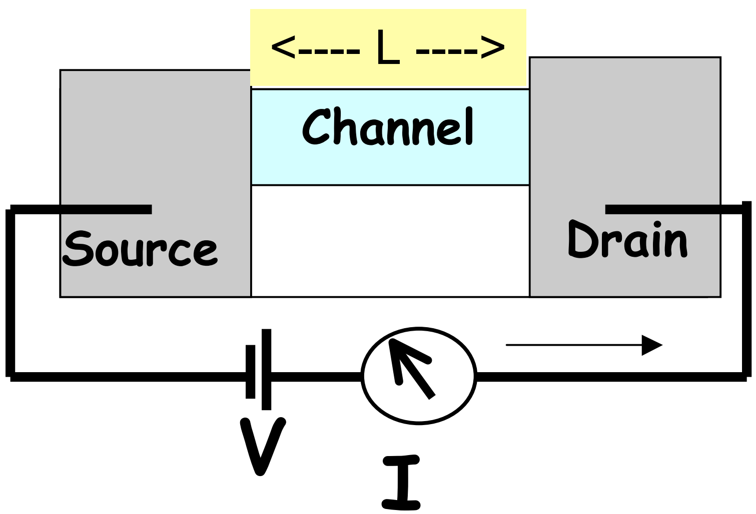
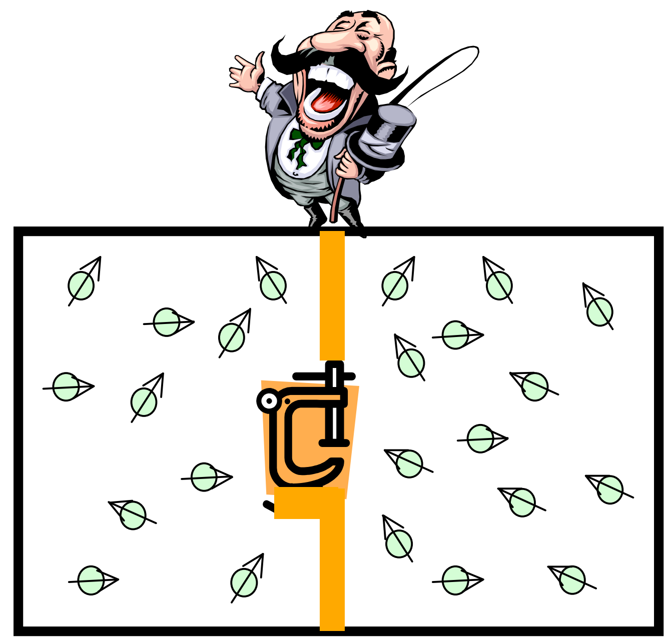
Nanodevices & Maxwell's demon

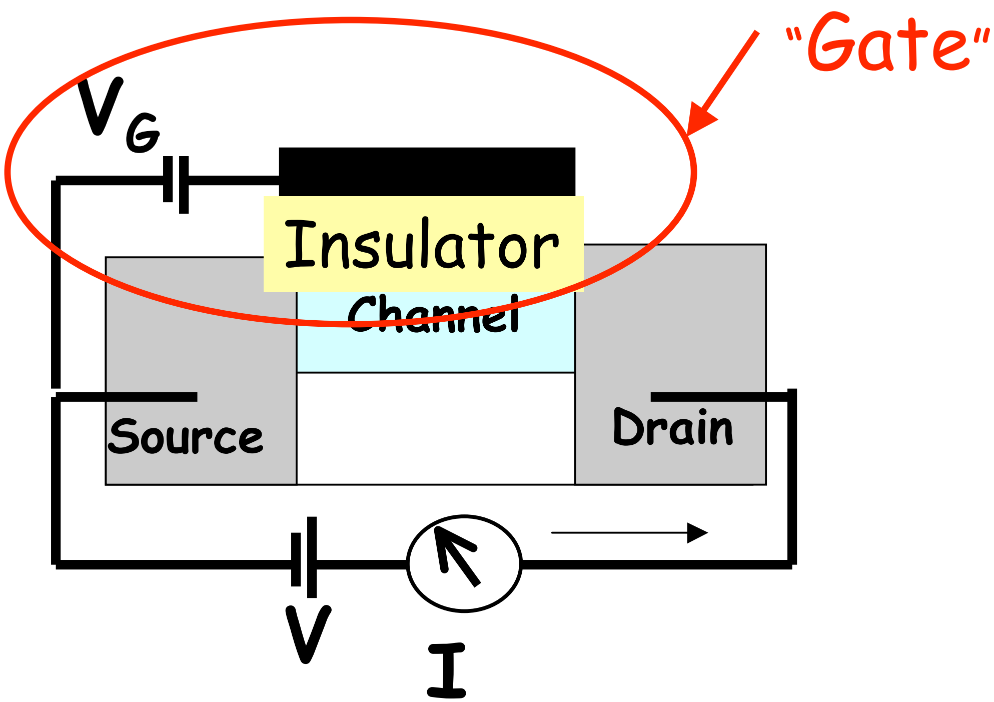




McCoy Lecture, Purdue
September 26, 2006

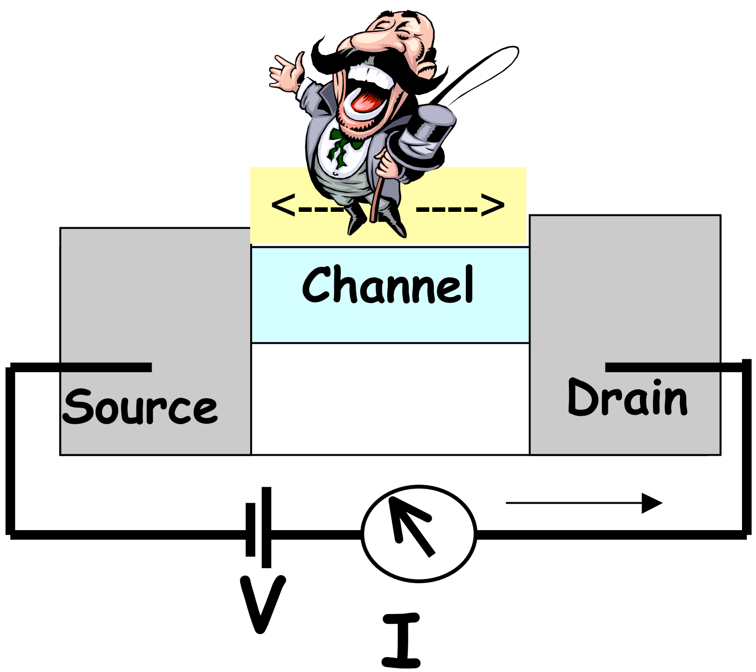
Supriyo Datta

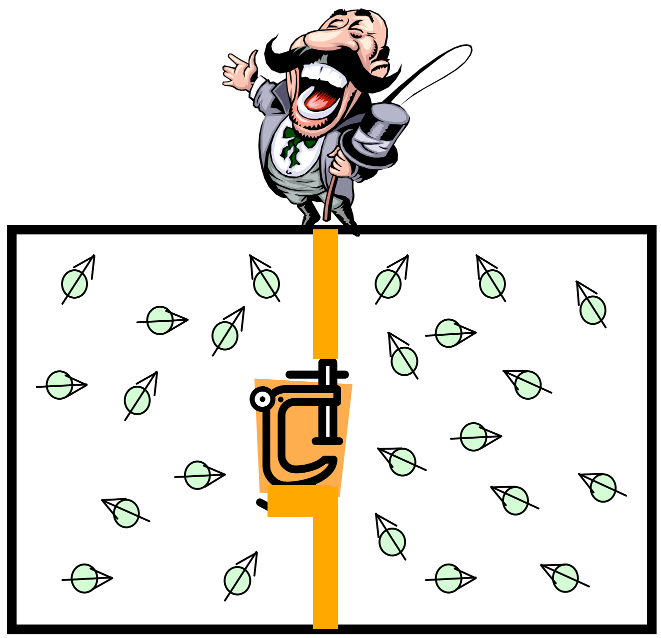
Nanodevices & Maxwell's demon



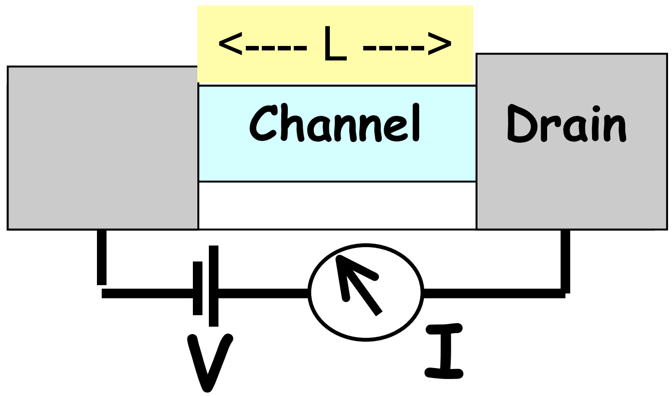
Transistor

Nanodevices & Maxwell's demon





Top-down view



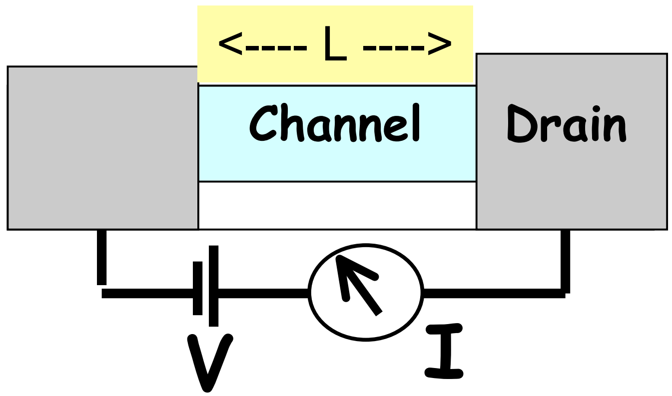
V = I R   or   I = V G

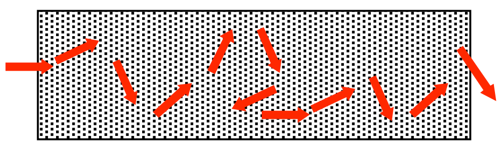
Conductance, G = 1/R

$$G = \sigma A / L$$

Conductivity

Top-down view





CHANNEL

$V = I\,R$ or $I = V\,G$

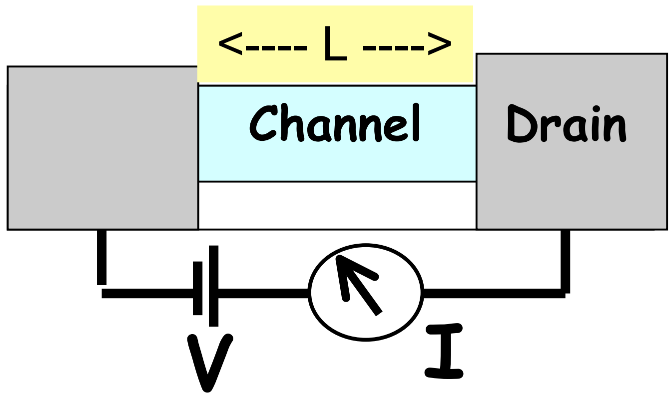
Conductance, $G = 1/R$

$$G = \sigma A / L$$

Conductivity

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

Top-down view

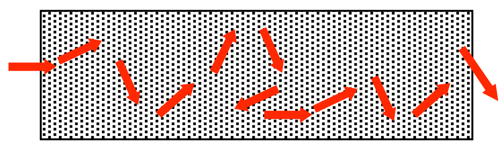


V = I R or I = V G

Conductance, G = 1/R

$$G = \sigma A / L$$

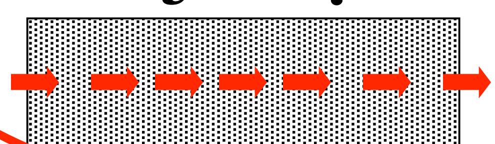
Conductivity



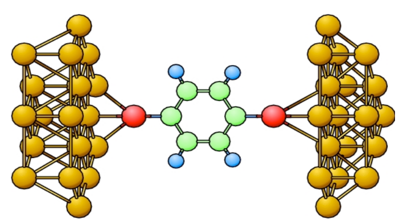
CHANNEL

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

$\tau = ?$

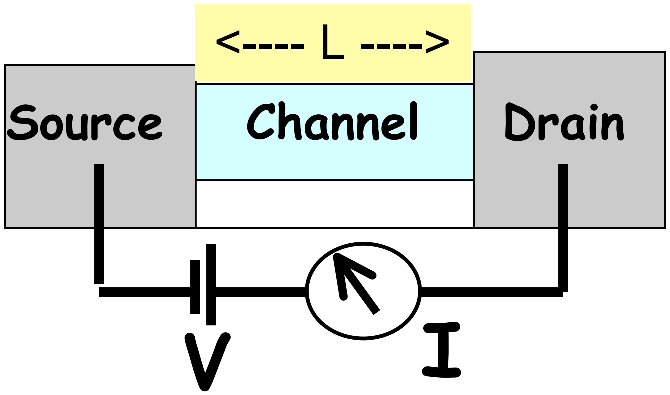


m = ? n = ?



"Very complicated"

Bottom-up View

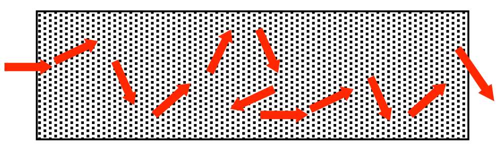


Ohm's law

"Top"

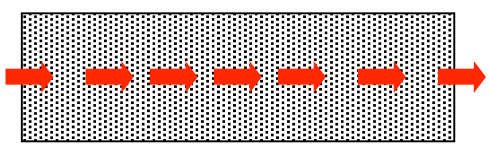
$$I = GV \quad , \quad G = \sigma A / L$$

