

Chapter 5 Bipolar Amplifiers

- **5.1 General Considerations**
- **5.2 Operating Point Analysis and Design**
- **5.3 Bipolar Amplifier Topologies**
- **5.4 Summary and Additional Examples**

Bipolar Amplifiers

General Concepts

- Input and Output Impedances
- Biasing
- DC and Small-Signal Analysis

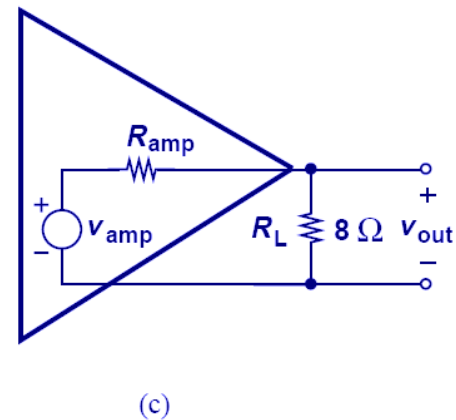
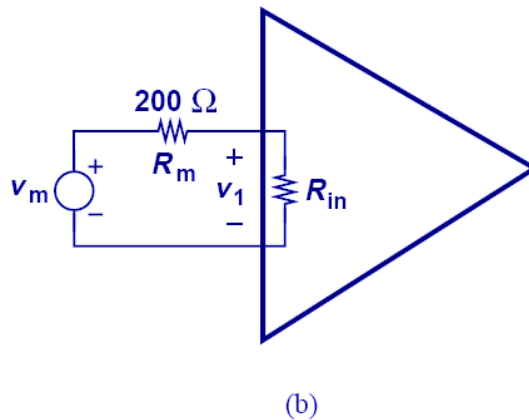
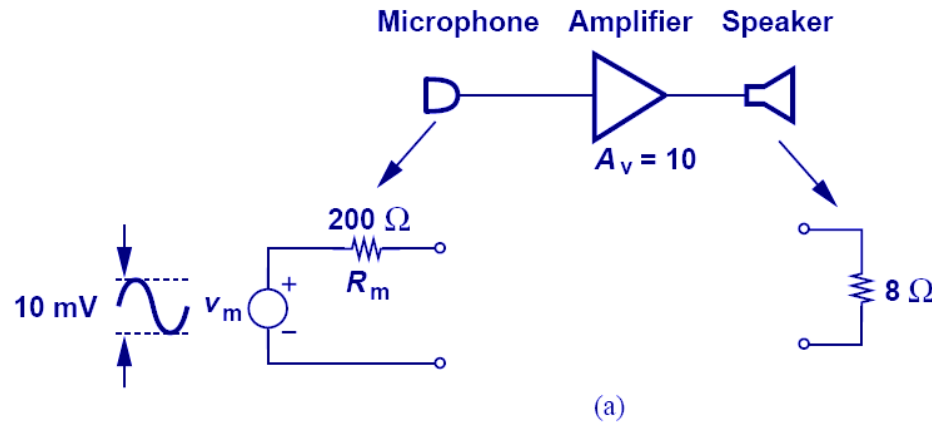
Operating Point Analysis

- Simple Biasing
- Emitter Degeneration
- Self-Biasing
- Biasing of PNP Devices

Amplifier Topologies

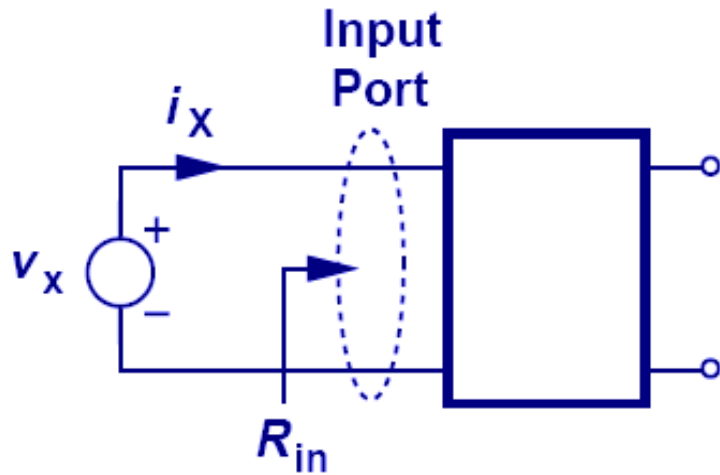
- Common-Emitter Stage
- Common-Base Stage
- Emitter Follower

Voltage Amplifier

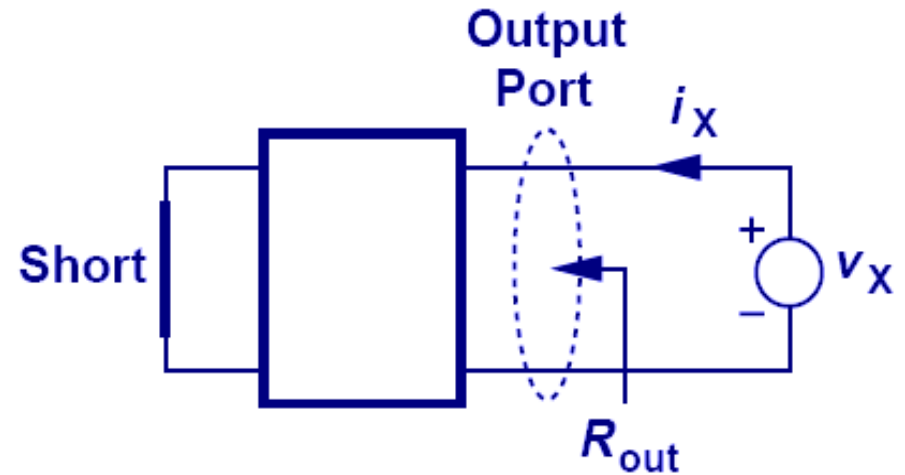


- In an ideal voltage amplifier, the input impedance is infinite and the output impedance zero.
- But in reality, input or output impedances depart from their ideal values.

Input/Output Impedances



(a)

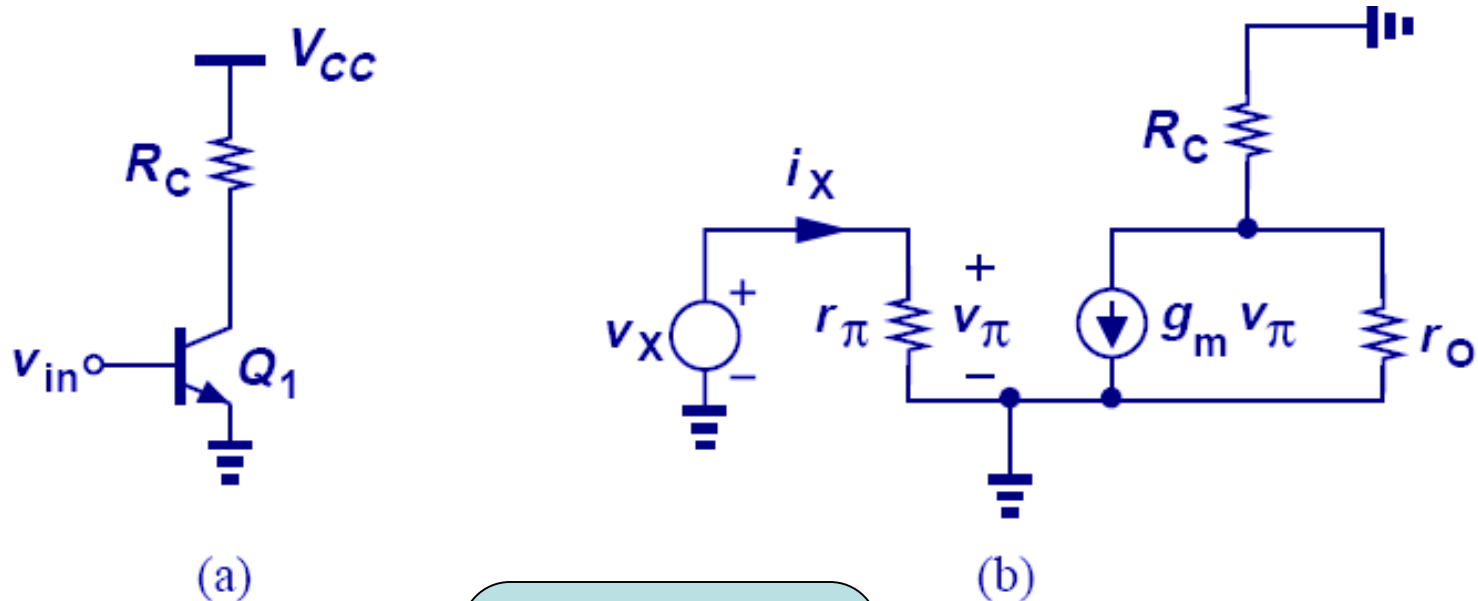


(b)

$$R_x = \frac{V_x}{i_x}$$

➤ The figure above shows the techniques of measuring input and output impedances.

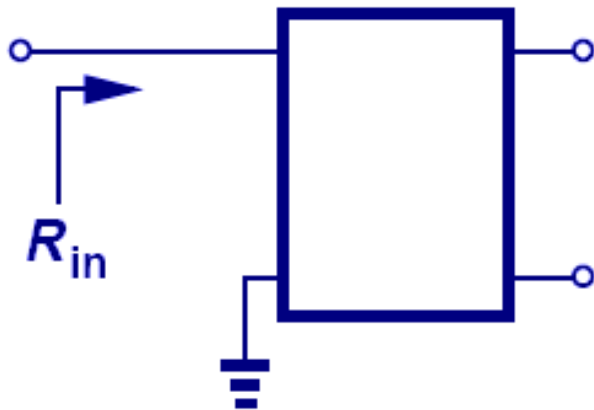
Input Impedance Example I



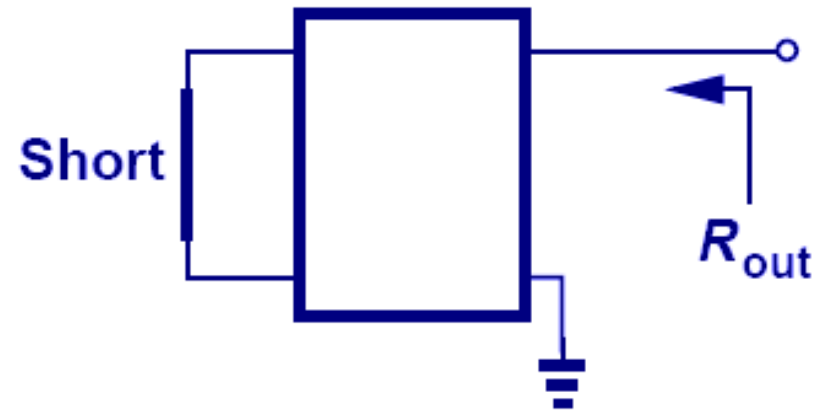
$$\frac{v_X}{i_X} = r_\pi$$

➤ When calculating input/output impedance, small-signal analysis is assumed.

Impedance at a Node



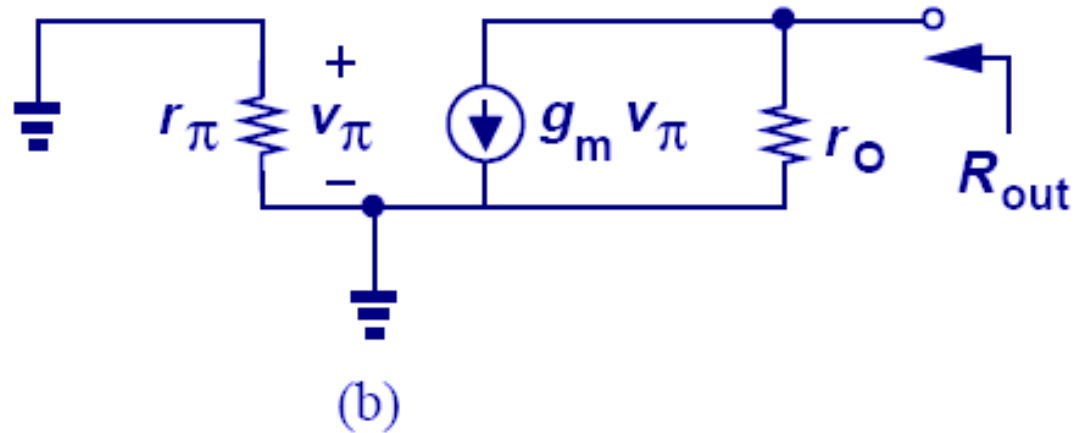
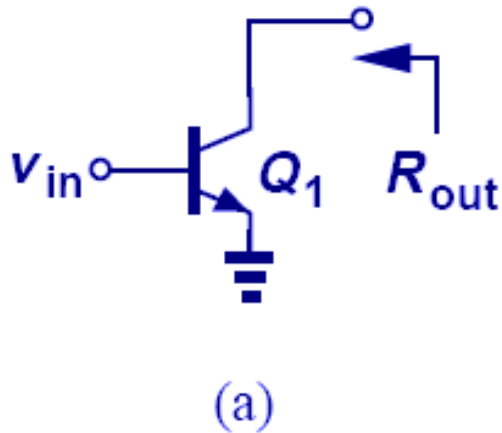
(a)



(b)

- When calculating I/O impedances at a port, we usually ground one terminal while applying the test source to the other terminal of interest.

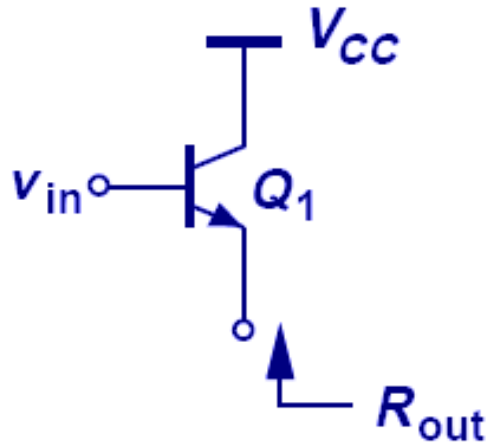
Impedance at Collector



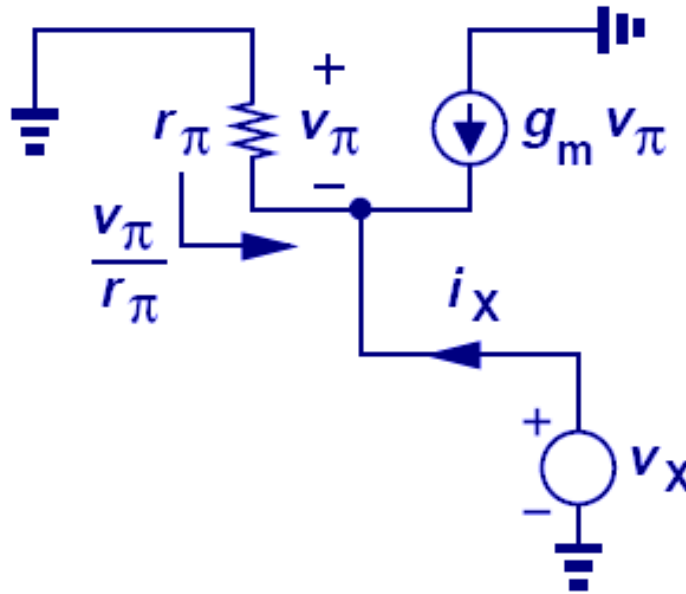
$$R_{out} = r_o$$

- With Early effect, the impedance seen at the collector is equal to the intrinsic output impedance of the transistor (if emitter is grounded).

Impedance at Emitter



(a)



(b)

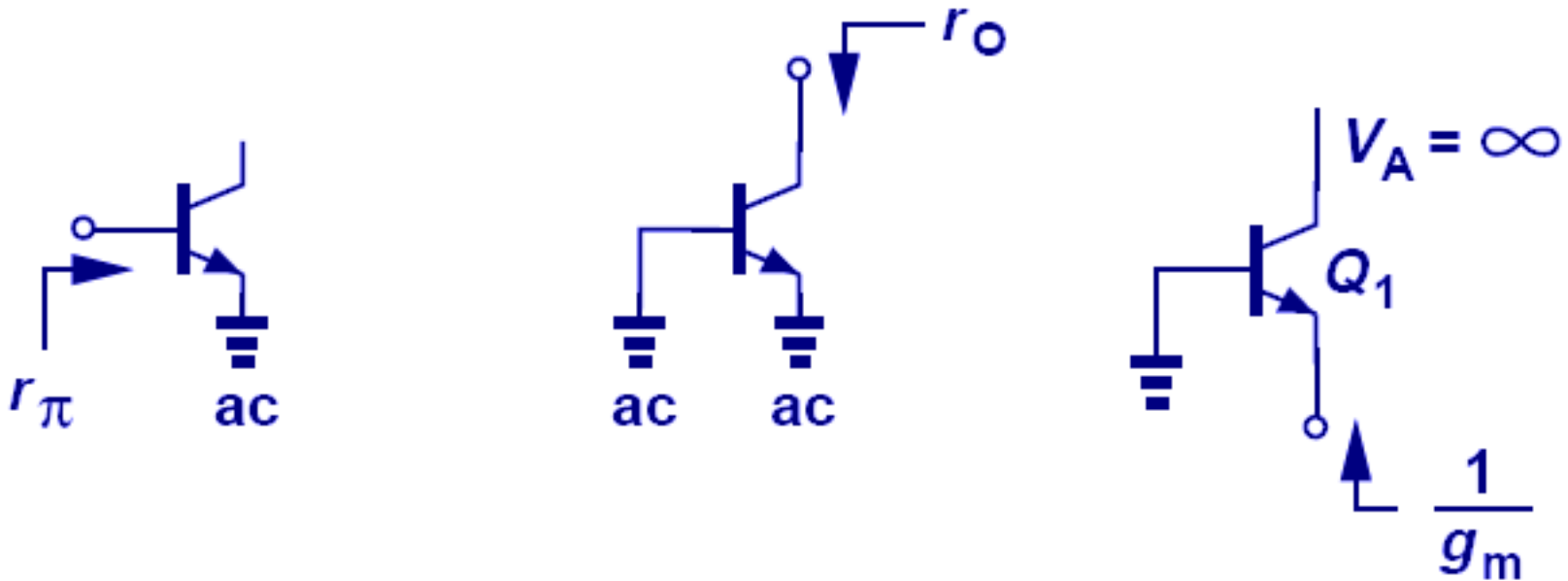
$$\frac{v_x}{i_x} = \frac{1}{g_m + \frac{1}{r_\pi}}$$

$$R_{out} \approx \frac{1}{g_m}$$

$$(V_A = \infty)$$

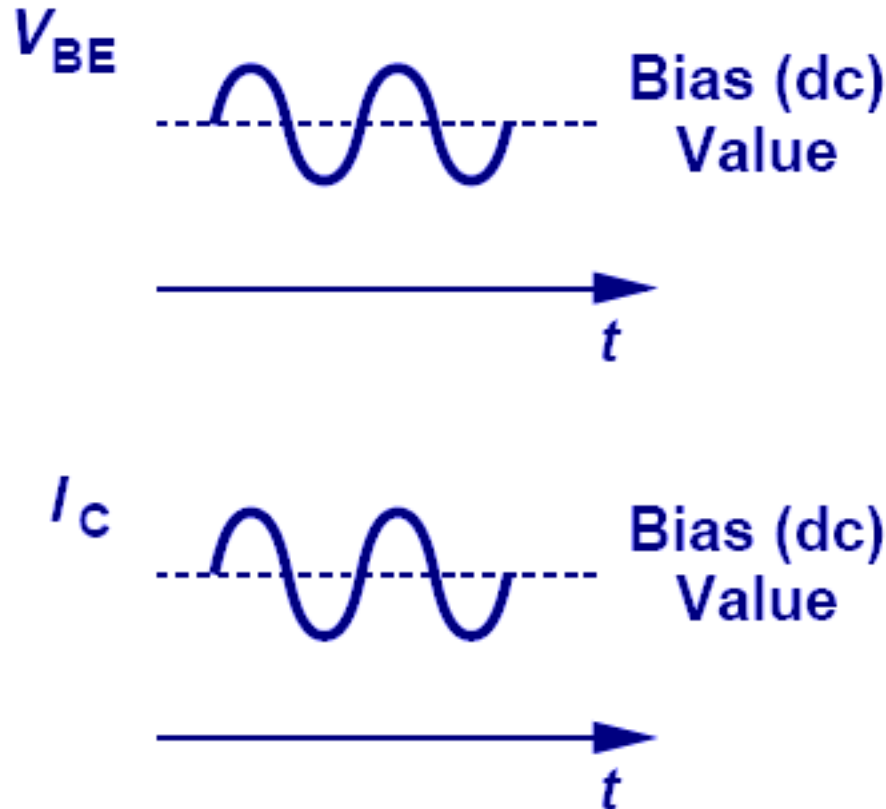
- The impedance seen at the emitter of a transistor is approximately equal to one over its transconductance (if the base is grounded).

Three Master Rules of Transistor Impedances



- **Rule # 1:** looking into the base, the impedance is r_π if emitter is (ac) grounded.
- **Rule # 2:** looking into the collector, the impedance is r_o if emitter is (ac) grounded.
- **Rule # 3:** looking into the emitter, the impedance is $1/g_m$ if base is (ac) grounded and Early effect is neglected.

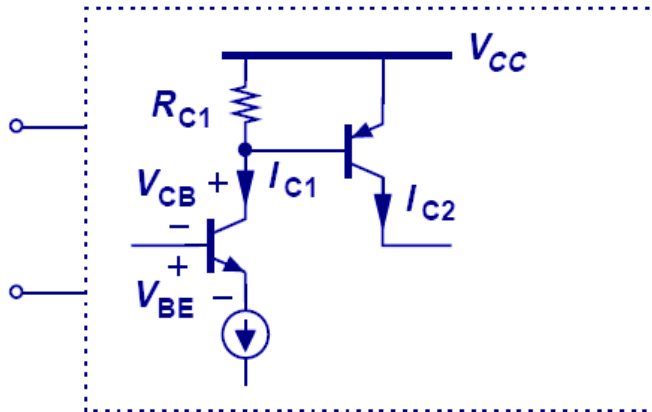
Biassing of BJT



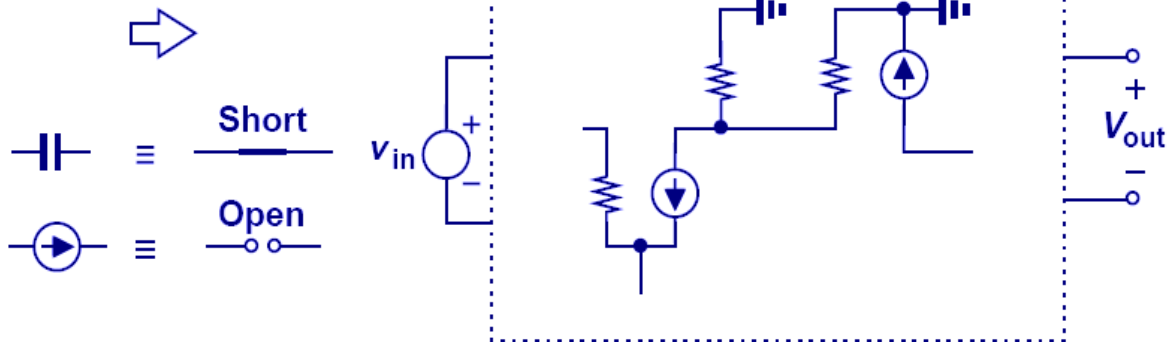
- Transistors and circuits must be biased because (1) transistors must operate in the active region, (2) their small-signal parameters depend on the bias conditions.

DC Analysis vs. Small-Signal Analysis

DC Analysis

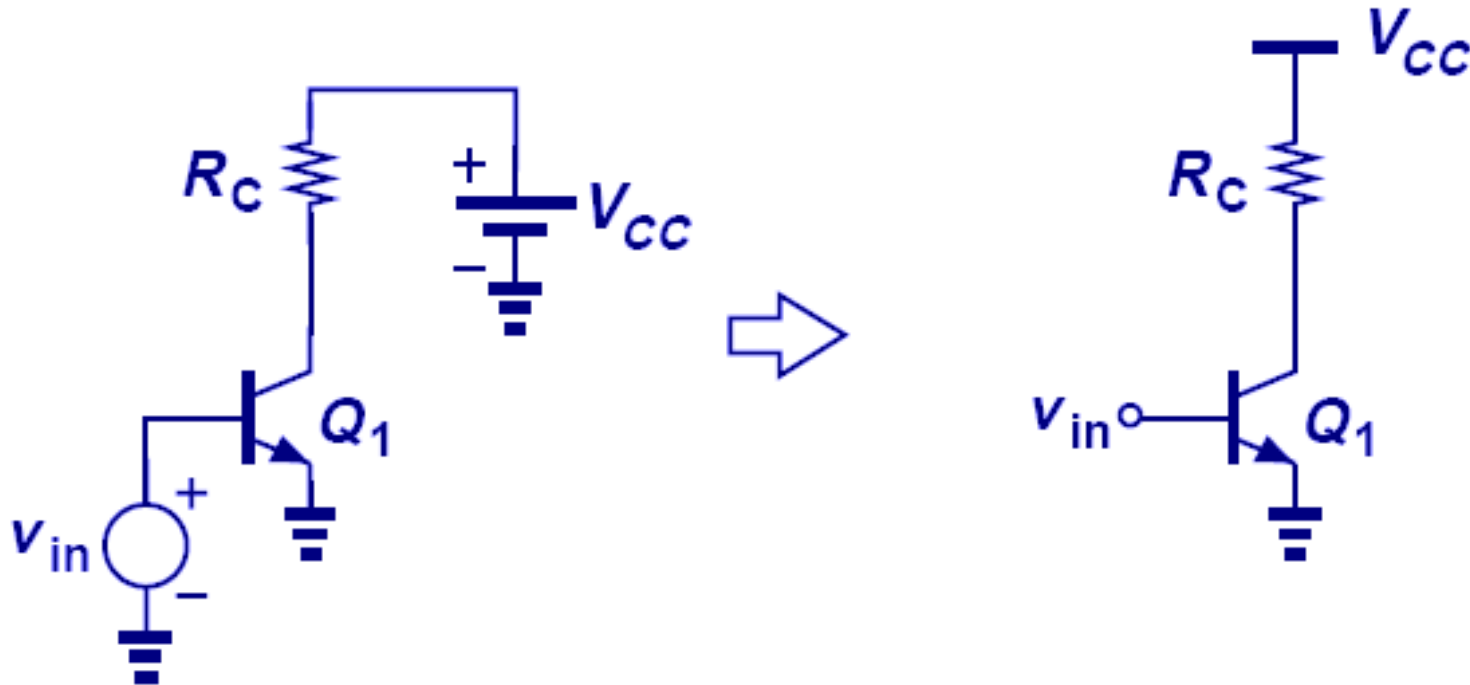


Small-Signal Analysis



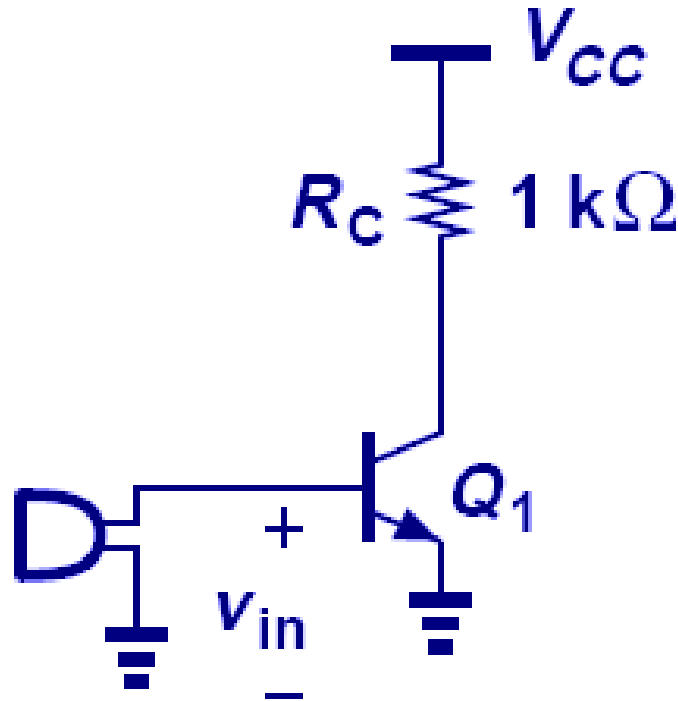
- First, DC analysis is performed to determine operating point and obtain small-signal parameters.
- Second, sources are set to zero and small-signal model is used.

Notation Simplification



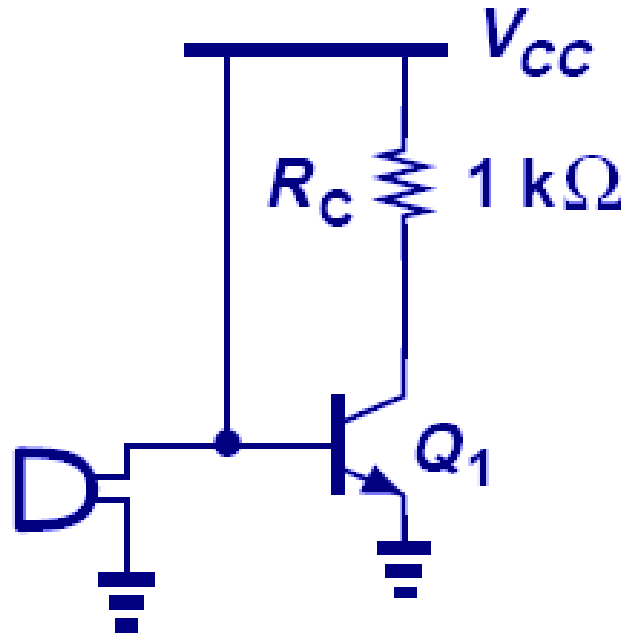
- Hereafter, the battery that supplies power to the circuit is replaced by a horizontal bar labeled V_{CC} , and input signal is simplified as one node called V_{in} .

Example of Bad Biasing



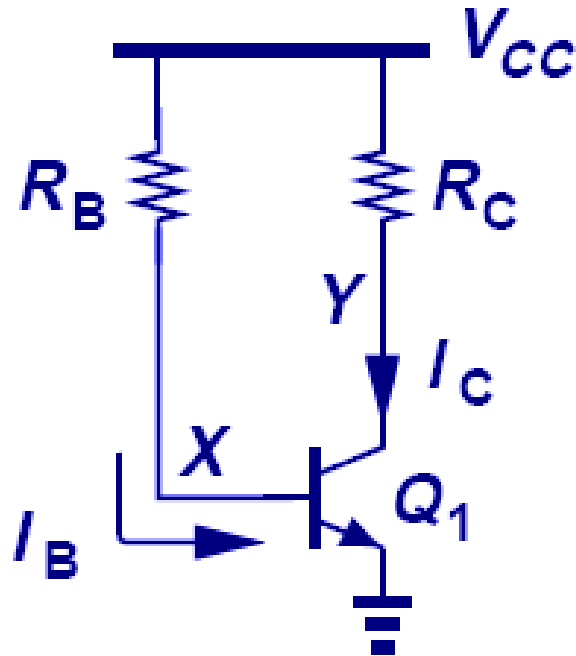
- The microphone is connected to the amplifier in an attempt to amplify the small output signal of the microphone.
- Unfortunately, there's no DC bias current running thru the transistor to set the transconductance.

