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***Dr. Charles Kim***

# Common-Emitter Amplifier

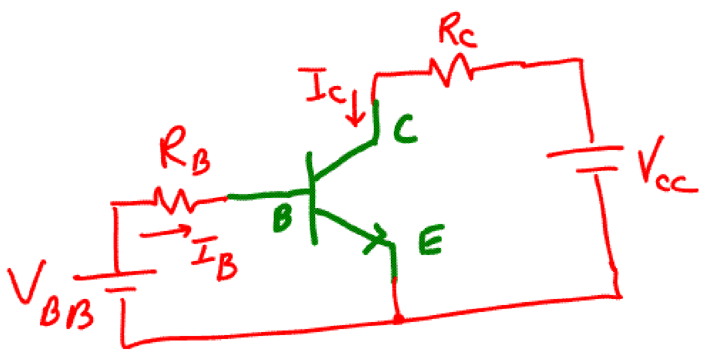
## A. Before We Start

As the title of this lab says, this lab is about designing a Common-Emitter Amplifier, and this in this stage of the lab course is premature, in my opinion, of course. How can one design a BJT amplifier only after one simple characteristic experiment? Maybe students are all brilliant or this subject is already covered in a class, extensively. Even with that assumption, experiment with a BJT amplifier should come before asking for designing such circuit. Even before that, a much simpler circuit investigation would be more beneficial to understand the Common-Emitter Amplifier.

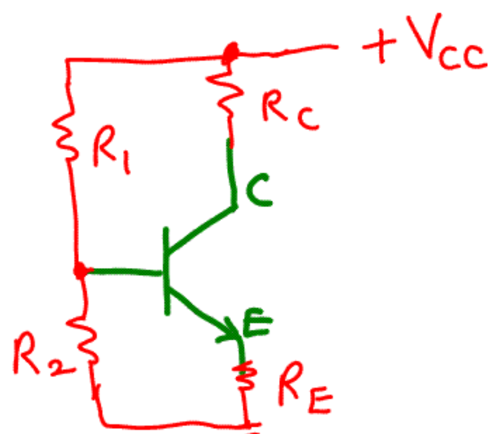
## B. Common-Emitter Amplifier Experiment

### *B.1 Theory*

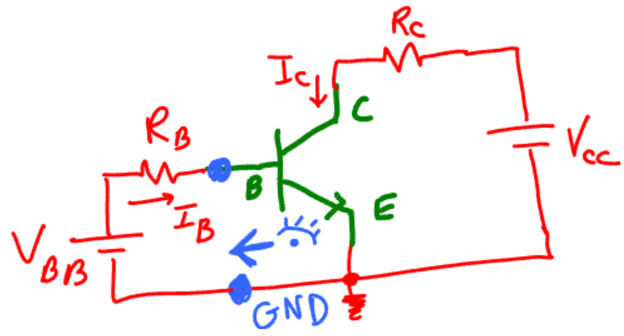
Let's start our discussion on Common Emitter Amplifier (CE Amp), rather from the first BJT Lab, in which we discussed about Base voltage and Collector voltage in the operating region. To revive your memory, here I bring the CE circuit configuration. This DC voltage application into BJT is usually called "DC Biasing"



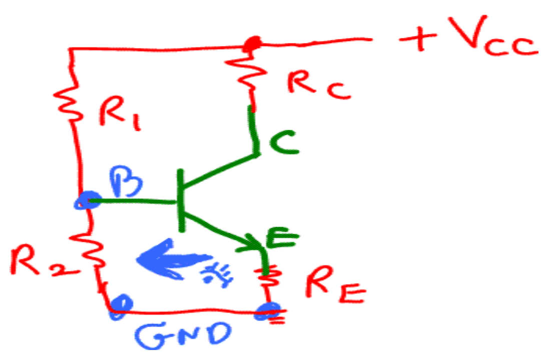

In CE circuit, however, more popular biasing method is to supply single DC voltage (instead of two: $V_{BB}$ and $V_{CC}$), also with a resistor at the Emitter. From this circuit, let's calculate the voltage corresponding to $V_{BB}$ and the resistance corresponding to $R_B$. From the upper circuit. Between B and GND, the voltage is $V_{BB}$ and equivalent resistance is $R_B$.



