Lecture 8

ANNOUNCEMENTS

- A summary of frequently misunderstood/missed concepts is now posted on the class website, and will be updated regularly.
- Graded HW assignments can be picked up in lab (353 Cory).
  → **Please indicate your lab section on your HW assignments!**

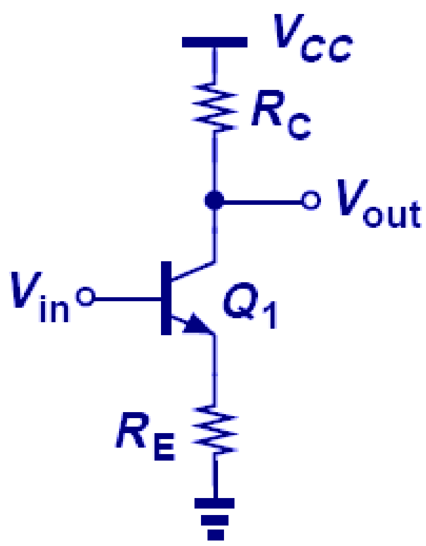
OUTLINE

- BJT Amplifiers (cont'd)
  - Common-emitter topology
    - CE stage with emitter degeneration
    - Impact of Early effect (r_o)

Reading: Finish Chapter 5.3.1

Emitter Degeneration

- By inserting a resistor in series with the emitter, we "degenerate" the CE stage.
- This topology will decrease the gain of the amplifier but improve other aspects, such as linearity, and input impedance.



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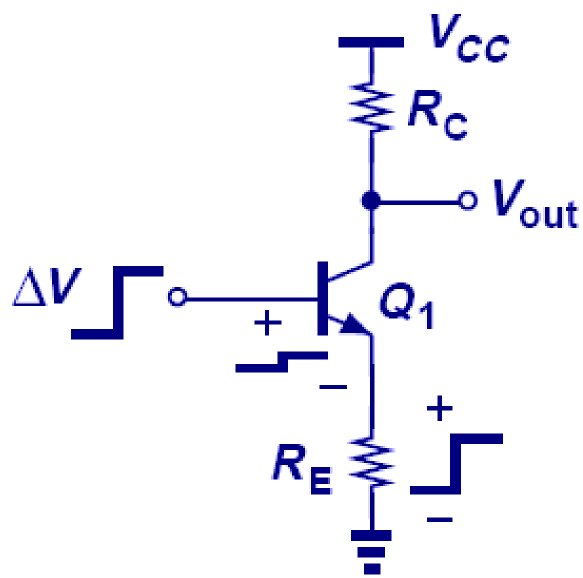
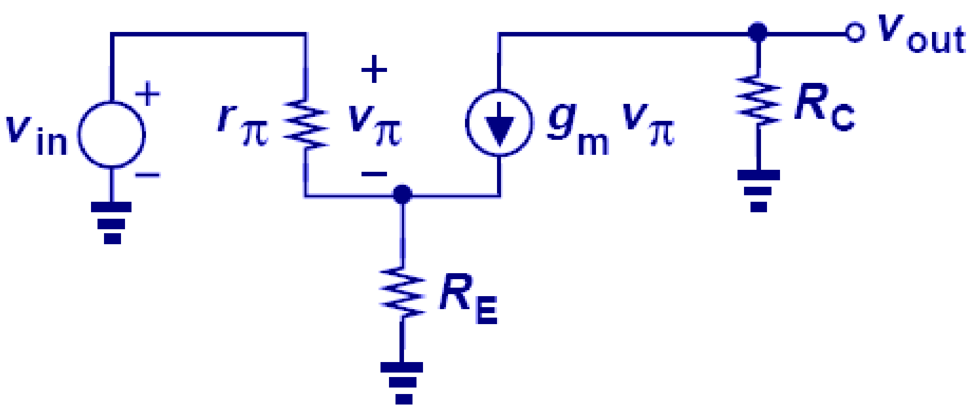


(b)

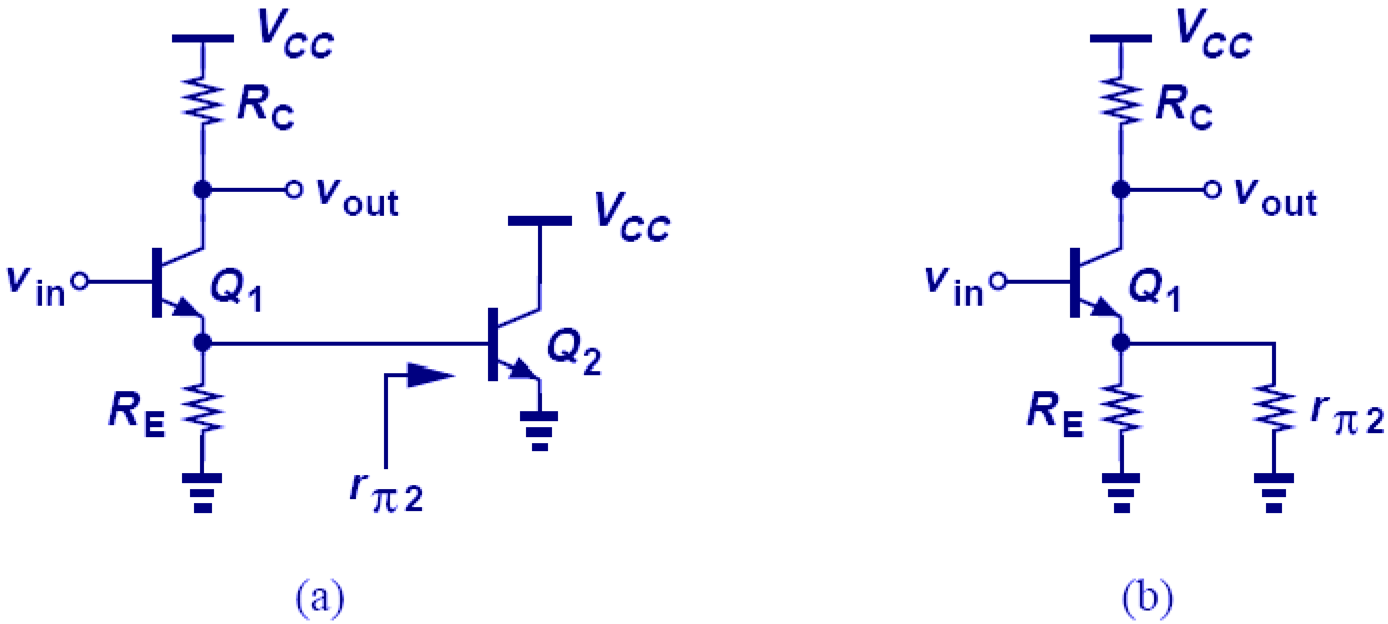
Small-Signal Analysis

- The gain of a degenerated CE stage = the total load resistance seen at the collector divided by $1/g_m$ plus the total resistance placed in series with the emitter.