$\gamma \equiv escape\ rate$



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

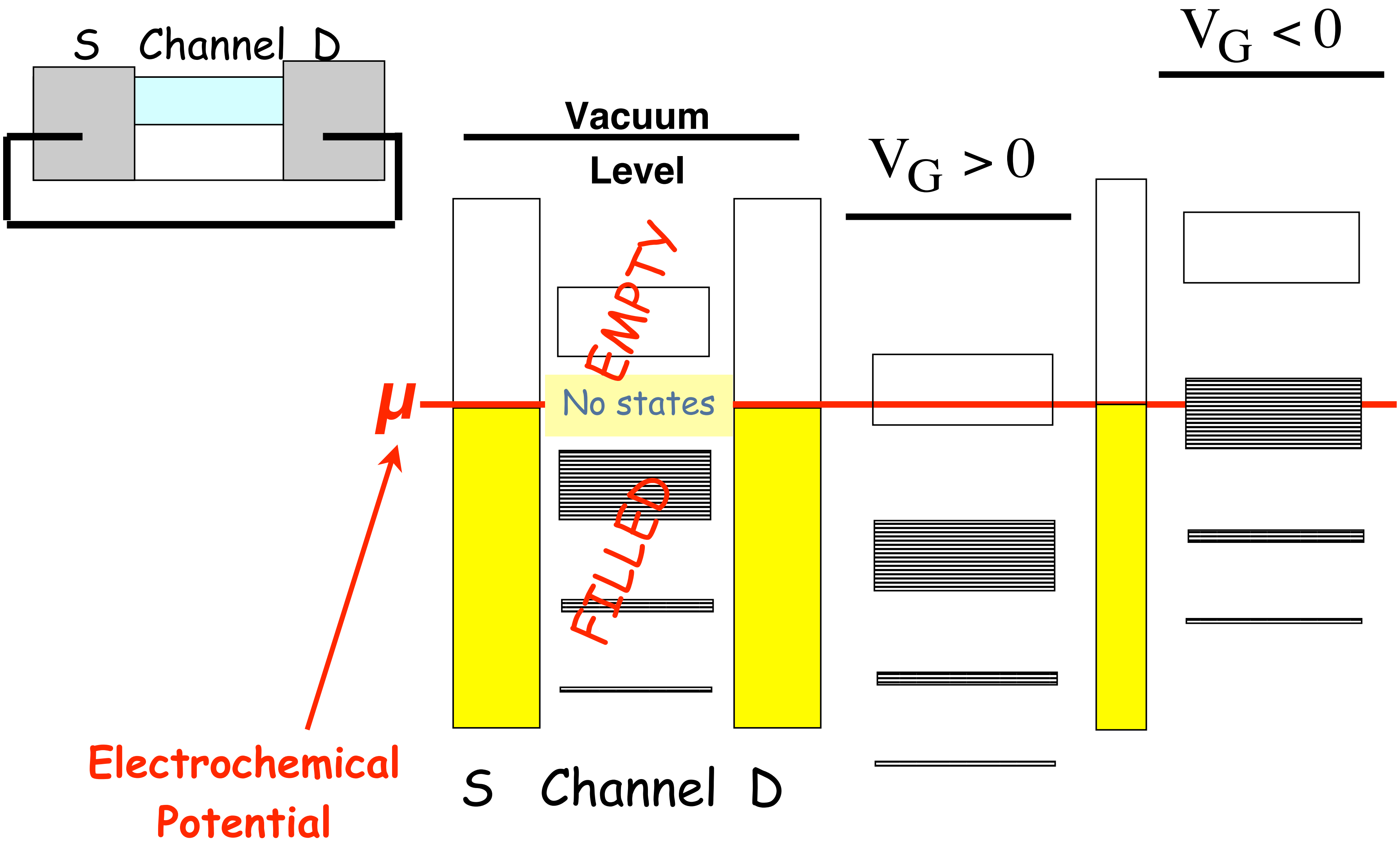
CHANNEL



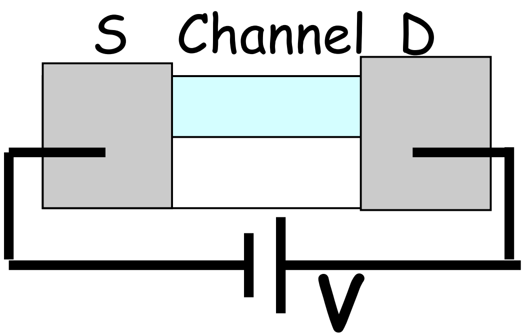
$$G = \underbrace{(q^2/h)}_{1/25.8\ K\Omega}$$

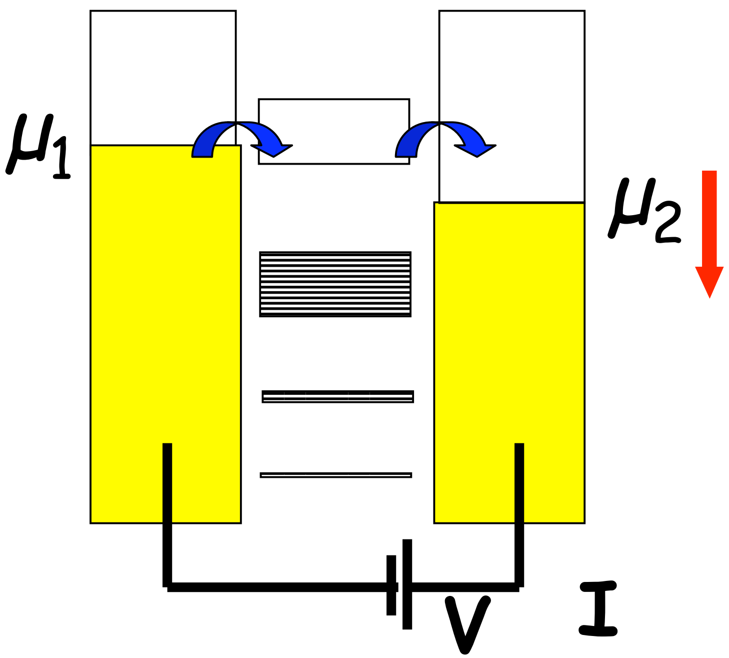
"Bottom"

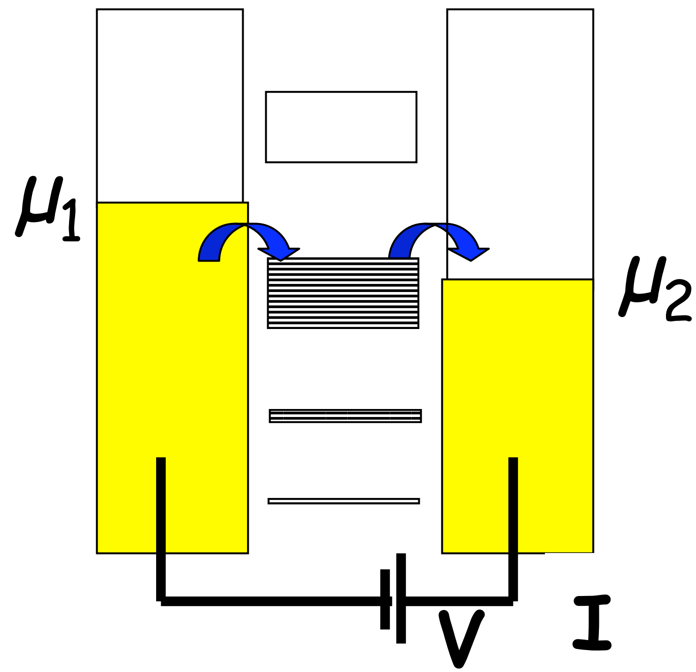
Equilibrium Energy Level Diagram



What makes electrons flow?



