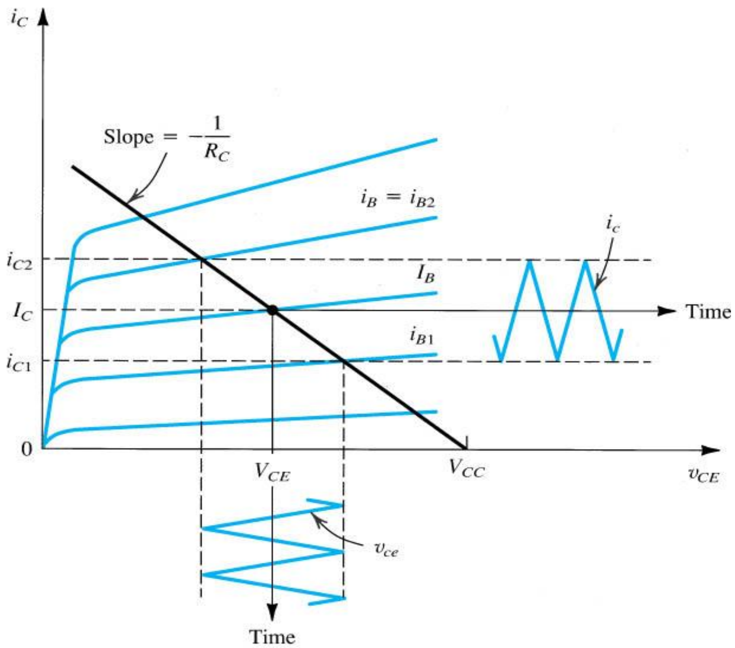
Bipolar Junction Transistors - III (BJT-III)

Analyzing Transistor Amplifiers

Transistor as an Amplifier



- Choose a proper Q-point

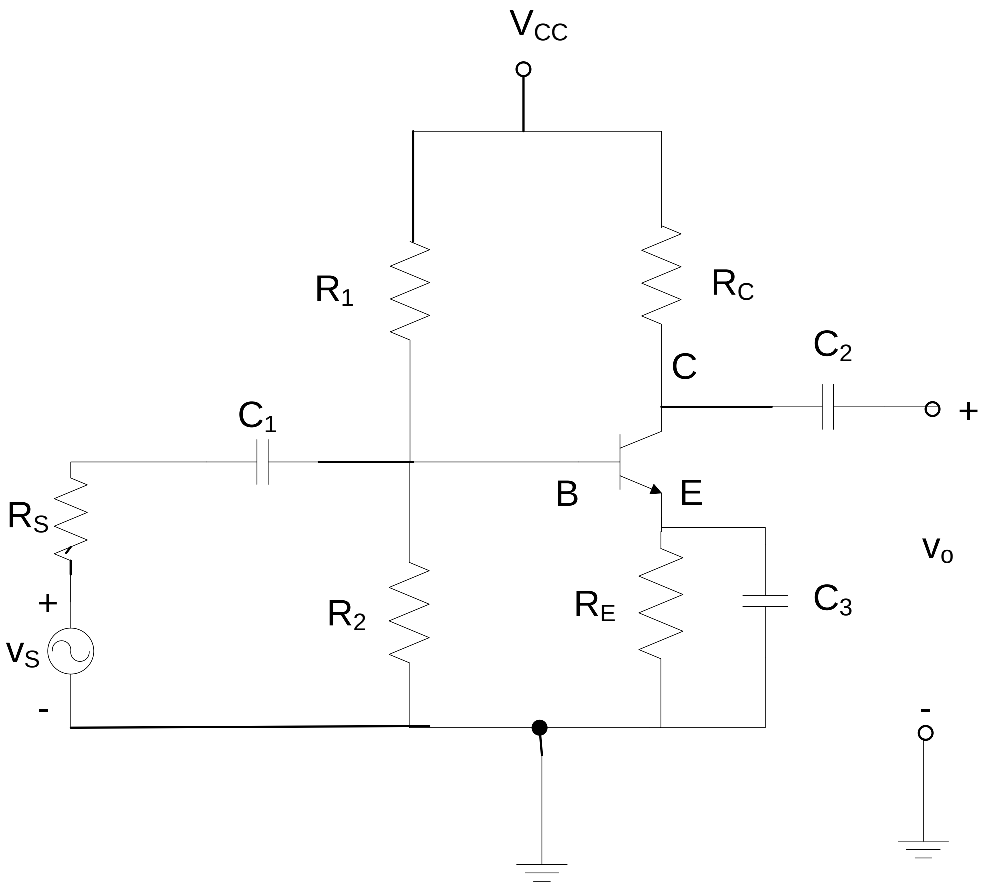
- Make sure that the input is such that the transistor does not get driven outside its active region

To Analyze a BJT Amplifier –

- Short all the bypass capacitors and connect power supplies (i.e. V_{CC}, V_{BB} etc.) to ground. *From the point of view of AC signals, capacitors are SHORT-CIRCUITS and the power supply points are equivalent to GROUND.*

- Replace transistor with its *small signal equivalent model*

Basic BJT Amplifier



C_1, C_2 - Coupling Capacitors

C_3 – Emitter Bypass Capacitor

C_1, C_2, C_3 values are chosen high enough so that under ac these act as a short circuit.

The coupling capacitor (C_1,C_2) is used to pass the ac input signal and block the dc voltage from the preceding circuit. (AC-Coupled Amplifier)

This prevents dc in the circuitry on the left of the coupling capacitor from affecting the bias.

The coupling capacitor also blocks the bias of the transistor from affecting the input signal source.

Special DC-Coupled Amplifiers needed if you want to amplify a signal which has a DC component!

The emitter bypass capacitor (C_3) is used to bypass the R_E and short circuits the ac signal through C_3 since voltage gain decreases because of presence of R_E

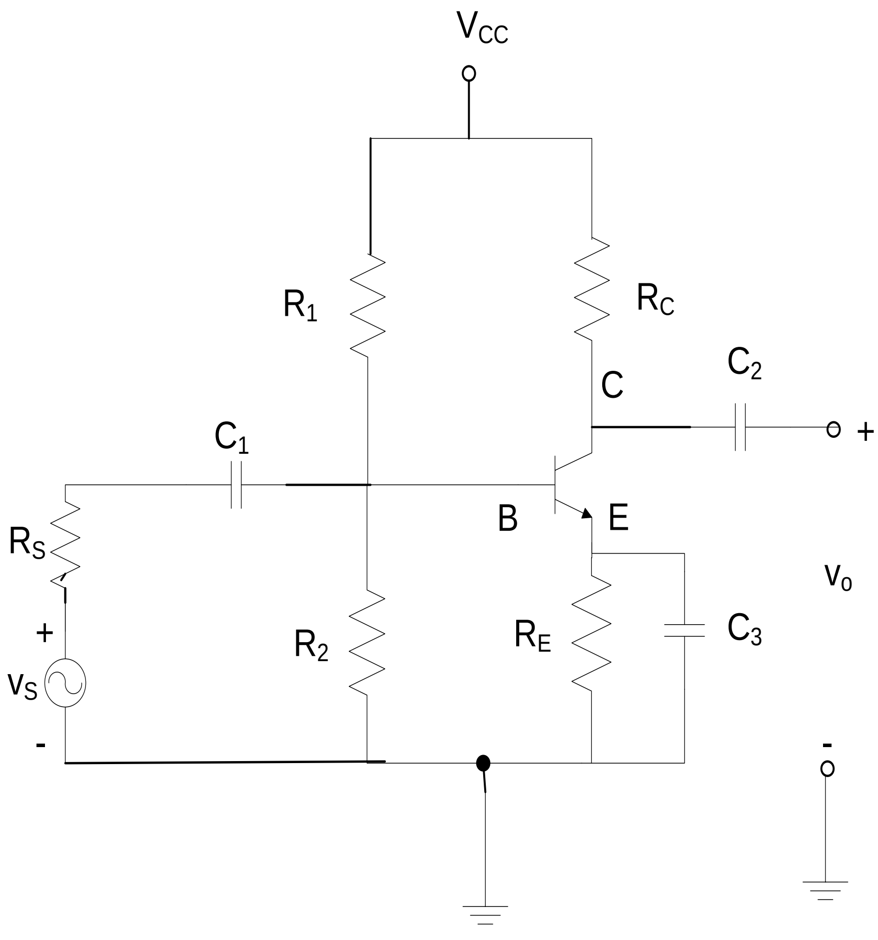
A.C. Equivalent Circuit is obtained by :

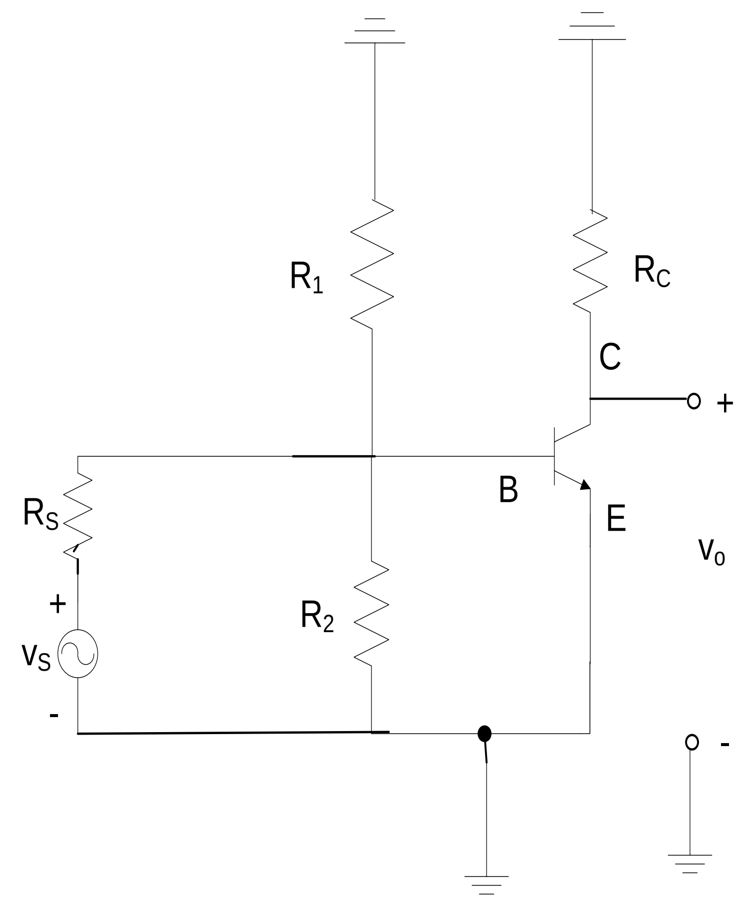
1. Setting all D.C. sources to 0 and replacing them by a short circuit equivalent

