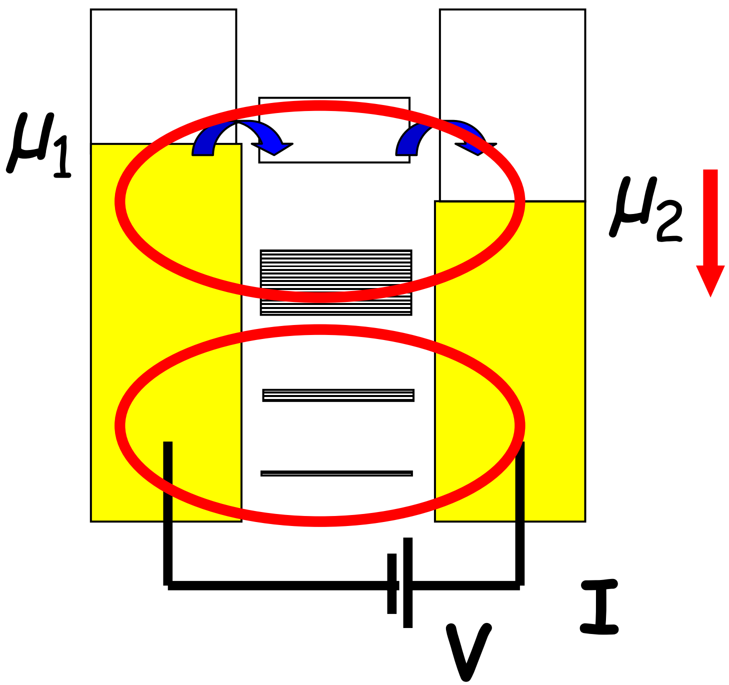
"Bottom"

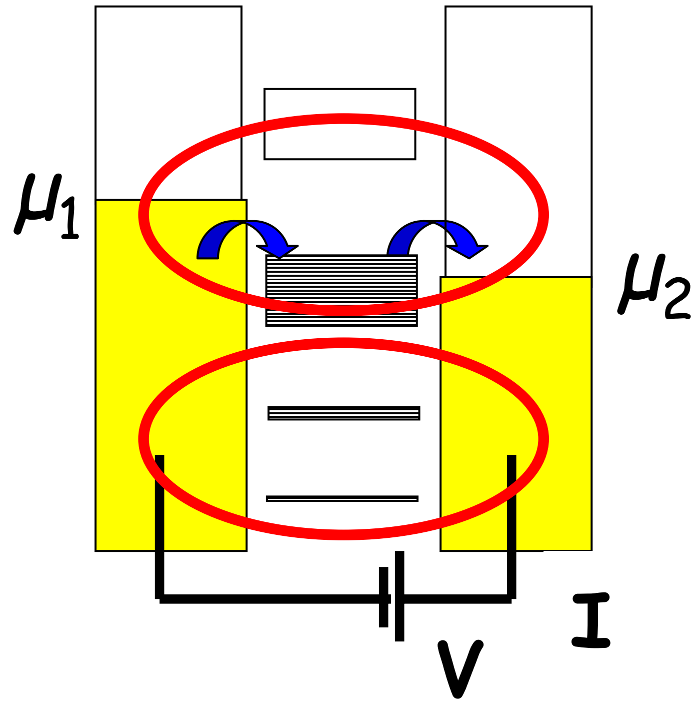
Equilibrium Energy Level Diagram



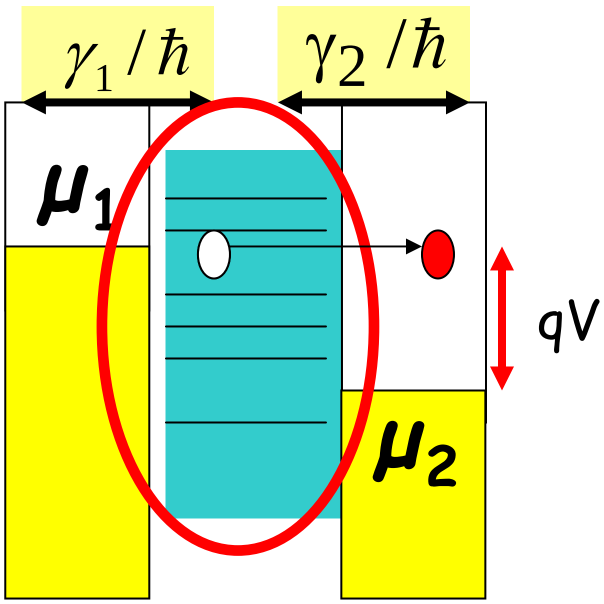
What makes electrons flow?







Escape rate



$\gamma/\hbar$: *Escape Rate*

γ has dimensions of energy

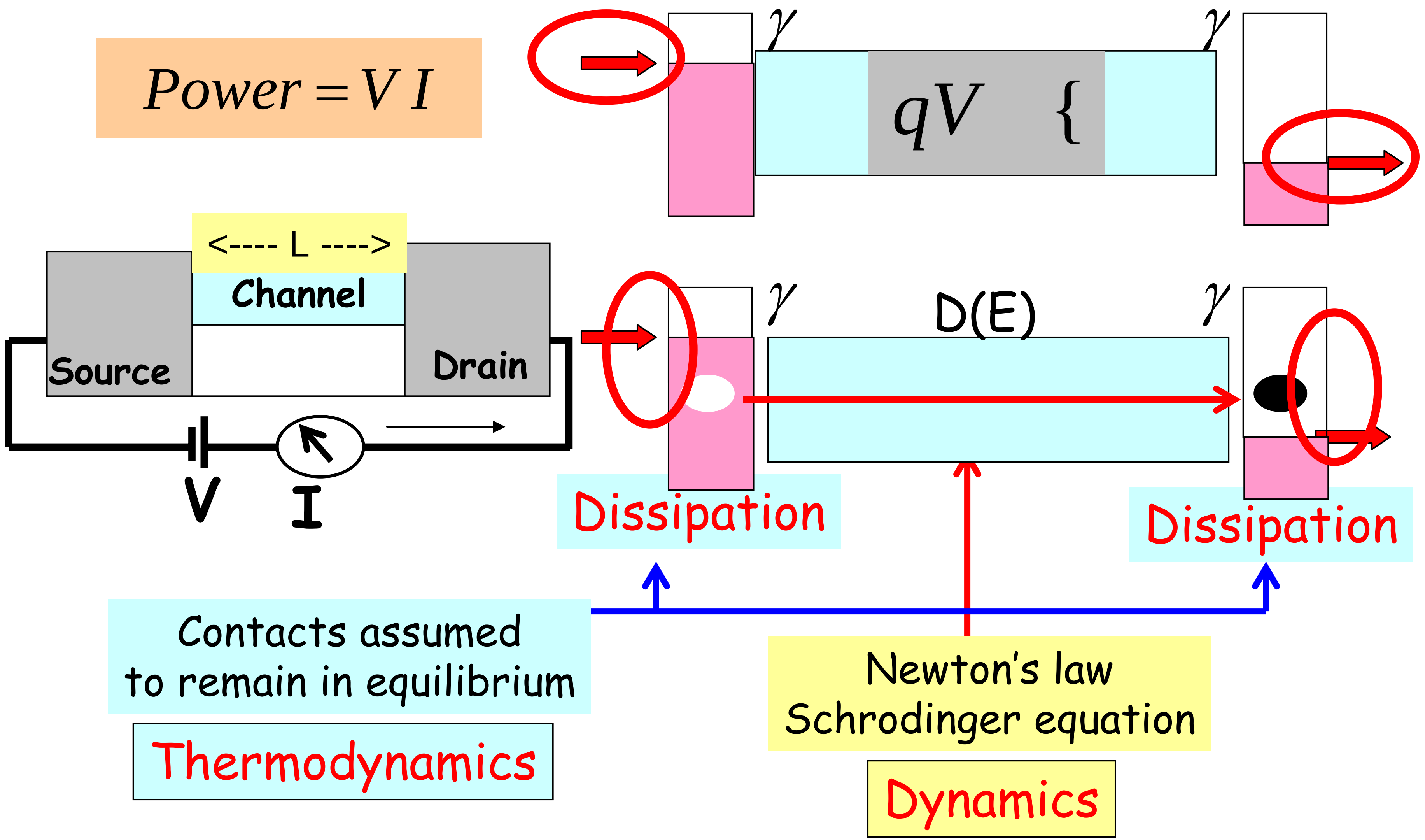
Current depends on Density of states, D(E) around the contact electrochemical potentials.

AND

on escape rates

$\gamma_1 \qquad \gamma_2$

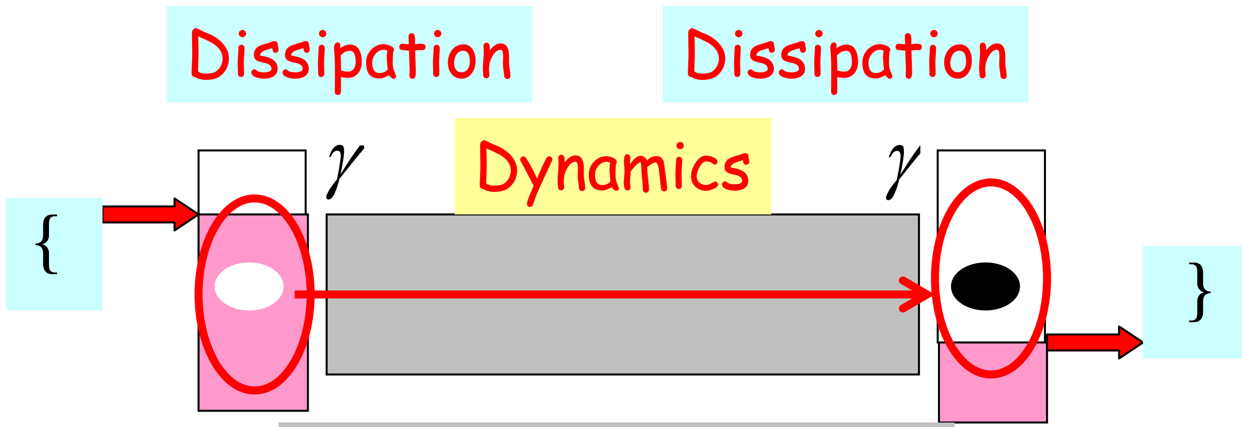
Where is the power dissipated ?



