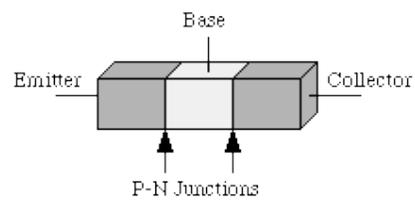# Transistors

Bipolar Junction Transistors (BJT)
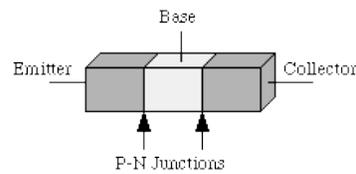
Transistor Basics

- A Bipolar Junction Transistor is a three layer (npn or pnp) semiconductor device.
- There are two pn junctions in the transistor.
- The three layers are called the emitter, base and collector.

Transistor Basics

- The base is lightly doped and sandwiched between the collector and the emitter. The collector is moderately doped and the emitter is heavily doped.
- The base region is much thinner than the either the collector or emitter regions. Typical base widths are about 10^{-6} m.
- The collector region is usually thicker than the emitter as the largest amount of heat is dissipated in the collector.
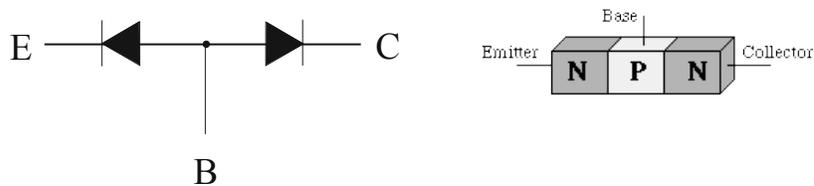

Transistor Basics
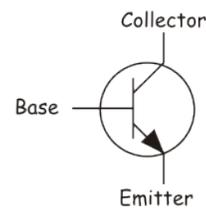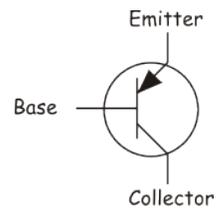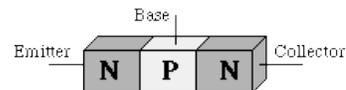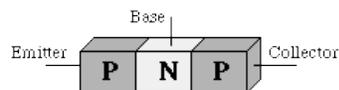
"Two-diode" Model

- A simple model of the transistor can be made out of two diodes placed back to back. (This doesn't really work but it is useful.)

Biasing the Transistor

- The transistor operates in three modes depending on how the pn junctions in the device are biased.
  - *Cutoff* - both junctions reverse biased.
  - *Saturation* - both junctions forward biased.
  - *Active* - base-emitter junction is forward biased and collector-base is reversed biased.
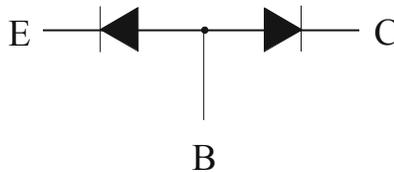
A Note About Labeling Voltages

- Voltages with capital letter subscripts are DC voltages, (V_{BE}, V_{CC}).
- When a voltage has a single subscript it is measured from the terminal to ground, (V_E, V_C).
- When a voltage has a double subscript with different letters it is the voltage measured between two terminals, (V_{BE}, V_{EC}).
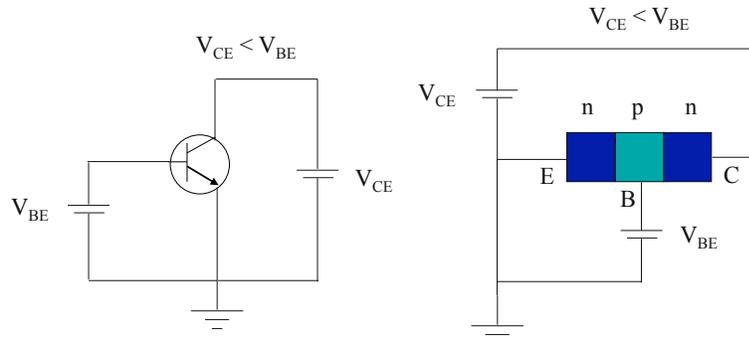- When a voltage has a double subscript with the same letters it is a supply voltage, (V_{EE}, V_{CC}).

