ECE 656: Electronic Transport in Semiconductors Fall 2017

Introduction to Thermoelectricity

Mark Lundstrom

Electrical and Computer Engineering
Purdue University
West Lafayette, IN USA

nanoHUB.org

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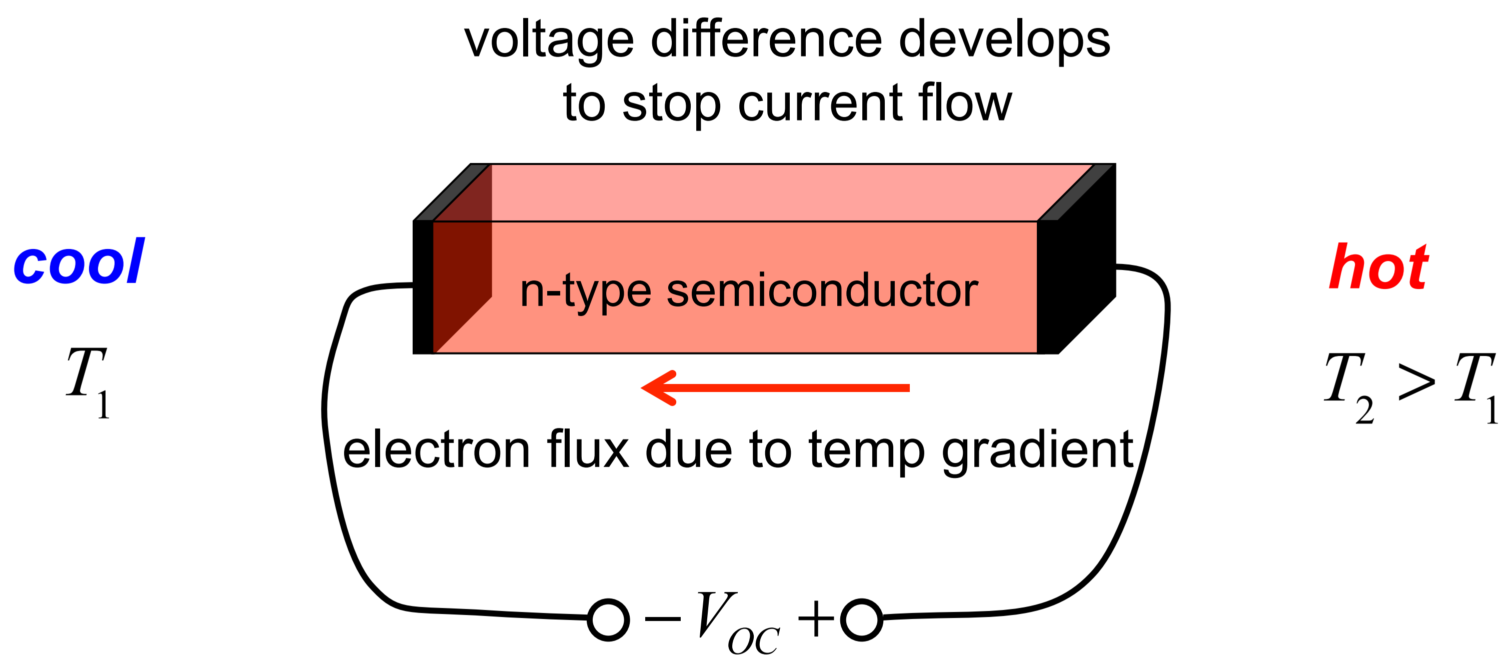
Purdue University

