Fundamentals of Microelectronics

- CH1 Why Microelectronics?
- CH2 Basic Physics of Semiconductors
- CH3 Diode Circuits
- CH4 Physics of Bipolar Transistors
- CH5 Bipolar Amplifiers
- CH6 Physics of MOS Transistors
- CH7 CMOS Amplifiers
- CH8 Operational Amplifier As A Black Box

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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

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Bipolar Amplifiers

General Concepts

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

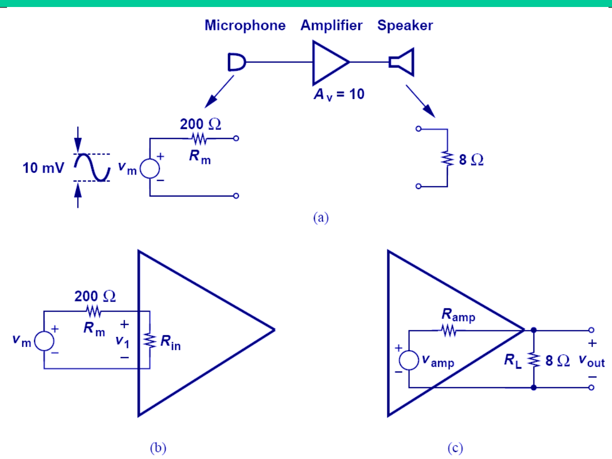
Operating Point Analysis

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

Amplifier Topologies

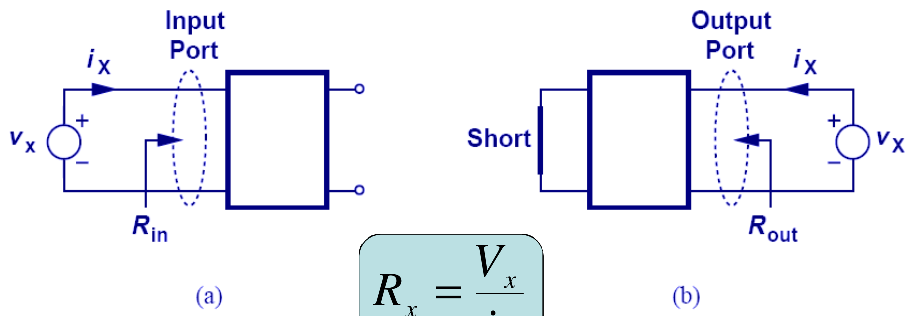
- Common−Emitter Stage
- Common−Base Stage
- Emtter Follower

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.

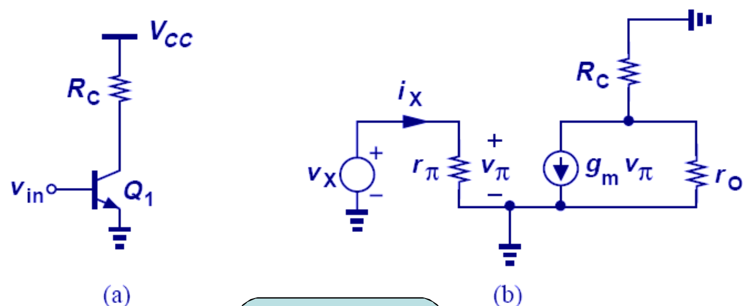
Input/Output Impedances



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

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

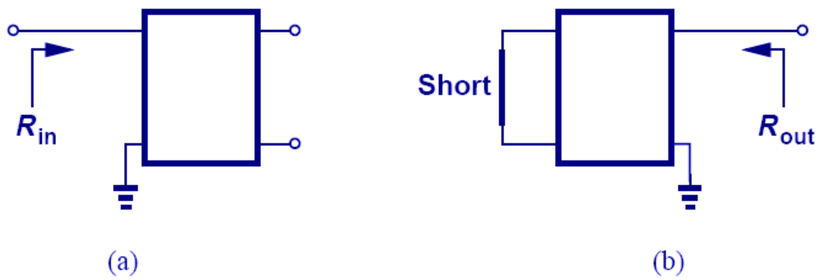
Input Impedance Example I



$$\frac{v_x}{i_x} = r_\pi$$

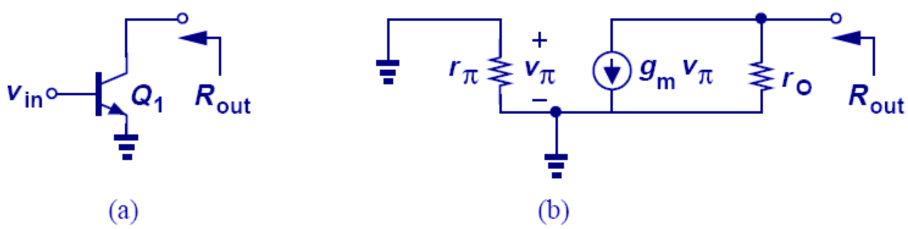
- **When calculating input/output impedance, small-signal analysis is assumed.**

Impedance at a Node



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

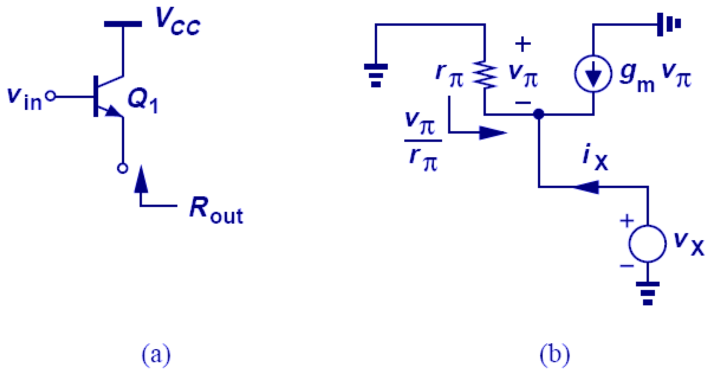
Impedance at Collector



$$R_{out} = r_o$$

- 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



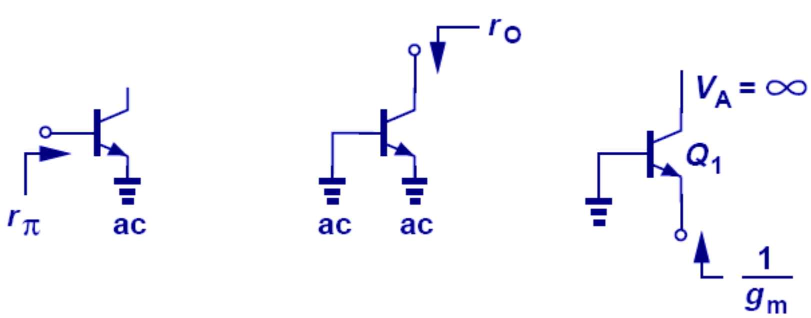
$$\frac{v_x}{i_x} = \frac{1}{g_m + \frac{1}{r_\pi}}$$