$$A_v = \frac{-g_m R_C}{1+g_m R_E} = \frac{-R_C}{\dfrac{1}{g_m}+R_E}$$

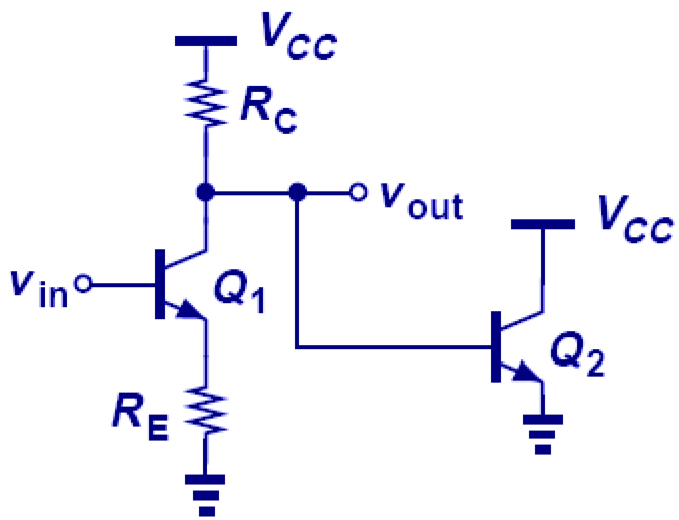
Emitter Degeneration Example 1



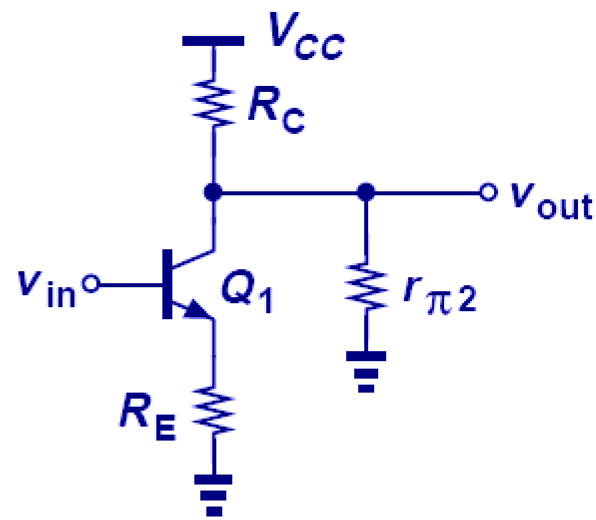
Note that the input impedance of Q_2 is in parallel with R_E.

$$A_v = -\frac{R_C}{\frac{1}{g_{m1}} + R_E \| r_{\pi 2}}$$

Emitter Degeneration Example 2



(a)



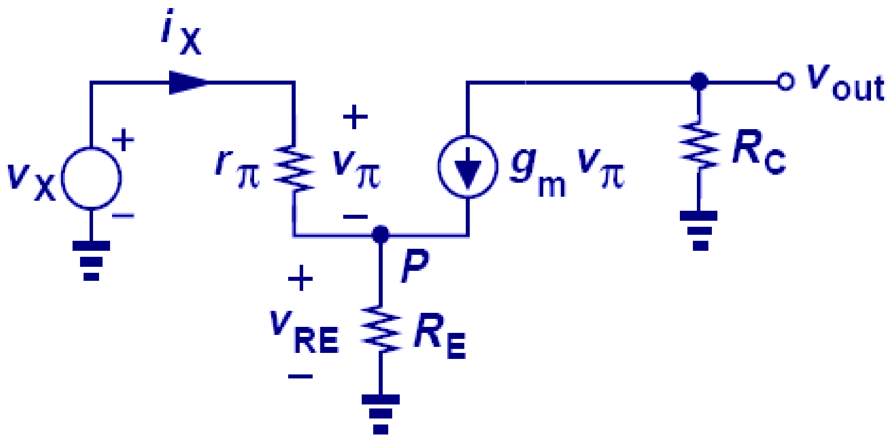
(b)

Note that the input impedance of Q_2 is in parallel with R_C.

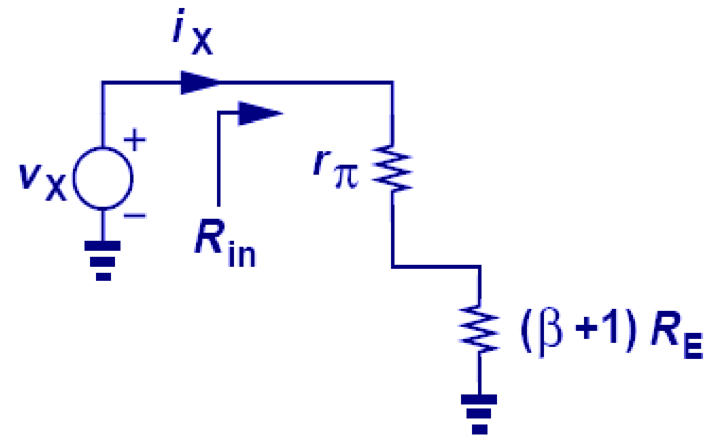
$$A_v = -\frac{R_C \parallel r_{\pi 2}}{\frac{1}{g_{m1}} + R_E}$$

Input Impedance of Degenerated CE Stage

- With emitter degeneration, the input impedance is increased from r_π to $r_\pi + (\beta+1)R_E$ — a desirable effect.



(a)



(b)

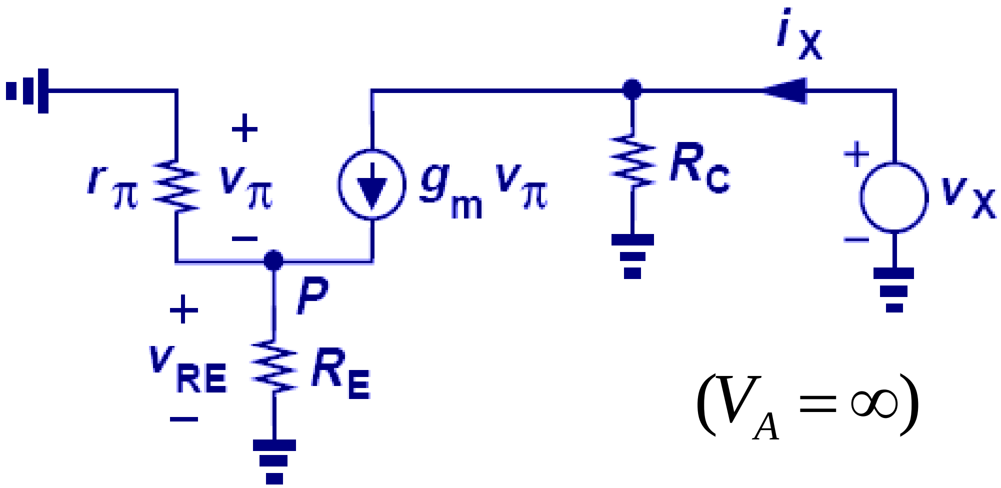
$$(V_A = \infty)$$

$$v_x = r_\pi i_x + R_E(1+\beta)i_x$$

$$R_{in} \equiv \frac{v_x}{i_x} = r_\pi + (\beta+1)R_E$$

Output Impedance of Degenerated CE Stage

- Emitter degeneration does not alter the output impedance, if the Early effect is negligible.