Another Example of Bad Biasing



- The base of the amplifier is connected to V_{CC} , trying to establish a DC bias.
- Unfortunately, the output signal produced by the microphone is shorted to the power supply.

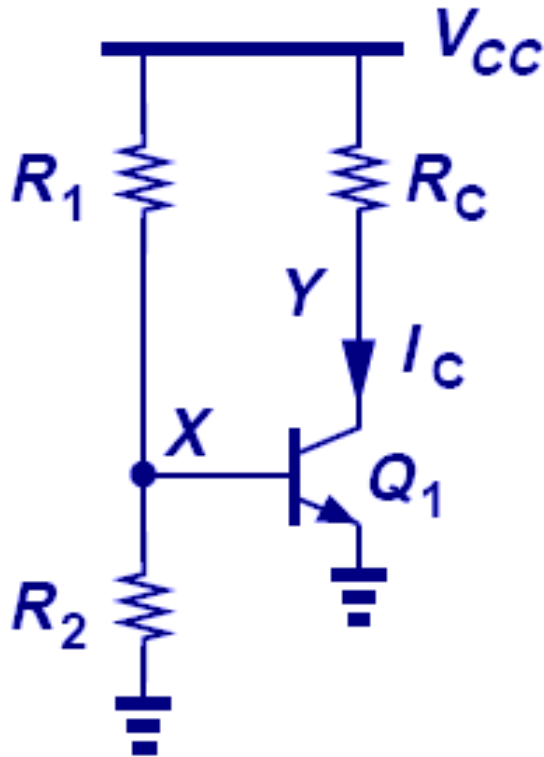
Biassing with Base Resistor



$$I_B = \frac{V_{CC} - V_{BE}}{R_B}, I_C = \beta \frac{V_{CC} - V_{BE}}{R_B}$$

- Assuming a constant value for V_{BE} , one can solve for both I_B and I_C and determine the terminal voltages of the transistor.
- However, bias point is sensitive to β variations.

Improved Biasing: Resistive Divider

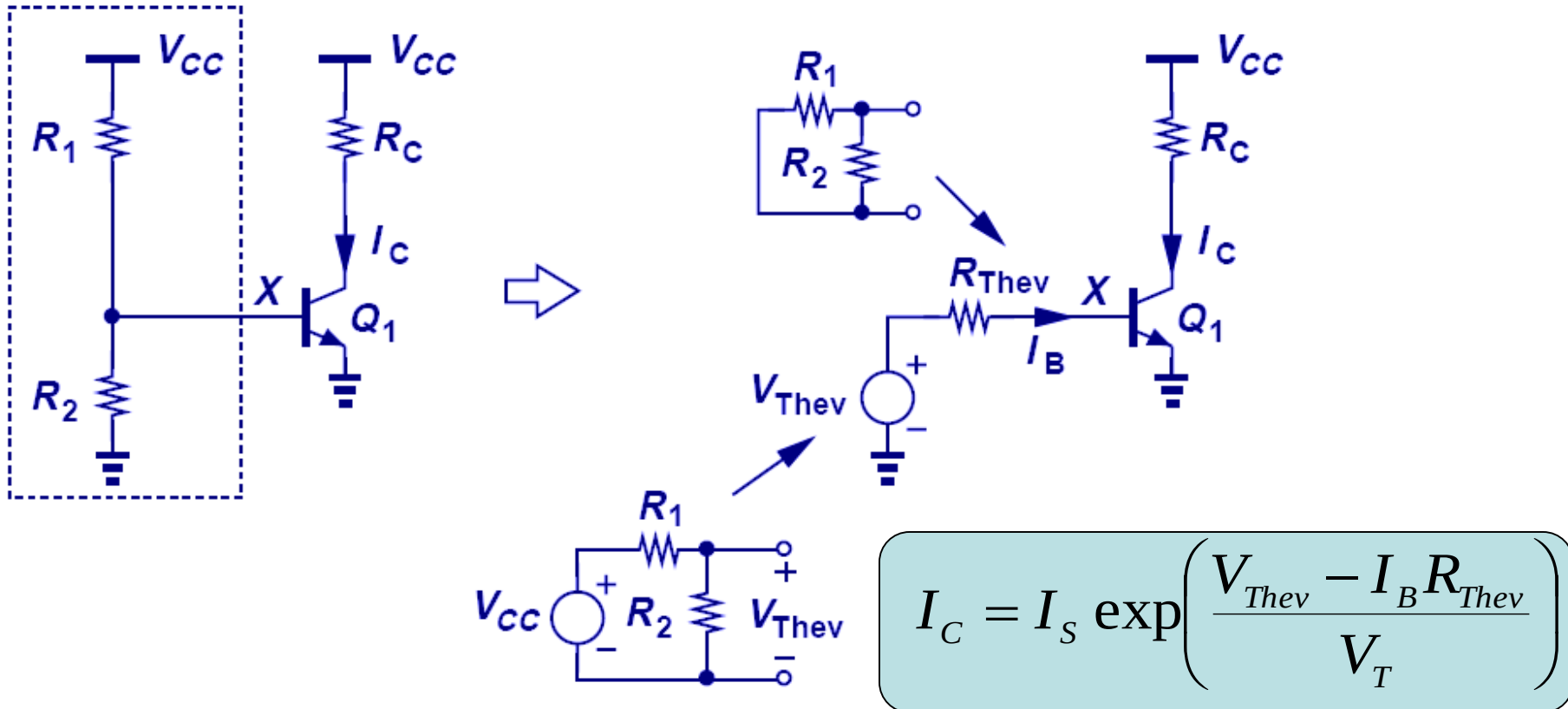


$$V_X = \frac{R_2}{R_1 + R_2} V_{CC}$$

$$I_C = I_S \exp\left(\frac{R_2}{R_1 + R_2} \frac{V_{CC}}{V_T}\right)$$

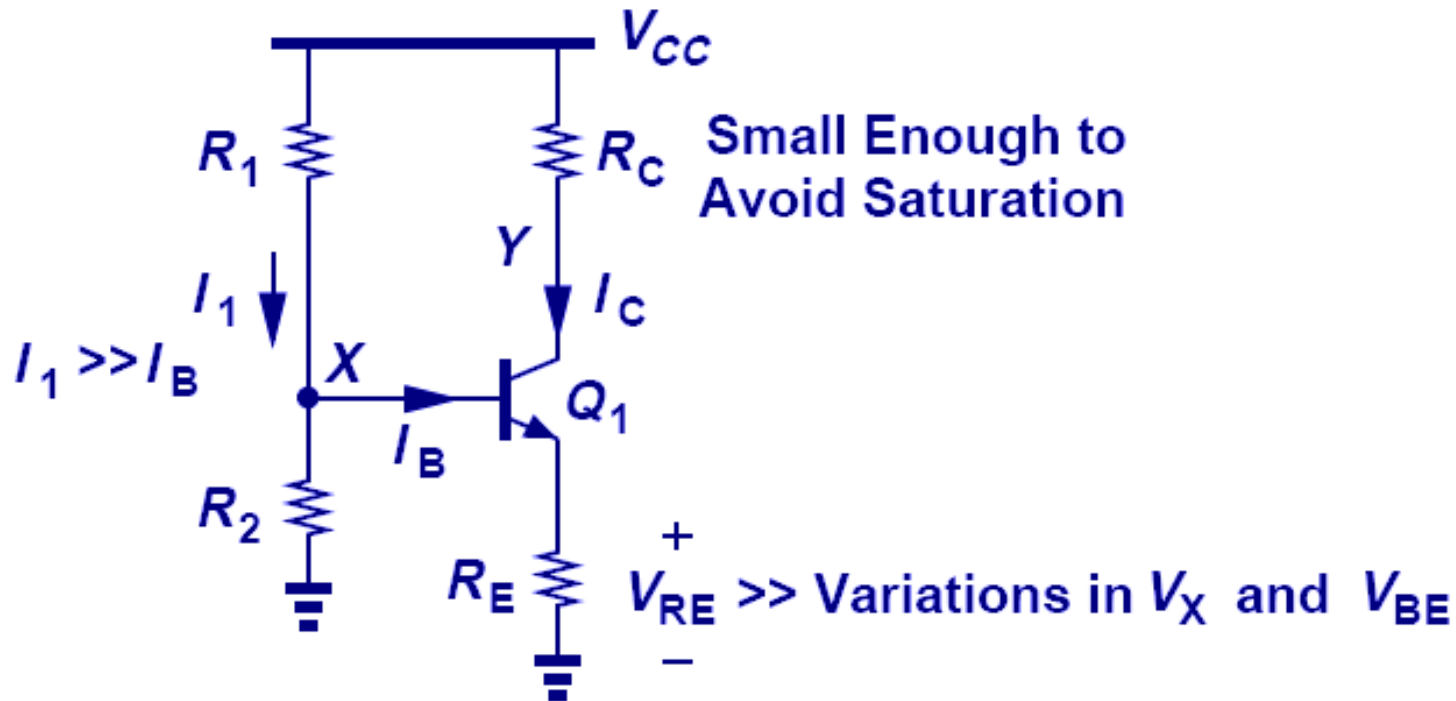
- Using resistor divider to set V_{BE} , it is possible to produce an I_C that is relatively independent of β if base current is small.

Accounting for Base Current



➤ With proper ratio of R_1 and R_2 , I_C can be insensitive to β ; however, its exponential dependence on resistor deviations makes it less useful.

Emitter Degeneration Biasing

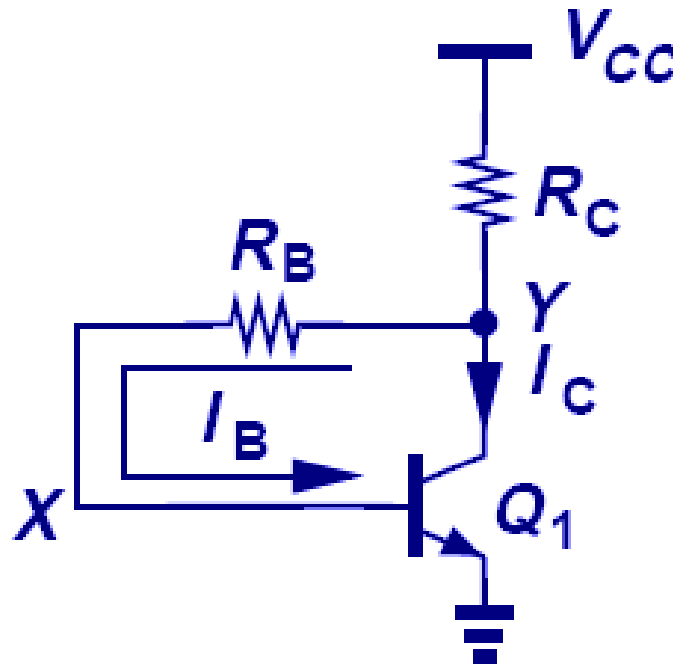


- The presence of R_E helps to absorb the error in V_X so V_{BE} stays relatively constant.
- This bias technique is less sensitive to β ($I_1 \gg I_B$) and V_{BE} variations.

Design Procedure

- Choose an I_C to provide the necessary small signal parameters, g_m , r_π , etc.
- Considering the variations of R_1 , R_2 , and V_{BE} , choose a value for V_{RE} .
- With V_{RE} chosen, and V_{BE} calculated, V_x can be determined.
- Select R_1 and R_2 to provide V_x .

Self-Biasing Technique



- This bias technique utilizes the collector voltage to provide the necessary V_x and I_B .
- One important characteristic of this technique is that collector has a higher potential than the base, thus guaranteeing active operation of the transistor.

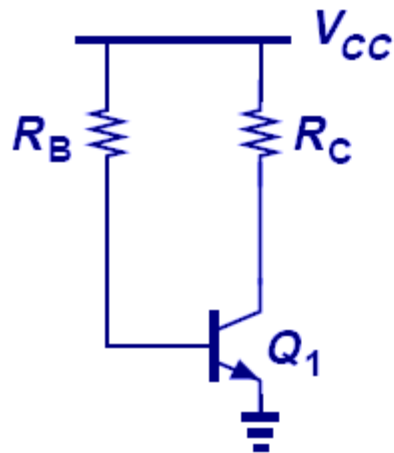
Self-Biasing Design Guidelines

$$(1) \quad R_C \gg \frac{R_B}{\beta}$$

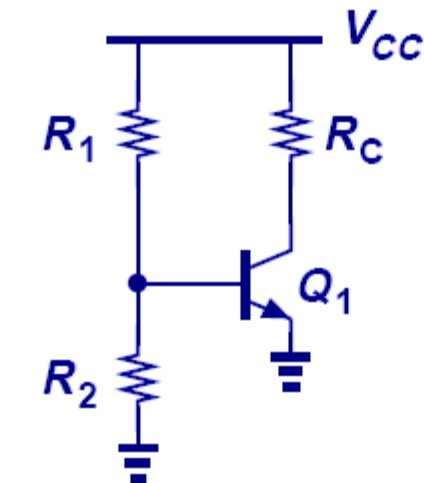
$$(2) \quad \Delta V_{BE} \ll V_{CC} - V_{BE}$$

- (1) provides insensitivity to β .
- (2) provides insensitivity to variation in V_{BE} .

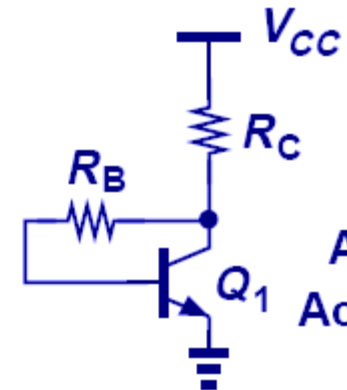
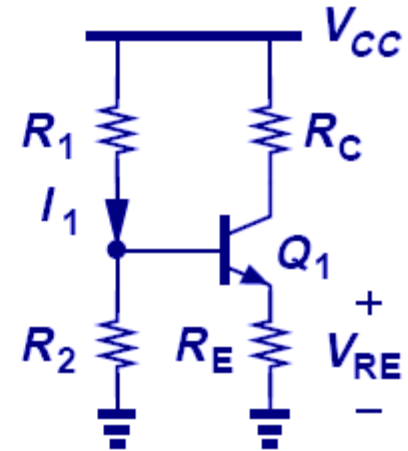
Summary of Biasing Techniques



Sensitive
to β

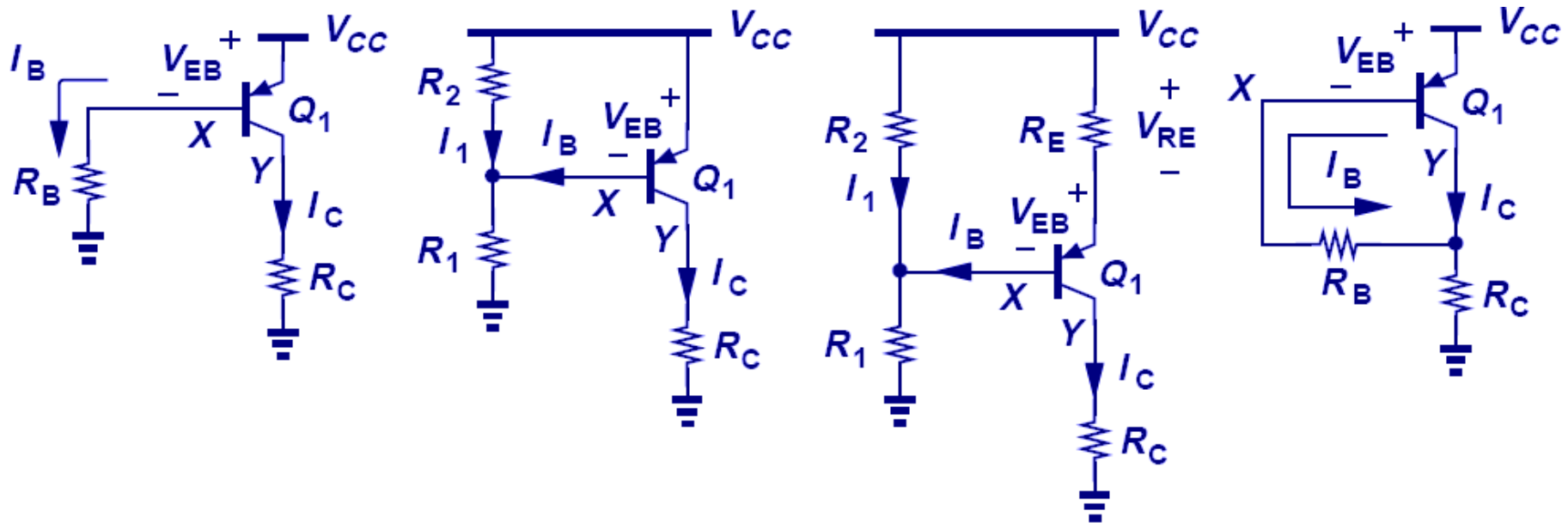


Sensitive
to Resistor Error



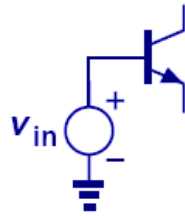
Always in
Active Mode

PNP Biasing Techniques

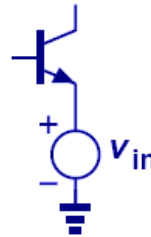


➤ Same principles that apply to NPN biasing also apply to PNP biasing with only polarity modifications.

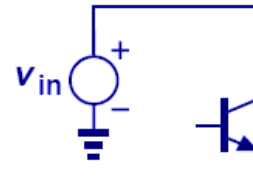
Possible Bipolar Amplifier Topologies



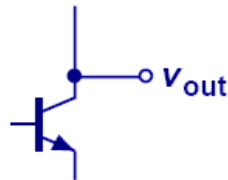
(a)



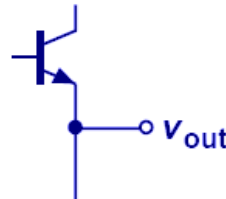
(b)



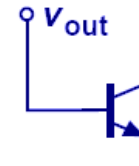
(c)



(d)



(e)



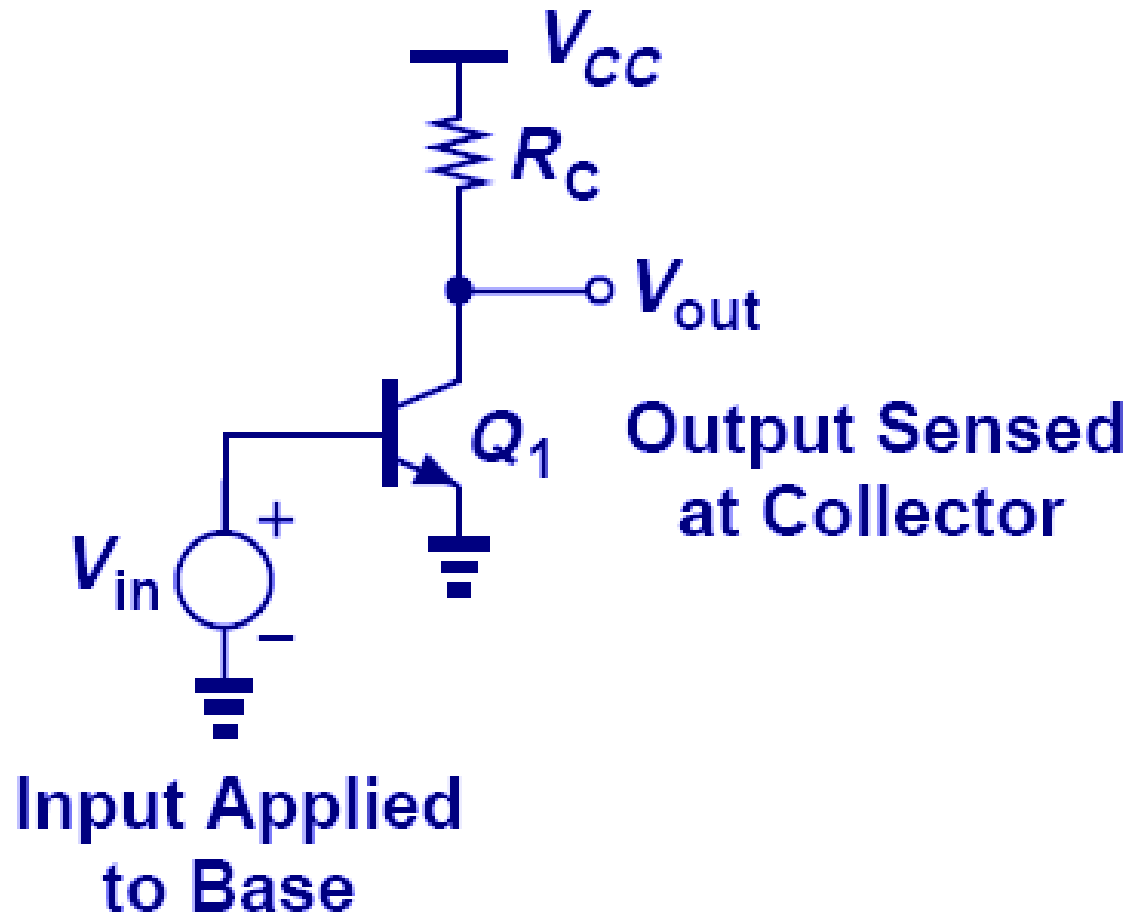
(f)

- Three possible ways to apply an input to an amplifier and three possible ways to sense its output.
- However, in reality only three of six input/output combinations are useful.

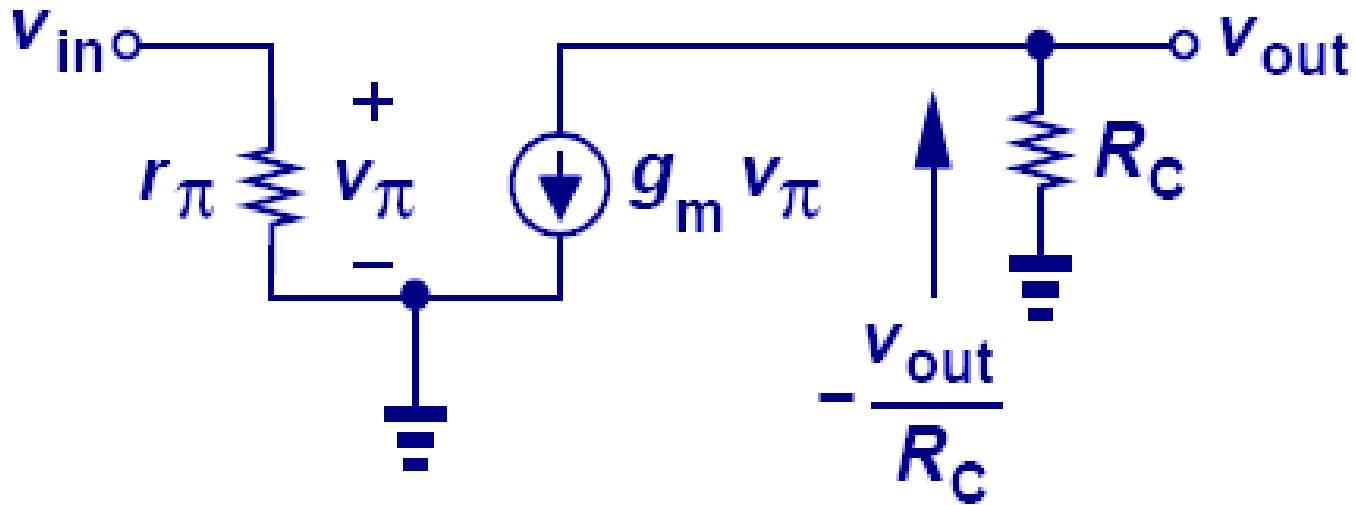
Study of Common-Emitter Topology

- ***Analysis of CE Core***
Inclusion of Early Effect
- ***Emitter Degeneration***
Inclusion of Early Effect
- ***CE Stage with Biasing***

Common-Emitter Topology



Small Signal of CE Amplifier

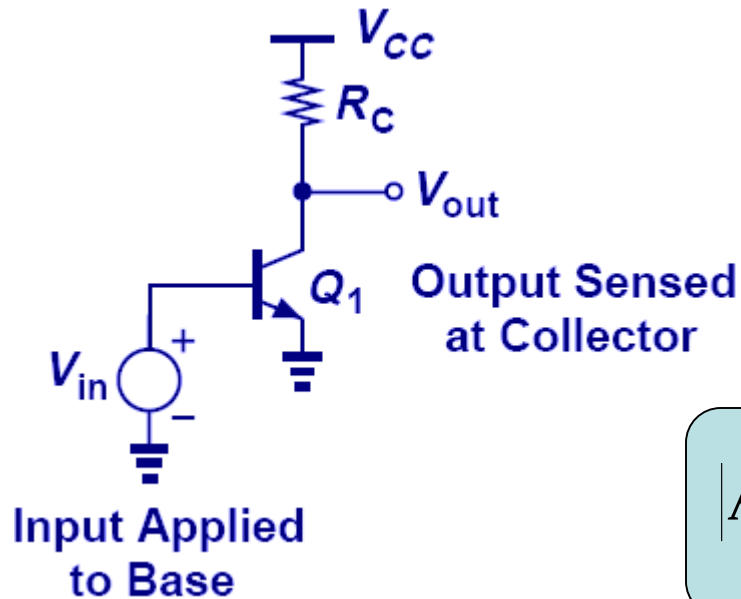


$$A_v = \frac{V_{out}}{V_{in}}$$

$$-\frac{V_{out}}{R_C} = g_m v_\pi = g_m V_{in}$$

$$A_v = -g_m R_C$$

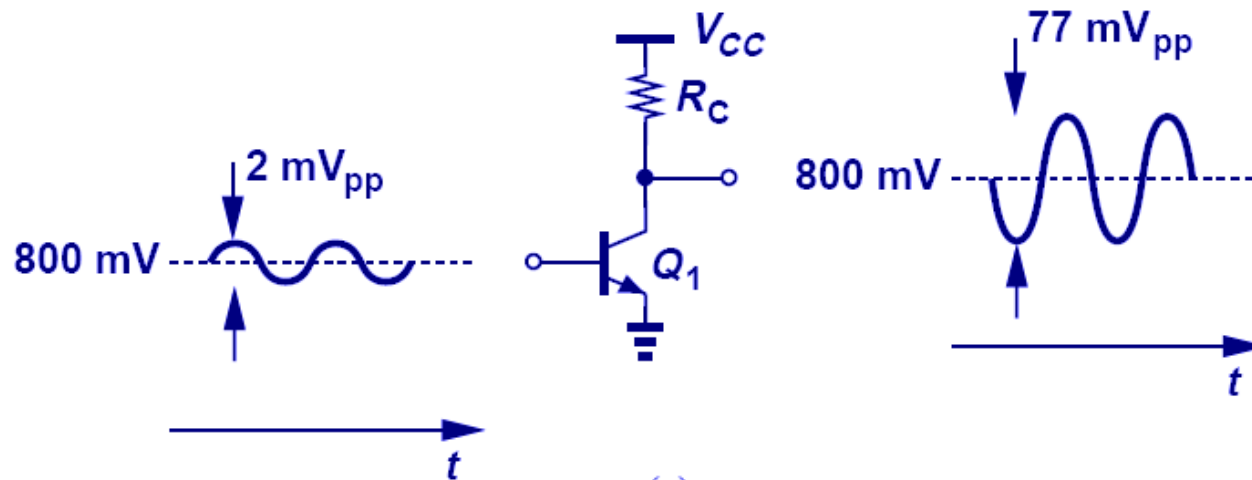
Limitation on CE Voltage Gain



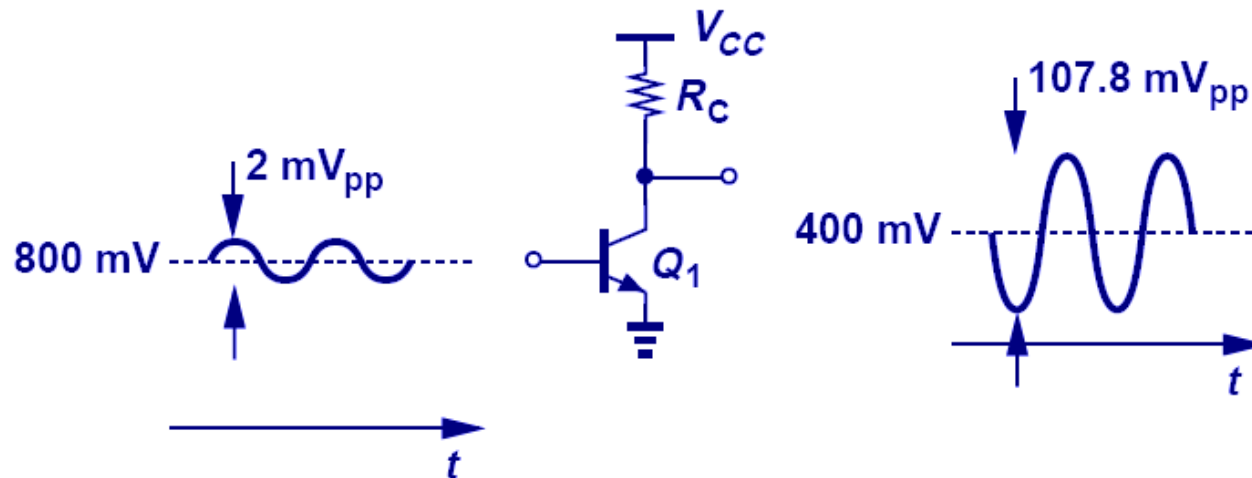
$$|A_v| = \frac{I_C R_C}{V_T} \quad |A_v| = \frac{V_{RC}}{V_T} \quad |A_v| < \frac{V_{CC} - V_{BE}}{V_T}$$

- Since g_m can be written as I_C/V_T , the CE voltage gain can be written as the ratio of V_{RC} and V_T .
- V_{RC} is the potential difference between V_{CC} and V_{CE} , and V_{CE} cannot go below V_{BE} in order for the transistor to be in active region.

