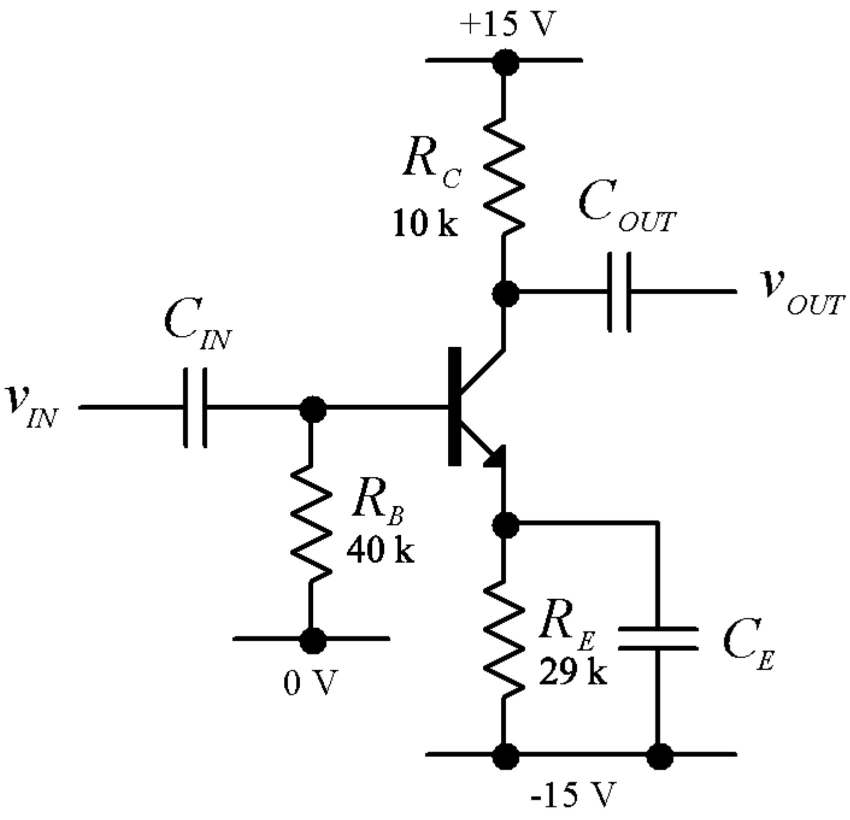
Practical Amplifier

- To analyse the circuit:
  - Determine quiescent conditions
  - Calculate mutual conductance
  - Calculate small signal performance
    - Voltage Gain
    - Input Impedance
    - Output Impedance
    - Cut-off frequency