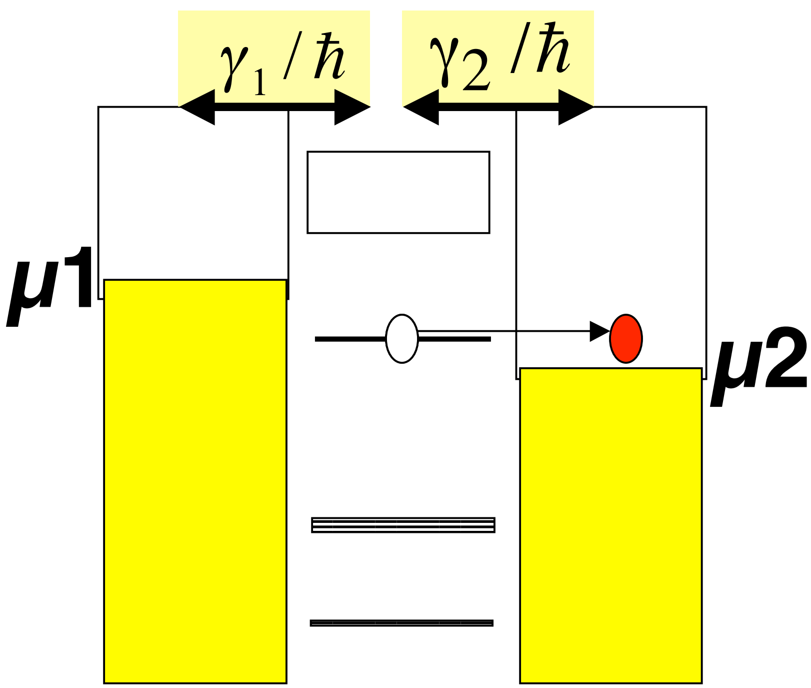


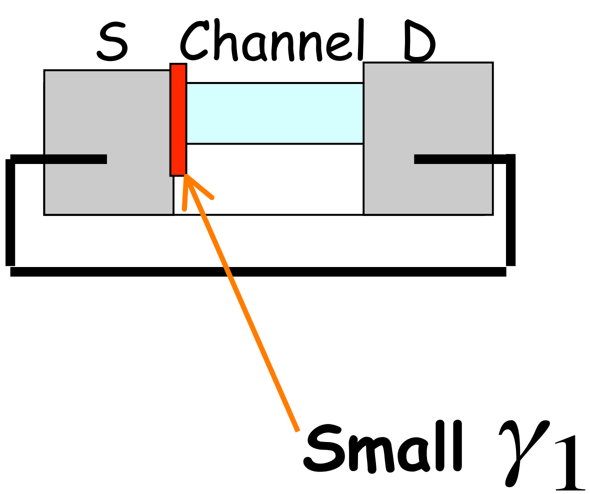


Escape rate

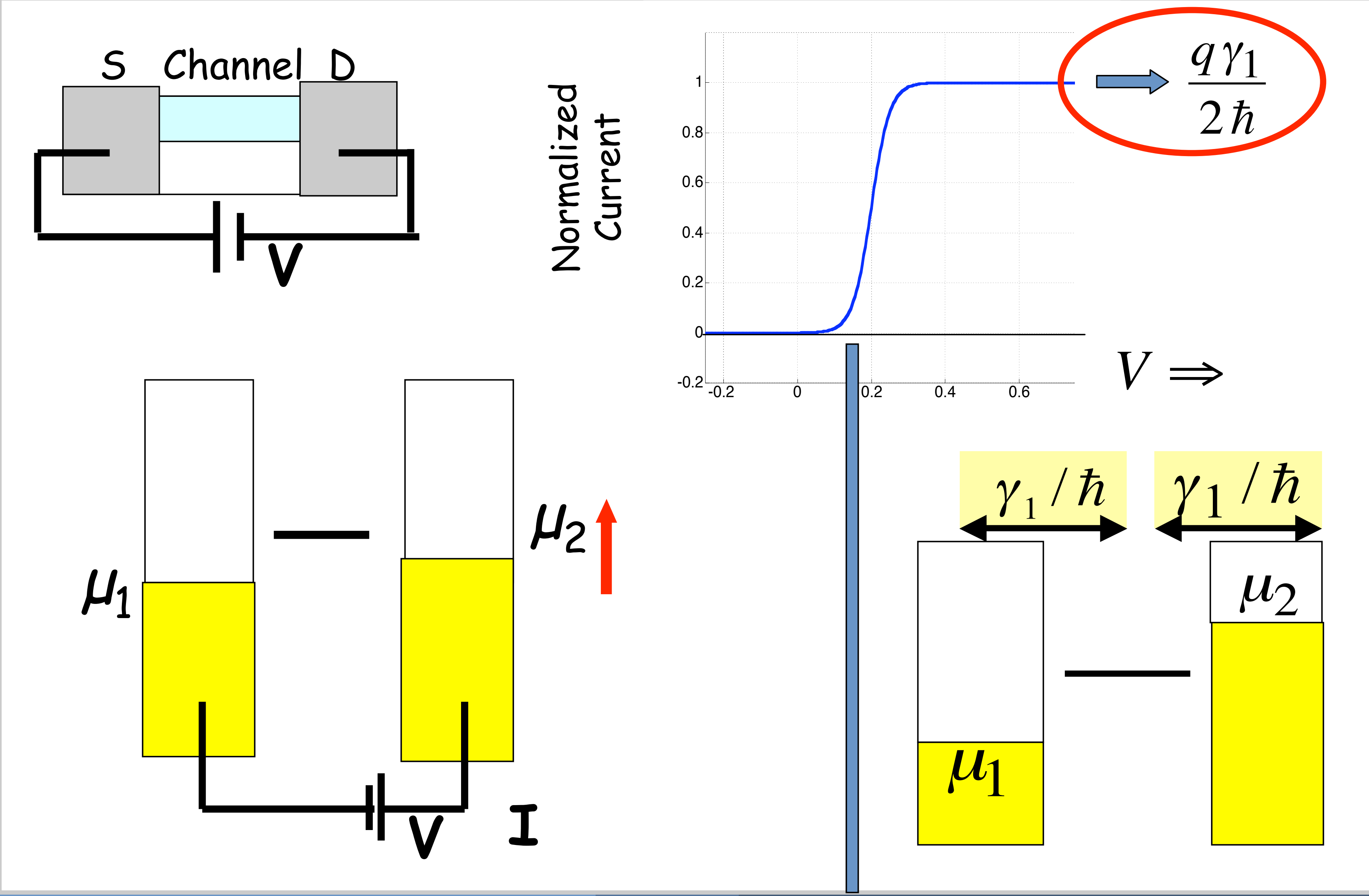
$$\gamma / \hbar : Escape\ Rate$$

$$\gamma \text{ has dimensions of energy}$$

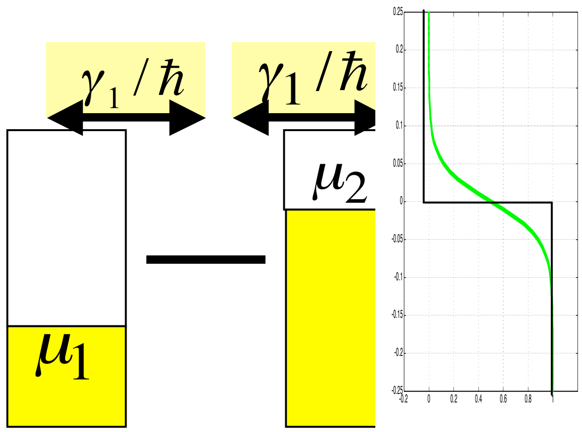


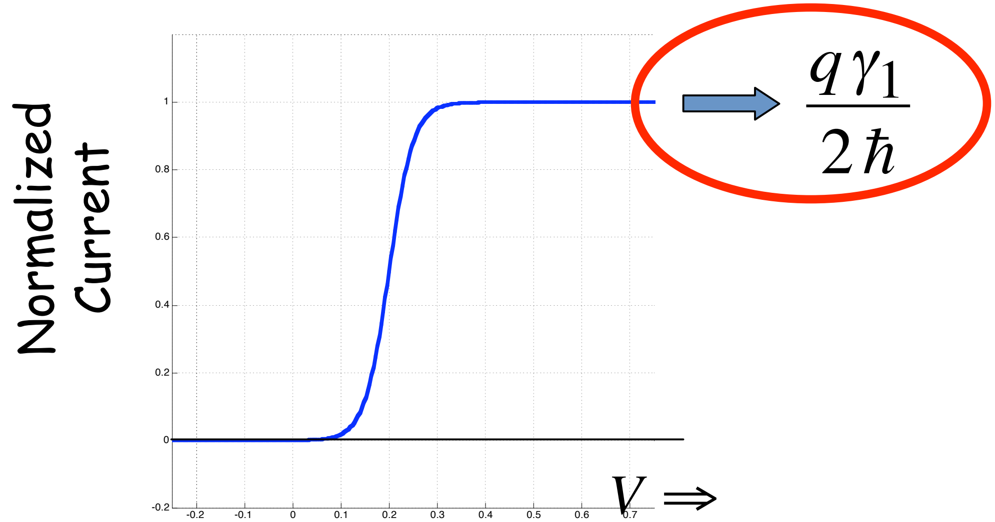


Current through a very small conductor

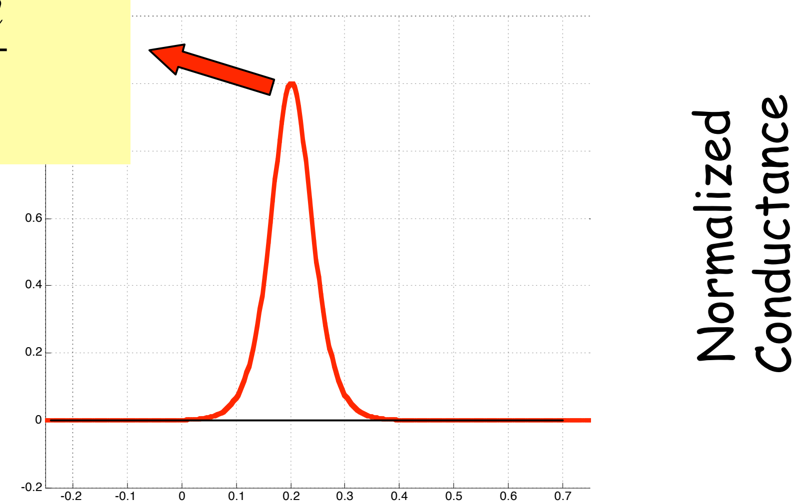


Conductance quantum

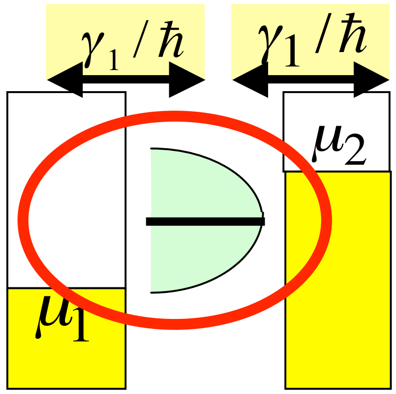


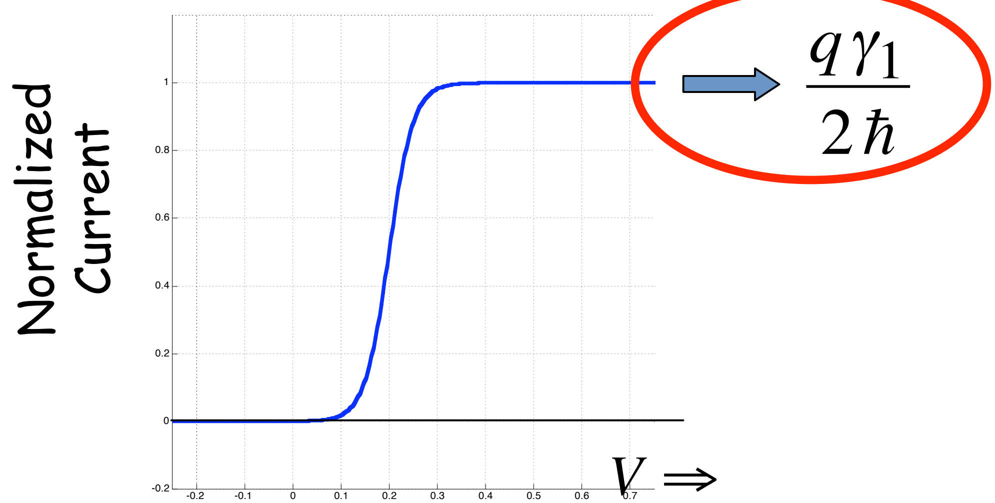


$$\frac{dI}{dV} \sim \frac{q\gamma_1/2\hbar}{4kT}$$



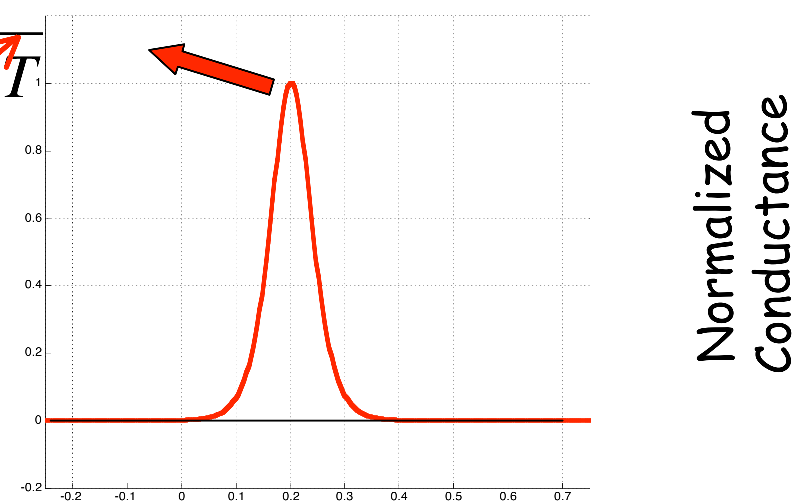
Conductance quantum





$$\frac{dI}{dV} \sim \frac{q\gamma_1/2\hbar}{2\gamma_1 + 4kT}$$

$$\sim \quad q^2/4\hbar \quad if \quad \gamma_1 >> kT$$



Conductance quantum

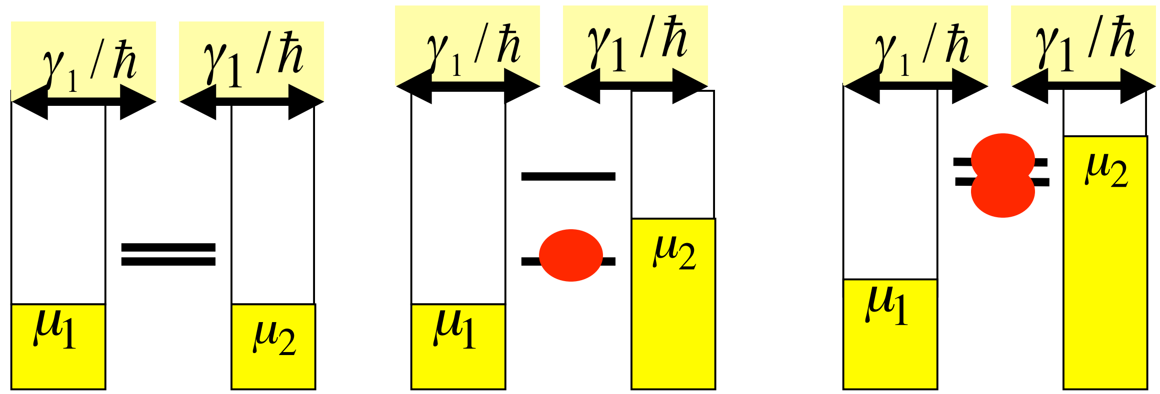
$$\sim \quad q^2/2\pi\hbar \quad \sim \quad 1/25.8\ K\Omega$$

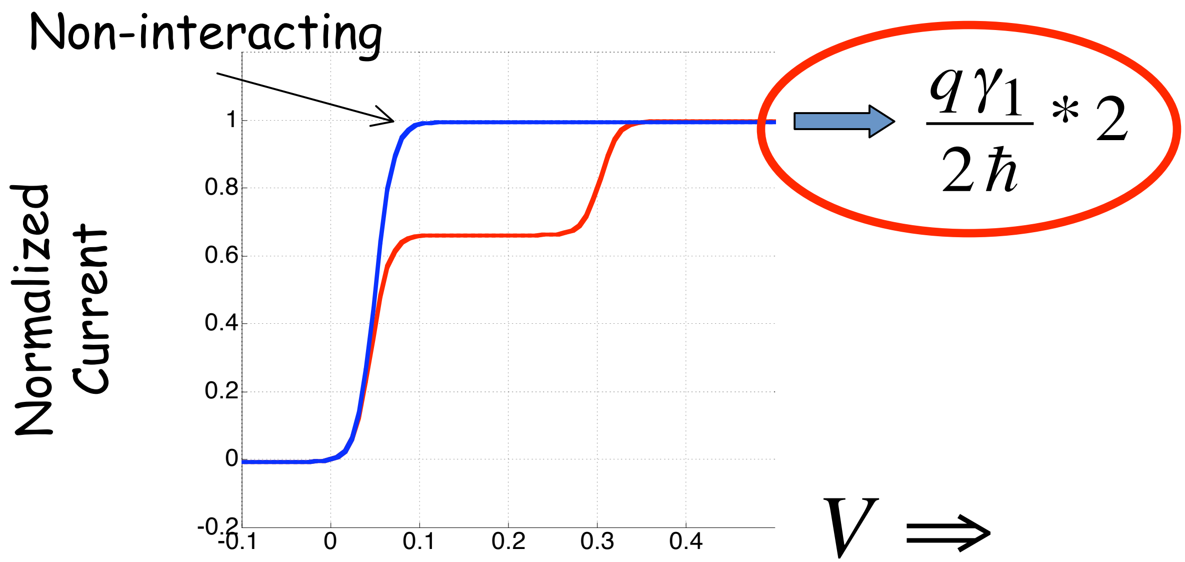
Single electron charging

U_0 : Increase in potential due to SINGLE electron

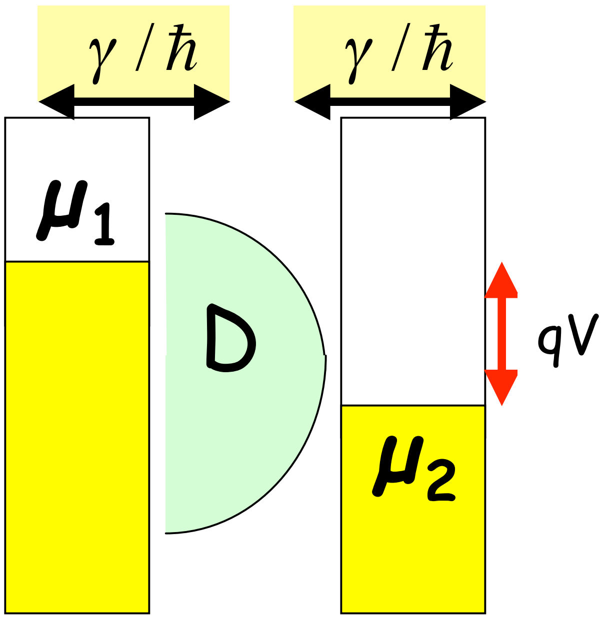
$>> \quad \gamma, kT$

"Self-interaction Correction"





Conductance: The bottom line



D: Density of states

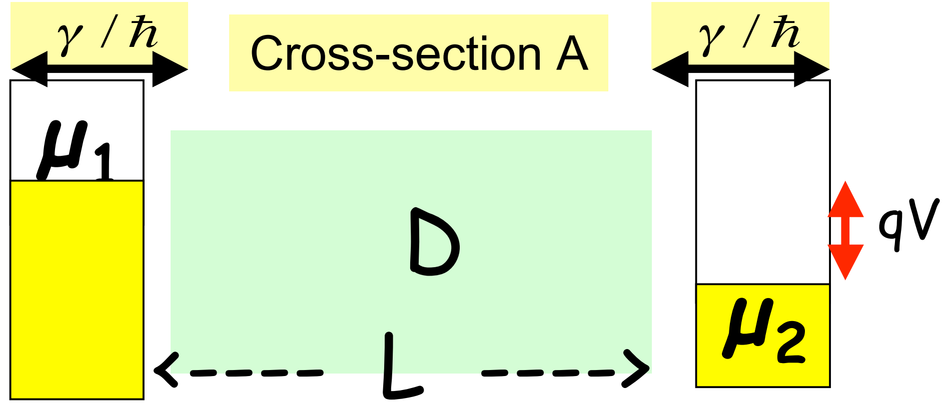
$$I \sim \underbrace{\frac{q\gamma}{2\hbar}}_{\text{Current per state}}$$

$$I/V = \underbrace{\frac{q^2}{2\pi\hbar}}_{\text{Conductance Quantum}} \underbrace{\langle \pi D \gamma \rangle}_{\text{Transmission}}$$

Ohm's Law

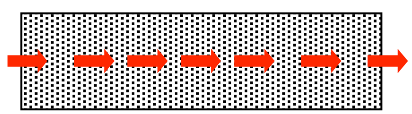
$$I/V = \frac{q^2}{2\pi\hbar}\langle \pi D \gamma \rangle$$

$$\underbrace{D}_{/eV} = \underbrace{N_0}_{/eV-m^3} \underbrace{AL}_{m^3}$$



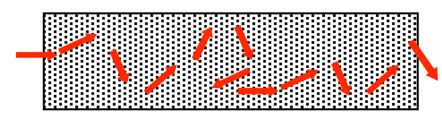
Can show that

Ballistic



$$\gamma \sim \frac{\hbar v}{L} \rightarrow D\gamma \sim A$$

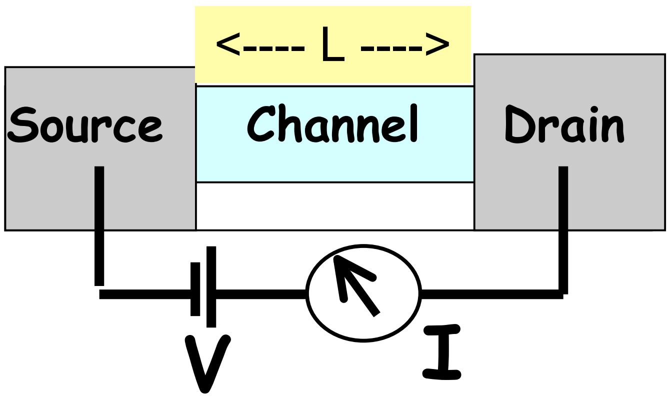
Diffusive

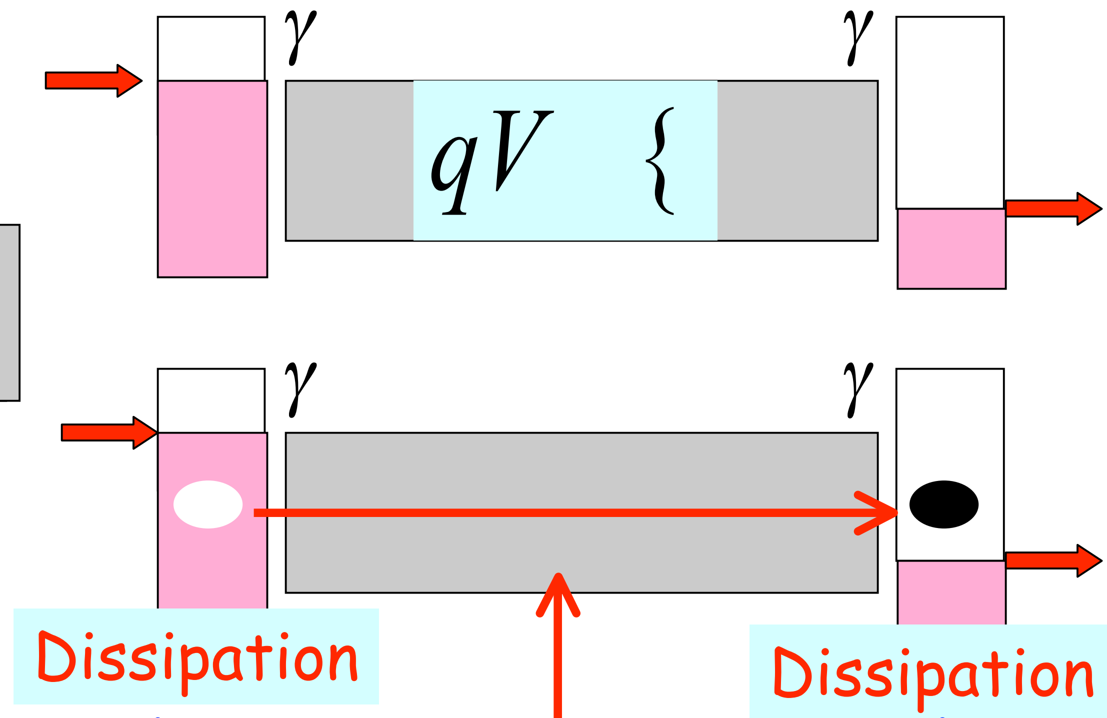


$$\gamma \sim \frac{2\hbar D}{L^2} \rightarrow D\gamma \sim A/L$$

Where is the power dissipated ?