Tradeoff between Voltage Gain and Headroom

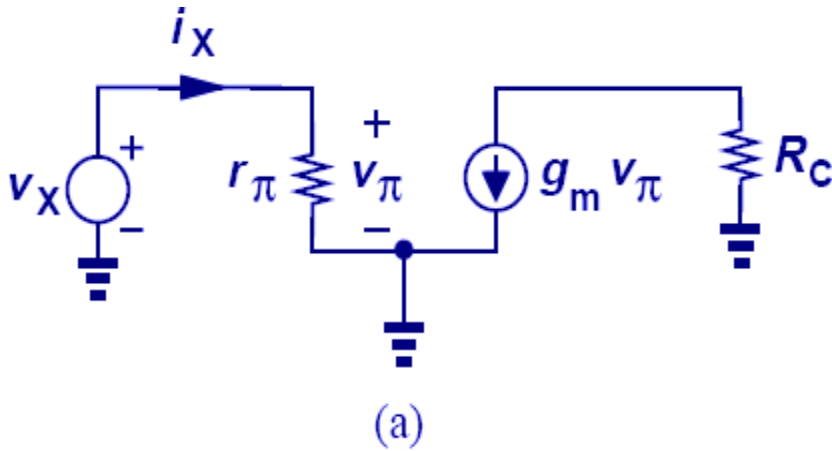


(a)

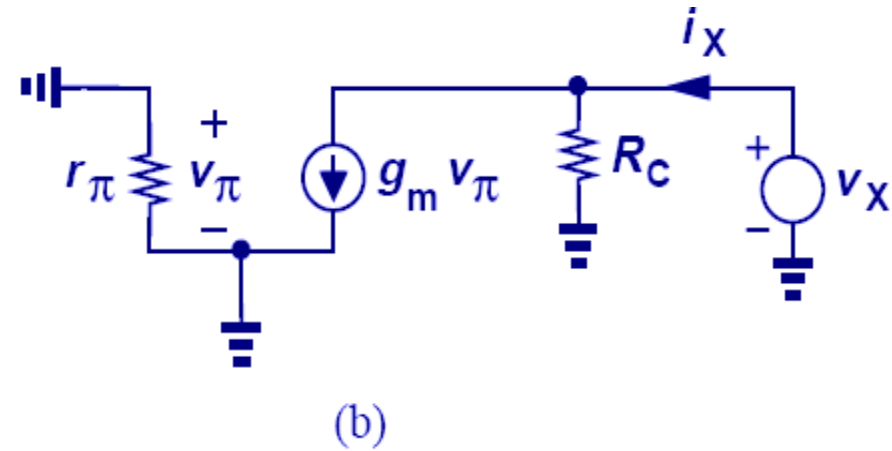


(b)

I/O Impedances of CE Stage



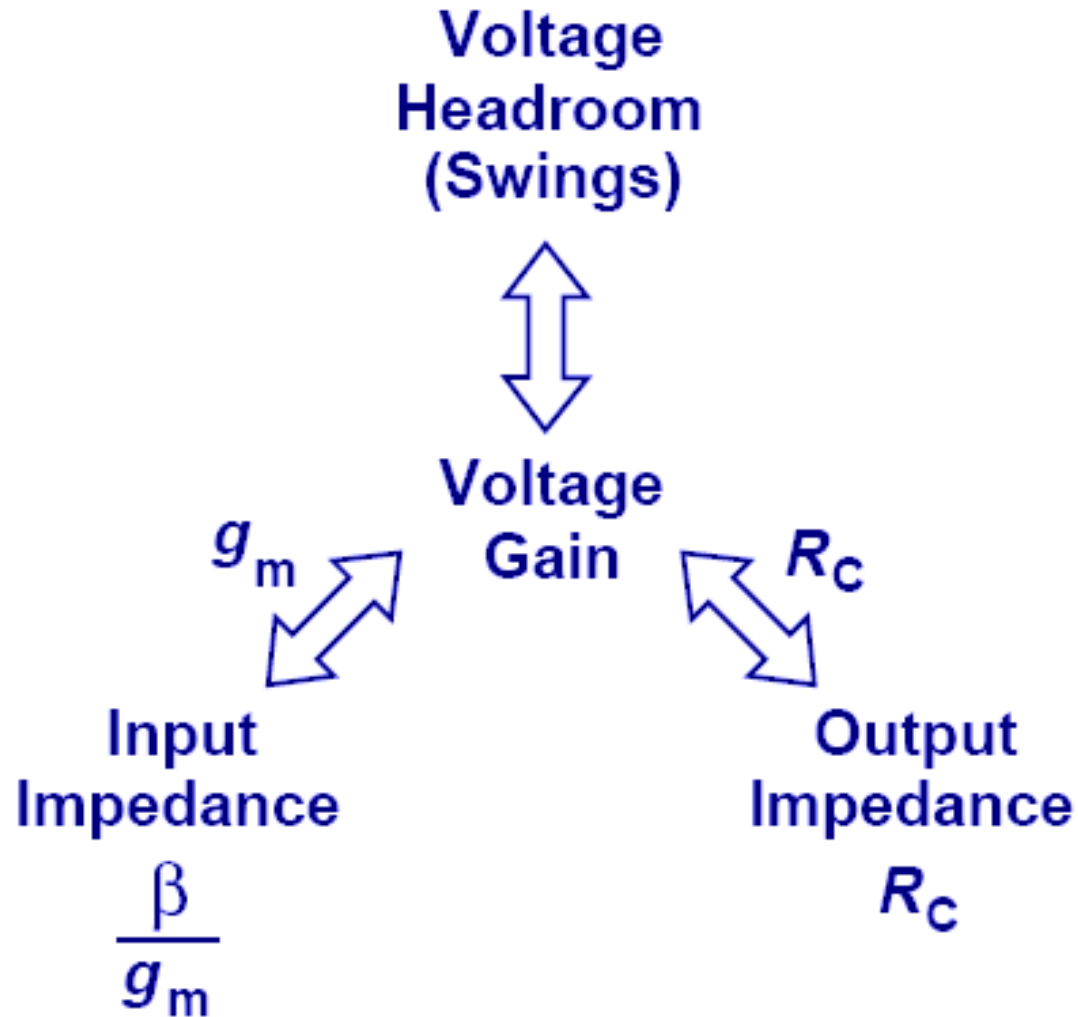
$$R_{in} = \frac{v_X}{i_X} = r_{\pi}$$



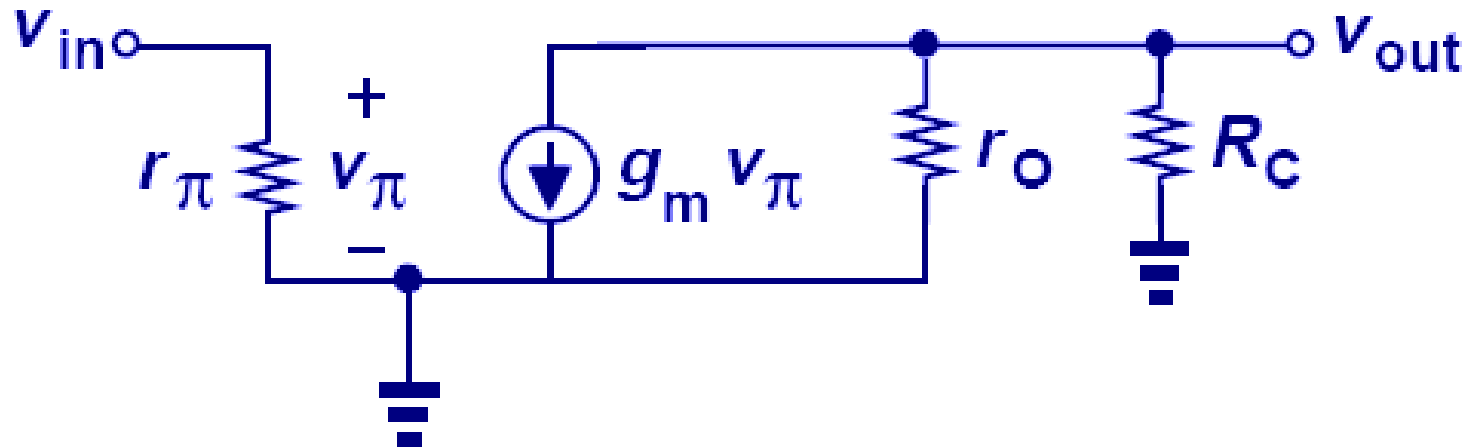
$$R_{out} = \frac{v_X}{i_X} = R_C$$

➤ When measuring output impedance, the input port has to be grounded so that $V_{in} = 0$.

CE Stage Trade-offs



Inclusion of Early Effect



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

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

➤ Early effect will lower the gain of the CE amplifier, as it appears in parallel with R_C .

Intrinsic Gain

$$A_v = -g_m r_O$$

$$|A_v| = \frac{V_A}{V_T}$$

- As R_C goes to infinity, the voltage gain reaches the product of g_m and r_O , which represents the maximum voltage gain the amplifier can have.
- The intrinsic gain is independent of the bias current.

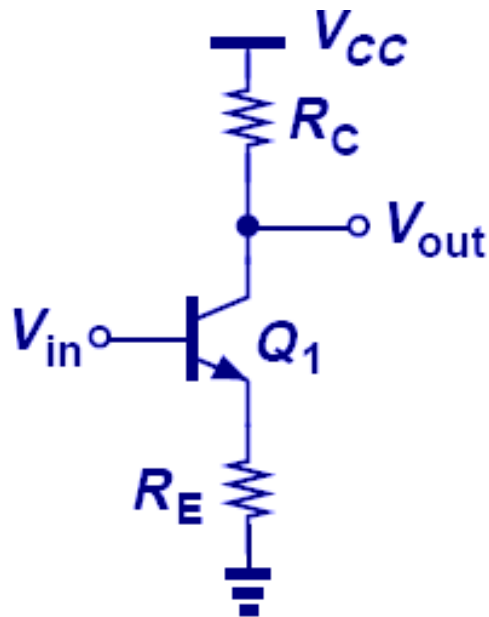
Current Gain

$$A_I = \frac{\dot{i}_{out}}{\dot{i}_{in}}$$

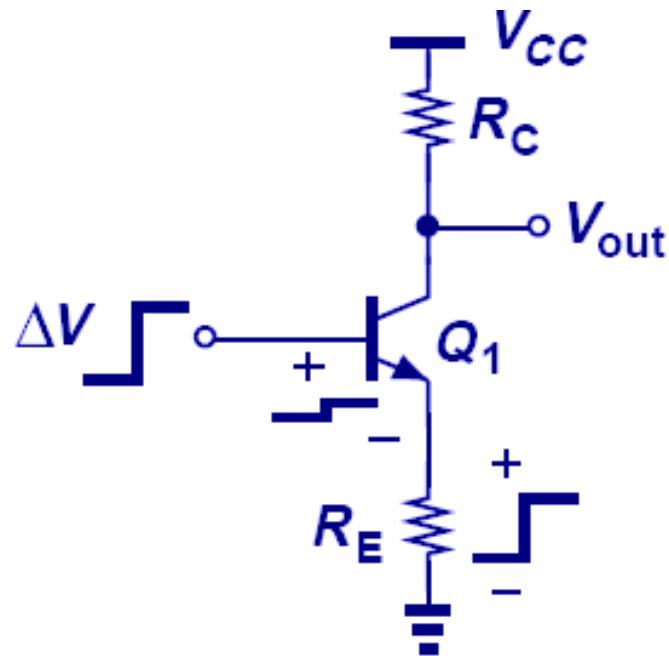
$$A_I|_{CE} = \beta$$

- Another parameter of the amplifier is the current gain, which is defined as the ratio of current delivered to the load to the current flowing into the input.
- For a CE stage, it is equal to β .

Emitter Degeneration



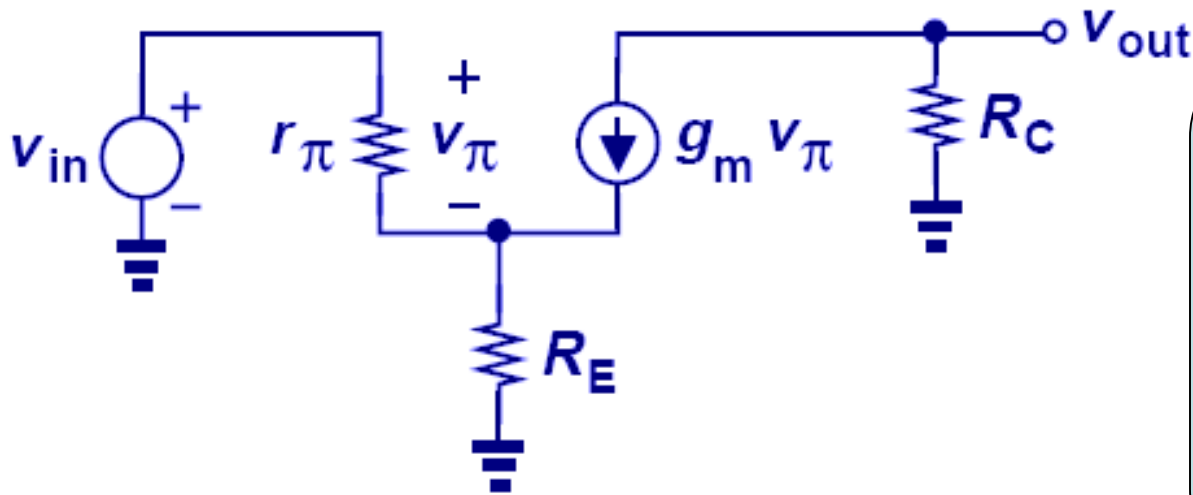
(a)



(b)

- 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.

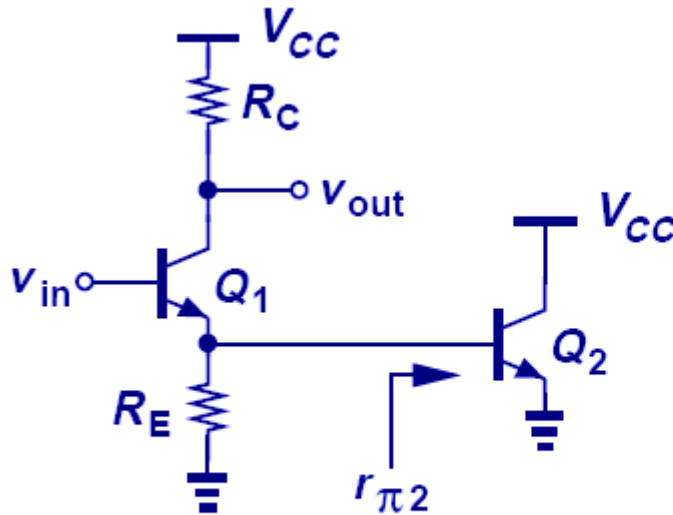
Small-Signal Model



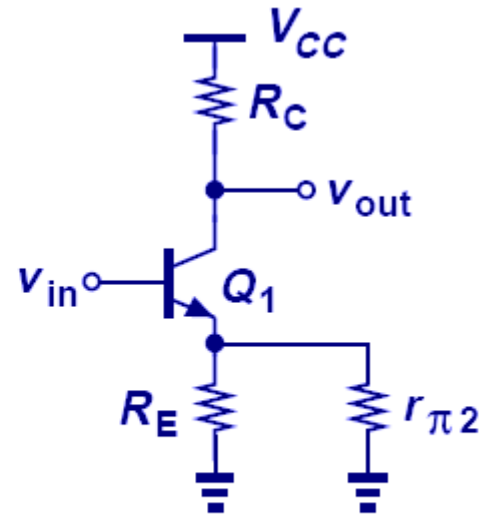
$$A_v = -\frac{g_m R_C}{1 + g_m R_E}$$
$$A_v = -\frac{R_C}{\frac{1}{g_m} + R_E}$$

- Interestingly, this gain is equal to the total load resistance to ground divided by $1/g_m$ plus the total resistance placed in series with the emitter.

Emitter Degeneration Example I



(a)

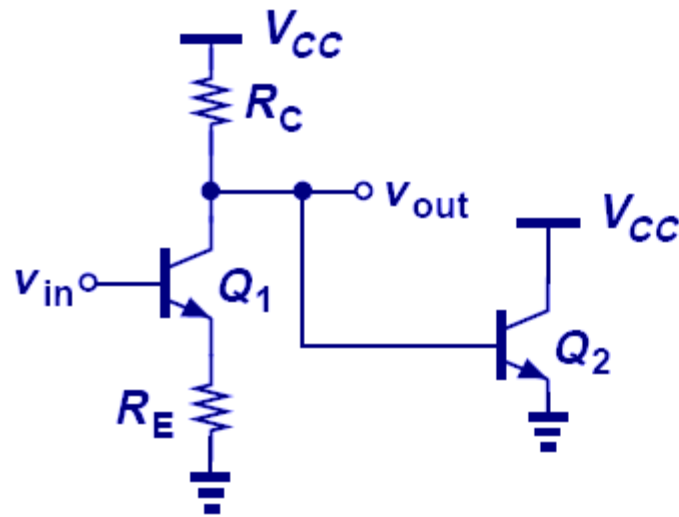


(b)

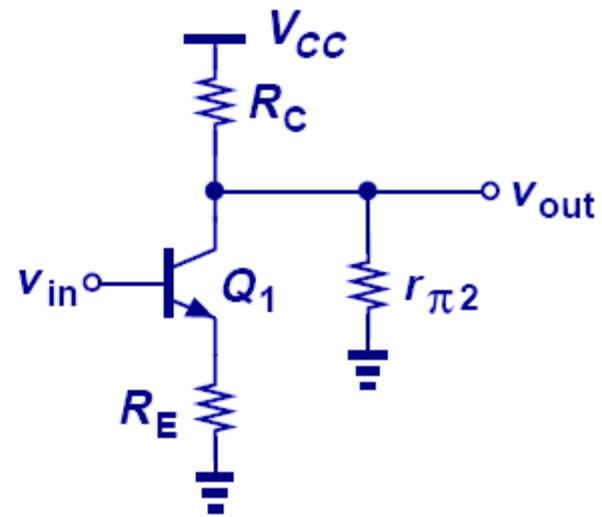
$$A_v = - \frac{R_C}{\frac{1}{g_{m1}} + R_E \parallel r_{\pi 2}}$$

- The input impedance of Q_2 can be combined in parallel with R_E to yield an equivalent impedance that degenerates Q_1 .

Emitter Degeneration Example II



(a)

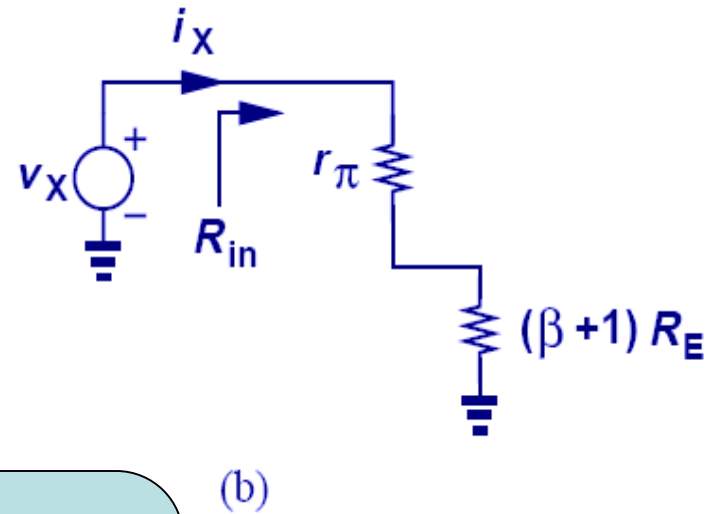
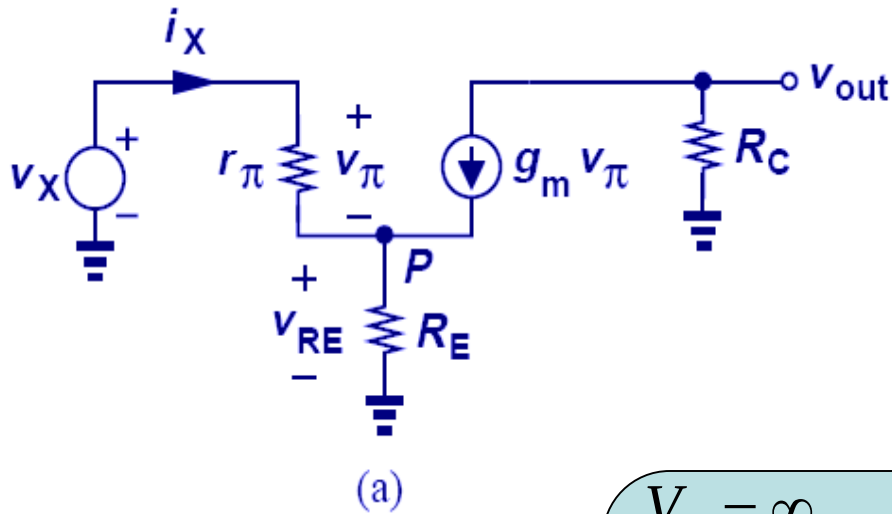


(b)

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

➤ In this example, the input impedance of Q_2 can be combined in parallel with R_C to yield an equivalent collector impedance to ground.

Input Impedance of Degenerated CE Stage



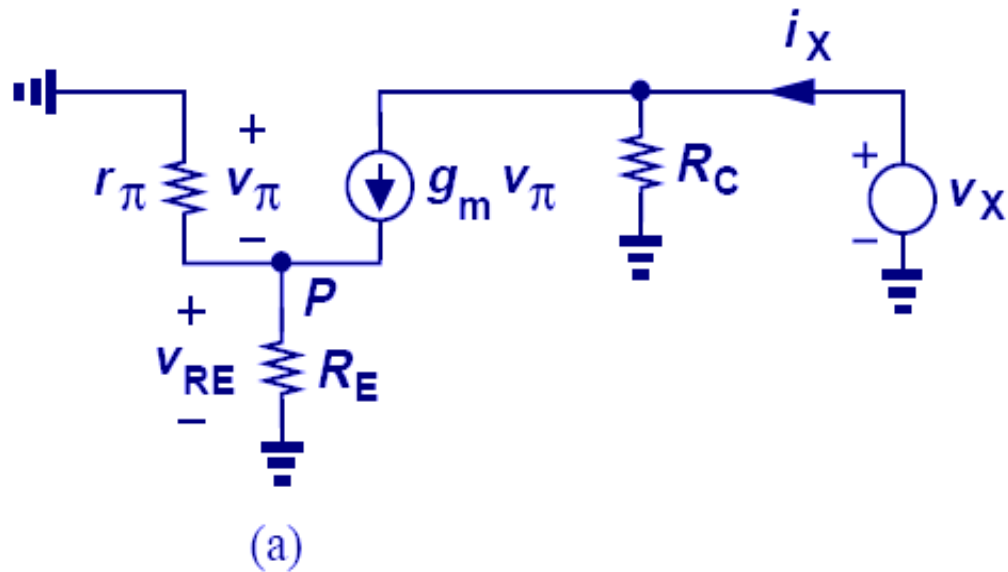
$$V_A = \infty$$

$$v_X = r_\pi i_X + R_E (1 + \beta) i_X$$

$$R_{in} = \frac{v_X}{i_X} = r_\pi + (\beta + 1) R_E$$

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

Output Impedance of Degenerated CE Stage



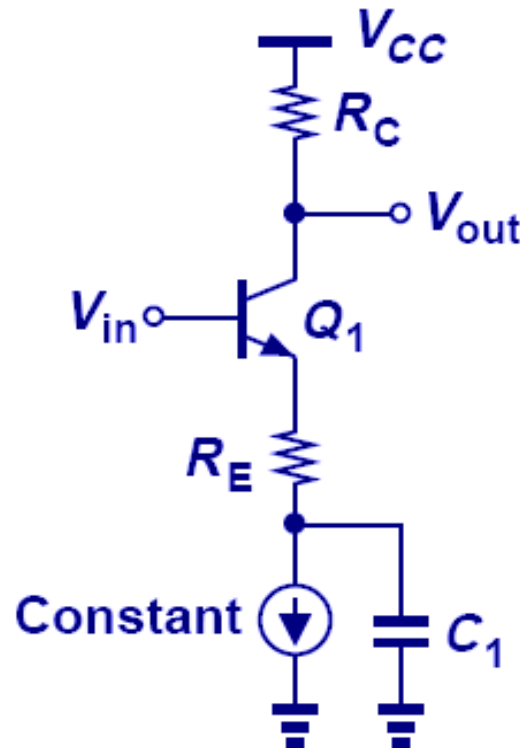
$$V_A = \infty$$

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

$$R_{out} = \frac{v_X}{i_X} = R_C$$

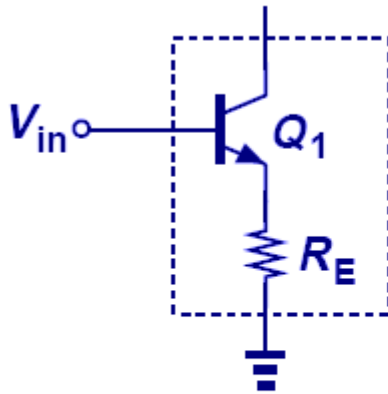
➤ Emitter degeneration does not alter the output impedance in this case. (More on this later.)

Capacitor at Emitter

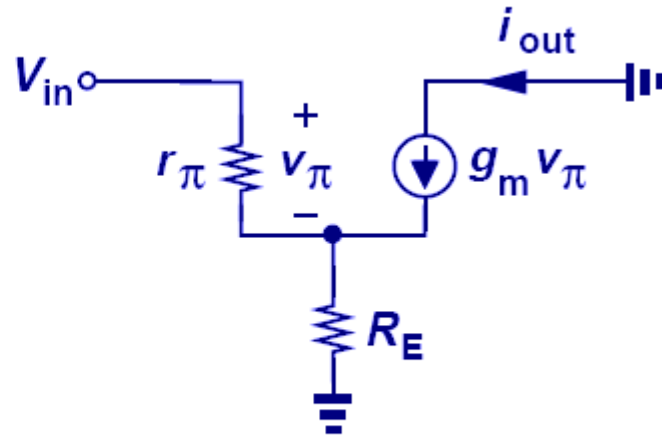


- At DC the capacitor is open and the current source biases the amplifier.
- For ac signals, the capacitor is short and the amplifier is degenerated by R_E .

Example: Design CE Stage with Degeneration as a Black Box



(a)



(b)

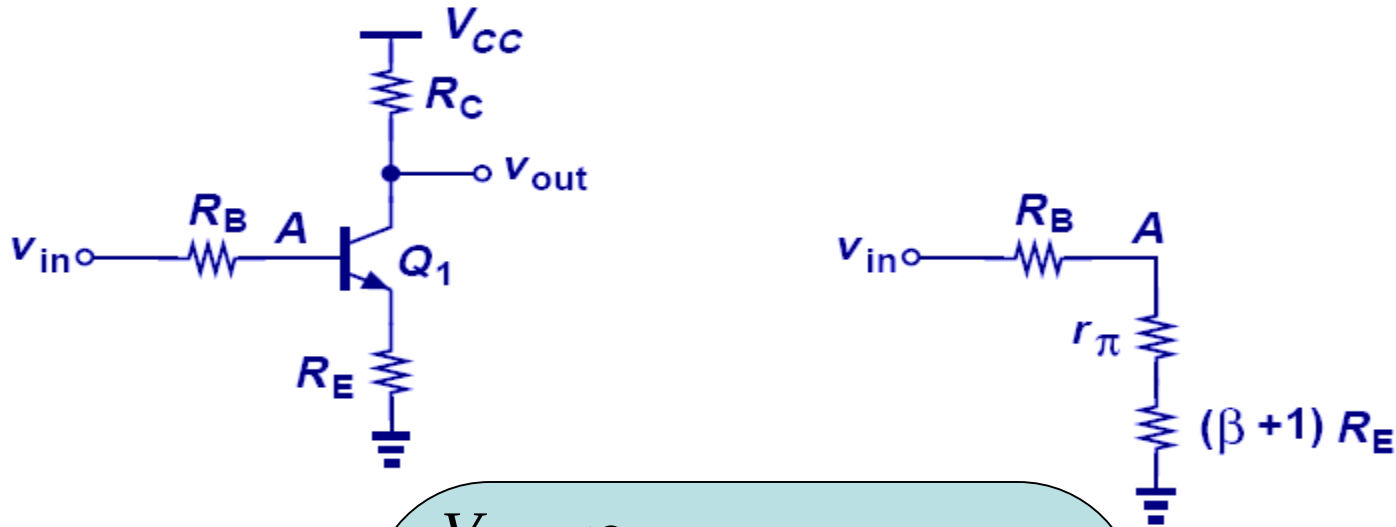
$$V_A = \infty$$

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

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

➤ If $g_m R_E$ is much greater than unity, G_m is more linear.

Degenerated CE Stage with Base Resistance



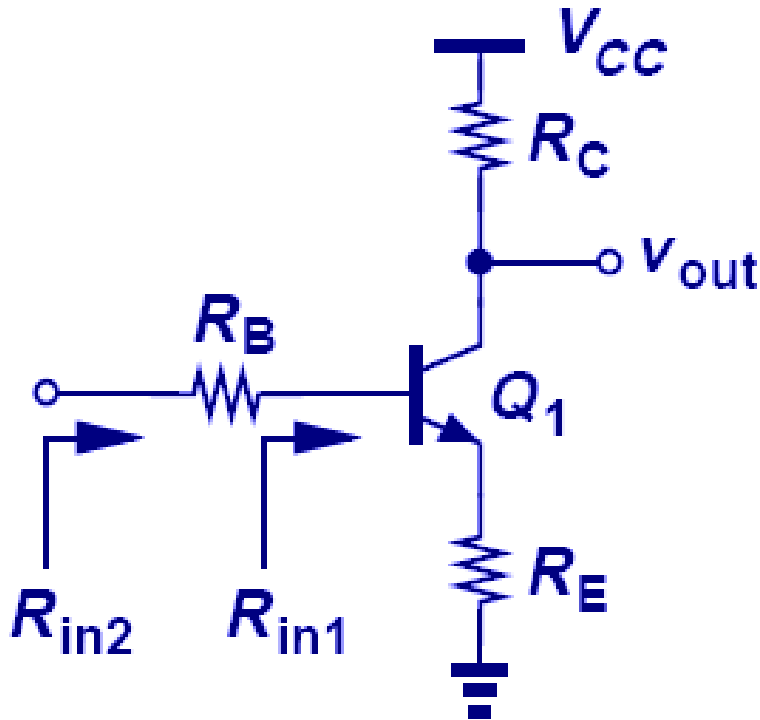
$$V_A = \infty$$

$$\frac{V_{out}}{V_{in}} = \frac{V_A}{V_{in}} \cdot \frac{V_{out}}{V_A}$$

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

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

Input/Output Impedances



$$V_A = \infty$$

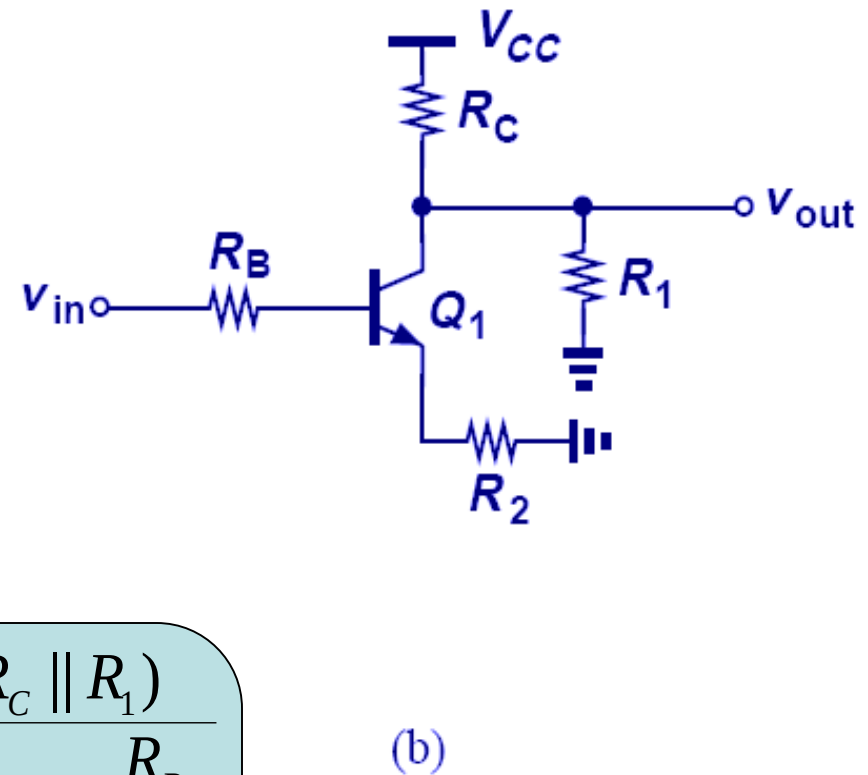
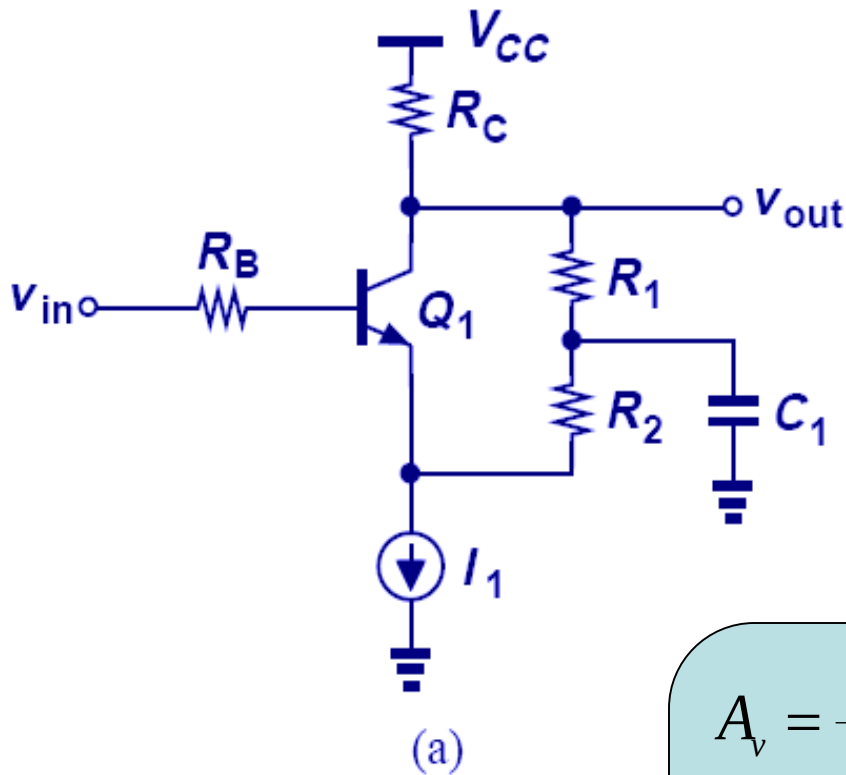
$$R_{in1} = r_{\pi} + (\beta + 1)R_E$$

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

$$R_{out} = R_C$$

➤ R_{in1} is more important in practice as R_B is often the output impedance of the previous stage.