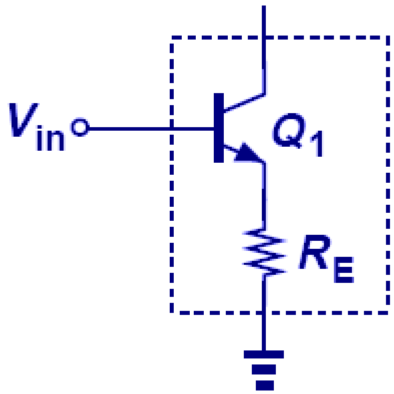
(a)

$$(V_A = \infty)$$

$$v_{in} = 0 = v_\pi + \left(\frac{v_\pi}{r_\pi} + g_m v_\pi\right) R_E \Rightarrow v_\pi = 0$$

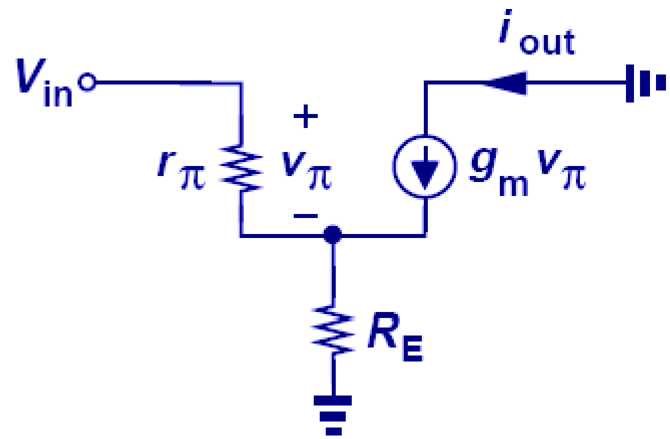
$$R_{out} \equiv \frac{v_x}{i_x} = R_C$$

Degenerated CE Stage as a “Black Box”



$$(V_A = \infty)$$

(a)



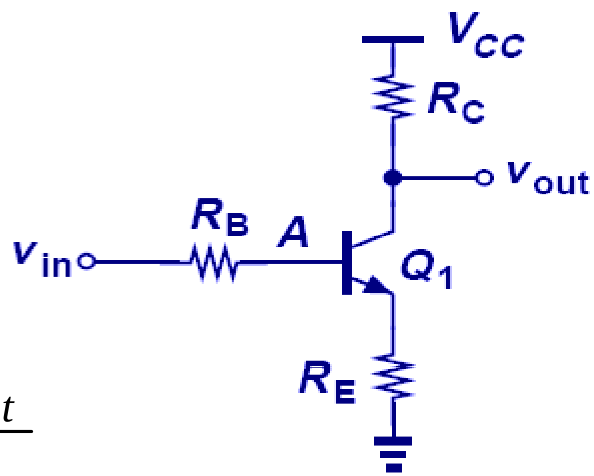
(b)

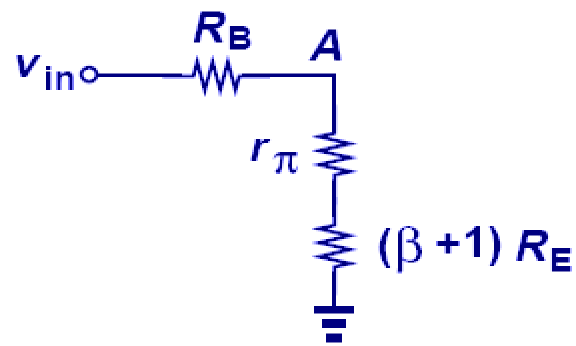
$$i_{out} = g_m \frac{v_{in}}{1 + (r_\pi^{-1} + g_m) R_E}$$

$$G_m \equiv \frac{i_{out}}{v_{in}} \approx \frac{g_m}{1 + g_m R_E}$$

- If $g_m R_E >> 1$, G_m is more linear.

Degenerated CE Stage with Base Resistance





$$(V_A = \infty)$$

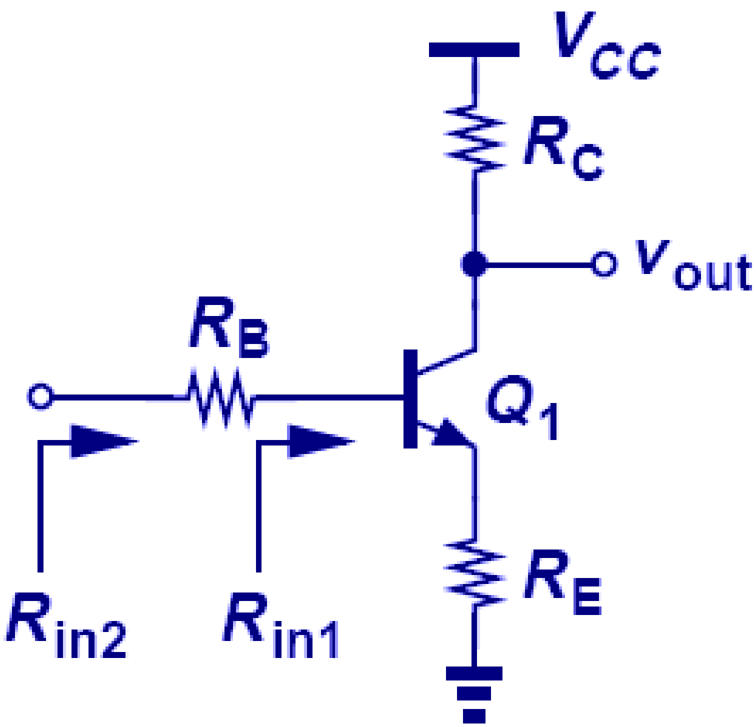
$$\frac{v_{out}}{v_{in}} = \frac{v_A}{v_{in}} \cdot \frac{v_{out}}{v_A}$$

$$\frac{v_{out}}{v_{in}} = \frac{-\beta R_C}{r_\pi + (\beta + 1)R_E + R_B}$$

$$A_v \approx \frac{-R_C}{\frac{1}{g_m} + R_E + \frac{R_B}{\beta + 1}}$$

Degenerated CE Stage: Input/Output Impedances

- R_{in1} is more important in practice, because R_B is often the output impedance of the previous stage.