$$Power = V\,I$$





Contacts assumed
to remain in equilibrium

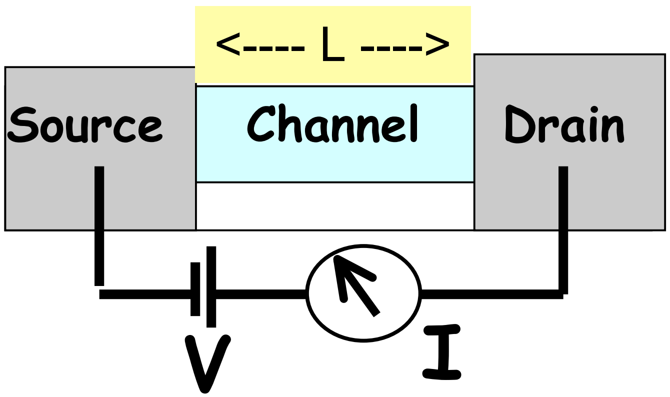
Thermodynamics

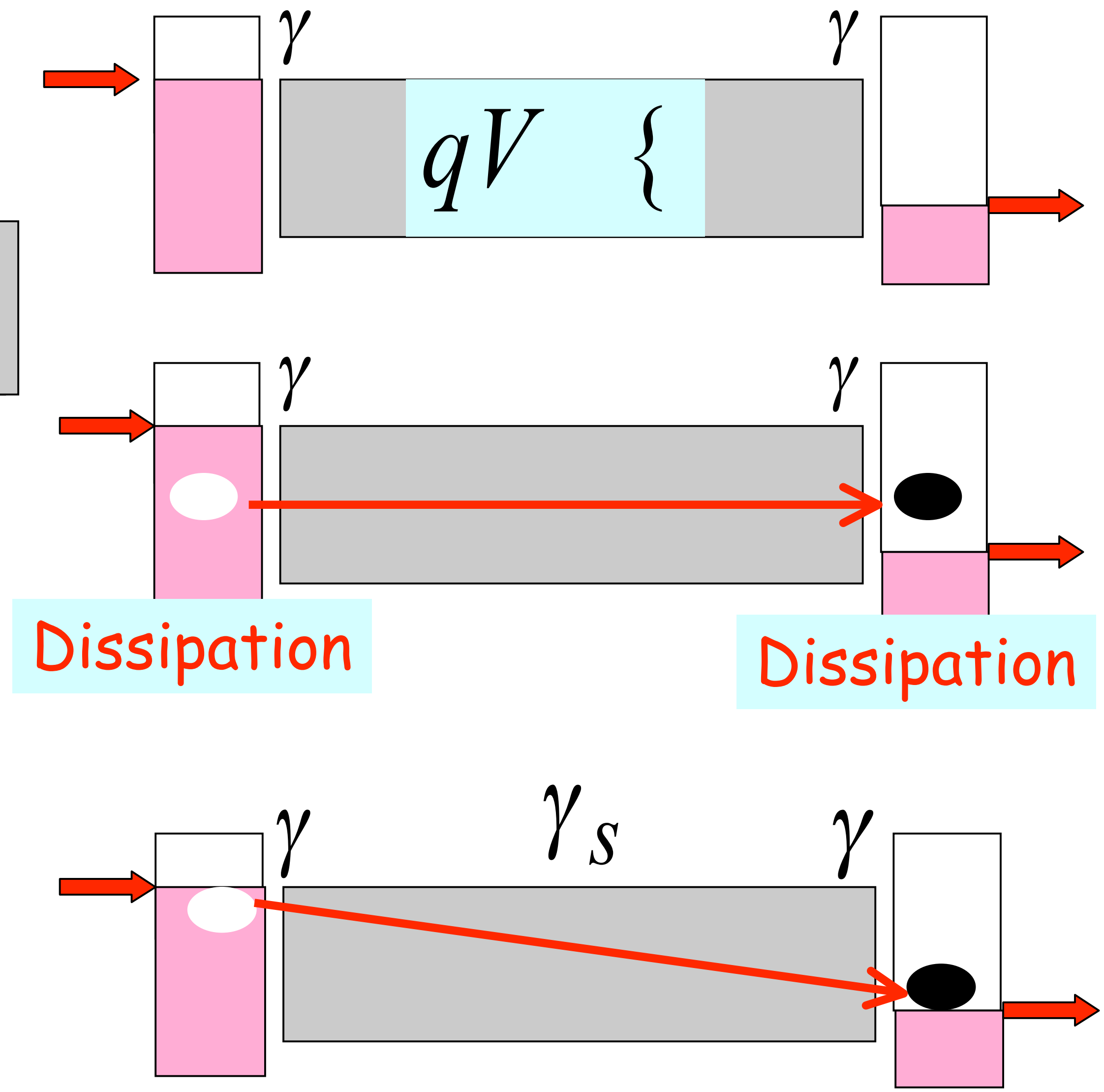
Newton's law
Schrodinger equation

Dynamics

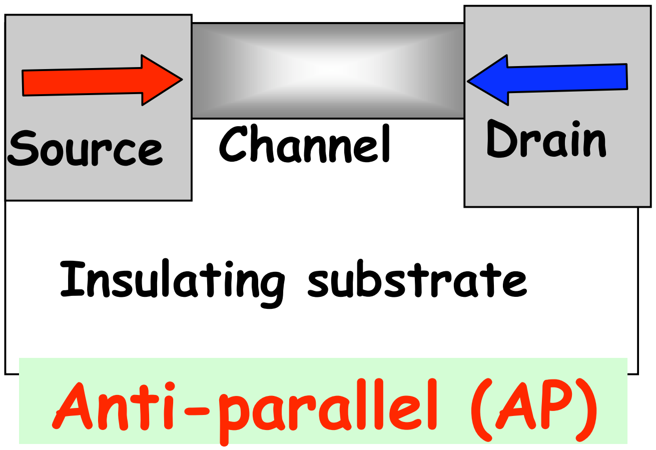
Where is the power dissipated ?

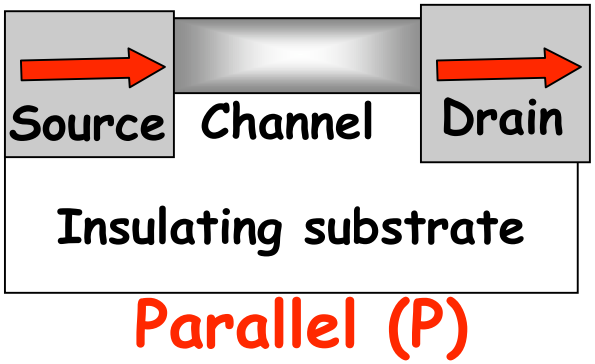
$$Power = V\,I$$

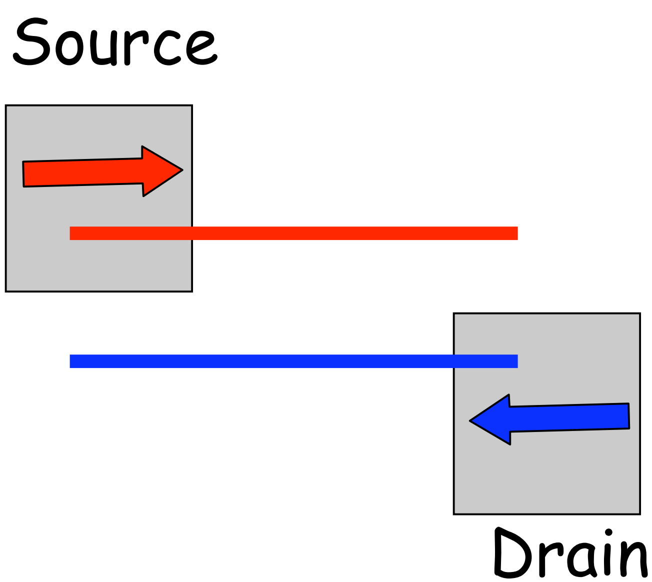


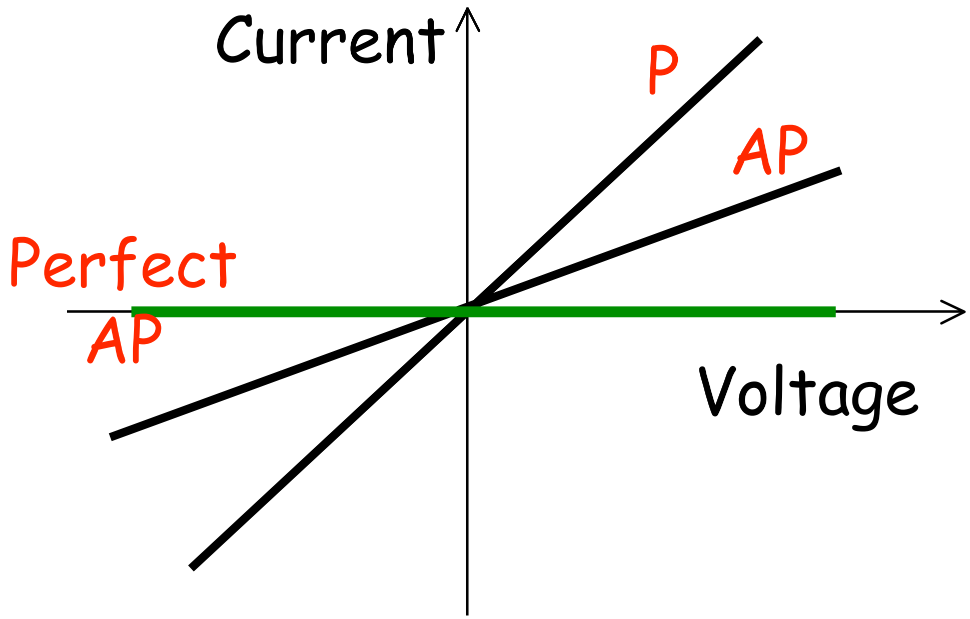


Spin Valves

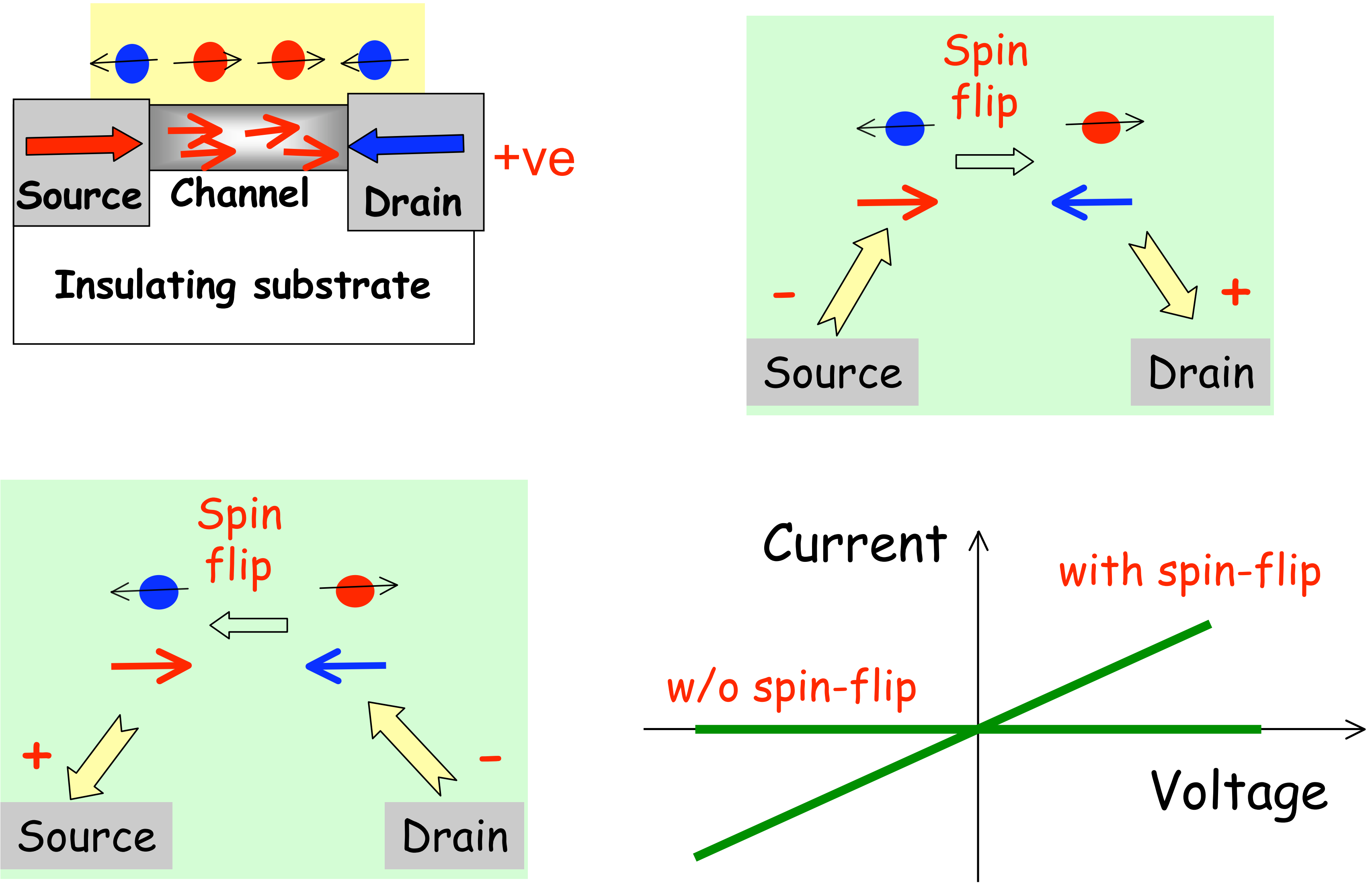

Source
Channel
Drain
Insulating substrate
Anti-parallel (AP)


Source
Channel
Drain
Insulating substrate
Parallel (P)