Cutoff

- Both junctions are reverse biased.
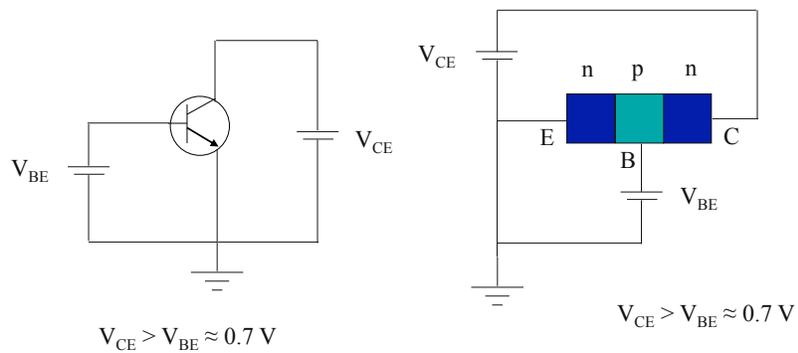- No current flows.
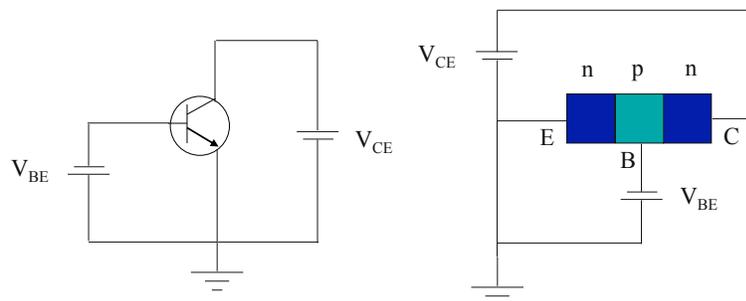
Saturation

- Both junctions are forward biased.
- Maximum current flows.

$$V_{CE} < V_{BE}$$

$$V_{CE} < V_{BE}$$

V_{CE} n   p   n

E   C

B

V_{BE}

V_{BE} V_{CE}

Active Region

- The BE junction is forward biased and the BC junction is reverse biased.
- The base-emitter voltage is approximately 0.5 - 0.7 volts (the turn-on voltage of the junction.

V_{CE} n   p   n

E   C

B

V_{BE}

V_{BE} V_{CE}

$$V_{CE} > V_{BE} \approx 0.7 \text{ V}$$

$$V_{CE} > V_{BE} \approx 0.7 \text{ V}$$

Active Region

- To make the biasing more obvious we can ground the base and use power supplies to bias the emitter and collector. Notice that the BE junction is forward biased and the BC junction is reverse biased.
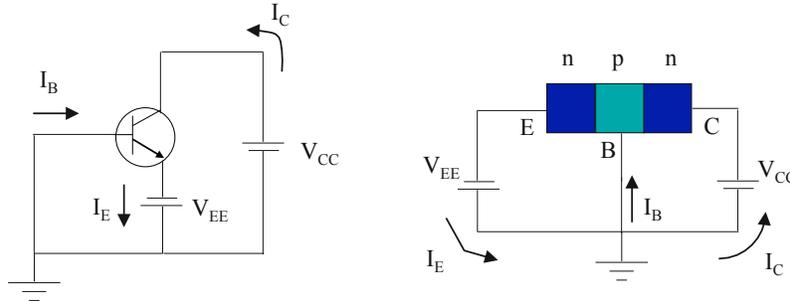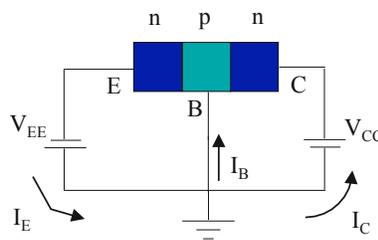

Active Operation

- With the BE junction forward biased electrons diffuse across the junction into the base.
- The base is very thin and lightly doped so there are relatively few holes in it compared with the electrons from the heavily doped emitter region.
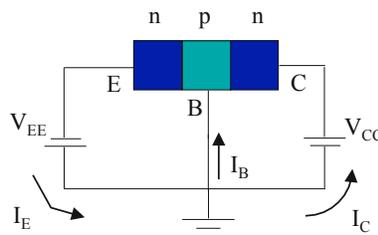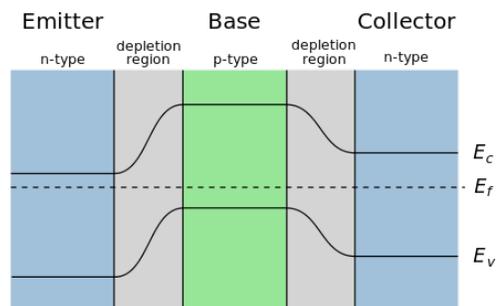
Active Operation

