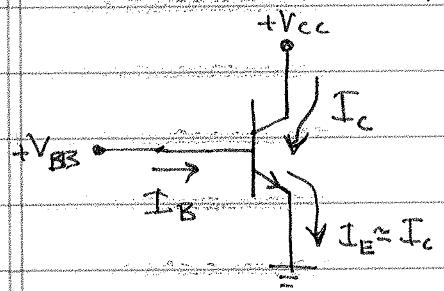
PHYSICS 220: Physical Electronics — Stoneking, Fall 2010

Notes on the Common-Emitter Amplifier

- The Bipolar Junction Transistor (BJT), when its terminals are properly biased, provides large current gain.

$$I_C = \beta I_B \quad \text{where } \beta \sim 100$$



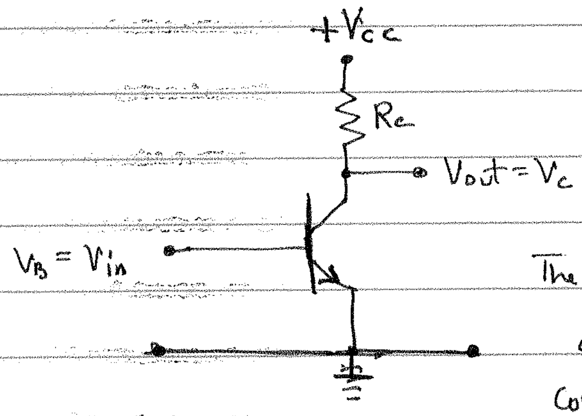
The base-emitter junction is forward-biased, $V_{BB} \gtrsim .6V$

The base-collector junction is reverse-biased.

$V_{CC} \gtrsim V_{BB}$

(npn transistor used throughout)

- Resistors can be used to convert currents into voltages. In the case of the common-emitter amp, ~~the~~ output voltage is taken from the collector and a resistor is used between the collector power supply and the transistor.



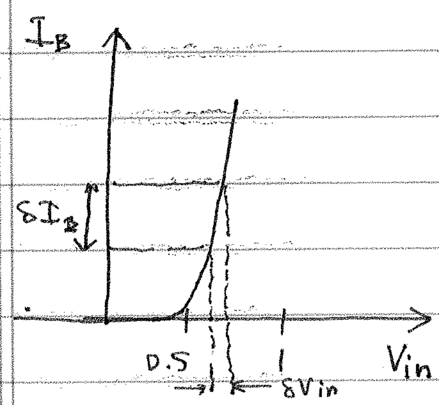
$$V_{out} = V_{cc} - I_c R_c$$

V_{cc}: fixed or "stiff" power supply

$I_c R_c$: varies as input signal varies.

The emitter terminal is "common" to the input and output of the circuit, hence the name <u>Common-emitter amplifier</u>

- The base current is very sensitive to the input voltage ... it is a pn junction in the forward-biased regime.



Shockley eq. $I_B = I_s \left(e^{V_B/V_T} - 1\right)$

$I_B \approx I_s e^{V_B/V_T}$ ← ignore in forward-bias regime

If $V_B = V_{BB} + \delta V_B$

V_{BB}: D.C. bias

δV_B: signal

$$\underset{\substack{\uparrow \\ \text{"quiescent" base current}}}{I_{Bq}} + \underset{\substack{\uparrow \\ \text{change in base current due to signal}}}{\delta I_B} = \left(I_s e^{V_{BB}/V_T}\right) e^{\delta V_B/V_T}$$

expand this for small signals $\delta V_B \ll V_T = 26\,mV$ at 300 K

$$I_{Bq} + \delta I_B = \underbrace{\left(I_s e^{V_{BB}/V_T}\right)}_{I_{Bq}} \left(1 + \frac{\delta V_B}{V_T}\right)$$

(Note: Both I_s and V_T are temperature-dependent at fixed V_{BB}).

So... $\delta I_B = I_{Bq} \dfrac{\delta V_B}{V_T}$ The base ~~to~~ emitter junction "looks" like at resistor to small variations in the input voltage...

