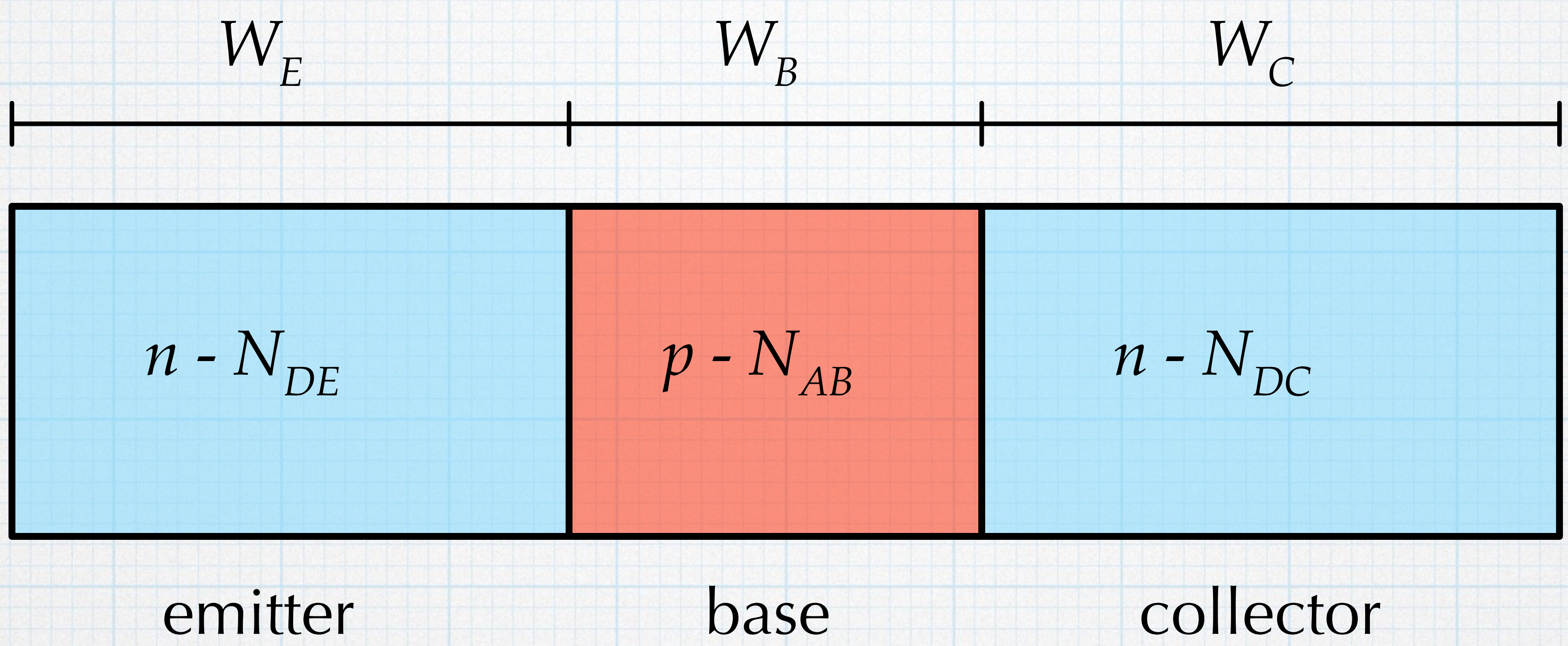
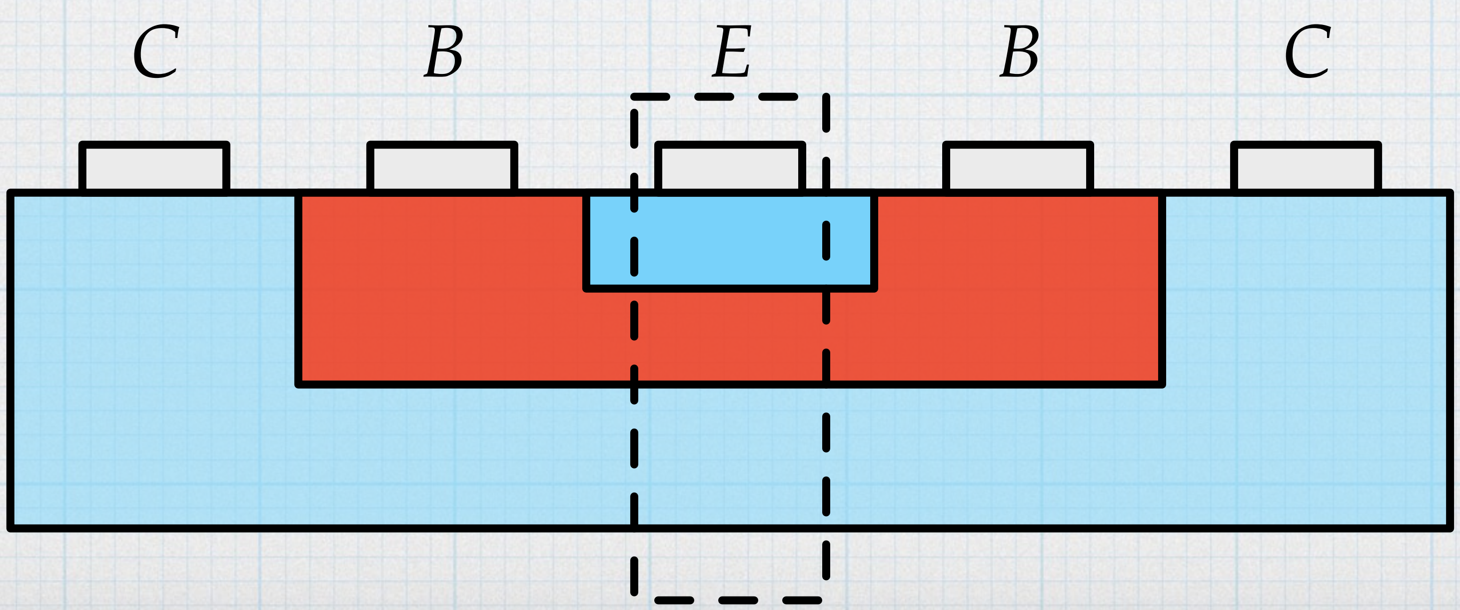
npn Bipolar Junction Transistor