2. Replacing all capacitors by a short circuit equivalent

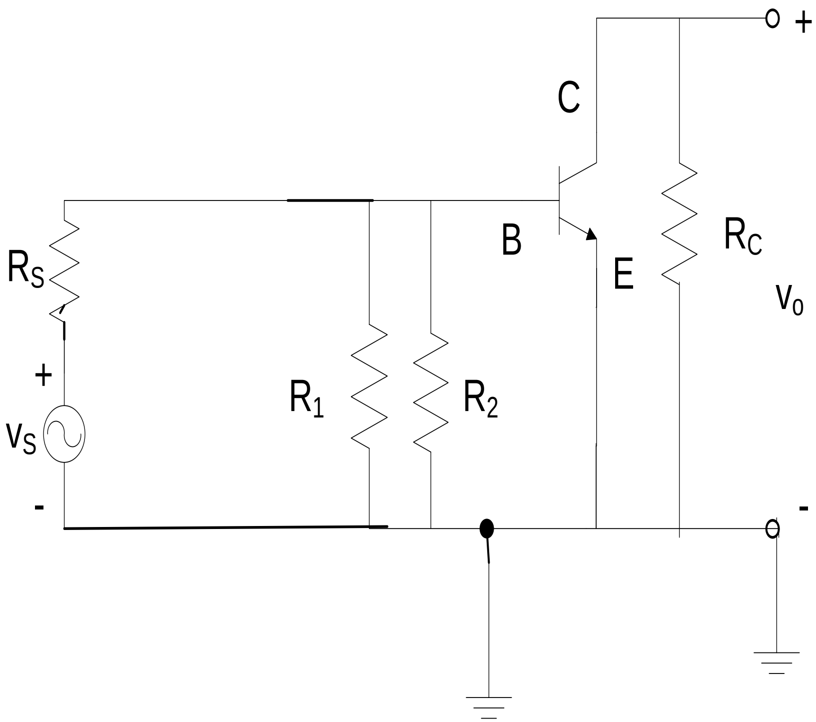
3. Removing all elements bypassed by the short circuit equivalents introduced in steps 1 and 2

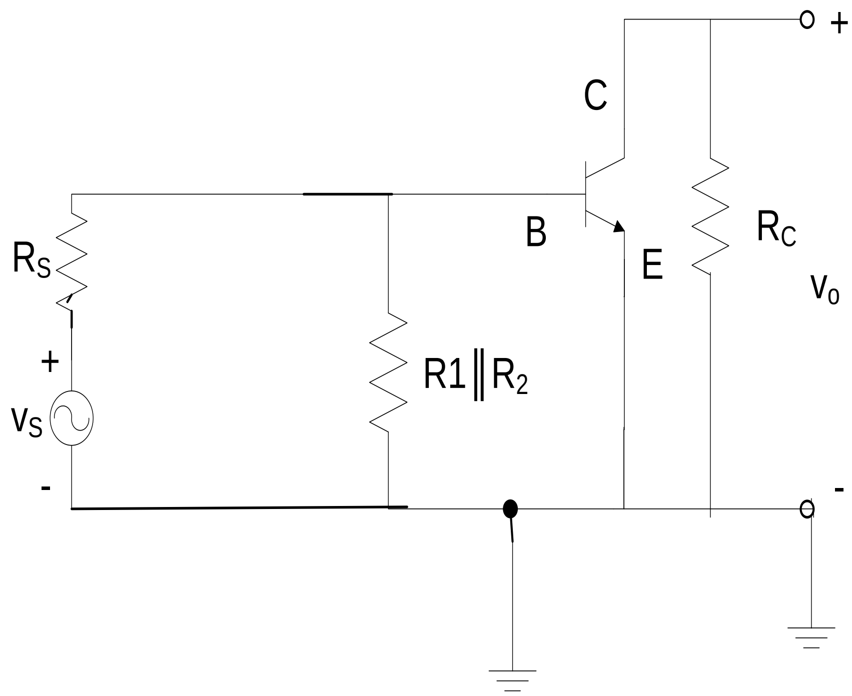
4. Redrawing the network in a more convenient and logical form





Basic BJT Amplifier → **A.C. Equivalent Circuit**





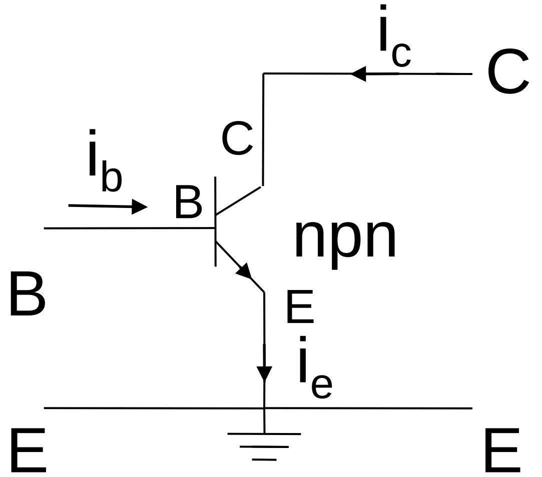
Simplify circuit by replacing R_1 and R_2 with R_B $R_B = R_1 || R_2$

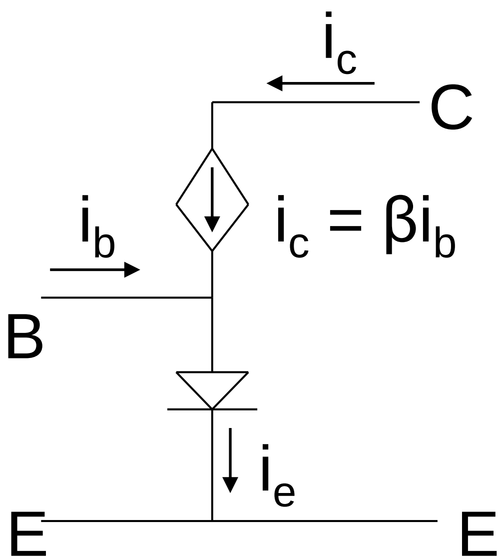
We now replace the transistor with its *small signal equivalent circuit*.

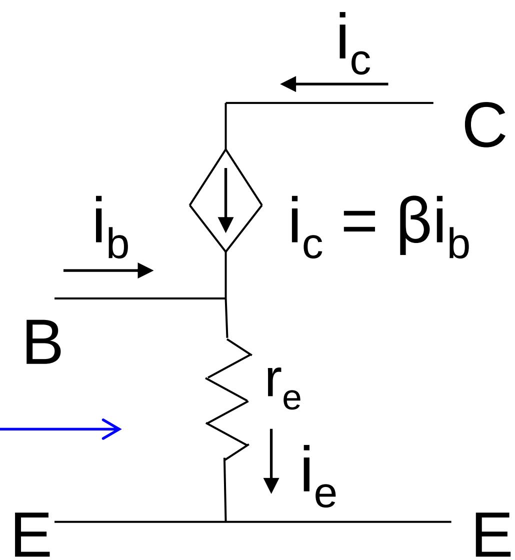
The details of this would be available from the manufacturer's specifications for the transistor.

Small Signal AC Equivalent Model for an NPN Transistor used in the Common Emitter Configuration

(Reverse the current and diode directions for PNP)





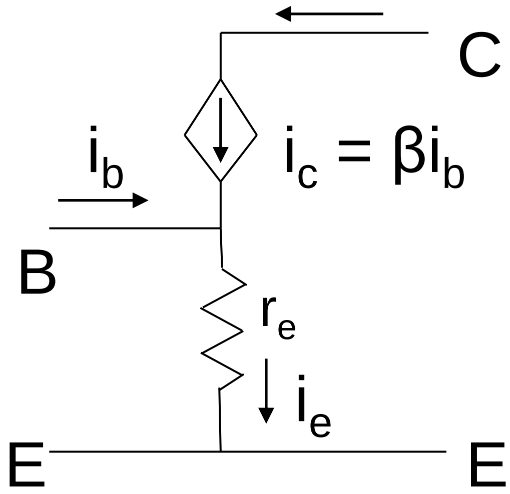


Replace BE diode by its equivalent resistance r_e

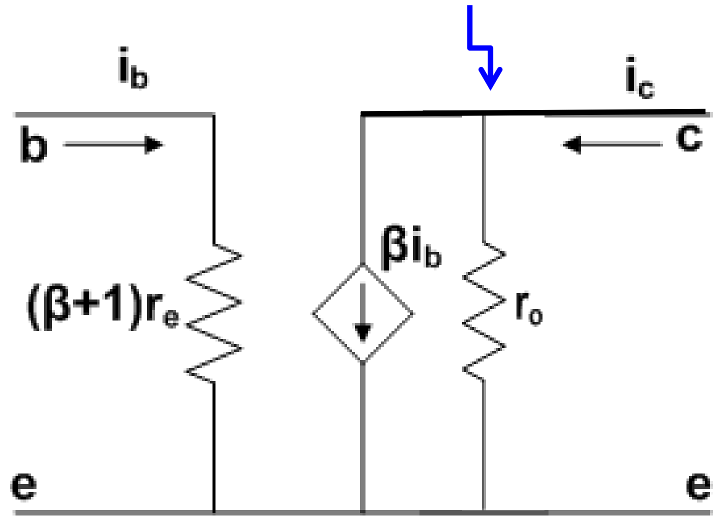
$$r_e = \frac{V_T}{I_E} = \frac{26\ \mathrm{mV}}{I_E}$$

I_E is the DC Emitter Current

Small Signal AC Equivalent Model for an NPN Transistor used in the Common Emitter Configuration



Add r_o to represent the output impedance of the transistor

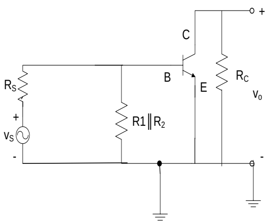


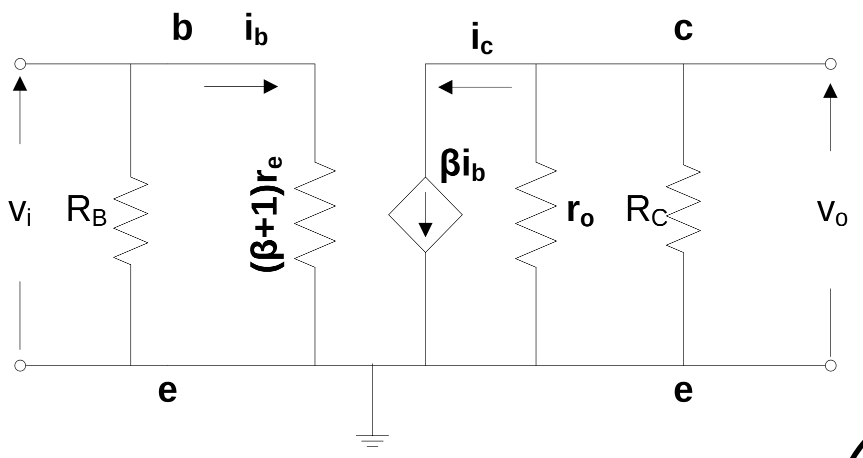
This is known as the r_e Model for the Common Emitter configuration

r_o large (typically 40-50 KΩ and may be ignored in simplifed analysis! (When can we ignore it?)

