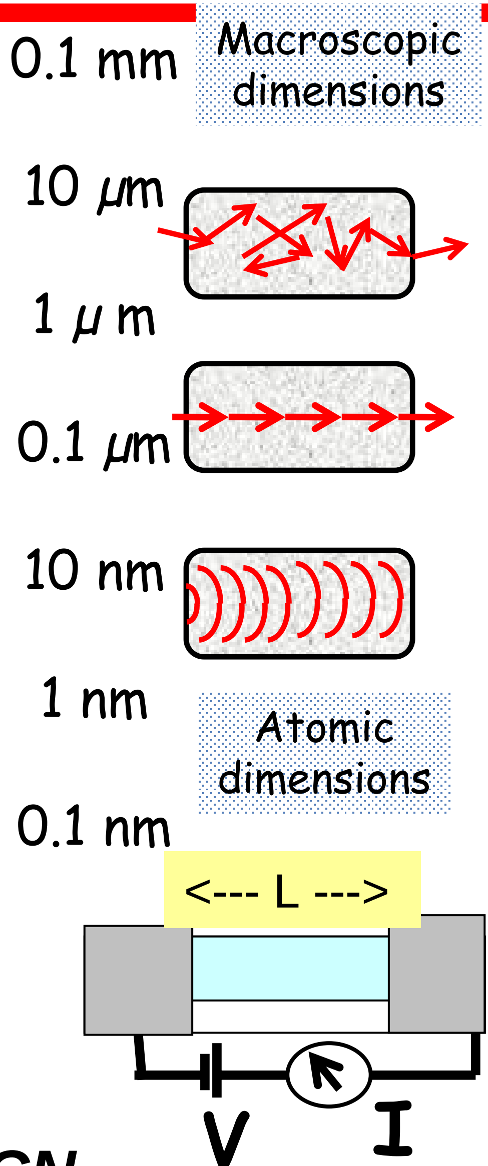
Nanoelectronics



and the meaning of resistance

1a,b: What and where is the resistance?

2a,b: Quantum transport

3a,b: Spins and magnets

4a,b: Maxwell's demon

5a,b: Correlations and entanglement

0.1 mm

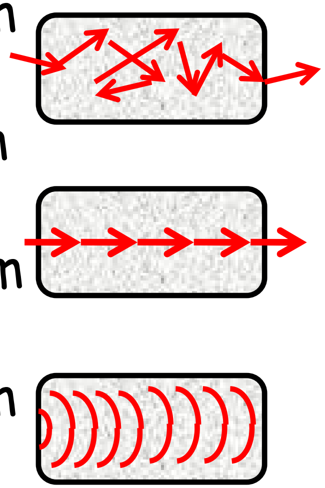
Macroscopic dimensions

10 μm

1 μm

0.1 μm

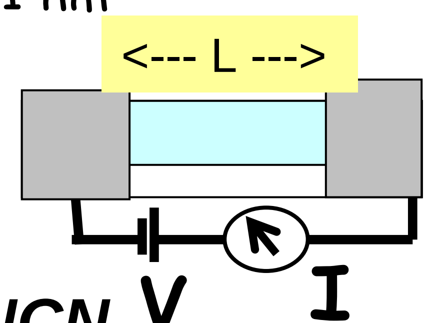
10 nm



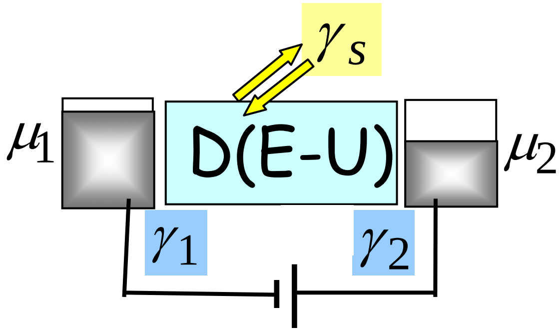
1 nm

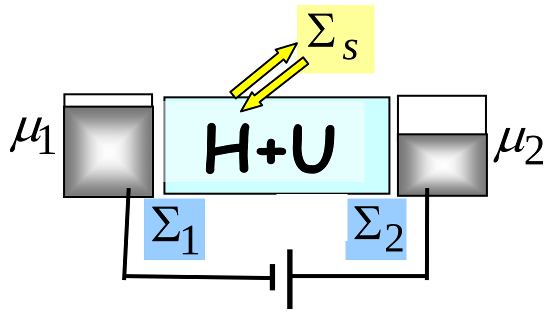
Atomic dimensions

0.1 nm



Lectures 1a,b:
Simple model





Lectures 2a,b:
Microscopic model

Lectures 3a,b:
Add spin

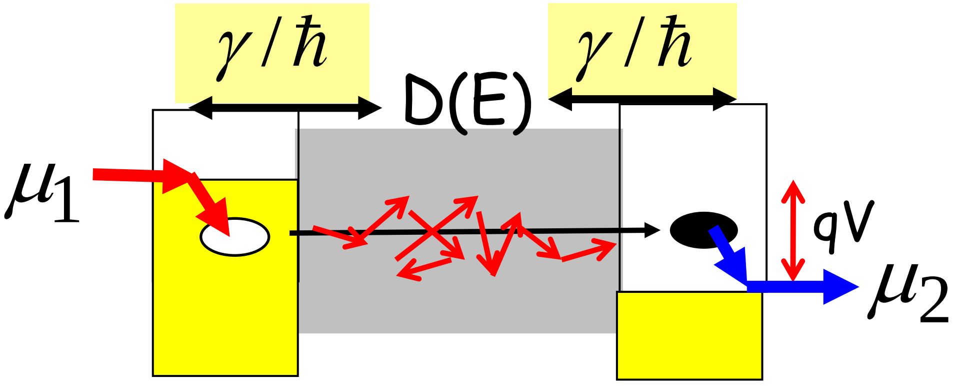
Lectures 4a,b:
Energy exchange and the second law

NCN

http://www.nanohub.org/courses/cqt

Supriyo Datta

Where is the heat (I^2R) ?