[Order of magnitude $r_\pi \approx \dfrac{26\,mV}{.01\,mA} \sim 2.6\,k\Omega$] $\Longleftarrow$ $r_\pi = \dfrac{V_T}{I_{Bq}}$

Horowitz & Hill call ~~this~~ the Ebers-Moll resistance $r_e = \dfrac{r_\pi}{\beta}$ s.t. $r_e = \dfrac{V_T}{I_{cq}}$

- Since the collector current is β times the base current...

$$\delta I_c = \underbrace{\beta I_{Bq}}_{I_{cq} \text{ quiescent collector current}} \cdot \frac{\delta V_B}{V_T} \quad \text{or} \quad = \frac{\beta\, \delta V_B}{r_\pi}$$

- Changes in the output voltage due to ~~on~~ changes in the input voltage → Amplifier gain

$$V_{out_q} + \delta V_{out} = \underbrace{V_{cc} - I_{cq} R_c}_{V_{out_q} \text{ quiescent D.C. output voltage}} - R_c\, \delta I_c$$

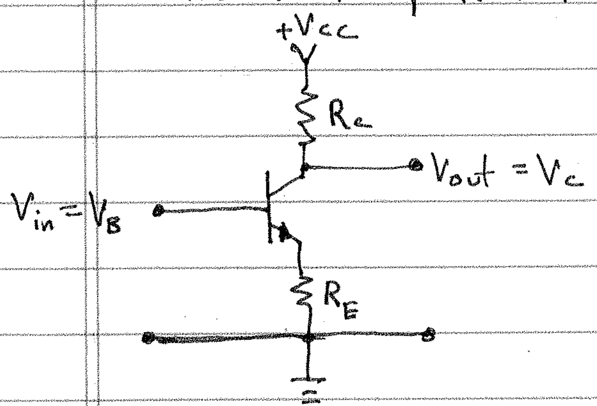
$$\text{So} \quad \delta V_{out} = -R_c\, \delta I_c = -\frac{R_c \beta}{r_\pi}\, \delta V_{in}$$

$\uparrow = \delta V_B$

- Voltage Gain $A_v = \dfrac{\delta V_{out}}{\delta V_{in}} = \boxed{\dfrac{-R_c \beta}{r_\pi}}$

Positive swing in δV_{in} increases δI_B and δI_c making δV_{out} swing negative → Inverting amplifier.

• The gain ~~of~~ obtained on the previous page depends on the current gain parameter, β, for the transistor, and on the temperature (and quiescent operating point)-dependent effective resistance, r_π. To make the amplifier performance less dependent on these unreliable factors, add a resistor to the emitter portion of the circuit.



This addition constitutes an application of "negative feedback" and is a sacrifice of gain for other performance characteristics.

Now it is the voltage difference between the base and emitter (no longer grounded) that determines the collector current (and hence the output voltage)

$$\delta I_B = \frac{1}{r_\pi} \cdot \left(\underset{\uparrow \text{base}}{\delta V_{in}} - \delta V_E \right)$$

The emitter voltage is $V_E = I_E R_E = (\beta+1) I_B R_E$

$$\delta V_E = (\beta+1) R_E \, \delta I_B$$

$$\delta I_B = \frac{\delta V_{in}}{r_\pi} \underset{\uparrow}{-} \frac{(\beta+1) R_E}{r_\pi} \delta I_B$$

negative feedback ... reduces the magnitude of the change in I_B

Solve for δI_B

$$\delta I_B \left(1 + \frac{(\beta+1) R_E}{r_\pi} \right) = \frac{\delta V_{in}}{r_\pi}$$

$$\delta I_B = \frac{\delta V_{in}}{r_\pi + (\beta+1) R_E} \longrightarrow \delta I_c = \beta \, \delta I_B = \frac{\beta \, \delta V_{in}}{r_\pi + (\beta+1) R_E}$$

from the previous page.. $\delta V_{out} = -R_c \delta I_c$ so..

$$\delta V_{out} = \frac{-\beta R_c}{r_\pi + (\beta+1)R_E} \delta V_{in}$$

and the gain is... $\boxed{A_v = \frac{-\beta R_c}{r_\pi + (\beta+1)R_E}}$

If $(\beta+1)R_E \gg r_\pi$ and $\beta \gg 1$ then this reduces to...

