Chapter 6 - BJTs
Threshold voltage: $V_T \approx 25.9$ mV.
Two junctions in BJT, EBJ (Emitter Base Junction) and CBJ (Collector Base Junction).

Mode	EBJ	CBJ
Cutoff	Reverse	Reverse
Active	Forward	Reverse
Saturation	Forward	Forward

NPN TRANSISTOR:
In the cutoff mode:
$V_{BC} < 0.4$ V | $V_{BE} < 0.5$ V |
$I_C = 0$ | $I_B = 0$
In the active mode:
$V_{BC} < 0.4$ V | $V_{BE} \approx 0.7$ V | $V_{CE} > 0.3$ V
$I_C = \beta I_B$ | $I_B > 0$
In the saturation mode:
$V_{BC} \approx 0.5$ V | $V_{BE} \approx 0.7$ V | $V_{CE_{SAT}} \approx 0.2$ V
$I_C = \beta_{forced} I_B$ | $I_B > 0$

PNP TRANSISTOR:
In the cutoff mode:
$V_{CB} < 0.4$ V | $V_{EB} < 0.5$ V |
$I_C = 0$ | $I_B = 0$
In the active mode:
$V_{CB} < 0.4$ V | $V_{EB} \approx 0.7$ V | $V_{EC} > 0.3$ V
$I_C = \beta I_B$ | $I_B > 0$
In the saturation mode:
$V_{CB} \approx 0.5$ V | $V_{EB} \approx 0.7$ V | $V_{EC_{SAT}} \approx 0.2$ V
$I_C = \beta_{forced} I_B$ | $I_B > 0$

Current relationships in a BJT transistor.
I_S is known as Saturation Current
$i_E = i_C + i_B$ | $i_E = \frac{\beta+1}{\beta} i_C$ | $i_C = \alpha i_E$ | $\alpha = \frac{\beta}{\beta+1}$ | $\beta = \frac{\alpha}{1-\alpha}$
α is the **common-base current gain**.
A BJT is in the Saturation Region if - The CBJ is Forward biased by more than 0.4V - The Ratio of i_C/i_B is lower than β

$$i_C = I_s e^{v_{BE}/V_T}$$

Considering the Early voltage

$$i_C = I_s e^{v_{BE}/V_T}\left(1 + \frac{v_{CE}}{V_A}\right)$$

$$r_o = \left[\frac{\delta i_c}{\delta v_{CE}}\bigg|_{V_{BE}=\text{constant}}\right]^{-1}$$

$$r_o = \frac{V_A + V_{CE}}{I_C}$$

$$r_o = \frac{V_A}{I_C'}$$

Where $I_C' = I_s e^{V_{BE}/V_T}$

$$R_{CE_{\text{SAT}}} \equiv \frac{\delta v_{CE}}{\delta i_C}\bigg|_{i_B = I_B | i_C = I_{C_{\text{SAT}}}}$$

Amplifier stuff
$v_{CE} = V_{CC} - i_C R_C$
Operating point Q occurs at (V_{BE}, V_{CE}).

$$A_v = -\left(\frac{I_C}{V_T}\right) R_C = -\frac{V_{RC}}{V_T}$$

$$V_{RC} = V_{CC} - V_{CE}$$

$$A_{vmax} \approx \frac{V_{CC}}{V_T}$$

Small signal stuff
$i_C = I_C + \frac{I_C}{V_T} v_{be}$
$i_C = I_C + i_c$
$i_c = \frac{I_C}{V_T} v_{be}$

$i_c = g_m v_{be}$

$g_m = \frac{I_C}{V_T}$

Base current:
$i_B = \frac{i_C}{\beta} = \frac{I_C}{\beta} + \frac{1}{\beta}\frac{I_C}{V_T} v_{be}$
$i_B = I_B + i_b$
$i_b = \frac{1}{\beta}\frac{I_C}{V_T} v_{be}$
We know that $I_C/V_T = g_m$ so
$i_b = \frac{g_m}{\beta} v_{be}$
The small-signal input resistance looking into the base, is denoted by r_π and is defined as
$r_\pi \equiv \frac{v_{be}}{i_b} = \frac{\beta}{g_m} = \frac{V_T}{I_B}$

Emitter current:
$i_E = \frac{i_C}{\alpha} = \frac{I_C}{\alpha} + \frac{i_c}{\alpha}$
$i_E = I_E + i_e$
$i_e = \frac{i_c}{\alpha} = \frac{I_C}{\alpha V_T} v_{be} = \frac{I_E}{V_T} v_{be}$
Small-signal resistance looking into the emitter is
$r_e \equiv \frac{v_{be}}{i_e}$
$r_e = \frac{V_T}{I_E}$
$r_e = \frac{\alpha}{g_m} \approx \frac{1}{g_m}$

Relationship between r_π and r_e:
$v_{be} = i_b r_\pi = i_e r_\pi$
$r_\pi = (i_e/i_b) r_e$
$r_\pi = (\beta+1) r_e$

Voltage gain of the amplifier:
$A_v \equiv \frac{v_{ce}}{v_{be}} = -g_m R_C$
$A_v = -\frac{I_C R_C}{V_T}$