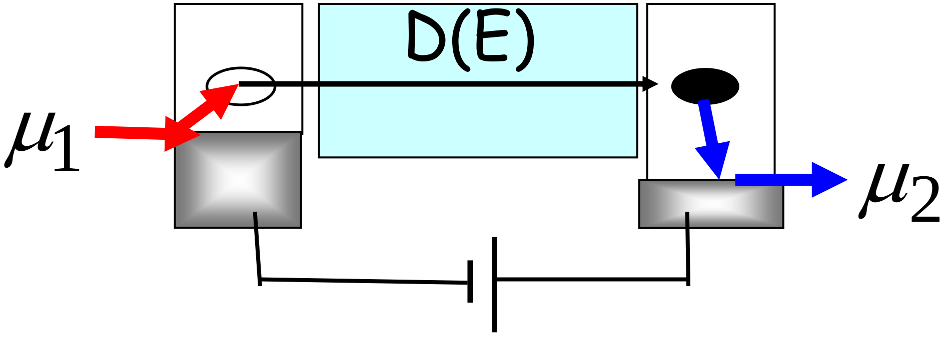


$$V/I = \frac{25.8\ K\Omega}{2}\ \frac{1}{T}$$

$$P = V\,I$$

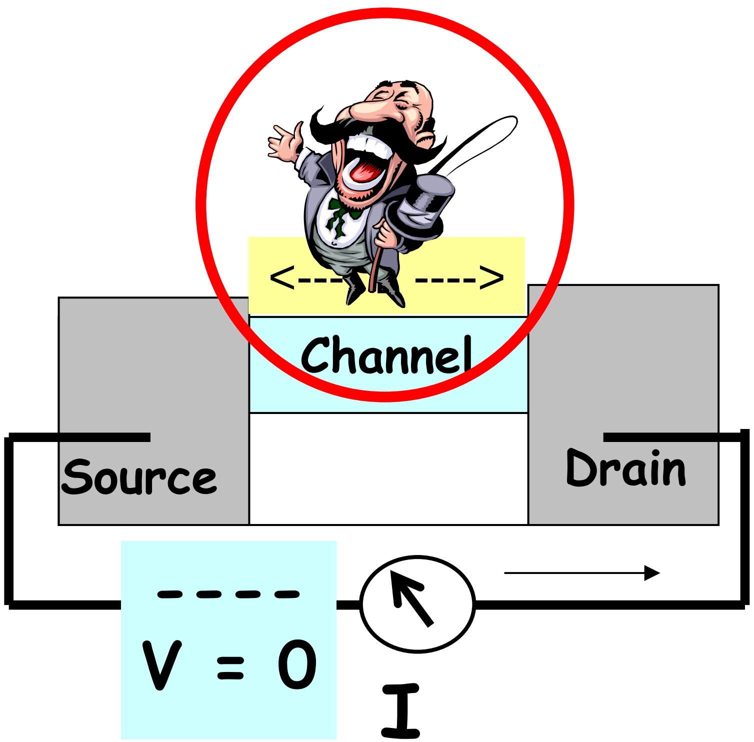
$$= qV * \frac{N}{t}$$

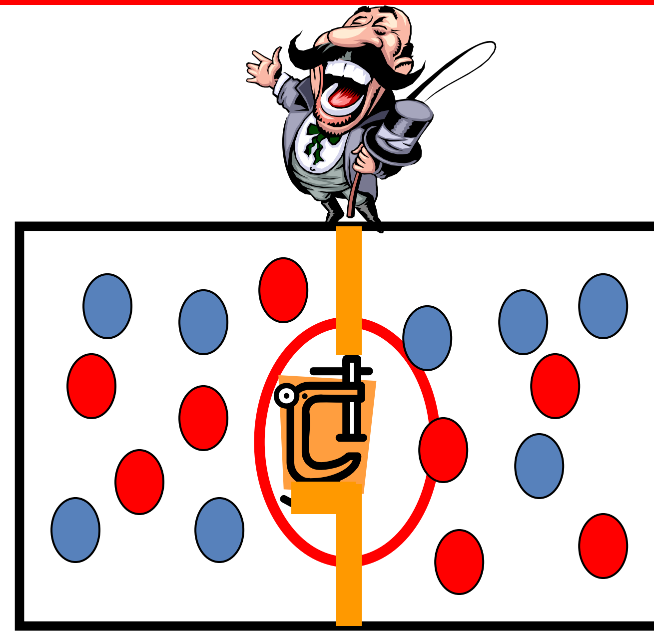
Thermoelectric cooler

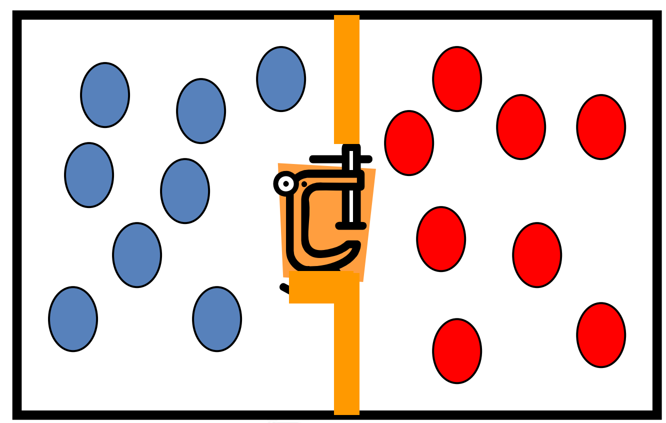


Electronic Maxwell's Demon

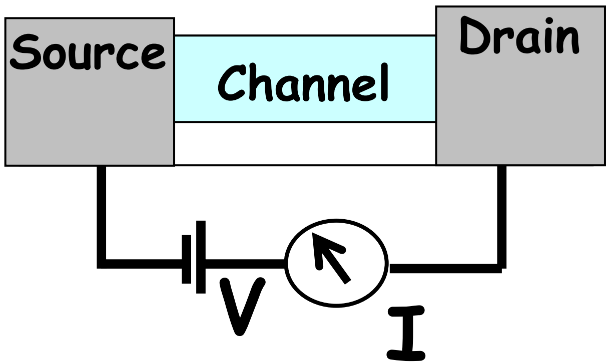
Electronic demon

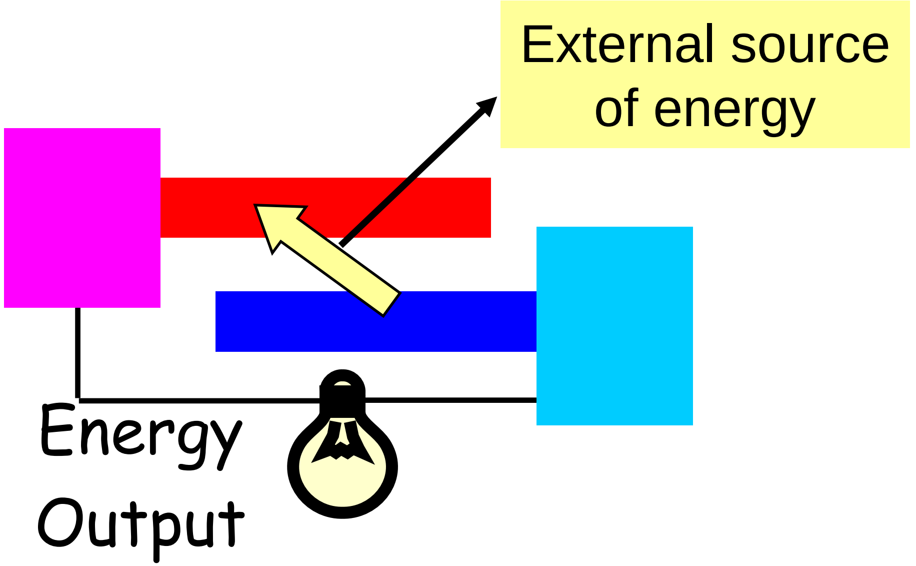