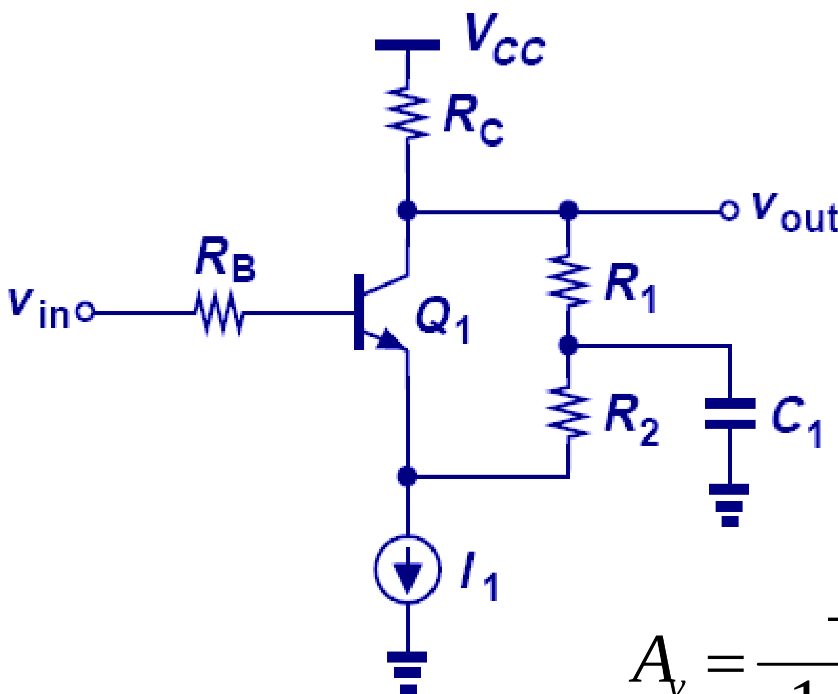
$$(V_A = \infty)$$

$$R_{in1} = r_\pi + (\beta + 1)R_E$$

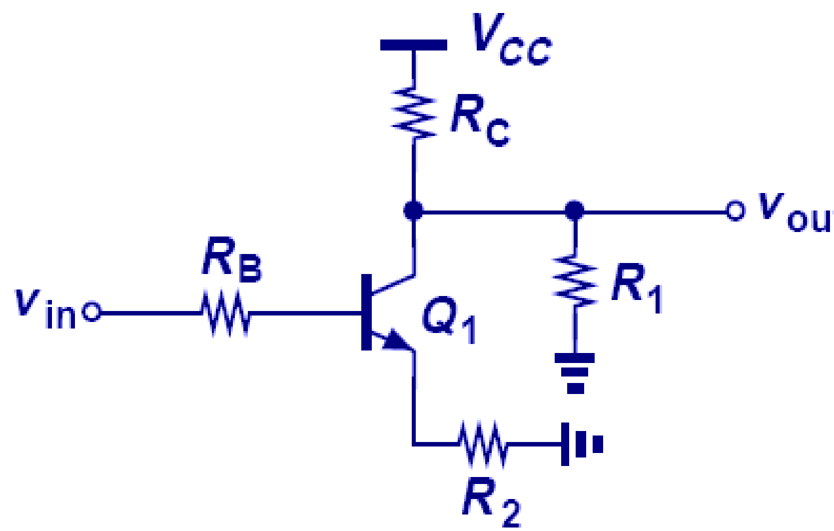
$$R_{in2} = R_B + r_\pi + (\beta + 1)R_E$$

$$R_{out} = R_C$$

Emitter Degeneration Example 3



(a)



(b)

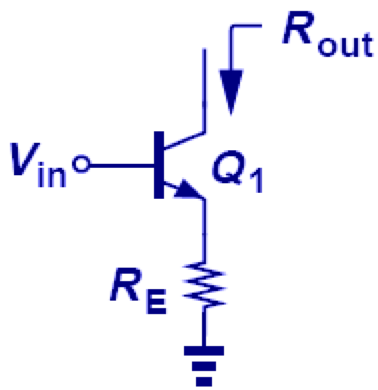
$$A_v = \frac{-(R_C \| R_1)}{\frac{1}{g_m} + R_2 + \frac{R_B}{\beta+1}}$$

$$R_{in} = r_\pi + (\beta+1)R_2 + R_B$$

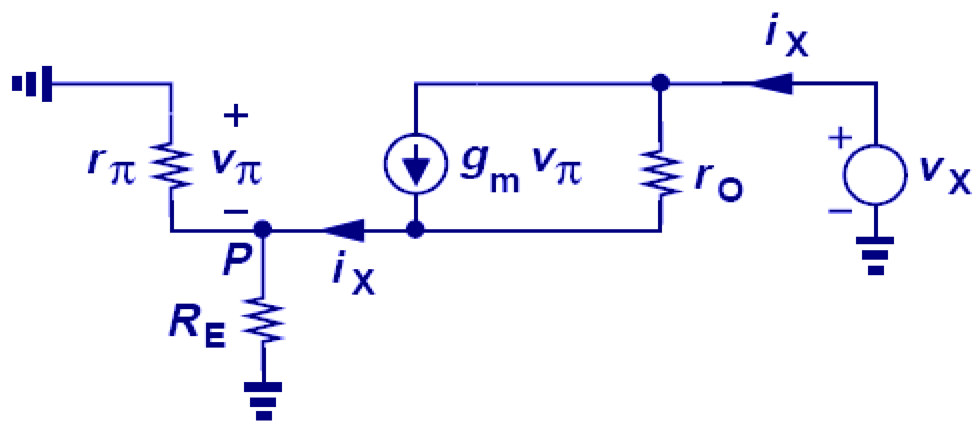
$$R_{out} = R_C \| R_1$$

Output Impedance of Degenerated CE Stage with $V_A<\infty$

- Emitter degeneration boosts the output impedance.
  - This improves the gain of the amplifier and makes the circuit a better current source.