Dynamics and dissipation

Separate dynamics
+ dissipation

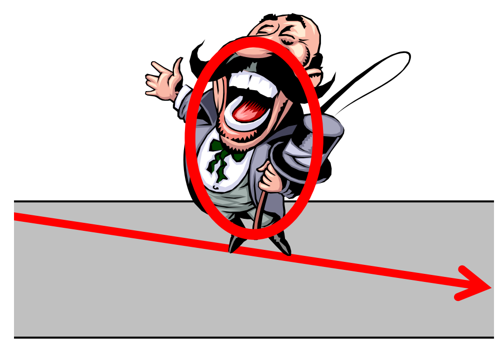
Landauer model



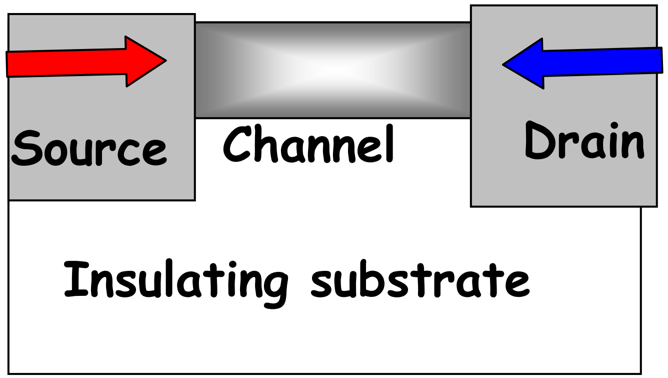
Newton's law
Schrodinger equation

Mixed dynamics
+ dissipation

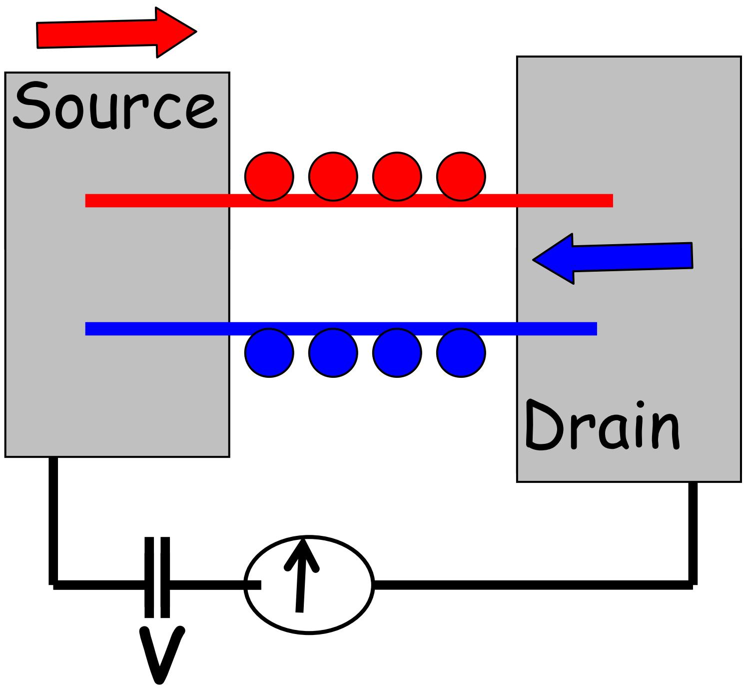
Boltzmann
NEGF

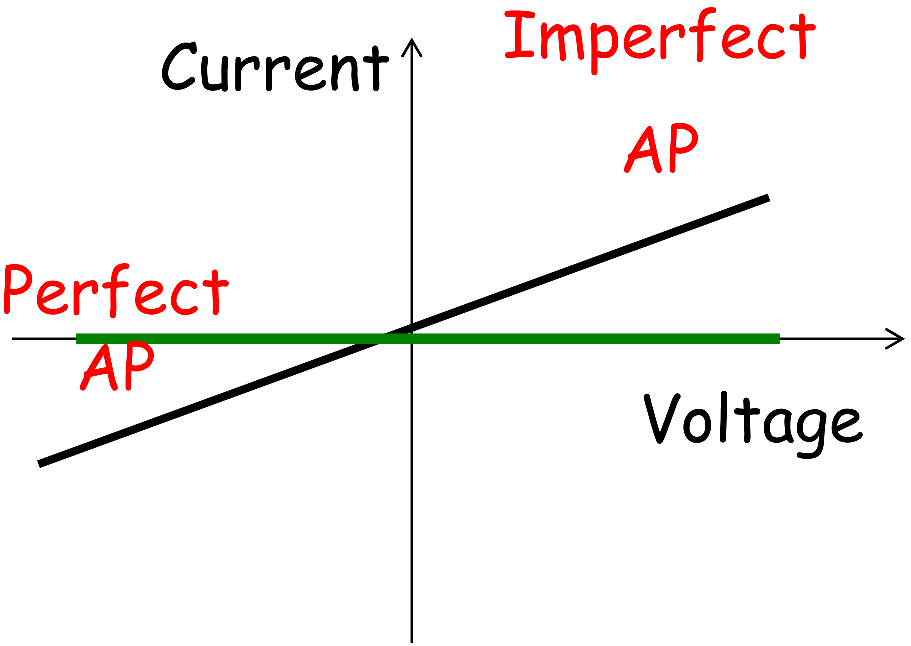


Spin Valves

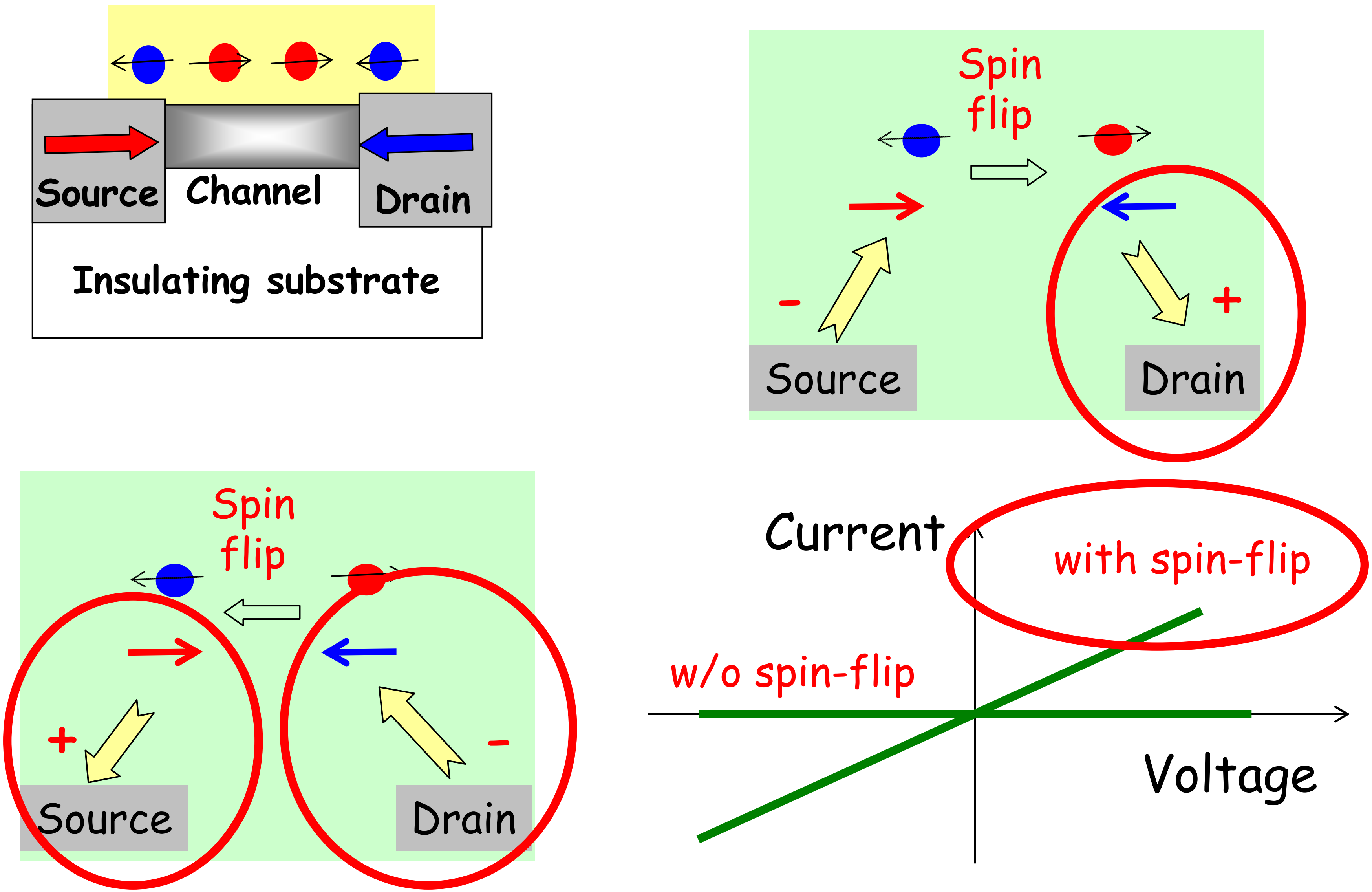


Anti-parallel (AP)