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

$$(V_A = \infty)$$

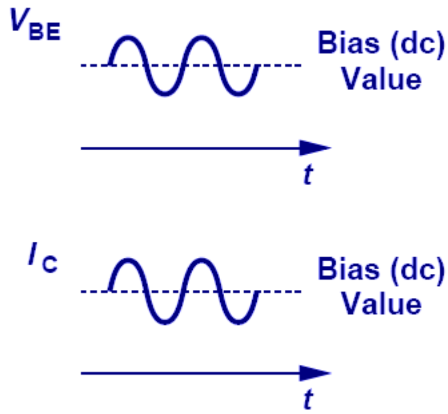
- **The impedance seen at the emitter of a transistor is approximately equal to one over its transconductance (if the base is grounded).**

Three Master Rules of Transistor Impedances



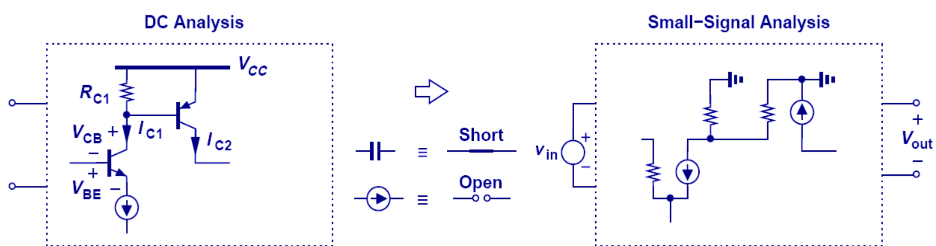
- **Rule # 1: looking into the base, the impedance is rπ if emitter is (ac) grounded.**
- **Rule # 2: looking into the collector, the impedance is ro if emitter is (ac) grounded.**
- **Rule # 3: looking into the emitter, the impedance is 1/gm if base is (ac) grounded and Early effect is neglected.**

Biasing of BJT



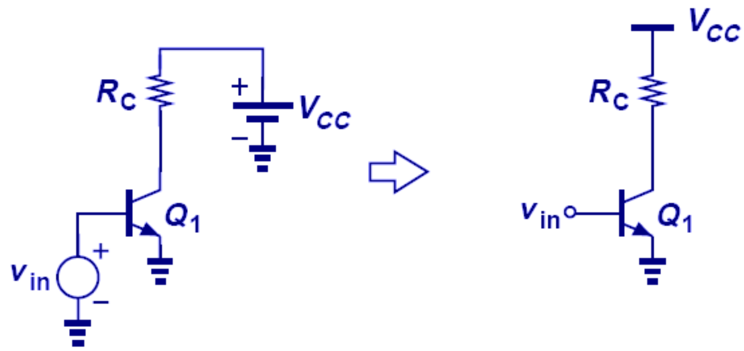
- **Transistors and circuits must be biased because (1) transistors must operate in the active region, (2) their small-signal parameters depend on the bias conditions.**

DC Analysis vs. Small-Signal Analysis



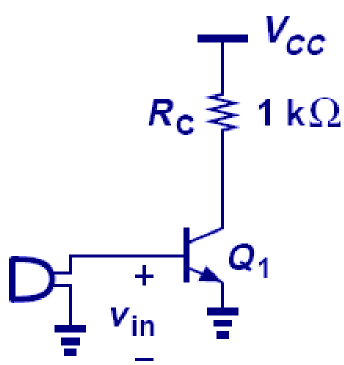
- **First, DC analysis is performed to determine operating point and obtain small-signal parameters.**
- **Second, sources are set to zero and small-signal model is used.**

Notation Simplification



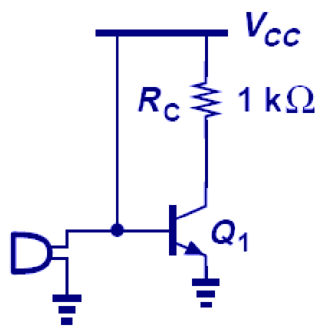
- Hereafter, the battery that supplies power to the circuit is replaced by a horizontal bar labeled Vcc, and input signal is simplified as one node called Vin.

Example of Bad Biasing



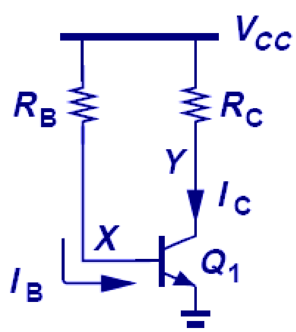
- The microphone is connected to the amplifier in an attempt to amplify the small output signal of the microphone.
- Unfortunately, there's no DC bias current running thru the transistor to set the transconductance.

Another Example of Bad Biasing



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

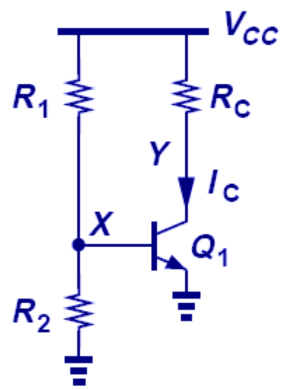
Biasing with Base Resistor



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

- Assuming a constant value for VBE, one can solve for both IB and IC and determine the terminal voltages of the transistor.
- However, bias point is sensitive to β variations.

Improved Biasing: Resistive Divider

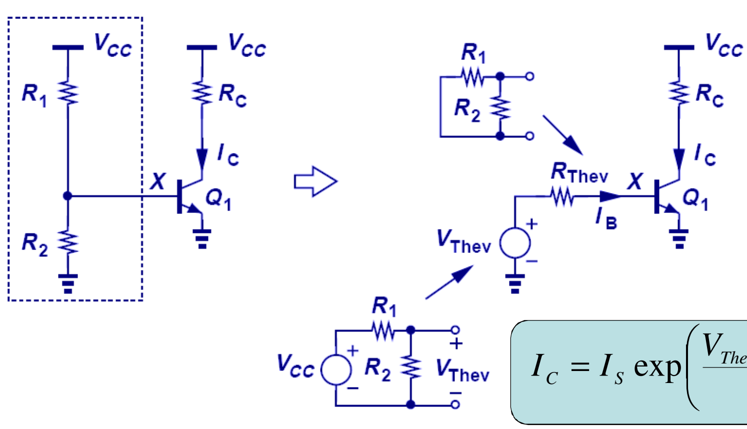


$$V_X = \frac{R_2}{R_1 + R_2} V_{CC}$$

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

- **Using resistor divider to set VBE, it is possible to produce an IC that is relatively independent of β if base current is small.**