Emitter Degeneration Example III

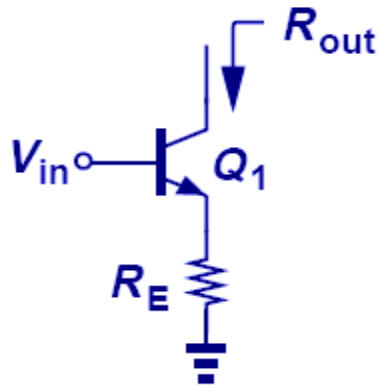


$$A_v = \frac{-(R_C \parallel R_1)}{\frac{1}{g_m} + R_2 + \frac{R_B}{\beta + 1}}$$

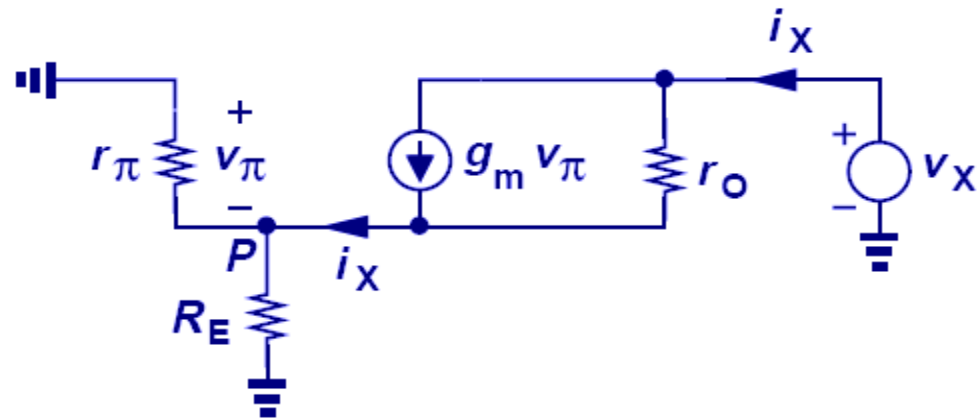
$$R_{in} = r_{\pi} + (\beta + 1)R_2$$

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

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



(a)



(b)

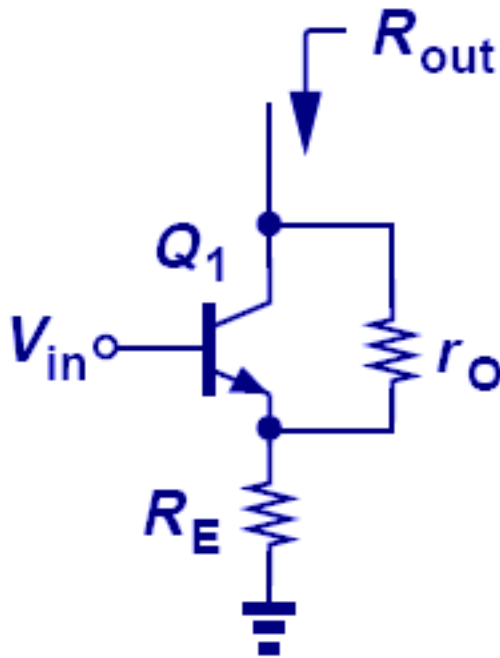
$$R_{out} = [1 + g_m (R_E \parallel r_\pi)] r_O + R_E \parallel r_\pi$$

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

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

- Emitter degeneration boosts the output impedance by a factor of $1 + g_m (R_E \parallel r_\pi)$.
- This improves the gain of the amplifier and makes the circuit a better current source.

Two Special Cases



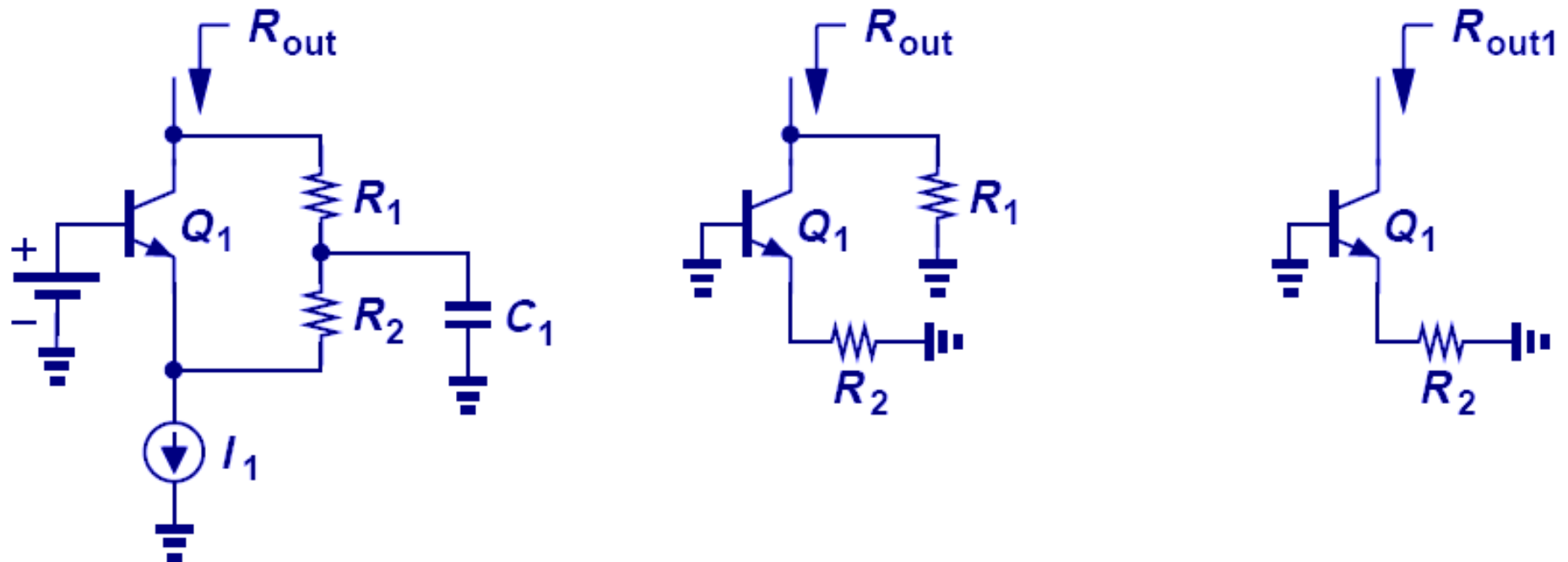
1) $R_E \gg r_\pi$

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

2) $R_E \ll r_\pi$

$$R_{out} \approx (1 + g_m R_E) r_O$$

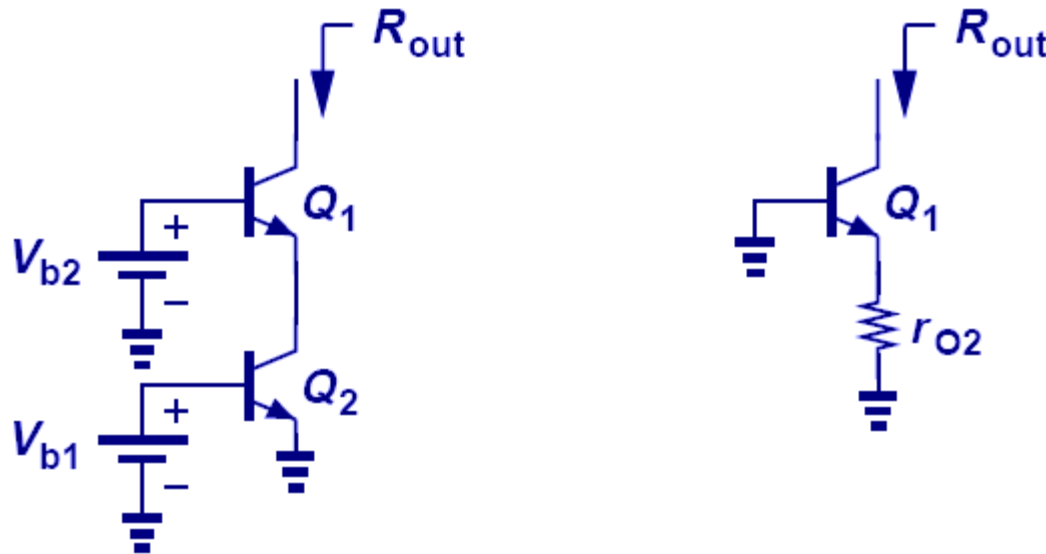
Analysis by Inspection



$$R_{out} = R_1 \parallel R_{out1} \implies R_{out1} = [1 + g_m (R_2 \parallel r_\pi)] r_o \implies R_{out} = [1 + g_m (R_2 \parallel r_\pi)] r_o \parallel R_1$$

➤ 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.

Example: Degeneration by Another Transistor



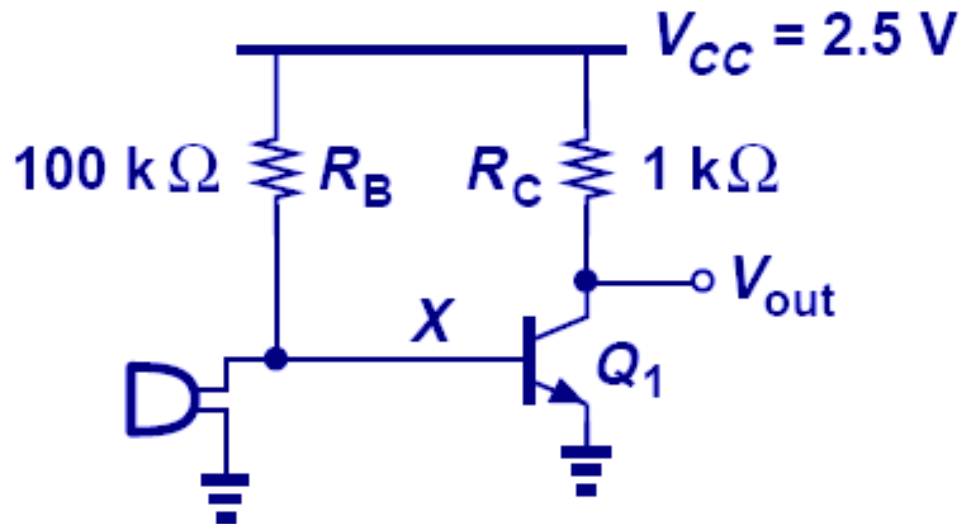
$$R_{out} = [1 + g_{m1}(r_{O2} \parallel r_{\pi1})]r_{O1}$$

➤ Called a “cascode”, the circuit offers many advantages that are described later in the book.

Study of Common-Emitter Topology

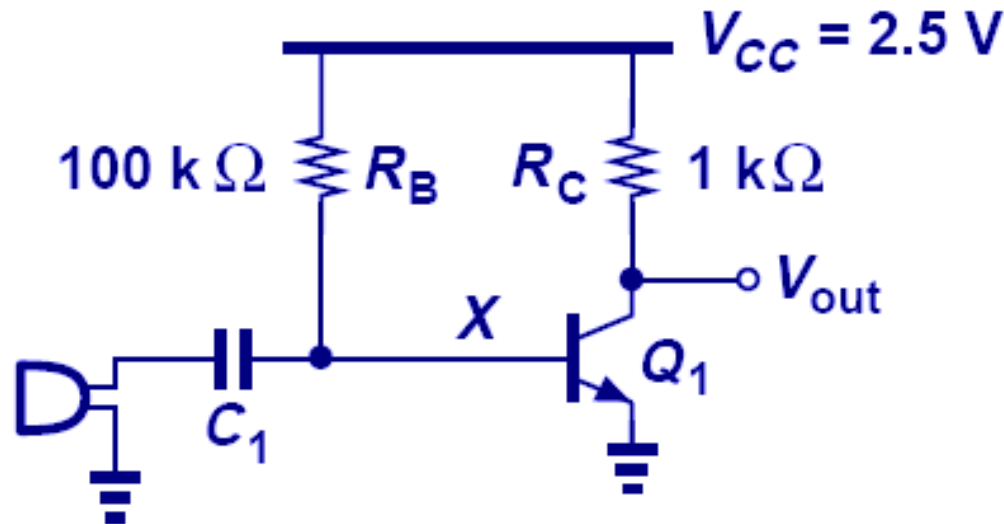
- **Analysis of CE Core**
Inclusion of Early Effect
- **Emitter Degeneration**
Inclusion of Early Effect
- ***CE Stage with Biasing***

Bad Input Connection



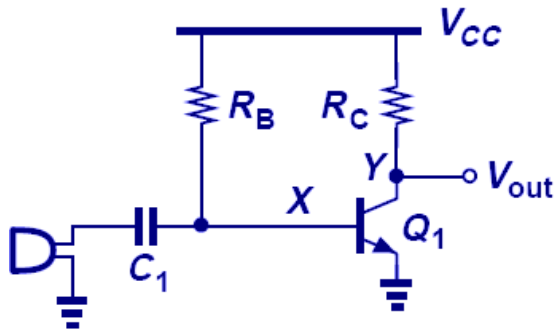
- Since the microphone has a very low resistance that connects from the base of Q_1 to ground, it attenuates the base voltage and renders Q_1 without a bias current.

Use of Coupling Capacitor

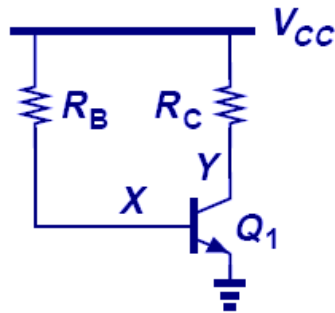


- Capacitor isolates the bias network from the microphone at DC but shorts the microphone to the amplifier at higher frequencies.

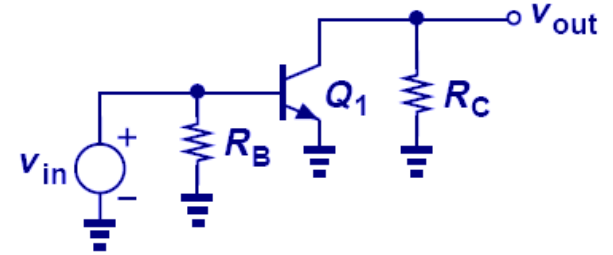
DC and AC Analysis



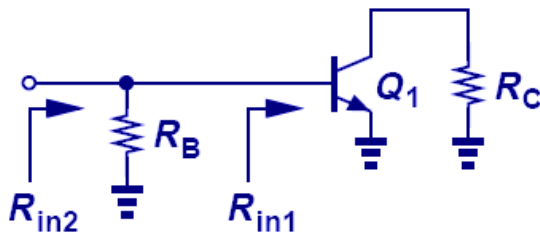
(a)



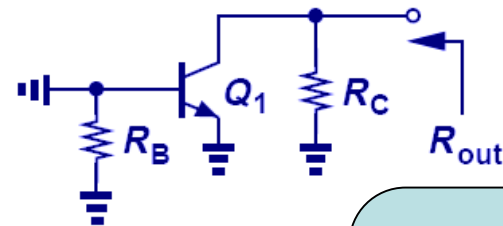
(b)



(c)



(d)



(e)

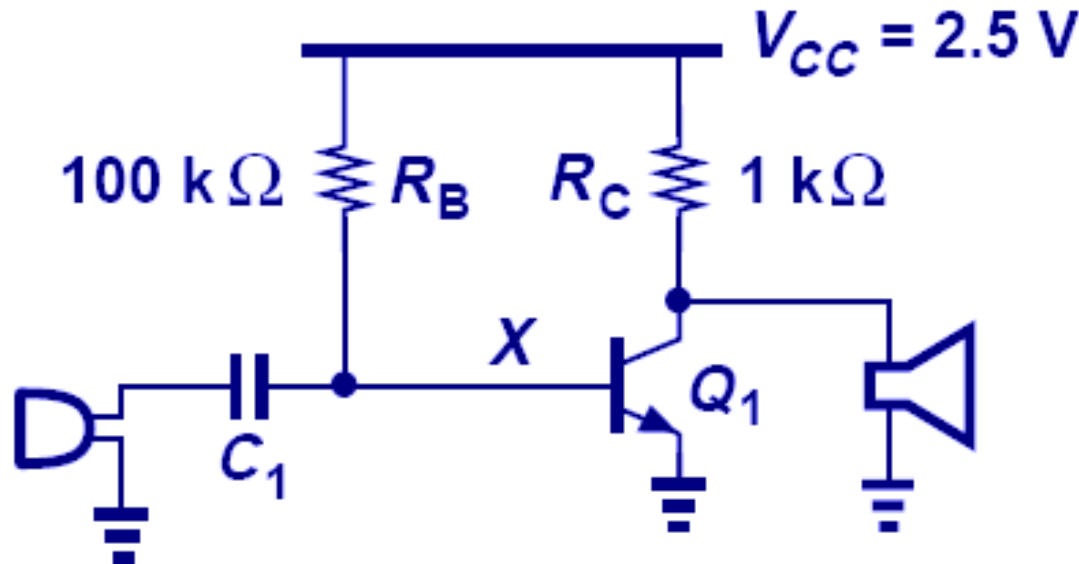
$$A_v = -g_m (R_C \parallel r_o)$$

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

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

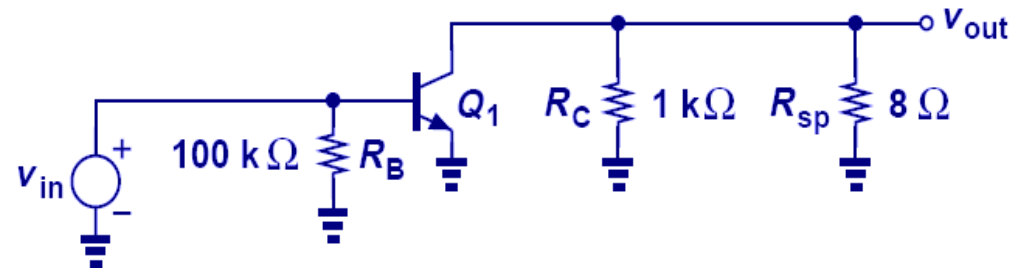
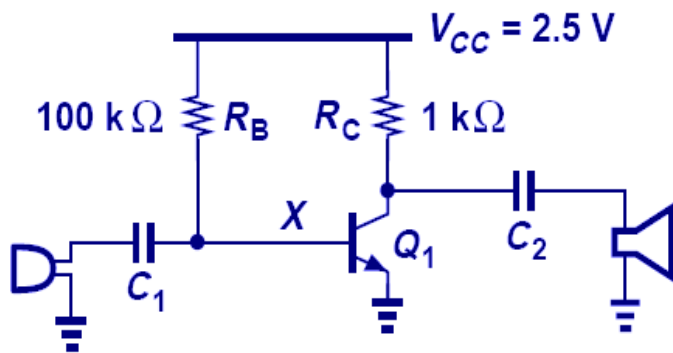
➤ Coupling capacitor is open for DC calculations and shorted for AC calculations.

Bad Output Connection



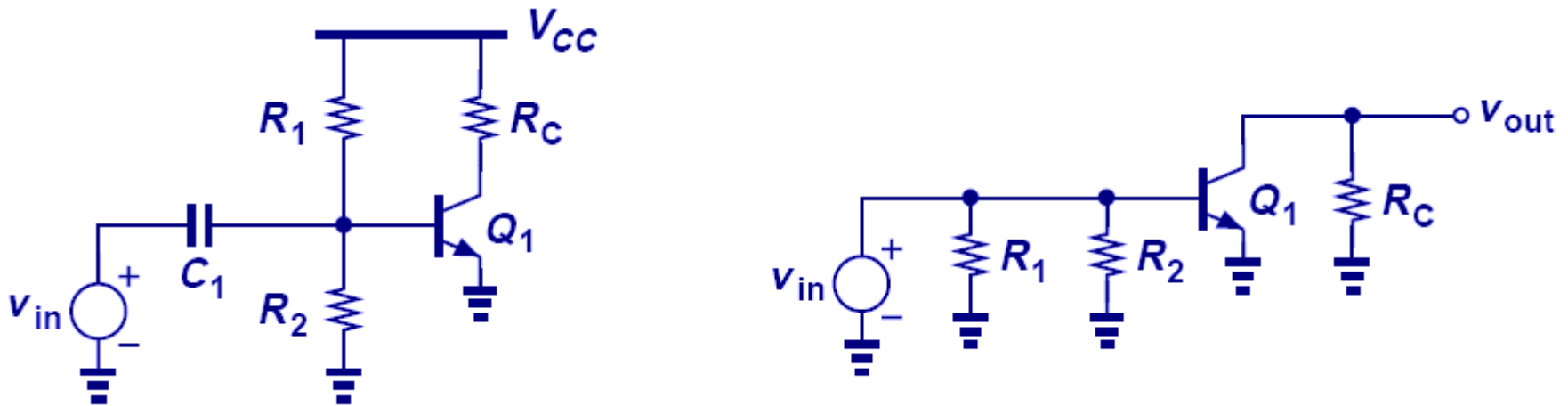
- Since the speaker has an inductor, connecting it directly to the amplifier would short the collector at DC and therefore push the transistor into deep saturation.

Still No Gain!!!



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

CE Stage with Biasing

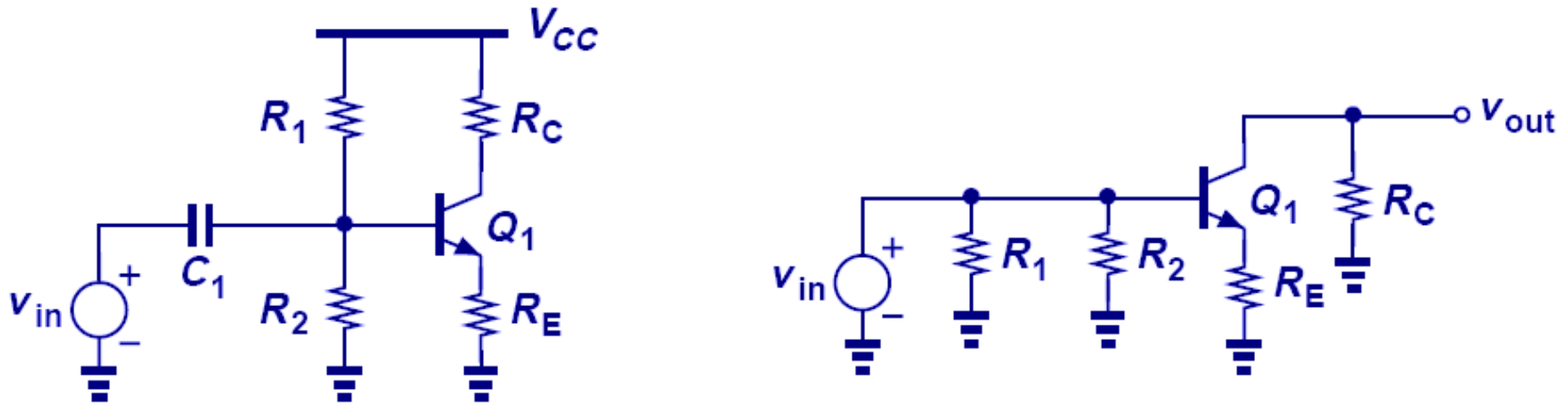


$$A_v = -g_m (R_C \parallel r_o)$$

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

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

CE Stage with Robust Biasing

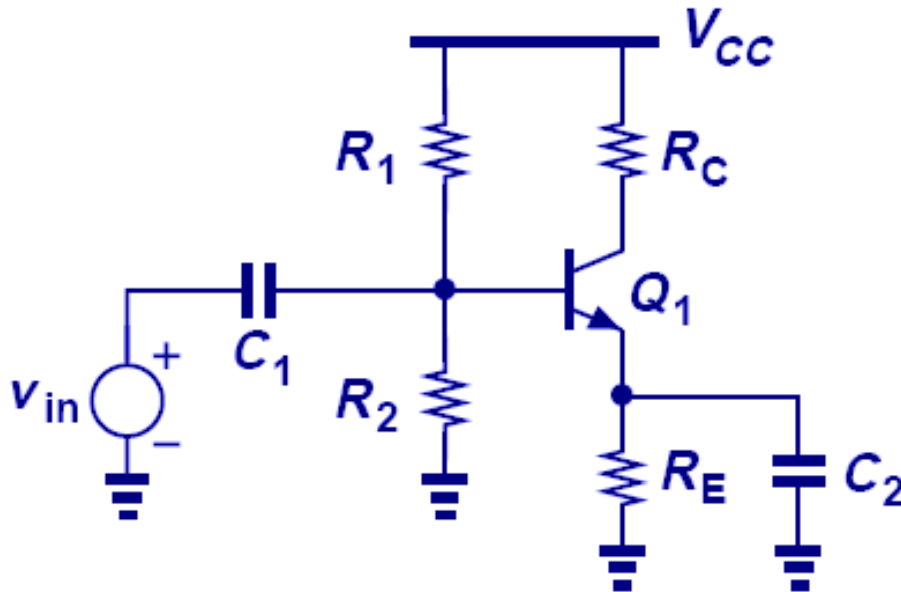


$$A_v = \frac{-R_C}{\frac{1}{g_m} + R_E}$$

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

$$R_{out} = R_C$$

Removal of Degeneration for Signals at AC



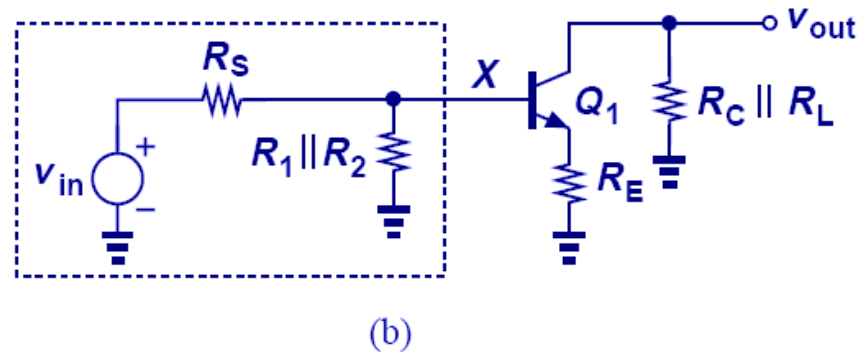
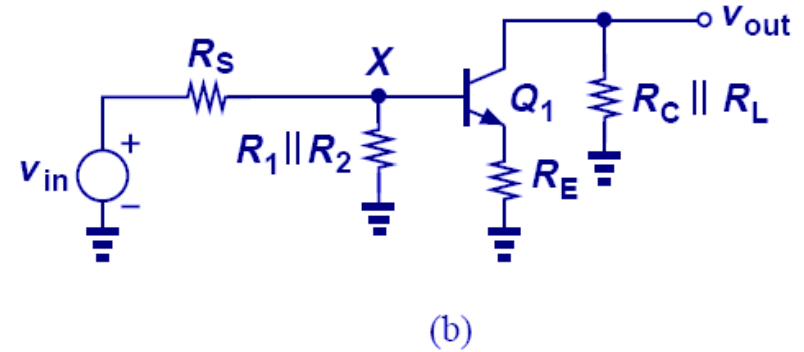
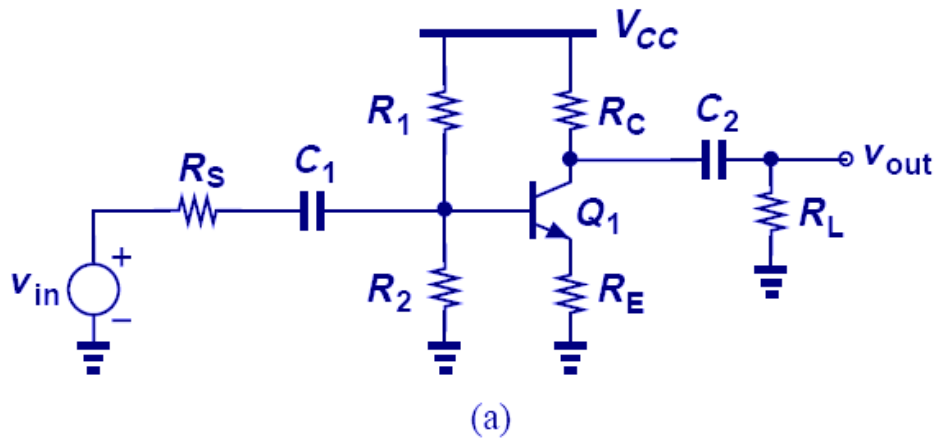
$$A_v = -g_m R_C$$

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

$$R_{out} = R_C$$

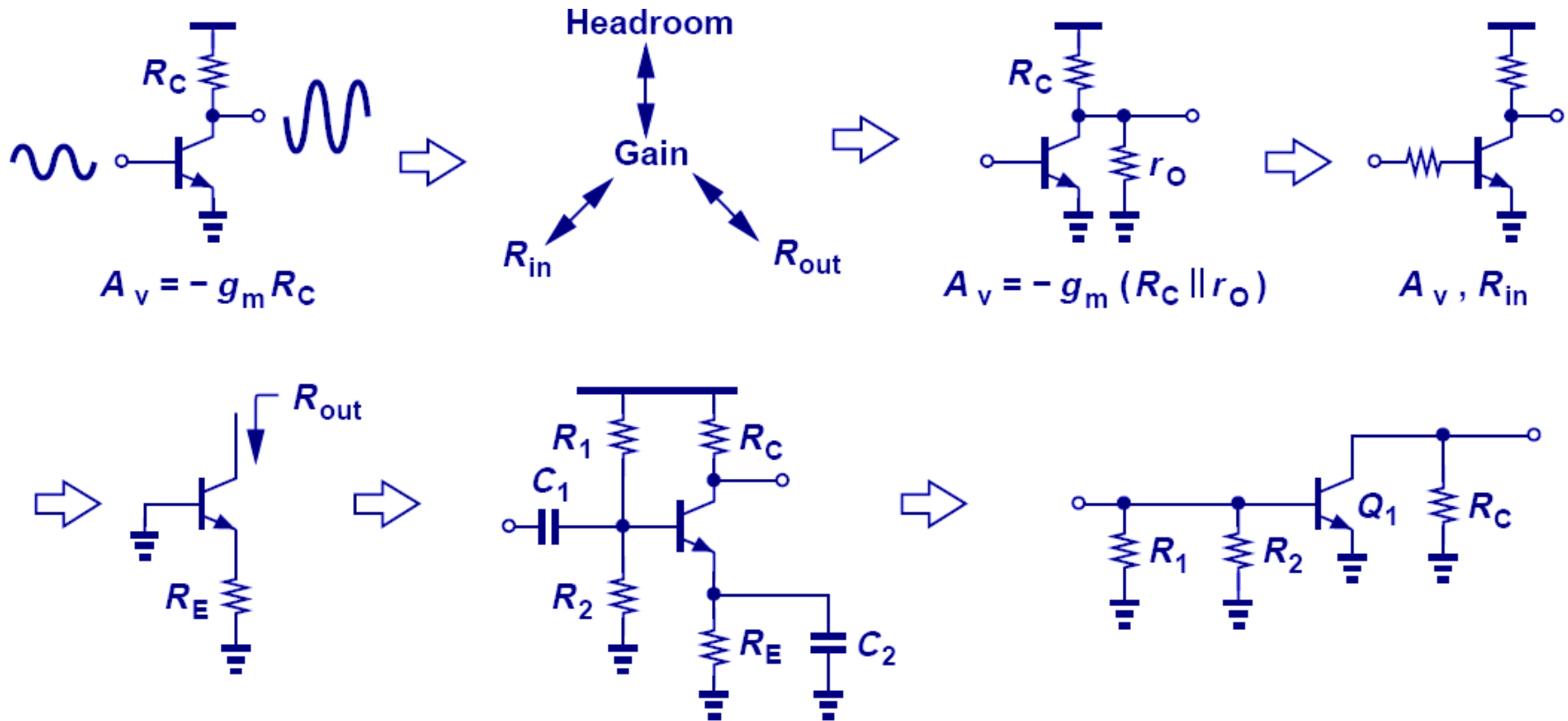
➤ Capacitor shorts out R_E at higher frequencies and removes degeneration.