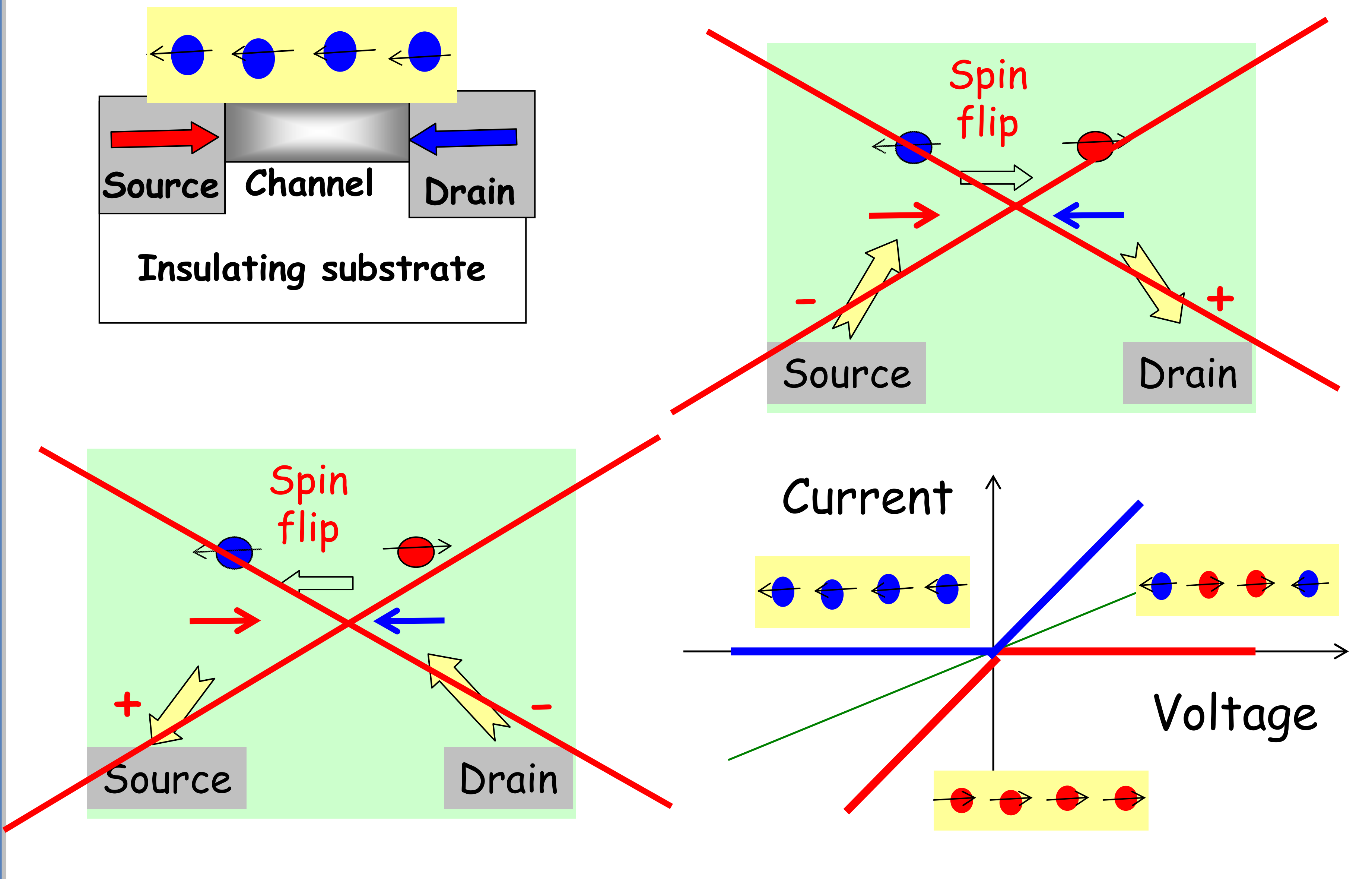




Perfect AP with Spin-flip Impurities



Perfect AP with Spin-polarized gate



Current at zero voltage ! !

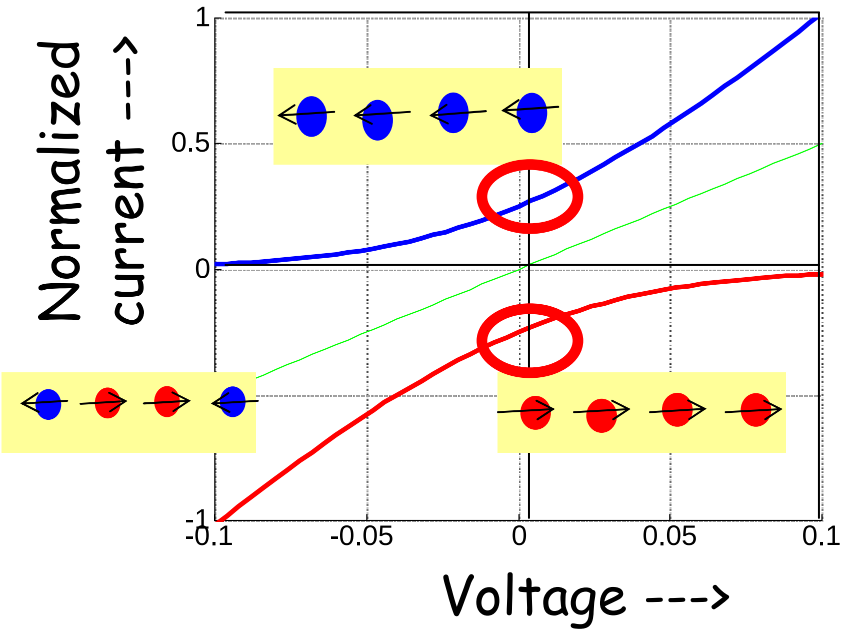
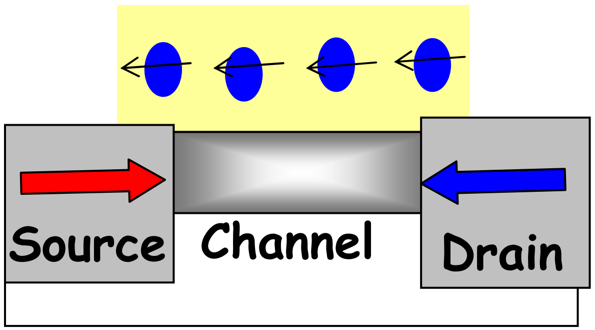
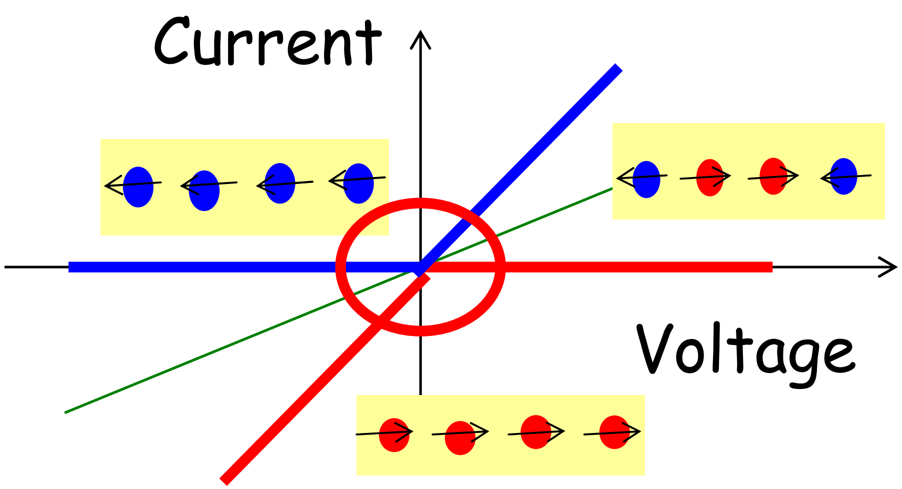
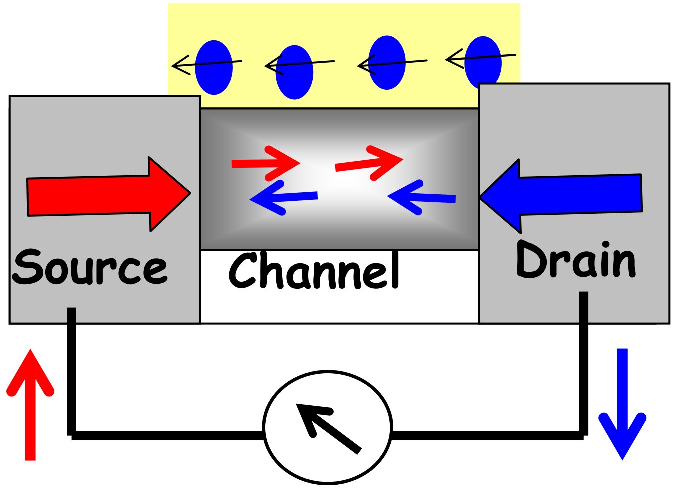