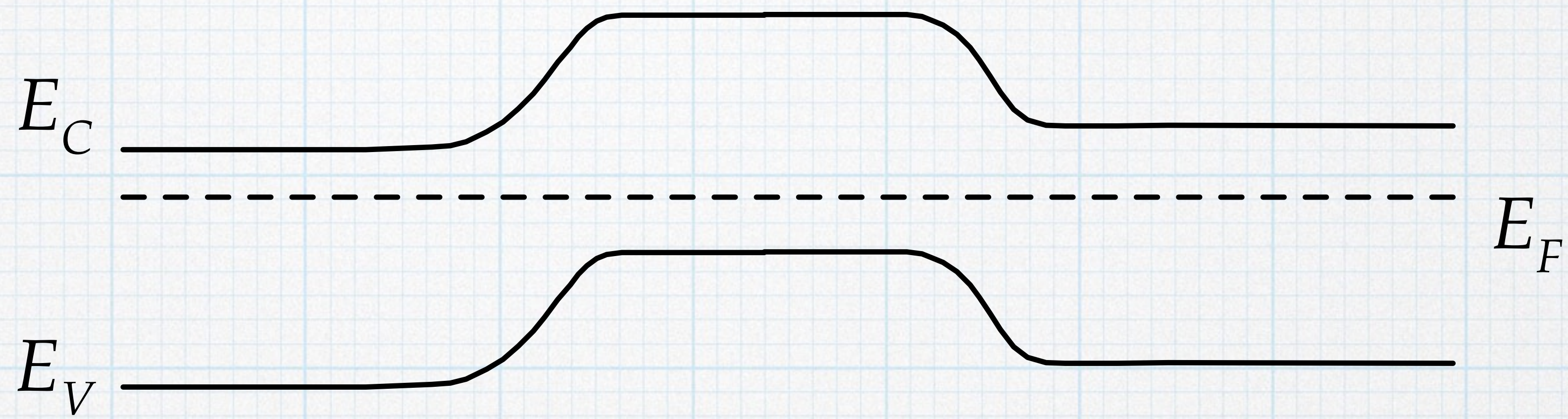
N_{DE}, N_{AB}, N_{DC} — uniform doping levels in emitter, base, and collector.