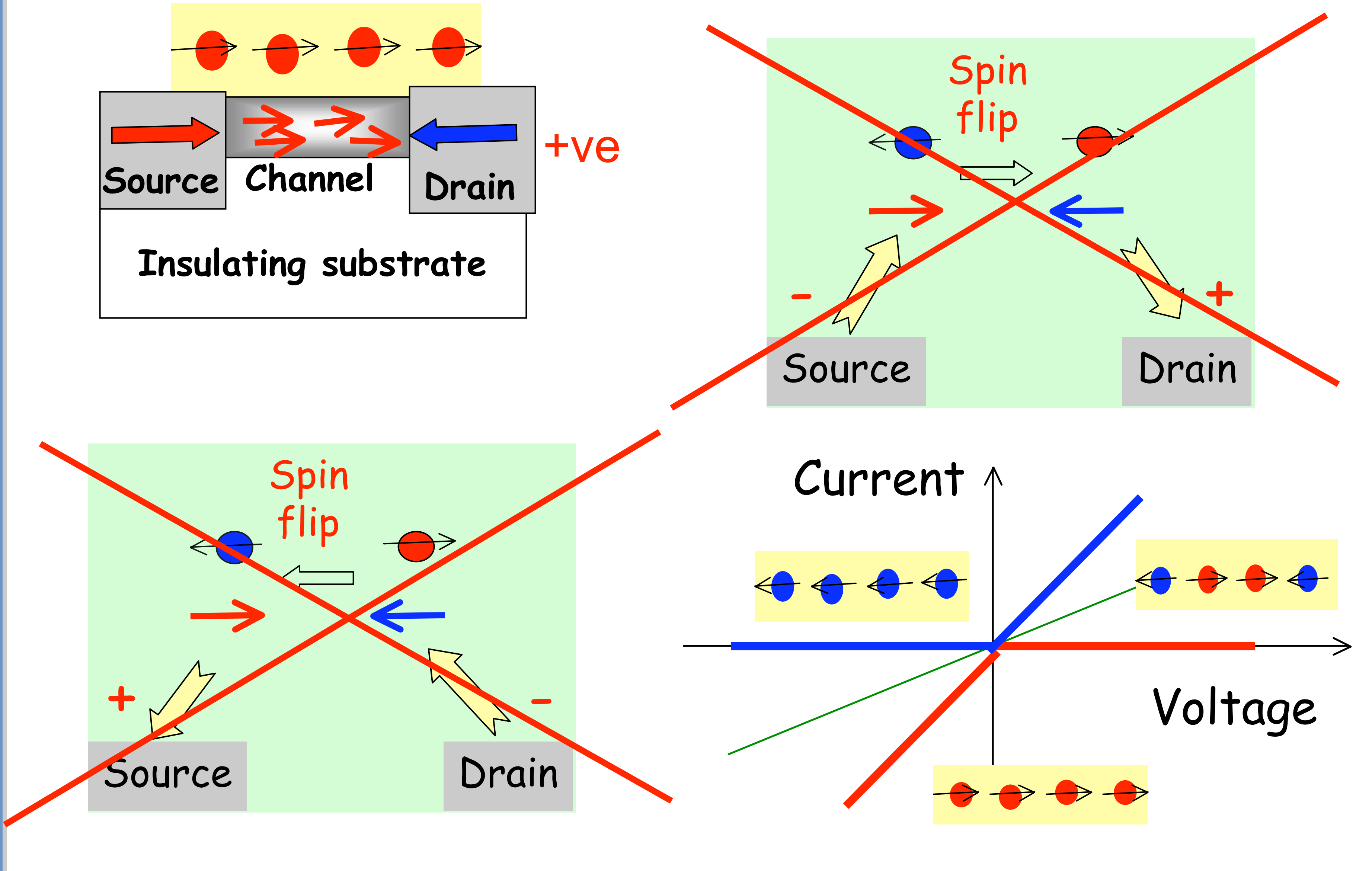

Source
Drain


Current
P
AP
Perfect
AP
Voltage

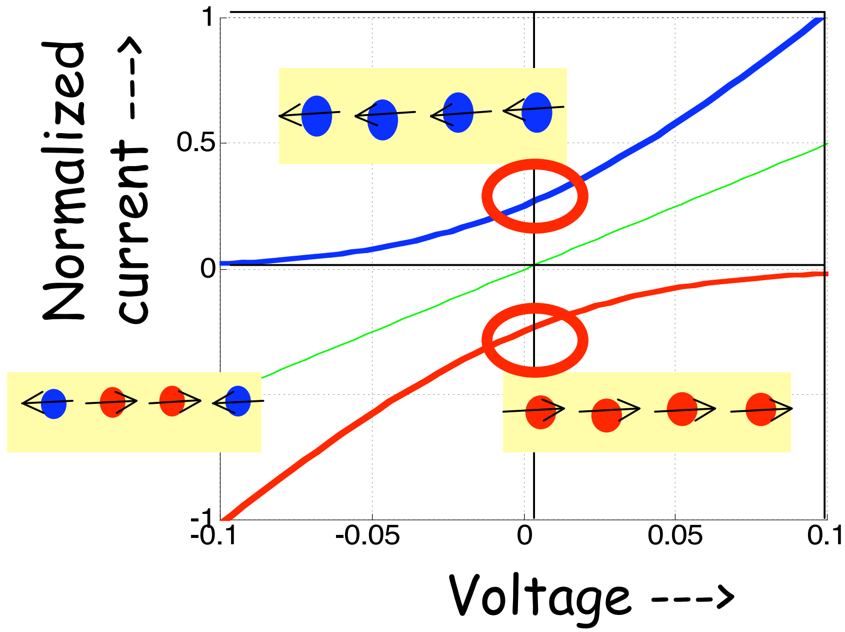
Perfect AP with Spin-flip Impurities

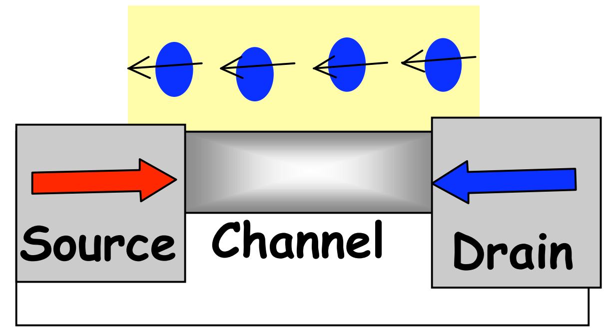


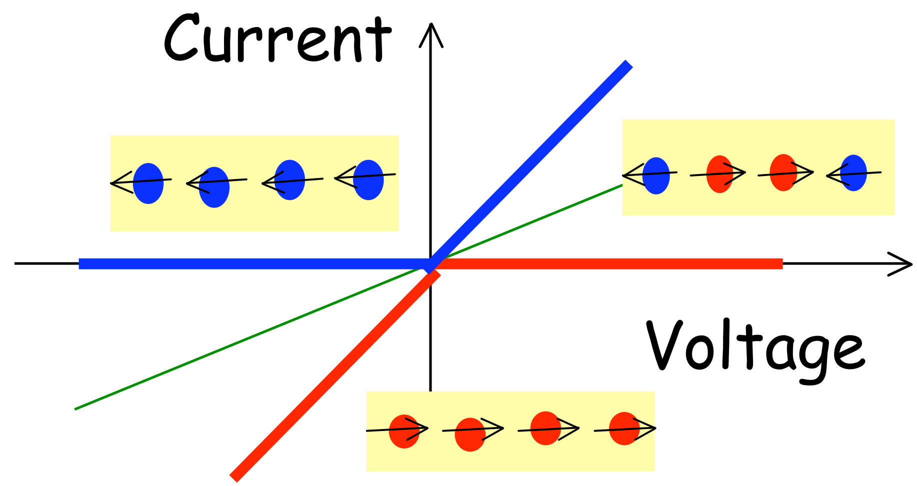
Perfect AP with Spin-polarized gate



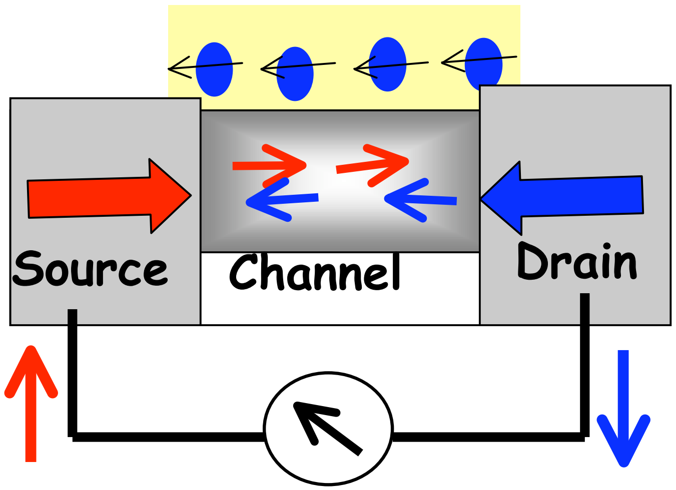
Current at zero voltage ! !

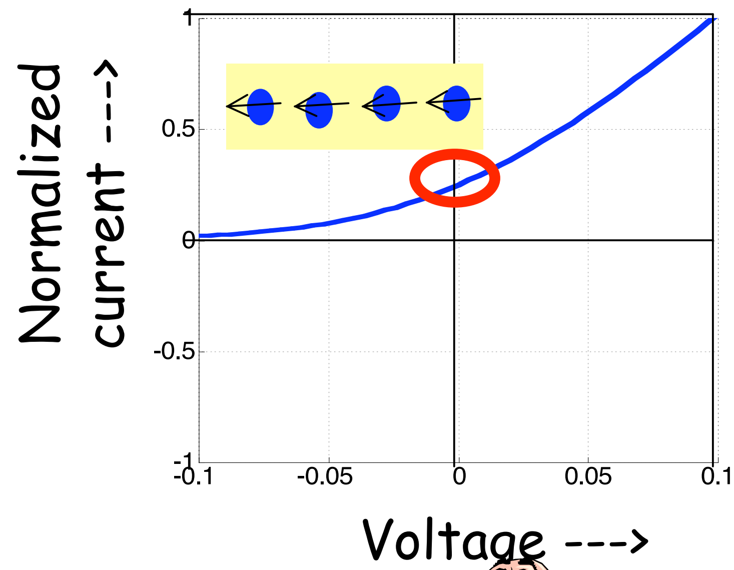


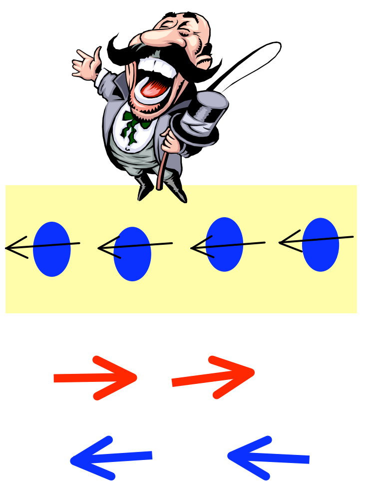


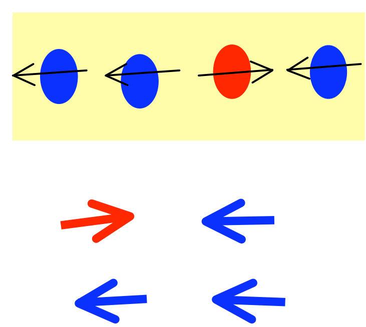


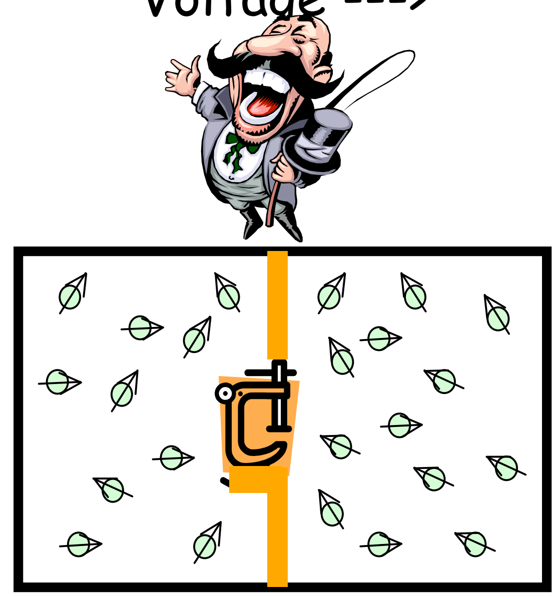
Device to "demon"



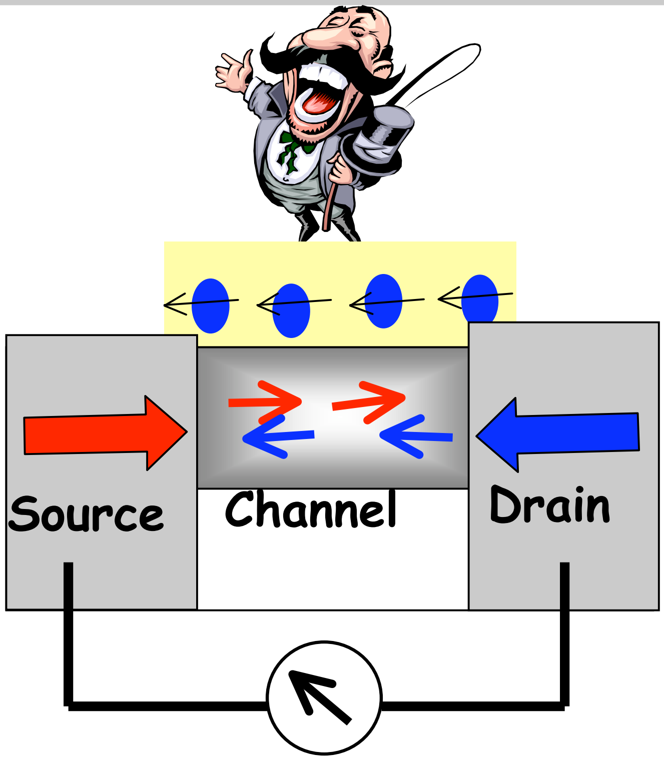


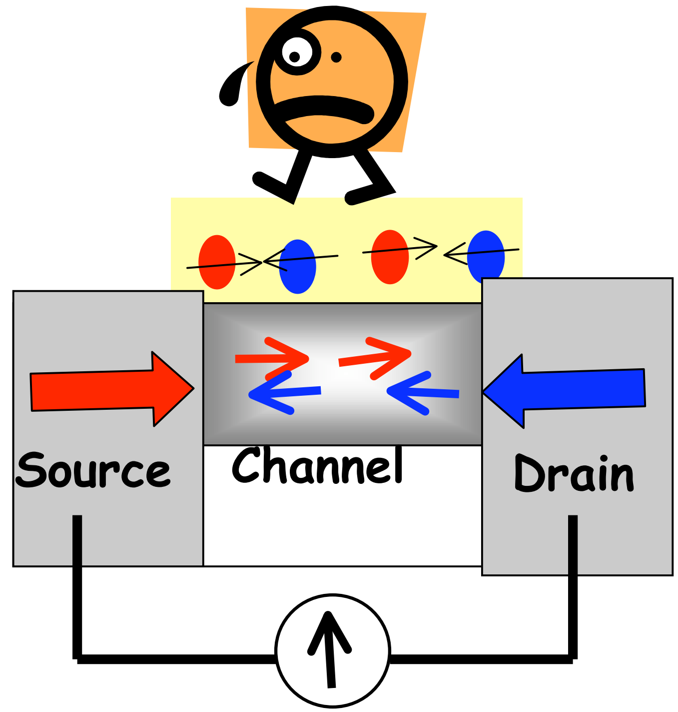






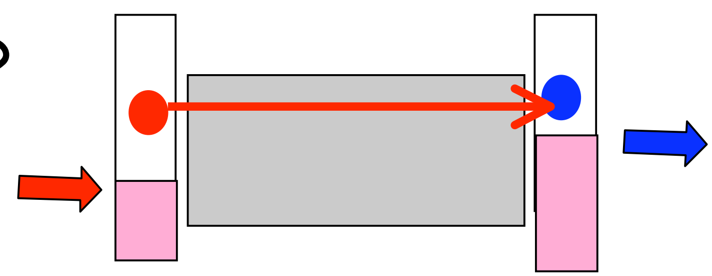
Current stops eventually ...



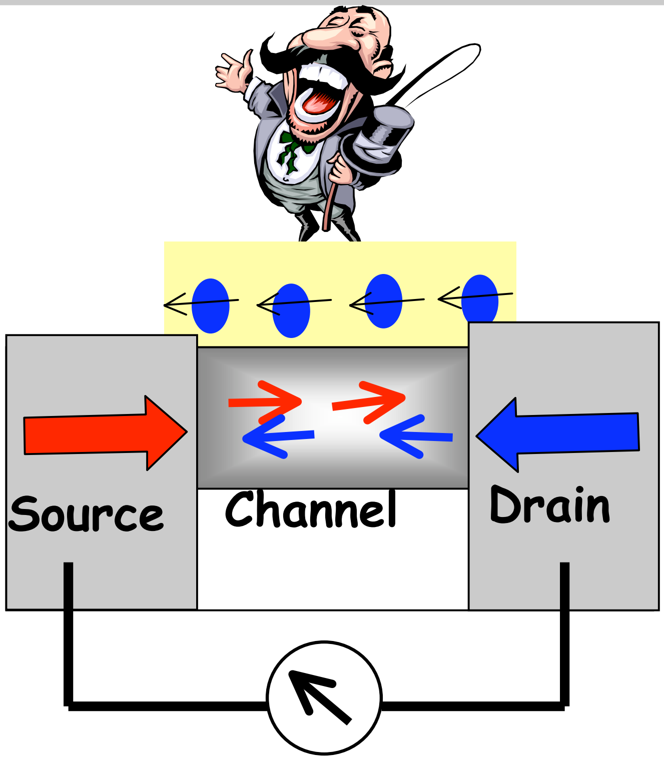


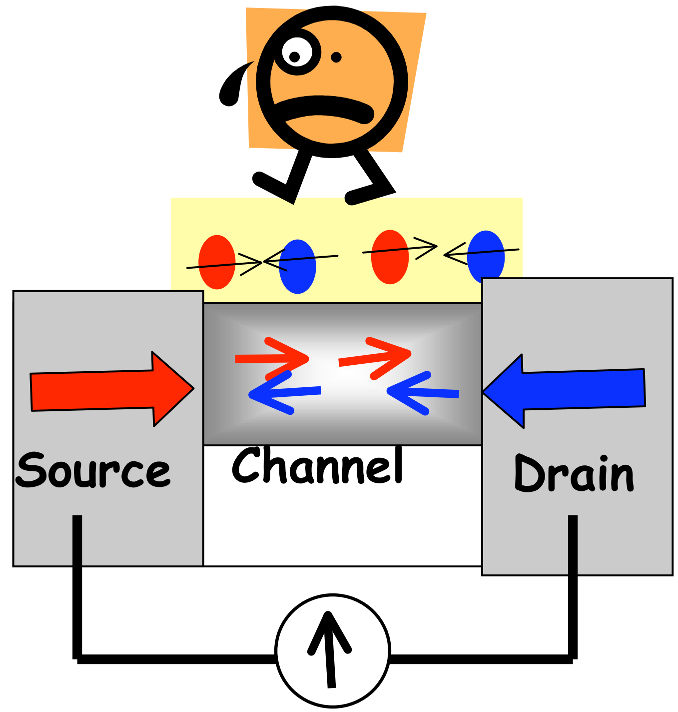
Where did the energy come from ?