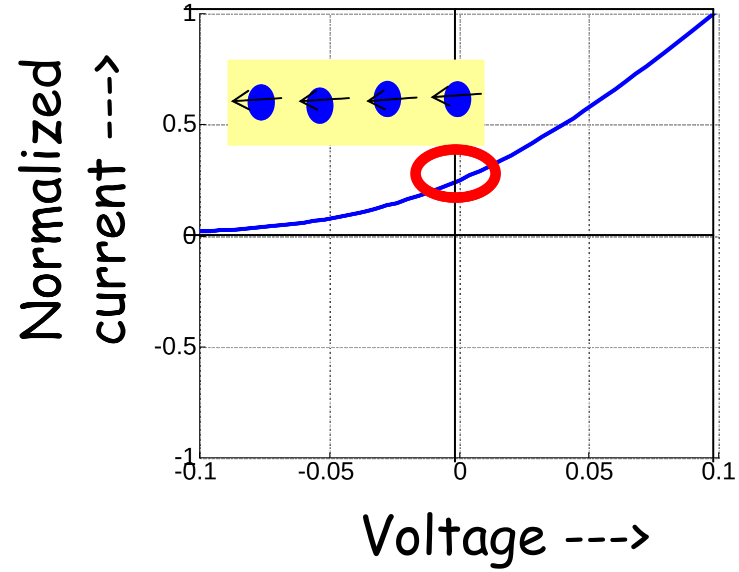
Fig : 1A

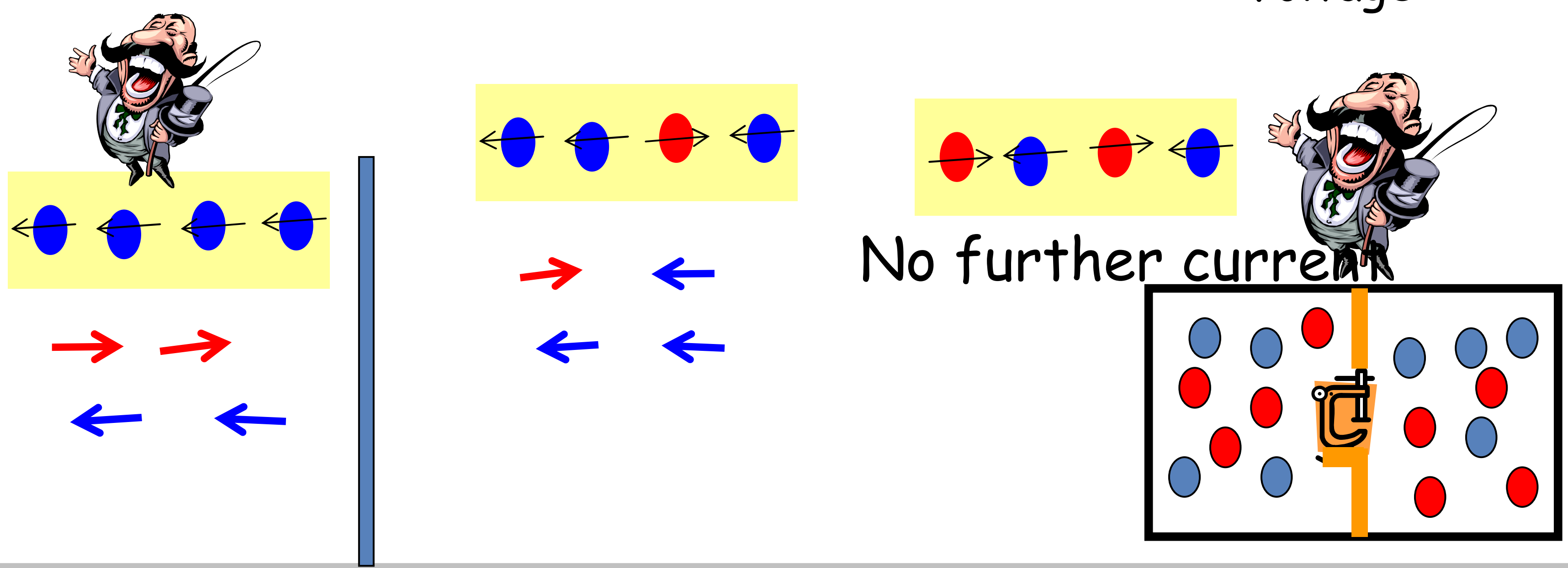




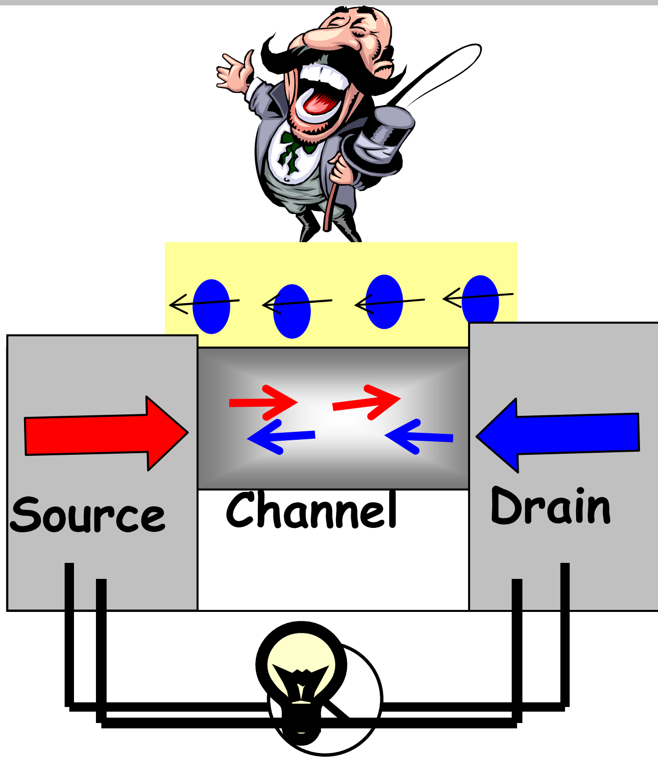
Device to "demon"

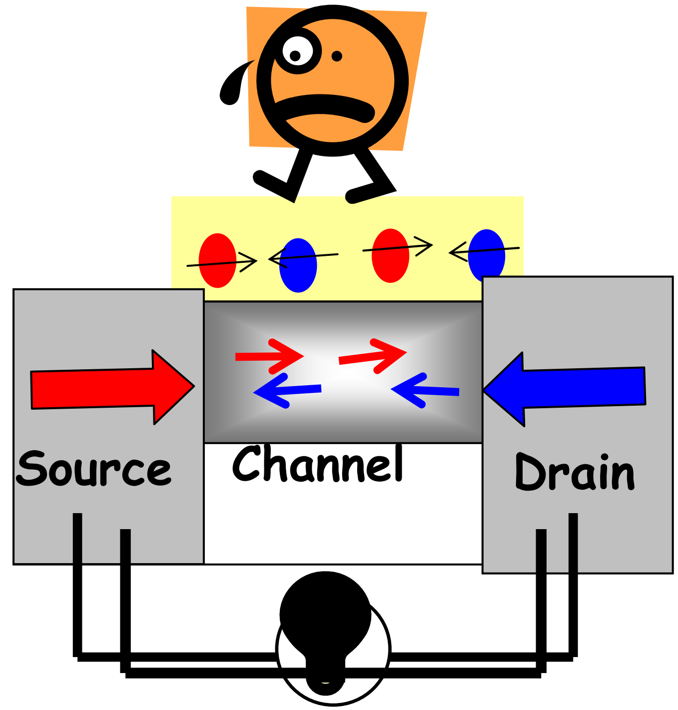


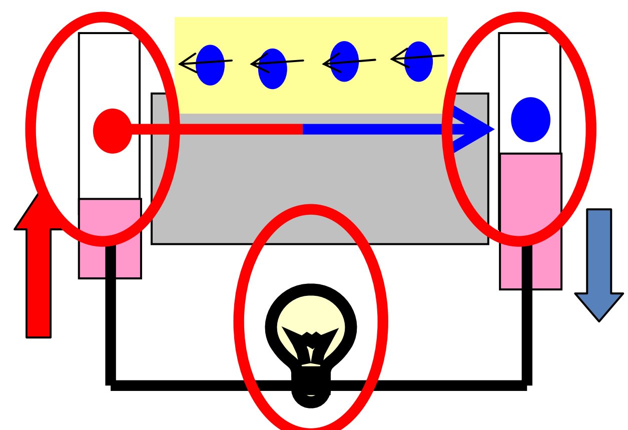




Where did the energy come from?