Using the r_e small signal model (for AC signal analysis)

(Without Source and Load Resistances)





$$i_b = \frac{v_i}{(\beta+1)r_e}$$

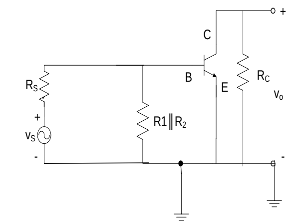
$$\frac{v_o}{r_o \parallel R_C} = -\beta i_b$$

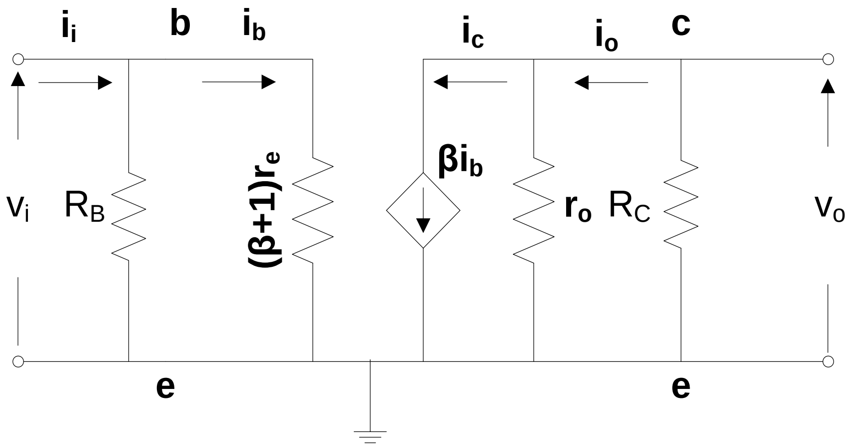
$$A_v = \frac{v_o}{v_i} = -\left(\frac{\beta}{\beta+1}\right)\frac{R_C \parallel r_o}{r_e}$$

Note the phase reversal between input and output

For $r_o >> R_C$ and $\beta >> 1$ $\quad A_v = -\frac{R_C}{r_e}$

(Without Source and Load Resistances)





Output Impedance

$$Z_O = R_C \| r_o$$

$$i_i = \frac{v_i}{[R_B \| (\beta+1)r_e]} \Rightarrow$$

Input Impedance

$$Z_i = \frac{v_i}{i_i} = R_B \| (\beta+1)r_e$$

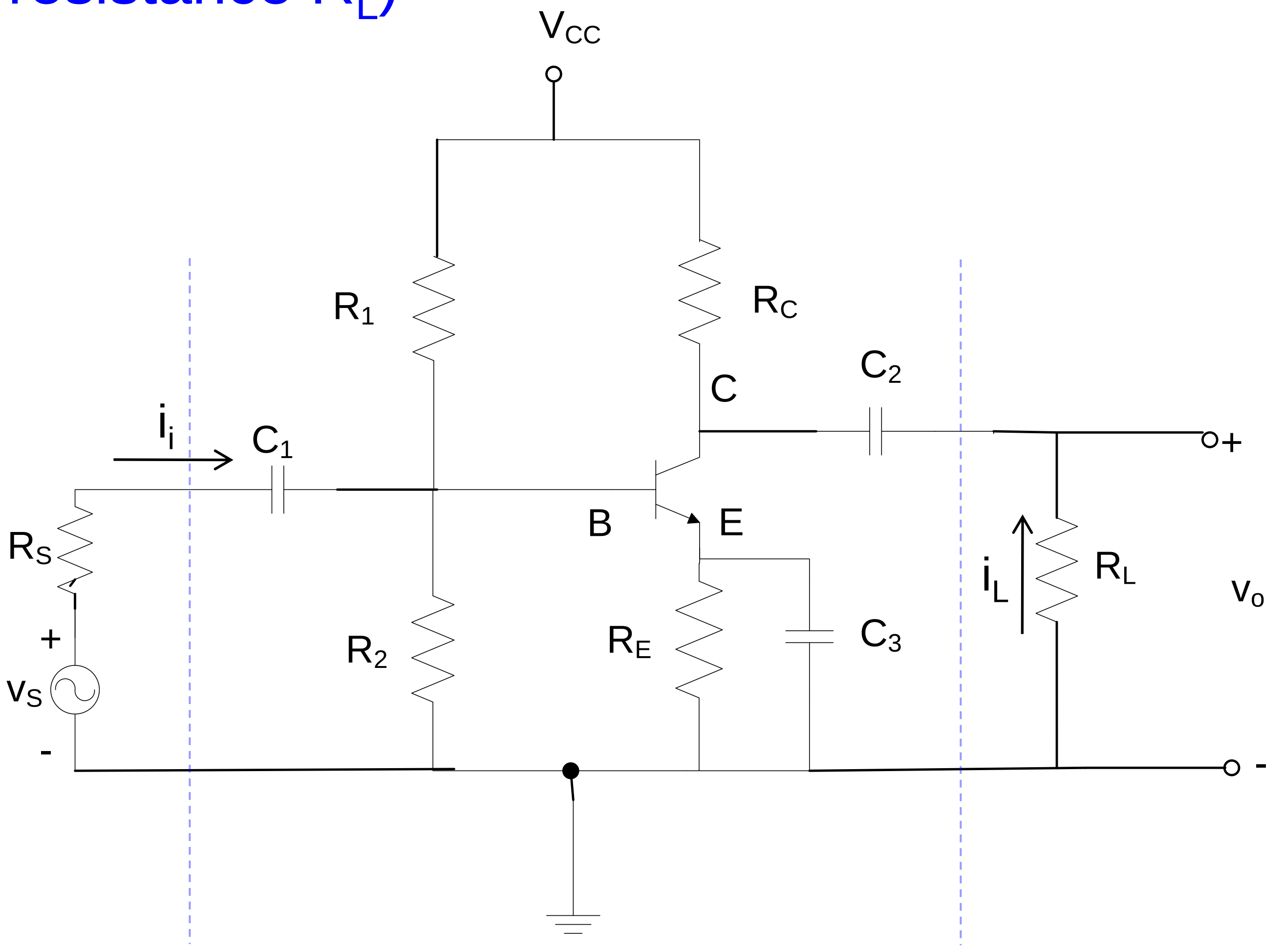
$$i_b = i_i \frac{R_B}{R_B + (\beta+1)r_e}$$

$$i_o = \beta i_b \frac{r_o}{r_o + R_C}$$

Current Gain

$$A_i = \frac{i_o}{i_i} = \beta\left(\frac{R_B}{R_B + (\beta+1)r_e}\right)\left(\frac{r_o}{r_o + R_C}\right)$$

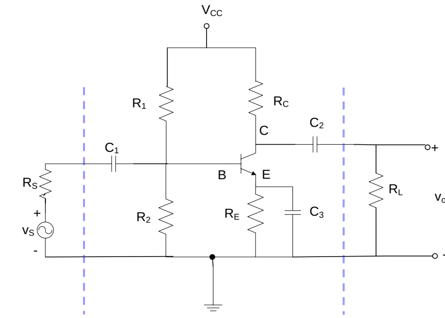
Basic BJT Amplifier (with source resistance R_S and load resistance R_L)



$$A_V^* = \frac{v_o}{v_S}$$

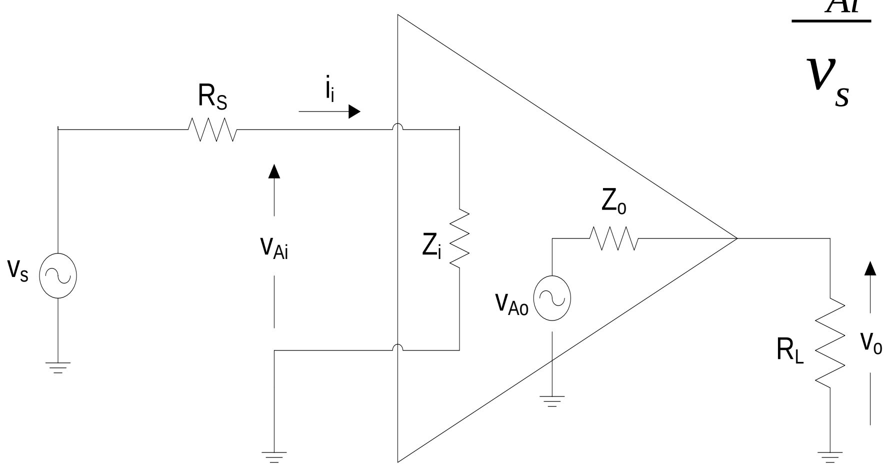
Note that the circuit between the dotted lines is what we have analyzed before

Finding A_V Voltage Gain



1. Use the same procedure as before except you now have to add R_S and R_L to the circuit **Try this approach yourself!**