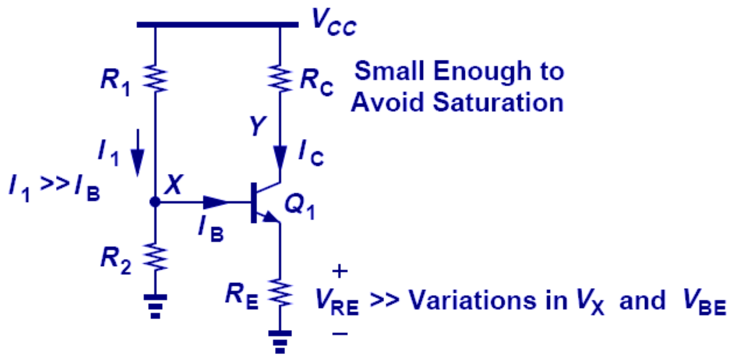
Accounting for Base Current



$$I_C = I_S \exp\left(\frac{V_{Thev} - I_B R_{Thev}}{V_T}\right)$$

- **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

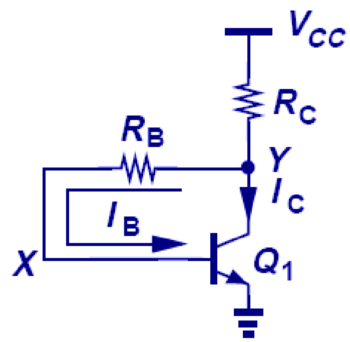


- The presence of R_E helps to absorb the error in V_X so V_{BE} stays relatively constant.
- This bias technique is less sensitive to β ($I_1 >> I_B$) and V_{BE} variations.

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.

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Self-Biasing Design Guidelines

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

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

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

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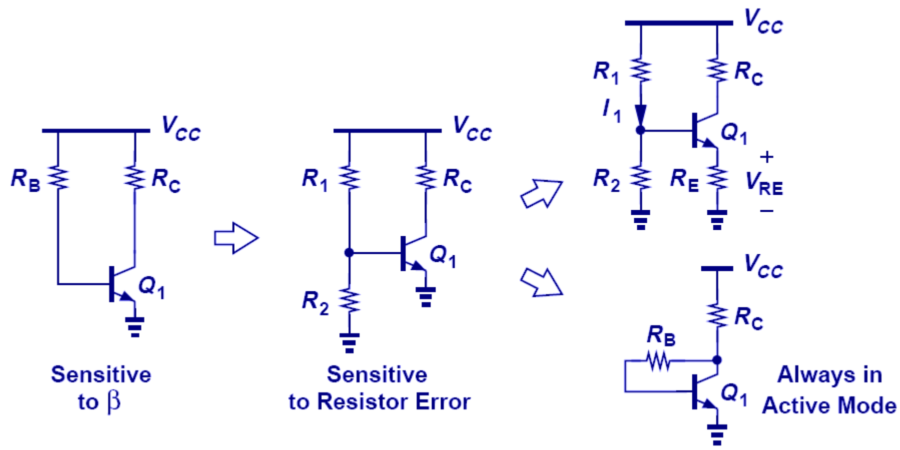
Summary of Biasing Techniques



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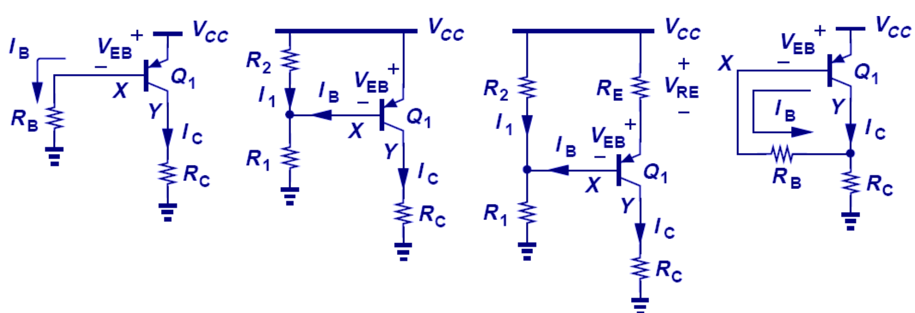
PNP Biasing Techniques



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

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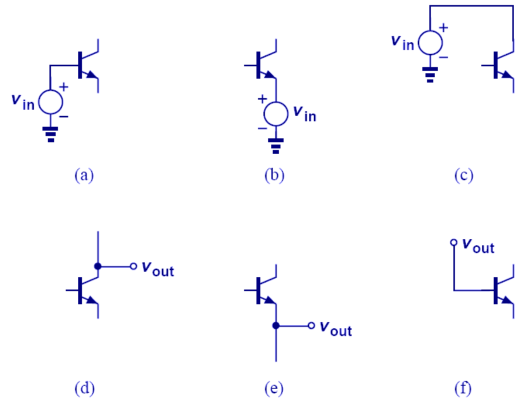
Possible Bipolar Amplifier Topologies

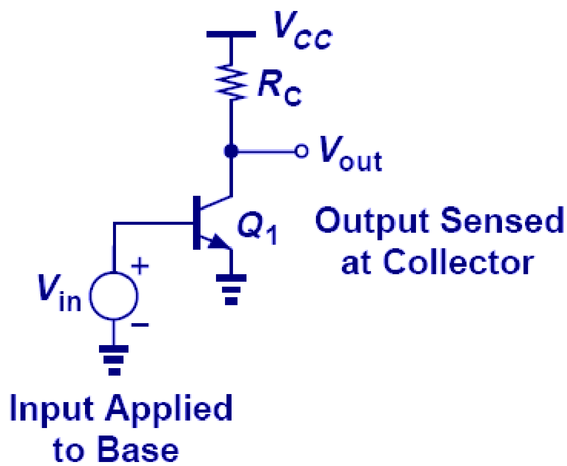


- Three possible ways to apply an input to an amplifier and three possible ways to sense its output.
- However, in reality only three of six input/output combinations are useful.