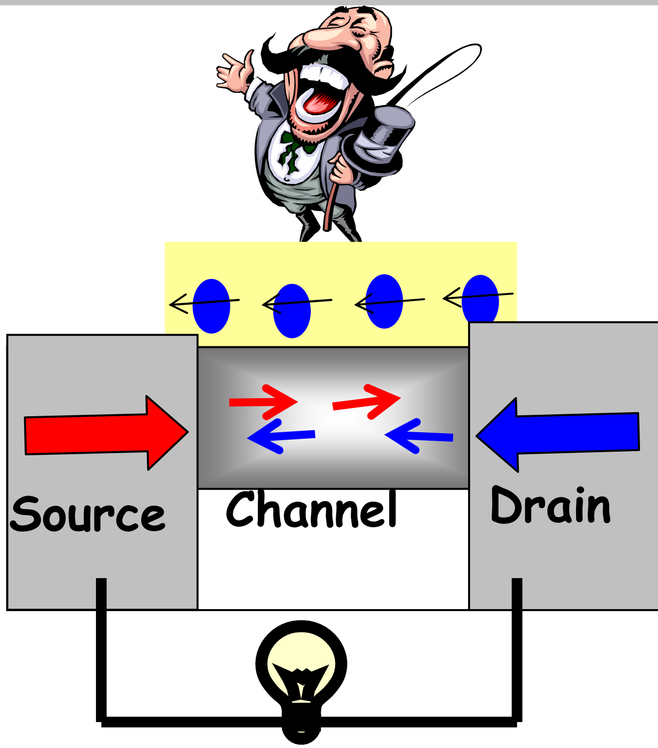


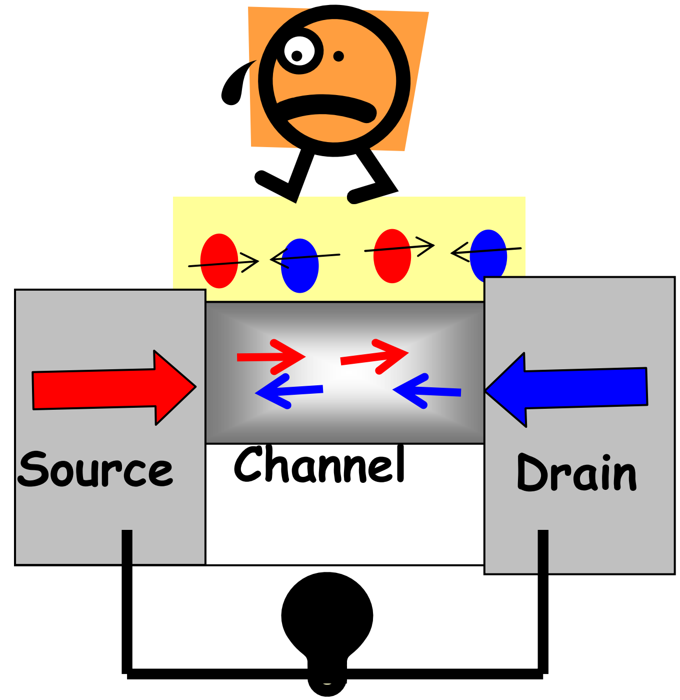




Answer: From the contacts

Second law ?