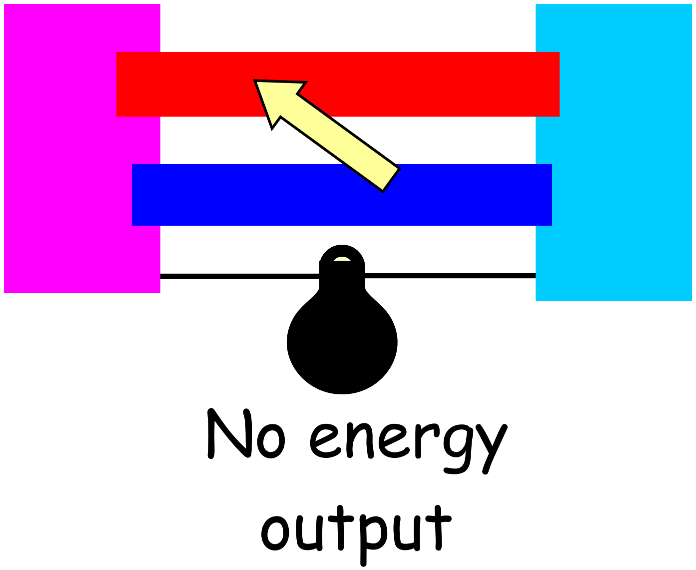




Two-channel devices

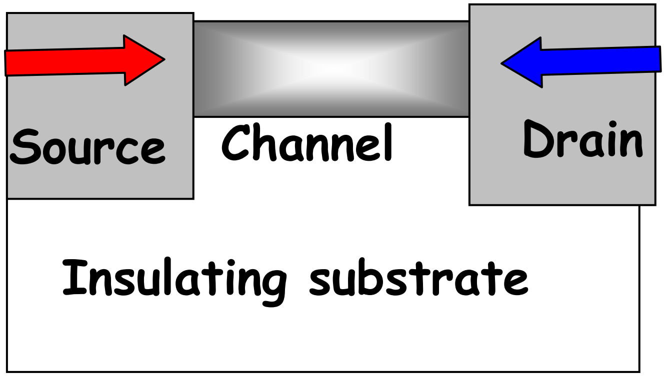




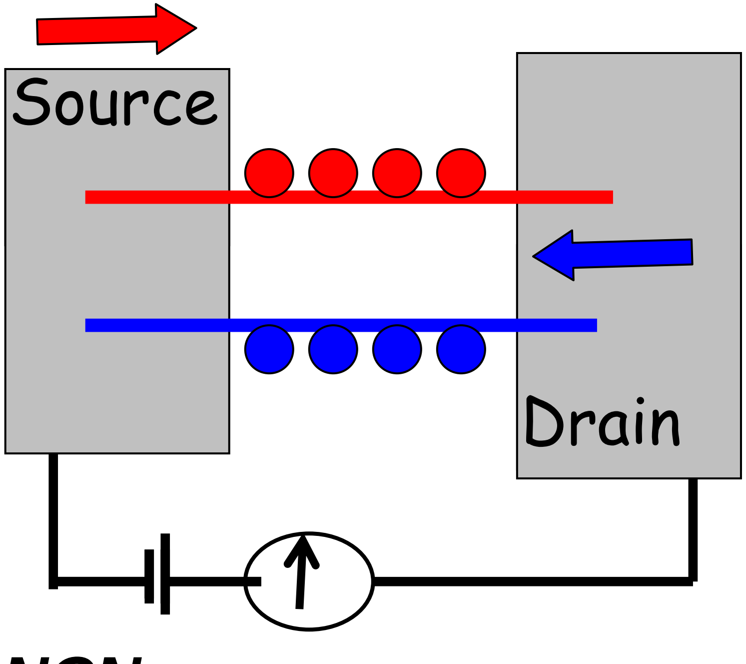


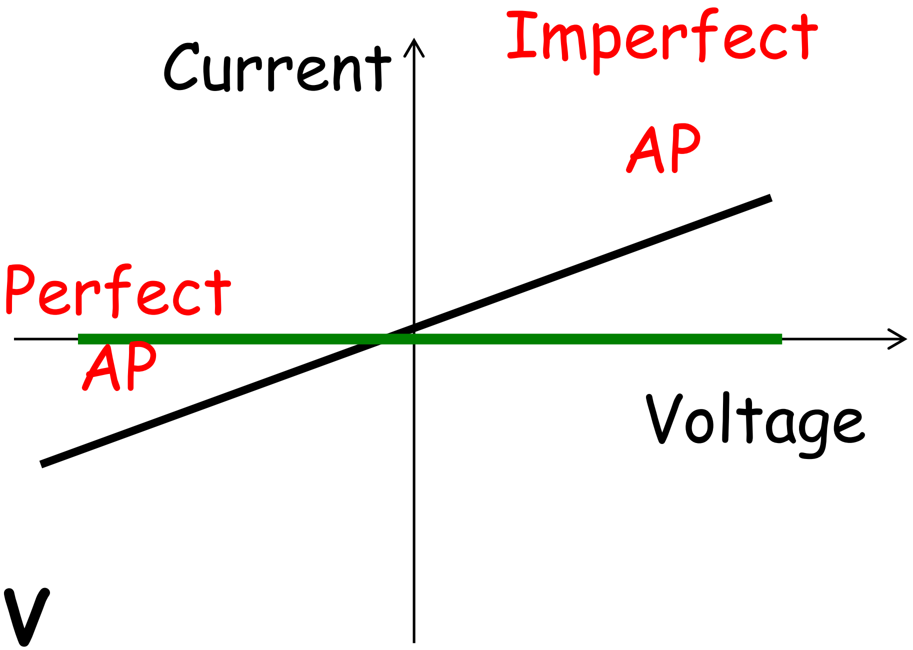
Can we get an energy output if the external source does NOT provide any energy?

Spin Valves

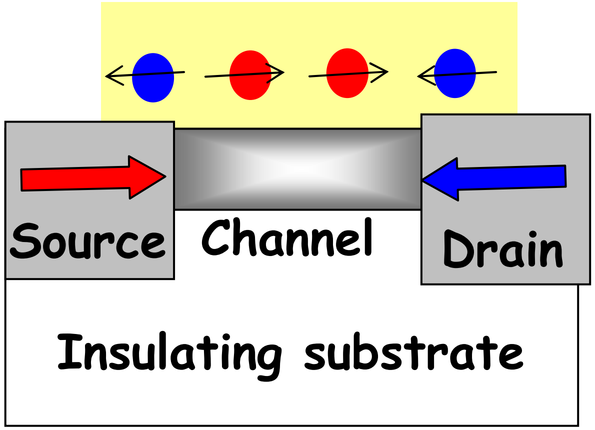


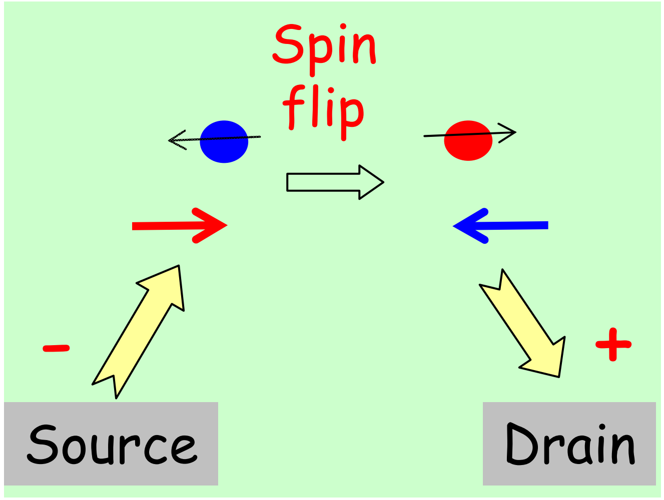
Anti-parallel (AP)