(a)



(b)

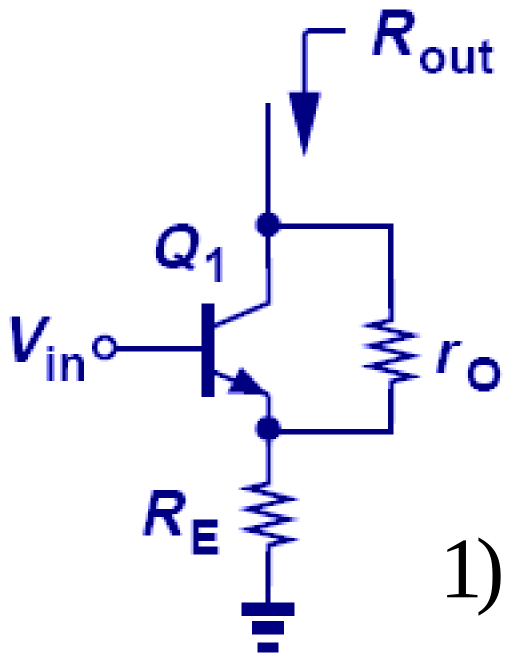
$$R_{out} = [1 + g_m (R_E \parallel r_\pi)] r_O + R_E \parallel r_\pi$$

$$R_{out} = r_O + (g_m r_O + 1)(R_E \parallel r_\pi)$$

$$R_{out} \approx r_O [1 + g_m (R_E \parallel r_\pi)]$$

Two Special Cases

Stage with explicit depiction of r_o:

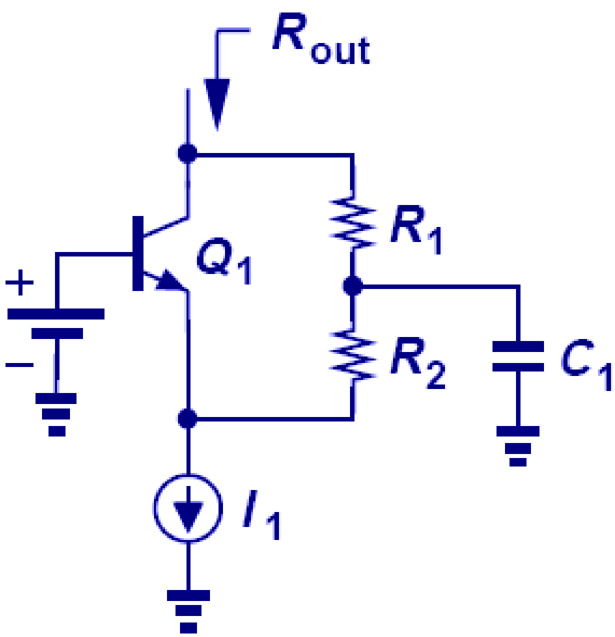


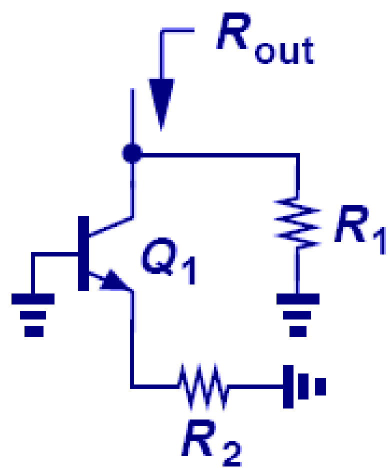
$$1)\ R_E >> r_\pi :\ R_{out} \approx r_O(1+g_m r_\pi) \approx \beta r_O$$

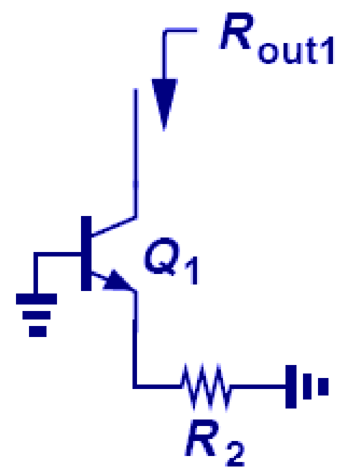
$$2)\ R_E << r_\pi :\ R_{out} \approx (1+g_m R_E) r_O$$

Analysis by Inspection

- This seemingly complicated circuit can be greatly simplified by first recognizing that the capacitor creates an AC short to ground, and gradually transforming the circuit to a known topology.

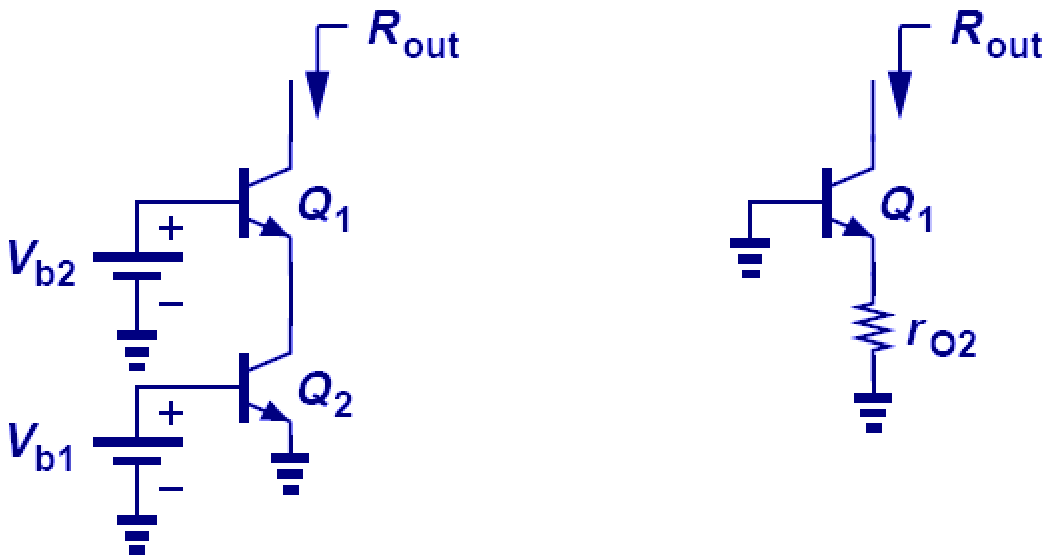






$$R_{out} = R_1 \parallel R_{out1} \Longrightarrow R_{out1} = \left[1 + g_m (R_2 \parallel r_\pi)\right] r_O \Longrightarrow R_{out} = \left[1 + g_m (R_2 \parallel r_\pi)\right] r_O \parallel R_1$$

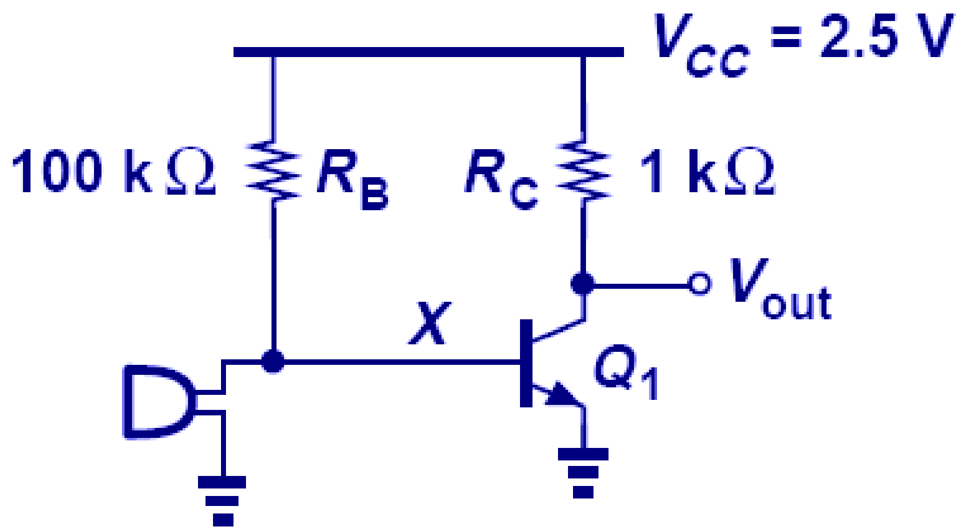
Example: Degeneration by Another BJT



$$R_{out} = [1 + g_{m1}(r_{O2} \| r_{\pi1})] r_{O1}$$

- Called a "cascode", this circuit offers many advantages that we will study later...