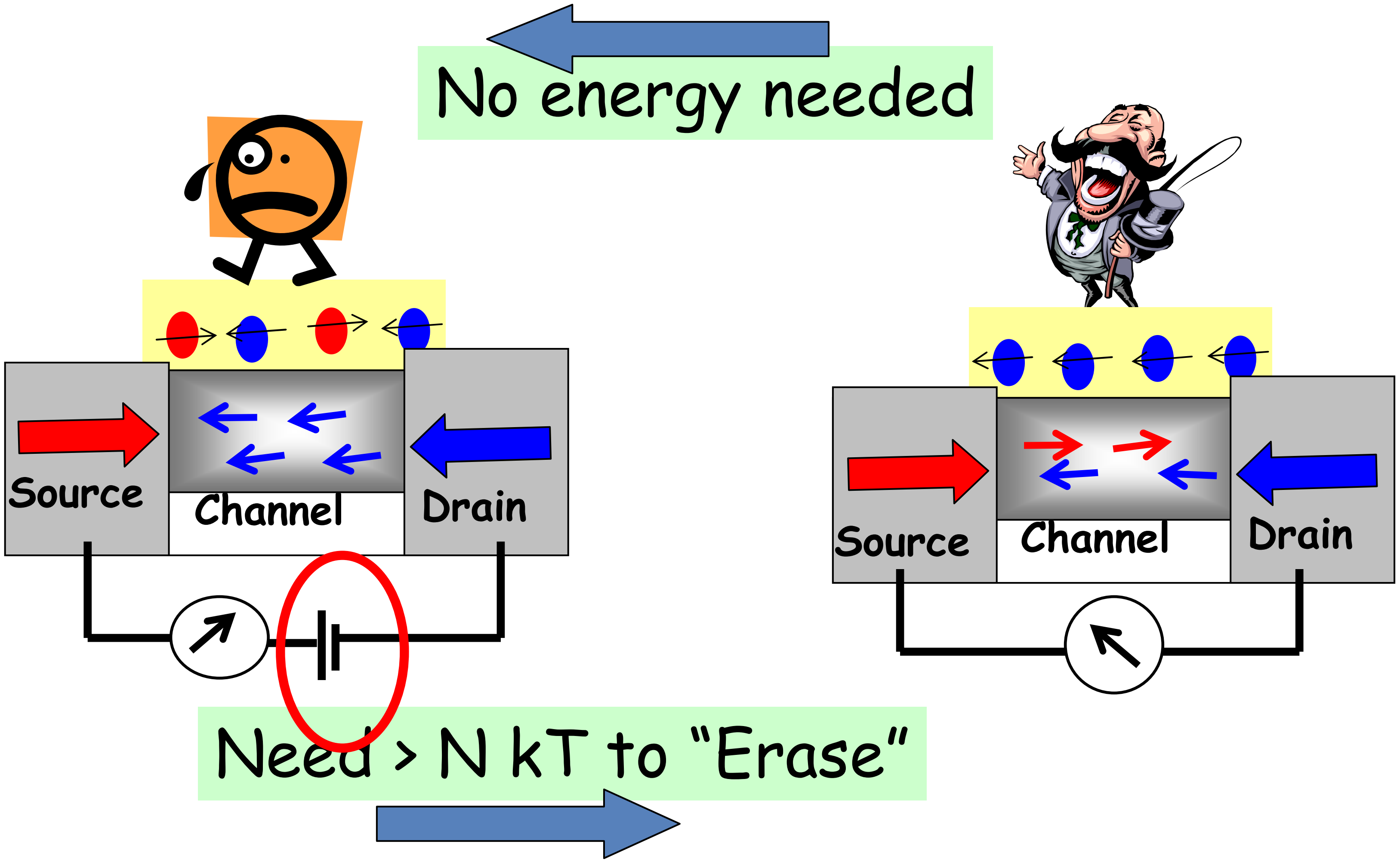
$S = 0$

$S = k \ln W$

$S = Nk \ln 2$

Energy upto $T \Delta S$ may be extracted

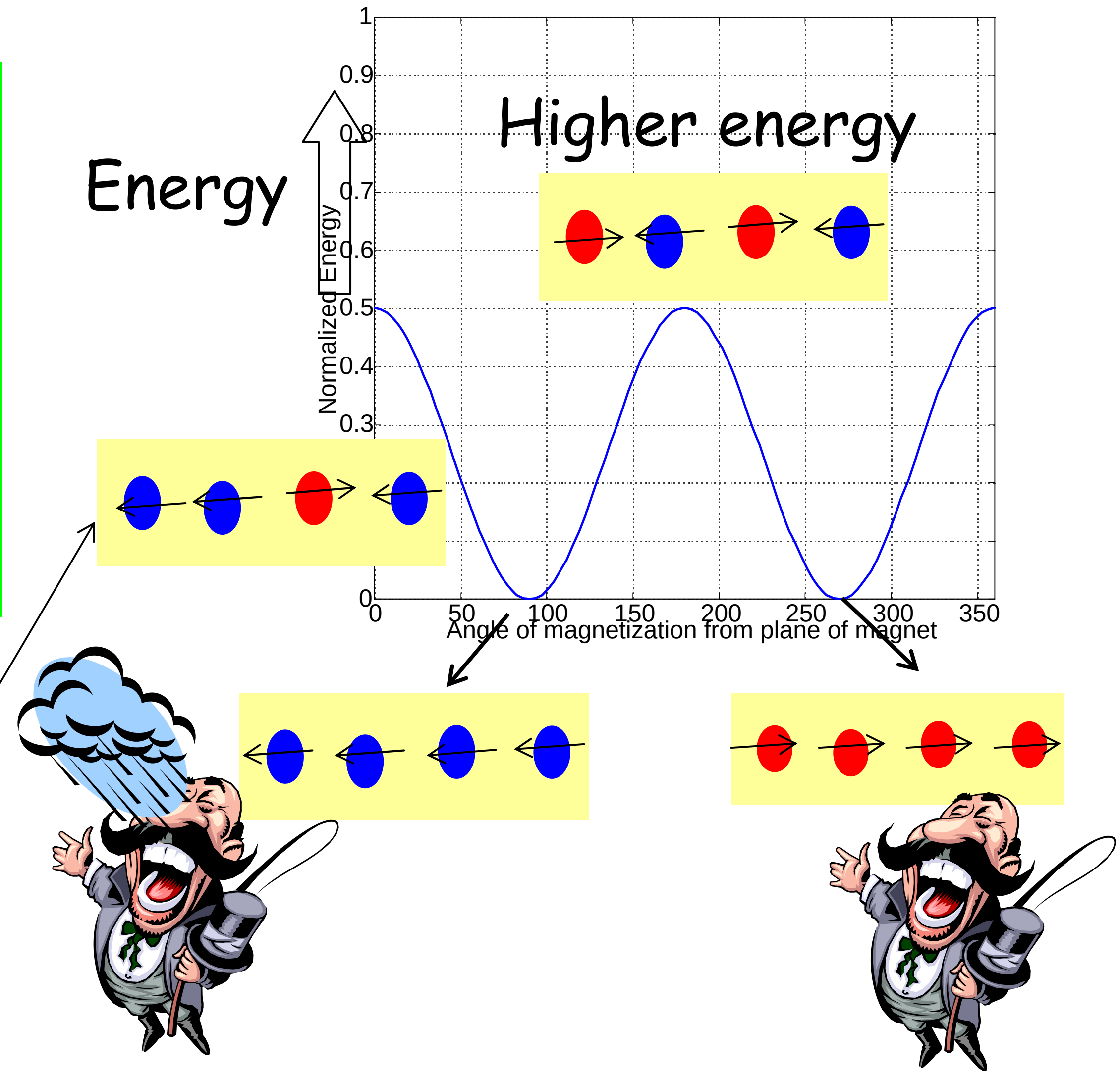
Resetting the demon takes energy



Maxwell's demon, ed. H.S.Leff and A.F.Rex,
ISBN 0-691-08727-X pbk

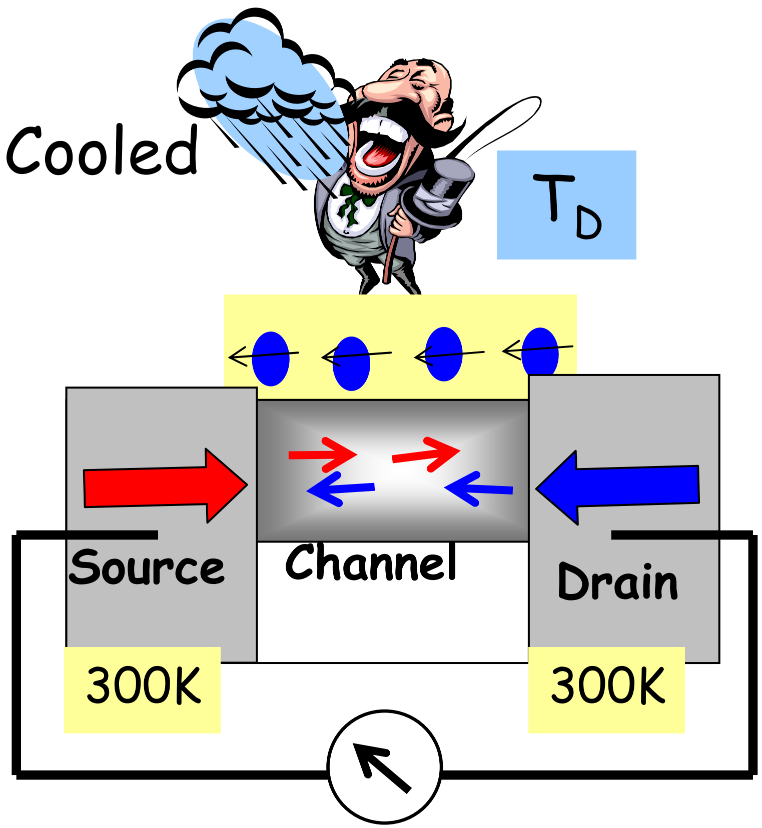
Nanomagnets : Bistable demons

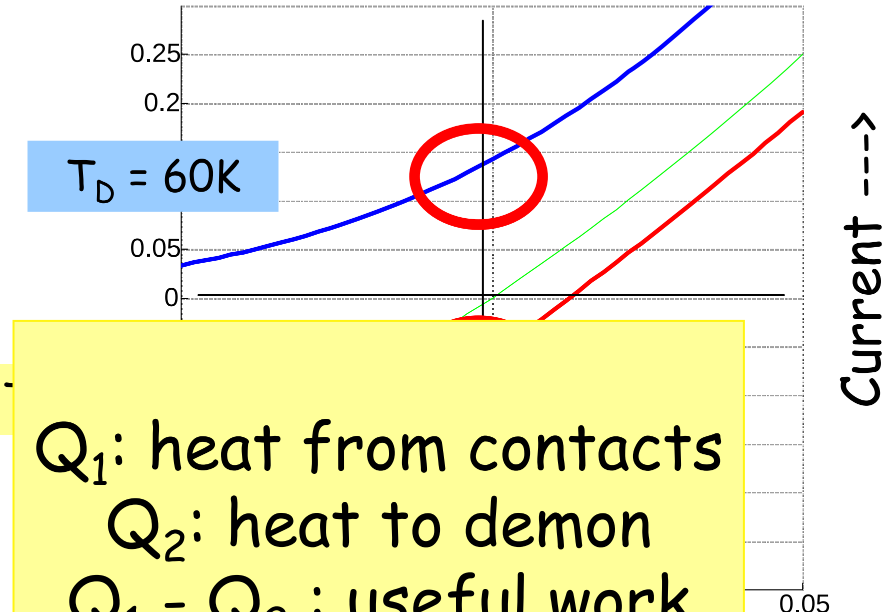
.. A finite-sized demon .. gets so hot that he cannot see very well after a while ..", Feynman lectures, Vol.1, 46-5.



Flipping a spin costs energy

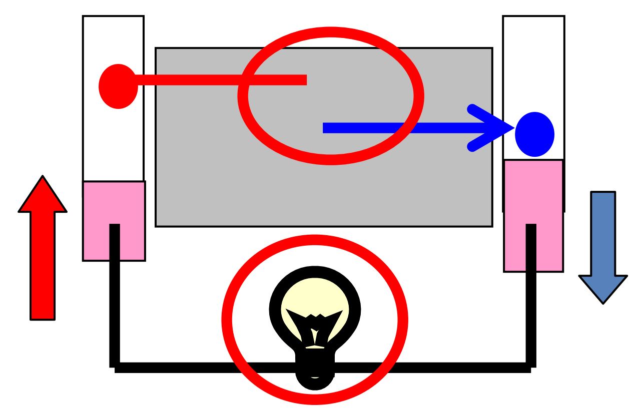
The cool demon as a heat engine



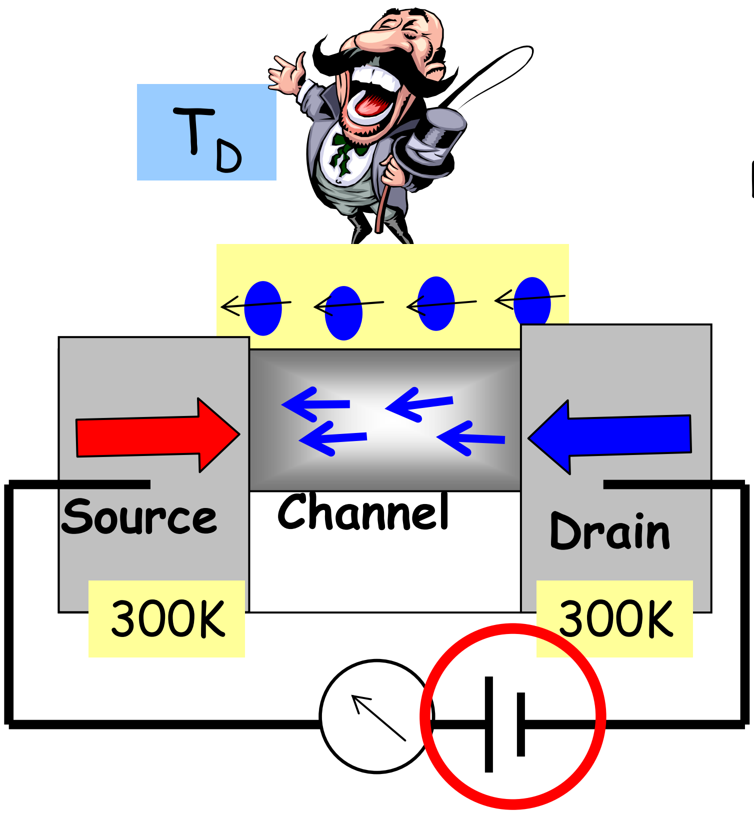


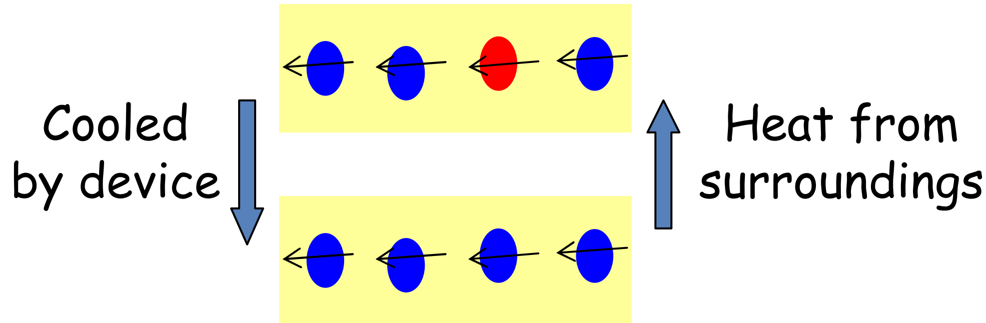
Q_1: heat from contacts
Q_2: heat to demon
Q_1 - Q_2 : useful work