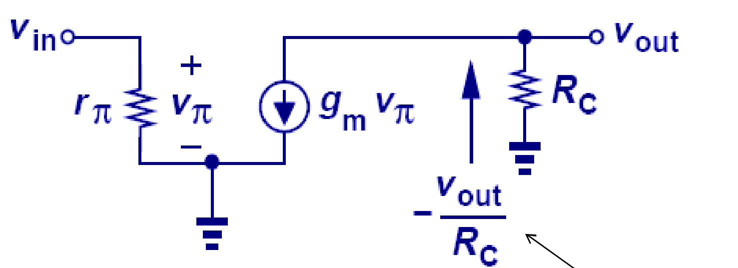
Study of Common-Emitter Topology

- ***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



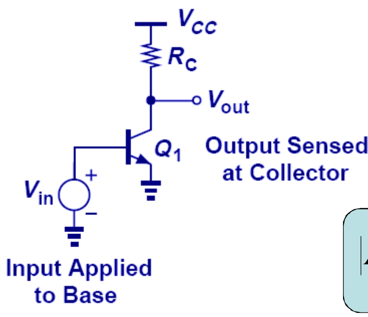
Current

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

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

$$A_v = -g_m R_C$$

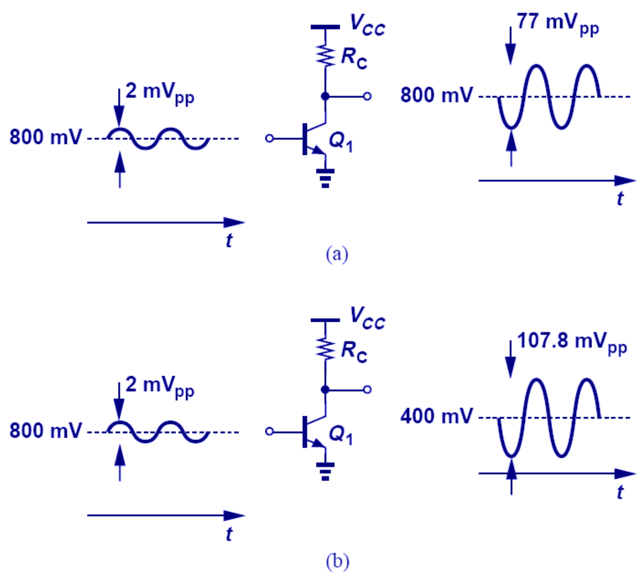
Limitation on CE Voltage Gain



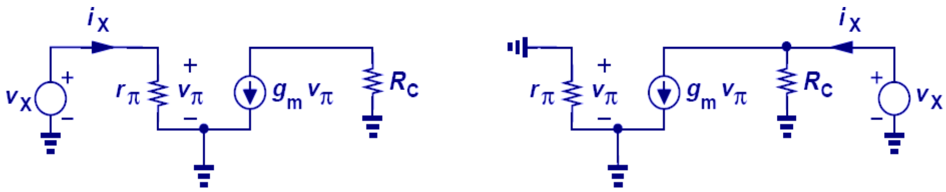
$$|A_v| = \frac{I_C R_C}{V_T} \qquad |A_v| = \frac{V_{RC}}{V_T} \qquad |A_v| < \frac{V_{CC} - V_{BE}}{V_T}$$

- **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



I/O Impedances of CE Stage



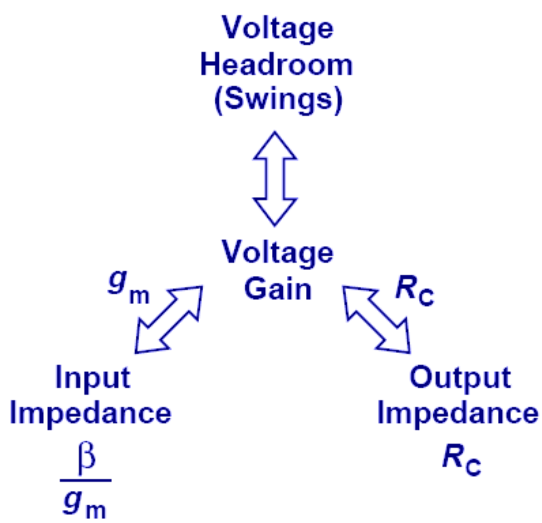
(a) (b)

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

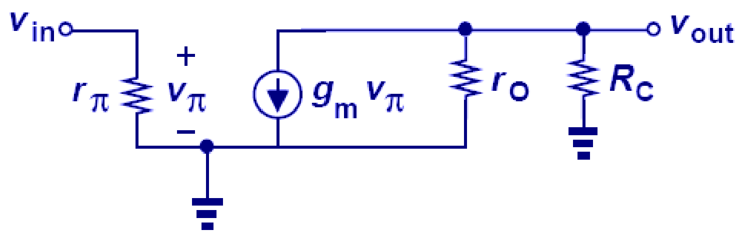
$$R_{out} = \frac{v_X}{i_X} = R_C$$

- 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.

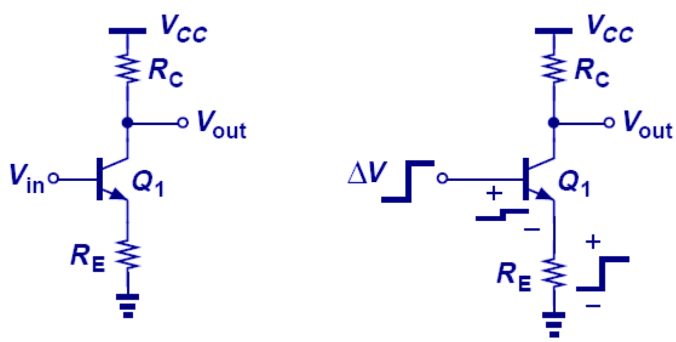
Current Gain

$$A_I = \frac{i_{out}}{i_{in}}$$

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

- 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.

