

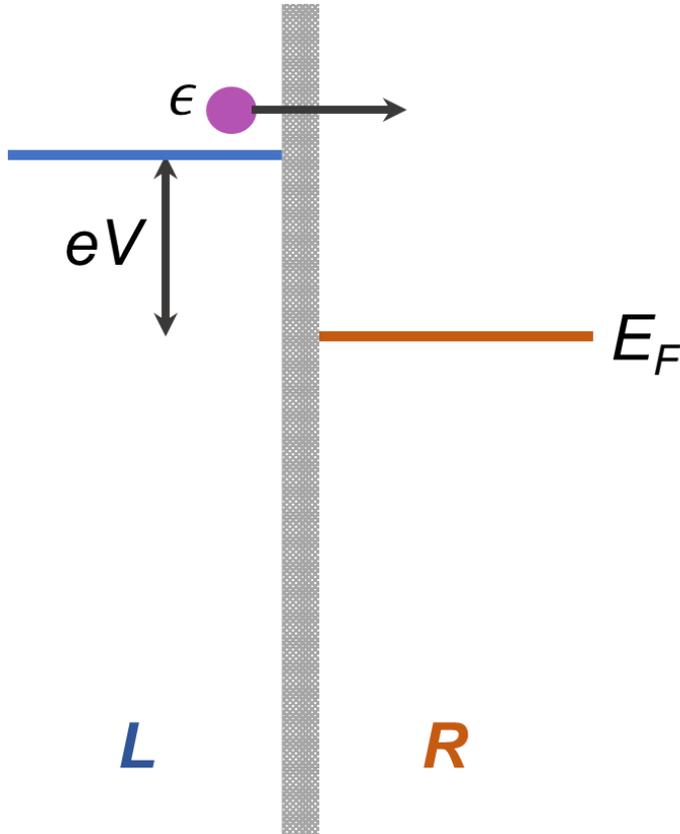
Tunneling

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Phenomenological derivation of tunneling current



$$\Gamma_f = |\mathcal{T}|^2 \int d\epsilon n_L(\epsilon) f_L(\epsilon) n_R(\epsilon + eV) [1 - f_R(\epsilon + eV)]$$

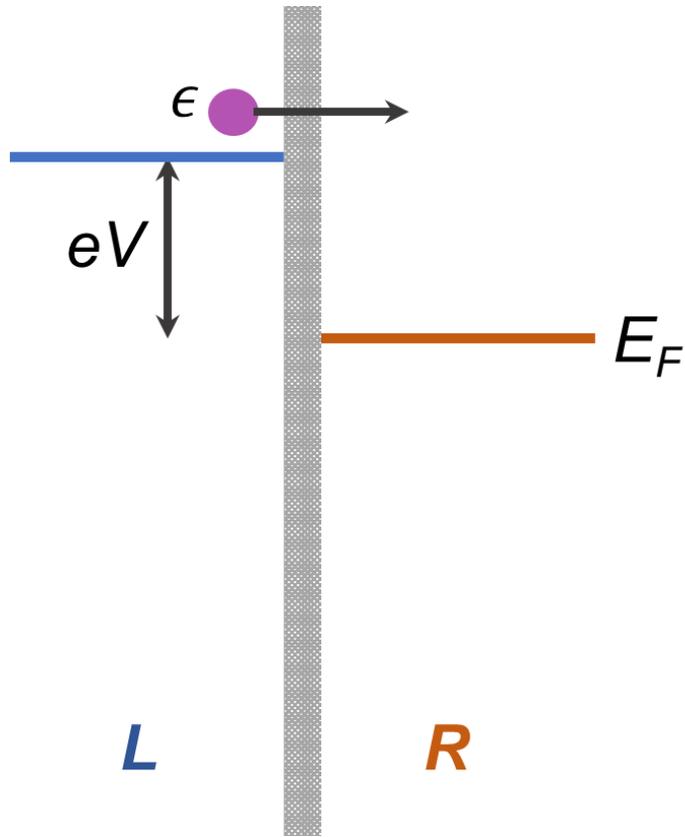
$$\Gamma_b = |\mathcal{T}|^2 \int d\epsilon n_R(\epsilon + eV) f_R(\epsilon + eV) n_L(\epsilon) [1 - f_L(\epsilon)]$$

Net electrical current through the junction:

$$I = e(\Gamma_f - \Gamma_b)$$

$$I = \frac{1}{eR_T} \int d\epsilon n_L(\epsilon) n_R(\epsilon + eV) [f_L(\epsilon) - f_R(\epsilon + eV)]$$