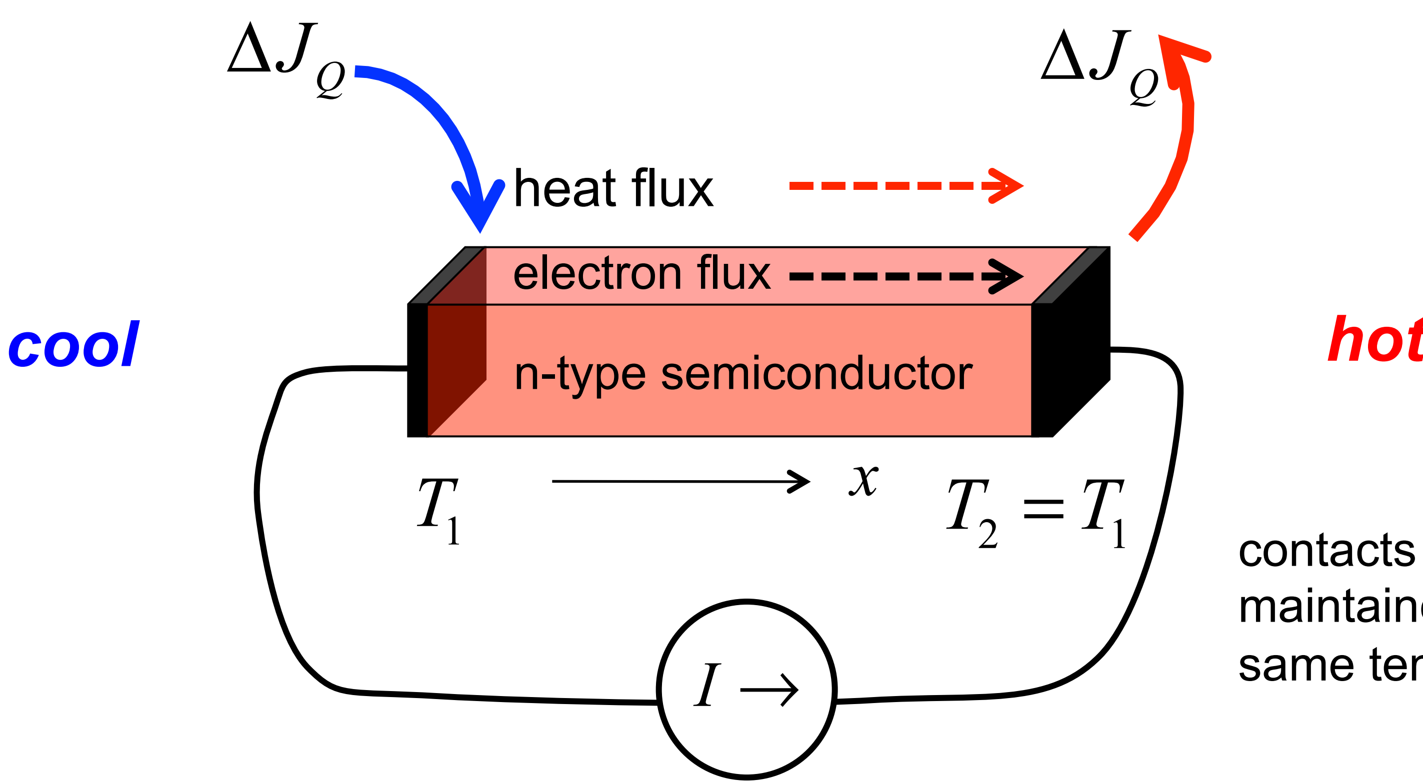
Seebeck effect



Temperature gradients give rise to an open circuit voltage, which is known as the Seebeck effect. We expect a **positive** voltage for an n-type semiconductor (and **negative** voltage for a p-type semiconductor.)