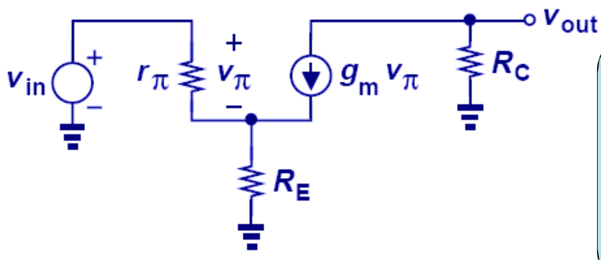
Emitter Degeneration



(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

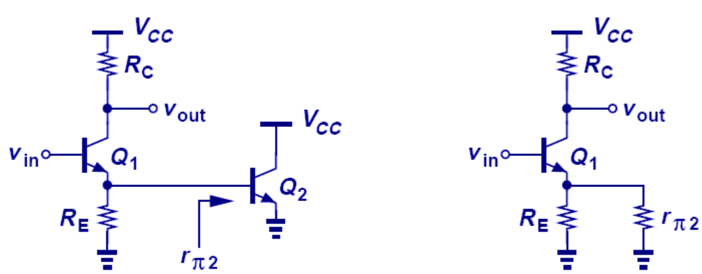


$$A_v = -\frac{g_m R_C}{1 + g_m R_E}$$

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

- 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

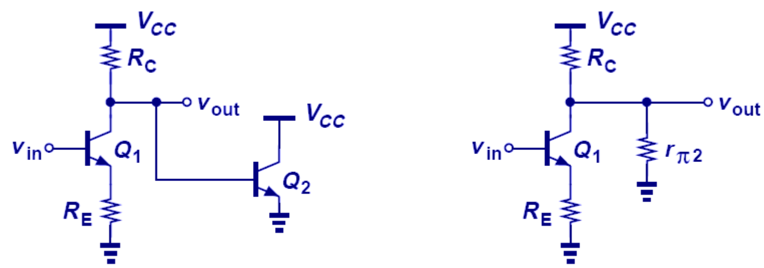


(a) (b)

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

- 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

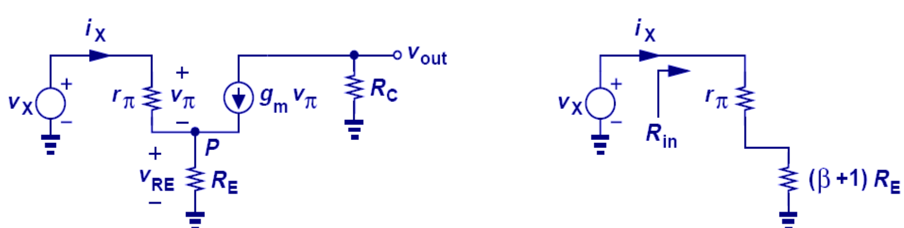


(a) (b)

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

- 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



(a) (b)

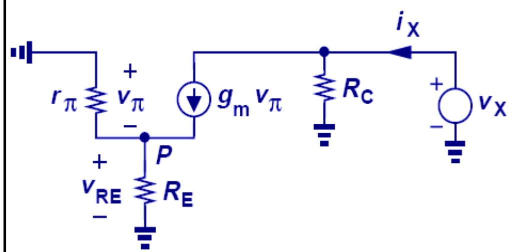
$$V_A = \infty$$

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

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

- 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



(a)

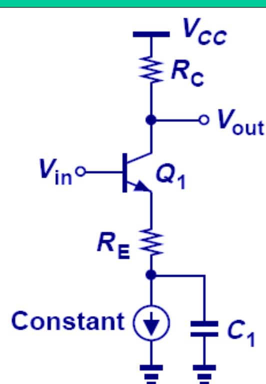
$$V_A = \infty$$

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

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

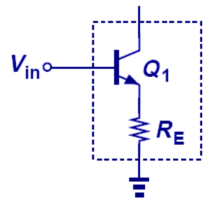
- Emitter degeneration does not alter the output impedance in this case. (More on this later.)

Capacitor at Emitter

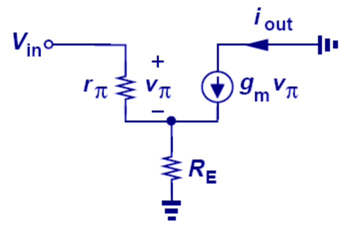


- At DC the capacitor is open and the current source biases the amplifier.
- For ac signals, the capacitor is short and the amplifier is degenerated by R_E.

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.

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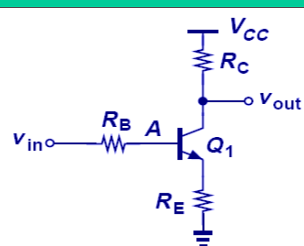
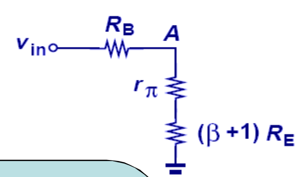
Degenerated CE Stage with Base Resistance





$$V_A = \infty$$

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

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

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

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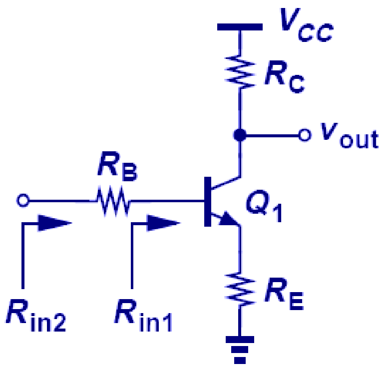
Input/Output Impedances



$$V_A = \infty$$

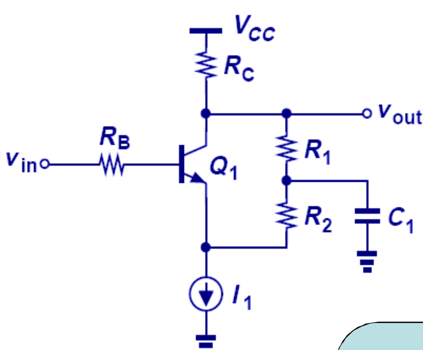
$$R_{in1} = r_\pi + (\beta + 1)R_E$$

$$R_{in2} = R_B + r_{\pi 2} + (\beta + 1)R_E$$

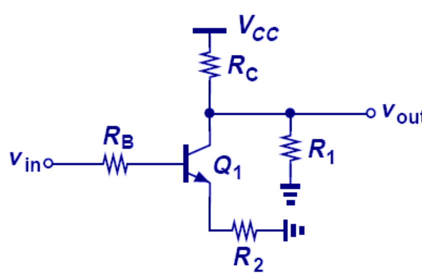
$$R_{out} = R_C$$

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

Emitter Degeneration Example III



(a)



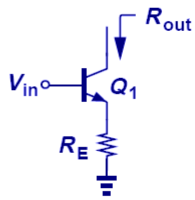
(b)

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

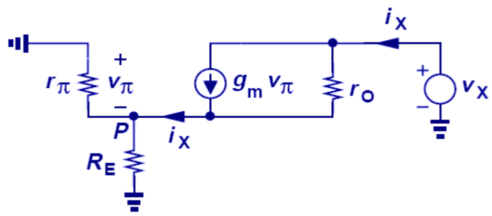
$$R_{in} = r_\pi + (\beta + 1)R_2$$

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

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



(a)

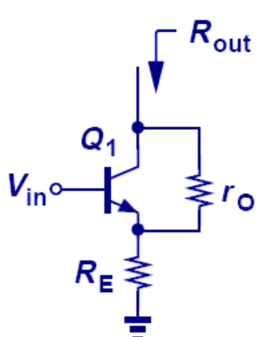


(b)