2. Use the results we got for A_v, Z_i and Z_o for the earlier case. **This approach is given below.**

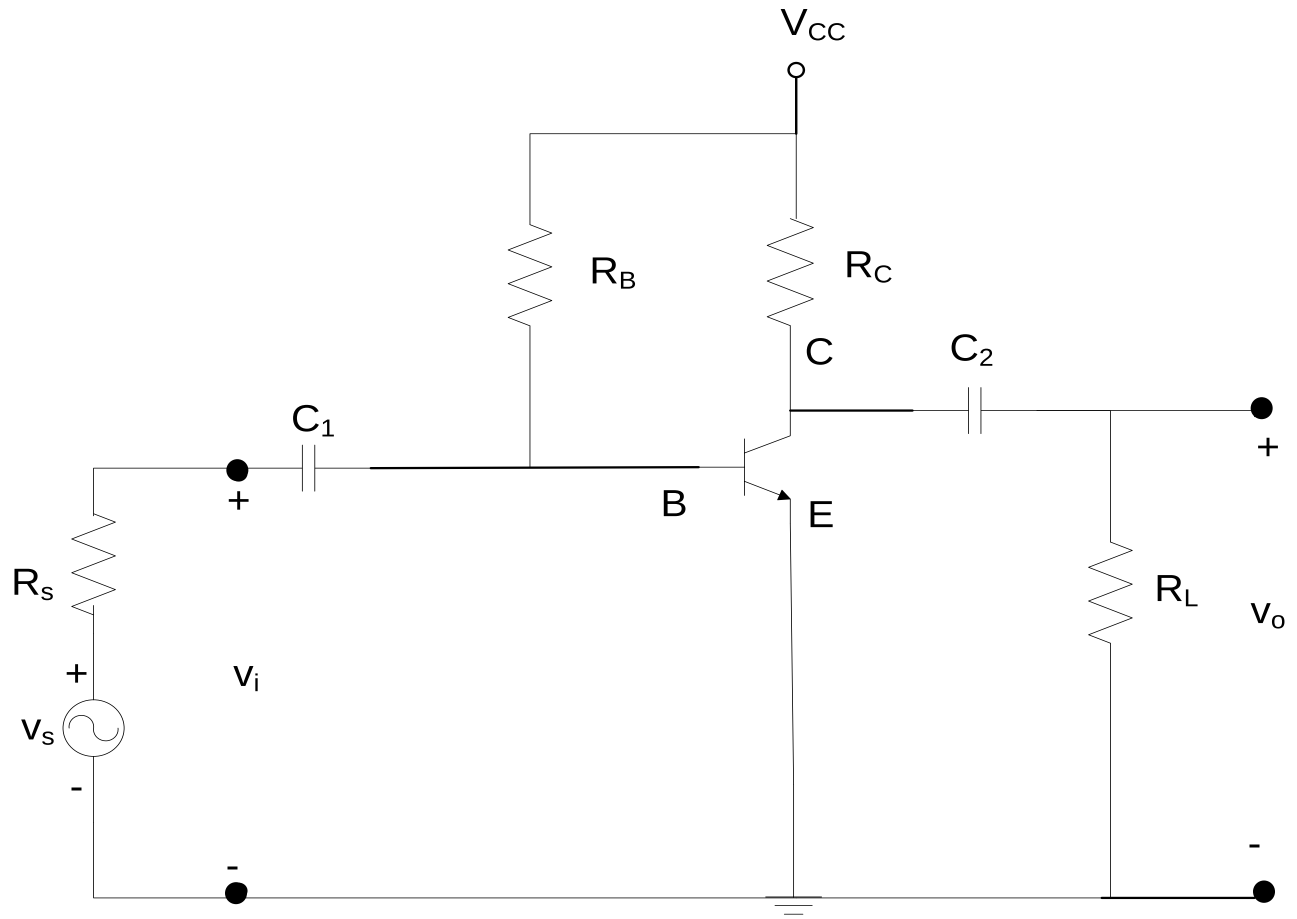


$$\frac{v_{Ai}}{v_s} = \frac{Z_i}{Z_i + R_s} \qquad \frac{v_o}{v_{Ao}} = \frac{R_L}{R_L + Z_o}$$

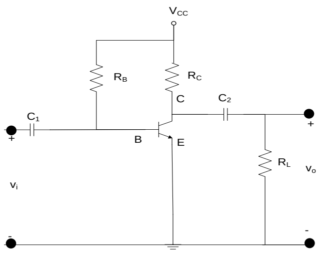
$$A_v^* = \frac{v_o}{v_s} = \frac{v_o}{v_{Ao}} \frac{v_{Ao}}{v_{Ai}} \frac{v_{Ai}}{v_s}$$

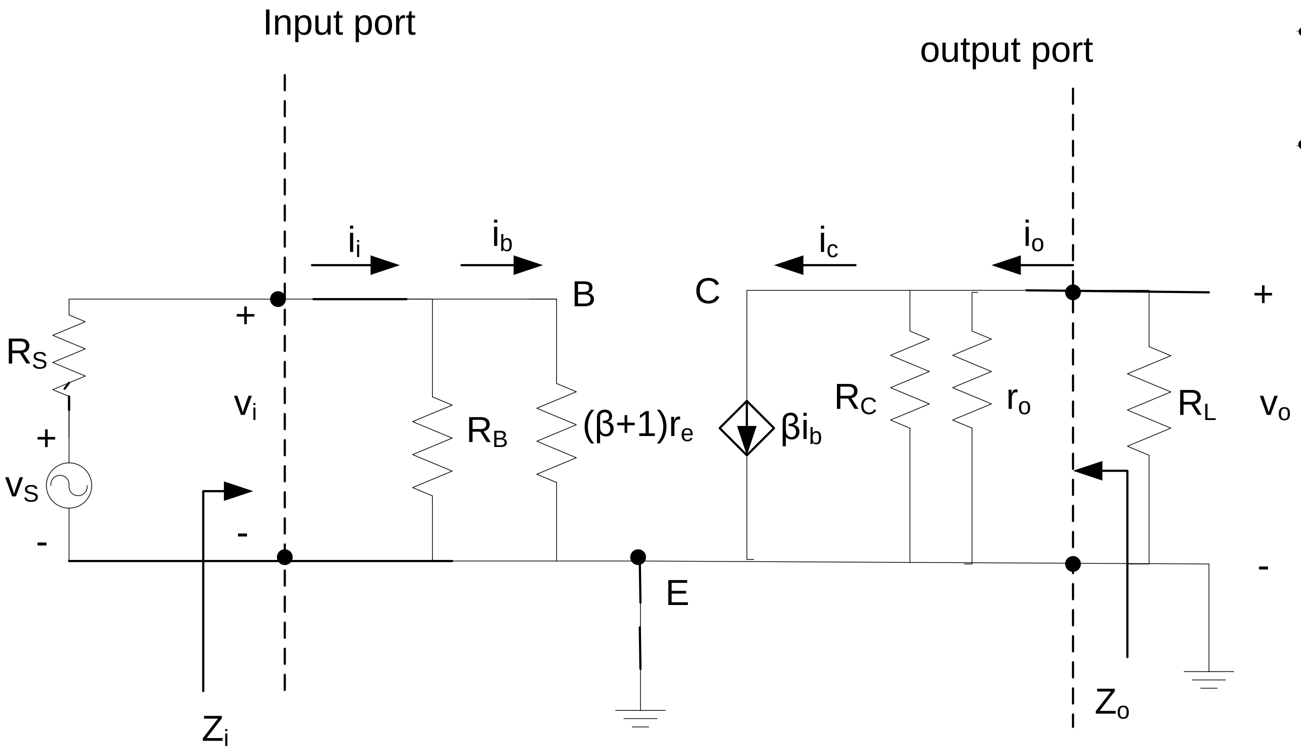
$$= \frac{R_L}{R_L + Z_o} A_v \frac{Z_i}{Z_i + R_s}$$

Fixed Bias Transistor Amplifier



Fixed Bias Transistor Amplifier

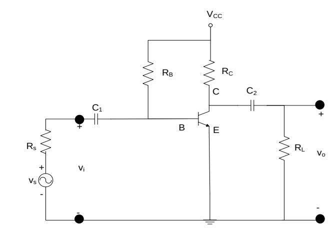




$$Z_i = R_B \,||\, (\beta+1)r_e$$

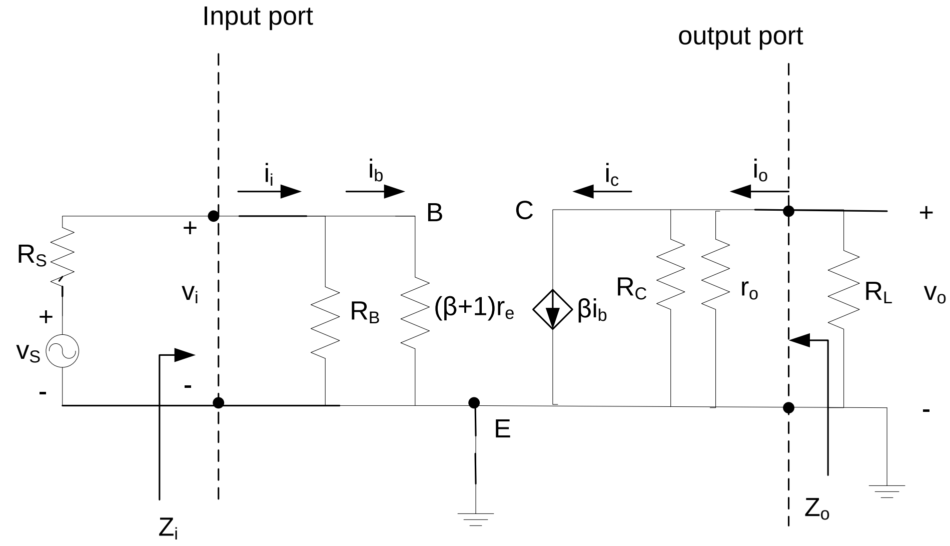
$$Z_o = R_C \,||\, r_o \cong R_C \qquad \text{if } r_o >> R_C$$

Fixed Bias Transistor Amplifier



$$i_b = \left(\frac{v_S}{R_S + R_B \parallel (\beta+1) r_e} \right) \left(\frac{R_B}{R_B + (\beta+1) r_e} \right)$$

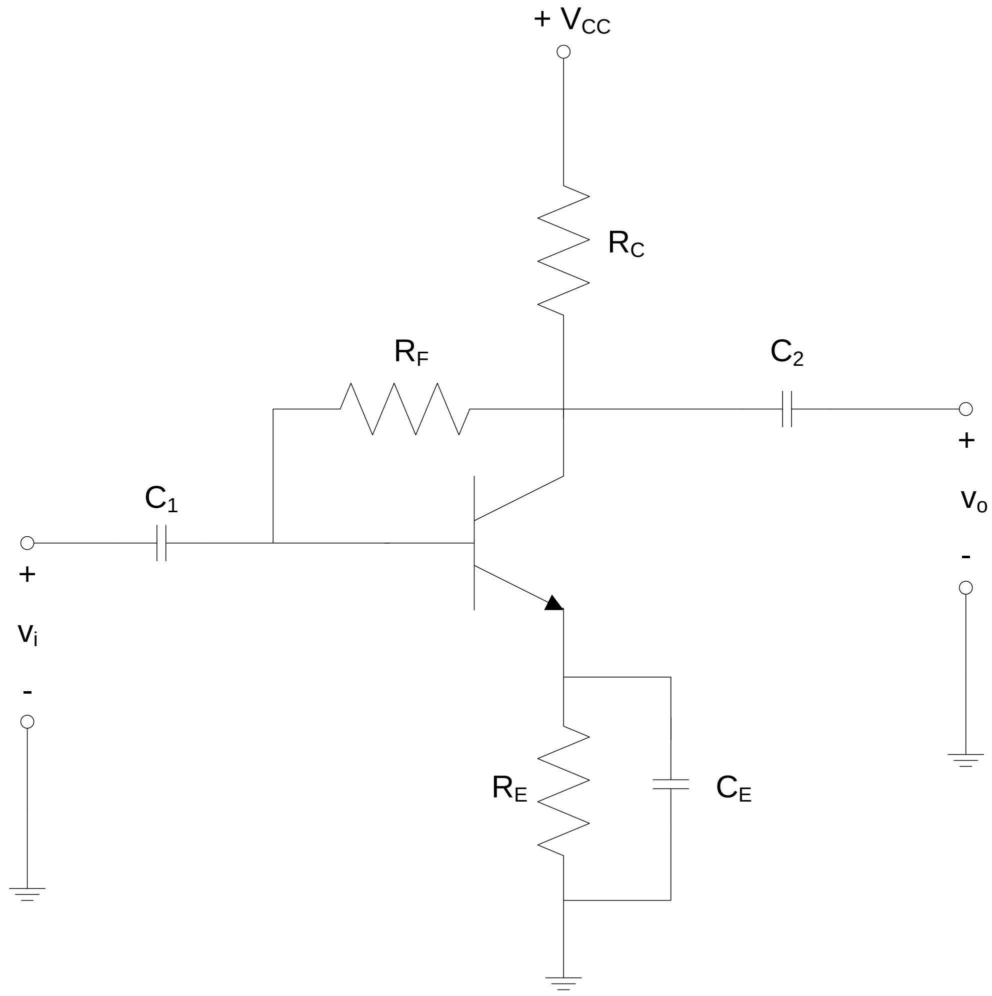
$$v_o = -\beta i_b (R_C \parallel r_o \parallel R_L) \cong -\beta i_b (R_C \parallel R_L)$$



