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
Nanoelectronics and the meaning of Resistance

0.1 mm

Lectures 1a,b: Simple model

0.1 µm

Lectures 2a,b: Microscopic model

10 µm

Lectures 3a,b: Add spin

1 µm

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

0.1 µm

Macroscopic dimensions

10 nm

Atomic dimensions

10 nm

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Where is the heat ($I^2R$) ?

\[
\frac{V}{I} = \frac{25.8 \, K \Omega}{2} \frac{1}{T}
\]

\[
P = VI
\]

\[
= qV \frac{N}{t}
\]
Electronic Maxwell's Demon

Electronic demon

Source

\[ V = 0 \]

Drain

Channel

\[ \text{I} \]

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Two-channel devices

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

Anti-parallel (AP)

Insulating substrate

Source Channel Drain

Perfect AP

Imperfect AP

Current

Perfect

Imperfect

Voltage

V

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Perfect AP with Spin-flip Impurities

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Perfect AP with Spin-polarized gate

Source  Channel  Drain

Insulating substrate

Spin flip

Source  Drain

Current

Voltage

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Non-zero temperatures

Current at zero voltage!!
Electronic Maxwell's demon?

No further current
Where did the energy come from?

Answer: From the contacts

Source Channel Drain

Source Channel Drain
Where did the energy come from?

- Energy from each contact
- Energy Output

Diagram showing energy output and current as functions of voltage for different resistances (Low R, Optimal R, High R).
How much can we extract?

Contacts to Load

How much energy can we extract from the contacts?

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

\[ N_B + N_R = N \]
How small can we make $V$?

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

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

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

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

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

$$\frac{1 - f}{f} = \exp\left(\frac{E - \mu}{kT}\right)$$
How small can we make $V$?

Steady-state condition:

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

\[
\frac{N_B}{N - N_B} = e^{qV/kT} \quad \text{2x}
\]

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

\[
\frac{N_B}{N} \uparrow \quad \Delta E = qV \Delta N_B(V) \sim 4NkT
\]

\[
qV/kT \rightarrow
\]

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Can dissipate less by being patient..

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

\[
dE = qV \, dN_B(V)
\]

\[
E' = NkT \int_0^{\infty} dx \, x \ln 2
\]

\[
= NkT \ln 2
\]

\[
\frac{N_B}{N} = \frac{1}{1 + e^{-2x}}, \quad \frac{qV}{kT} \equiv 2x
\]
** Flow is asymmetric

How much energy does our battery have to provide?

At LEAST $NkT \ln 2$ from battery to contacts

How much energy can we extract from the contacts?

At MOST $NkT \ln 2$ from contacts to load
Entrophy and the second law

Contact “Demon”

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

\[E > NkT \ln 2\]

Contact “Demon”

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

\[E < NkT \ln 2\]

At LEAST
\[NkT \ln 2\]
from battery
to contacts

At MOST
\[NkT \ln 2\]
from contacts
to load

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Entropy as “fuel”

\[ E \leq NkT \ln 2 \approx 2.5 \text{ KJ/mole} \]

\[ NkT = 6.023 \times 10^{23} \times 0.025 \times 1.6 \times 10^{-19} \text{ J/mole} \]

cf. Coal \approx 400 \text{ KJ/mole}
Oil \approx 5000 \text{ KJ/mole}
** Origin of entropic forces

\[ S = k \log W \]

\[ W = 2^N, \quad S = Nk \ln 2 \]

\[ S = 0, \quad W = 1 \]

Need energy

Gives up energy

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