- As there are few holes in the base for the electrons to combine with most of the electrons diffuse in to the reverse biased collector-base junction where the electric field in the depletion region sweeps them across into the collector.
- Remember electrons are the "minority carriers" in the p material so they are swept across the depletion region.
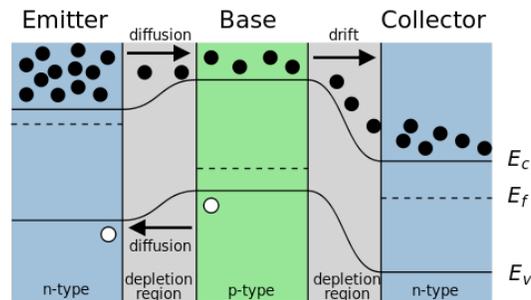

Active Operation

Unbiased:

- A simplified electron energy diagram for the npn transistor.

Active Operation

Biased:

Emitter   Base   Collector

- A simplified electron energy diagram for the npn transistor.

Active Operation

- A small percentage of the electrons injected in to the base from the emitter do recombine with the holes in the base.
- If left alone the base would slowly become more negative until the flow of electrons across the base stopped. Electrons leave the base via the wire contact maintaining the small amount of holes in the base.
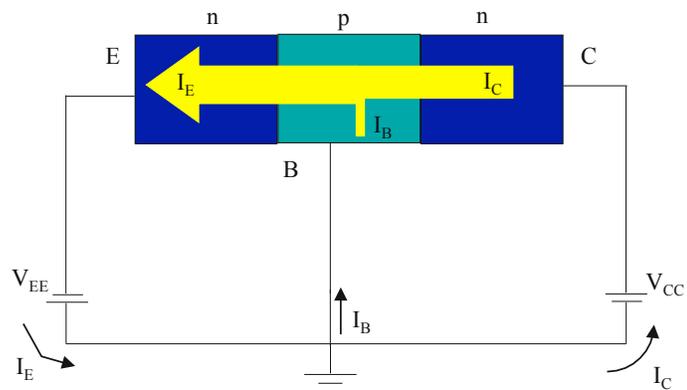- This flow of electrons is the small base current.
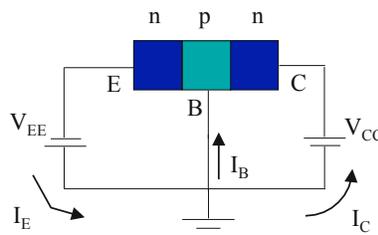
Active Operation

Electron flow through the transistor
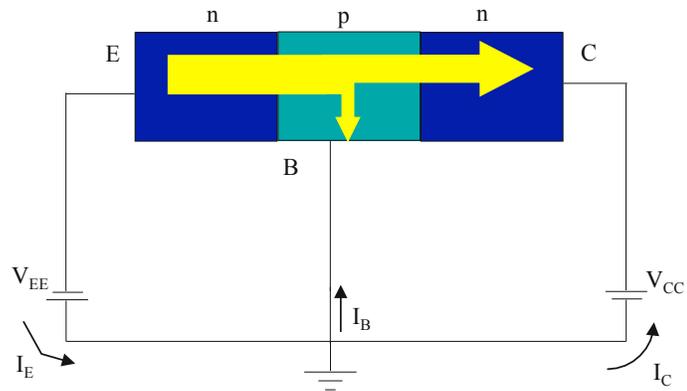
Active Operation

Conventional Current

Active Operation

- Kirchoff's rule gives us

$$I_E = I_C + I_B$$

- The dc alpha is the ratio of collector to emitter current.

$$\alpha = \frac{I_C}{I_E}$$

- Typical transistors have values of α that range from 0.95 to 0.995.