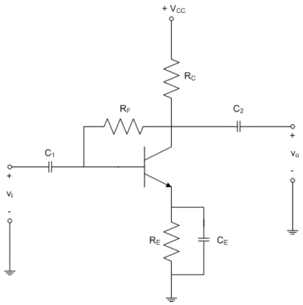
$$A_V = \frac{v_o}{v_s} = -\left(\frac{\beta (R_C \parallel R_L)}{R_S + R_B \parallel (\beta+1) r_e} \right) \left(\frac{R_B \parallel (\beta+1) r_e}{(\beta+1) r_e} \right)$$

$$\cong -\frac{R_C \parallel R_L}{r_e} \qquad \text{for} \qquad R_B \parallel (\beta+1) r_e >> R_S$$

Emitter and Collector Feedback Bias



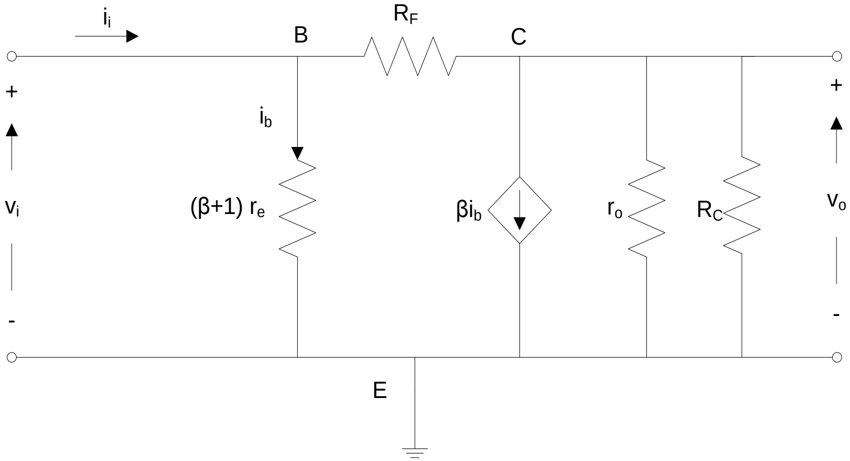
Emitter and Collector Feedback Bias



Voltage Gain Calculation

$$i_b = \frac{v_i}{(\beta+1)r_e}$$

$$\frac{v_i - v_o}{R_F} - \frac{v_o}{r_o \parallel R_C} = \beta i_b = \frac{\beta}{\beta+1}\frac{v_i}{r_e}$$



We can of course solve this to get the exact gain $A_V = v_o / v_i$

Assuming β>>1 and $r_o >> R_C$, we get

$$-v_o\left[\frac{1}{R_F} + \frac{1}{R_C}\right] = v_i\left[\frac{1}{r_e} - \frac{1}{R_F}\right]$$

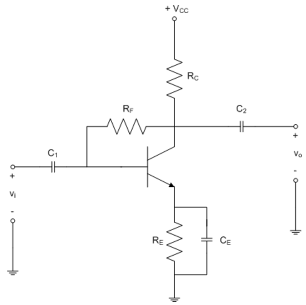
Since typically, $r_e << R_F$

$$A_v = \frac{v_o}{v_i} \cong -\frac{R_F \parallel R_C}{r_e} \cong -\frac{R_C}{r_e}$$

For $R_F >> R_C$

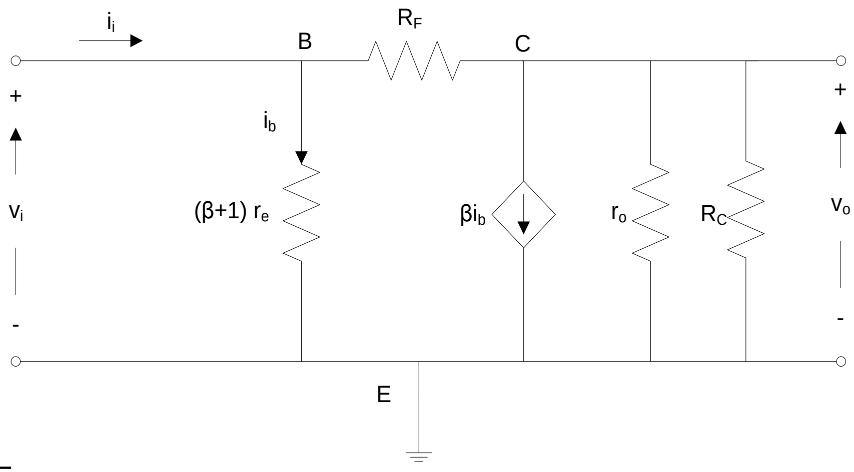
Emitter and Collector Feedback Bias

Calculating the Input Impedance



$$i_i = \frac{v_i}{(\beta+1)r_e} + \frac{v_i - v_o}{R_F}$$

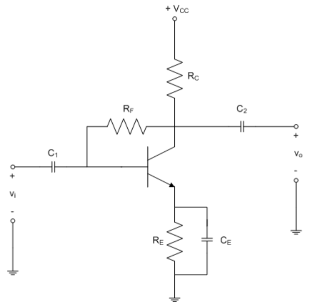
$$\cong v_i\left[\frac{1}{\beta r_e} + \frac{1}{R_F} + \frac{R_C}{R_F r_e}\right]$$



Input Impedance

$$Z_i = \frac{v_i}{i_i} \cong \frac{1}{\left[\frac{1}{\beta r_e} + \frac{1}{R_F} + \frac{R_C}{R_F r_e}\right]} \cong \frac{r_e}{\frac{1}{\beta} + \frac{R_C}{R_F}}$$

Emitter and Collector Feedback Bias



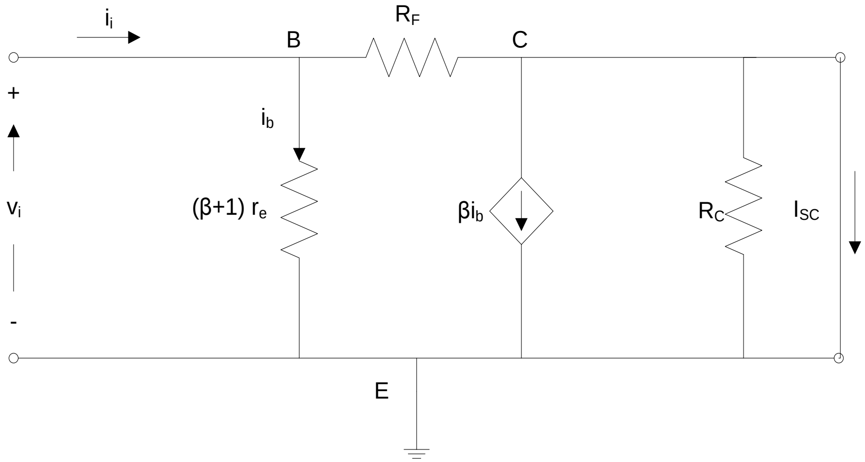
Calculating the Output Impedance

We do this as $Z_o = V_{OC}/I_{SC}$

$V_{OC} = v_o = A_V v_i$ and then use the following circuit to get I_{SC} Ignore r_o

$$I_{SC} = \frac{v_i}{R_F} - \beta i_b = \frac{v_i}{R_F} - \frac{\beta}{\beta+1}\frac{v_i}{r_e}$$

$$\cong -\frac{v_i}{r_e}$$

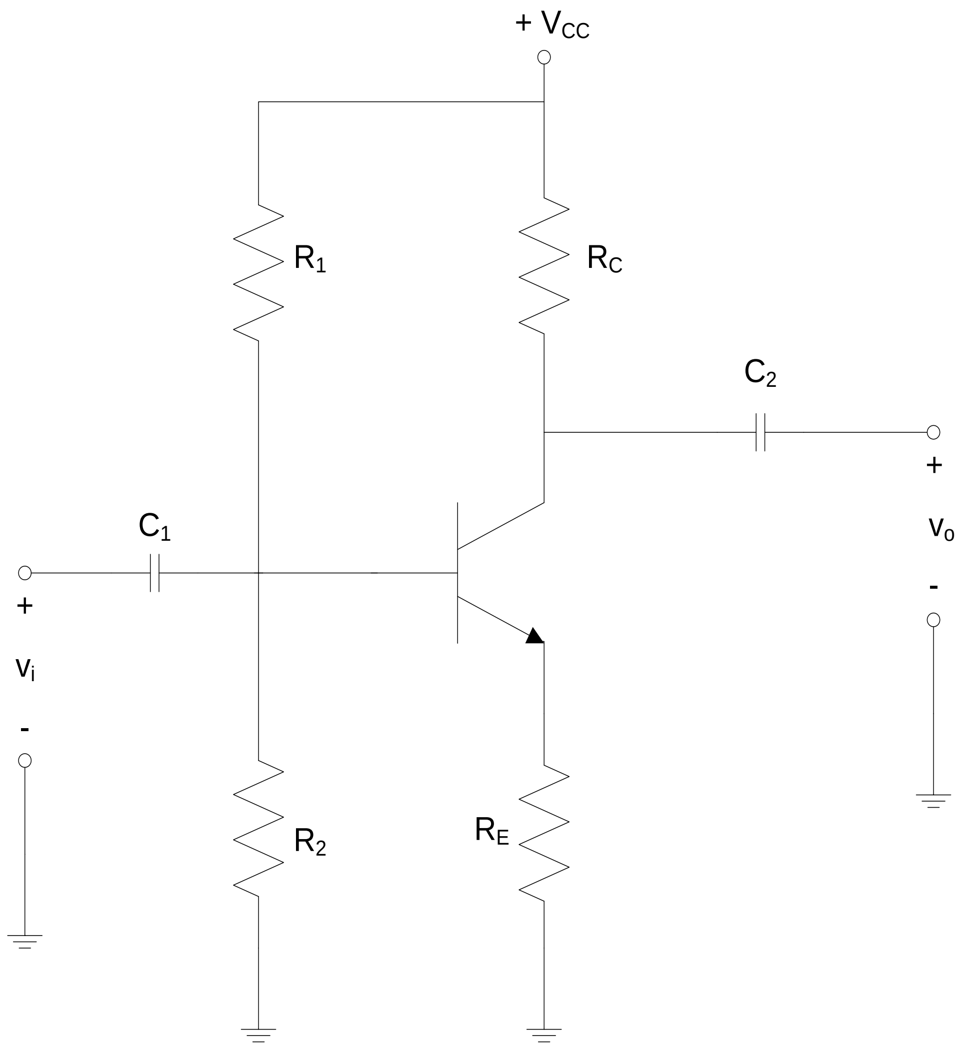


Using $A_v = -\frac{R_C \parallel R_F}{r_e}$ we get

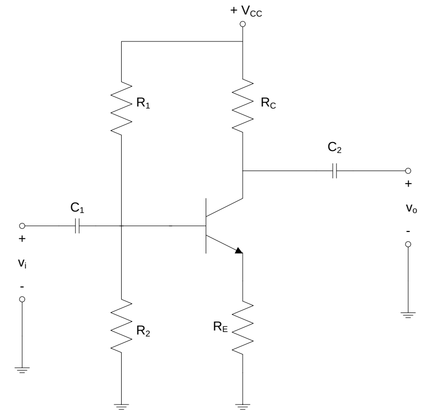
Output Impedance $Z_o = R_C \parallel R_F$