Quiescent Conditions



$$I_B \approx 0 \Rightarrow I_{RB} \approx 0 \Rightarrow V_B \approx 0$$

$$V_{BE} \approx 0.5\,\text{V} \Rightarrow V_E \approx -0.5\,\text{V}$$

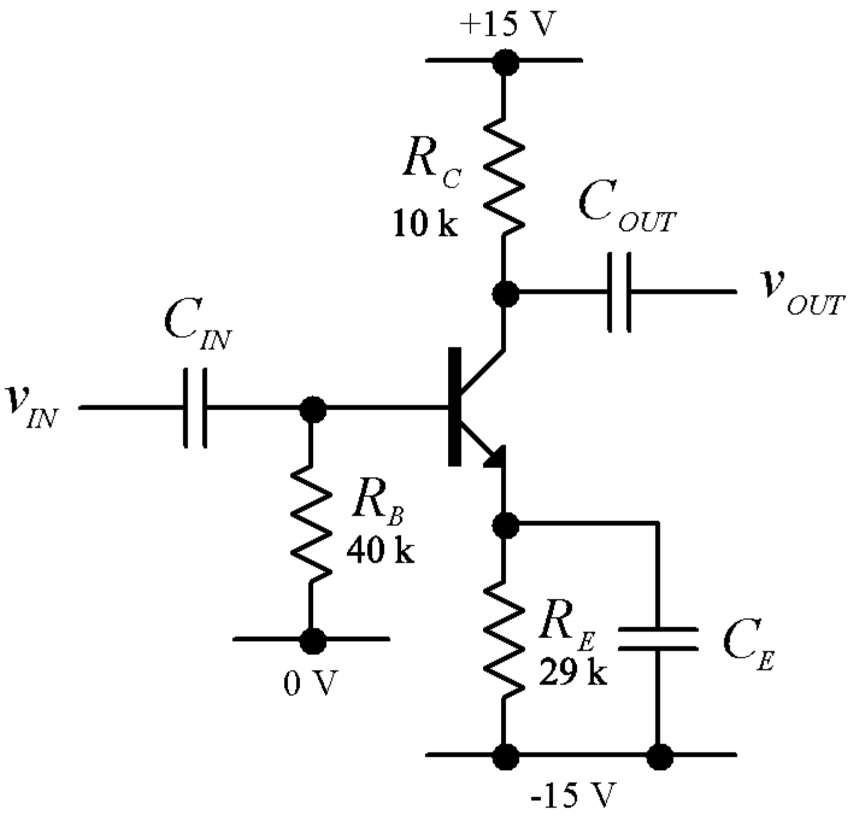
$$I_E = I_{RE} = \frac{V_E - (-15)}{R_E}$$

$$= \frac{14.5}{29} = 0.5\,\text{mA} \approx I_C$$

$$V_C = 15 - I_C R_C$$

$$= 15 - 0.5 \times 10 = 10\,\text{V}$$

Small Signal Analysis: Voltage Gain



As before:

$$i_C = g_m v_{BE} = g_m v_{IN}$$

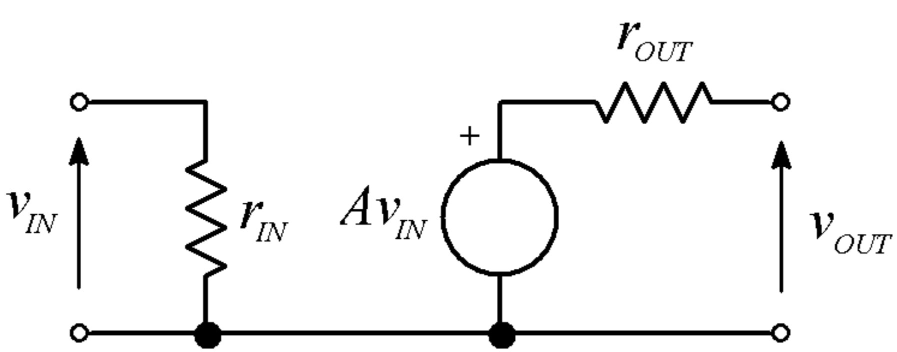
$$\frac{v_{OUT}}{i_C} = \frac{\mathrm{d}V_{OUT}}{\mathrm{d}I_C} = -R_C$$

$$\frac{v_{OUT}}{v_{IN}} = \frac{v_{OUT}}{i_C} \times \frac{i_C}{v_{IN}} = -R_C g_m$$

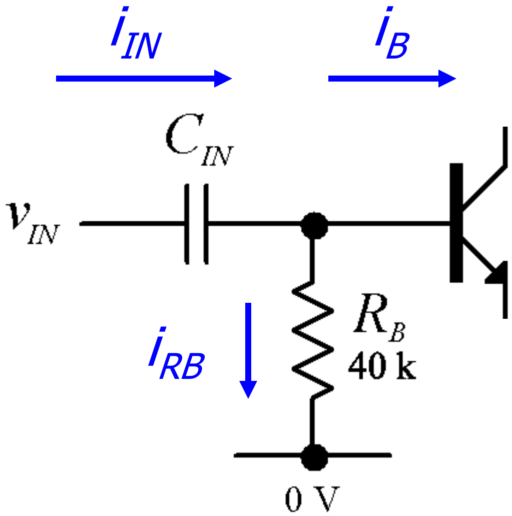
$$= -R_C \times \frac{I_C}{V_T} = -10^4 \times \frac{0.5}{25} = -200$$