Active Operation

- The ratio of the dc collector current to the dc base current is the dc beta rating of the transistor. (Also called h_{FE}.)
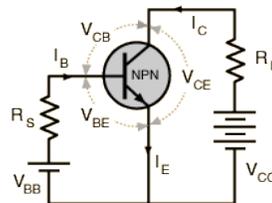
$$\beta = \frac{I_C}{I_B}$$

- The dc beta can be related to the dc alpha.
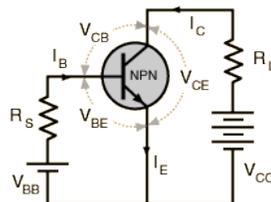
$$\alpha = \frac{\beta}{\beta + 1}$$

Transistor Curves

- To understand why the transistor in the active region can be used as an amplifier we can look at *collector characteristic curves*.
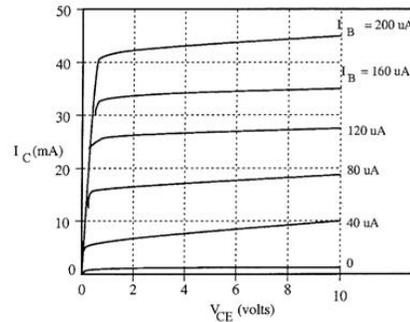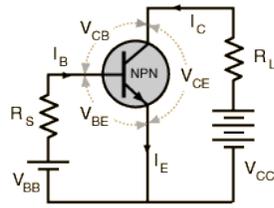- A version of the common-emitter circuit:

Transistor Curves

- The voltage difference between the collector and emitter V_{CE} can be adjusted by varying V_{CC}.
- Likewise varying V_{BB} adjusts the value of I_B.
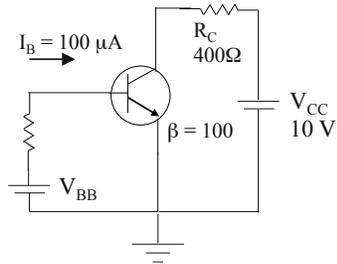
Transistor Curves

How a Transistor Amplifies

- The base current I_B controls the value of the collector current I_C, (and emitter current I_E).
- The transistor acts like a valve controlling the flow of current through the transistor from collector to emitter.
- The "handle" of the valve is controlled by I_B with more base current being analogous to a more open valve.
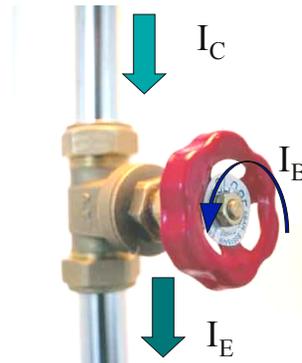
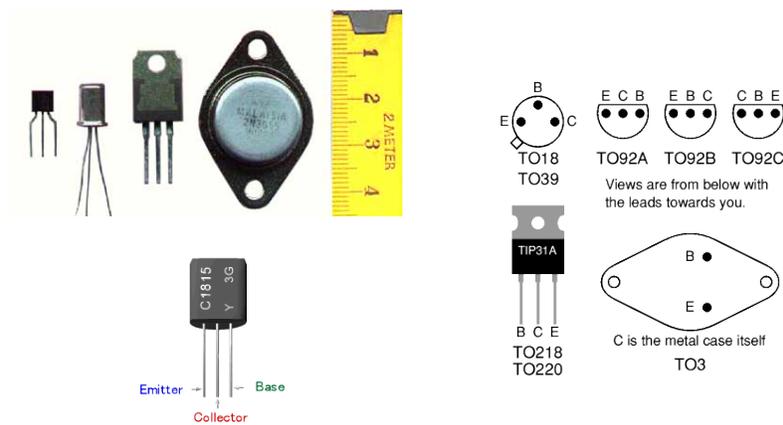# Example

$$I_C = \beta I_B = (100)(100\,\text{mA}) = 10\,\text{mA}$$

$$V_{CE} = V_{CC} - I_C R_C = 10\,\text{V} - (10\,\text{mA})(400\,\Omega) = 6\,\text{V}$$

$$V_{CB} = V_{CE} - V_{BE} = 6.0\,\text{V} - 0.7\,\text{V} = 5.3\,\text{V}$$
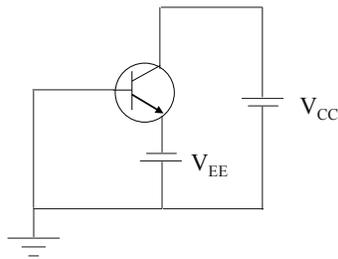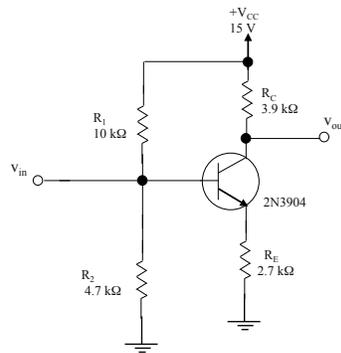
Cases

Transistor Amplifiers

Biasing

Biasing for the Active Region

- In order for a transistor amplifier to work the transistor must be in the active region.
- One option is to bias the transistor by a using a number of power supplies.