W_E, W_B, W_C — physical widths of emitter, base, and collector.



npn band diagram

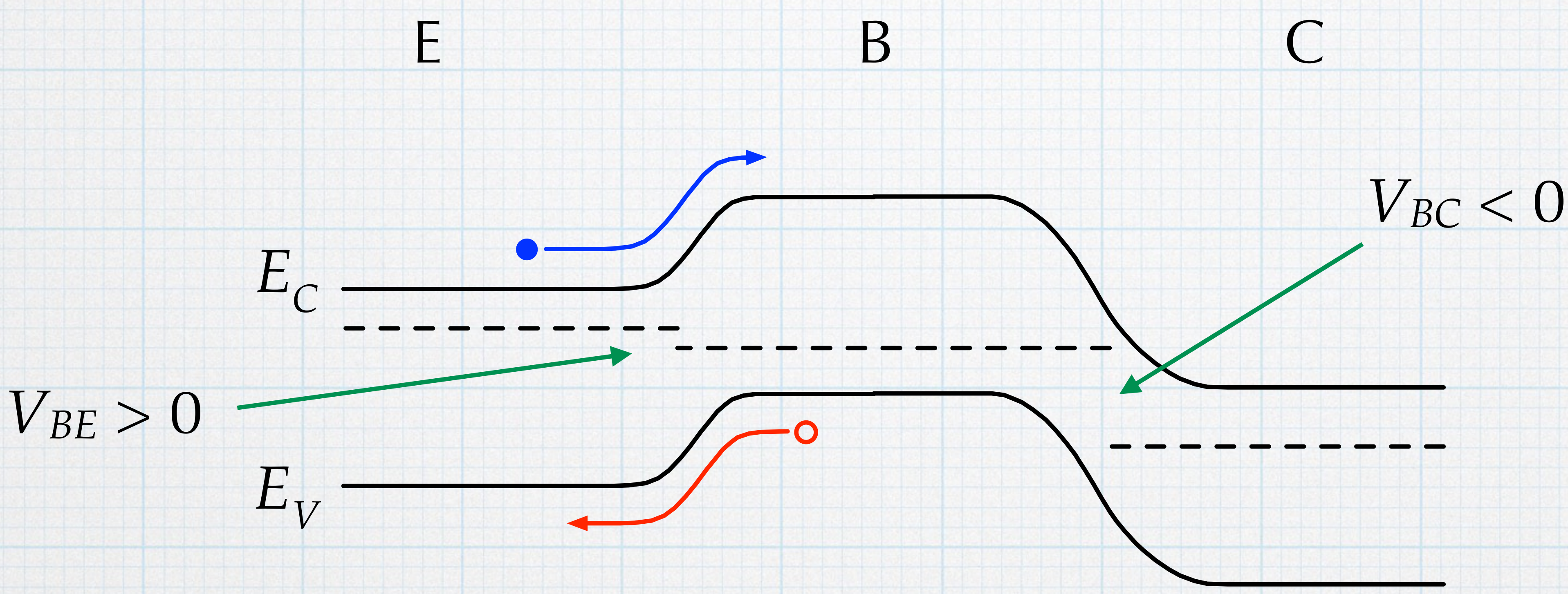
equilibrium



4 modes of operation

	base-emitter (V_{BE})	base-collector (V_{BC})
forward active	forward ($V_{BE} > 0$)	reverse ($V_{BC} < 0$)
saturation	forward ($V_{BE} > 0$)	forward ($V_{BC} > 0$)
off	reverse ($V_{BE} < 0$)	reverse ($V_{BC} < 0$)
reverse active	reverse ($V_{BE} > 0$)	forward ($V_{BC} > 0$)