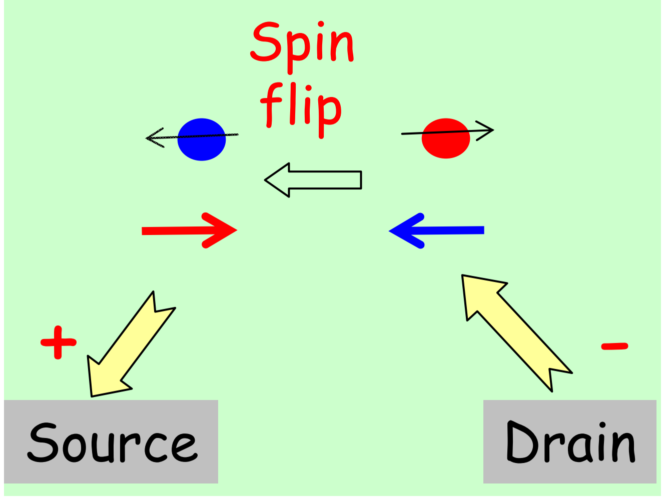


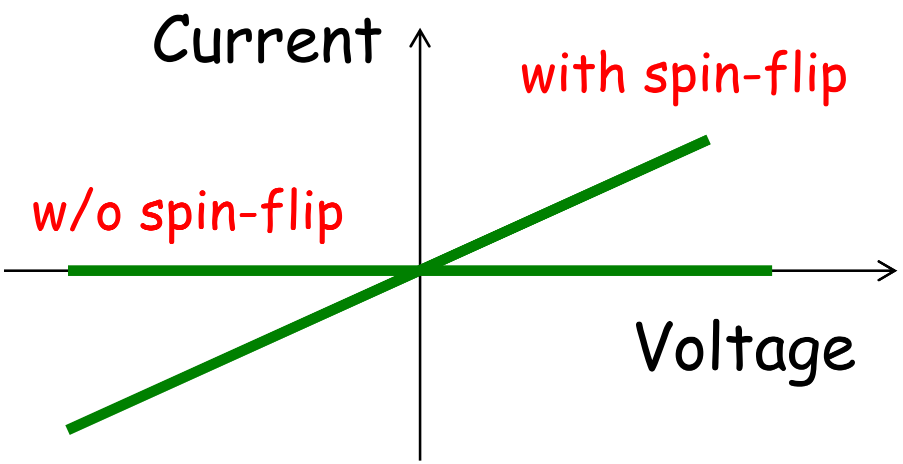


Perfect AP with Spin-flip Impurities

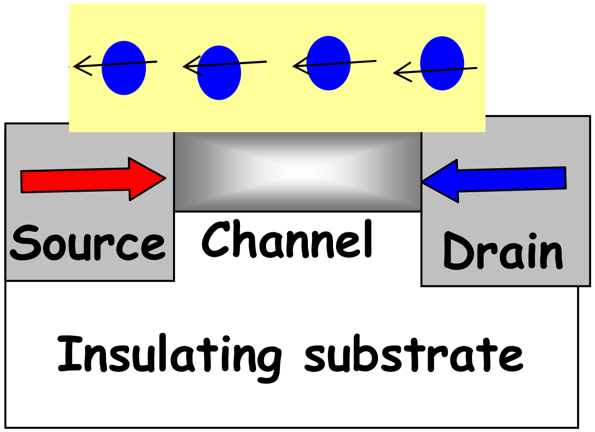


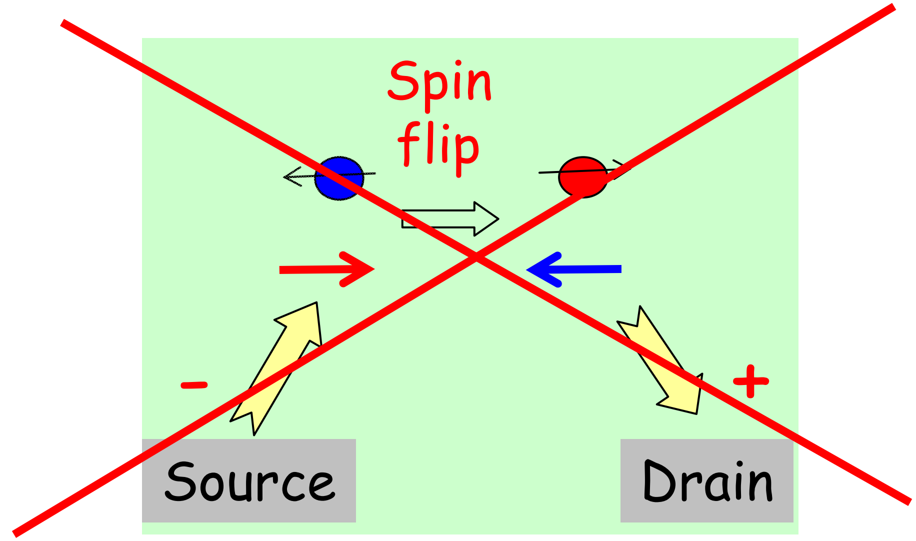


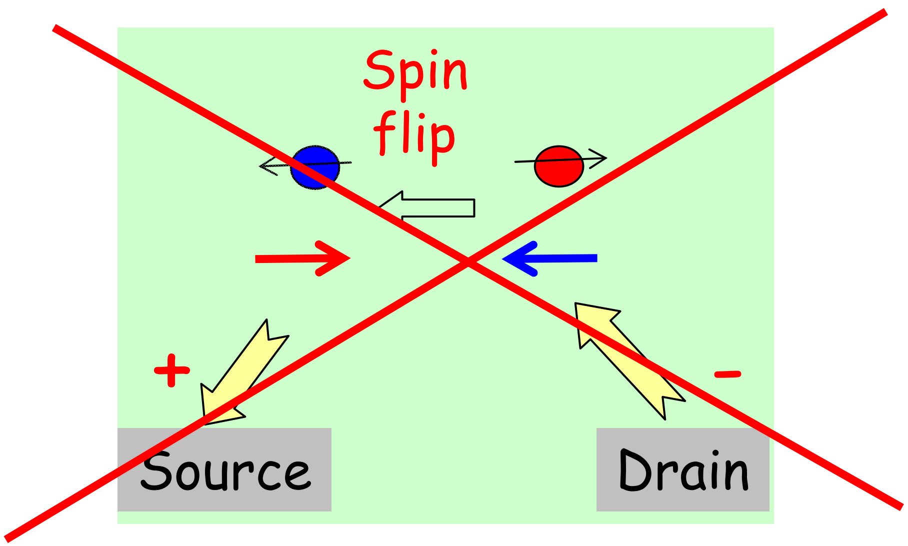


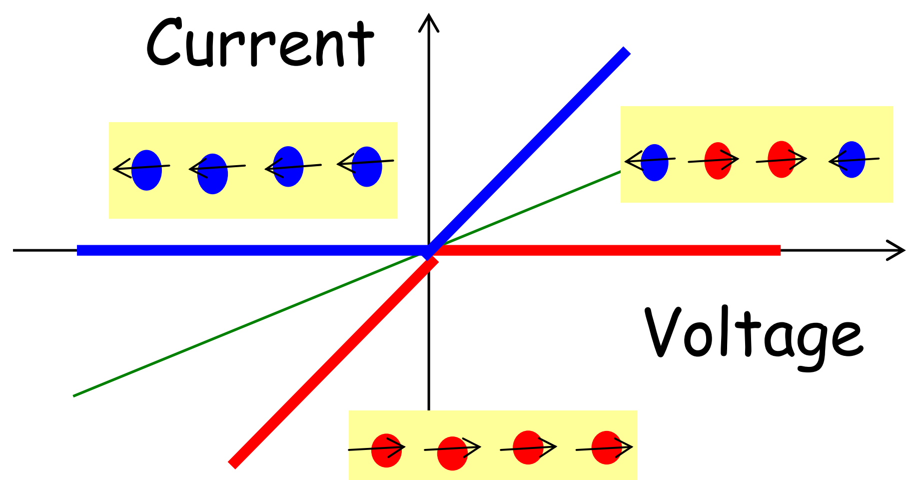


Perfect AP with Spin-polarized gate

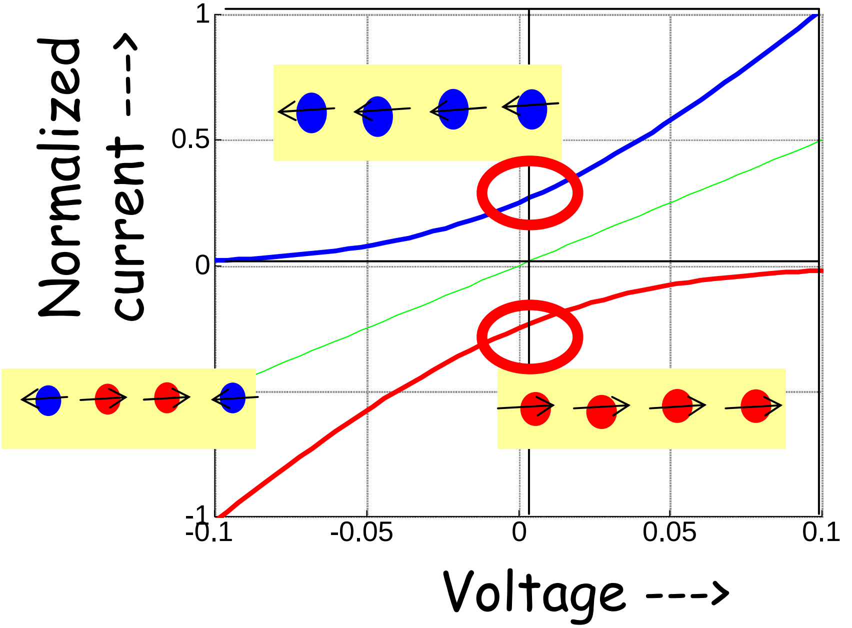


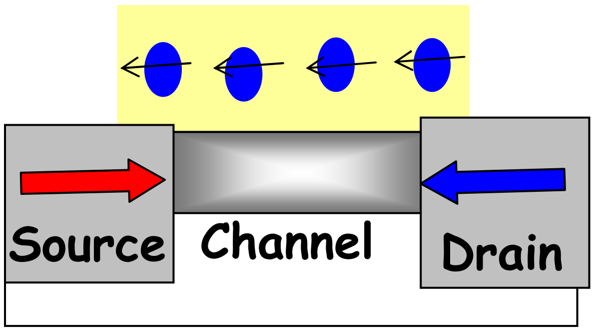




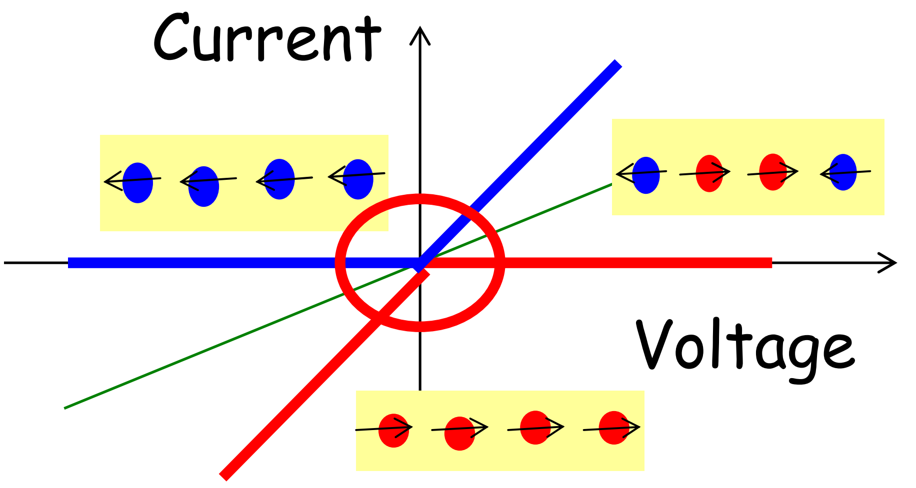