Voltage-Divider Biasing

- The most common method of biasing a transistor is to use a single supply and a voltage divider circuit.
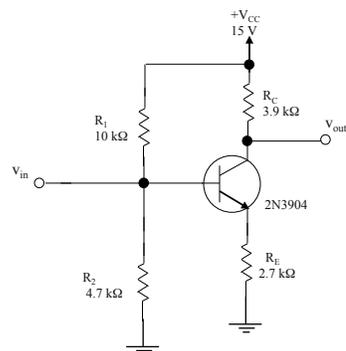

Voltage-Divider Biasing

- The resistors R_1 and R_2 form a simple voltage divider.

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

- The DC emitter voltage can be found from V_B.

$$V_E = V_B - V_{BE} = V_B - 0.7\,\text{V}$$
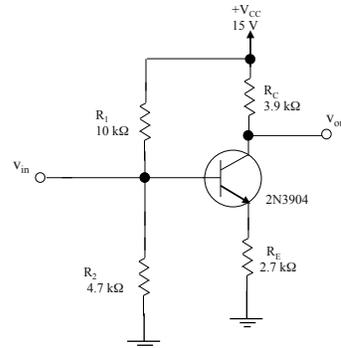

15

Voltage-Divider Biasing

- Likewise the emitter current can be found from

$$I_E = \frac{V_E}{R_E}$$

- The collector current and DC collector voltage are

$$I_C \cong I_E$$

$$V_C = V_{CC} - I_C R_C$$

Q-Point

- We still need to determine the optimal values for the DC biasing in order to choose resistors, etc.
- This bias point is called the quiescent or Q-point as it gives the values of the voltages when no input signal is applied.
- To determine the Q-point we need to look at the range of values for which the transistor is in the active region.
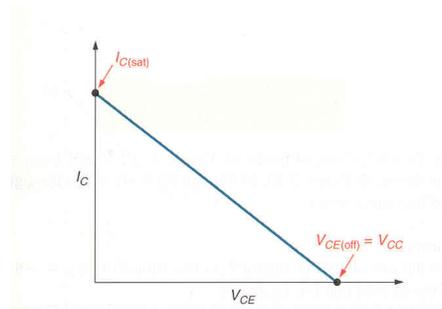
Load Line

- At saturation the resistance offered by the transistor is effectively zero so the current is a maximum determined by V_{CC} and the resistors R_E and R_C.
- When the transistor is in cutoff no current flows so $V_{CE} = V_{CC}$.
- If we connect these two points with a straight line we get all possible values for I_C and V_{CE} for a given amplifier.
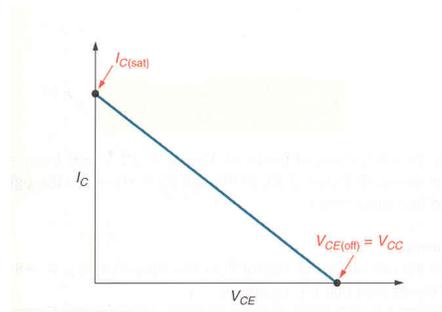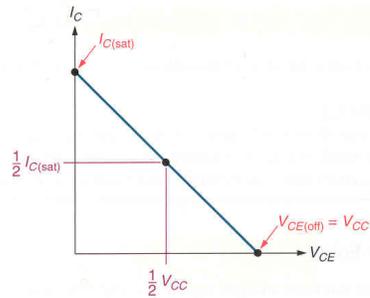

Q-point

- To determine the q-point we overlay the load line on the collector curves for the transistor.
- The Q-point is where the load line intersects the appropriate collector curve.
- For example if the amplifier is operated at $I_B = 20$ μA the Q-point is as shown on the graph.
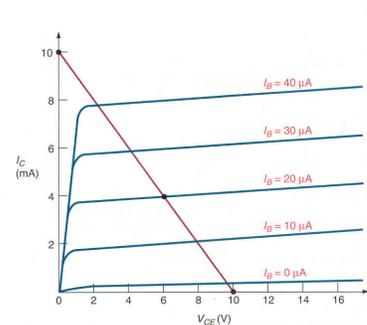
Midpoint biased

- When the Q-point is chosen so that V_{CE} is half of V_{CC} and I_C is half of $I_{C(sat)}$ the amplifier is said to be midpoint biased.