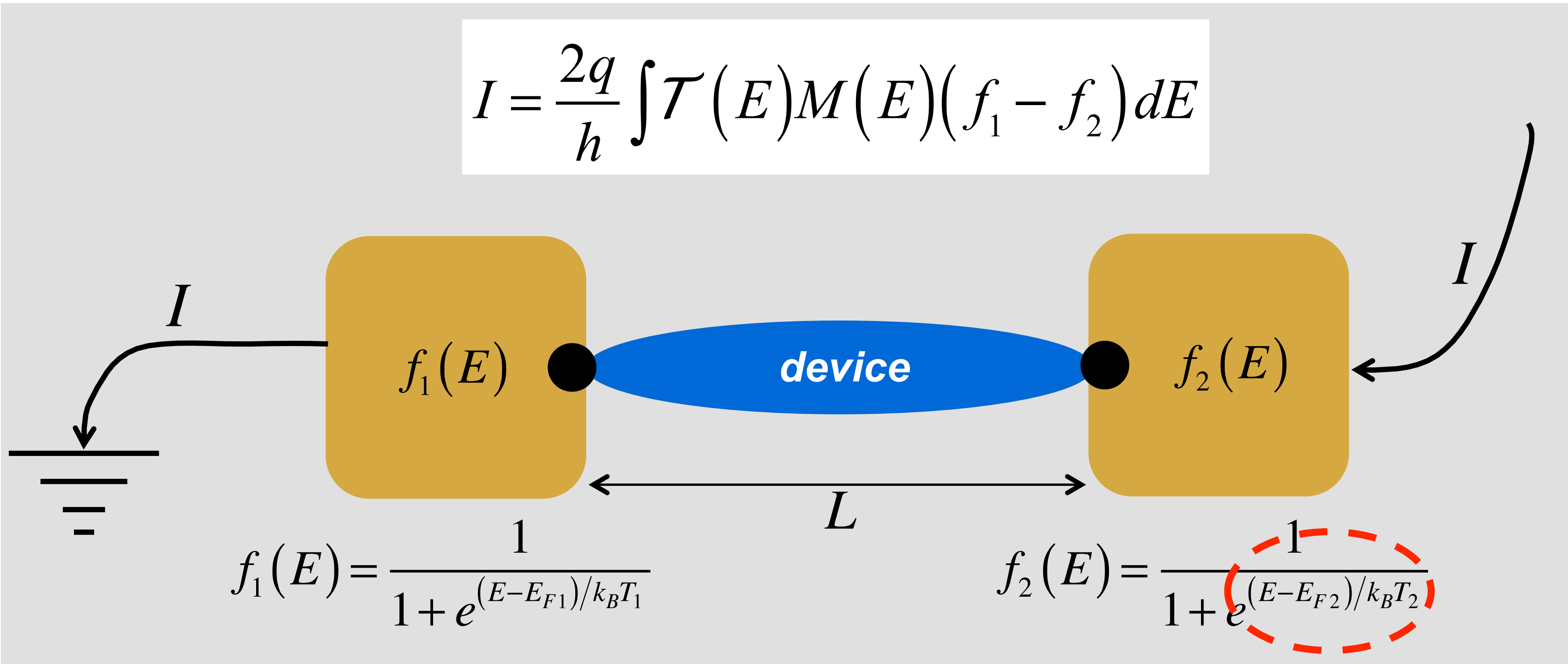
Peltier effect

$J_n < 0$ $\quad J_n/(-q) > 0$ $\quad J_Q = \pi_n J_n > 0$



contacts maintained at same temperature

Nano to macro device



Driving "forces" for current flow: Differences in Fermi level and differences in temperature.

(In the bulk: Gradients in quasi-Fermi level and temperature.)

The "coupled current equations"

$$I = G\Delta V + S_T \Delta T$$

$$I_Q = -TS_T \Delta V - K_0 \Delta T$$

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$$\Delta V = RI - S\Delta T$$

$$I_Q = -\pi I - K_e \Delta T$$

$$J = \sigma \mathcal{E} - s_T\, dT/dx$$

$$J_Q = TS_T \mathcal{E} - \kappa_0\, dT/dx$$

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$$\mathcal{E} = \rho J + S\frac{dT}{dx}$$

$$J_Q = \pi J - \kappa_e \frac{dT}{dx}$$

(diffusive transport)

Transport equations and coefficients

TE transport equations

$$\Delta V = RI - S\Delta T$$

$$I_Q = -\Pi I - K_e \Delta T$$

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$$\mathcal{E} = \rho J + S\frac{dT}{dx}$$

$$J_Q = \pi J - \kappa_e \frac{dT}{dx}$$

TE transport coefficients

$\rho = 1/\sigma$	S
π	κ_e

(diffusive transport)