Complete CE Stage

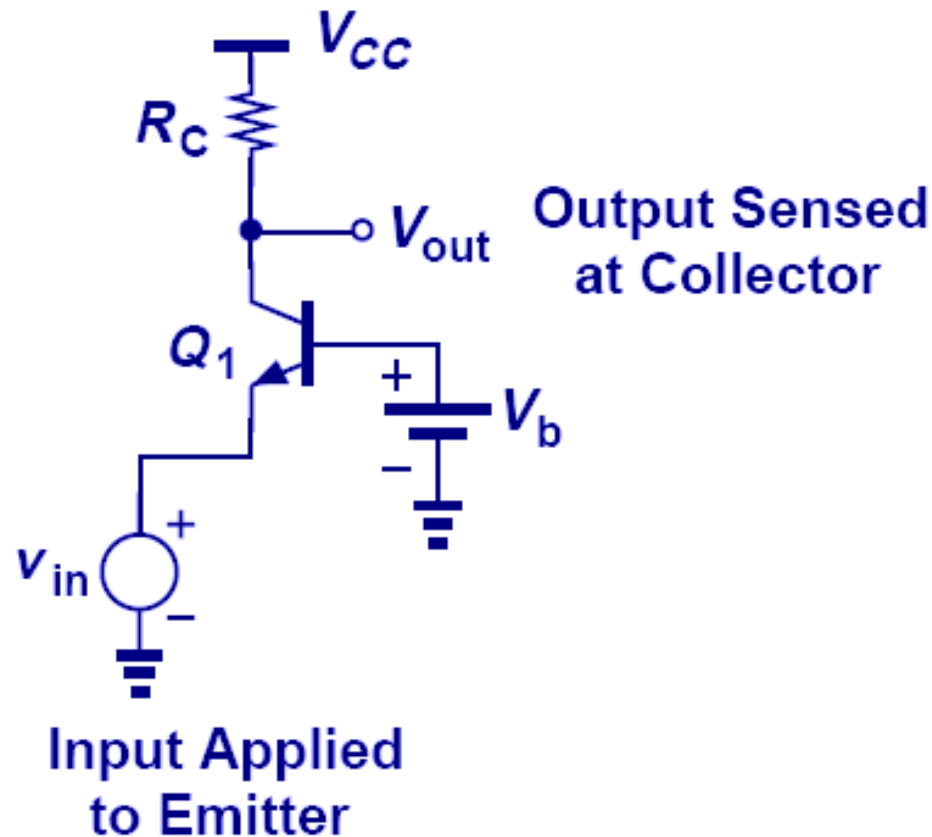


$$A_v = \frac{-R_C \parallel R_L}{\frac{1}{g_m} + R_E + \frac{R_s \parallel R_1 \parallel R_2}{\beta + 1}}$$

Summary of CE Concepts

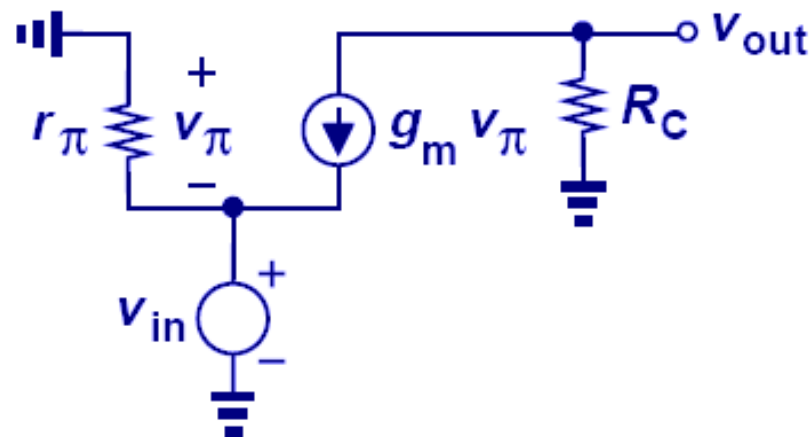
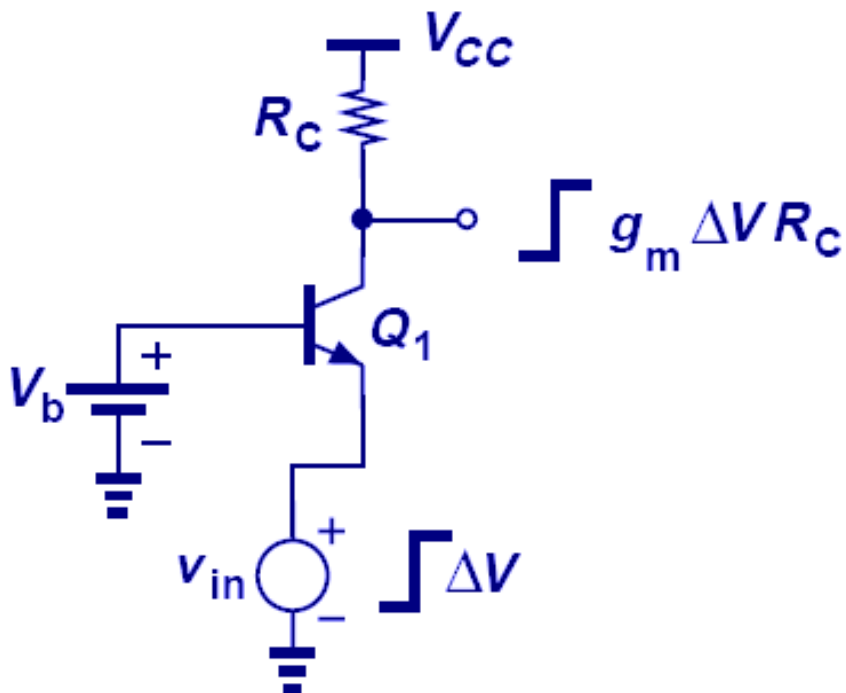


Common Base (CB) Amplifier



- In common base topology, where the base terminal is biased with a fixed voltage, emitter is fed with a signal, and collector is the output.

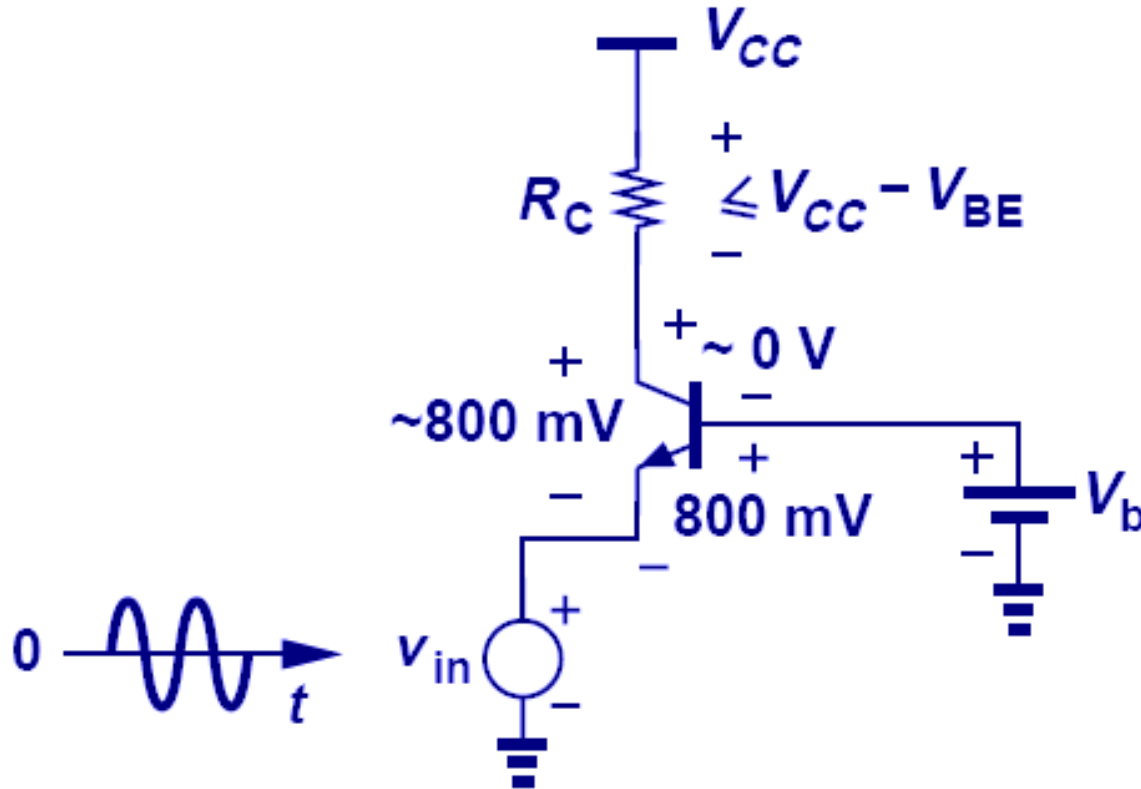
CB Core



$$A_v = g_m R_C$$

- The voltage gain of CB stage is $g_m R_C$, which is identical to that of CE stage in magnitude and opposite in phase.

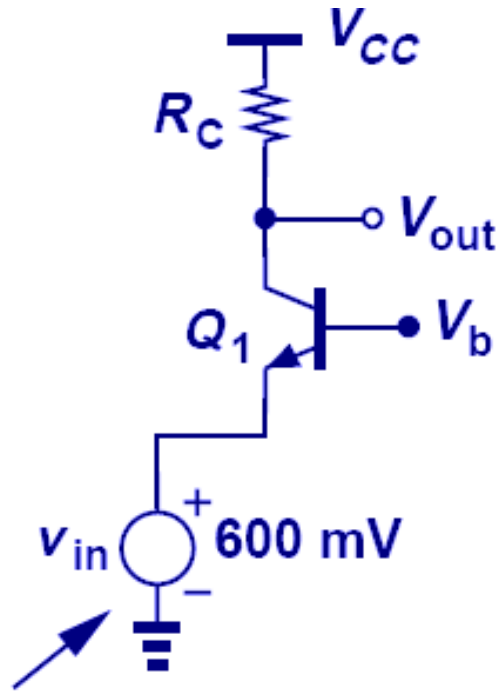
Tradeoff between Gain and Headroom



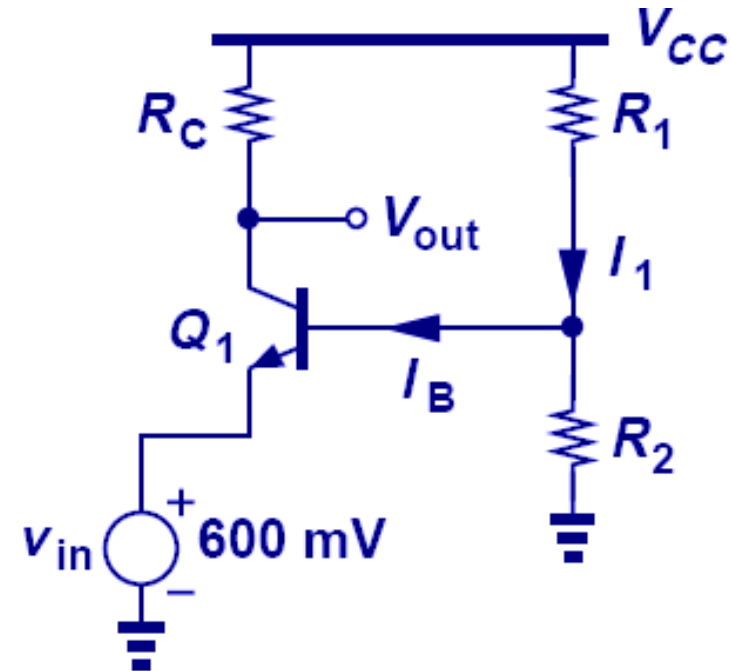
$$A_v = \frac{I_C}{V_T} \cdot R_C$$
$$= \frac{V_{CC} - V_{BE}}{V_T}$$

- To maintain the transistor out of saturation, the maximum voltage drop across R_C cannot exceed $V_{CC} - V_{BE}$.

Simple CB Example



Thermometer

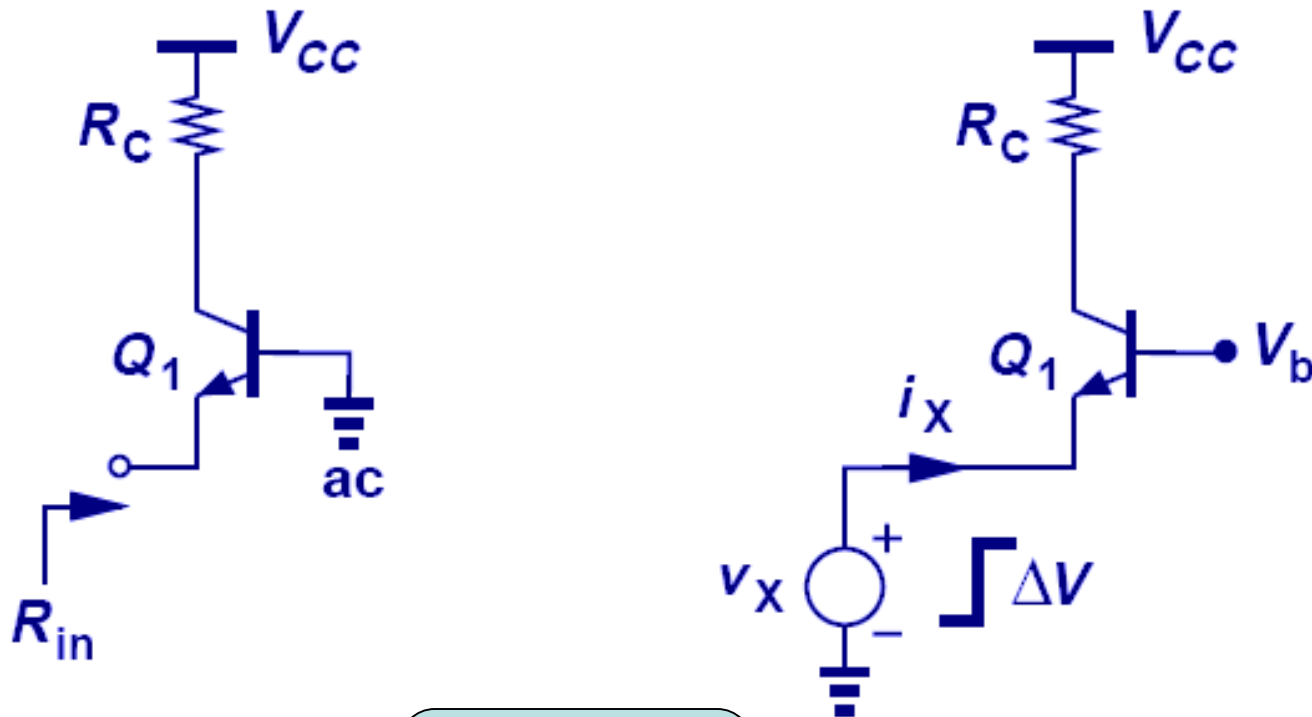


$$A_v = g_m R_C = 17.2$$

$$R_1 = 22.3 K\Omega$$

$$R_2 = 67.7 K\Omega$$

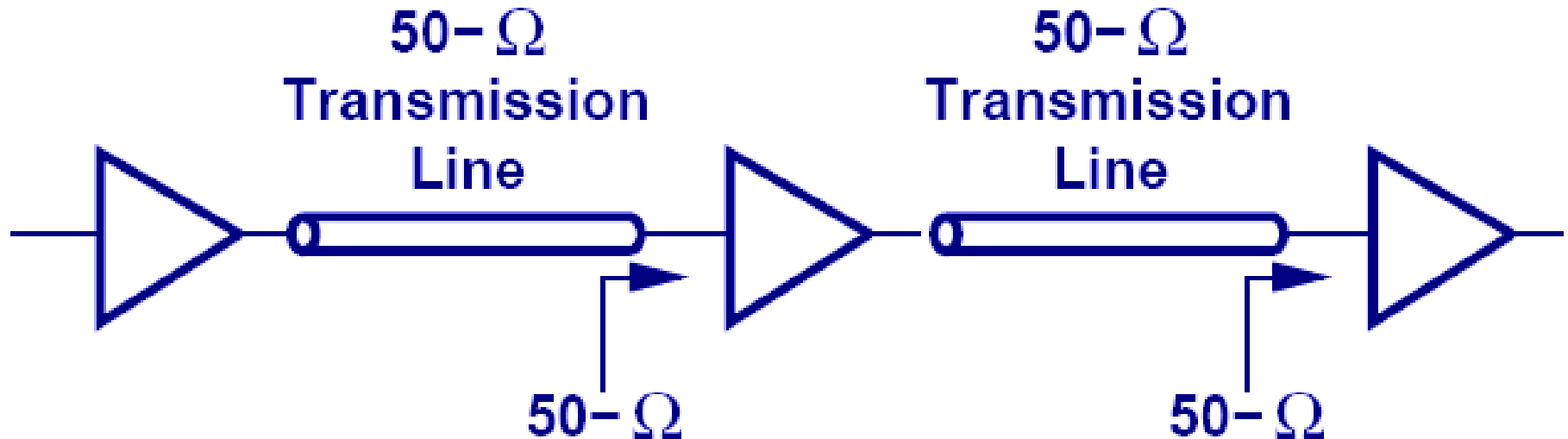
Input Impedance of CB



$$R_{in} = \frac{1}{g_m}$$

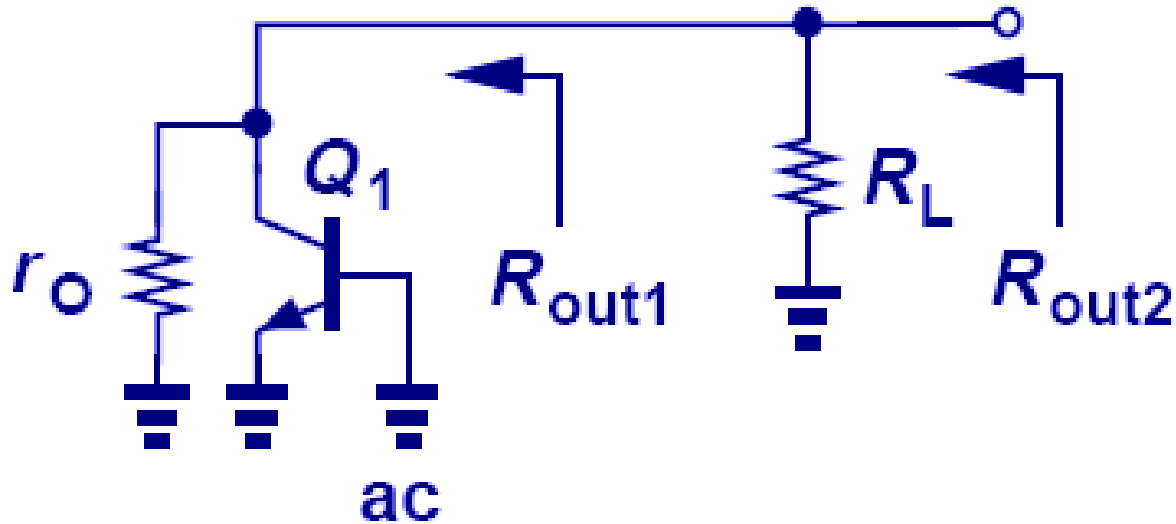
- The input impedance of CB stage is much smaller than that of the CE stage.

Practical Application of CB Stage



- To avoid “reflections”, need impedance matching.
- CB stage’s low input impedance can be used to create a match with $50\text{ }\Omega$.

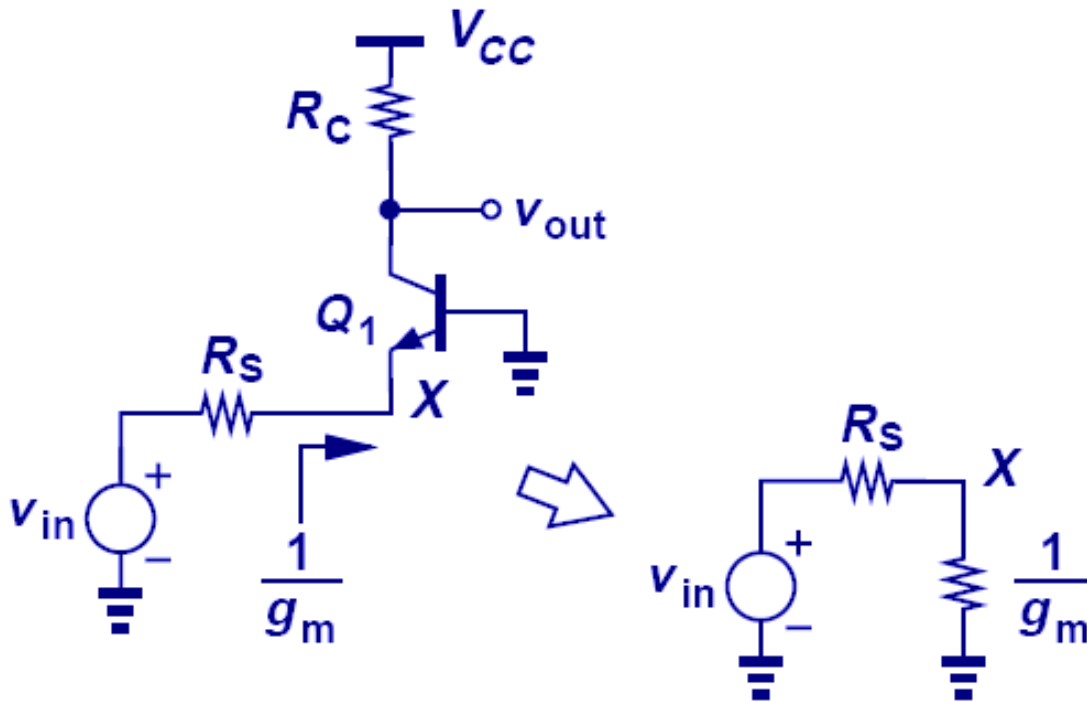
Output Impedance of CB Stage



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

- The output impedance of CB stage is similar to that of CE stage.

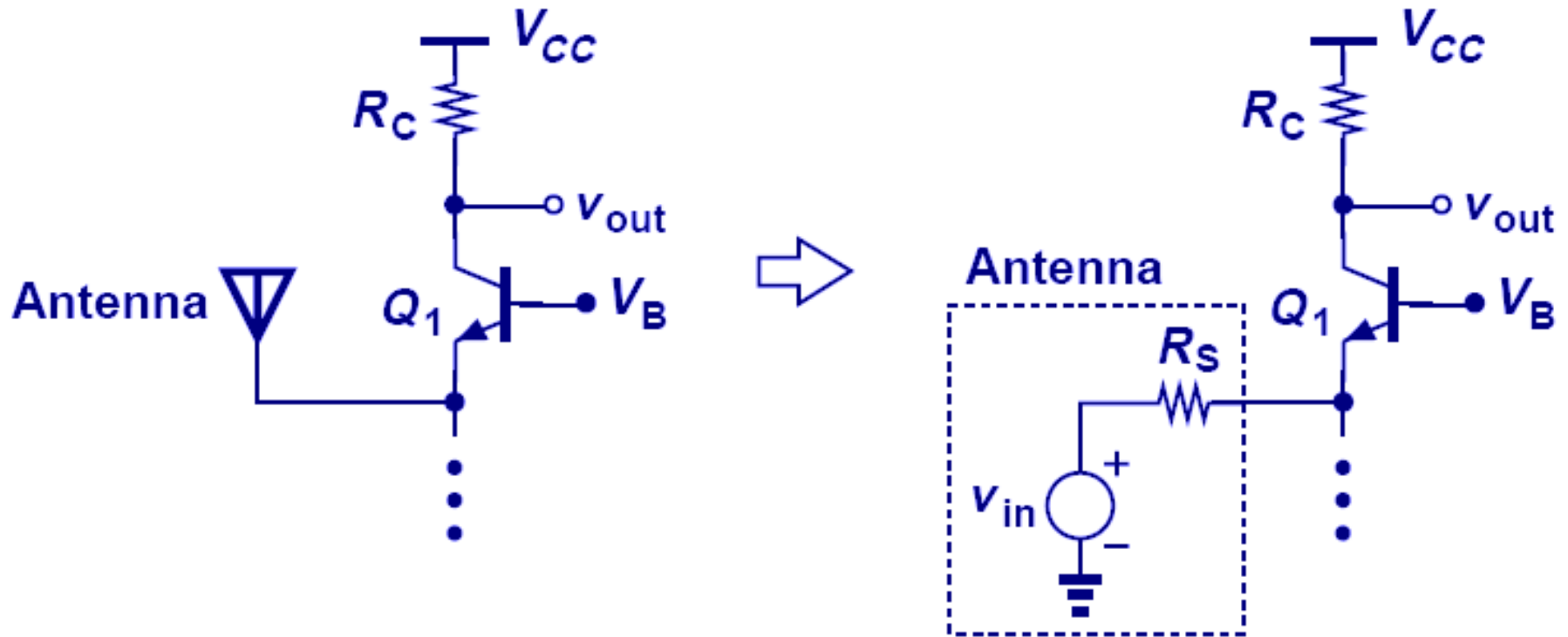
CB Stage with Source Resistance



$$A_v = \frac{R_C}{\frac{1}{g_m} + R_S}$$

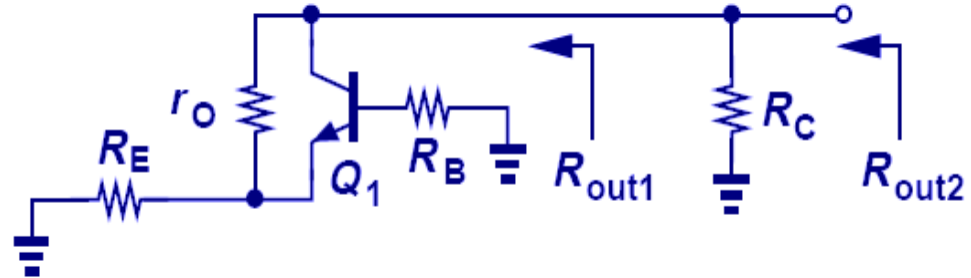
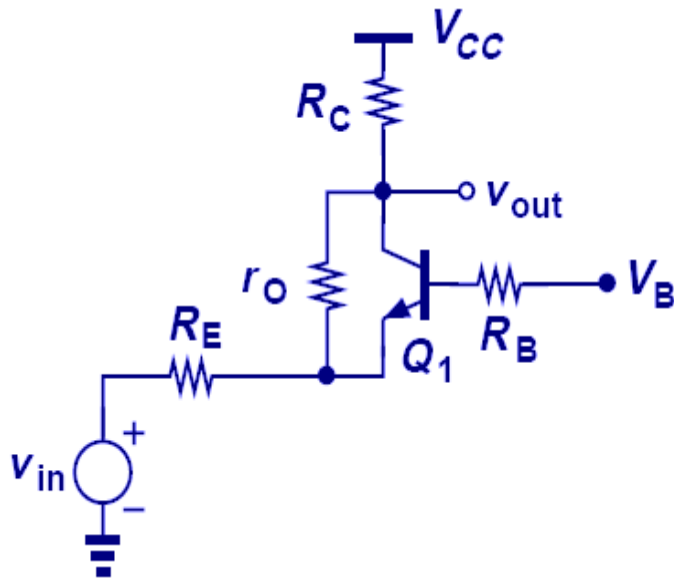
- With an inclusion of a source resistor, the input signal is attenuated before it reaches the emitter of the amplifier; therefore, we see a lower voltage gain.
- This is similar to CE stage emitter degeneration; only the phase is reversed.

Practical Example of CB Stage



- An antenna usually has low output impedance; therefore, a correspondingly low input impedance is required for the following stage.