Input and Output Impedance

- Unlike the op-amp, transistor amplifiers have significant output impedances and finite input impedances
  - R_{IN} can be comparable with the source resistance of the input signal
  - R_{OUT} can be comparable with the load resistance



Input Impedance



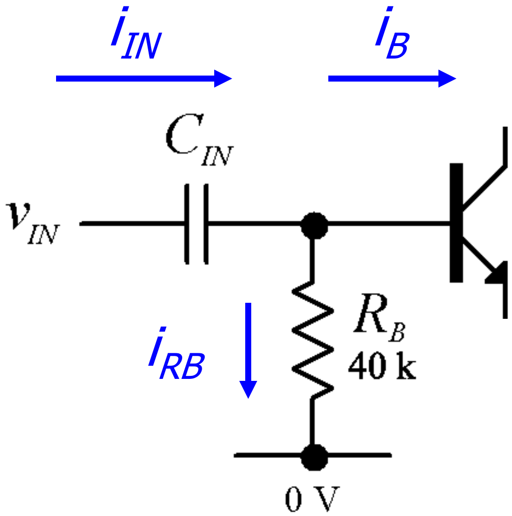
- Input impedance, r_{IN}, is the ratio of the small signal input voltage and the small signal input current

$$r_{IN} = \frac{v_{IN}}{i_{IN}} \qquad i_{IN} = i_{RB} + i_B$$

$$i_{RB} = \frac{v_{IN}}{R_B}$$

$$i_B = \frac{i_C}{\beta} = \frac{v_{IN} g_m}{\beta}$$

Input Impedance (cont)



$$i_{IN} = i_{RB} + i_B = \frac{v_{IN}}{R_B} + \frac{v_{IN} g_m}{\beta}$$

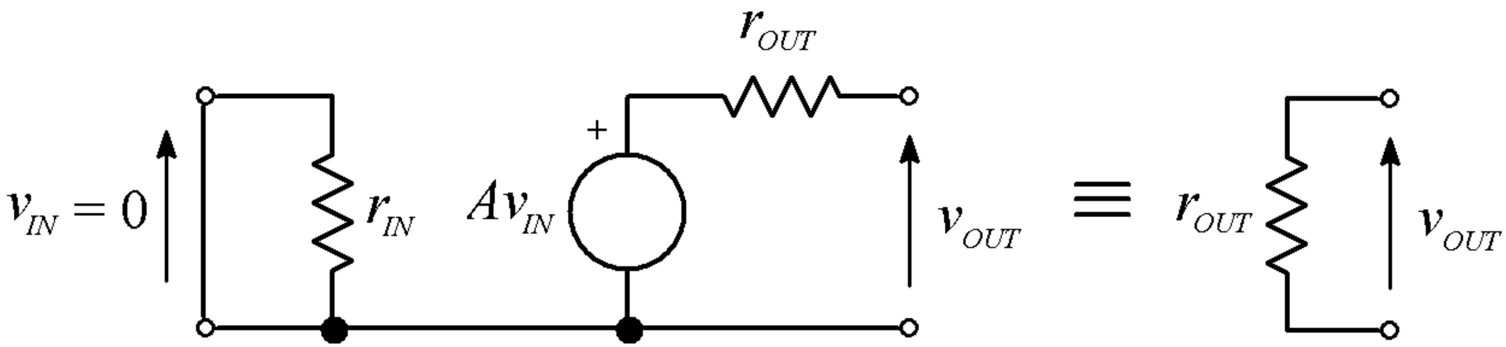
$$r_{IN} = \frac{v_{IN}}{i_{IN}} = \frac{1}{1/R_B + g_m/\beta} = R_B \,\|\, \frac{\beta}{g_m}$$