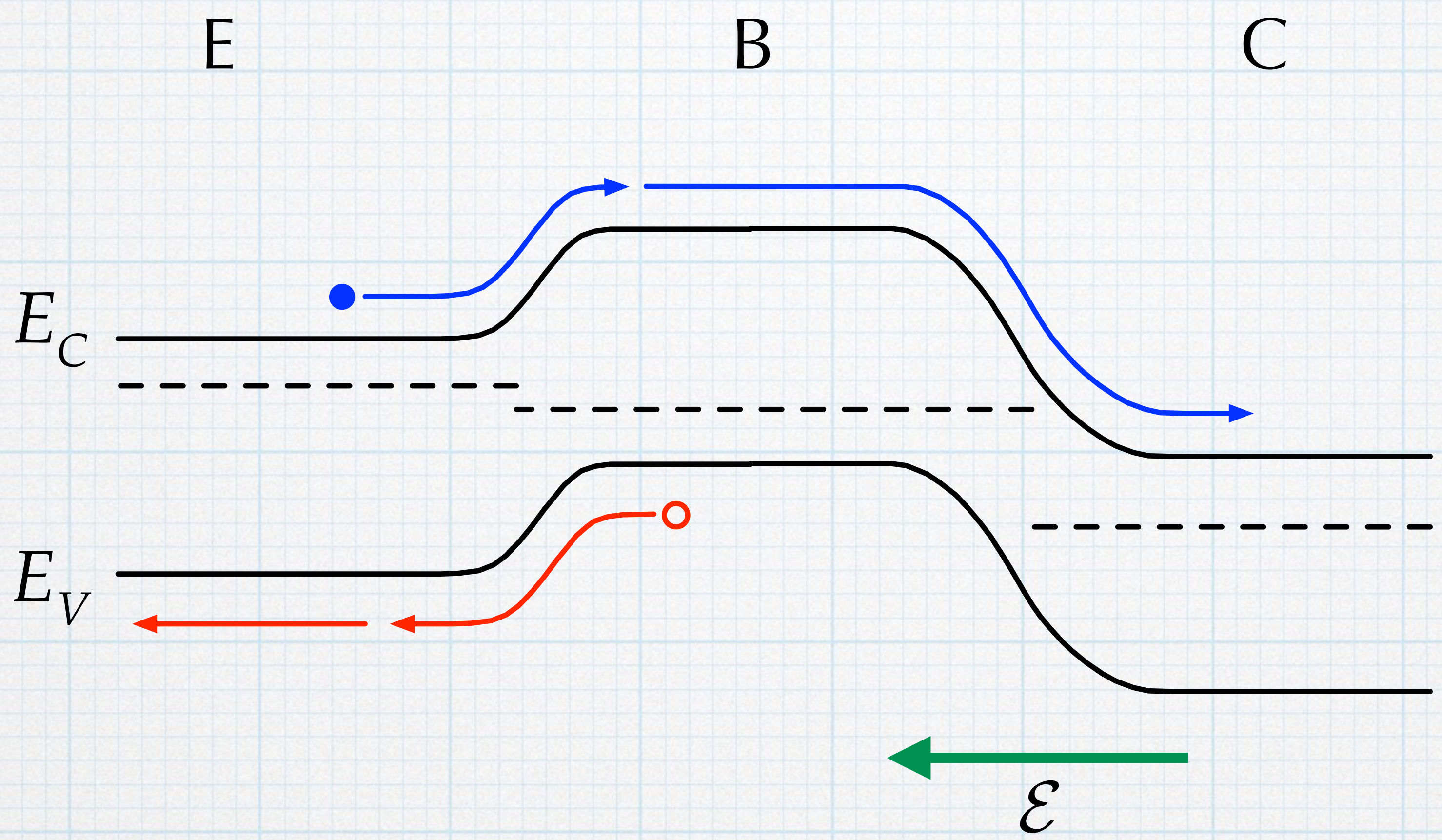
npn forward active bias



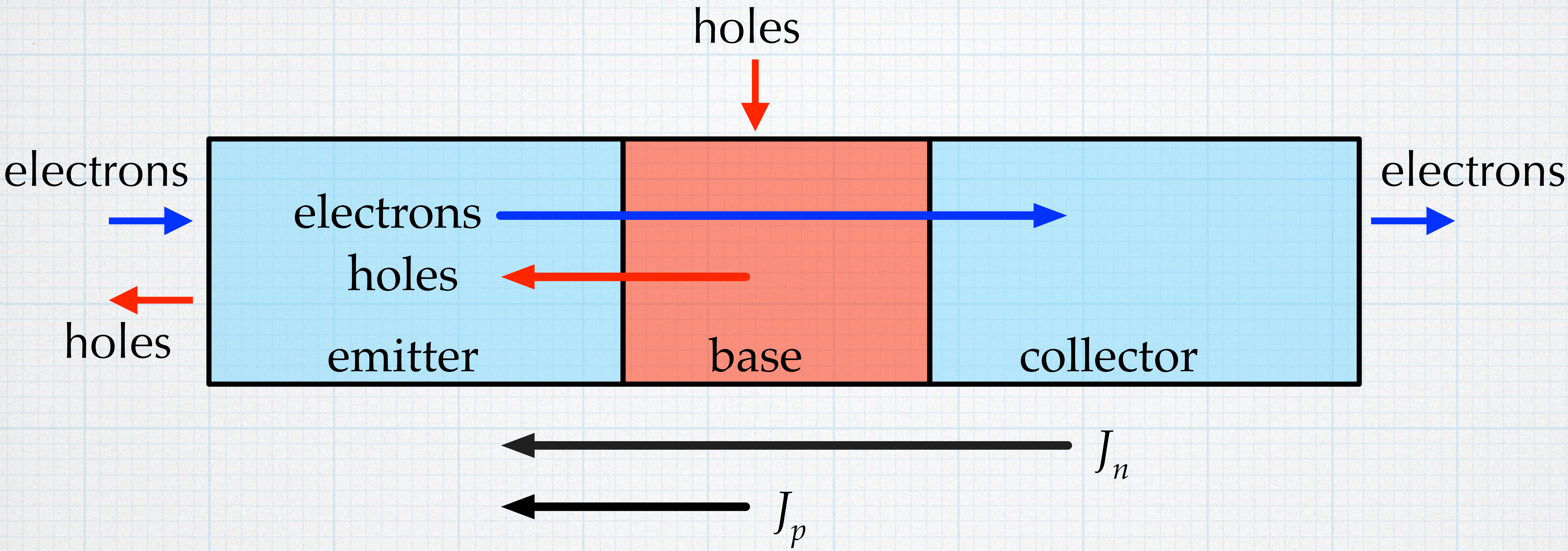
Electrons and holes will be injected across the base-emitter junction. No injection across the base-collector junction.

Injected holes will diffuse across the emitter region and recombine at the contact. Injected electrons diffuse across the base region and end up…where?

npn forward active bias



The electrons will diffuse across the base region. When they get to the high electric field at the B-C, they will be swept across and into the collector. They end up as collector current!



We need to calculate only two internal current: Jn and Jp.

Then the external currents are:

$I_{base} = J_p \cdot A_{BE}$

$I_{collector} = J_n \cdot A_{BE}$

$I_{emitter} = (J_p + J_n) \cdot A_{BE}$

The base and emitter currents depend on the base-emitter junction — not surprising. Collector current depends only on the base-emitter junction — very surprising!