Non-zero temperatures

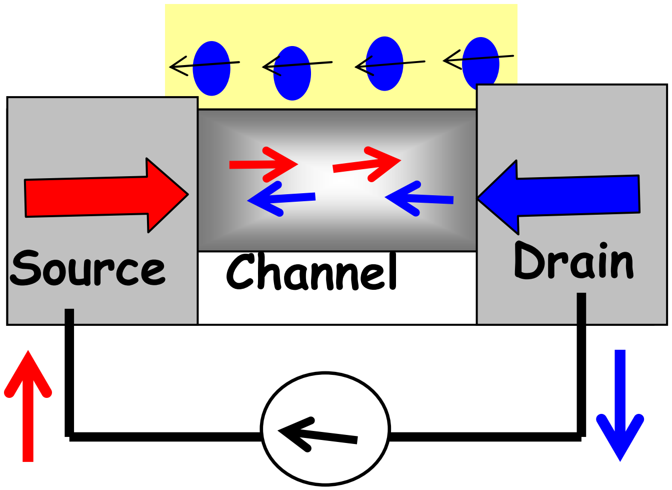


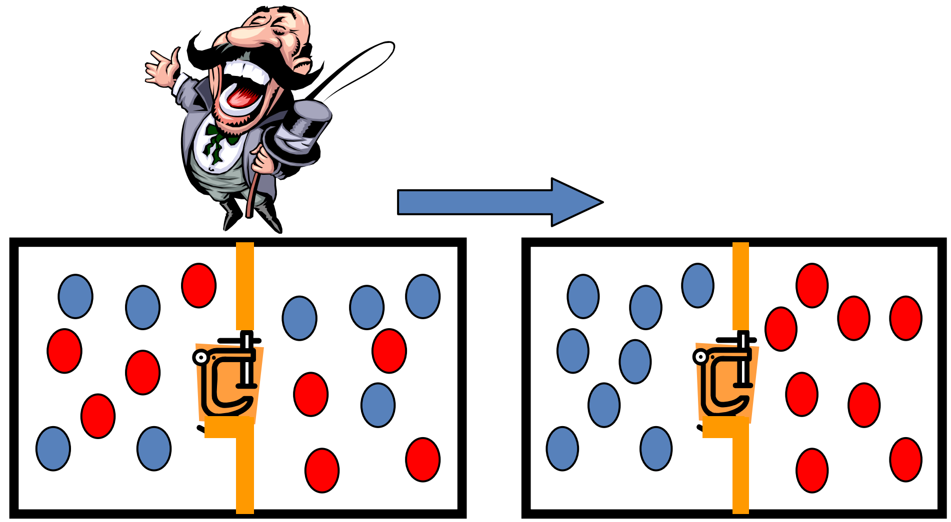


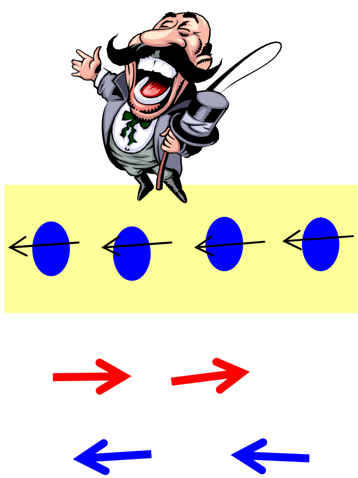
Current at zero voltage ! !

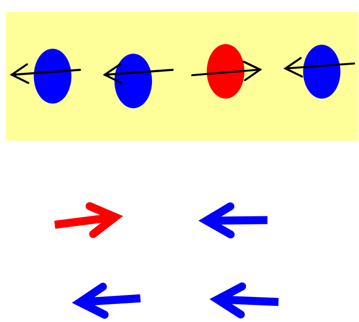


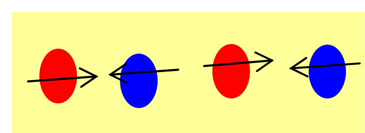
Electronic Maxwell's demon ?





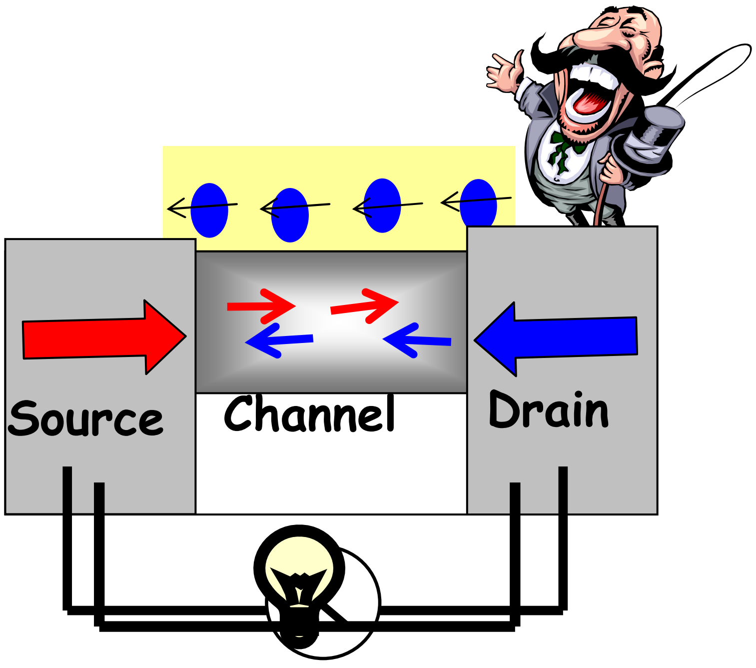


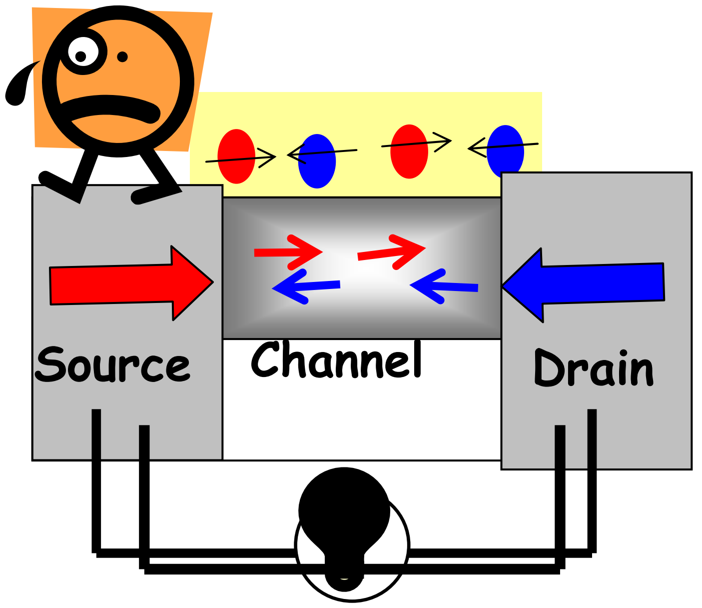


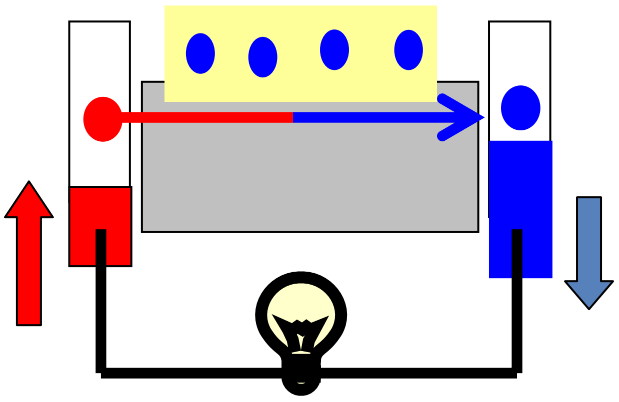


No further current

Where did the energy come from?