NB. $\quad g_m = \dfrac{i_C}{v_{BE}} \quad \& \quad r_E = \dfrac{v_{BE}}{i_E}$

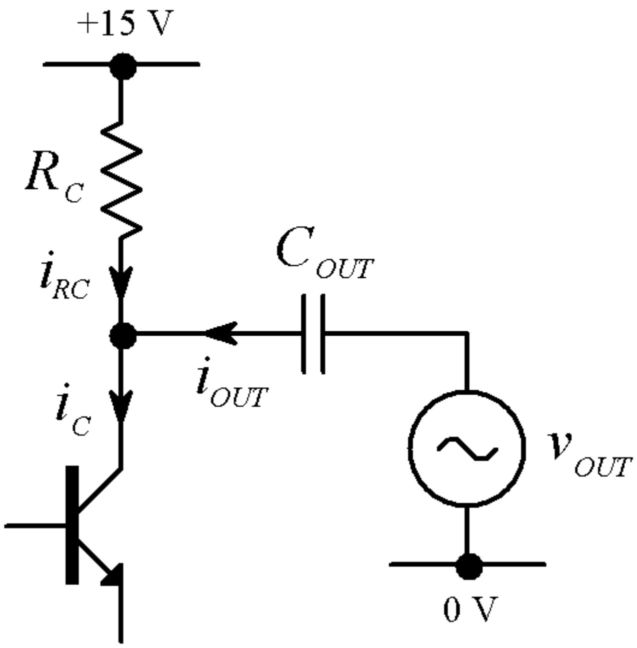
$$\therefore g_m \approx \frac{1}{r_E}$$

Output Impedance

- One way to measure r_{OUT} is:
  - Short the input to 0 V
  - Output now looks like just r_{OUT}



Output Impedance (cont)



$$v_{IN} = 0 \Rightarrow i_C = 0$$

Applying Kirchoff's current law:

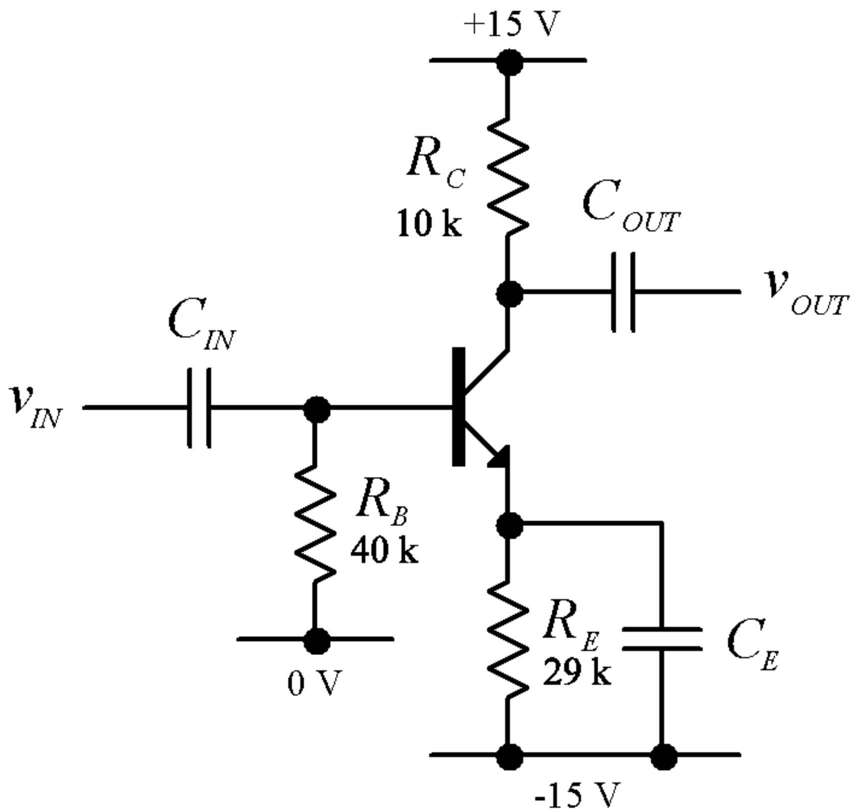
$$i_C = i_{RC} + i_{OUT} = 0 \Rightarrow i_{OUT} = -i_{RC}$$