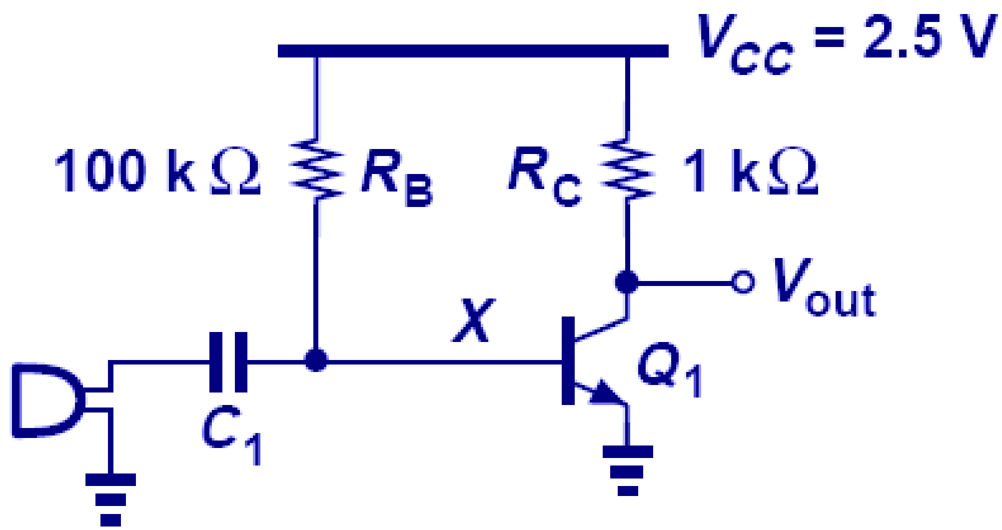
Bad Input Connection



- Since the microphone has a very low resistance (connecting the base of Q_1 to ground), it attenuates the base voltage and renders Q_1 with a very small bias current.

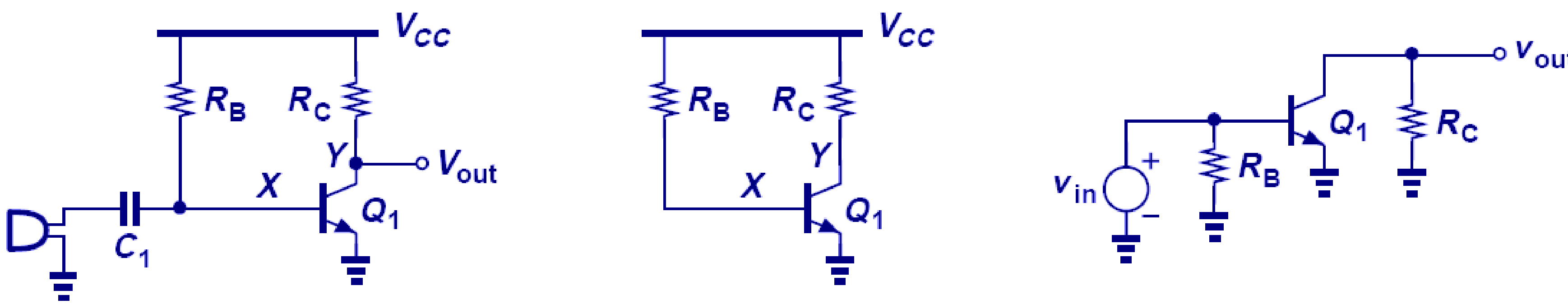
Use of Coupling Capacitor

- A capacitor is used to isolate the DC bias network from the microphone , and to short (or “couple”) the microphone to the amplifier at higher frequencies.



DC and AC Analysis

- The coupling capacitor is replaced with an open circuit for DC analysis, and then replaced with a short circuit for AC analysis.

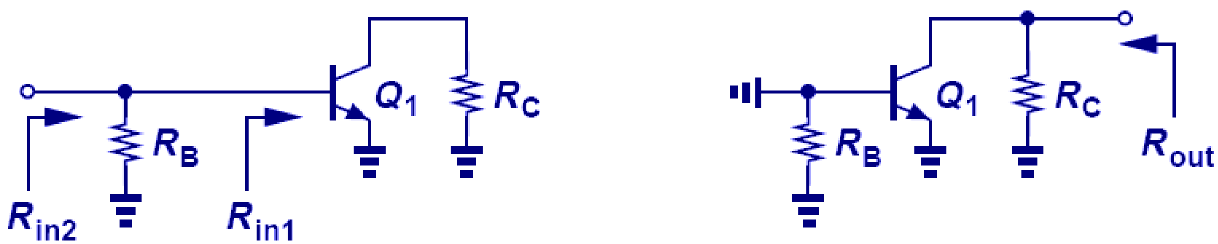


(a) (b) (c)