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

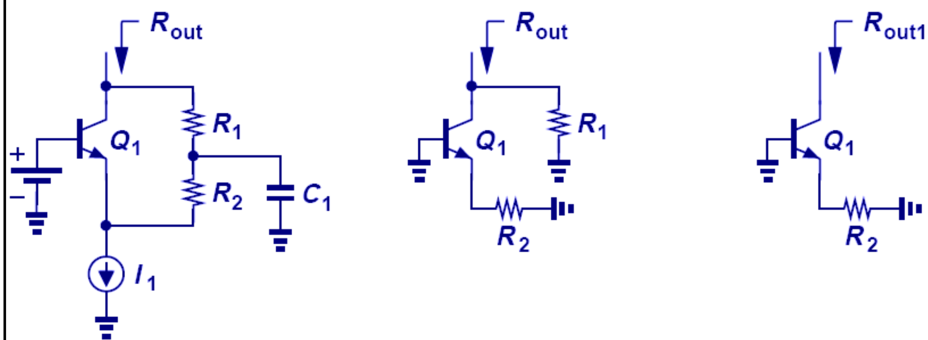
- **Emitter degeneration boosts the output impedance by a factor of $1+g_m(R_E||r_\pi)$.**
- **This improves the gain of the amplifier and makes the circuit a better current source.**

Two Special Cases



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

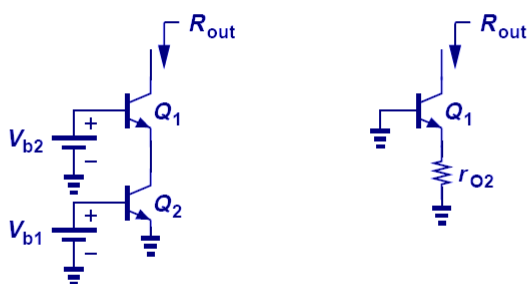
Analysis by Inspection



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

- 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



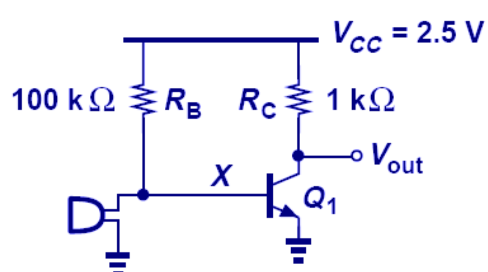
$$R_{out} = [1 + g_{m1}(r_{O2} \parallel r_{\pi1})]r_{O1}$$

- Called a "cascode", the circuit offers many advantages that are described later in the book.

Study of Common-Emitter Topology

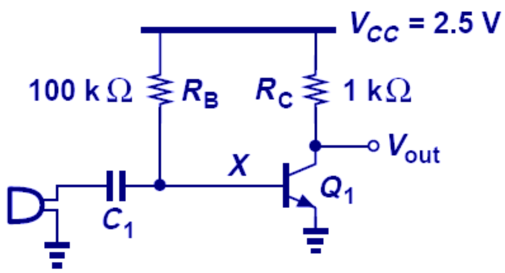
- Analysis of CE Core
  - Inclusion of Early Effect
- Emitter Degeneration
  - Inclusion of Early Effect
- *CE Stage with Biasing*

Bad Input Connection



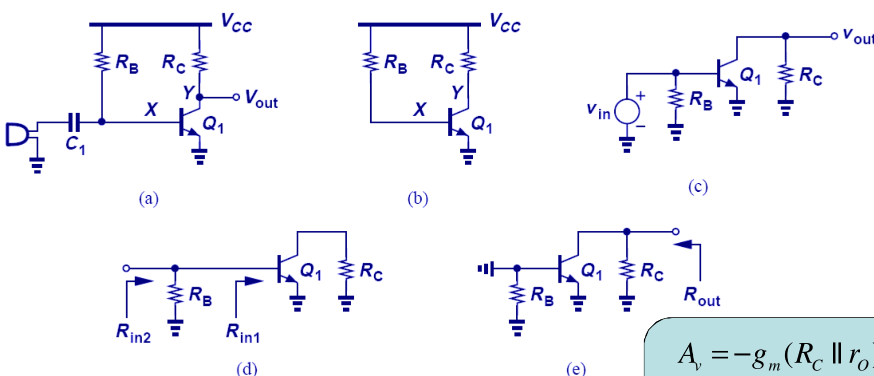
- Since the microphone has a very low resistance that connects from the base of Q_1 to ground, it attenuates the base voltage and renders Q_1 without a bias current.

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



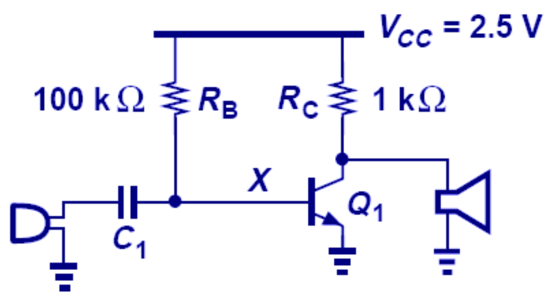
$$A_v = -g_m(R_C \parallel r_O)$$

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

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

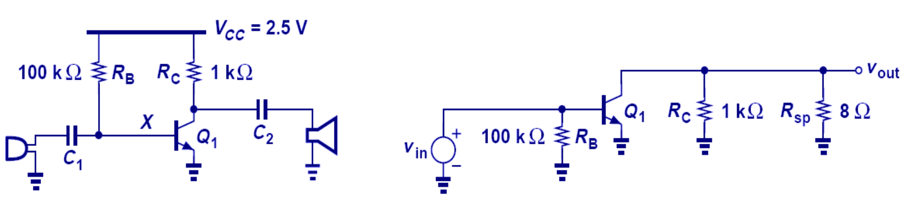
- Coupling capacitor is open for DC calculations and shorted for AC calculations.

Bad Output Connection



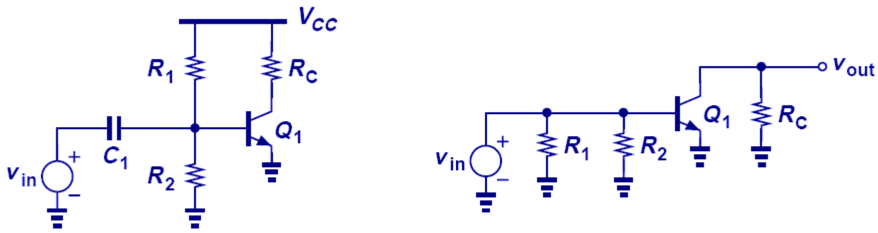
- Since the speaker has an inductor, connecting it directly to the amplifier would short the collector at DC and therefore push the transistor into deep saturation.