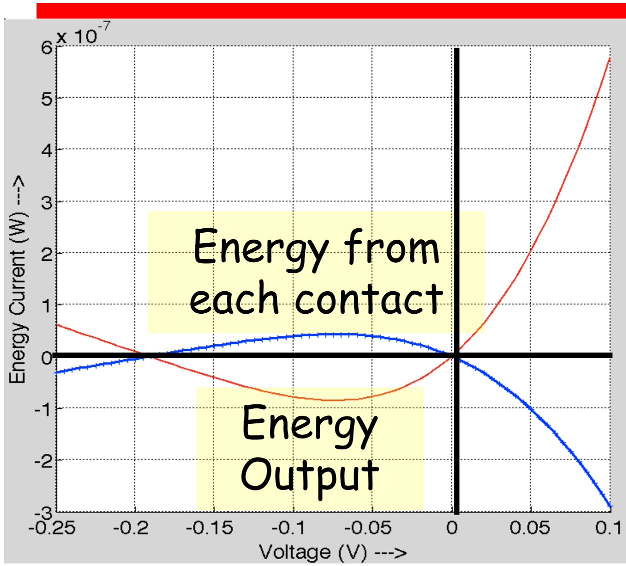


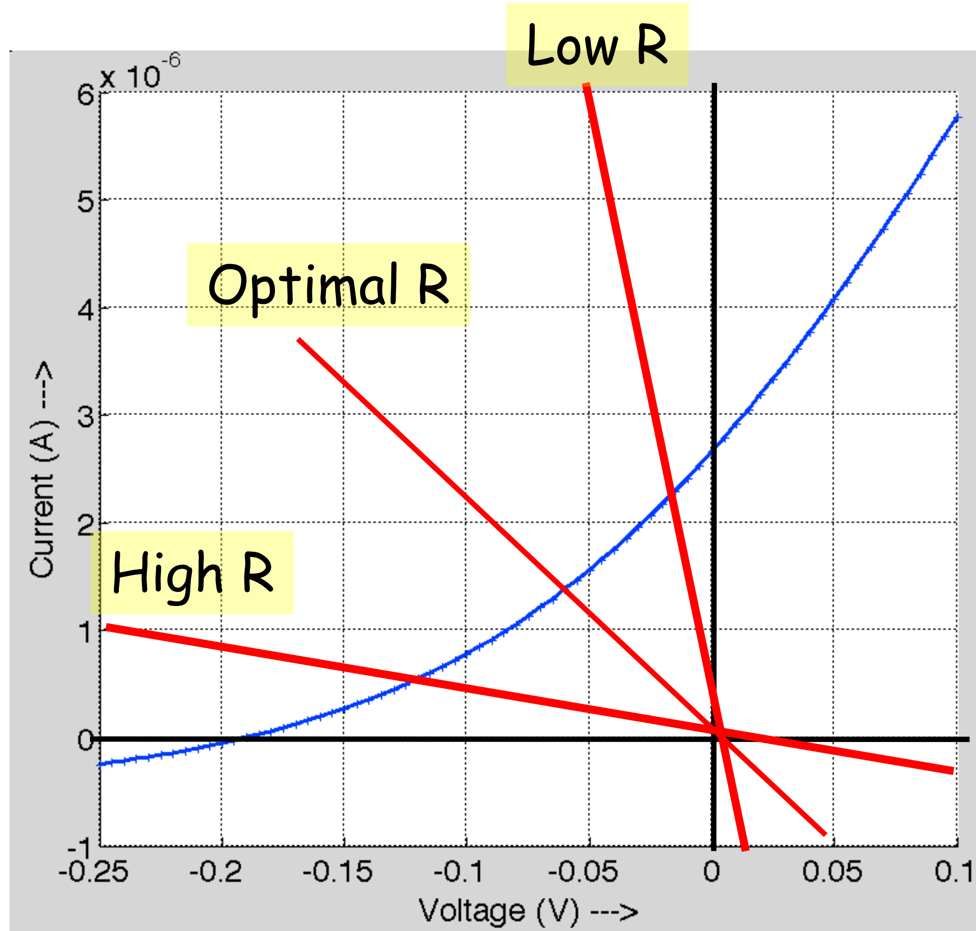


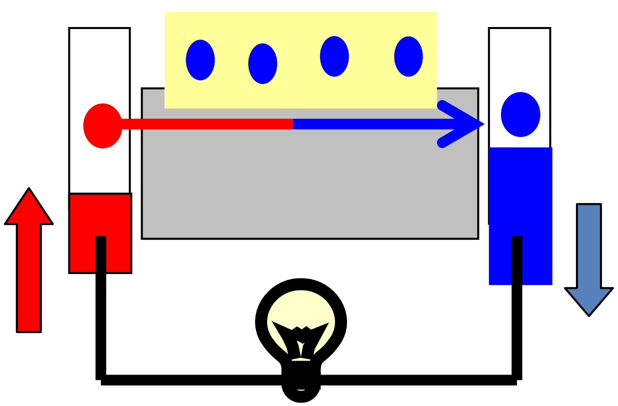


Answer:
From the
contacts

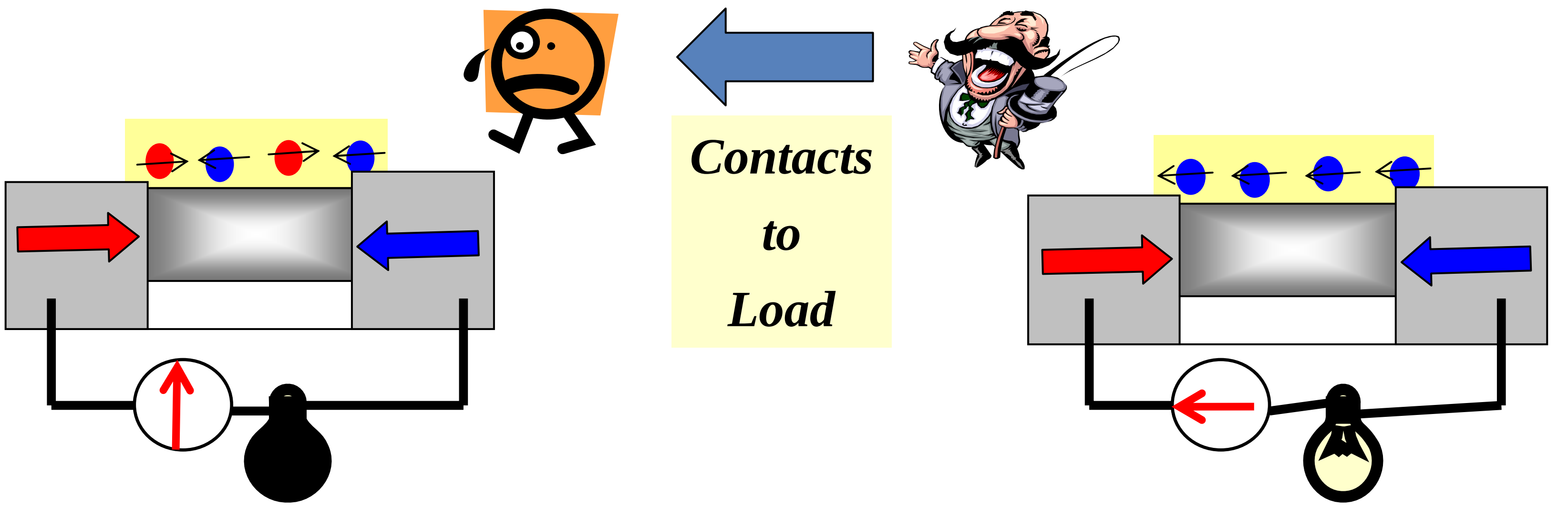
Where did the energy come from?



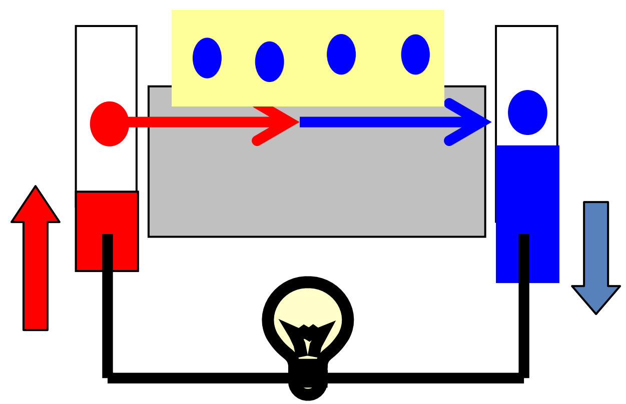




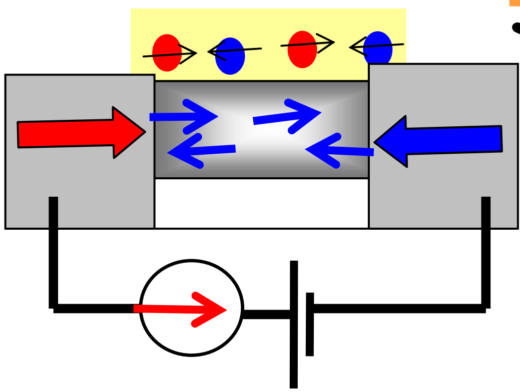
How much can we extract ?

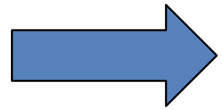


How much energy can we extract from the contacts?



How much do we have to supply for the reverse process?

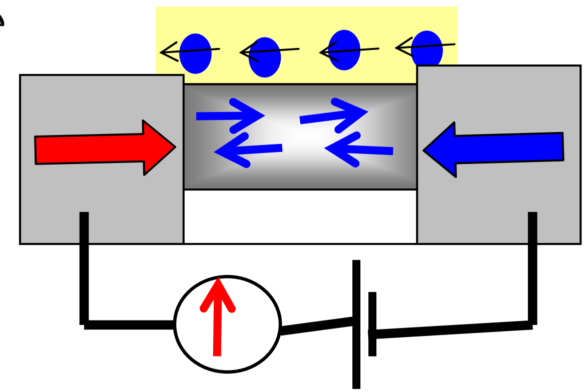




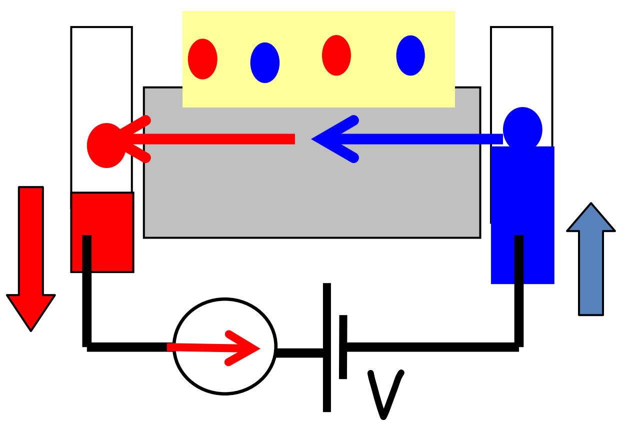
Battery

to

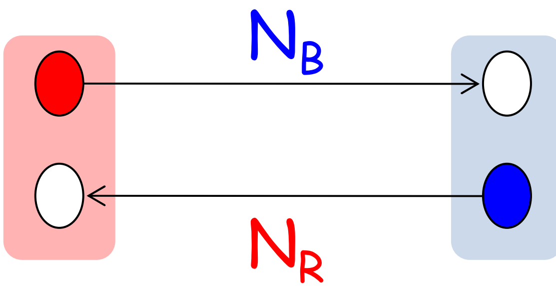
Contacts



$$N_B + N_R = N$$



How small can we make V ?