$\boxed{A_v = \frac{-R_c}{R_E}}$ Independent of transistor characteristics and temperature!

need $R_E \gg 26\,\Omega$ $\left(\frac{r_\pi}{\beta+1}\right)$

- Establishing the quiescent operating point for the common-emitter amplifier: In order to amplify the A.C. component of the input voltage, there must be a steady or quiescent current through the transistor ... the transistor must be "on". The output is taken at the collector which has a quiescent voltage...

$$V_{cq} = V_{cc} - I_{cq} R_c$$

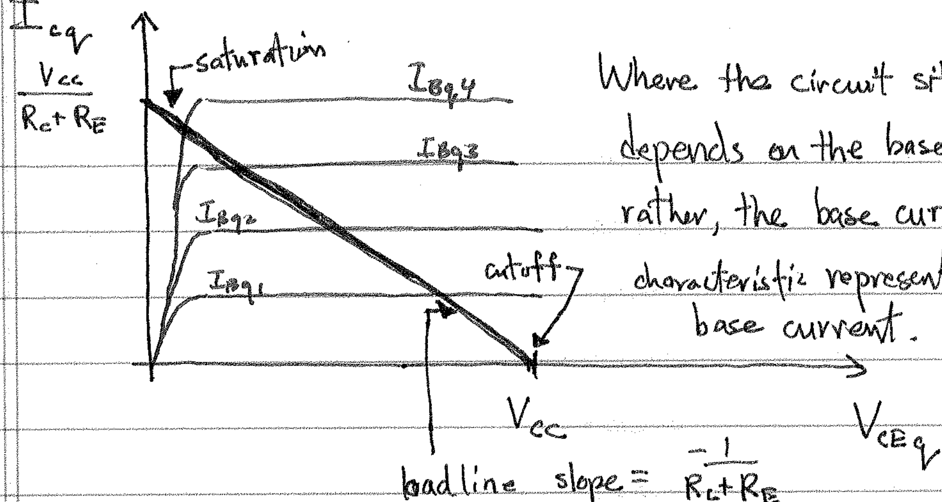
Or, the quiescent collector-emitter voltage is...

$$V_{CEq} = V_{cc} - I_{cq} R_c - I_{Eq} R_E \approx V_{cc} - I_{cq}(R_c + R_E)$$

for large β. $I_{cq} \approx I_{Eq}$

This represents a linear relationship between I_{cq} and V_{CEq}

and is the collector circuit "load line".

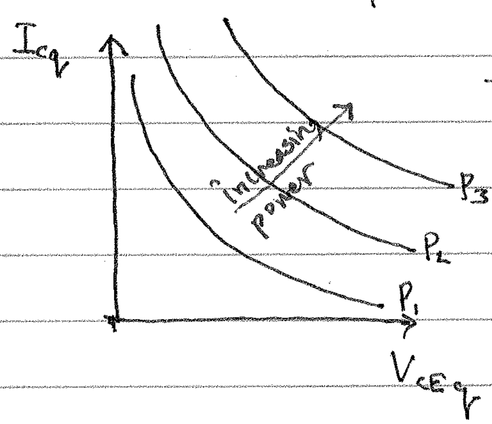


Where the circuit sits on the load line depends on the base to emitter bias or rather, the base current. Each horizontal characteristic represents a different quiescent base current.

The optimal position for the Q-point is near the middle of the load line ~~in order~~ to allow maximal and symmetric ~~swing~~ oscillation about that point without distorting the output (due to either cutoff or saturation).

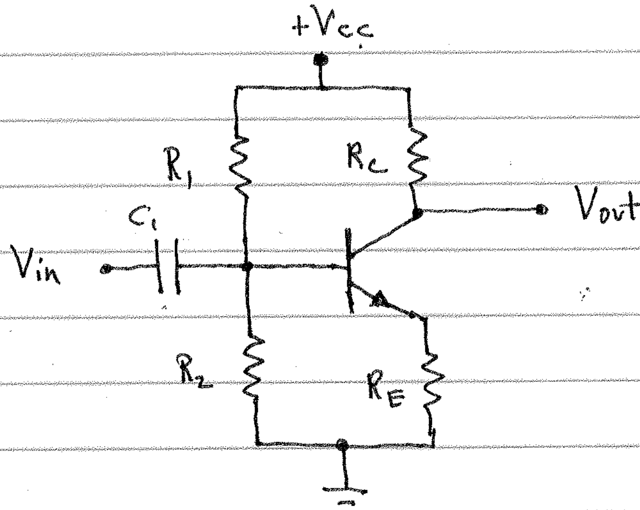
- Power limit: Most of the power dissipated in the transistor is localized to the region of ~~large~~ strong electric field associated with the reverse biased collector-base junction. Overall the dissipated power is (approximately) $P = I_{cq} V_{CEq}$

Curves of constant power are hyperbolae in the graph of I_{cq} vs. V_{CEq}



The circuit elements V_{cc}, R_c, and R_E should be selected so that the load line lies well below the ~~power~~ constant power contour associated with the maximum power dissipation in the transistor.