Phenomenological derivation for heat current

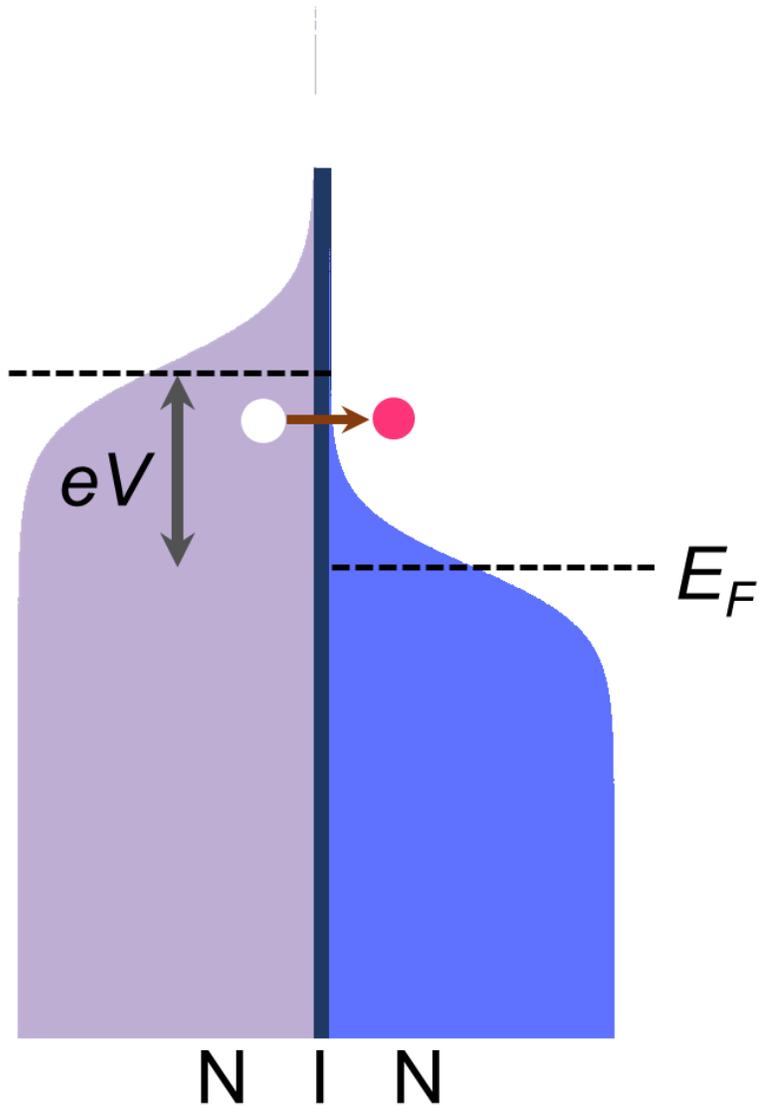


$$\dot{Q}_{L \rightarrow R} = |\mathcal{T}|^2 \int d\epsilon (\epsilon - eV) n_L(\epsilon - eV) n_R(\epsilon) f_L(\epsilon - eV) [1 - f_R(\epsilon)]$$

$$\dot{Q}_{R \rightarrow L} = |\mathcal{T}|^2 \int d\epsilon (\epsilon - eV) n_L(\epsilon - eV) n_R(\epsilon) f_R(\epsilon) [1 - f_L(\epsilon - eV)]$$

$$\begin{aligned} \dot{Q}_L &= \dot{Q}_{L \rightarrow R} - \dot{Q}_{R \rightarrow L} \\ &= \frac{1}{e^2 R_T} \int d\epsilon (\epsilon - eV) n_L(\epsilon - eV) n_R(\epsilon) [f_L(\epsilon - eV) - f_R(\epsilon)] \end{aligned}$$

NIN junction



$$\dot{Q}_L = \frac{1}{e^2 R_T} \int d\epsilon (\epsilon - eV) n_L(\epsilon - eV) n_R(\epsilon) [f_L(\epsilon - eV) - f_R(\epsilon)]$$

$$\dot{Q}_{NIN} = \frac{1}{e^2 R_T} \int_{-\infty}^{\infty} d\epsilon (\epsilon - eV) \{f_N(\epsilon - eV) - f_N(\epsilon)\}$$

$$\dot{Q}_{NIN} = -\frac{V^2}{2R_T}$$