$$A_v = -g_m(R_C \parallel r_O)$$

$$R_{in} = r_\pi \parallel R_B$$

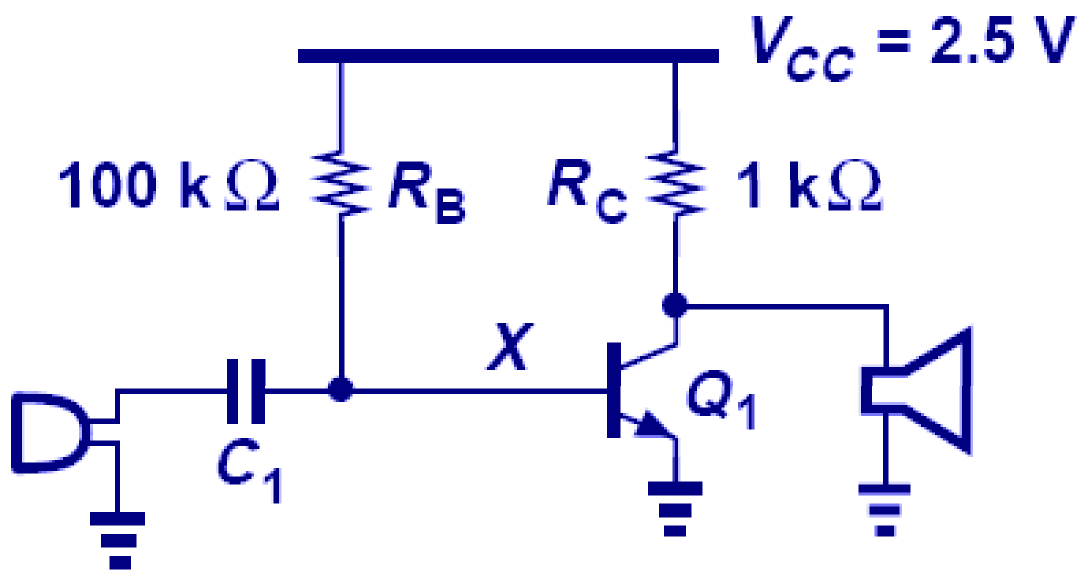
$$R_{out} = R_C \parallel r_O$$



(d) (e)

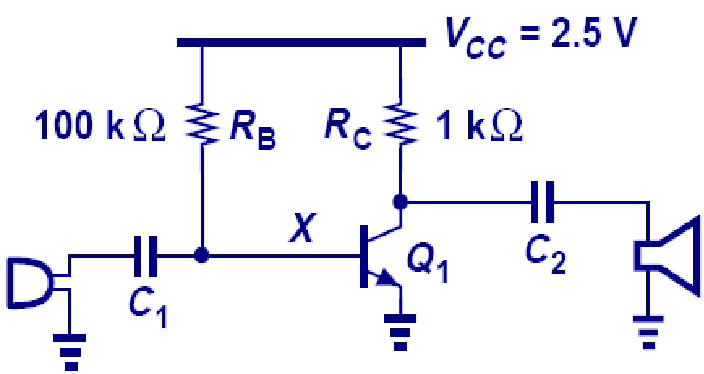
Bad Output Connection

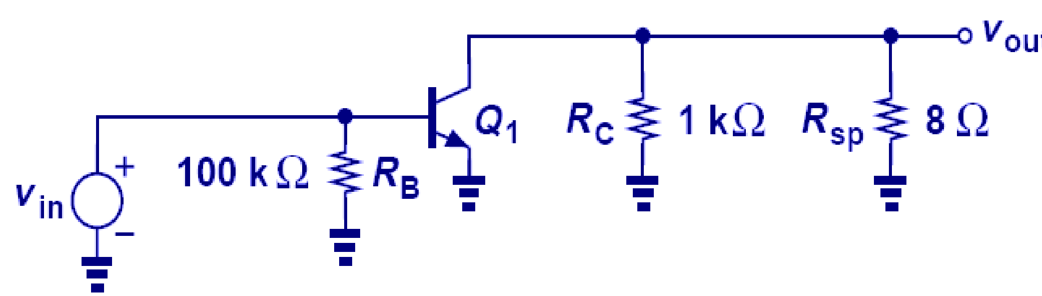
- Since the speaker has an inductor with very low DC resistance, connecting it directly to the amplifier would ~short the collector to ground, causing the BJT to go into deep saturation mode.



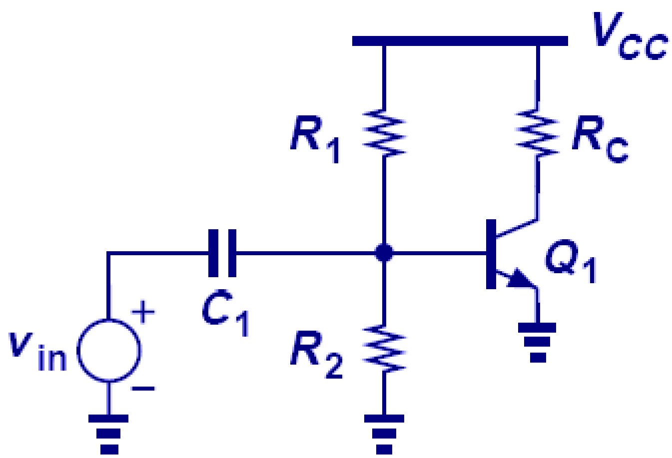
Use of Coupling Capacitor at Output

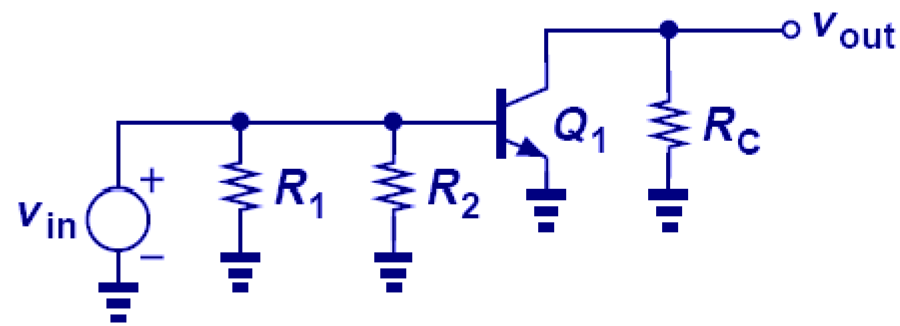
- The AC coupling indeed allows for correct biasing. However, due to the speaker's small input impedance, the overall gain drops considerably.