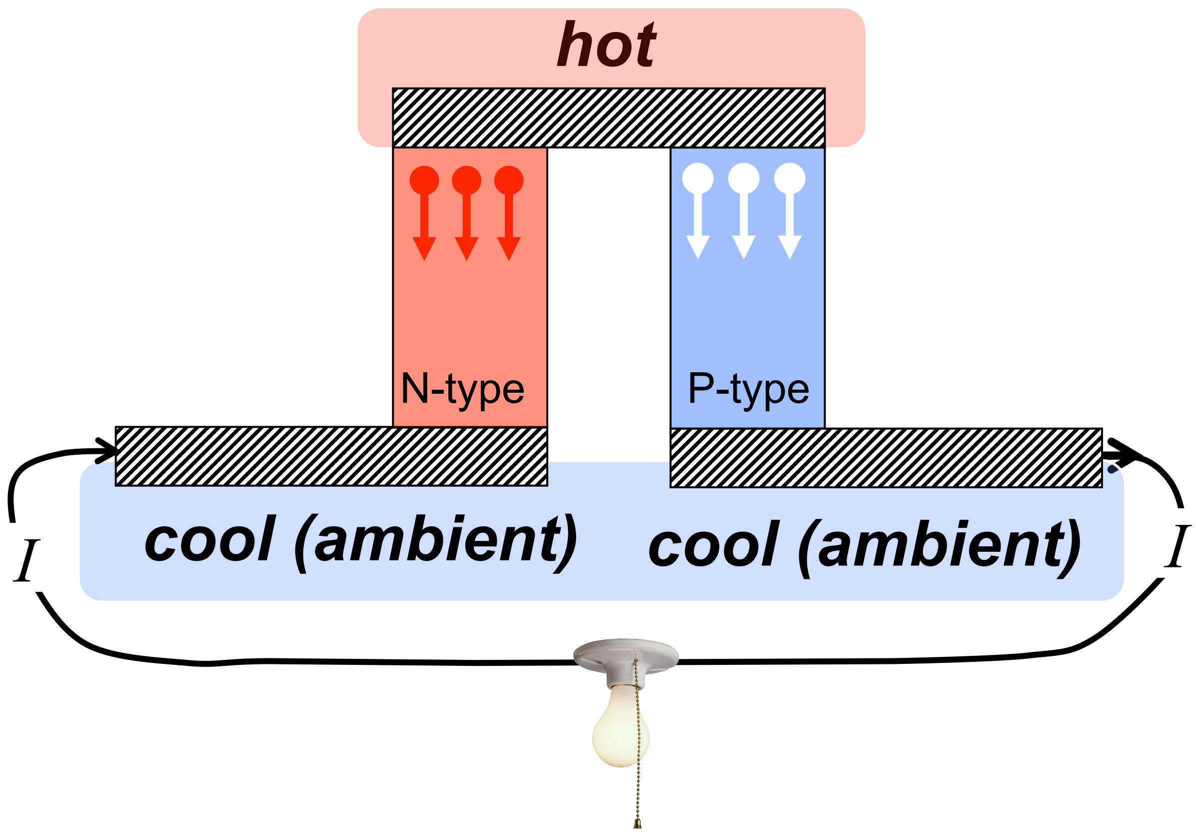
$$R = \rho L/A$$

Goals

1) To understand the transport **equations** and how to apply them.

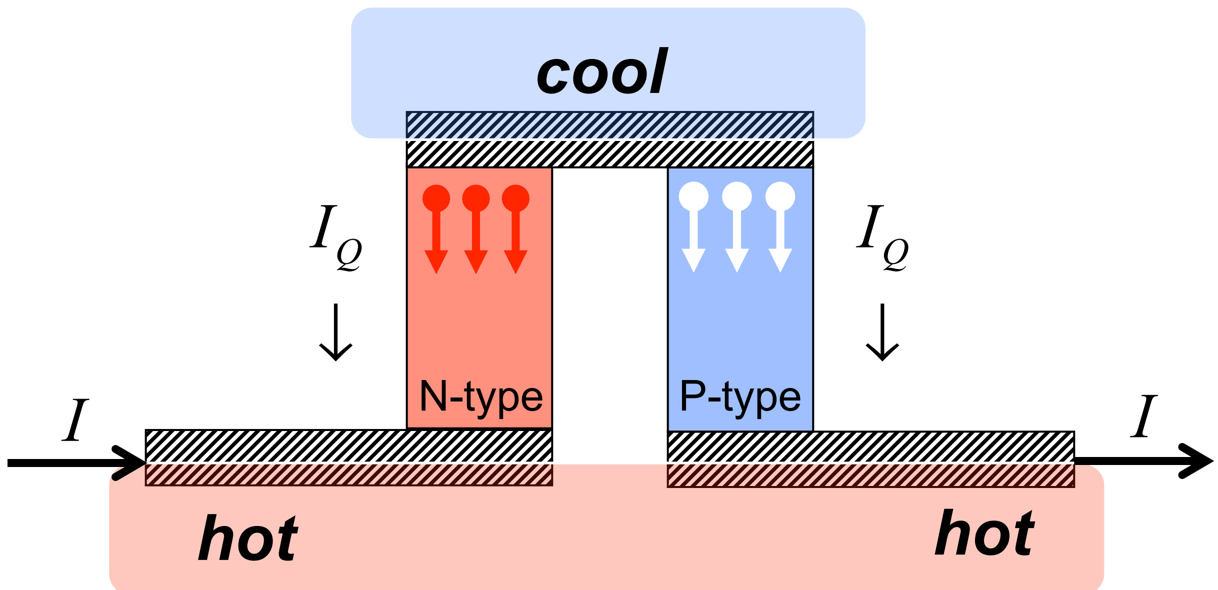
2) To understand the transport **coefficients** and how they relate to material parameters.