Carnot's principle $$\frac{Q_1}{kT} < \frac{Q_2}{kT_D}$$



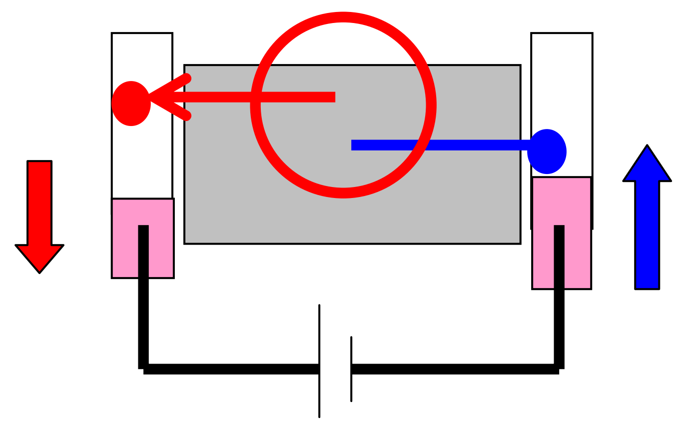
Cooling the demon: Refrigerator





Q_1: heat delivered to contacts
Q_2: heat taken from demon

Battery delivers Q_1 - Q_2



Carnot's principle

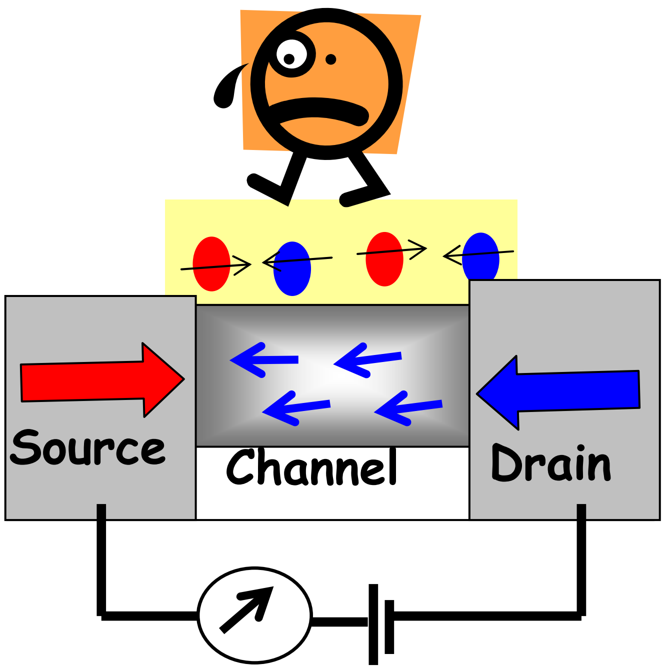
$$\frac{Q_1}{kT} > \frac{Q_2}{kT_D}$$

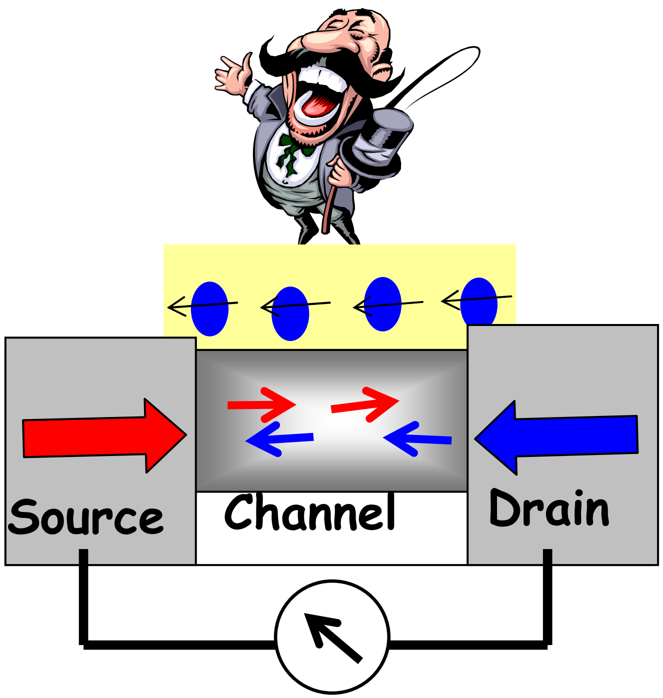
Why is the flow unidirectional ?

S = Nk ln 2

No energy needed

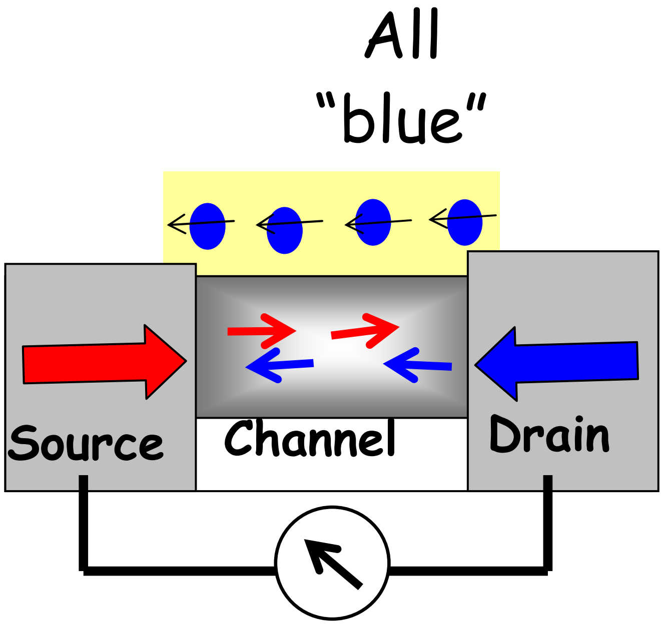
S = 0

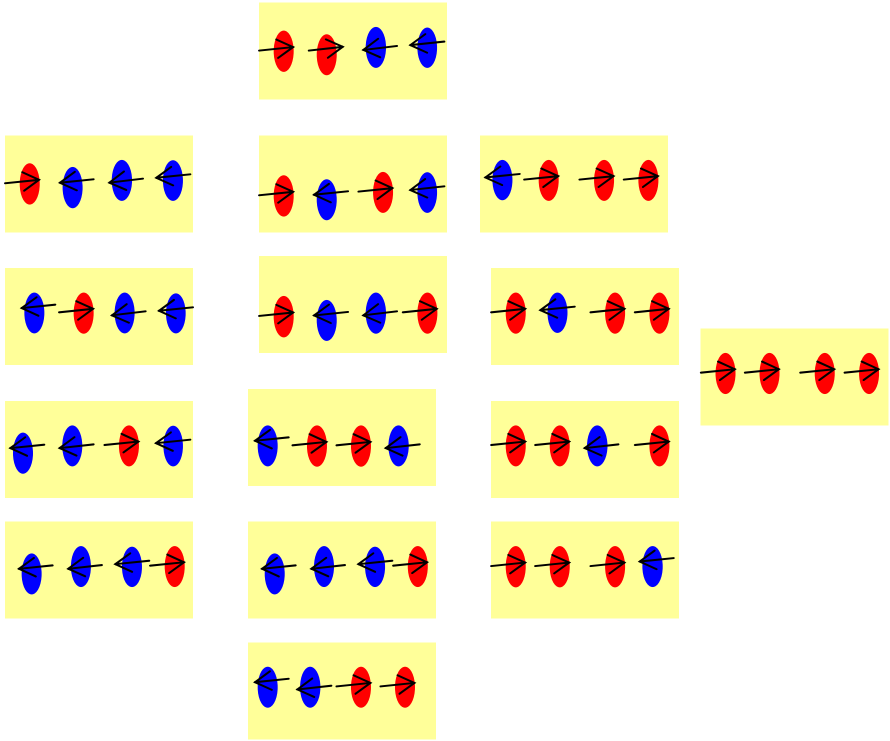




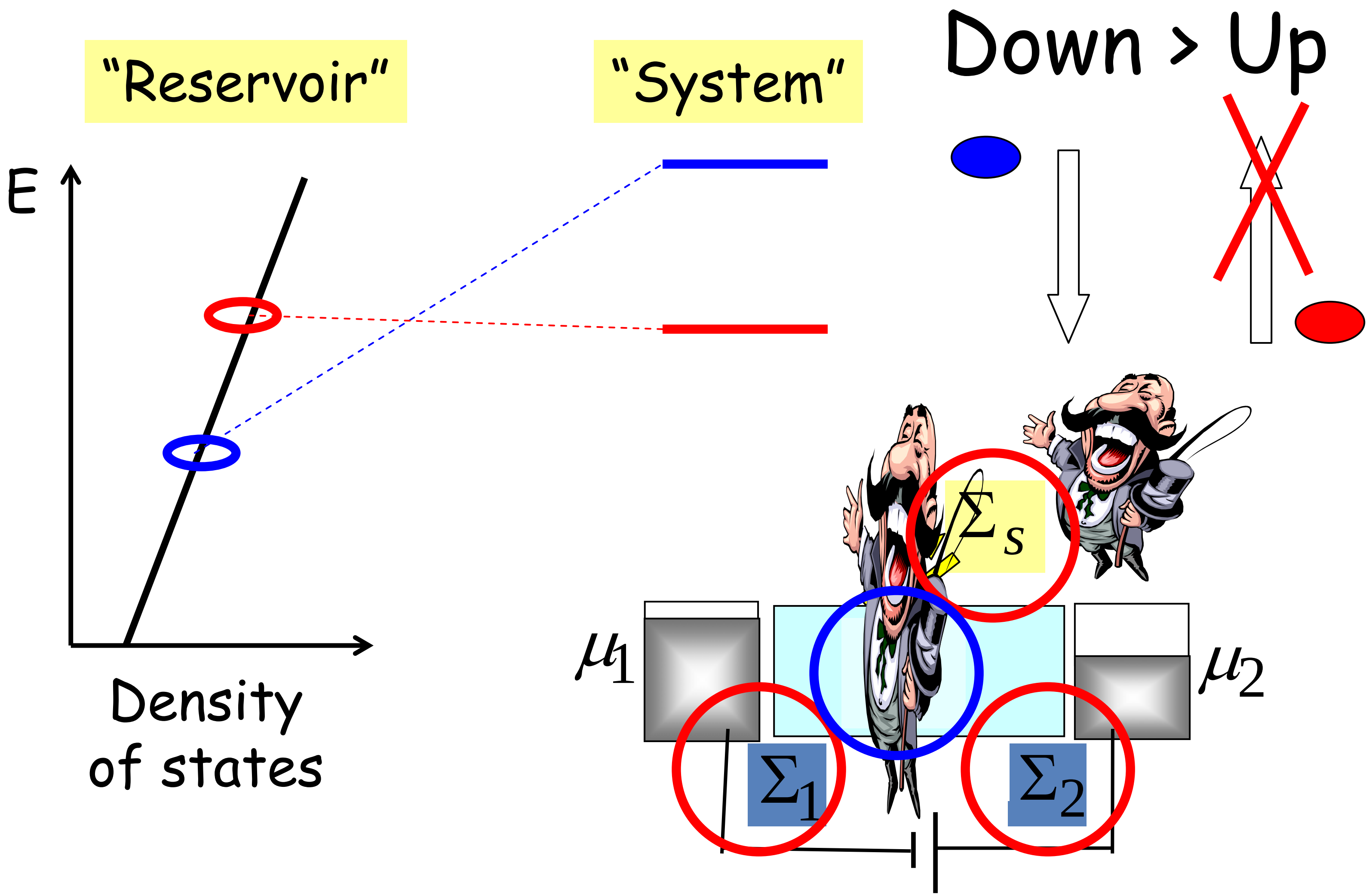
Need > N kT to "Erase"