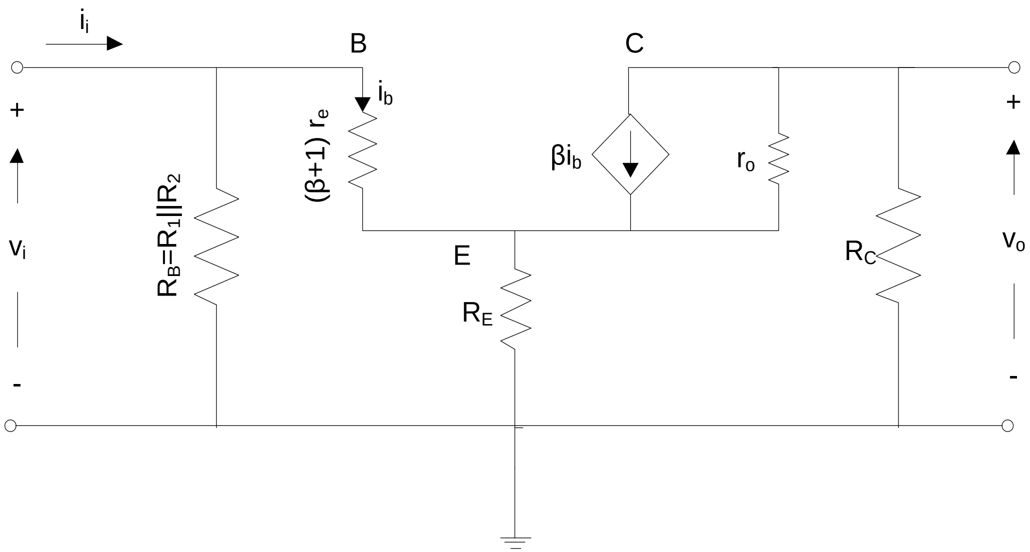
or $Z_o = R_C \parallel r_o \parallel R_F$ if we take r_o into account

Amplifier with Un-bypassed Emitter Resistance



Amplifier with Un-bypassed Emitter Resistance



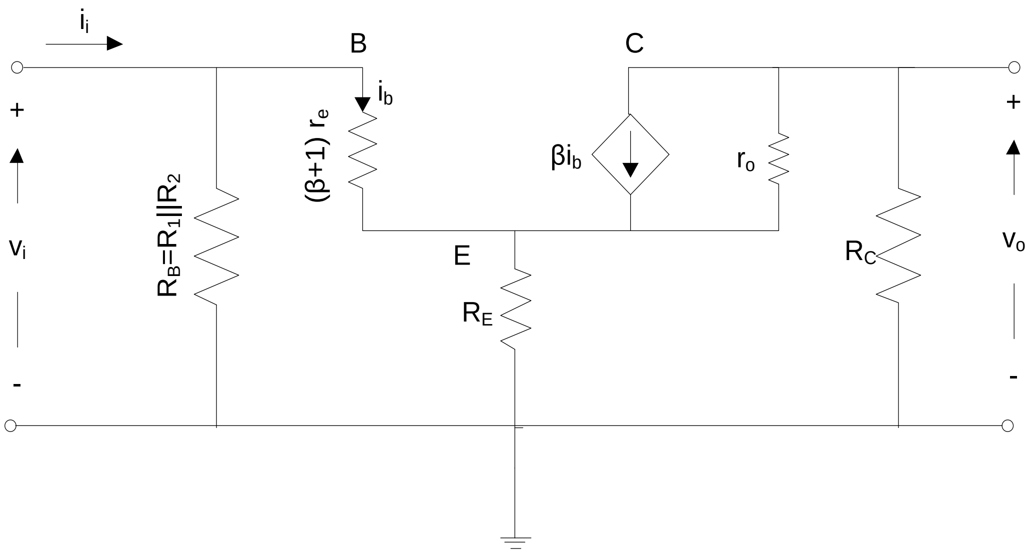


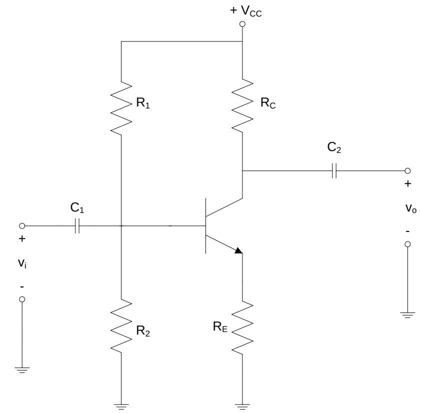
$$v_i = (\beta+1)i_b r_e + (\beta+1)i_b R_E \qquad v_o = -\beta i_b R_C$$ Neglecting r_o

Voltage Gain $$A_V = \frac{v_o}{v_i} = -\left(\frac{\beta}{\beta+1}\right)\frac{R_C}{r_e + R_E} \cong -\frac{R_C}{r_e + R_E} \cong -\frac{R_C}{R_E}$$

Note that voltage gain reduces compared to the circuit where the emitter resistance has been bypassed using a capacitor!

Amplifier with Un-bypassed Emitter Resistance





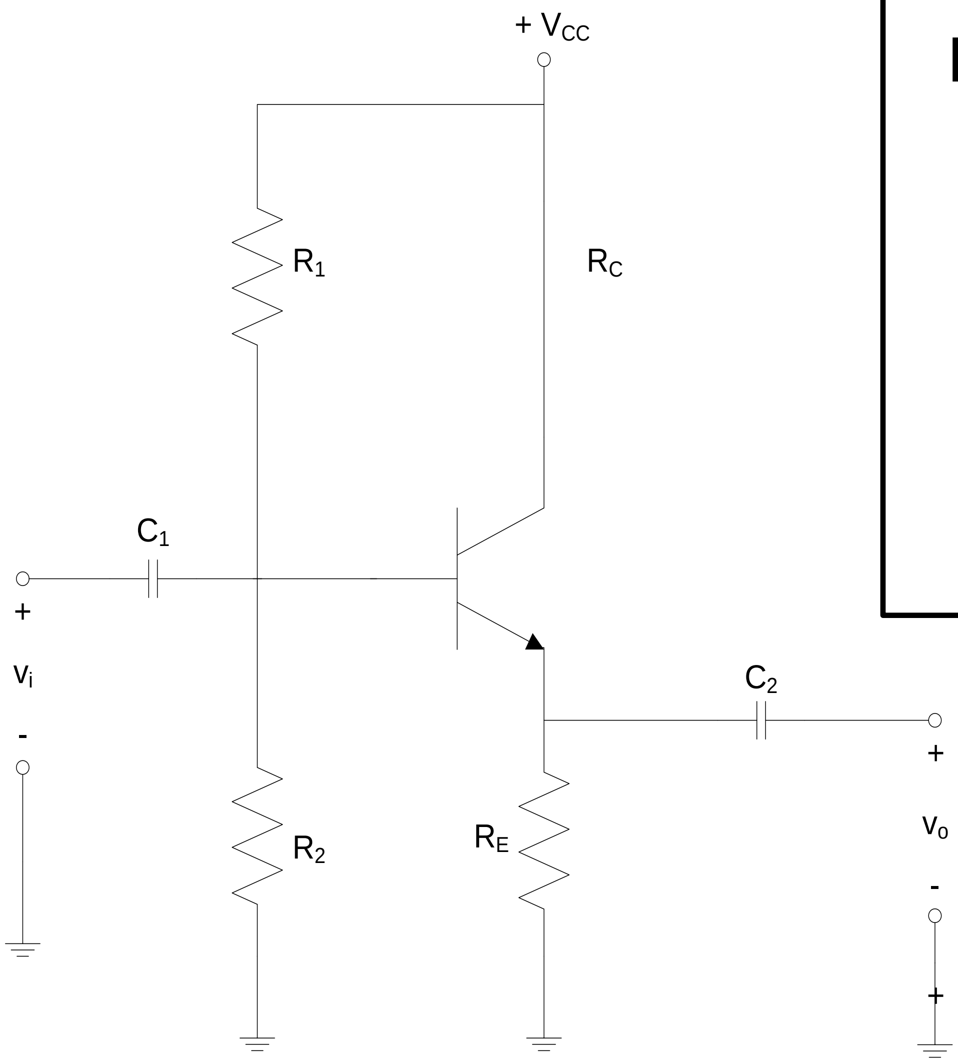
Output Impedance $Z_O = R_C$ (neglecting r_o)

$$v_i = (\beta+1) i_b r_e + (\beta+1) i_b R_E \quad \Rightarrow \quad \frac{v_i}{i_b} = (\beta+1)(r_e + R_E) = Z_{BE} \quad \text{(say)}$$

Input Impedance $Z_i = R_B \,||\, Z_{BE} = R_B \,||\, \left[(\beta+1)(r_e + R_e)\right]$

(higher than before)

Emitter Follower Circuit



Bias (Q-Point)