Optimum Biasing

- Midpoint biasing allows optimum ac operation of the amplifier. When an ac signal is applied to the base of the transistor, I_C and V_{CE} both vary about the Q-point. With the Q-point center the values can make the maximum deviations from the Q-point either above or below.
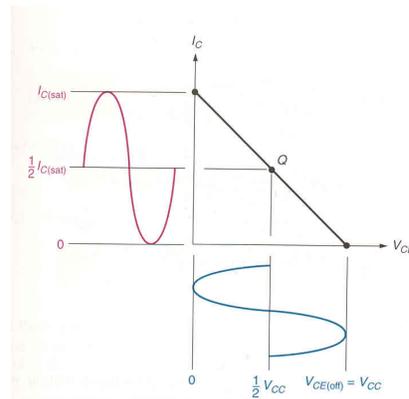
Transistor Amplifiers

Gain and Impedance

Gains

- AC Gain is the ratio between the ac output and ac input signal.
- Voltage:
$$A_v = \frac{v_{out}}{v_{in}}$$

- Current:
$$A_i = \frac{i_{out}}{i_{in}}$$

- Power:
$$A_p = \frac{P_{out}}{P_{in}}$$

Decibels

- Gains are sometimes expressed in terms of decibels.
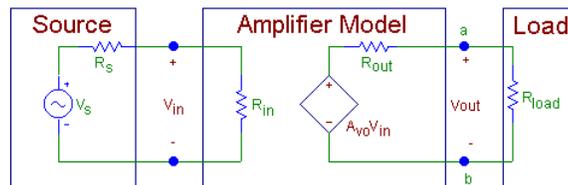- dB Power Gain:

$$A_{p(dB)} = 10 \log A_p$$

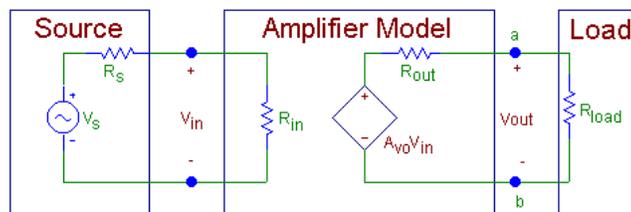- dB Voltage Gain

$$A_{v(dB)} = 20 \log A_v$$

Basic Amplifier Model

- The basic amplifier is characterized by its gains, input impedance and output impedance.
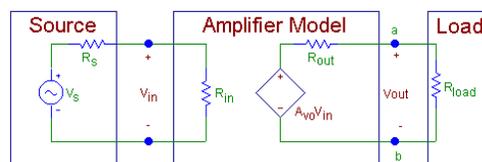
The Ideal Amplifier

- The ideal amplifier has infinite input impedance ($R_{in} = \infty$), zero output impedance ($R_{out} = 0$) and infinite gain (if desired).

Amplifier Input Impedance (Z_{in})

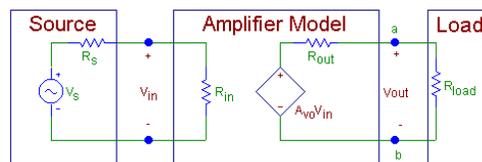- If we assume that the input impedance of our amplifier is purely resistive then the signal voltage at input (v_{in}) is

$$v_{in} = v_s \frac{Z_{in}}{R_s + Z_{in}}$$
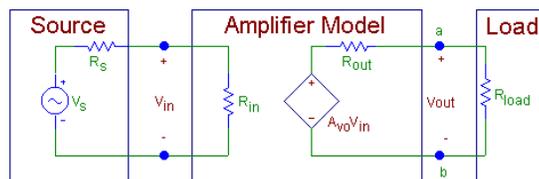
Output Impedance (Z_{out})

- If we assume that the output impedance of our amplifier is purely resistive then the signal voltage at output (v_{out}) is

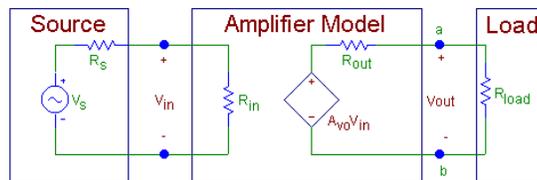$$v_{out} = A_{vo} v_{in} \frac{R_L}{Z_{out} + R_L}$$