Entropy as a driving force

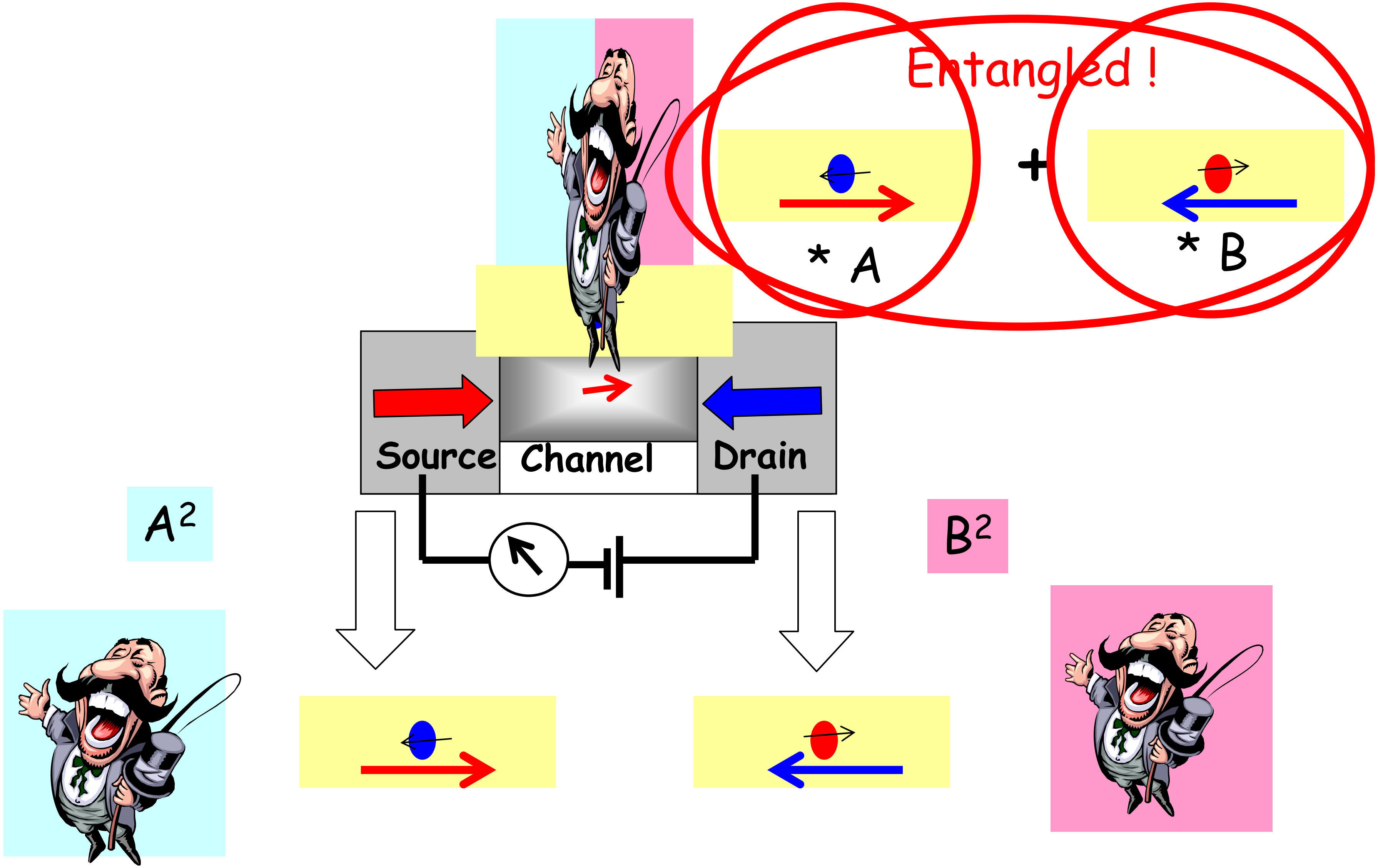




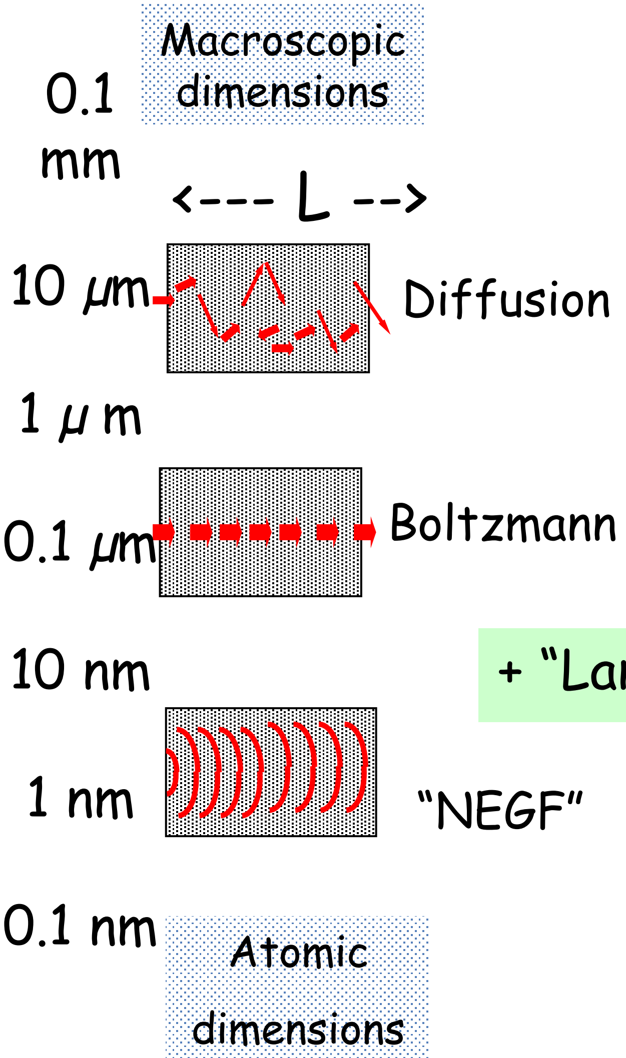
Entropy-driven vs. dynamic processes



Entangled "demon"

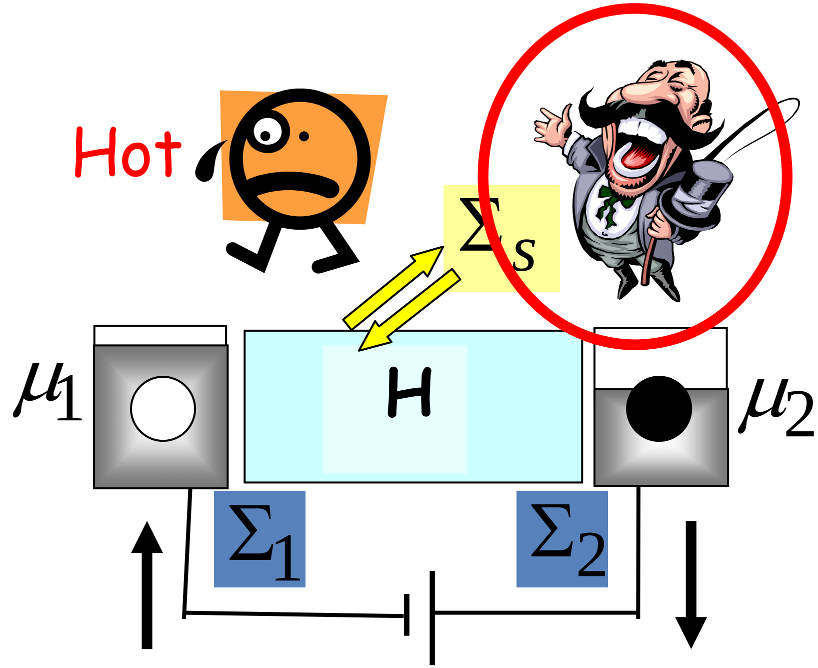


Unified model for nanodevices



"Even simple things .. work .. in only one direction because it has some ultimate contact with the rest of the universe .."
Feynman lectures, Vol.1, 46-8

+ "Landauer" =



Nanowires, nanotubes, molecules .....

Switches, energy conversion ...