$R_B = R_1 || R_2$

$V_{BB} = V_{CC} R_2 / (R_1 + R_2)$

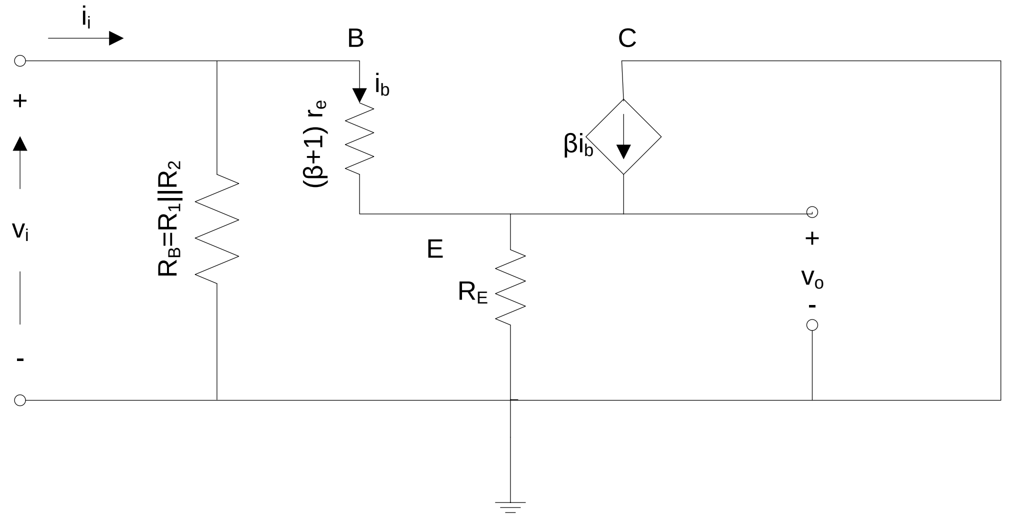
$$I_B = \frac{V_{BB} - 0.7}{R_B + (\beta + 1) R_E}$$

$$I_C = \beta I_B$$

$$V_{CE} = V_{CC} - (\beta + 1) I_B R_E$$

Emitter Follower Circuit

Simplified equivalent circuit omitting r_o



$$v_i = i_b(\beta+1)r_e + (\beta+1)i_b R_E$$
$$= (\beta+1)i_b(r_e + R_E)$$
$$v_0 = (\beta+1)i_b R_E$$

Voltage Gain

$$A_v = \frac{v_0}{v_i} = \frac{R_E}{r_e + R_E} < 1$$

Input Impedance $\quad Z_i = \dfrac{v_i}{i_i} = R_B \,||\, \left[(\beta+1)(r_e + R_E)\right]$

$$V_{OC} = v_o = v_i \frac{R_E}{r_e + R_E} \qquad I_{SC} = (\beta+1)i_{b,SC} \qquad i_{b,SC} = \frac{v_i}{(\beta+1)r_e}$$

Output Impedance $\quad Z_o = \dfrac{V_{OC}}{I_{SC}} = r_e \,||\, R_E \cong r_e$

Why use the Emitter-Follower Configuration?

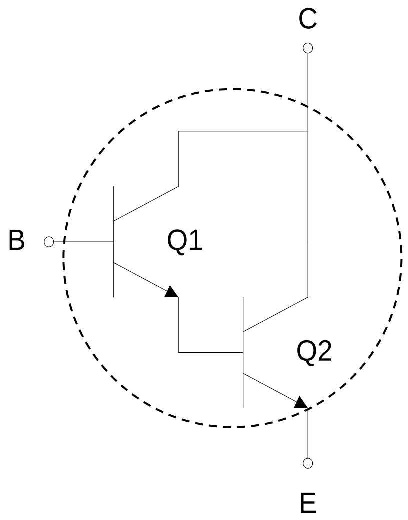
The Emitter Follower circuit does not provide any voltage gain (Gain ≈ 1) but is useful for impedance matching purposes.

For example, as an interface between a high-output impedance sensor and a low input impedance detection circuit.

This is because it has a high input impedance and a low output impedance – recall that impedances should be matched for maximum power transfer.

Darlington Connection

How can we get very large values of β?



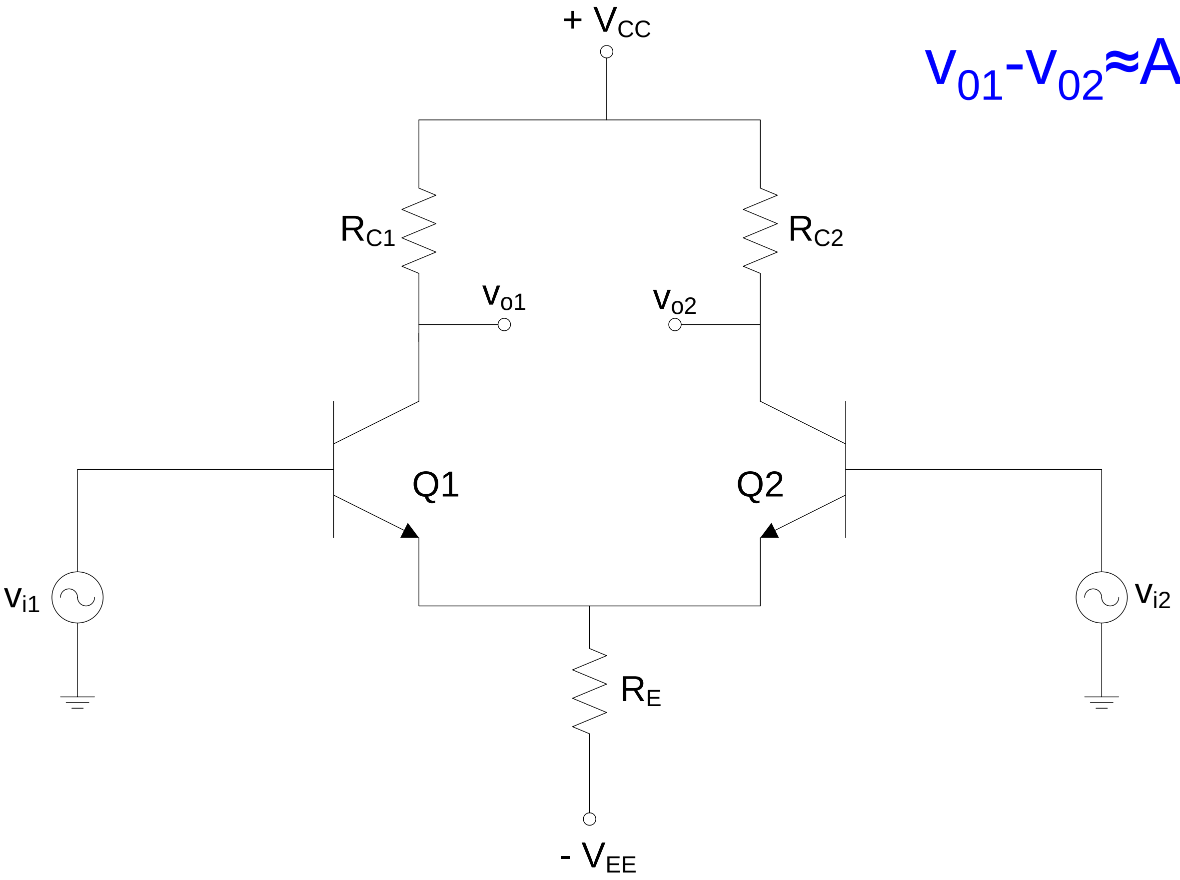
$$\beta_{overall}=\beta_1\beta_2+\beta_1+\beta_2$$