The electron current in the base is determined by the boundary conditions at either end.

Base extends for x = 0 (emitter side) to x = W_B (collector side)

Ignoring depletion-layer widths with the base:

$$n_p(0) = n_{po} \exp\left(\frac{qV_{BE}}{kT}\right)$$

$$n_p(W_B) = n_{po} \exp\left(\frac{qV_{BC}}{kT}\right)$$

(Subtle point: We are using n_p rather than Δn_p.

If base-collector junction is reverse-biased (qV_{BC} < –3kT)

$$n_p(W_B) \approx 0$$

Then, assuming no recombination in the base.

$$\frac{\partial n_p(x)}{\partial x} \approx -\frac{n_p(W_B) - n_p(0)}{W_B} = -\frac{n_{po}}{W_B} \exp\left(\frac{qV_{BE}}{kT}\right)$$

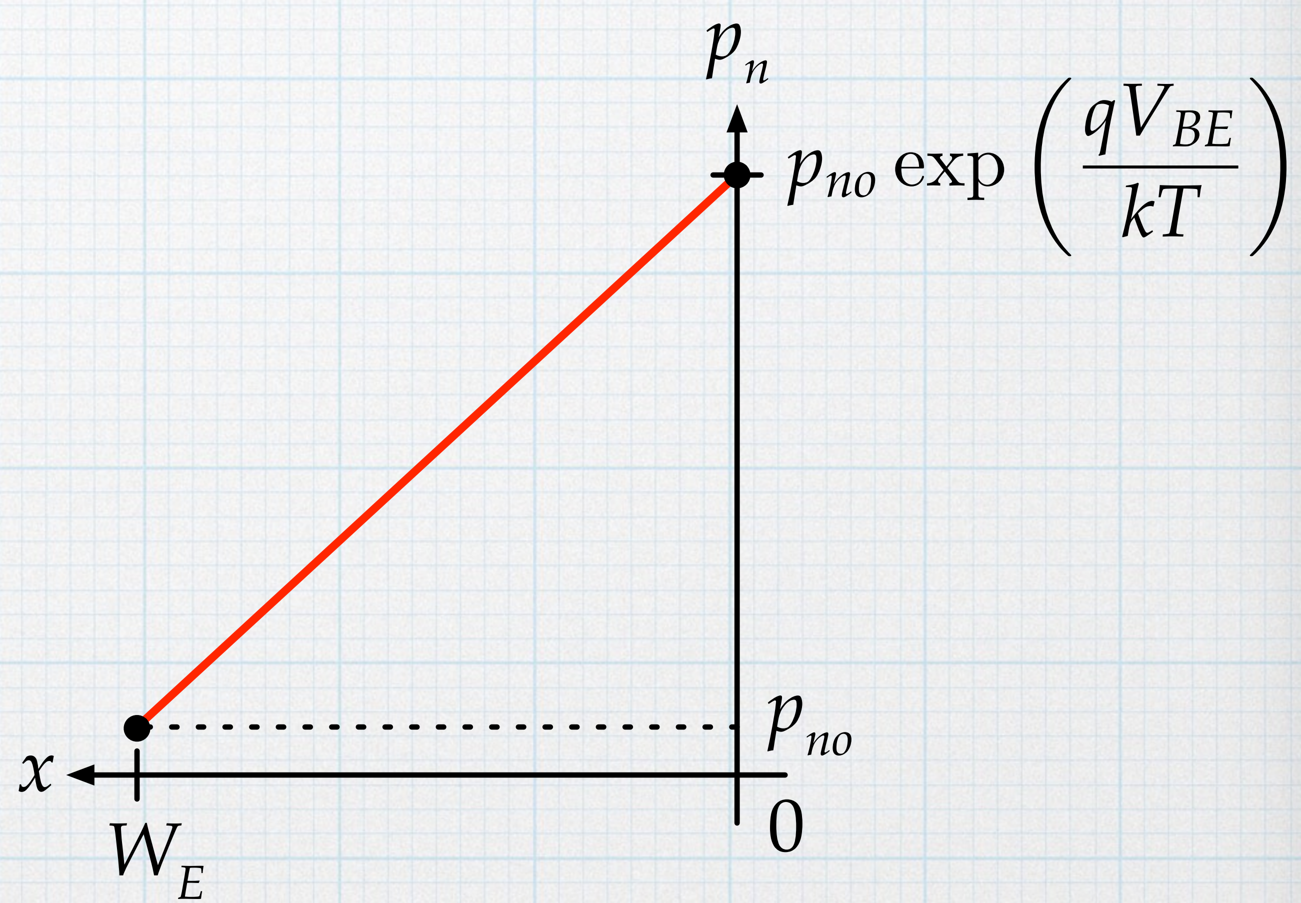
Start by calculating the (boring and useless) hole current. To simplify, we will ignore the depletion-layer width on the emitter side of the B-E junction. Also, we will assume that the minority carrier diffusion length of the holes in the emitter is very long. Therefore, all recombination occurs at the emitter contact, and a straight-line minority carrier profile results.