By Ohm's law:

$$V_C = 15 - I_{RC} R_C \Rightarrow \frac{v_C}{i_{RC}} = -R_C = \frac{v_{OUT}}{i_{RC}}$$

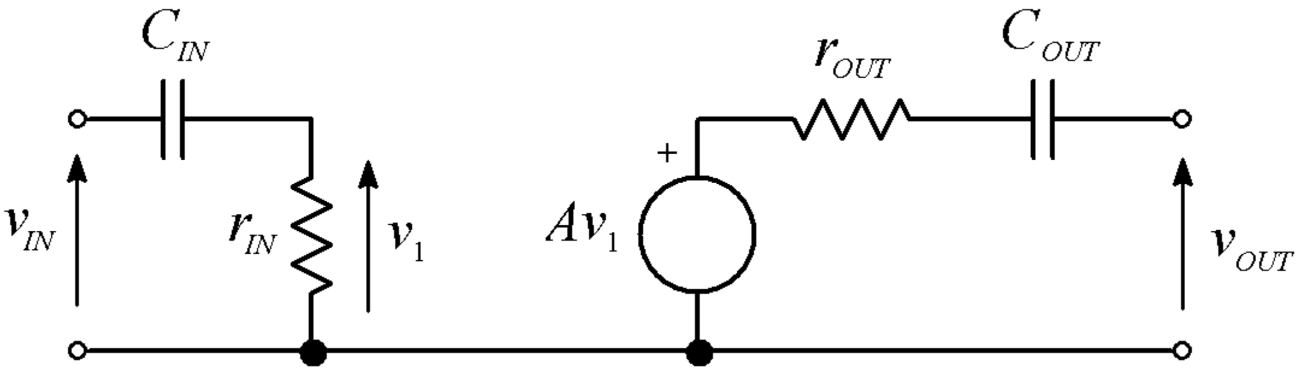
$$r_{OUT} = \frac{v_{OUT}}{i_{OUT}} = -\frac{v_{OUT}}{i_{RC}} = -\left(-R_C\right) = R_C$$

Coupling Capacitors



- Capacitor C_{OUT} is needed to remove the d.c. component of the collector voltage
- Capacitor C_{IN} is needed to allow the base voltage to be offset from 0V
- In both cases this is known as *coupling*
- Both capacitors are chosen to look like short circuits at operating frequencies
- Their reactance will, however, become significant at low frequencies

Equivalent Circuit



$$v_1 = v_{IN} \frac{r_{IN}}{r_{IN} + 1/ j2\pi f C_{IN}} = v_{IN} \frac{1}{1 + 1/ j2\pi f r_{IN} C_{IN}}$$

$$|v_1| = |v_{IN}| \frac{1}{\sqrt{1 + 1/(2\pi f r_{IN} C_{IN})^2}}$$

Cut-Off Frequency

Cut-off frequency, or –3dB point, is when the gain of the amplifier falls by a factor of √2

$$\frac{|v_1|}{|v_{IN}|} = \frac{1}{\sqrt{2}} = \frac{1}{\sqrt{1+1/(2\pi f_C r_{IN} C_{IN})^2}}$$

$$\Rightarrow 1+1/(2\pi f_C r_{IN} C_{IN})^2 = 2 \Rightarrow 2\pi f_C r_{IN} C_{IN} = 1$$