Effects of Input and Output Impedance

- $v_s = 15$ mV, $R_s = 20\Omega$, $R_L = 1.2$kΩ
- $A_{vo} = 340$, $Z_{in} = 980\Omega$, $Z_{out} = 250\Omega$
- $v_{out} = 4.14$ V, $A_{v(eff)} = 276$

Effects of Input and Output Impedance

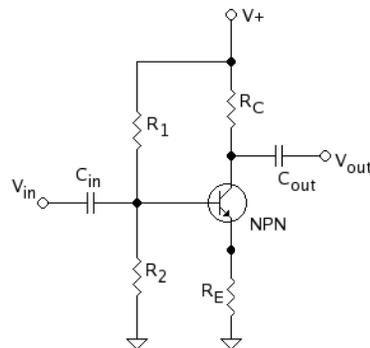- $v_s = 15$ mV, $R_s = 20\Omega$, $R_L = 1.2$kΩ
- $A_{vo} = 340$, $Z_{in} = 8$kΩ, $Z_{out} = 20\Omega$
- $v_{out} = 5.0$ V, $A_{v(eff)} = 333$
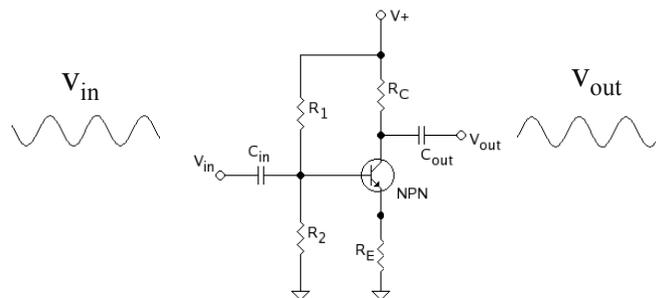

Transistor Amplifiers

The Common Emitter Amplifier

Basic Design

Phase relationships

- The output voltage is 180 degrees out of phase with the input voltage.
- The output current is in phase with the input current

AC Emitter Resistance

- The base-emitter junction has an *ac emitter resistance* that can be approximated by

$$r_e' \cong \frac{25\,\mathrm{mV}}{I_E}$$

- where

$$I_E = \frac{V_E}{R_E}$$

- This is a dynamic resistance that only appears in ac calculations.

AC beta

- The ac current gain for a transistor is different than the dc current gain.
- The ac current gain is defined as

$$\beta_{ac} = h_{fe} = \frac{i_c}{i_b}$$

- Note that this is the gain of the transistor not the amplifier.
- h_{fe} values are usually listed on the specification sheets for the transistor.

Coupling Capacitor

- In many applications amplifiers are connected in series with other amplifiers (cascaded) or with other complex circuits.
- Coupling capacitors are used to pass the ac signal from one stage to the next while blocking the dc signal.
- Coupling capacitors act as if they have infinite impedance for dc signals but very low impedance for ac signals.
- The dc equivalent of a circuit can be determined by replacing the capacitors by breaks in the circuits (open circuit).
- The ac equivalent of a circuit can be determined by replacing capacitors by shorts in the circuit.
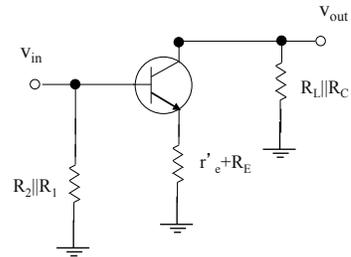
AC Equivalent
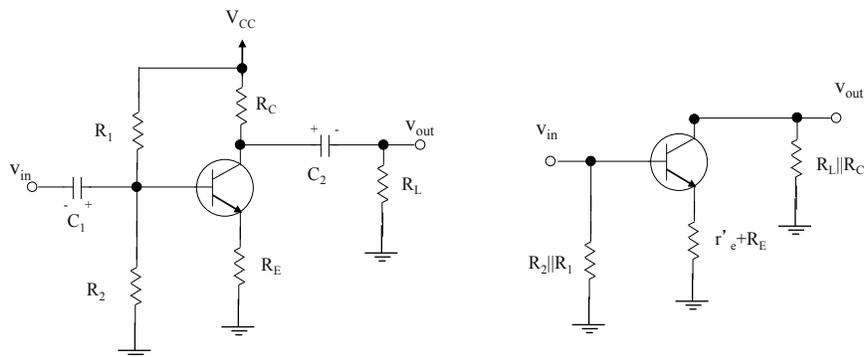
Gain for the CE Amp