$$J_p = -qD_p \frac{\partial\left[p_n(x)\right]}{\partial x}$$

$$= \frac{qD_p p_{no}}{W_E}\left[\exp\left(\frac{qV_{BE}}{kT}\right) - 1\right]$$

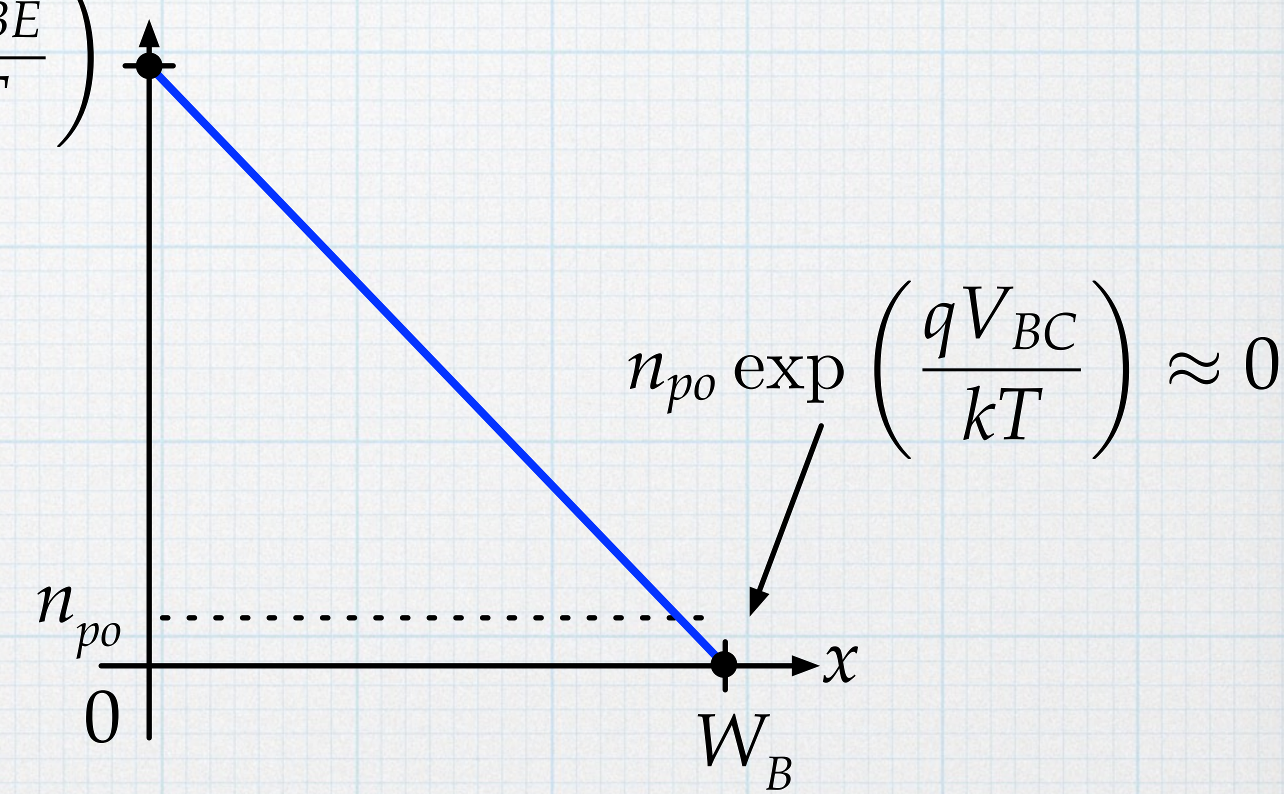
$$\approx \frac{qD_p n_i^2}{N_{DE} W_E}\exp\left(\frac{qV_{BE}}{kT}\right)$$