Application: TE power generation



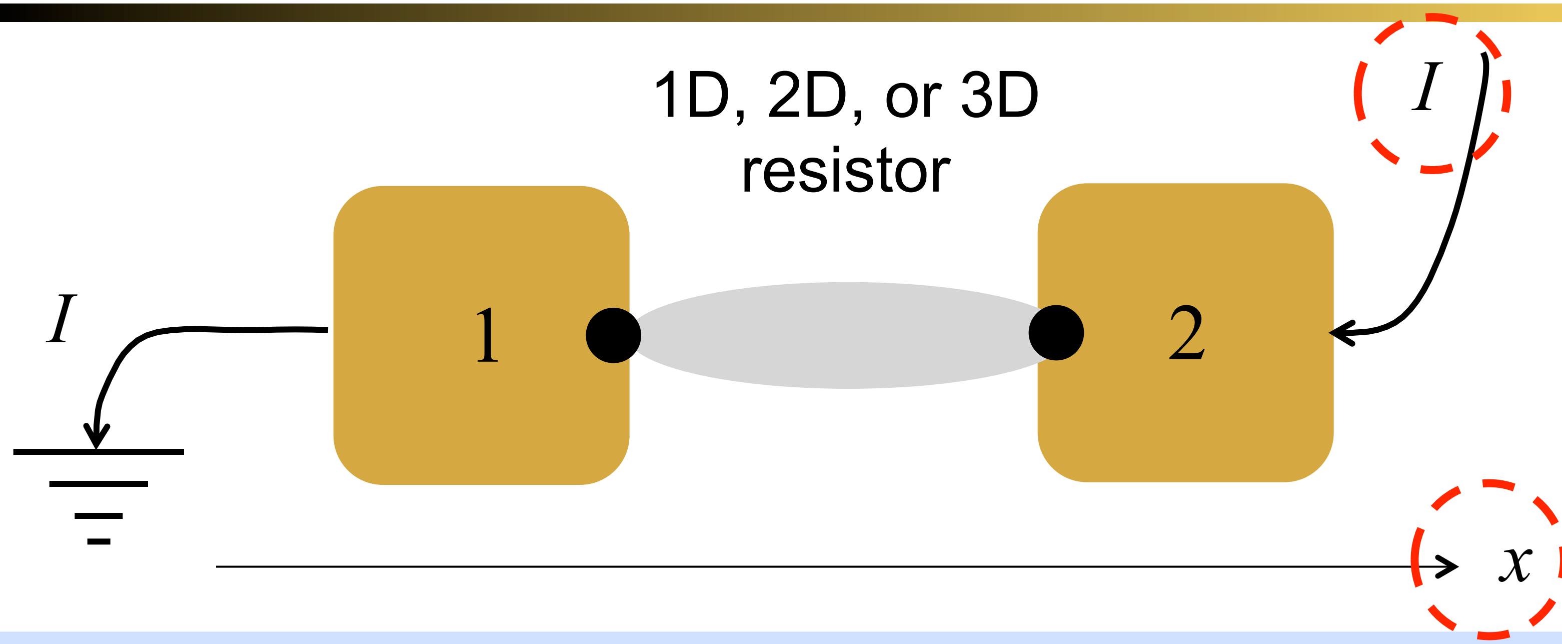
1) How much heat can be converted into electricity?
(what determines the efficiency?)

Application: TE cooling



1) What determines the maximum temperature difference?
2) How much heat can be pumped?
3) What is the coefficient of performance?