- The voltage gain for the CE amp can be derived using the ac equivalent circuit.

$$v_{in} = i_e\left(r_e' + R_E\right)$$

$$v_{out} = i_c\left(R_C\|R_L\right)$$

$$A_v = \frac{v_{out}}{v_{in}} = \frac{i_c\left(R_C\|R_L\right)}{i_e\left(r_e' + R_E\right)} \cong \frac{\left(R_C\|R_L\right)}{\left(r_e' + R_E\right)}$$

Input impedance

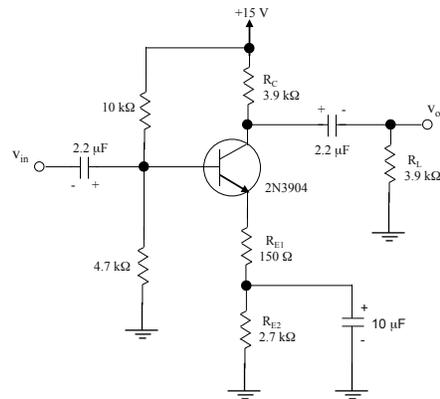- The input impedance of a CE amplifier with voltage-divider biasing is given by

$$Z_{in} = R_1\|R_2\|Z_{in(base)}$$

- The ac input impedance of the transistor base is
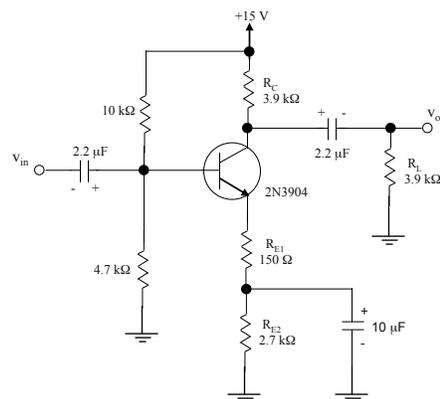
$$Z_{in(base)} = h_{fe}r_e'$$

Swamping

- A bypass capacitor can be used to reduce the ac resistance of the R_E but maintain the gain-stabilization properties of an external emitter resistor.
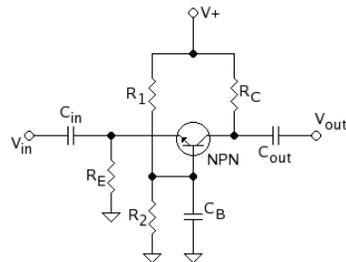

All Together Now

- Assume ac current gain is 150 for the transistor.
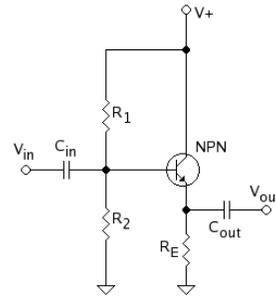- Find A_v, and Z_{in}.

Other Basic Amplifier Designs

Common-Base

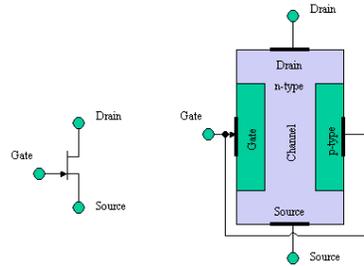Common-Collector
(Emitter-Follower)

Transistors

Field Effect Transistors (FETs)

Junction Field Effect Transistors

- Width of conducting channel is controlled by gate voltage.
- Source → emitter
- Drain → collector
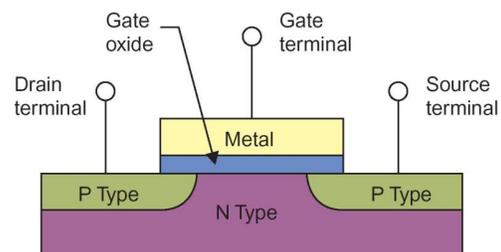- Gate → Base

JFETs vs. BJTs

- JFETs have an extremely high input impedance for a given gain as compared to BJTs.
- Smaller size
- Higher frequency response
- Voltage controlled rather than current controlled

MOSFET

- Metal Oxide Semiconductor FET
- Very low current devices
- Most VLSI circuits use MOSFETs.
- Two types:
  - Enhancement
  - Depletion

MOSFET

- Enhancement

MOSFET

- Depletion