If the cut-off frequency, f_C, is specified and r_{IN} has been calculated:

$$C_{IN} = \frac{1}{2\pi f_C r_{IN}}$$

NB. This assumes that C_{OUT} still looks like a short circuit

C_{OUT}

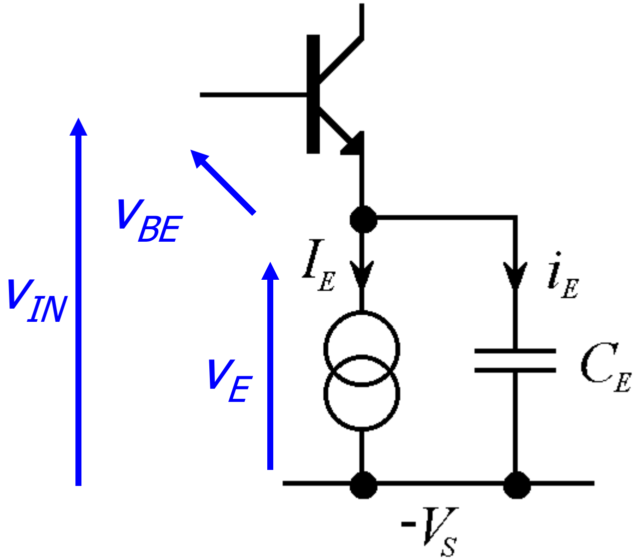
- For the lower cut-off frequency calculation to be valid, C_{OUT} should still look like a short circuit at f_C

$$\Rightarrow X_C = \frac{1}{2\pi f_C C_{OUT}} << r_{OUT}$$

- Typically, choose:

$$C_{OUT} \geq \frac{1}{2\pi \frac{f_C}{10} r_{OUT}}$$

Emitter Capacitor



For the highest voltage gain,

$$v_{BE} \approx v_{IN} \Rightarrow v_{BE} >> v_E$$

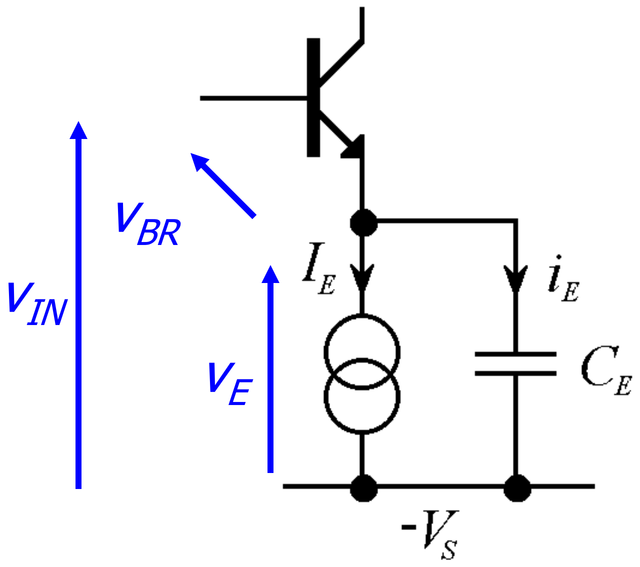
But, $v_{BE} = \dfrac{i_C}{g_m} = i_E r_E$

where, $r_E \approx \dfrac{1}{g_m} = \dfrac{V_T}{I_C}$

Also, $v_E = \dfrac{i_E}{j2\pi f C_E}$

$$\therefore v_E\, j2\pi f C_E = \frac{v_{BE}}{r_E}$$

Emitter Capacitor (cont)



For C_E to not interfere at f_C:

$$v_{BE} >> v_E$$

Where, $v_E j2\pi f_C C_E = \frac{v_{BE}}{r_E}$

$$\Rightarrow 2\pi f_C C_E r_E << 1$$

To make sure, choose,

$$C_E \geq \frac{1}{2\pi \frac{f_C}{10} r_E}$$

NB. Use r_E $(= V_T / I_C)$ not R_E for this calculation!

Summary

- In the context of the common-emitter amplifier we have covered:
  - Small signal analysis
  - Mutual conductance
  - Input/output impedance
  - Coupling capacitor requirements and cut-off frequencies
- Next time:
  - Applying the same principles to the *differential amplifier*
  - It’s actually a much easier circuit to analyse – honest!
  - Make sure you’re happy with the fundamentals by then!