Answer: From the contacts



Second law ?





$S = 0$

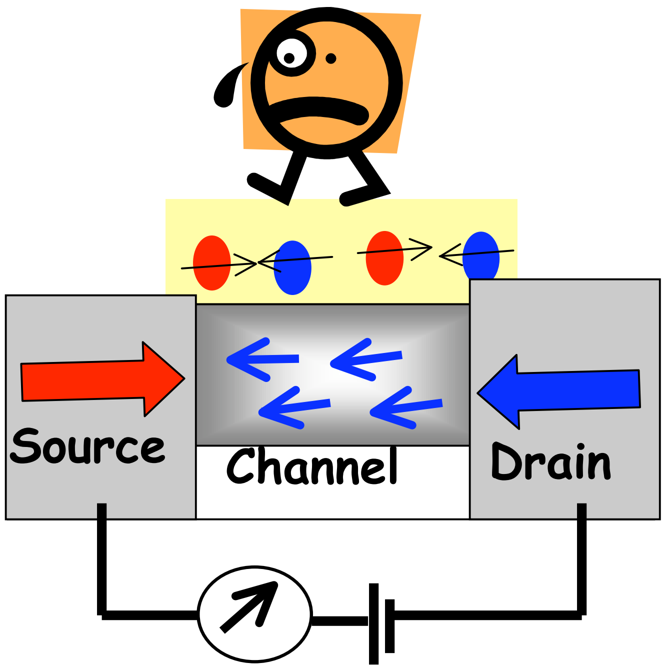
$S = k \ln W$

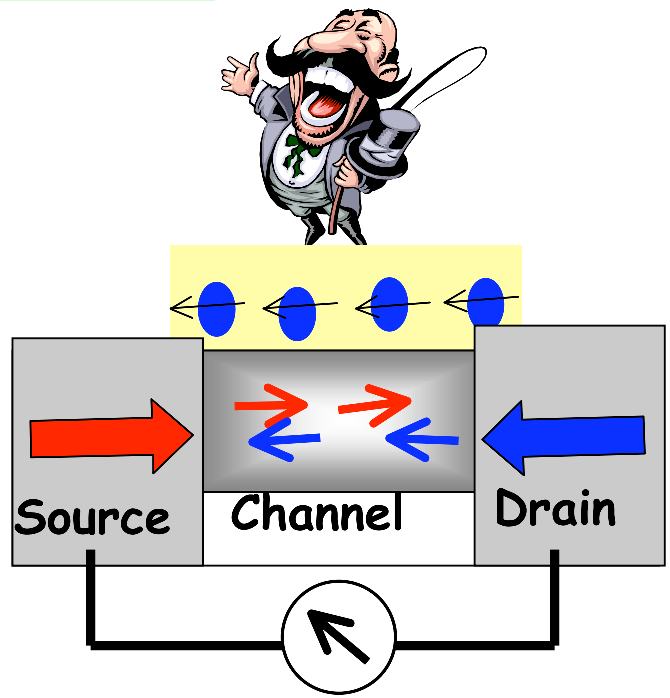
$S = Nk \ln 2$

Energy upto $T\Delta S$ may be extracted

Resetting the demon takes energy

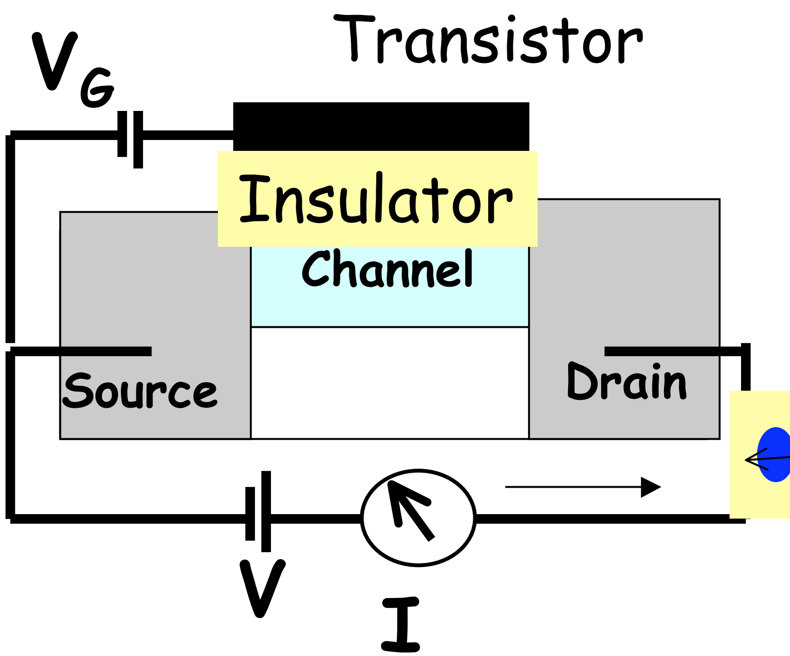
No energy needed





Need > N kT to "Erase"

Nanomagnets : Bistable demons

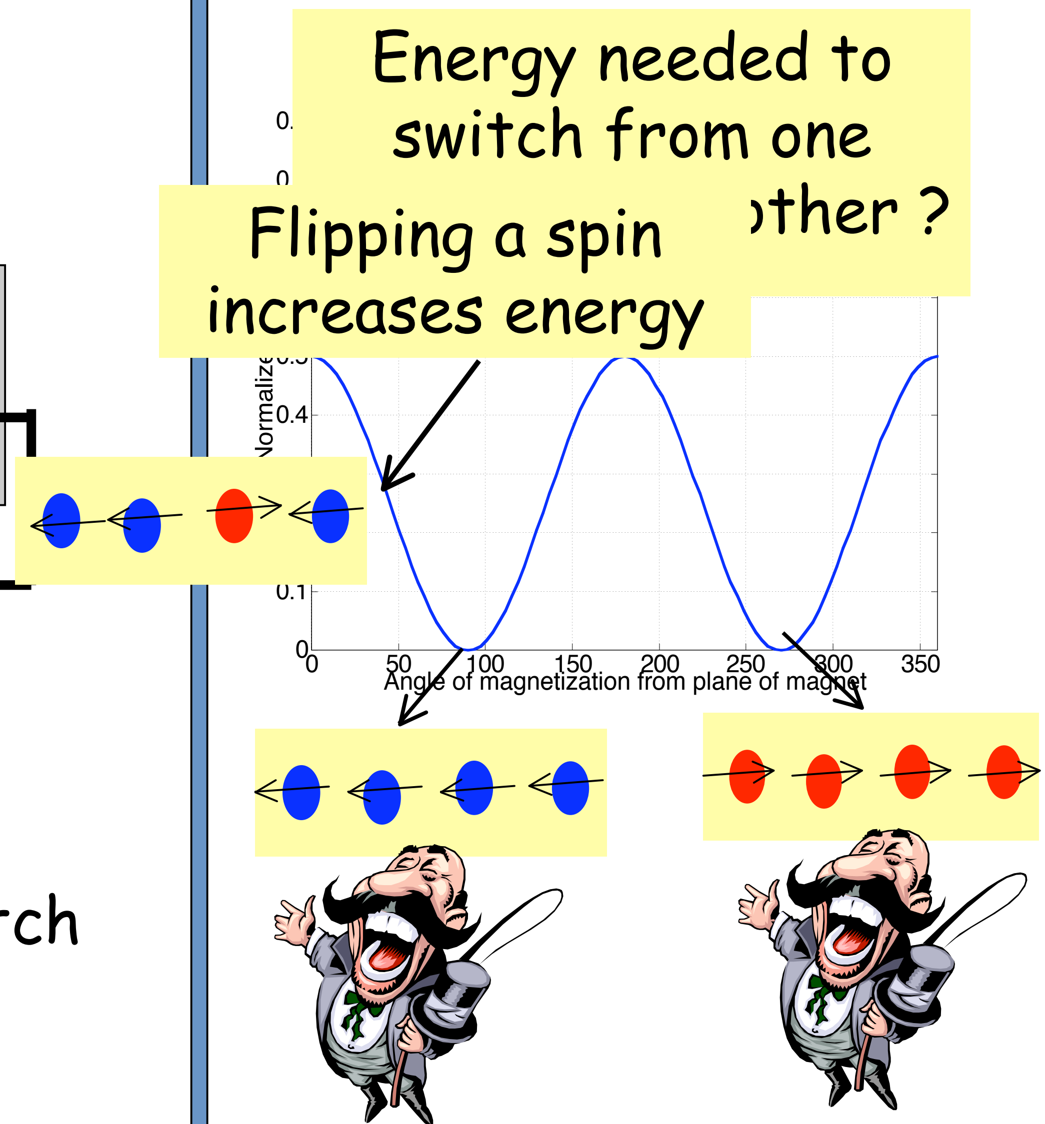


P = 10^4 electrons

x (40 kT)

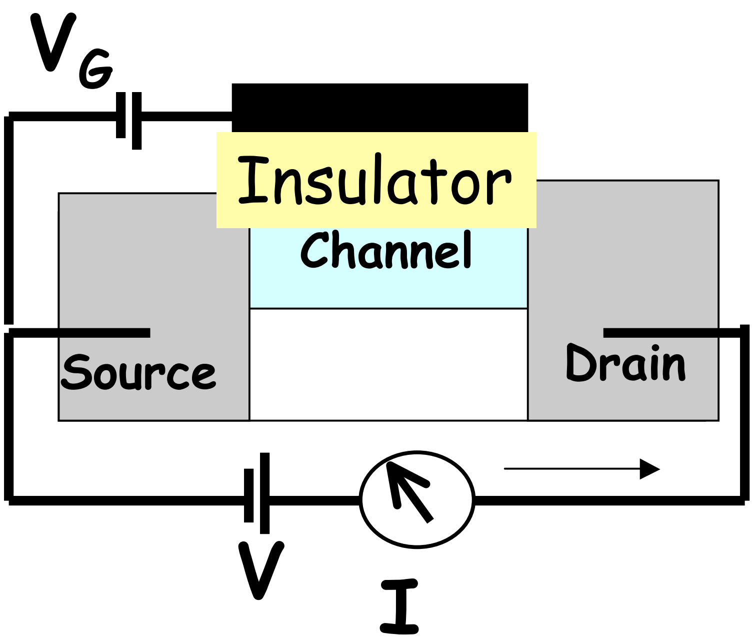
x 10^9 Hz

= 1 μW / switch



NRI

Transistor



P = 10^4 electrons

x (40 kT)

x 10^9 Hz

= 1 μW / switch

Nanoelectronics Research Initiative (NRI)

Launched by SIA & NSF

Objective: Explore options for producing a low power switch

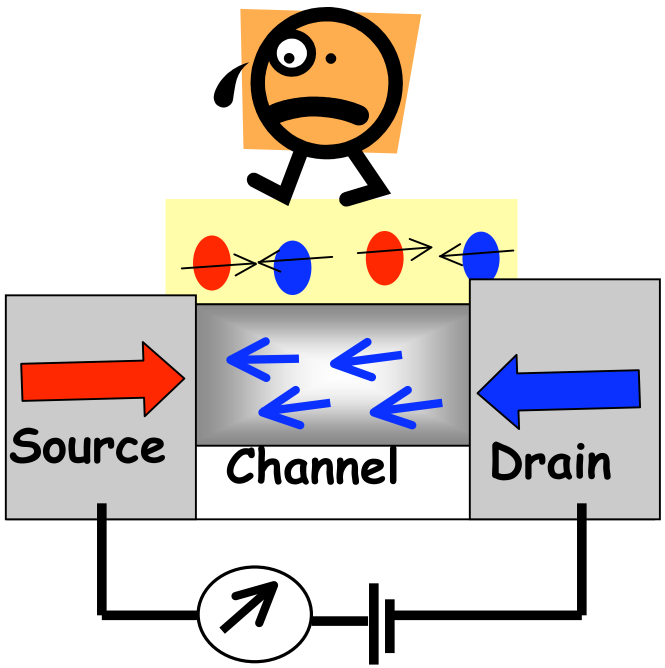
Mark Lundstrom
Ashraf Alam
Kaushik Roy
Gerhard Klimeck

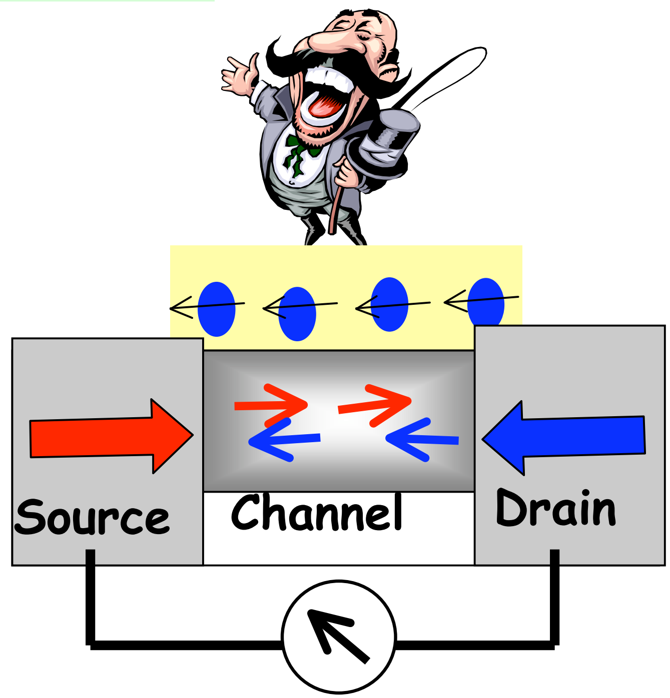
Why is the flow unidirectional ?

S = Nk ln 2

No energy needed

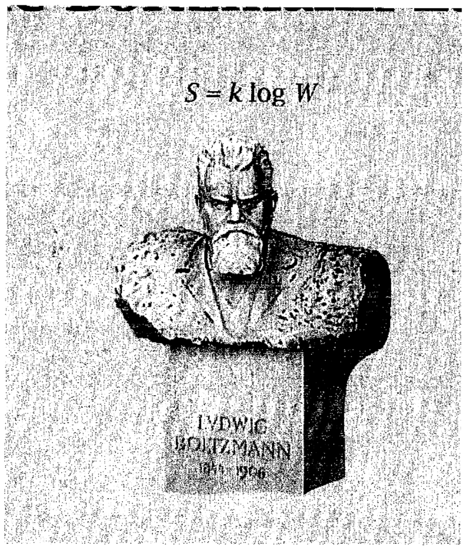
S = 0





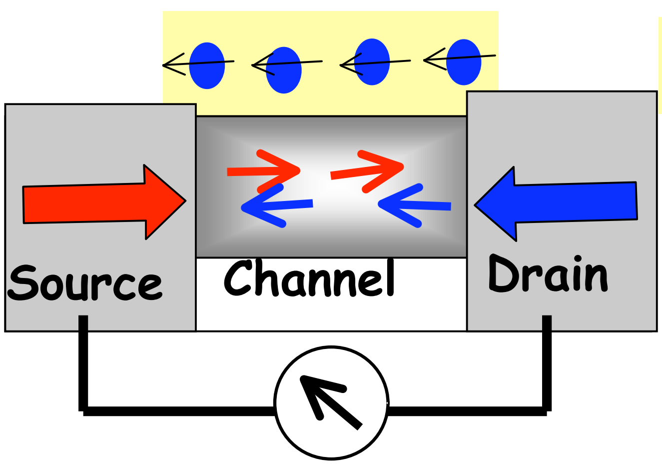
Need > N kT to “Erase”