- Four-resistor bias circuit: It is desirable to minimize the number of separate D.C. power supplies that are needed to establish the Q-point and render the circuit receptive to input signals. The standard method is to use the supply that provides $+V_{cc}$ to also provide V_{Bq}, the quiescent base voltage, through a voltage divider.



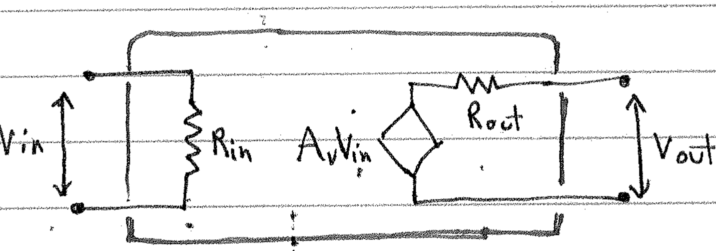
R_1 and R_2 form a voltage divider with input $+V_{cc}$ such that its output, V_{Bq} ...

$$V_{Bq} = \underbrace{\frac{R_2}{R_1+R_2} V_{cc}}_{} \cong \underbrace{I_{Eq} R_E}_{V_{Eq}} + \underbrace{0.6\,V}_{\text{forward-biased base to emitter junction voltage.}}$$

For this to hold, the base current I_{Bq} must be small compared to the current through R_1 and R_2

The input coupling capacitor C_1 is necessary, in order to avoid perturbing the Q-point when the signal source is attached. The amplifier will therefore operate on (i.e. amplify) only the A.C. part of the input signal. Stay tuned for analysis of frequency-dependent effects.

• Input and Output Impedance : Input impedance is an important characteristic for an amplifier and one we generally like to be large for voltage amplifiers. This reduces the loading of the signal source. When considering these quantities, it is helpful to view the circuit of interest in the following effective representation

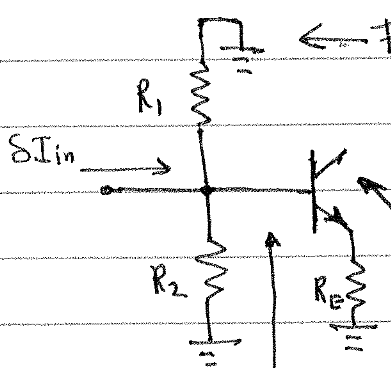


In general input and output resistors should be replaced with impedances that can have imaginary components (capacitance, usually).

We are here neglecting the coupling capacitor... the input is A.C. at sufficiently high frequency that the impedance of the capacitor is negligible.

The input resistance is then ... $R_{in} = \dfrac{\delta V_{in}}{\delta I_{in}}$

For our circuit, the input current has three parallel paths to ground:



← For A.C. signals, an ideal D.C. voltage source looks like a short circuit to ground. The power supply does not permit A.C. voltages to appear across its terminals.

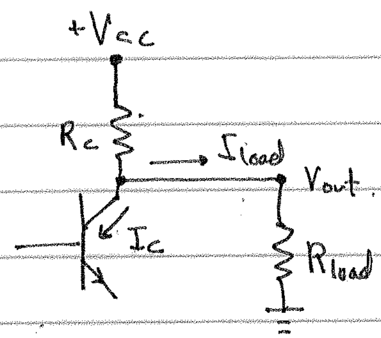
The reverse-biased base-to-collector junction looks like an open circuit.

The effective input impedance of the path to the base of the transistor can be obtained from the equation on the bottom of page 3. $R_{in_t} = \dfrac{\delta V_B}{\delta I_B} = r_\pi + (\beta+1)R_E$

So, the overall input resistance of the amplifier is...

$$\boxed{R_{in} = R_1 \parallel R_2 \parallel R_{int}}$$

The output resistance can be predicted from the collector/output circuit



When a load is attached to the output, additional current must flow through R_c to supply the load. The collector current is not (much) affected by the load as long as the DC output is not dragged down (loaded down) so much that the transistors Q-point is broght to saturation.