Hybrid-π model includes the r_π resistor:
$i_e = \frac{v_{be}}{r_\pi} + g_m v_{be}$
$\frac{v_{be}}{r_\pi}(1 + g_m r_\pi)$
$g_m v_{be} = g_m(i_b r_\pi)$

T-model includes the r_e resistor:
$g_m = I_C/V_T$
$r_e = \frac{V_T}{I_E} = \frac{\alpha}{g_m}$

If we include r_o, the output voltage becomes:
$v_o = -g_m v_{be}(R_C \parallel r_0)$

Three different amplifier configurations:
Common-emitter:
Common-base
Common-collector (also known as **emitter follower**)

But first, for all amplifier configurations:
$R_{in} \equiv \frac{v_i}{i_i}$
$v_i = \frac{R_{in}}{R_{in}+R_{sig}} v_{sig}$

$A_{vo} \equiv \frac{v_o}{v_i}\Big|_{R_L=\infty}$
$R_x = \frac{v_x}{i_x}$

$v_o = \frac{R_L}{R_L+R_o} A_{vo} v_i$
$A_v \equiv \frac{v_o}{v_i} = A_{vo}\frac{R_L}{R_L+R_O}$

$G_v \equiv \frac{v_o}{v_{sig}}$
$G_v = \frac{R_{in}}{R_{in}+R_{sig}} A_v$

$R_{in} = r_\pi$
$v_o = -(g_m v_\pi)(R_C \parallel r_o)$
$A_{vo} = -g_m(R_C \parallel r_o)$

Often, you can neglect r_o, so:
$A_{vo} \approx (-g_m R_C)$

R_o is output resistance.
$R_o = R_C \parallel r_o$

$A_v = -\alpha \frac{R_C \| R_L \| r_o}{r_e}$
$A_v = -\alpha \frac{\text{Total resistance in collector}}{\text{Total resistance in emitter}}$

$G_v = -\beta \frac{R_C \| R_L \| r_o}{R_{sig} + r_\pi}$

Common emitter with emitter resistance:

$$\begin{aligned} A_v &= A_{vo}\frac{R_L}{R_L+R_o} \\ &= -\alpha\frac{R_C}{r_e+R_e}\,\frac{R_L}{R_L+R_C} \\ &= -\alpha\frac{R_C \parallel R_L}{r_e+R_e} \end{aligned}$$

$$A_{vo} = -\frac{\alpha}{r_e}\,\frac{R_C}{1+R_e/r_e}$$

$$A_{vo} = -\frac{g_m R_C}{1+R_e/r_e} \simeq -\frac{g_m R_C}{1+g_m R_e}$$

$$\begin{aligned} v_o &= -i_c R_C \\ &= -\alpha i_e R_C \end{aligned}$$

) gives

$$A_{vo} = -\alpha\frac{R_C}{r_e+R_e}$$

$$\frac{R_{\text{in}}(\text{with } R_e \text{ included})}{R_{\text{in}}(\text{without } R_e)} = \frac{(\beta+1)(r_e+R_e)}{(\beta+1)r_e}$$

$$= 1 + \frac{R_e}{r_e} \simeq 1 + g_m R_e$$

Common base:

$$R_{\text{in}} = r_e$$

$$v_o = -\alpha i_e R_C$$

$$i_e = -\frac{v_i}{r_e}$$

$$A_{vo} \equiv \frac{v_o}{v_i} = \frac{\alpha}{r_e} R_C = g_m R_C$$

$$\frac{v_i}{v_{\text{sig}}} = \frac{R_{\text{in}}}{R_{\text{sig}} + R_{\text{in}}} = \frac{r_e}{R_{\text{sig}} + r_e}$$

$$A_v = g_m (R_C \| R_L)$$

n now be obtained by multipl

$$G_v = \frac{r_e}{R_{\text{sig}} + r_e} g_m (R_C \| R_L)$$

$$= \alpha \frac{R_C \| R_L}{R_{\text{sig}} + r_e}$$

Common collector:

$$R_{\text{in}} = \frac{v_i}{i_b}$$

Substituting for $i_b = i_e/(\beta+1)$ where i_e is given by

$$i_e = \frac{v_i}{r_e + R_L}$$

$$R_{\text{in}} = (\beta+1)(r_e + R_L)$$

$$A_v \equiv \frac{v_o}{v_i} = \frac{R_L}{R_L + r_e}$$

$$A_{vo} = 1$$

$$R_o = r_e$$

$A_{vo} = 1$ yields A_v in Eq. (6.96), thus con

We now proceed to determine the ov

$$\frac{v_i}{v_{\text{sig}}} = \frac{R_{\text{in}}}{R_{\text{in}} + R_{\text{sig}}}$$

$$= \frac{(\beta+1)(r_e + R_L)}{(\beta+1)(r_e + R_L) + R_{\text{sig}}}$$

$$G_v \equiv \frac{v_o}{v_{sig}} = \frac{v_i}{v_{sig}} \times A_v$$

Eq. (6.96), results in

$$G_v = \frac{(\beta+1)R_L}{(\beta+1)R_L + (\beta+1)r_e + R_{\text{sig}}}$$

$$R_{\text{out}} = r_e + \frac{R_{\text{sig}}}{\beta+1}$$