CE Stage with Voltage-Divider Biasing



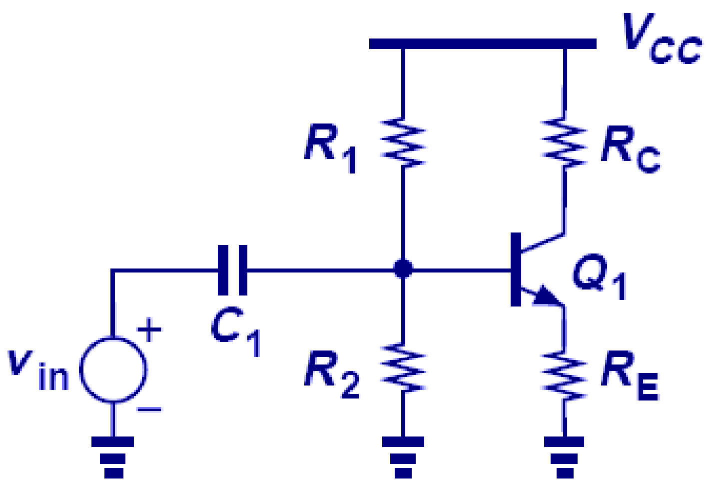


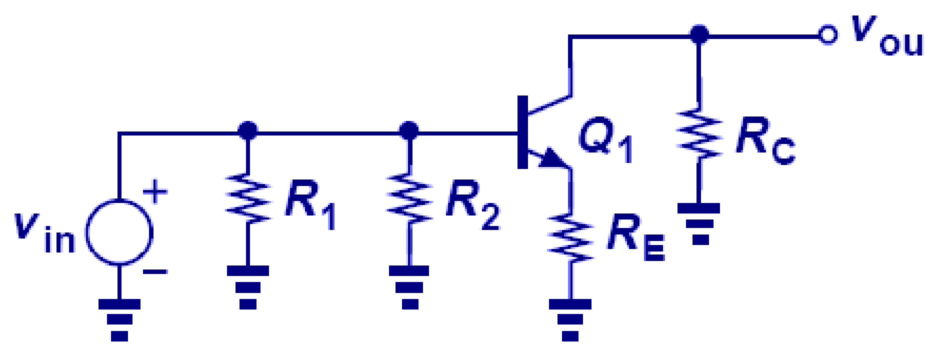
$$A_v = -g_m(R_C \,||\, r_O)$$

$$R_{in} = r_\pi \,||\, R_1 \,||\, R_2$$

$$R_{out} = R_C \,||\, r_O$$

CE Stage with Robust Biasing





$$(V_A = \infty)$$

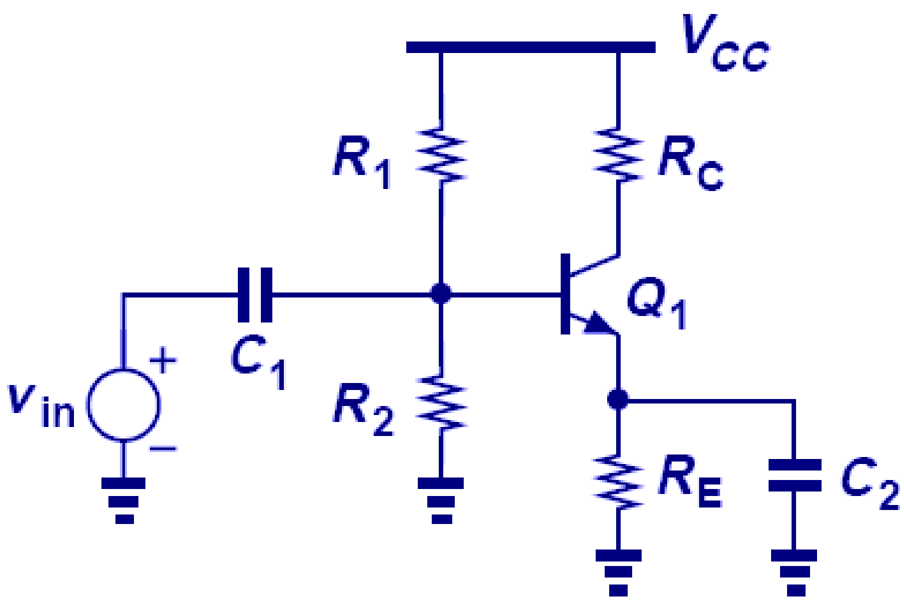
$$A_v = \frac{-R_C}{\dfrac{1}{g_m} + R_E}$$

$$R_{in} = \left[r_\pi + (\beta+1)R_E\right] \| R_1 \| R_2$$

$$R_{out} = R_C$$

Elimination of Emitter Degeneration for AC Signals

- The capacitor C_2 shorts out R_E at higher frequencies to eliminate the emitter degeneration.



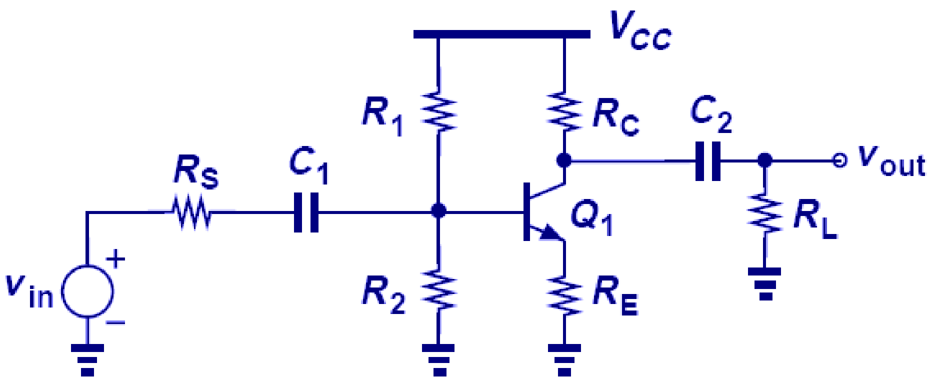
$$(V_A = \infty)$$

$$A_v = -g_m R_C$$

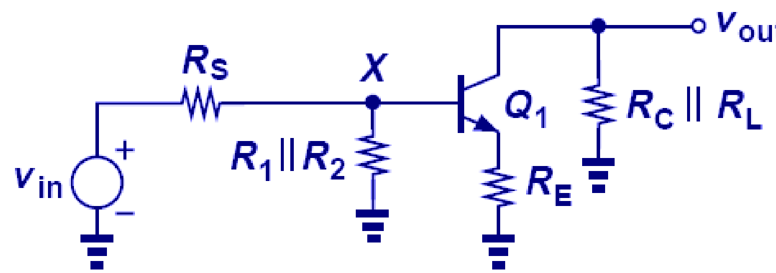
$$R_{in} = r_\pi \parallel R_1 \parallel R_2$$

$$R_{out} = R_C$$

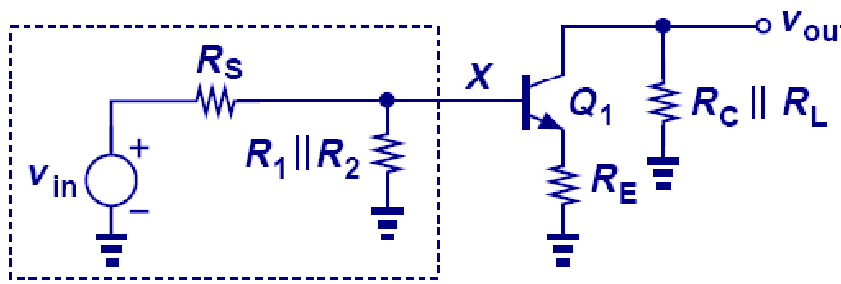
Complete CE Stage



(a)



(b)



(b)

$$A_v = \frac{-R_C \parallel R_L}{\frac{1}{g_m} + R_E + \frac{R_s \parallel R_1 \parallel R_2}{\beta + 1}} \cdot \frac{R_1 \parallel R_2}{R_1 \parallel R_2 + R_s}$$

Summary of CE Concepts