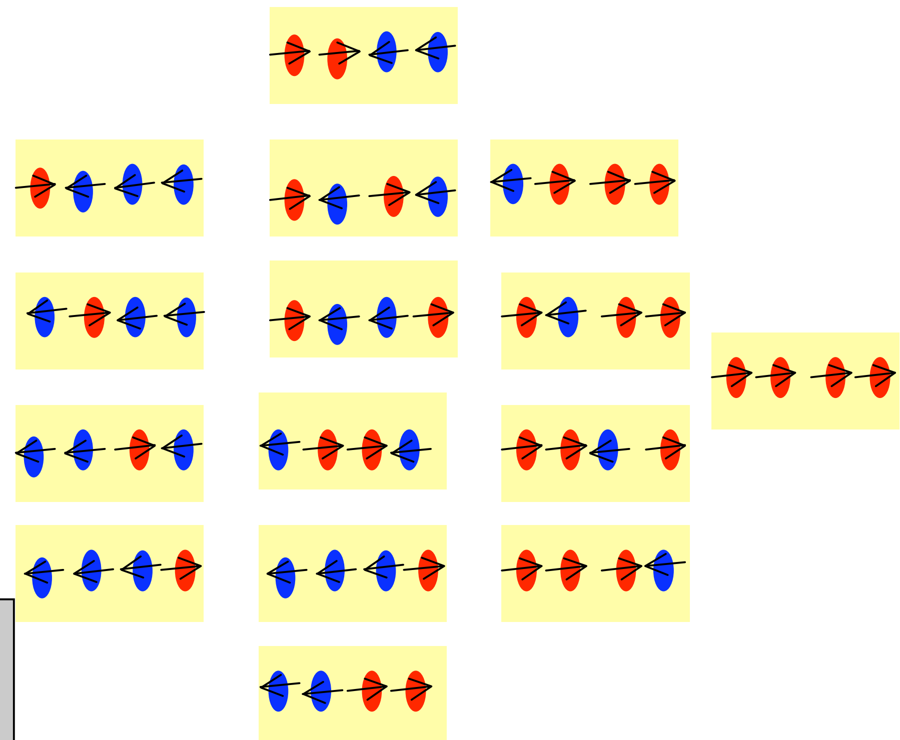
Entropy as a driving force



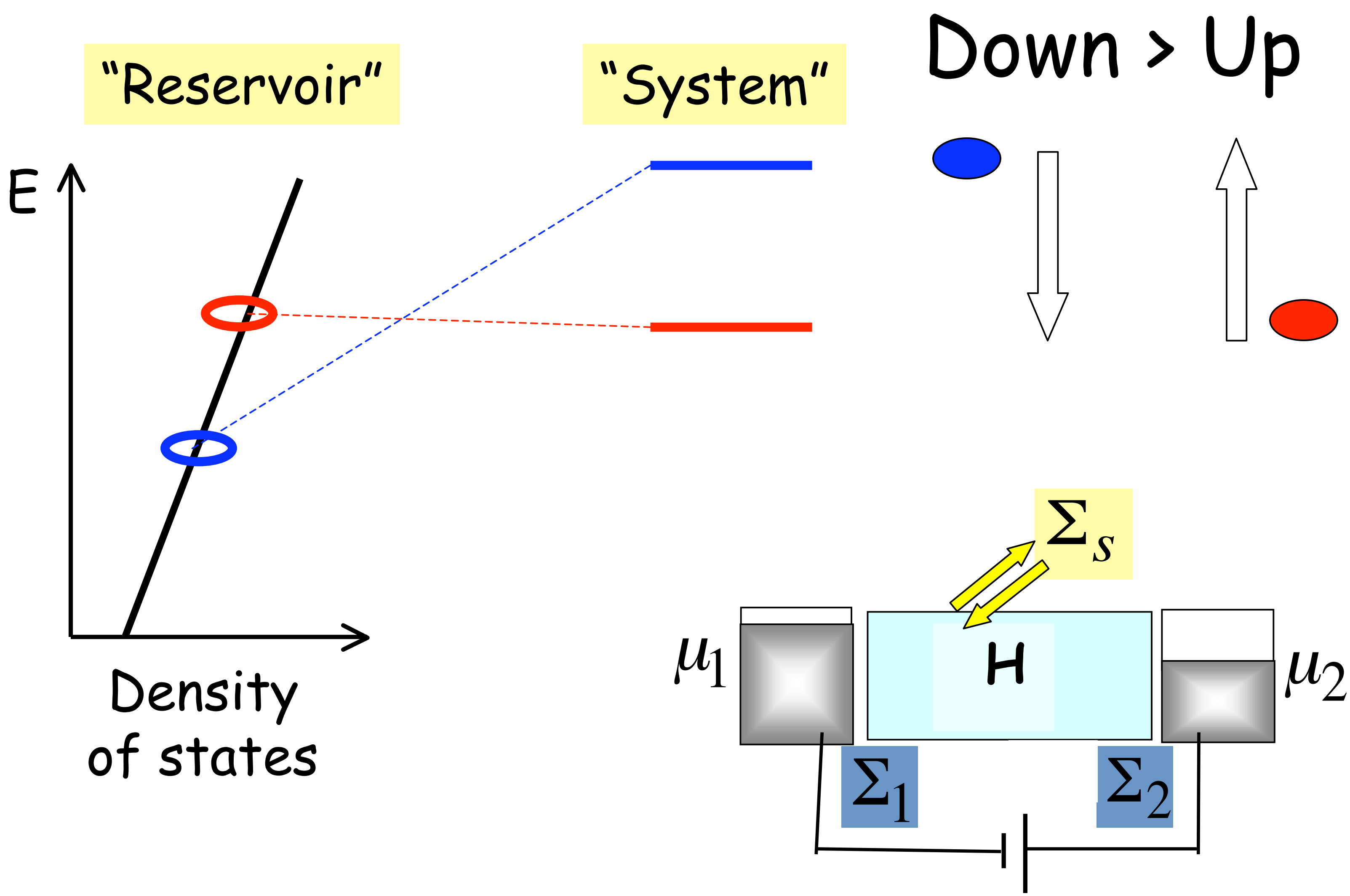
S = k log W

All
"blue"

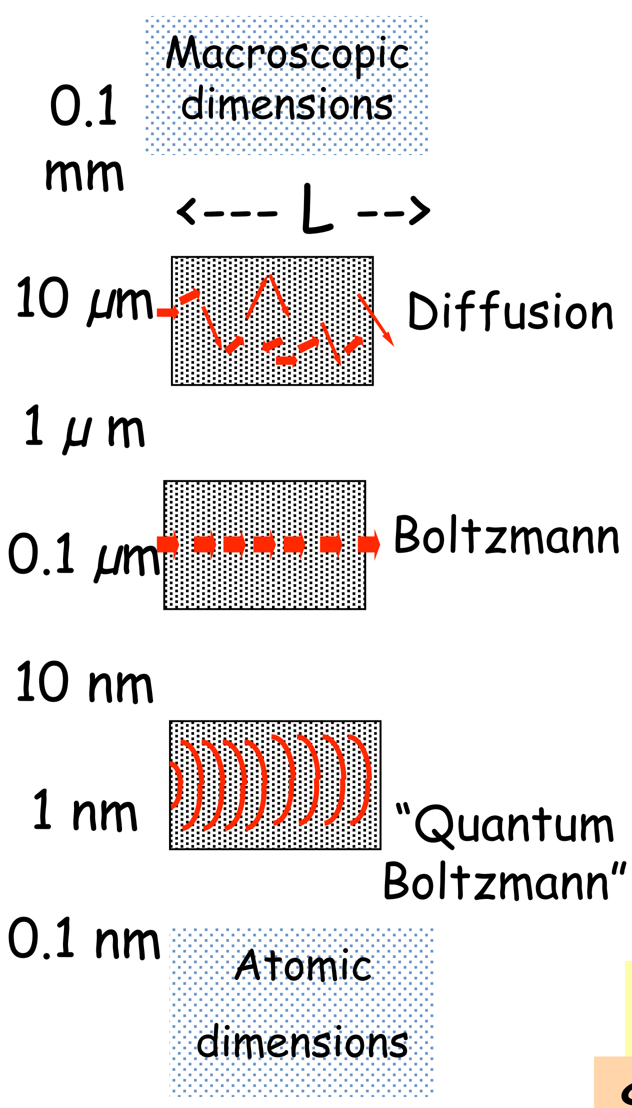


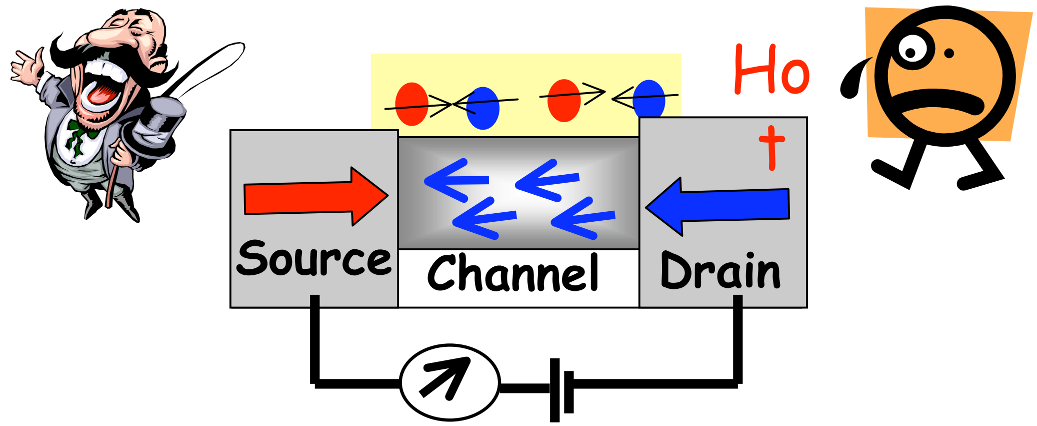


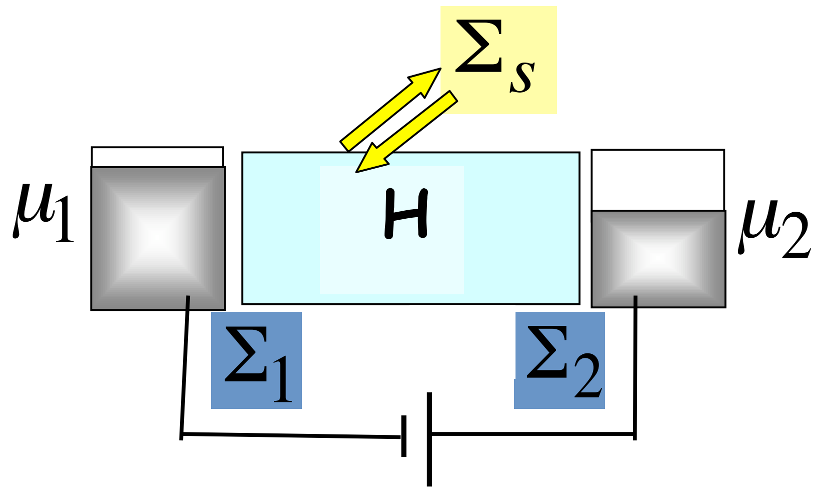
Entropy-driven vs. dynamic processes



Unified model for nanodevices



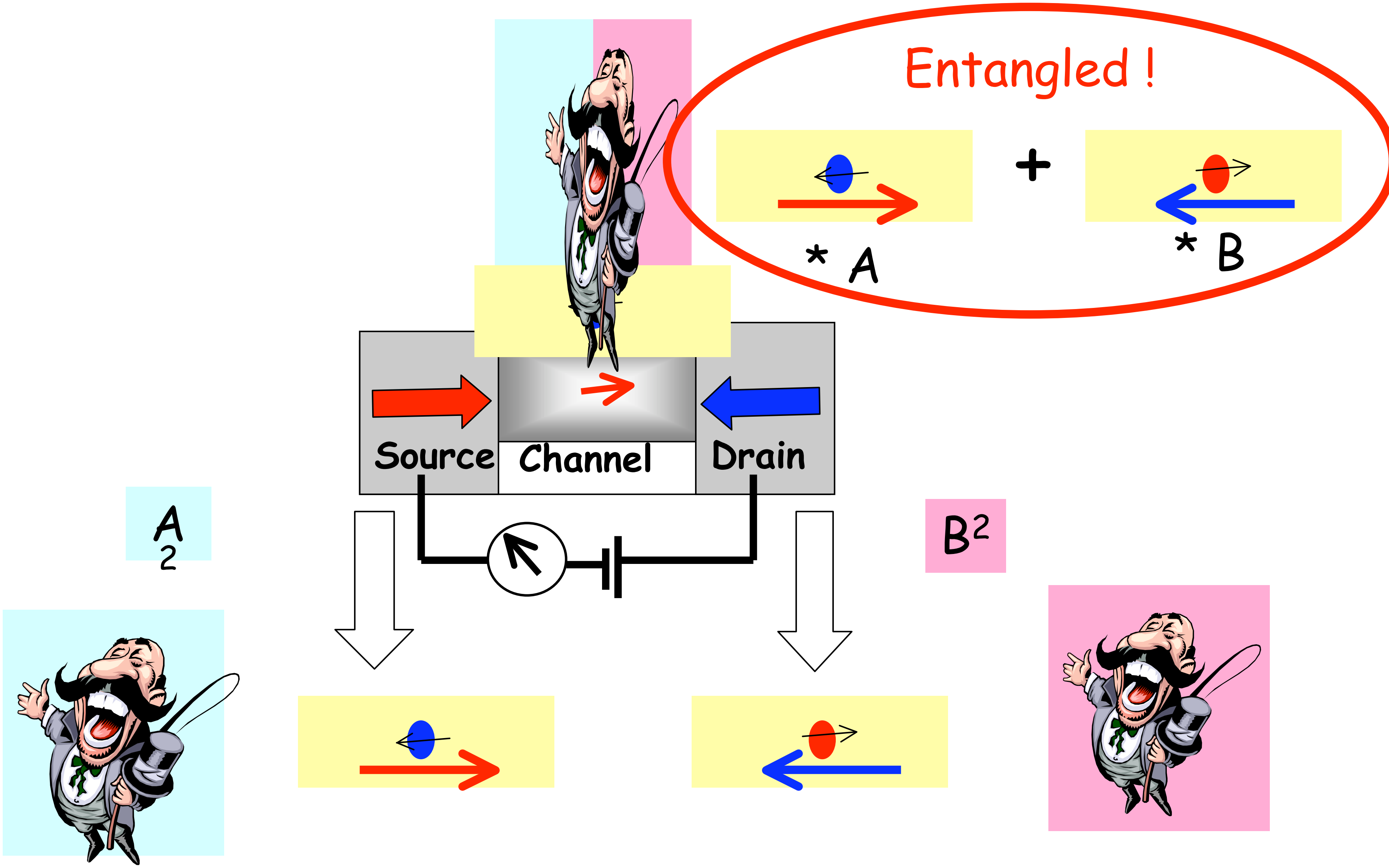




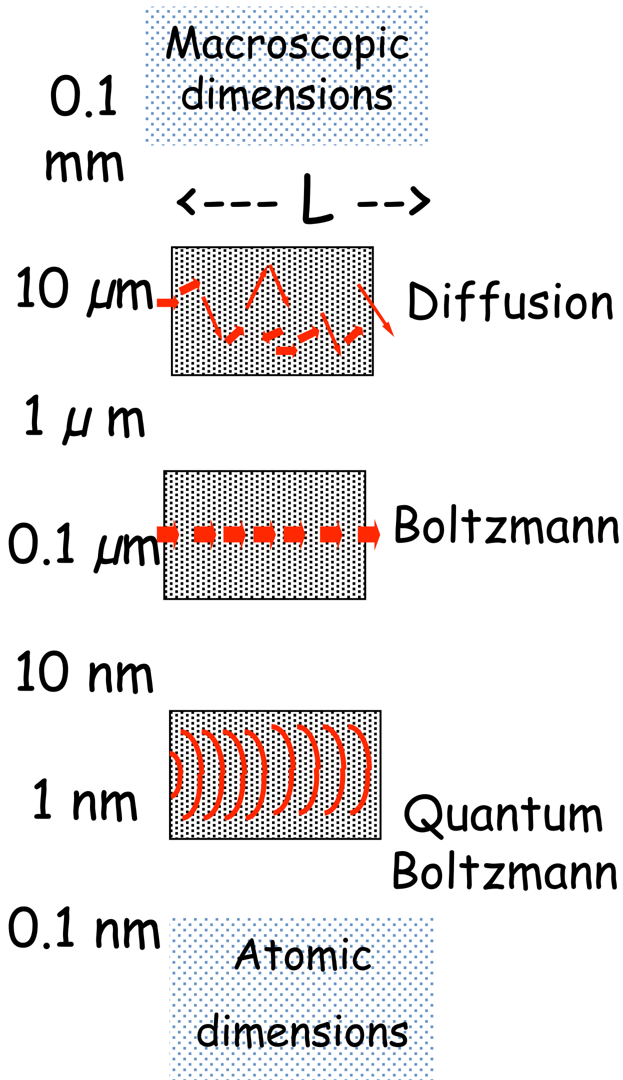
Nanowires, nanotubes, molecules .....