$$\beta_{overall}\approx \beta_1\beta_2$$

Darlington Pair

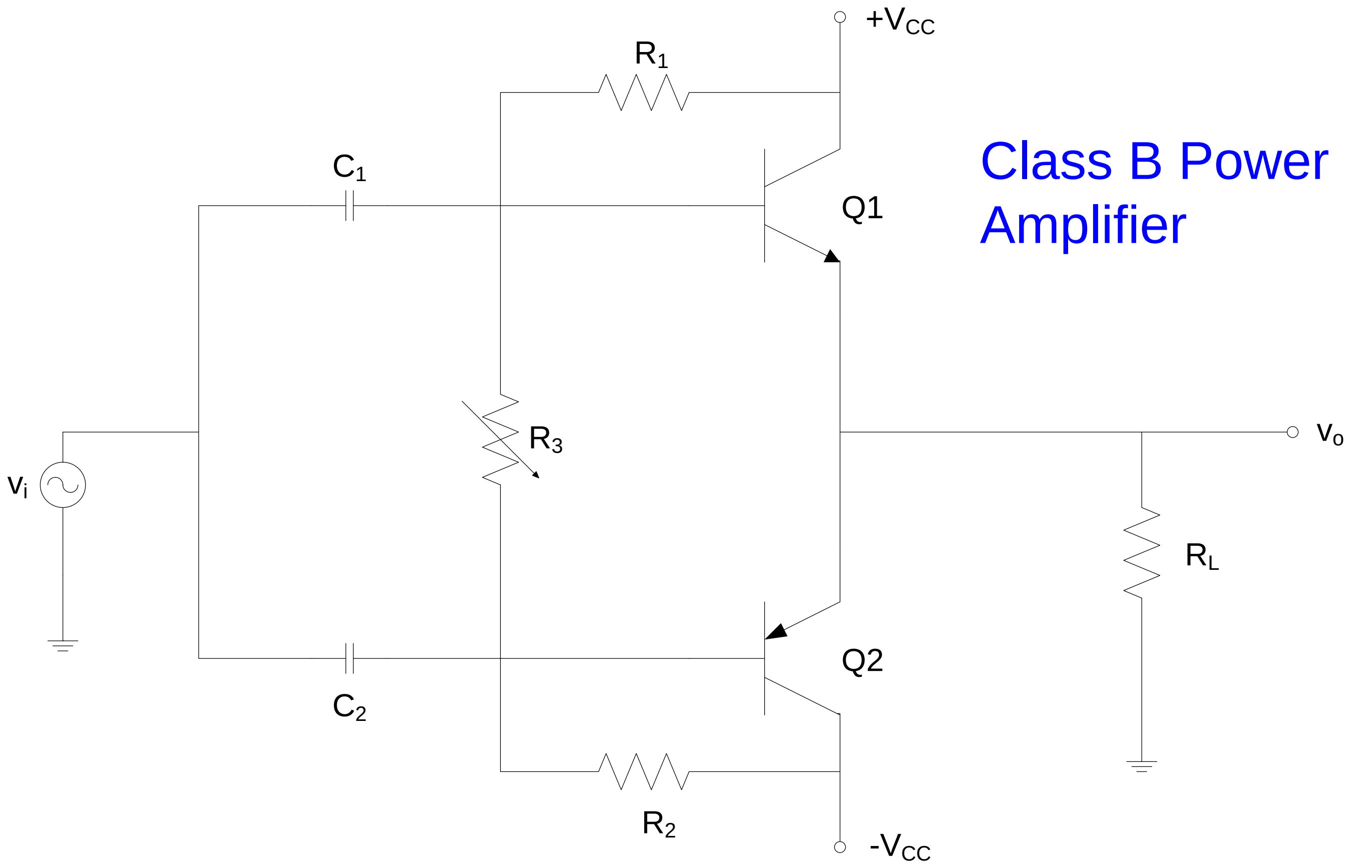
Differential Amplifier

How to amplify differential signals? i.e. $v_o = A_v(v_1 - v_2)$



$$v_{01} - v_{02} \approx A_v(v_{i1} - v_{i2})$$

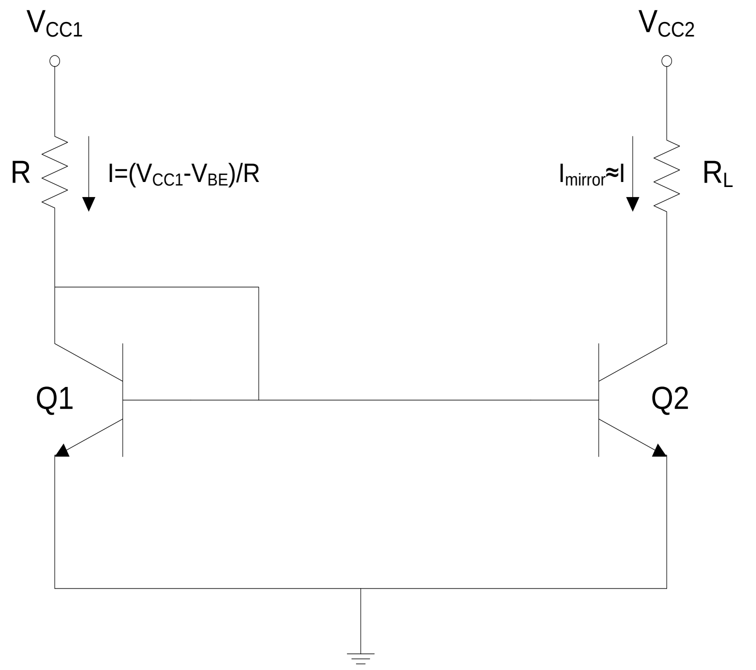
Push-Pull Configuration



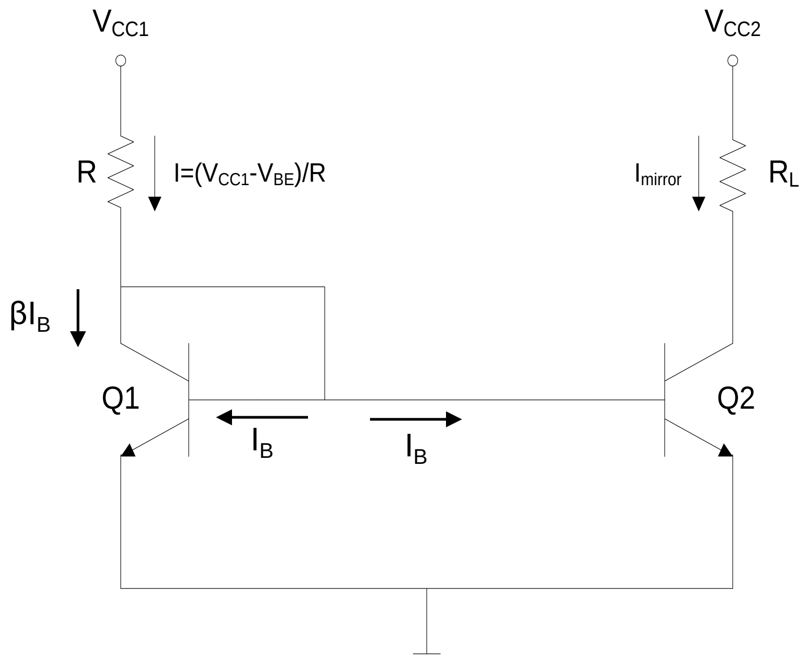
Class B Power Amplifier

Matched npn and pnp transistors used to make amplifiers with high efficiency. Typically used as Power Amplifiers.

Current Mirror Circuit



Current Mirror Circuit

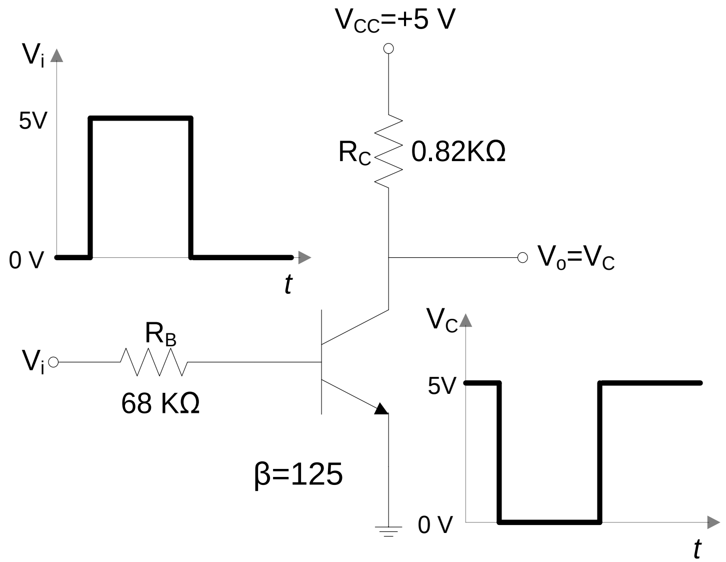


$$I = (\beta+2)I_B$$

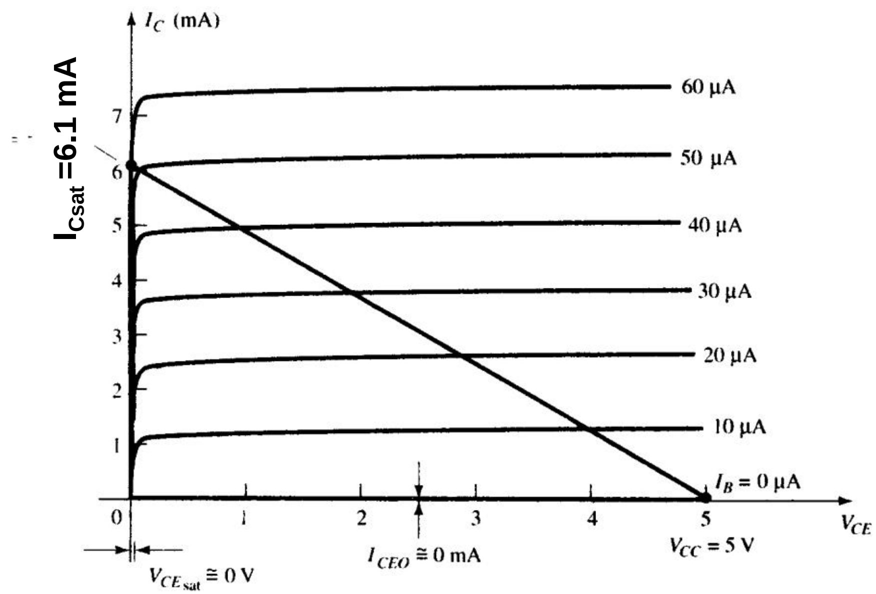
$$I_{mirror} = \beta I_B$$

$$I_{mirror} = \frac{1}{1+\frac{2}{\beta}} I$$

Transistor as a Switch



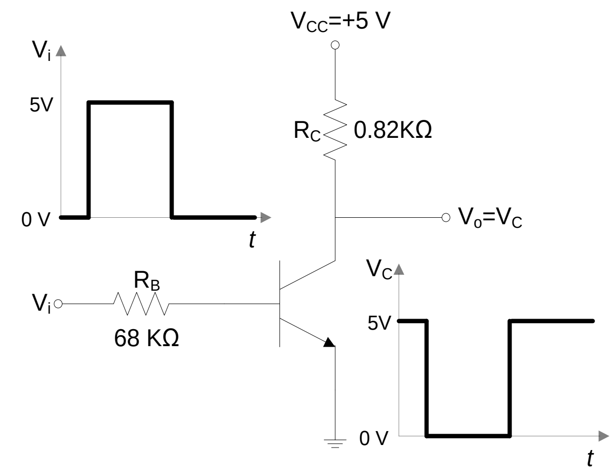
Transistor Inverter



I_C-V_{CE} Characteristics (β=125)

Assume (a) I_C=I_{CE0}=0 mA when I_B=0 μA
(b) V_{CEsat}=0 V *This is more typically* 0.1-0.3 V

Transistor as a Switch (Inverter)



(a) V_i=0 V — Transistor is OFF, I_C=0 and V_o=V_C=+5 V

(b) V_i=+5 V — Transistor is ON, V_{CEsat}=0 V

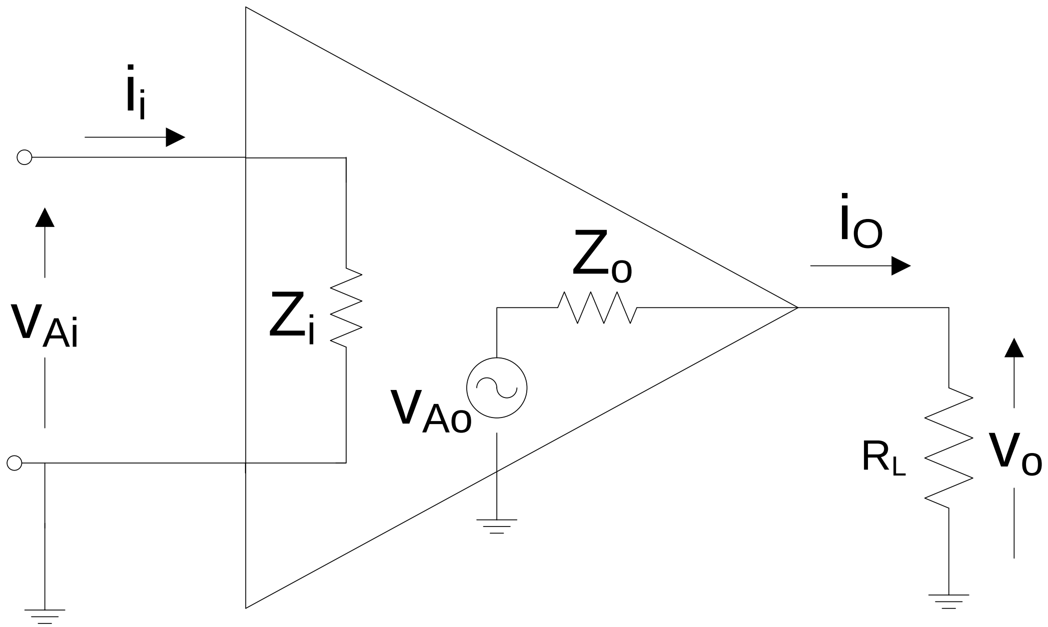
I_B=(5-0.7)/68=63 μA

I_{Csat}=V_{CC}/R_C=5/0.82=6.1 mA

Note that βI_B=7.88 ma > I_{Csat}=6.1 mA

Therefore, the transistor is indeed in saturation

Relationship between A_V, A_i, Z_i and Z_o



$$A_V = \frac{v_{Ao}}{v_{Ai}} \qquad Z_i = \frac{v_{Ai}}{i_i}$$

$$i_O = \frac{v_{Ao}}{Z_o + R_L} = \frac{A_V v_{Ai}}{Z_o + R_L} = \frac{A_V Z_i i_i}{Z_o + R_L}$$

$$\Rightarrow \quad A_i = \frac{i_O}{i_i} = \frac{A_V Z_i}{Z_o + R_L}$$