Realistic Output Impedance of CB Stage

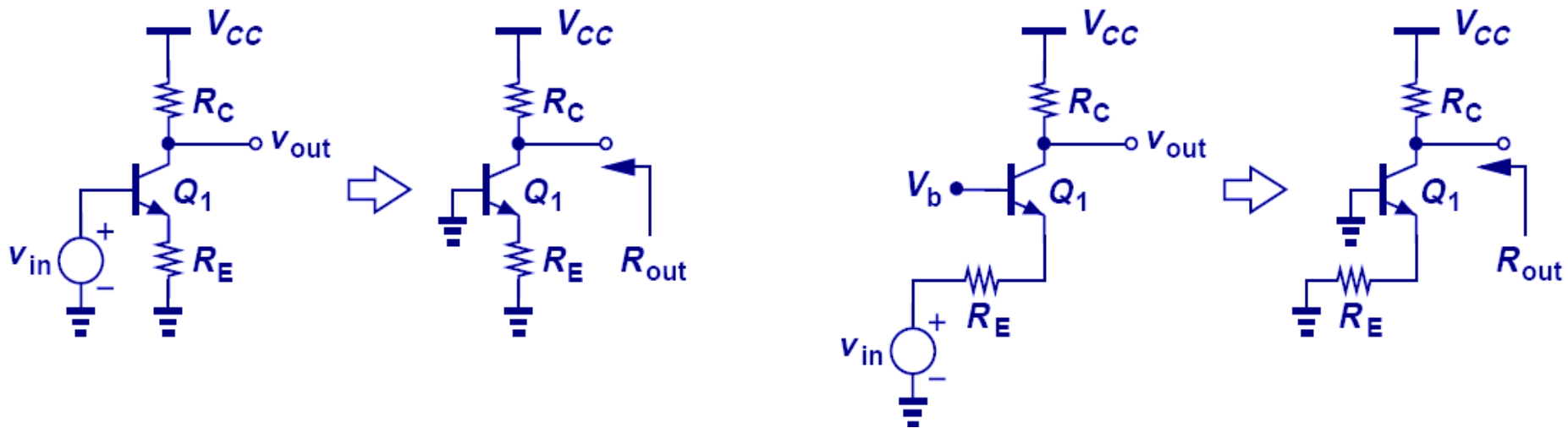


$$R_{out1} = [1 + g_m (R_E \parallel r_\pi)] r_o + (R_E \parallel r_\pi)$$

$$R_{out} = R_C \parallel R_{out1}$$

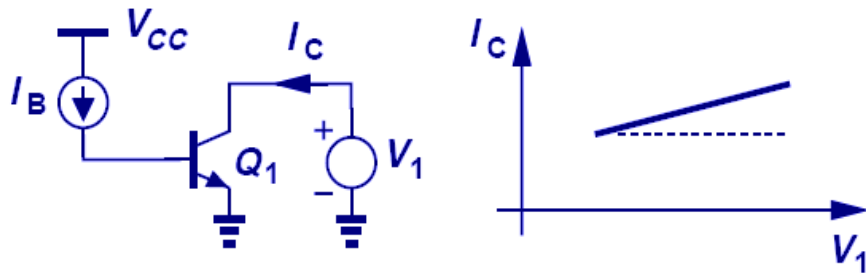
- The output impedance of CB stage is equal to R_C in parallel with the impedance looking down into the collector.

Output Impedance of CE and CB Stages

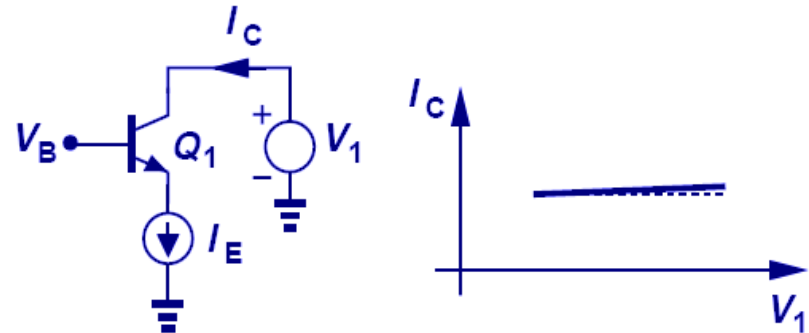


- The output impedances of CE, CB stages are the same if both circuits are under the same condition. This is because when calculating output impedance, the input port is grounded, which renders the same circuit for both CE and CB stages.

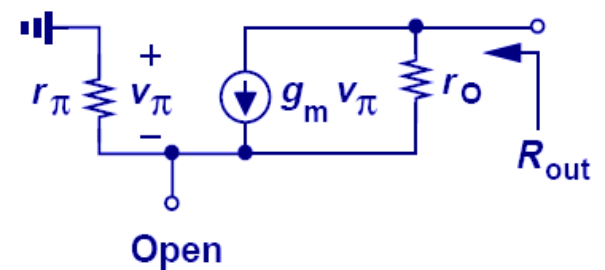
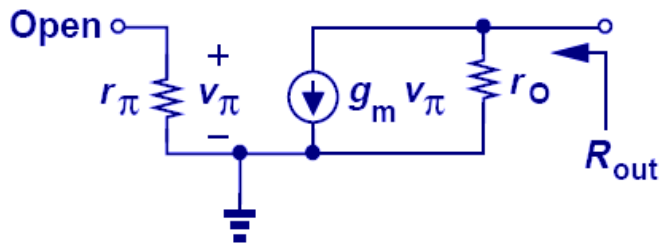
Fallacy of the “Old Wisdom”



(a)

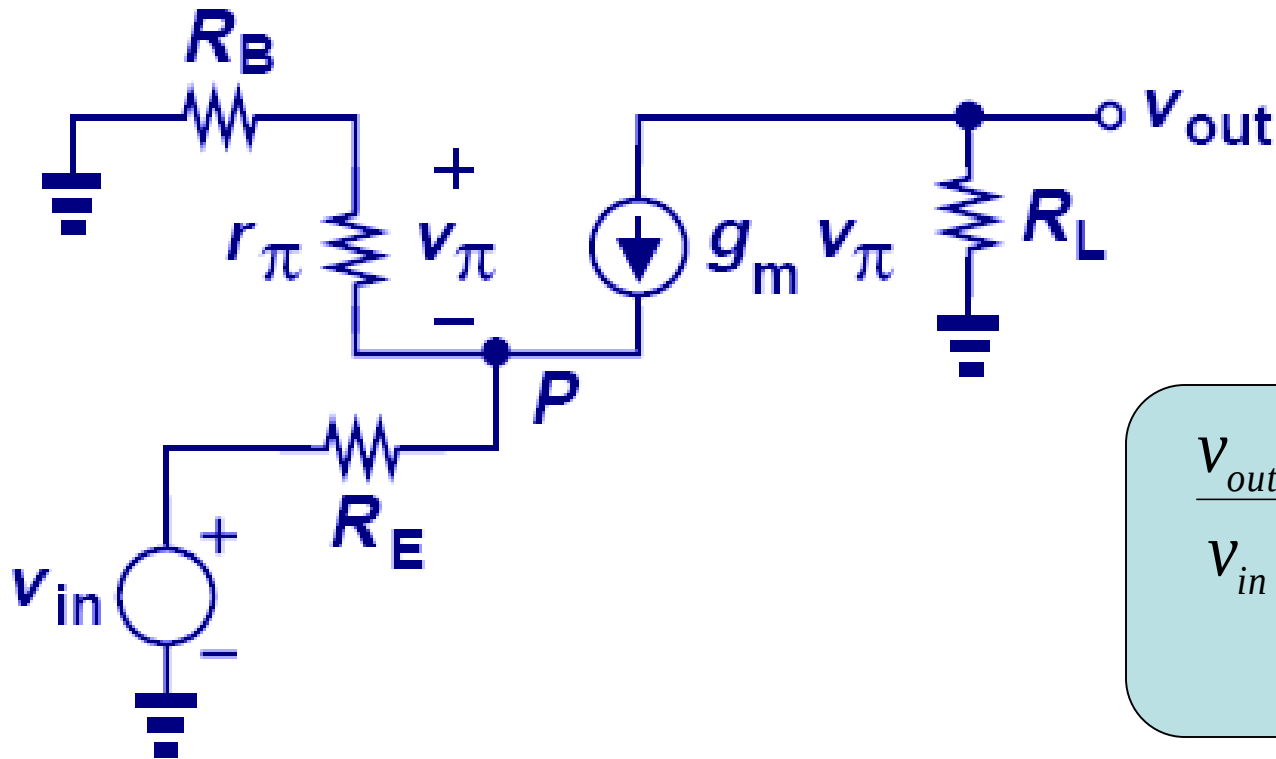


(b)



➤ The statement “CB output impedance is higher than CE output impedance” is flawed.

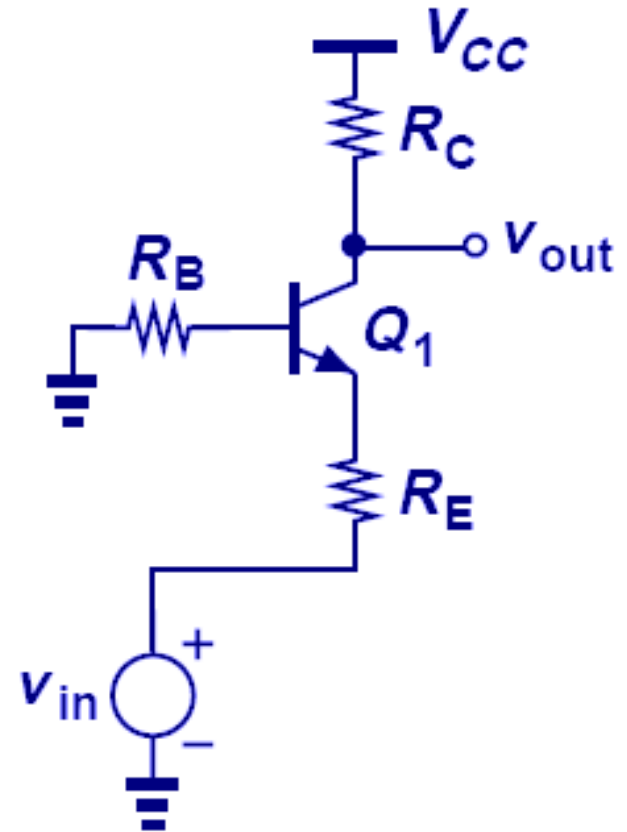
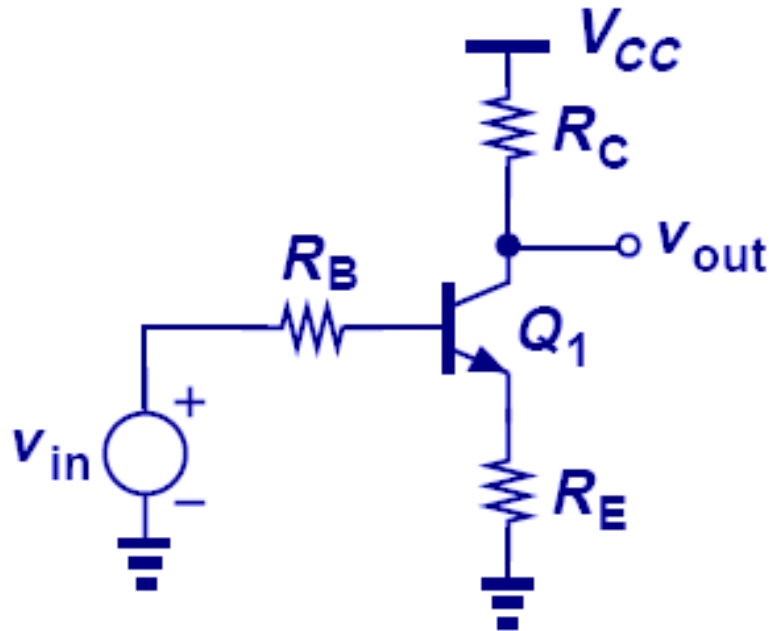
CB with Base Resistance



$$\frac{v_{out}}{v_{in}} \approx \frac{R_C}{R_E + \frac{R_B}{\beta + 1} + \frac{1}{g_m}}$$

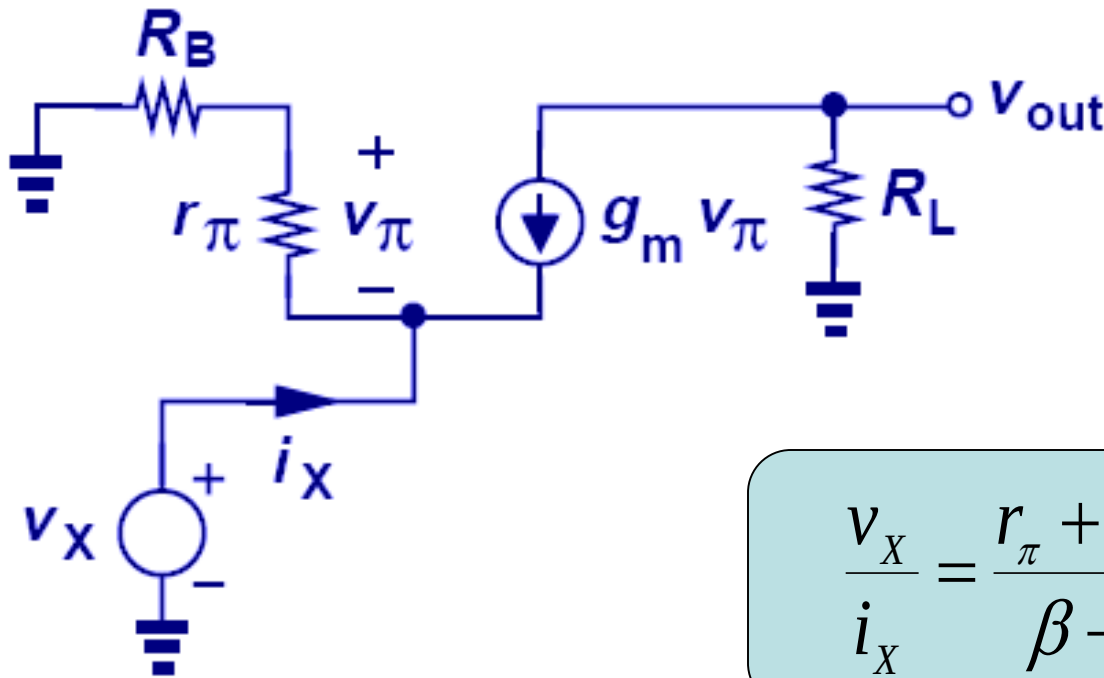
➤ With an addition of base resistance, the voltage gain degrades.

Comparison of CE and CB Stages with Base Resistance



- The voltage gain of CB amplifier with base resistance is exactly the same as that of CE stage with base resistance and emitter degeneration, except for a negative sign.

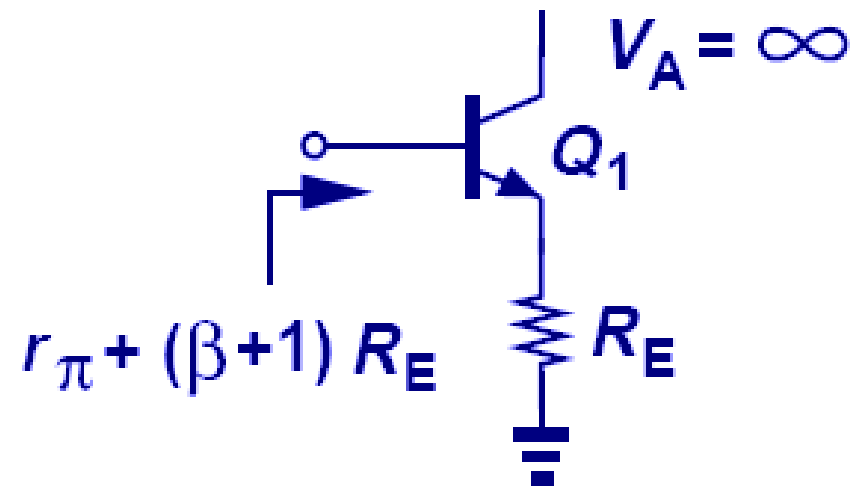
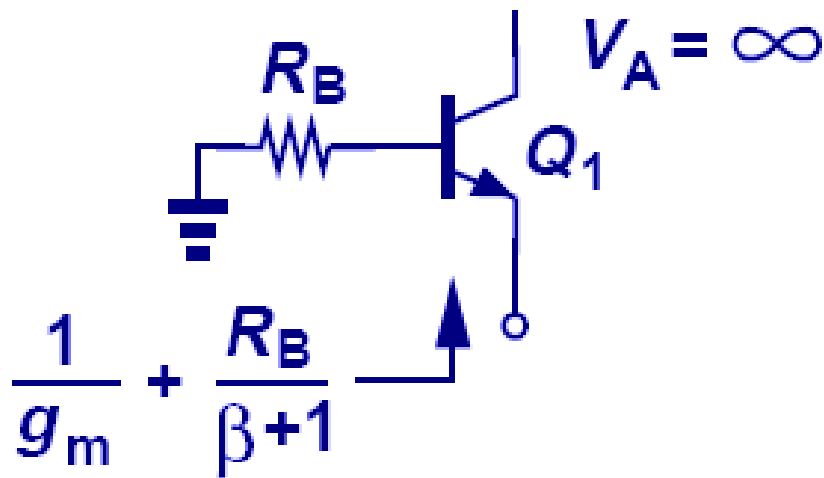
Input Impedance of CB Stage with Base Resistance



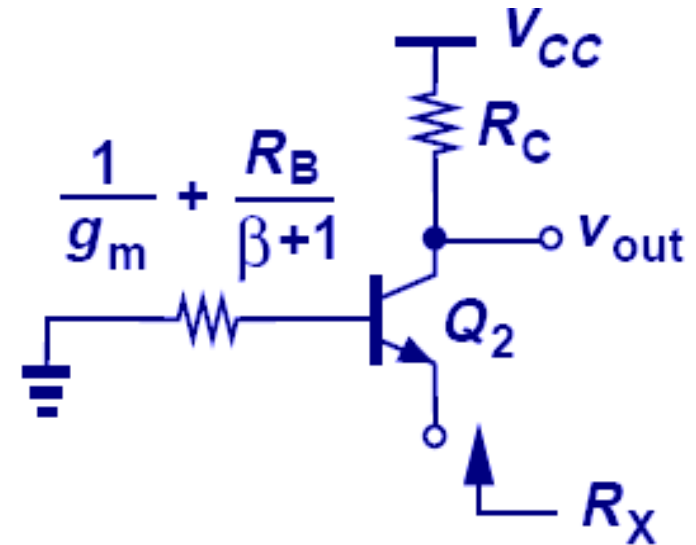
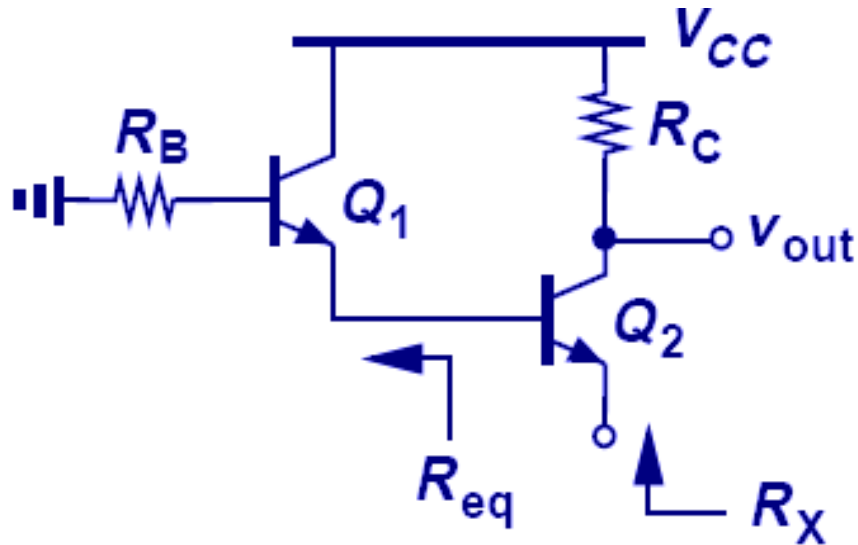
$$\frac{v_X}{i_X} = \frac{r_\pi + R_B}{\beta + 1} \approx \frac{1}{g_m} + \frac{R_B}{\beta + 1}$$

- The input impedance of CB with base resistance is equal to $1/g_m$ plus R_B divided by $(\beta+1)$. This is in contrast to degenerated CE stage, in which the resistance in series with the emitter is *multiplied* by $(\beta+1)$ when seen from the base.

Input Impedance Seen at Emitter and Base



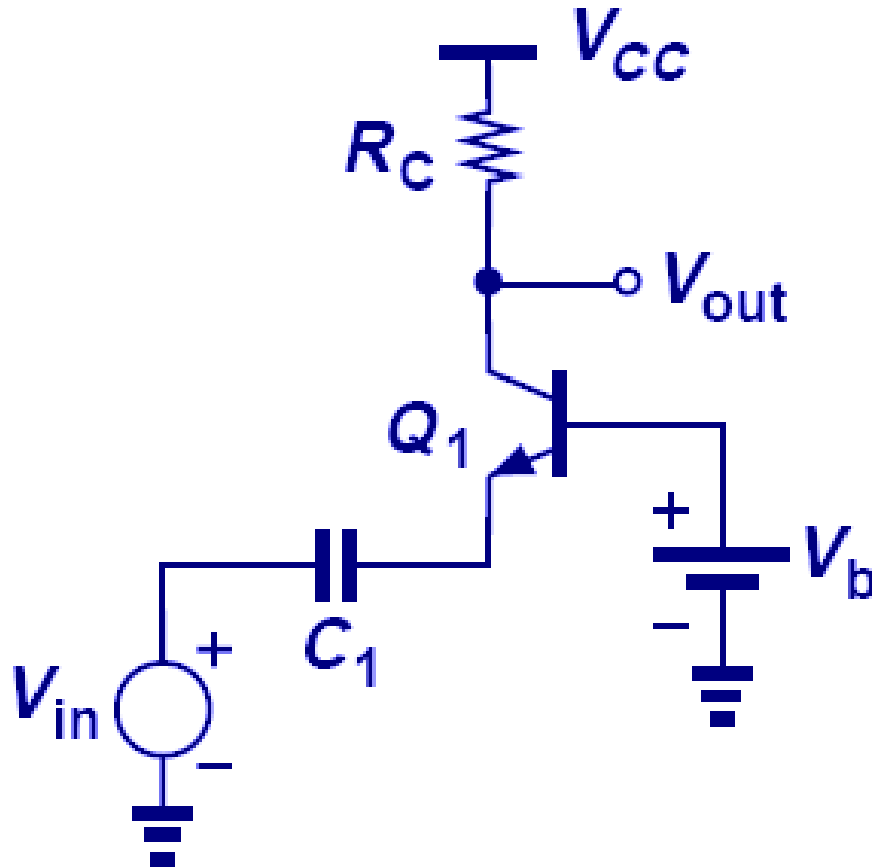
Input Impedance Example



$$R_X = \frac{1}{g_{m2}} + \frac{1}{\beta+1} \left(\frac{1}{g_{m1}} + \frac{R_B}{\beta+1} \right)$$

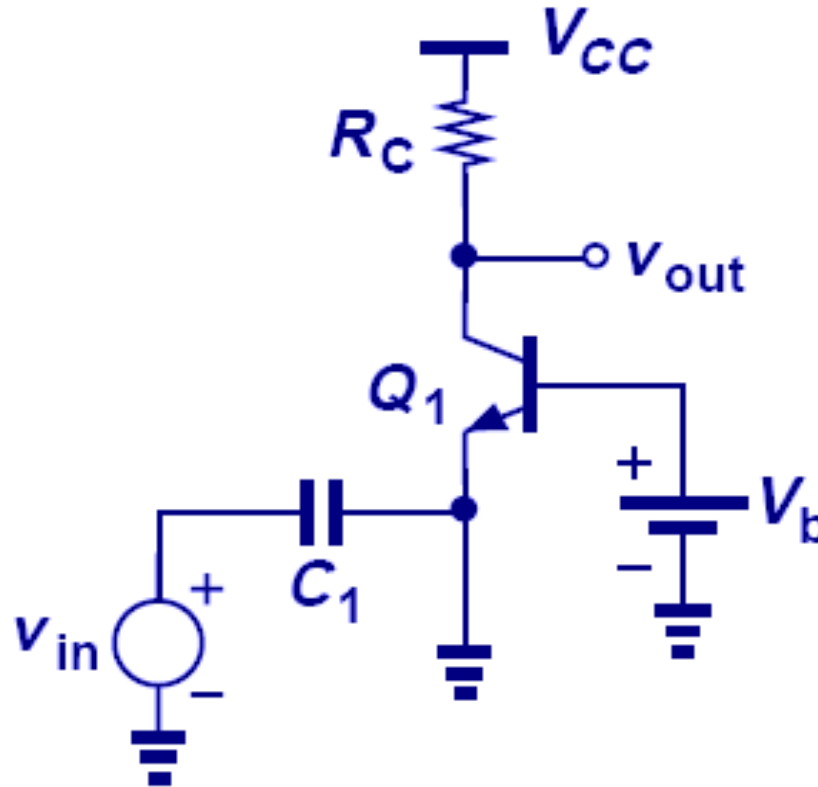
➤ To find the R_X, we have to first find R_{eq}, treat it as the base resistance of Q₂ and divide it by (β+1).

Bad Bias Technique for CB Stage



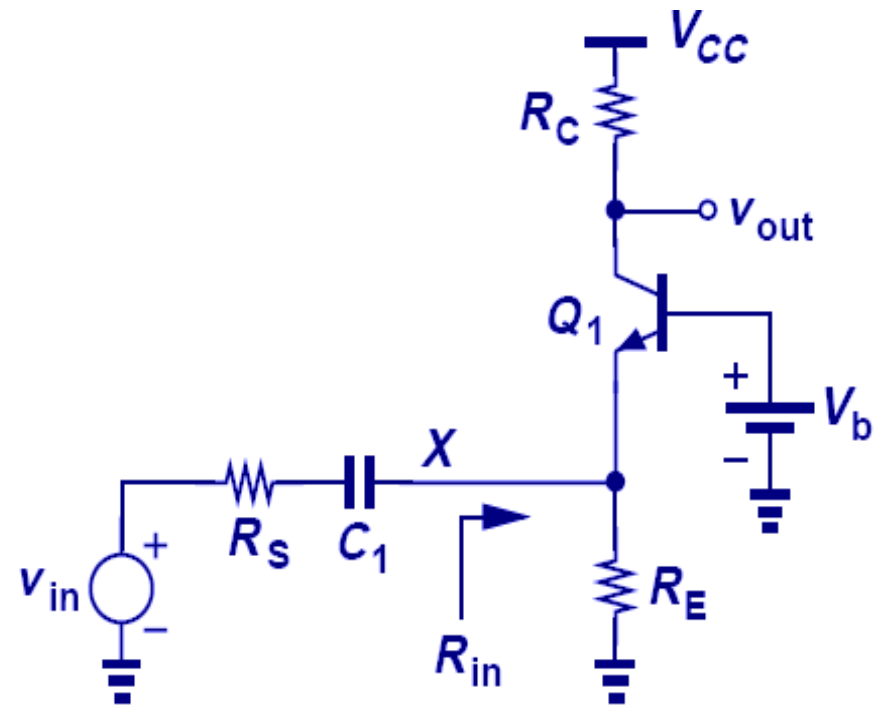
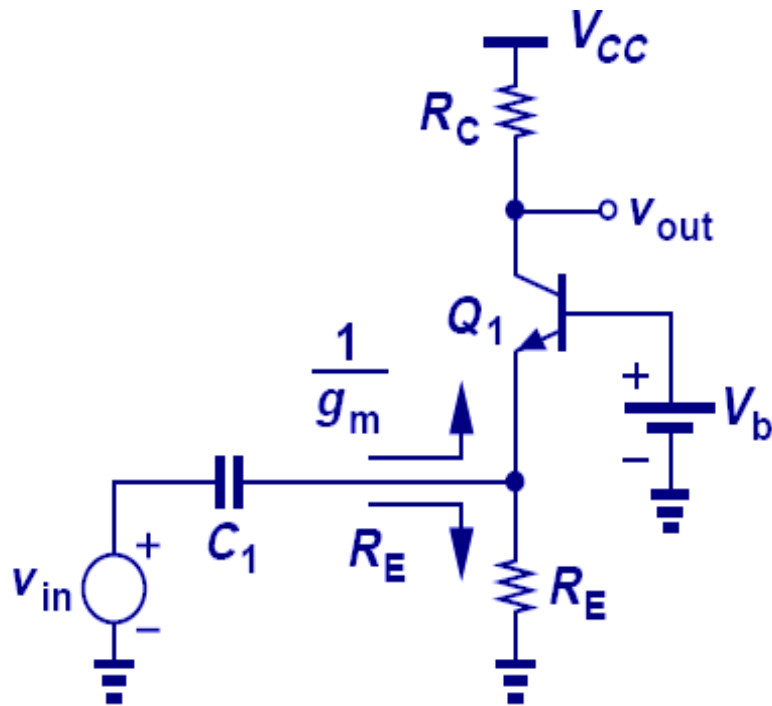
➤ Unfortunately, no emitter current can flow.

Still No Good



- In haste, the student connects the emitter to ground, thinking it will provide a DC current path to bias the amplifier. Little did he/she know that the input signal has been shorted to ground as well. The circuit still does not amplify.