Switches, energy conversion, cooling …

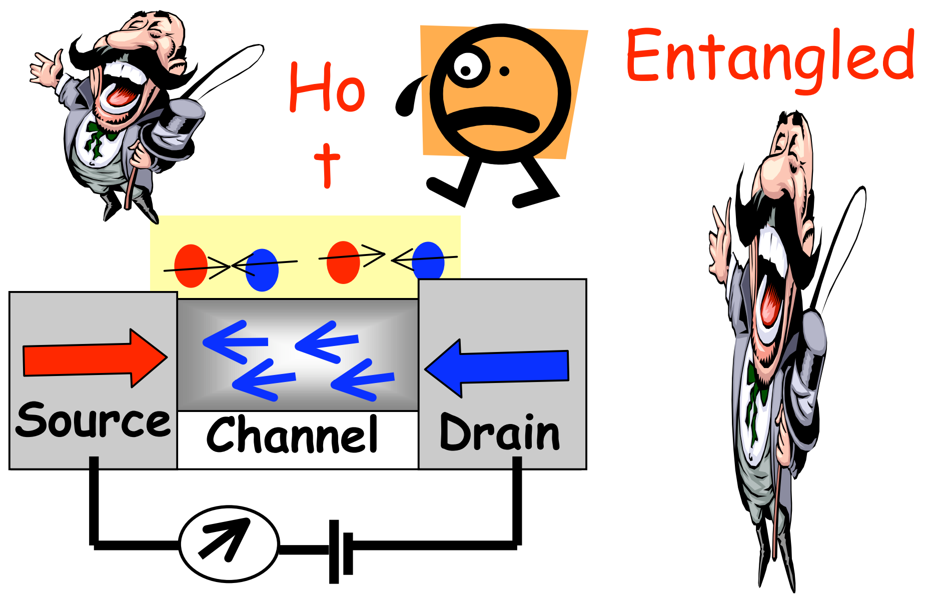
Entangled “demon”



"It is all about the contacts"



"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

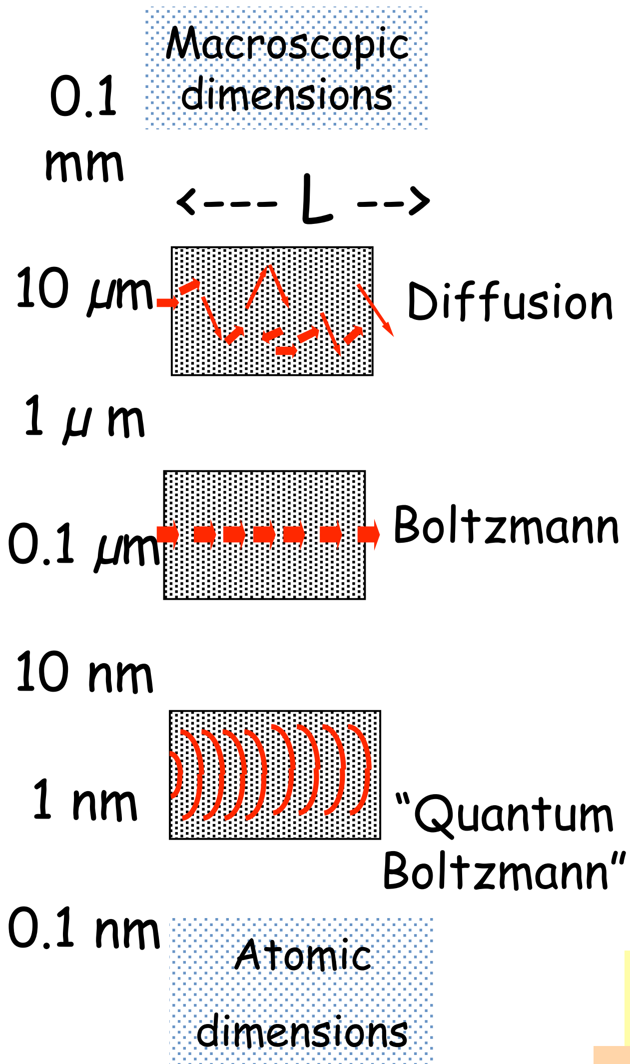


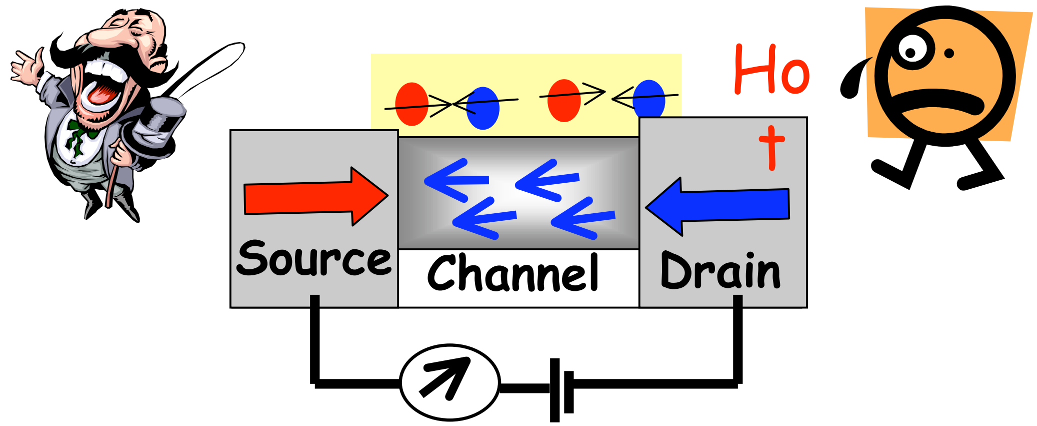
Acknowledgements

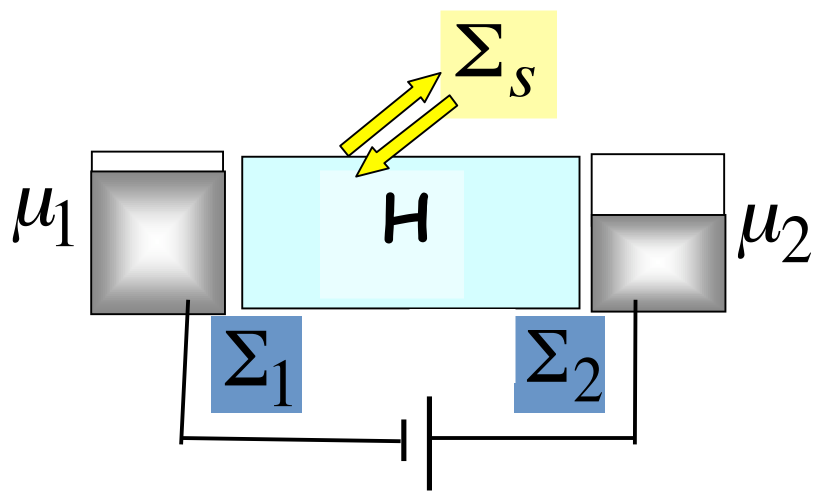
Thanks to Purdue and
to all my outstanding
students and colleagues,
supportive friends and family.

Questions & Answers

Unified model for nanodevices







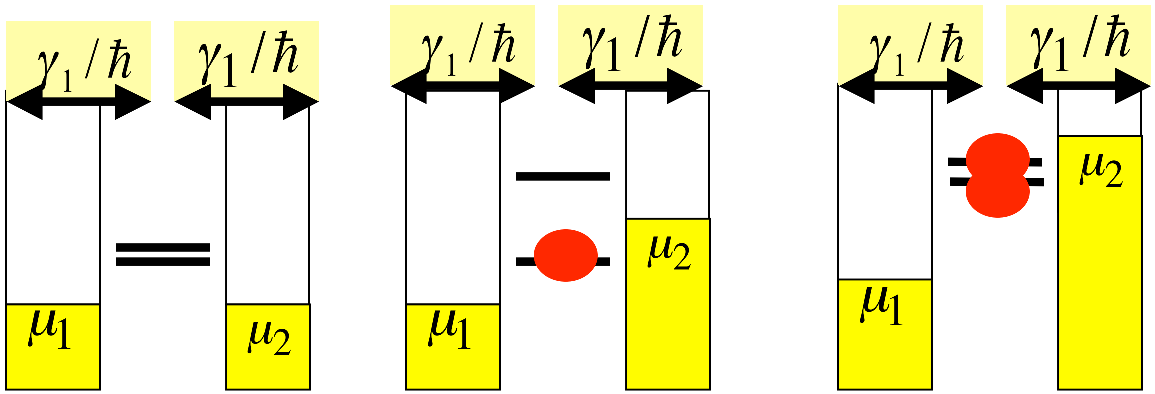
Nanowires, nanotubes, molecules .....

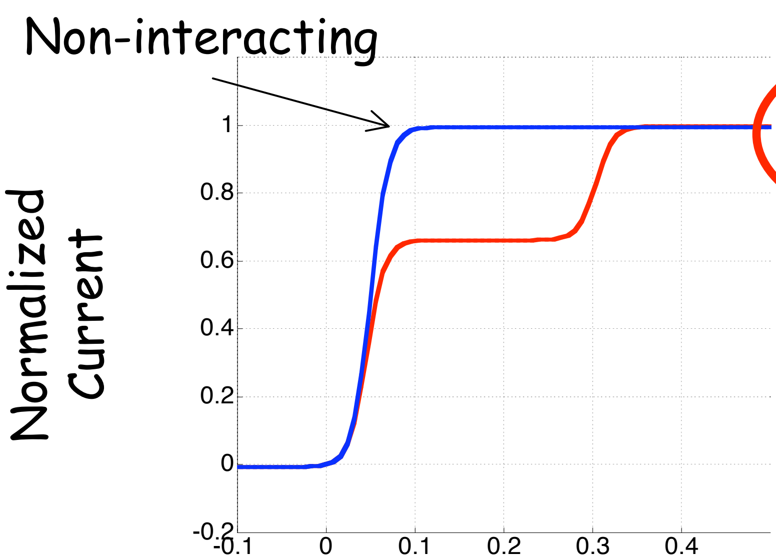
Switches, energy conversion, cooling ...

Single electron charging

U_0 : *Increase in potential due to SINGLE electron* >> γ, kT

"Self-interaction Correction"

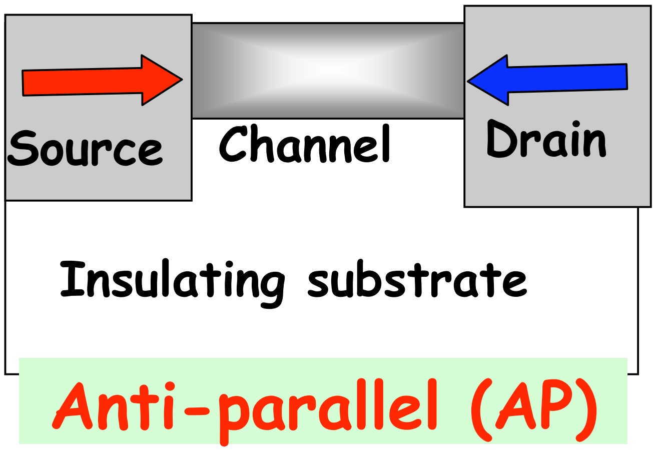


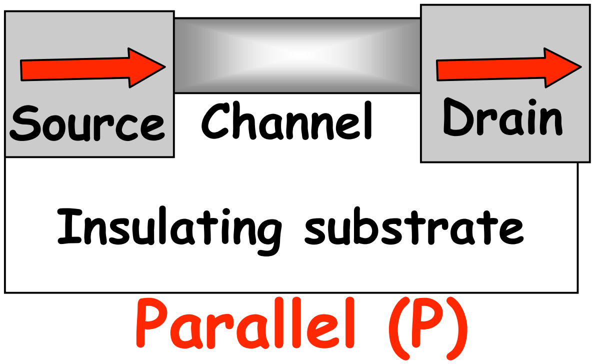


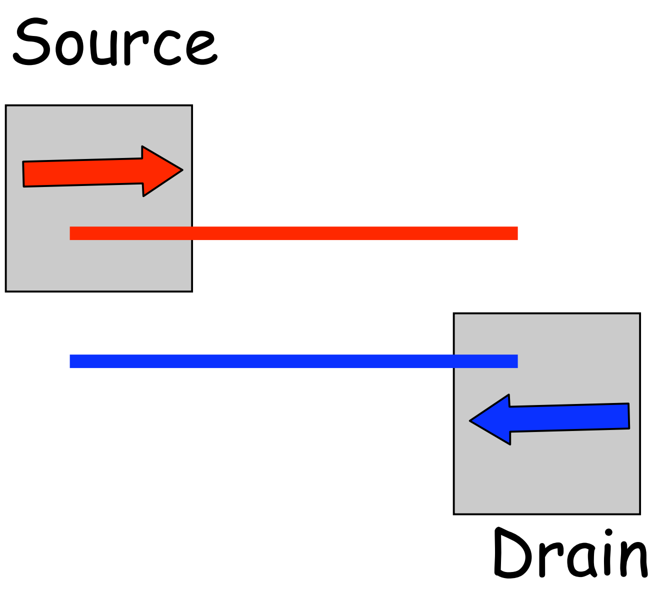
$$\frac{q\gamma_1}{2\hbar} * 2$$

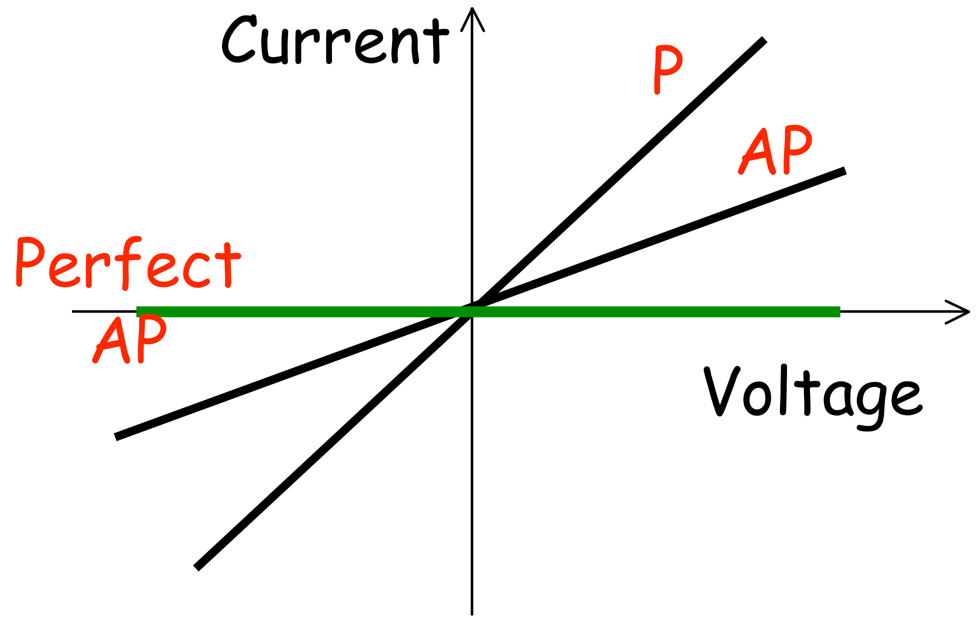
$V \Rightarrow$

Spin Valves


Source
Channel
Drain
Insulating substrate
Anti-parallel (AP)


Source
Channel
Drain
Insulating substrate
Parallel (P)


Source
Drain


Current
P
AP
Perfect
AP
Voltage