So... $V_{out} = V_{cc} - (I_c + I_{load}) R_c$

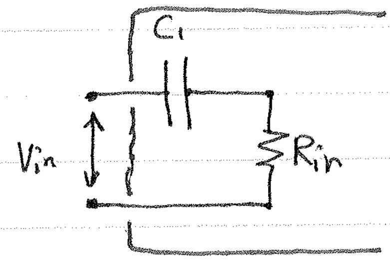
and $\boxed{R_{out} = -\frac{\delta V_{out}}{\delta I_{out}} = R_c}$

Since the output drops as the load current increases

- The desire to maximize R_{in} and minimize R_{out} for a voltage amplifier must complete with (or be traded off against) other amplifier characteristics like gain, bandwidth, and stability.

- **Frequency response:**

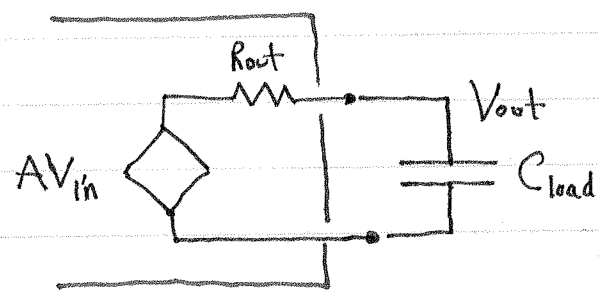
  - Low frequency roll-off: The input coupling capacitor in the common-emitter amplifier design forms a RC high pass filter with the input resistance (p.8).



The low frequency half-power frequency is therefore...

$$\boxed{f_{lo} = \frac{1}{2\pi R_{in} C_1}}$$

  - High frequency roll-off: There are a number of possible effects that can lead to low pass filtering or high frequency rolloff in the gain. The simplest one to understand is one that arises when the load attached to the output of the amplifier has capacitance. Then the output resistance and the load capacitance form a RC low pass filter (p.8)



The high frequency half-power point associated with load capacitance is...

$$\boxed{f_{hi} = \frac{1}{2\pi R_{out} C_{load}}}$$

R_{out} ↑ R_c

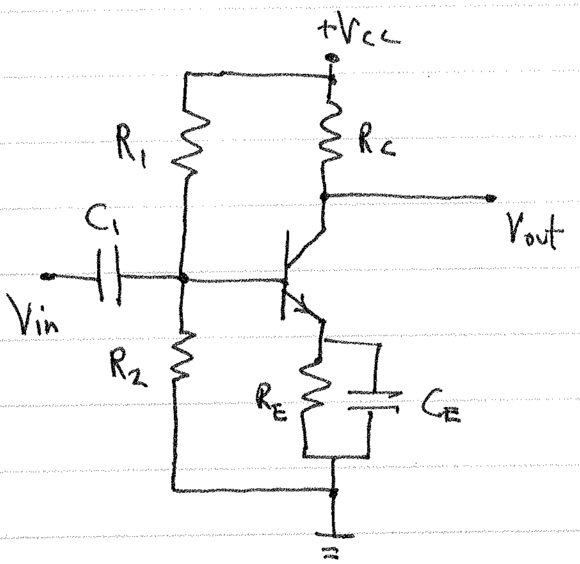
If the load is a coaxial cable (RG-58) connected to an oscilloscope, then

$$C_{load} \simeq 30\,\text{pF}/\text{ft.} \times L\,(\text{ft.}) + C_{scope}$$

C_{scope} ↑ typically ~ 20 pF

- Enhancing the gain using a bypass capacitor:

For A.C. signals, the midband gain can be enhanced by putting a capacitor in parallel with R_E. The capacitance should be chosen so that the impedance of the capacitor $\left(\frac{1}{\omega C}\right)$ is small compared to R_E at the frequencies of interest.



The input impedance of the transistor "looking into" the base is now frequency dependent and the low-frequency roll-off will therefore be affected.

Referring to p.4, the gain can be expected to reach values limited by the following

$$\boxed{A_{V,max} = -\frac{\cancel{\beta} R_c}{r_\pi}}$$

where $\frac{r_\pi}{\beta} \simeq 26\ \Omega$ at room temp.
with $\beta \simeq 100$
$I_{cq} \simeq 1\,mA$