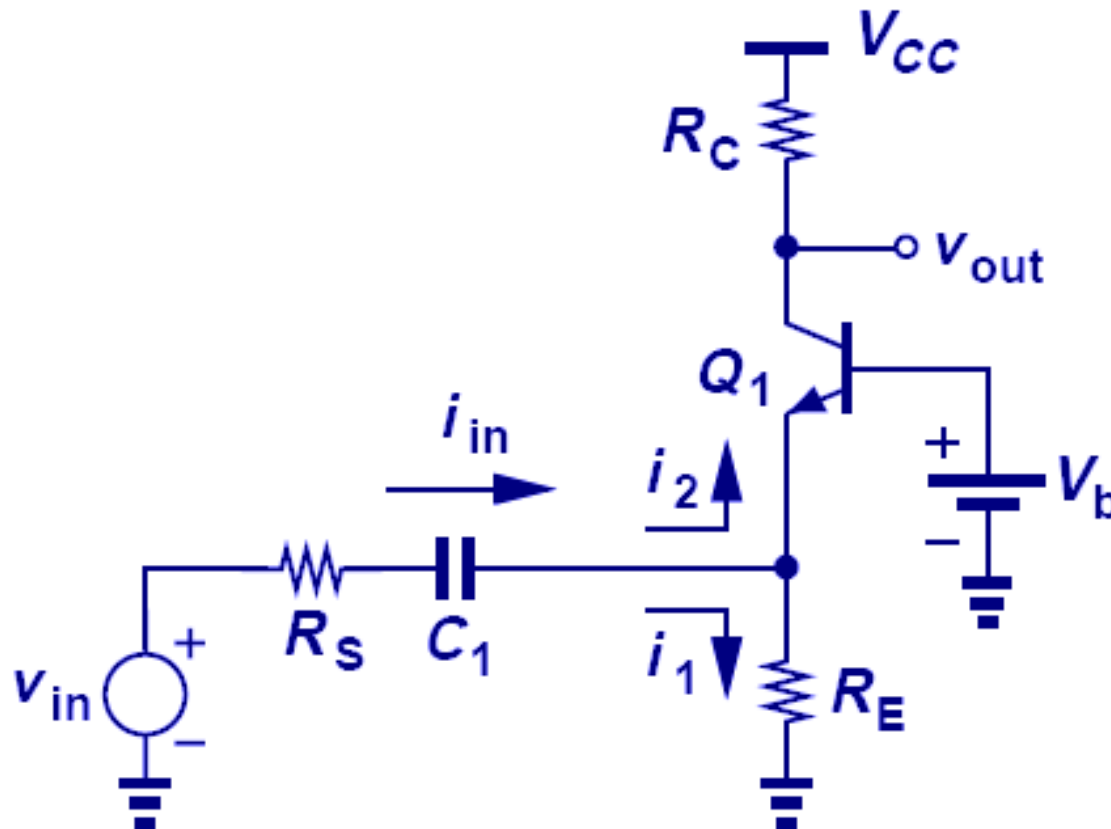
Proper Biasing for CB Stage



$$R_{in} = \frac{1}{g_m} \parallel R_E$$

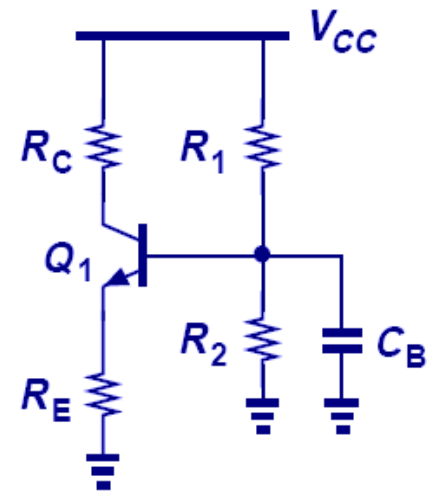
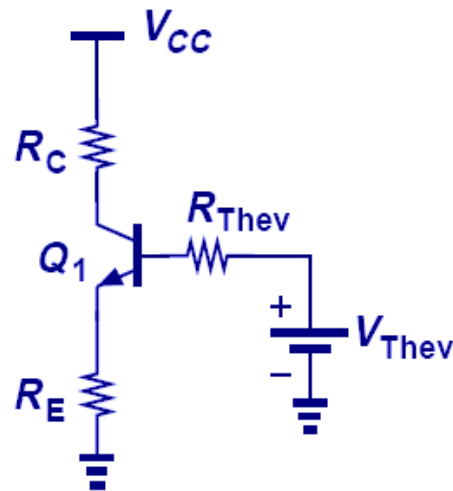
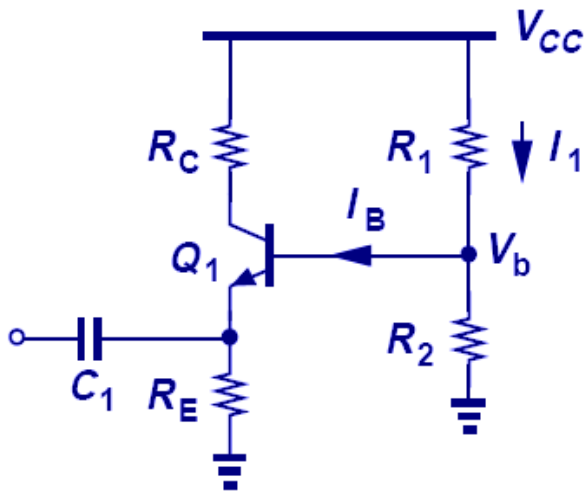
$$\frac{v_{out}}{v_{in}} = \frac{1}{1 + (1 + g_m R_E) R_S} g_m R_C$$

Reduction of Input Impedance Due to R_E



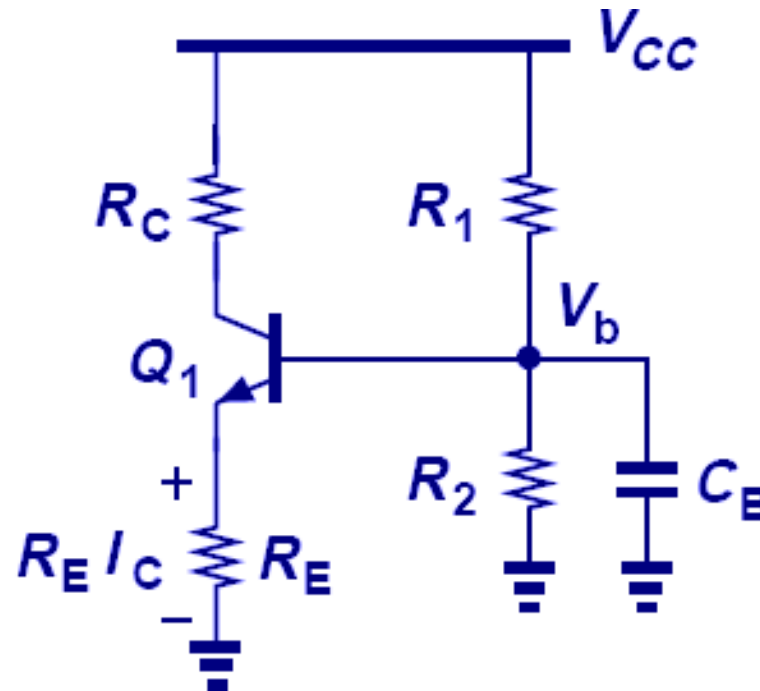
- The reduction of input impedance due to R_E is bad because it shunts part of the input current to ground instead of to Q_1 (and R_C).

Creation of V_b



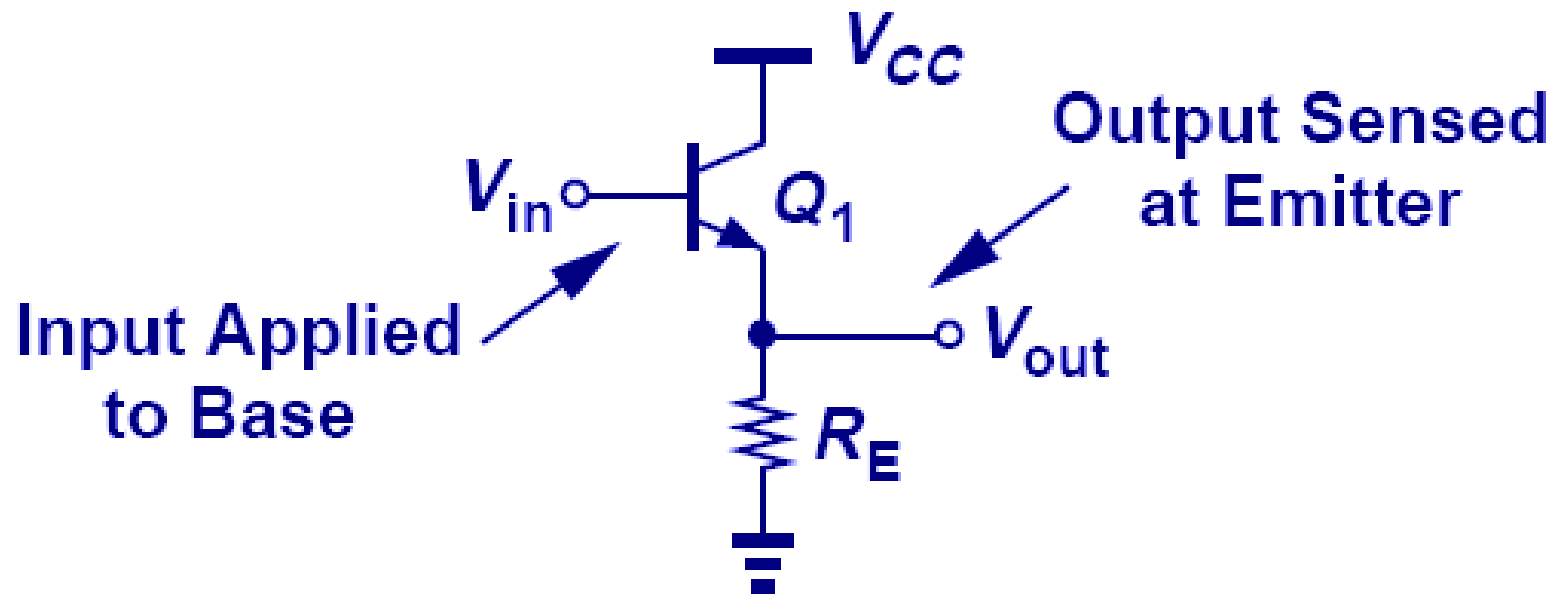
- Resistive divider lowers the gain.
- To remedy this problem, a capacitor is inserted from base to ground to short out the resistor divider at the frequency of interest.

Example of CB Stage with Bias

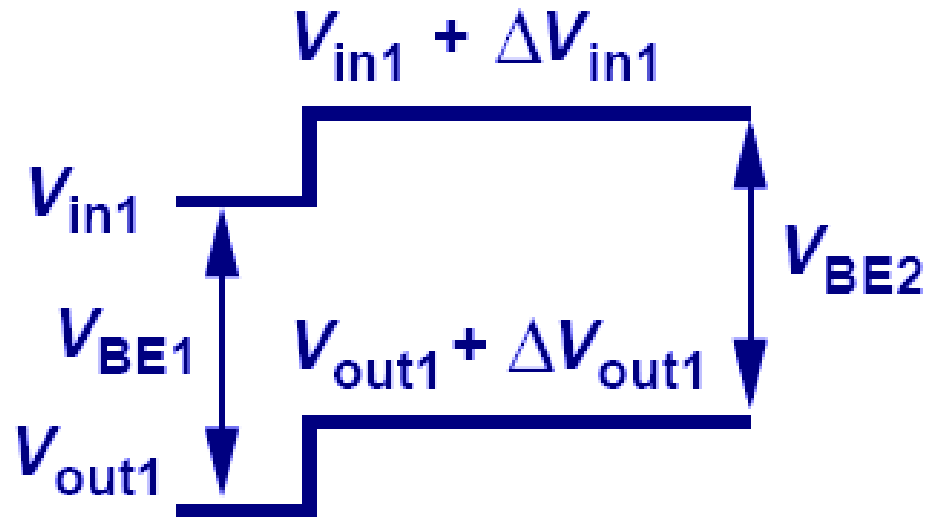
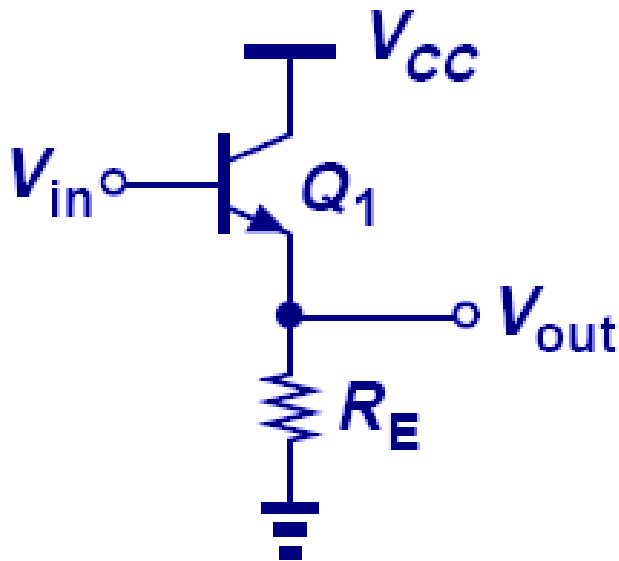


- For the circuit shown above, $R_E \gg 1/g_m$.
- R_1 and R_2 are chosen so that V_b is at the appropriate value and the current that flows thru the divider is much larger than the base current.
- Capacitors are chosen to be small compared to $1/g_m$ at the required frequency.

Emitter Follower (Common Collector Amplifier)

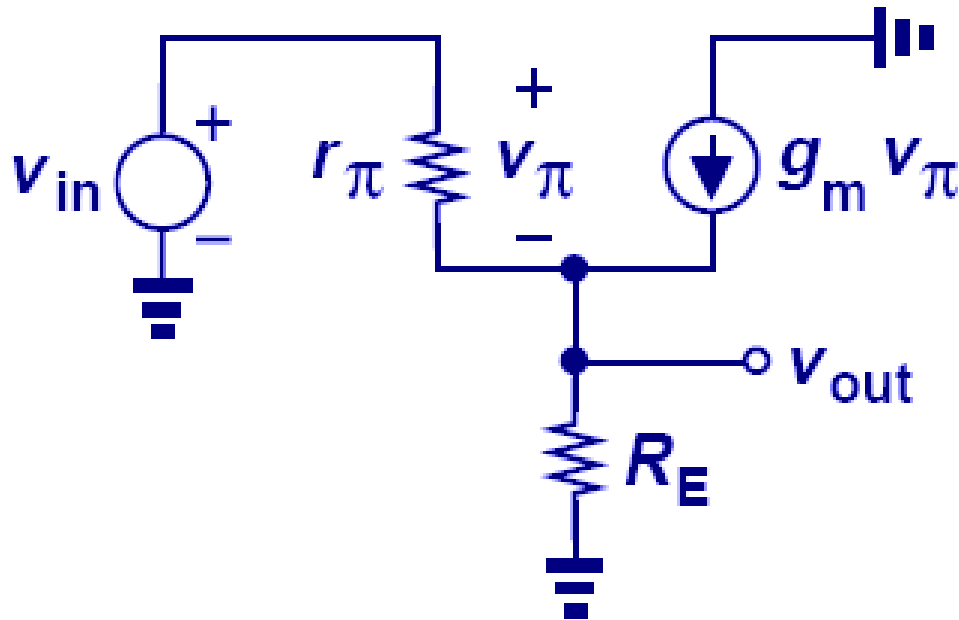


Emitter Follower Core



- When the input is increased by ΔV , output is also increased by an amount that is less than ΔV due to the increase in collector current and hence the increase in potential drop across R_E .
- However the absolute values of input and output differ by a V_{BE} .

Small-Signal Model of Emitter Follower

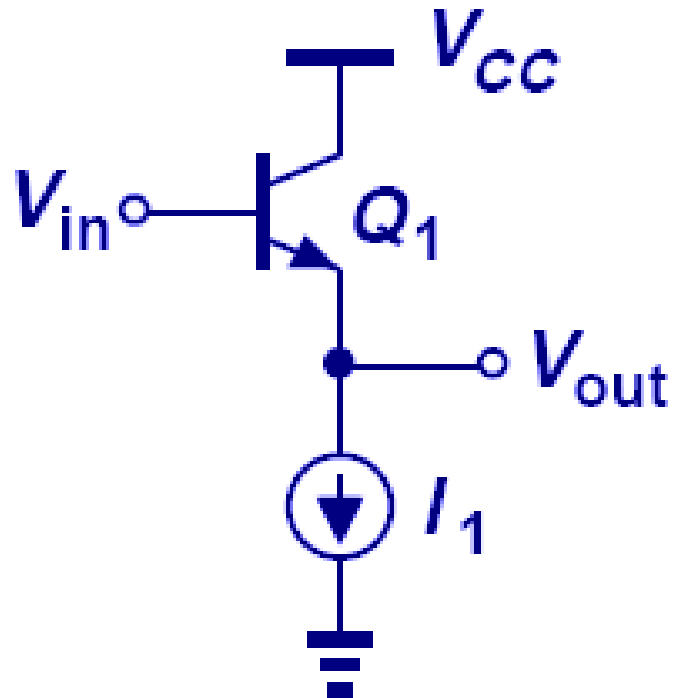


$$V_A = \infty$$

$$\frac{v_{out}}{v_{in}} = \frac{1}{1 + \frac{r_\pi}{\beta + 1} \cdot \frac{1}{R_E}} \approx \frac{R_E}{R_E + \frac{1}{g_m}}$$

➤ As shown above, the voltage gain is less than unity and positive.

Unity-Gain Emitter Follower

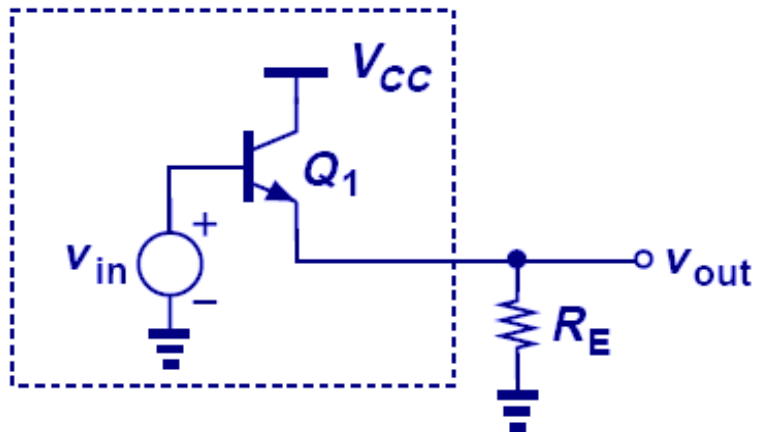


$$V_A = \infty$$

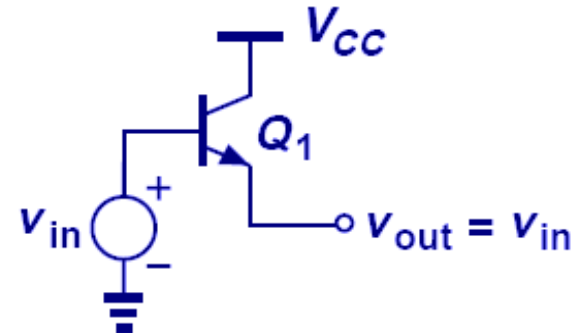
$$A_v = 1$$

- The voltage gain is unity because a constant collector current ($= I_1$) results in a constant V_{BE} , and hence V_{out} follows V_{in} exactly.

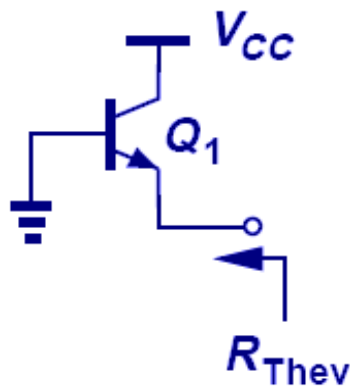
Analysis of Emitter Follower as a Voltage Divider



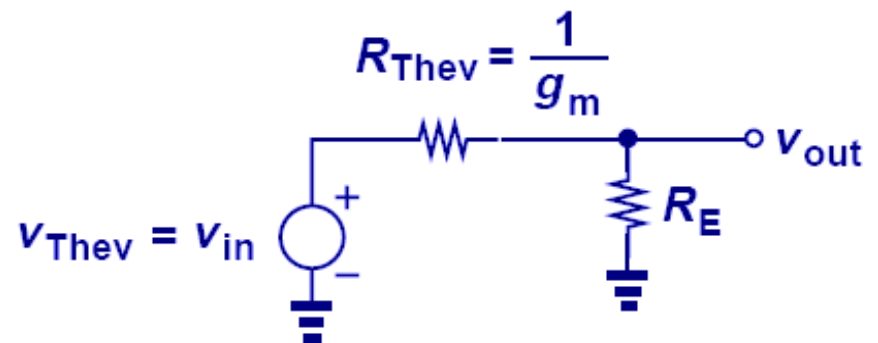
(a)



(b)



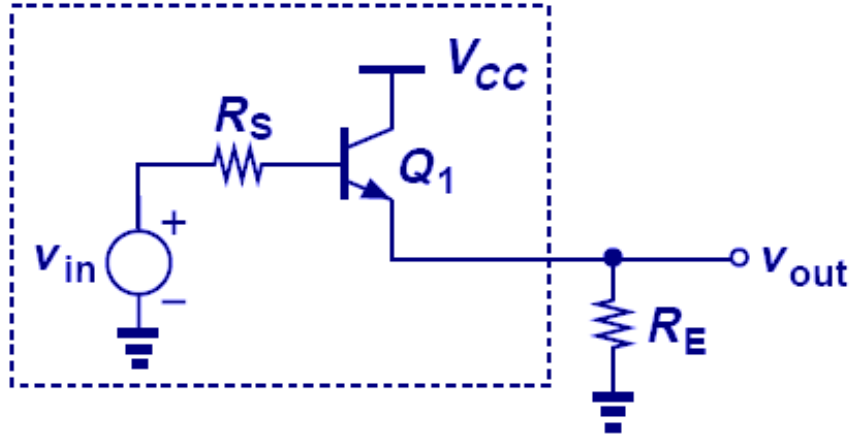
(c)



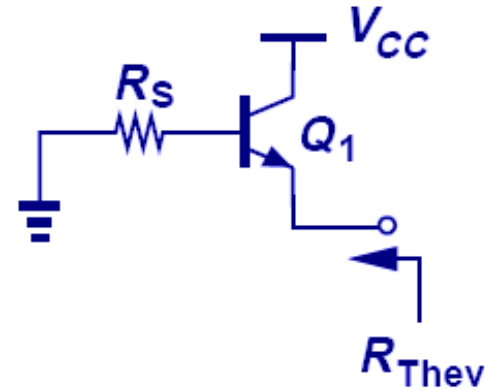
(d)

$$V_A = \infty$$

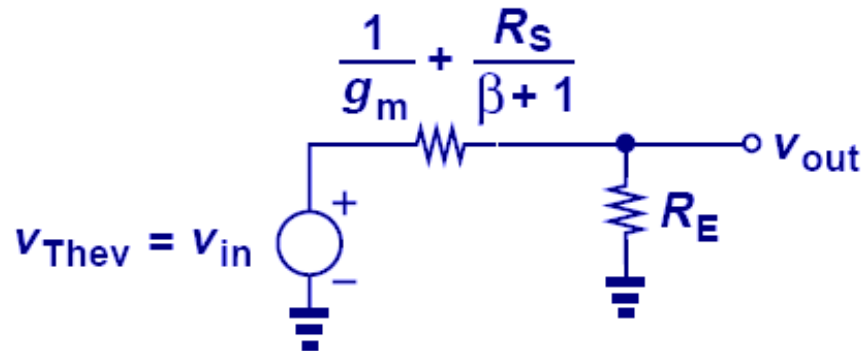
Emitter Follower with Source Resistance



(a)



(b)

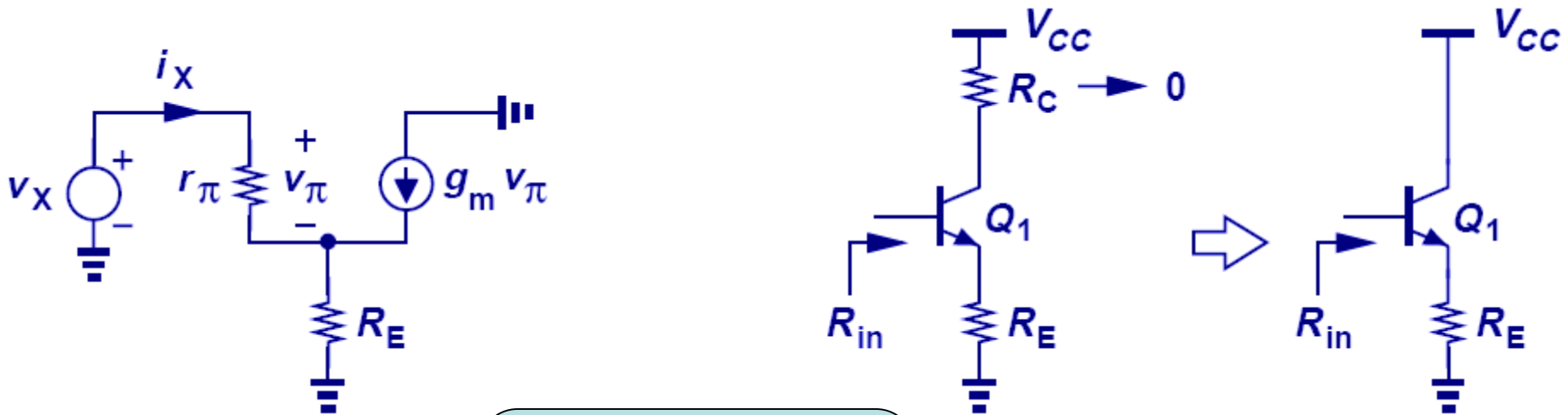


(c)

$$V_A = \infty$$

$$\frac{v_{out}}{v_{in}} = \frac{R_E}{R_E + \frac{R_S}{\beta+1} + \frac{1}{g_m}}$$

Input Impedance of Emitter Follower

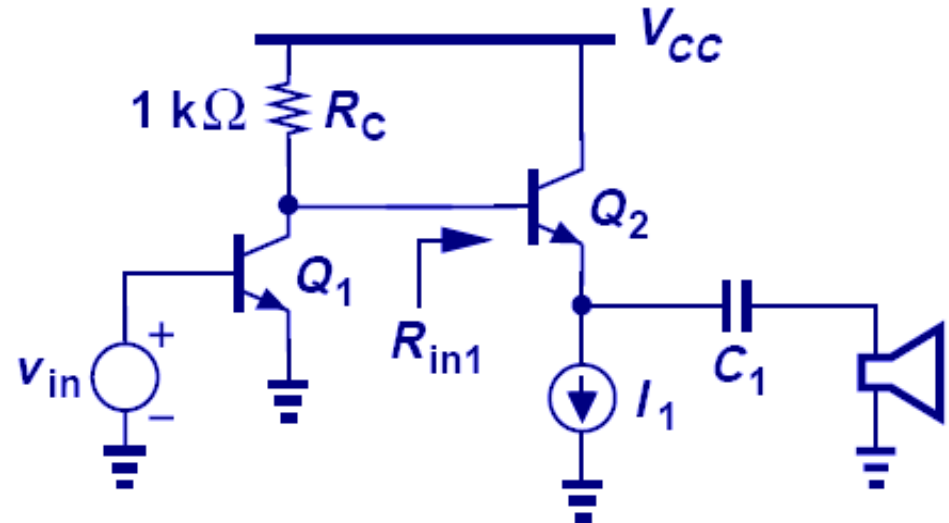
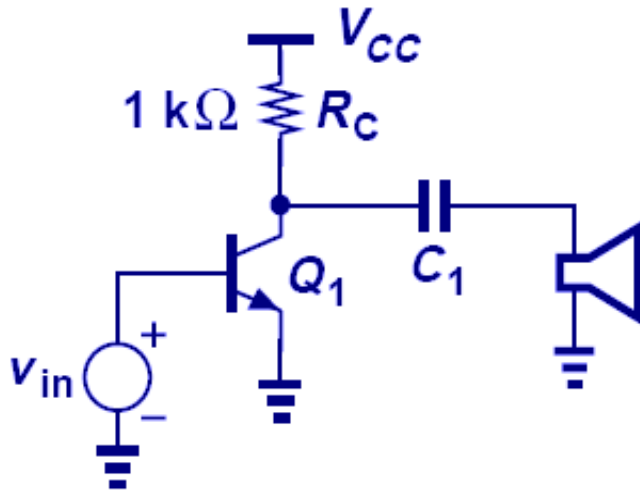


$$V_A = \infty$$

$$\frac{v_X}{i_X} = r_\pi + (1 + \beta)R_E$$

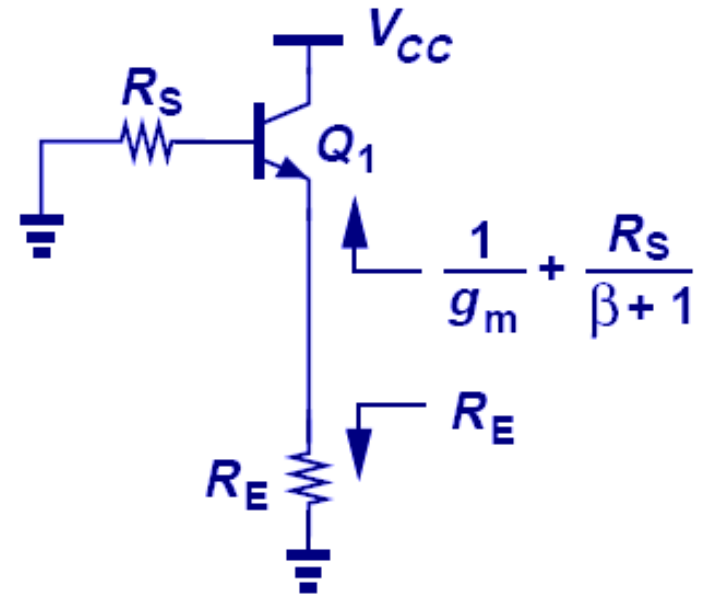
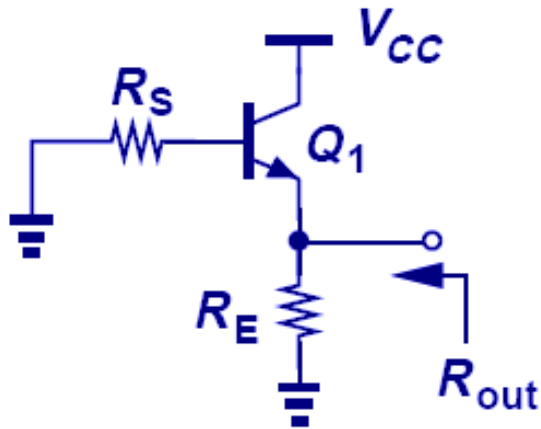
- The input impedance of emitter follower is exactly the same as that of CE stage with emitter degeneration. This is not surprising because the input impedance of CE with emitter degeneration does not depend on the collector resistance.

Emitter Follower as Buffer



- Since the emitter follower increases the load resistance to a much higher value, it is suited as a buffer between a CE stage and a heavy load resistance to alleviate the problem of gain degradation.

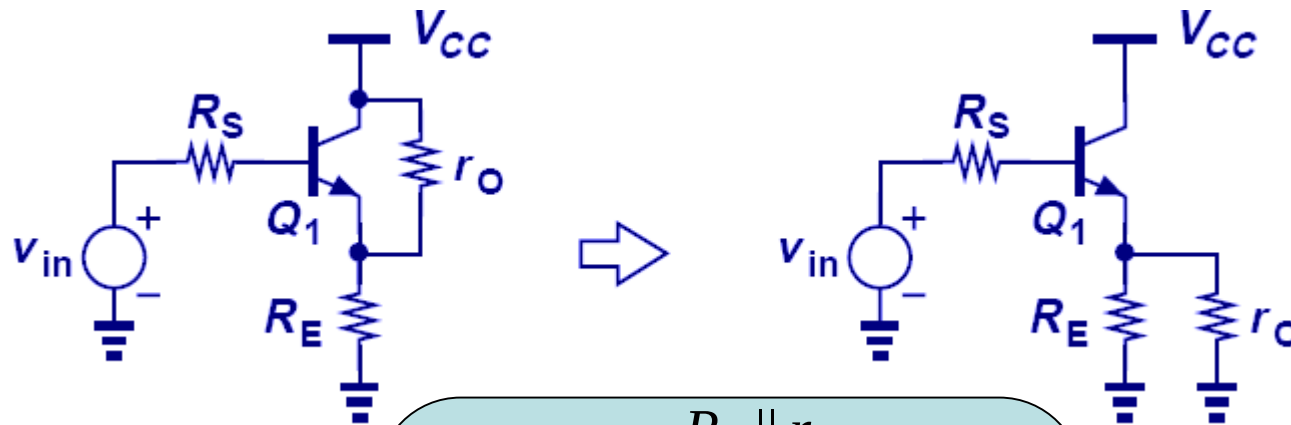
Output Impedance of Emitter Follower



$$R_{out} = \left(\frac{R_s}{\beta + 1} + \frac{1}{g_m} \right) \parallel R_E$$

➤ Emitter follower lowers the source impedance by a factor of $\beta + 1 \rightarrow$ improved driving capability.