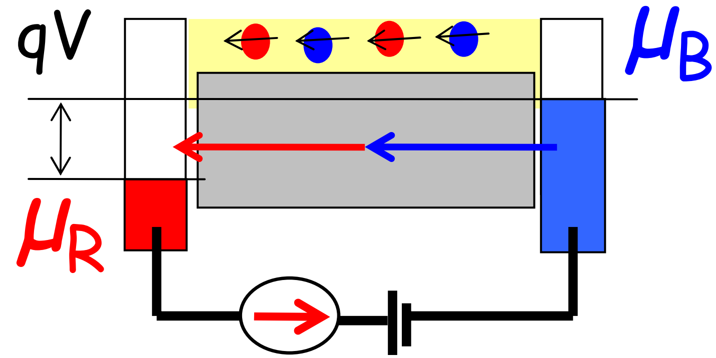
$$N_B f_R (1 - f_B) = N_R f_B (1 - f_R)$$

$$\frac{N_B}{N_R} = \frac{1 - f_R}{f_R} \, \frac{f_B}{1 - f_B}$$

$$= \exp\left(\frac{E - \mu_R}{kT}\right) \exp\left(\frac{\mu_B - E}{kT}\right)$$

$$= e^{qV/kT}$$

$N_B + N_R = N$



$$f = \frac{1}{1 + \exp\left(\frac{E - \mu}{kT}\right)}$$

$$\frac{1 - f}{f} = \exp\left(\frac{E - \mu}{kT}\right)$$

How small can we make V ?

Steady-state condition:

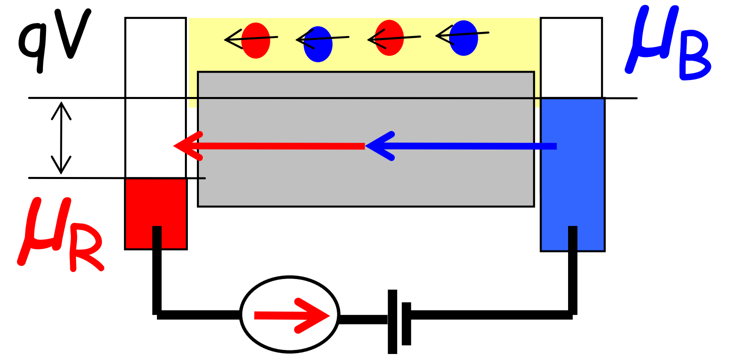
$$\frac{N_B}{N_R} = e^{qV/kT}$$

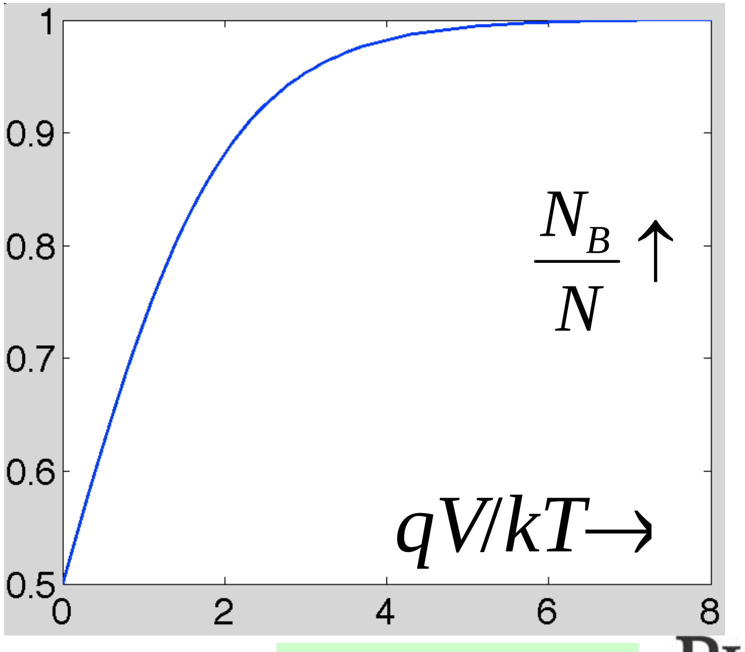
$$\frac{N_B}{N - N_B} = e^{qV/kT}$$

$$\boxed{2x}$$

$$\frac{N_B}{N} = \frac{1}{1 + e^{-2x}}$$

$N_B + N_R = N$





$$\Delta E$$

$$= qV \, \Delta N_B(V)$$

$$\sim 4NkT$$

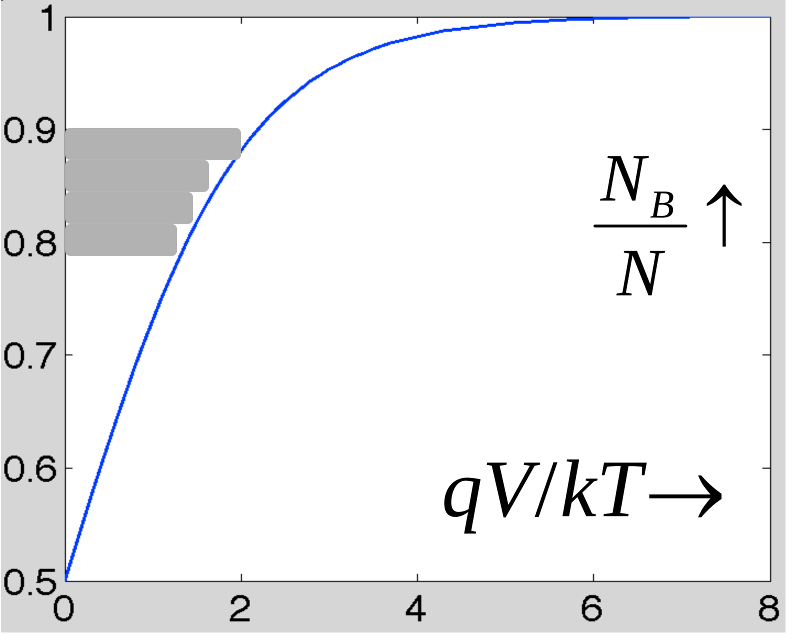
Can dissipate less by being patient ..

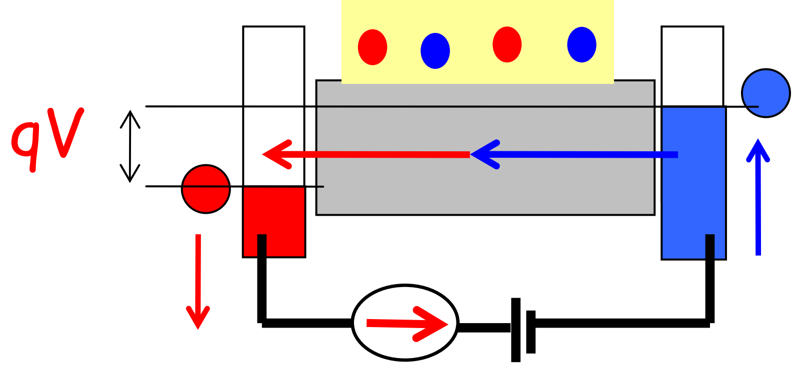
Instead of $\Delta E = qV\,\Delta N_B(V)$

$$dE = qV\,dN_B(V)$$

$$E = NkT \underbrace{\int_0^\infty dx\,x\,\mathrm{sech}^2 x}_{\ln 2}$$

$$= NkT\,\ln 2$$

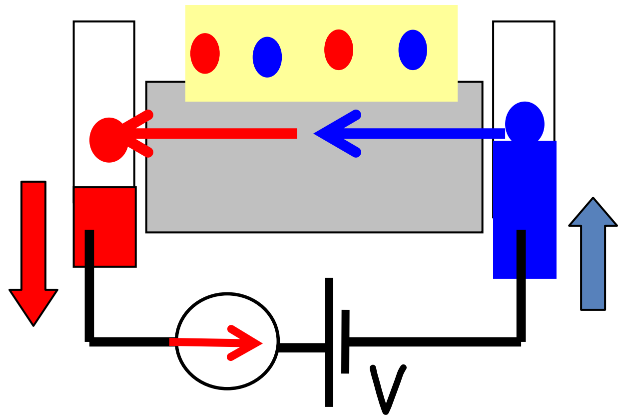




$$\frac{N_B}{N} = \frac{1}{1+e^{-2x}}, \quad \frac{qV}{kT} \equiv 2x$$

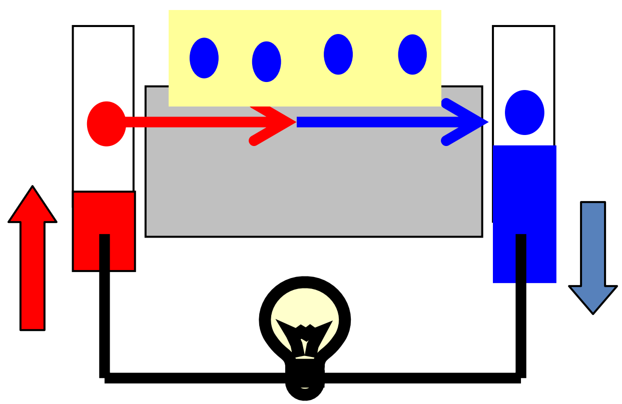
** Flow is asymmetric

How much energy does our battery have to provide?