Review of Landauer Approach



$$G = \frac{2q^2}{h} \int \mathcal{T}(E) M(E) \left(-\frac{\partial f_0}{\partial E} \right) dE$$

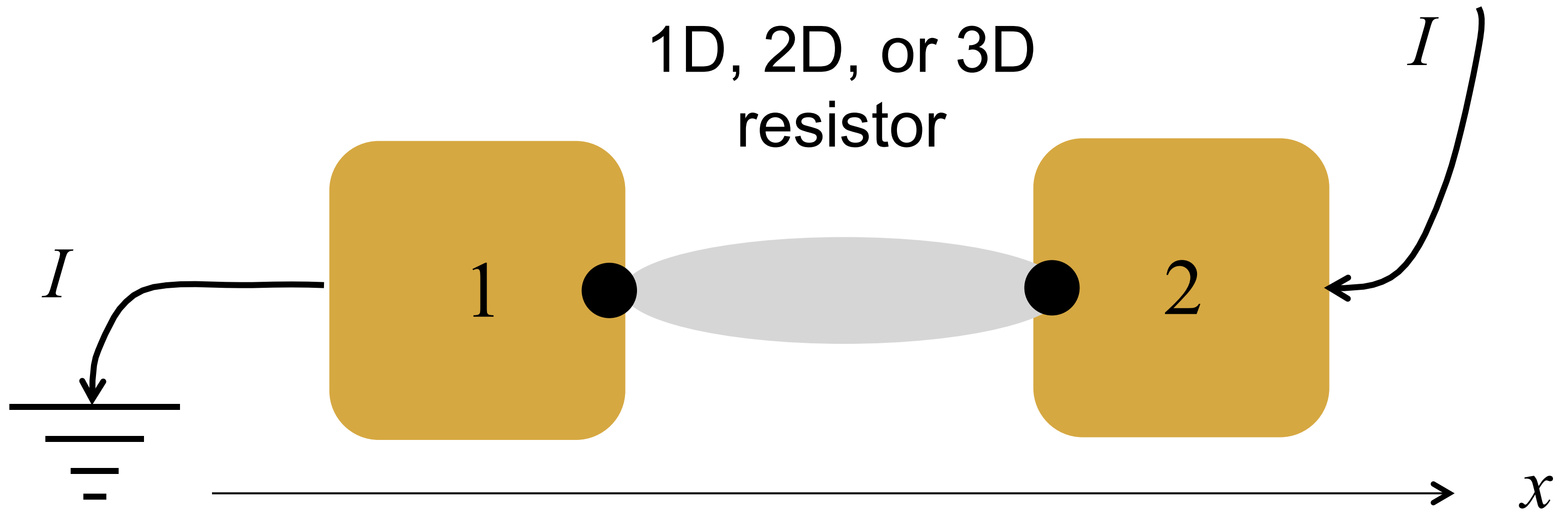
$$I = G \Delta V$$

$$G = \int G'(E)\, dE$$

$$G'(E) = \frac{2q^2}{h} \mathcal{T}(E) M(E) \left(-\frac{\partial f_0}{\partial E} \right)$$

"differential conductance"