Still No Gain!!!



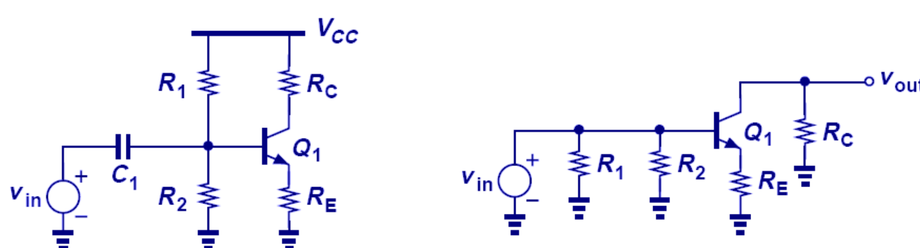
- In this example, the AC coupling indeed allows correct biasing. However, due to the speaker's small input impedance, the overall gain drops considerably.

CE Stage with Biasing



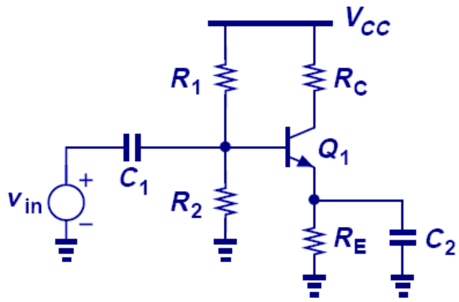
$$A_v = -g_m (R_C \parallel r_O)$$
$$R_{in} = r_\pi \parallel R_1 \parallel R_2$$
$$R_{out} = R_C \parallel r_O$$

CE Stage with Robust Biasing



$$A_v = \frac{-R_C}{\frac{1}{g_m} + R_E}$$
$$R_{in} = [r_\pi + (\beta+1)R_E] \parallel R_1 \parallel R_2$$
$$R_{out} = R_C$$

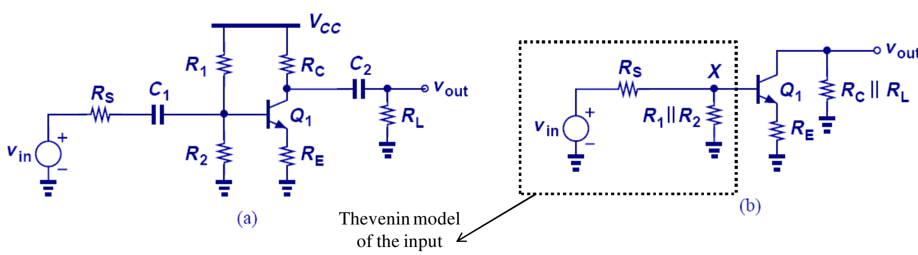
Removal of Degeneration for Signals at AC

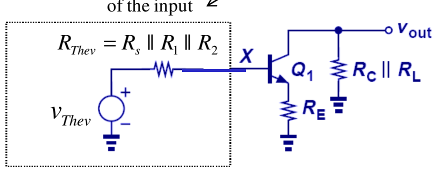


$$A_v = -g_m R_C$$
$$R_{in} = r_\pi \parallel R_1 \parallel R_2$$
$$R_{out} = R_C$$

- **Capacitor shorts out R_E at higher frequencies and removes degeneration.**

Complete CE Stage

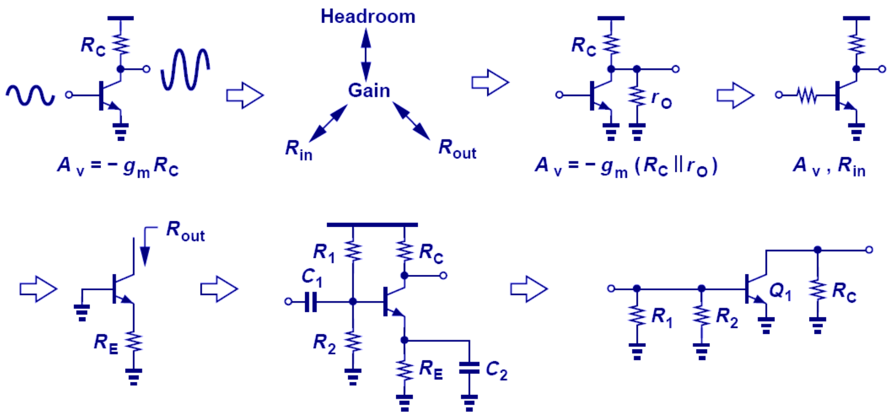




(b)

$$A_v = \underbrace{\frac{-R_C \parallel R_L}{\frac{1}{g_m} + R_E + \frac{R_s \parallel R_1 \parallel R_2}{\beta + 1}}}_{v_{out}/v_{Thev}} \underbrace{\frac{R_1 \parallel R_2}{R_1 \parallel R_2 + R_s}}_{v_{Thev}/v_{in}}$$

Summary of CE Concepts



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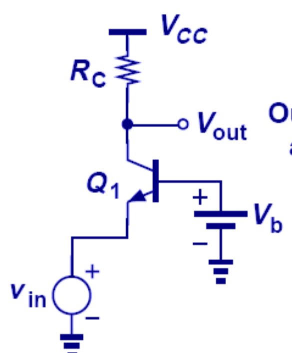
Common Base (CB) Amplifier



- 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.

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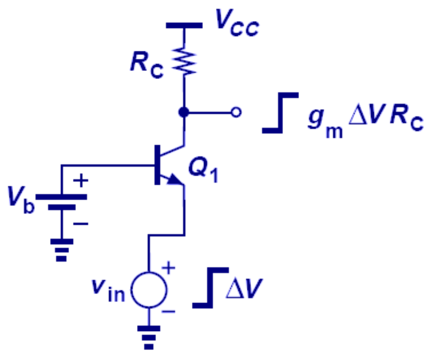
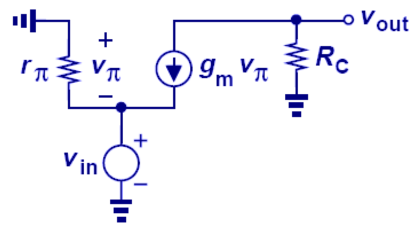
CB Core