Emitter Follower with Early Effect



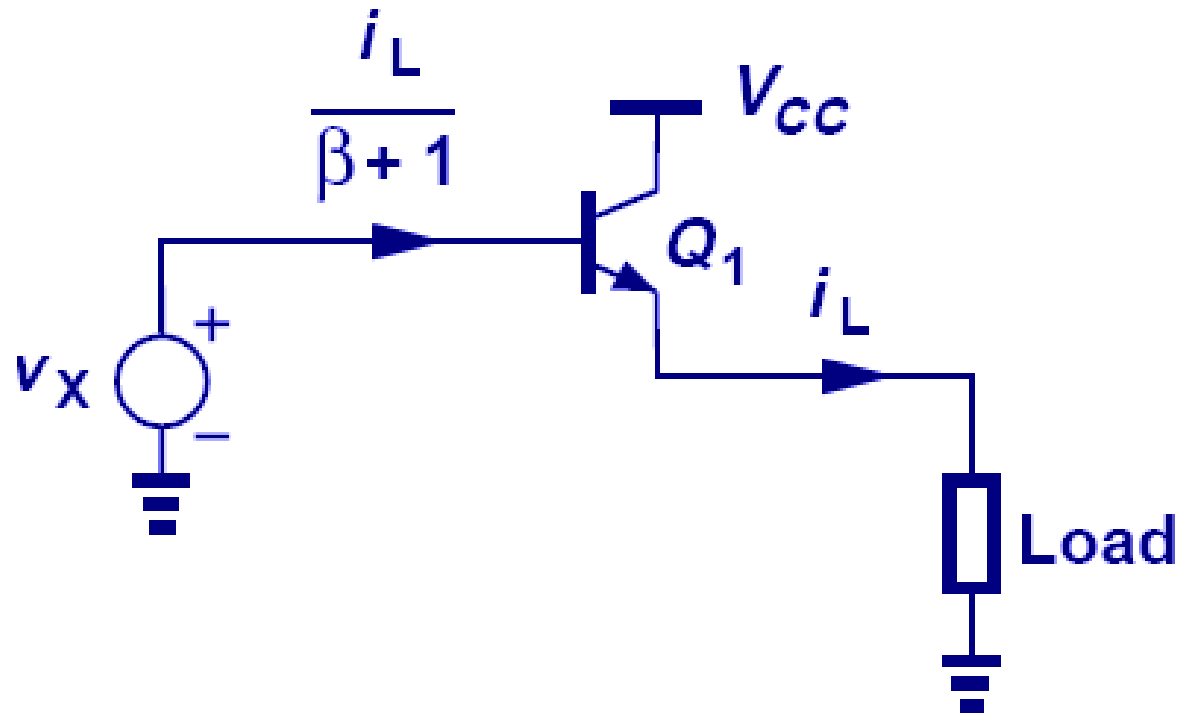
$$A_v = \frac{R_E \parallel r_o}{R_E \parallel r_o + \frac{R_S}{\beta + 1} + \frac{1}{g_m}}$$

$$R_{in} = r_{\pi} + (\beta + 1)(R_E \parallel r_o)$$

$$R_{out} = \left(\frac{R_S}{\beta + 1} + \frac{1}{g_m} \right) \parallel R_E \parallel r_o$$

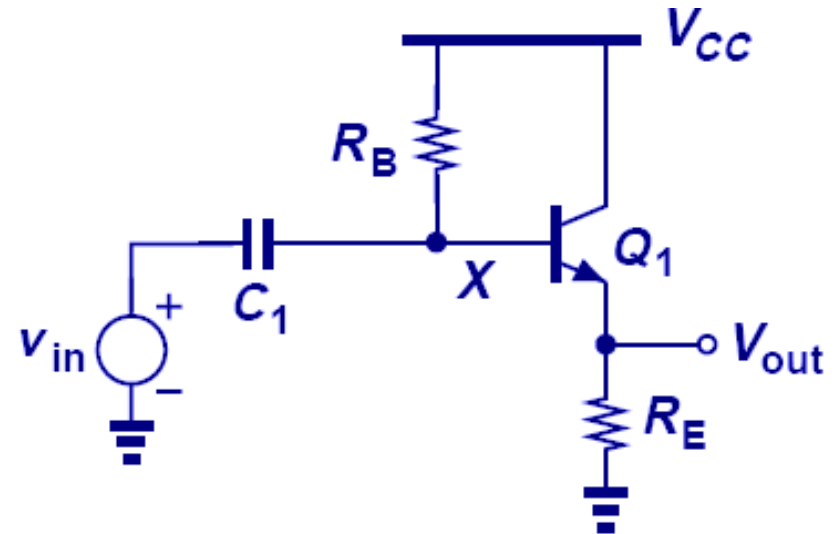
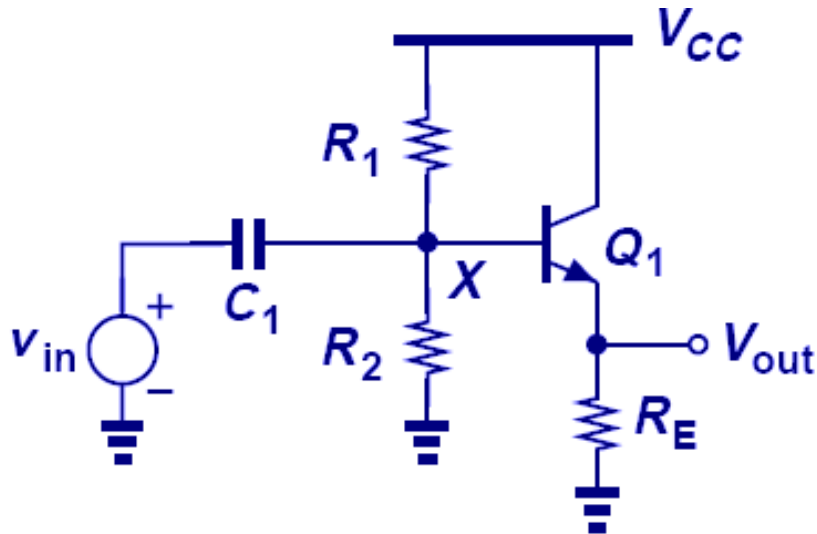
- Since r_o is in parallel with R_E , its effect can be easily incorporated into voltage gain and input and output impedance equations.

Current Gain



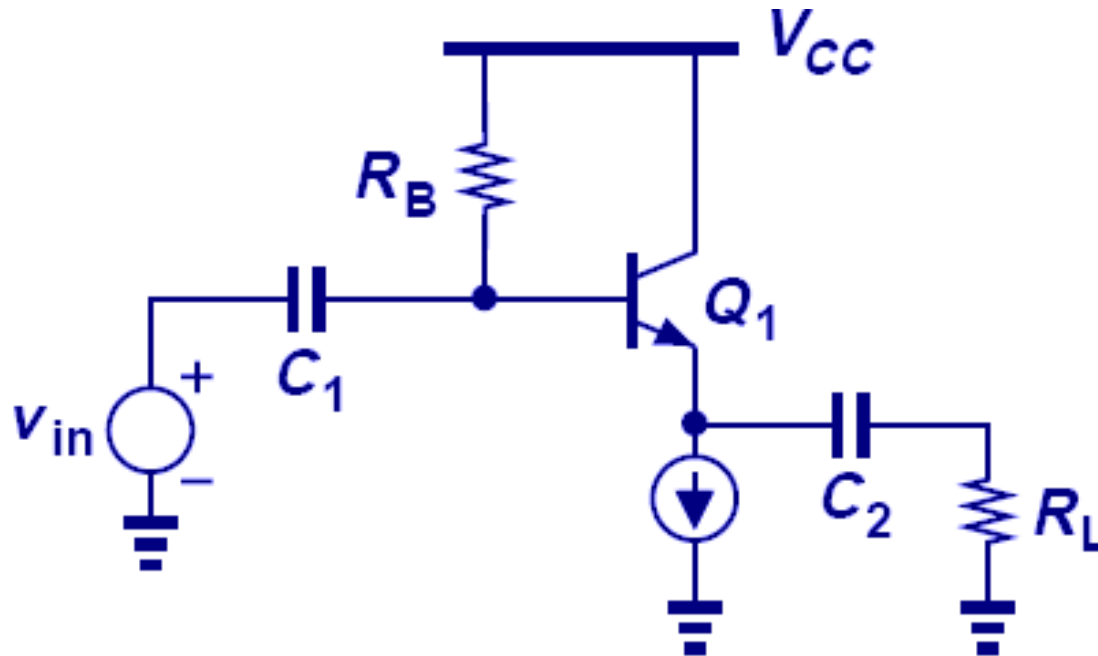
- There is a current gain of $(\beta+1)$ from base to emitter.
- Effectively speaking, the load resistance is multiplied by $(\beta+1)$ as seen from the base.

Emitter Follower with Biasing



- A biasing technique similar to that of CE stage can be used for the emitter follower.
- Also, V_b can be close to V_{cc} because the collector is also at V_{cc} .

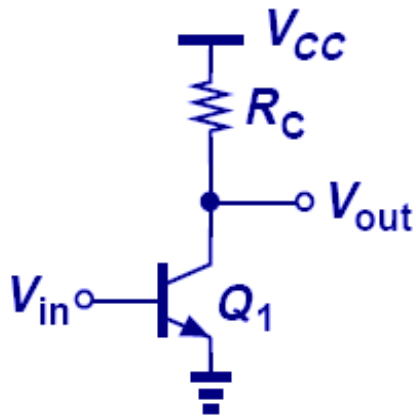
Supply-Independent Biasing



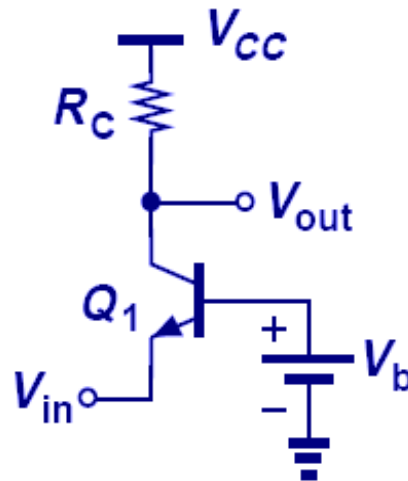
- By putting a constant current source at the emitter, the bias current, V_{BE} , and $I_B R_B$ are fixed regardless of the supply value.

Summary of Amplifier Topologies

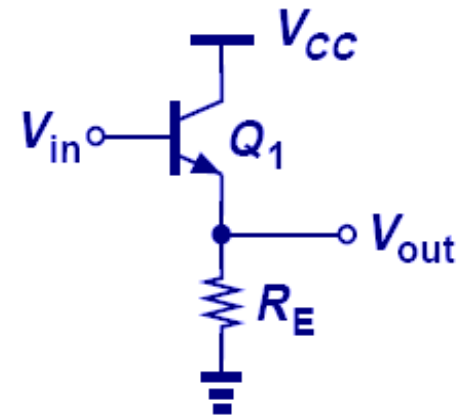
CE Stage



CB Stage

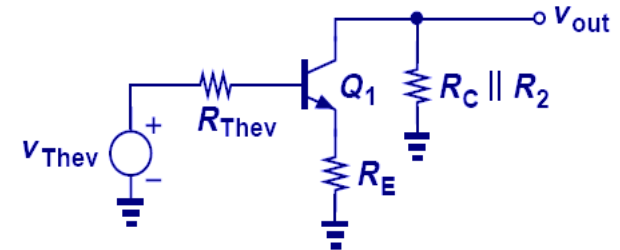
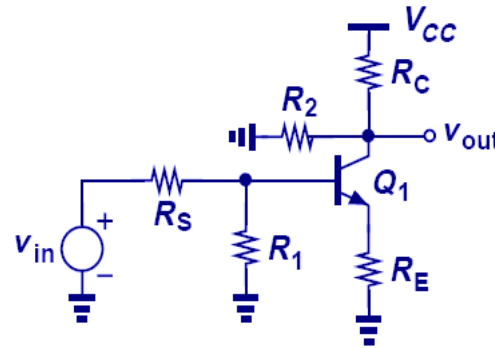
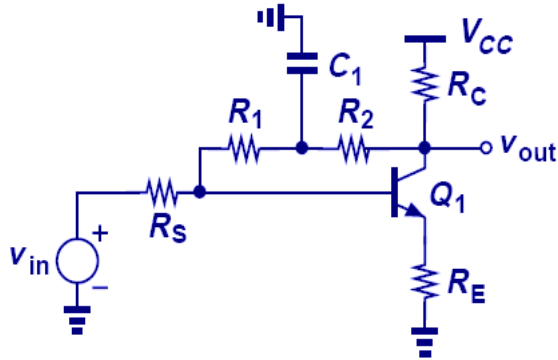


Follower



- The three amplifier topologies studied so far have different properties and are used on different occasions.
- CE and CB have voltage gain with magnitude greater than one, while follower's voltage gain is at most one.

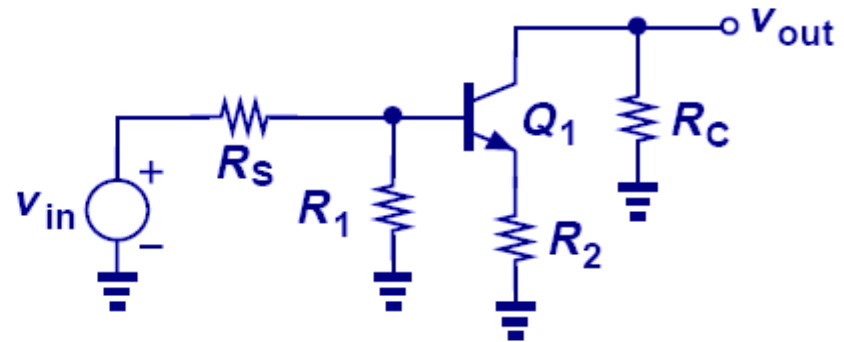
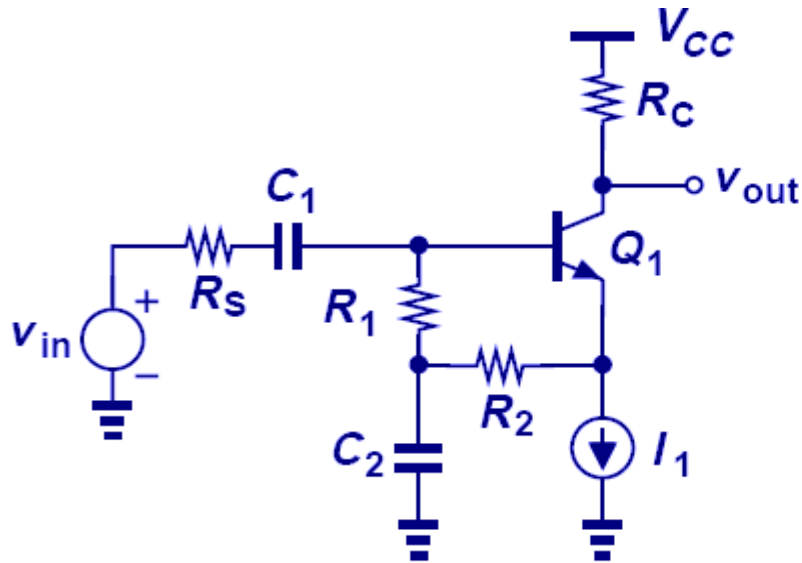
Amplifier Example I



$$\frac{v_{out}}{v_{in}} = - \frac{R_2 \parallel R_C}{\frac{R_1 \parallel R_S}{\beta + 1} + \frac{1}{g_m} + R_E} \cdot \frac{R_1}{R_1 + R_S}$$

- The keys in solving this problem are recognizing the AC ground between R_1 and R_2 , and Thevenin transformation of the input network.

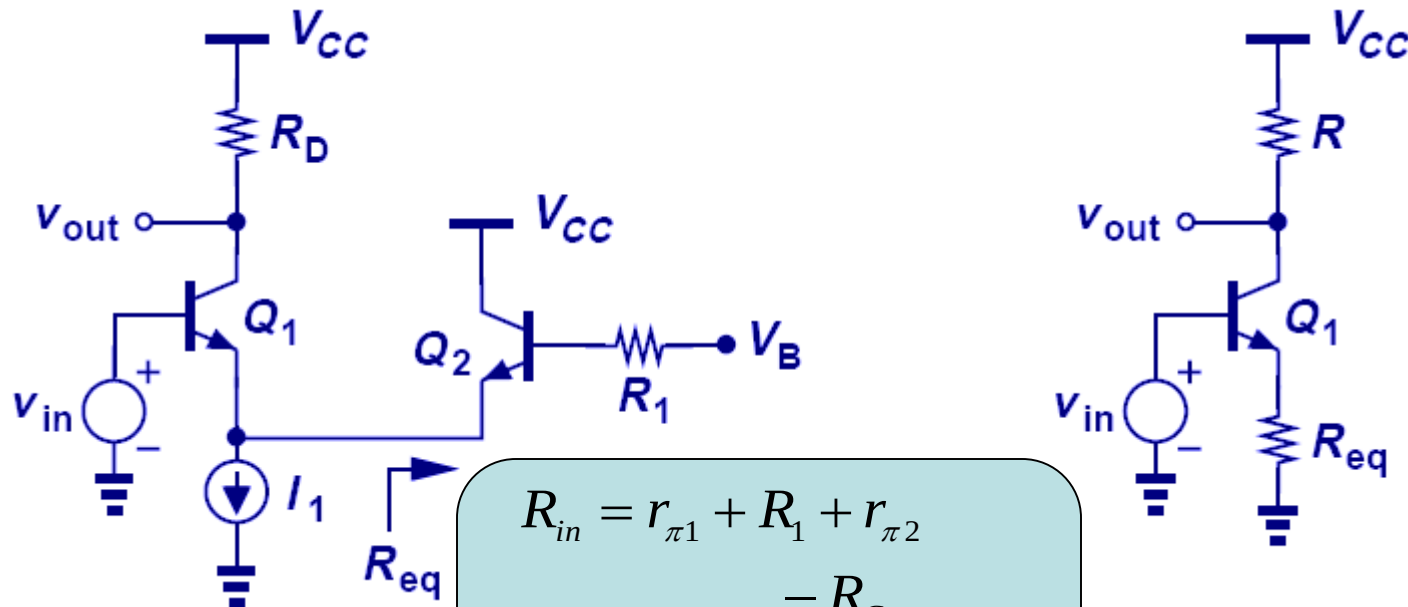
Amplifier Example II



$$\frac{v_{out}}{v_{in}} = - \frac{R_C}{\frac{R_S \parallel R_1}{\beta + 1} + \frac{1}{g_m} + R_2} \cdot \frac{R_1}{R_1 + R_S}$$

➤ Again, AC ground/short and Thevenin transformation are needed to transform the complex circuit into a simple stage with emitter degeneration.

Amplifier Example III

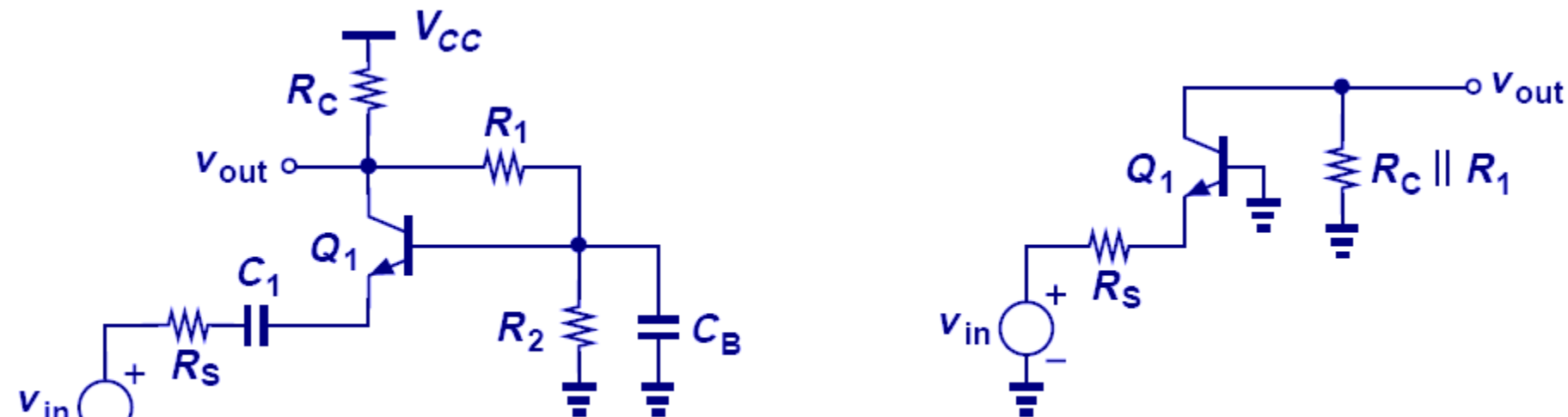


$$R_{in} = r_{\pi 1} + R_1 + r_{\pi 2}$$

$$A_v = \frac{-R_C}{\frac{1}{g_{m1}} + \frac{R_1}{\beta + 1} + \frac{1}{g_{m2}}}$$

- The key for solving this problem is first identifying R_{eq} , which is the impedance seen at the emitter of Q_2 in parallel with the infinite output impedance of an ideal current source. Second, use the equations for degenerated CE stage with R_E replaced by R_{eq} .

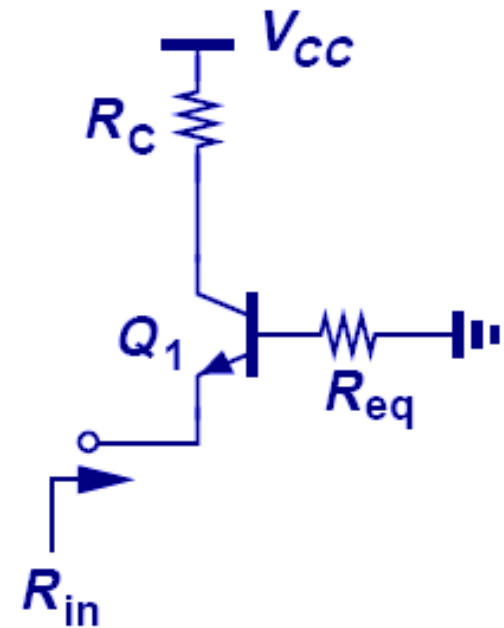
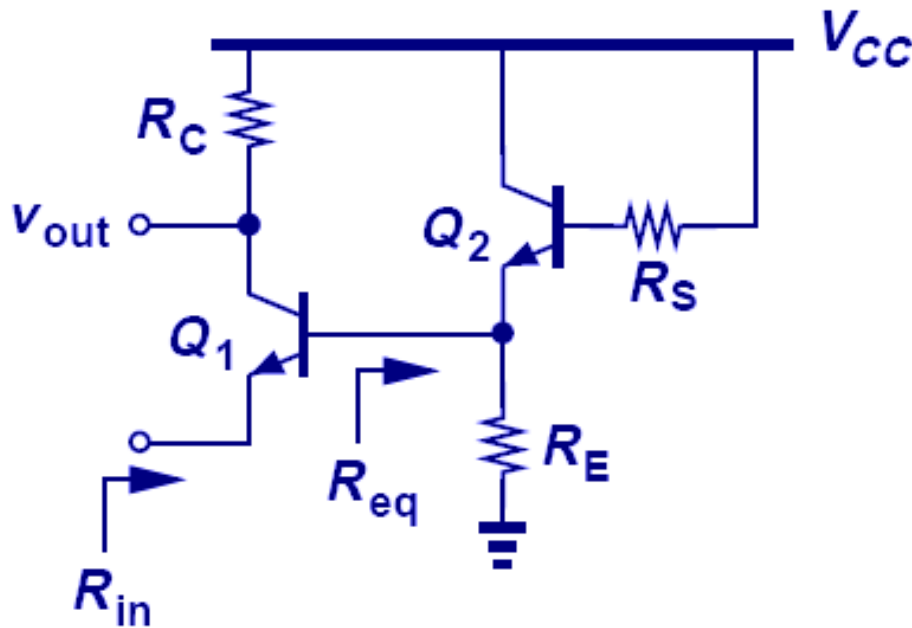
Amplifier Example IV



$$A_v = \frac{R_C \parallel R_1}{R_S + \frac{1}{g_m}}$$

- The key for solving this problem is recognizing that C_B at frequency of interest shorts out R_2 and provide a ground for R_1 .
- R_1 appears in parallel with R_C and the circuit simplifies to a simple CB stage.

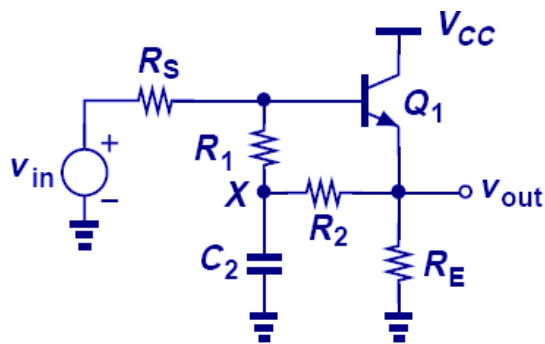
Amplifier Example V



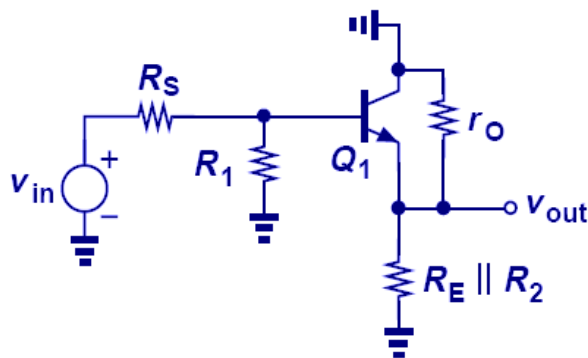
$$R_{in} = \frac{1}{\beta + 1} \left[\left(\frac{R_B}{\beta + 1} + \frac{1}{g_{m2}} \right) \parallel R_E \right] + \frac{1}{g_{m1}}$$

➤ The key for solving this problem is recognizing the equivalent base resistance of Q_1 is the parallel connection of R_E and the impedance seen at the emitter of Q_2 .

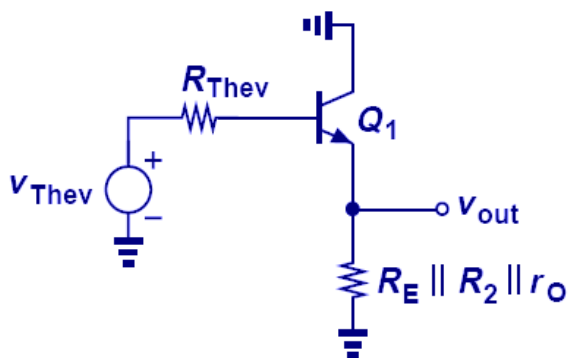
Amplifier Example VI



(a)



(b)



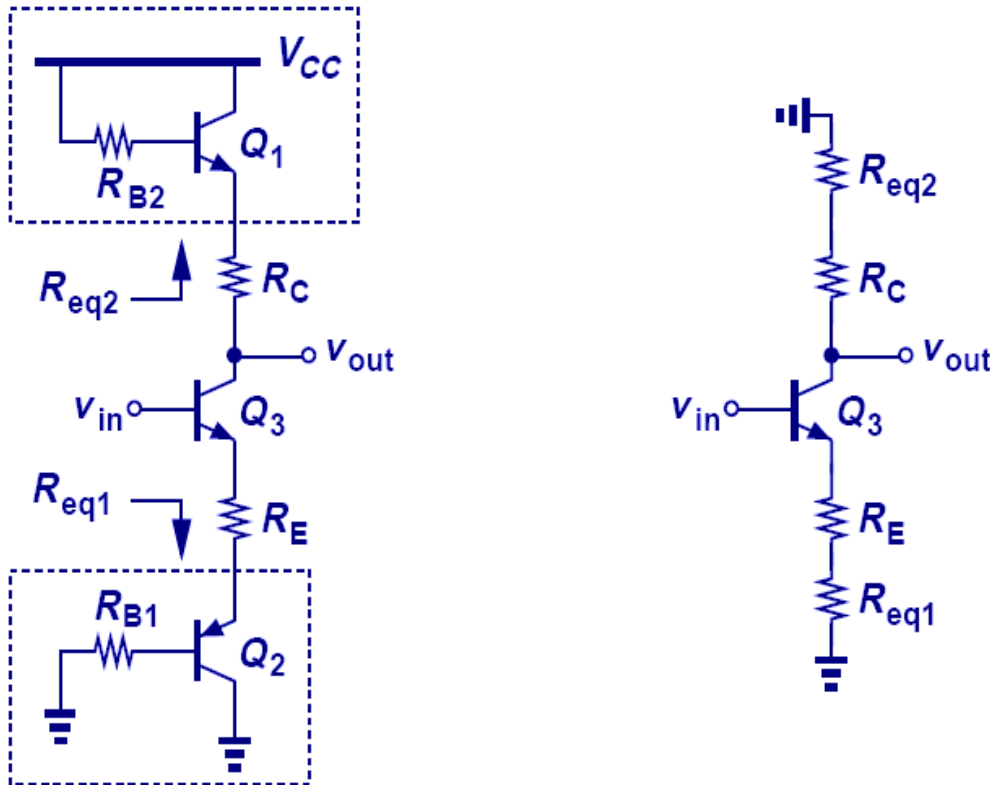
(c)

$$\frac{v_{out}}{v_{in}} = \frac{R_E \parallel R_2 \parallel r_o}{R_E \parallel R_2 \parallel r_o + \frac{1}{g_m} + \frac{R_S \parallel R_1}{\beta + 1}} \cdot \frac{R_1}{R_1 + R_S}$$

$$R_{out} = \left(\frac{R_S \parallel R_1}{\beta + 1} + \frac{1}{g_m} \right) \parallel R_E \parallel R_2 \parallel r_o$$

➤ The key in solving this problem is recognizing a DC supply is actually an AC ground and using Thevenin transformation to simplify the circuit into an emitter follower.

Amplifier Example VII



$$R_{in} = r_{\pi 1} + (\beta + 1) \left(R_E + \frac{R_{B1}}{\beta + 1} + \frac{1}{g_{m2}} \right)$$

$$R_{out} = R_C + \frac{R_{B2}}{\beta + 1} + \frac{1}{g_{m3}}$$

$$A_v = - \frac{R_C + \frac{R_{B2}}{\beta + 1} + \frac{1}{g_{m3}}}{\frac{R_{B1}}{\beta + 1} + \frac{1}{g_{m2}} + \frac{1}{g_{m1}}}$$

➤ Impedances seen at the emitter of Q_1 and Q_2 can be lumped with R_C and R_E , respectively, to form the equivalent emitter and collector impedances.