At LEAST NkT ln2 from battery to contacts

How much energy can we extract from the contacts?



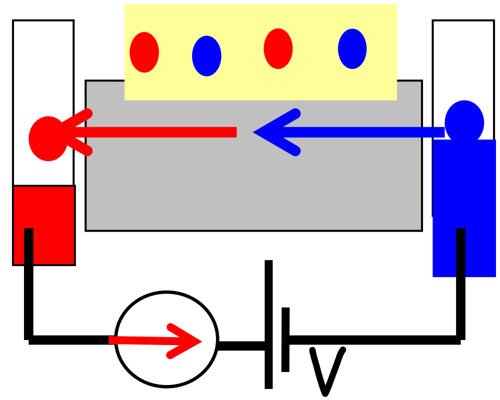
At MOST NkT ln2 from contacts to load

Entropy and the second law

Contact ***"Demon"***

$$(E/T) - Nk \ln 2 > 0$$

$$E > NkT \ln 2$$

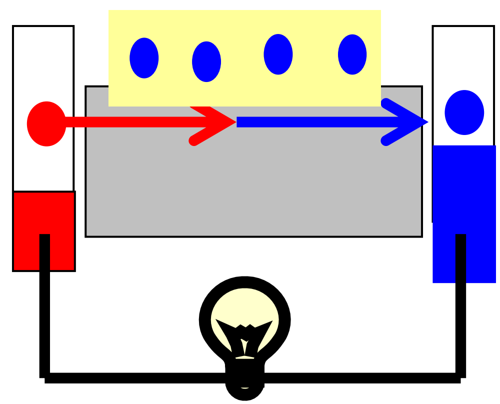


At LEAST NkT ln2 from battery to contacts

Contact ***"Demon"***

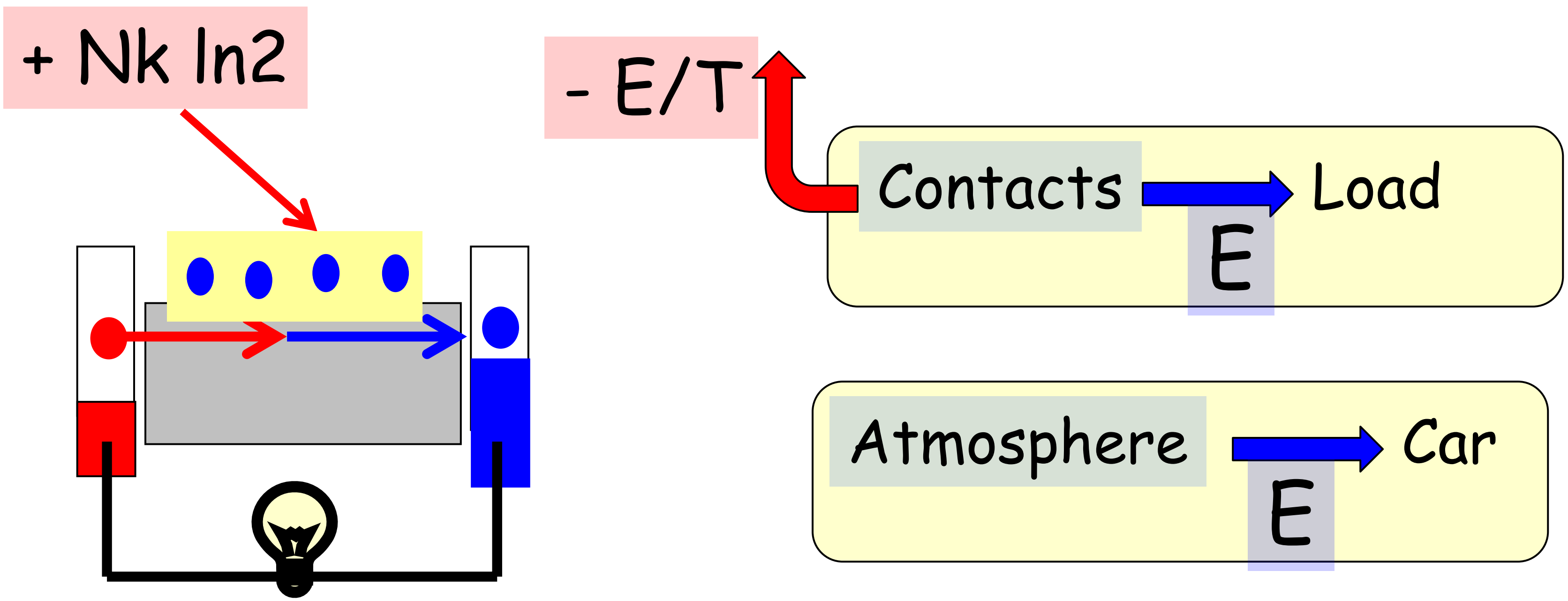
$$(-E/T) + Nk \ln 2 > 0$$

$$E < NkT \ln 2$$



At MOST NkT ln2 from contacts to load

Entropy as "fuel"



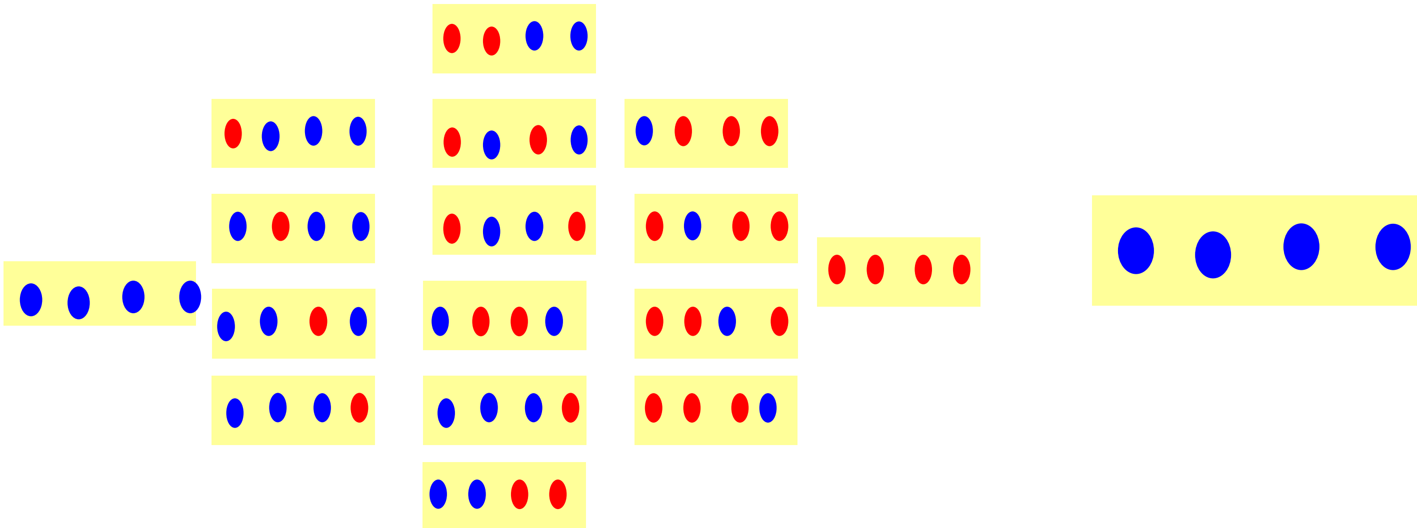
$$E \leq NkT \ln 2$$ ~ 2.5 KJ/mole

$NkT = 6.023 \times 10^{+23} \times 0.025 \times 1.6 \times 10^{-19}$ J/mole

cf. Coal ~ 400 KJ/mole

Oil ~ 5000 KJ/mole

** Origin of entropic forces



$S = k \log W$

$W = 2^N,\ S = Nk \ln 2$

$S = 0,\ W = 1$