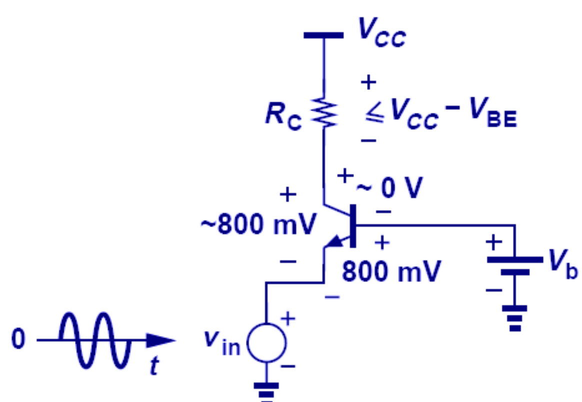




$$A_v = g_m R_C$$

- 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

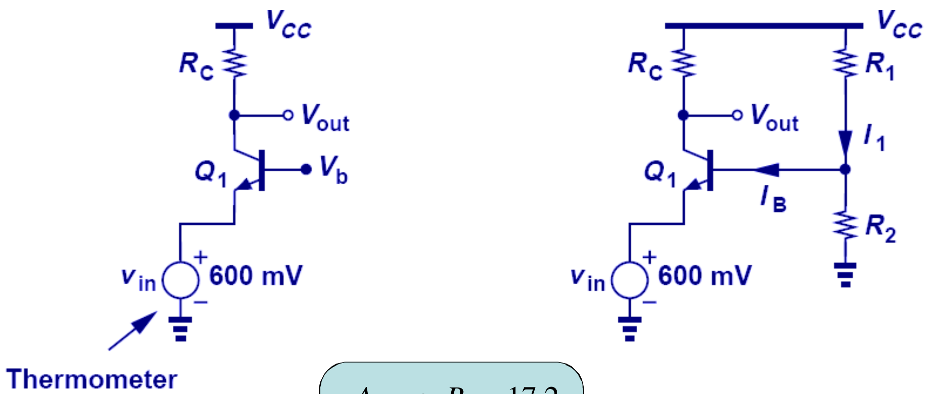


$$A_v = \frac{I_C}{V_T}.R_C$$

$$= \frac{V_{CC} - V_{BE}}{V_T}$$

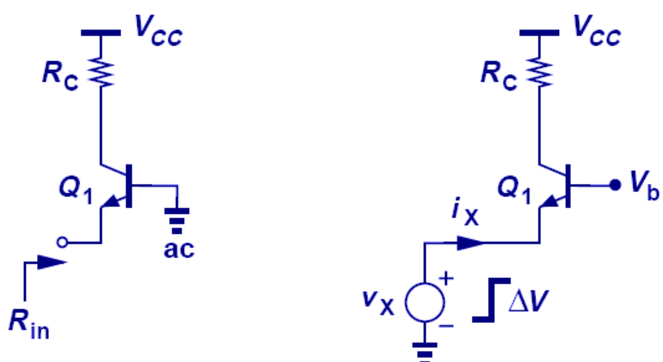
- To maintain the transistor out of saturation, the maximum voltage drop across R_C cannot exceed V_{CC}-V_{BE}.

Simple CB Example



$$A_v = g_m R_C = 17.2$$
$$R_1 = 22.3K\Omega$$
$$R_2 = 67.7K\Omega$$

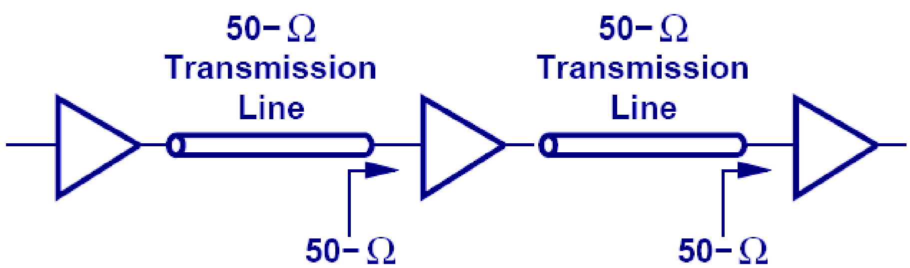
Input Impedance of CB



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

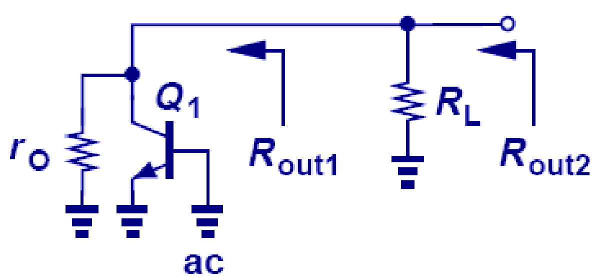
- The input impedance of CB stage is much smaller than that of the CE stage.

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 Ω.

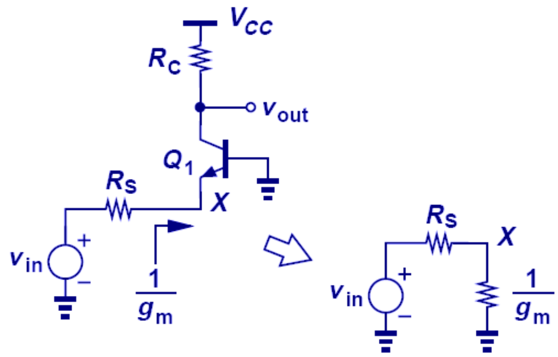
Output Impedance of CB Stage



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

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

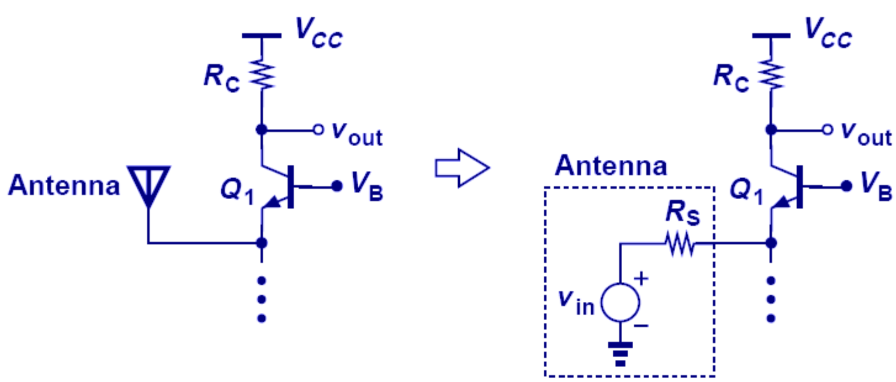
CB Stage with Source Resistance



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

- 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.