Diffusive transport in the bulk



$$I = G\Delta V$$

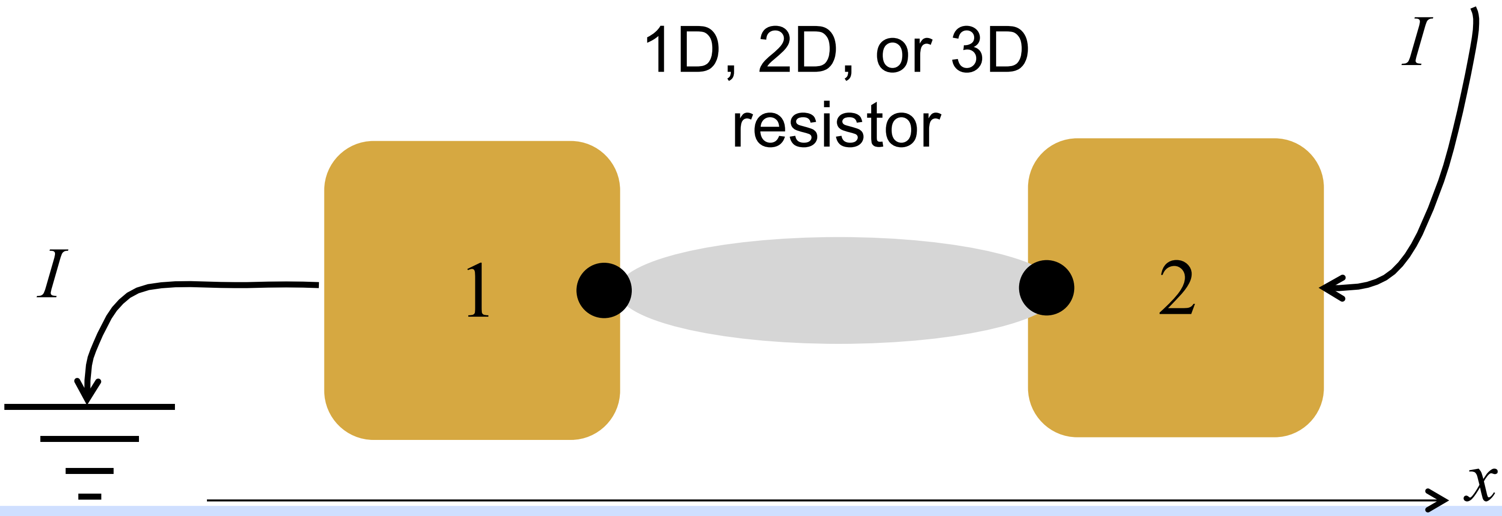
$$G = \sigma A/L$$

$$I = G\left(\Delta E_F/(-q)\right)$$

$$J_x = \sigma \mathcal{E}_x$$

$$J_x = \sigma \frac{d\left(F_n/q\right)}{dx}$$

Review of Landauer Approach



$$\sigma = \frac{2q^2}{h} \int \lambda(E) \frac{M(E)}{A} \left(-\frac{\partial f_0}{\partial E} \right) dE$$

$$\sigma = \int \sigma'(E)\, dE$$

$$J = \sigma \mathcal{E}$$

$$\sigma'(E) = \frac{2q^2}{h} \lambda(E) \frac{M(E)}{A} \left(-\frac{\partial f_0}{\partial E} \right)$$

"differential conductivity"

Ballistic to diffusive transport

$$\sigma = \frac{2q^2}{h}\int \lambda(E)\frac{M(E)}{A}\left(-\frac{\partial f_0}{\partial E}\right)dE \qquad \text{(diffusive)}$$

$$\sigma = G\frac{L}{A} = \frac{2q^2}{h}\int \mathcal{T}(E)L\frac{M(E)}{A}\left(-\frac{\partial f_0}{\partial E}\right)dE \qquad \text{(ballistic to diffusive)}$$

$$\mathcal{T}(E) = \frac{\lambda}{\lambda + L} \qquad \mathcal{T}(E)L = \frac{\lambda L}{\lambda + L} = \left(\frac{1}{\lambda(E)} + \frac{1}{L}\right)^{-1} \equiv \lambda_{app}$$

$$J = \sigma_{app}\mathcal{E} \qquad J = \sigma_{app}\frac{d(F_n/q)}{dx} \qquad \sigma_{app} = \frac{2q^2}{h}\int \lambda_{app}(E)\frac{M(E)}{A}\left(-\frac{\partial f_0}{\partial E}\right)dE$$

The plan

Derive the transport equations and transport coefficients.

We will focus on transport in the bulk, but the results are easily generalized to the ballistic and quasi-ballistic regimes.

The first transport equation describes charge transport (the electrical current).

The current equation

Under isothermal conditions, the electrical current in the bulk is:

$$J_n = \sigma_n d\left(F_n/q\right)/dx \qquad \sigma_n = \text{conductivity} = 1/\rho_n \quad \left(1/\Omega\text{-m}\right)$$

Alternatively, we can write this in the inverted form as:

$$d\left(F_n/q\right)/dx = \rho_n J$$

How do these equations change when there is a temperature gradient?

Current in the presence of a temp gradient

The answer is:

$$J = \sigma \frac{d\left(F_n/q\right)}{dx} - S\sigma \frac{dT}{dx}$$

S is the Seebeck coefficient in V/K.

Alternatively, we can write this equation as:

$$\frac{d\left(F_n/q\right)}{dx} = \rho J + S\frac{dT}{dx}$$

(inverted form of the equations)

Questions?