$$= J_{Sp}\exp\left(\frac{qV_{BE}}{kT}\right)$$



It's just a diode current, as we have seen before.
(Subtle point: The graph is drawn with positive x to the left. So for this situation, a positive hole current is flowing to the left.)

Now do the electrons. Again, ignore depletion-layer widths and recombination. Also, at the collector end of the base, the minority electron concentration is not n_{po}. Instead, using Shockley boundary conditions at the B-C (which is a reverse-biased junction), $n_p(W_B) \rightarrow 0$. This is a subtle distinction, but it is important.



$$J_n = qD_n \frac{\partial \left[n_p(x)\right]}{\partial x}$$

$$= \frac{qD_n n_{po}}{W_B} \exp\left(\frac{qV_{BE}}{kT}\right)$$

$$= \frac{qD_n n_i^2}{N_{AB} W_B} \exp\left(\frac{qV_{BE}}{kT}\right)$$

$$= J_{Sn} \exp\left(\frac{qV_{BE}}{kT}\right)$$

External (terminal) currents.

$$i_B = (A_{BE})\left(J_{Sp}\right)\exp\left(\frac{qV_{BE}}{kT}\right)$$

$$i_C = (A_{BE})\left(J_{Sn}\right)\exp\left(\frac{qV_{BE}}{kT}\right)$$

$$i_E = i_B + i_C = (A_{BE})\left(J_{Sp} + J_{Sn}\right)\exp\left(\frac{qV_{BE}}{kT}\right)$$

All currents depend on V_{BE} in exactly the same way. Although it is a messy exponential, they are all tracking together. It makes sense to look at the ratios:

$$\beta_F = \frac{i_C}{i_B} = \frac{J_{Sn}}{J_{Sp}} = \frac{D_n}{D_P}\cdot\frac{N_{DE}}{N_{AB}}\cdot\frac{W_E}{W_B}$$ Forward current gain.

We like this to be big, meaning that base current results in large electron current. (Small number of holes being injected into the emitter corresponds to a large number of electrons injected into the base.)

$i_C = \beta_F \cdot i_B$

$$\gamma_F = \frac{i_C}{i_E} = \frac{J_{Sn}}{J_{Sp} + J_{Sn}} = \frac{1}{1 + \frac{1}{\beta_F}}$$ emitter efficiency.

The electrons are the interesting part — linking the collector to the emitter. The holes injected into the base are junk. So, to make an ideal transistor, we would like to have all the current crossing the B-E be all electrons and no holes. To achieve this we would want $\beta_F \to \infty$, and $\gamma_F \to 1$. Ideal is not achievable, so make β_F big.

$\frac{D_n}{D_P}$ ranges from 2 to 10, depending on semiconductor.

$\frac{W_E}{W_B}$ could make this big in principle. But in practice, $W_E \sim W_B$.

$\frac{N_{DE}}{N_{AB}}$ can be made very large. This is the primary means for setting β_F.

In practice, we want make β_F “reasonably large”, $50 < \beta_F < 200$.