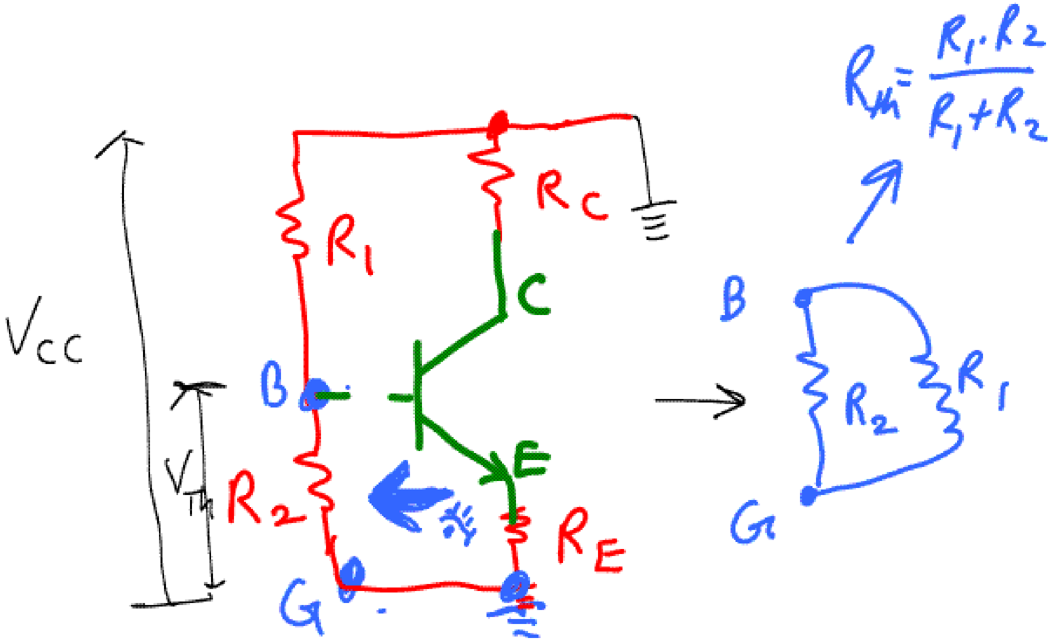
Similarly, on the single voltage biased circuit, we also try to find the equivalent voltage and resistance seen at the terminals B and GND.




Here we apply Thevenin theorem. The thevenin voltage can be acquired by finding the terminal voltage (at B and GND) after opening the terminal. Opening the terminals means we cut the wire between the Base and the junction of R1 and R2.

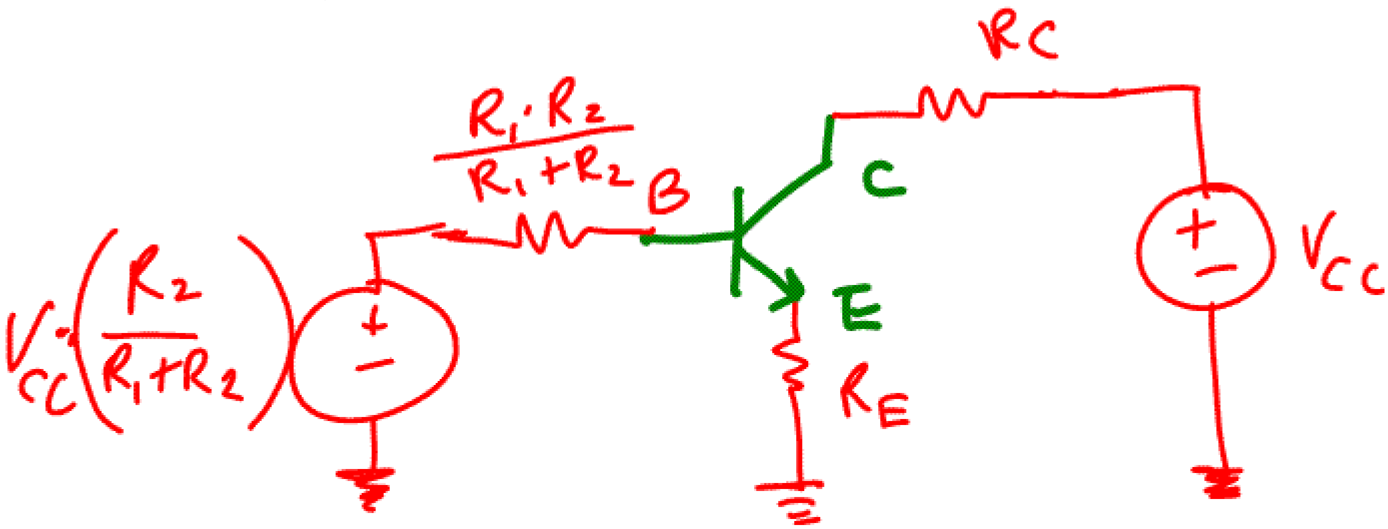



When you open the circuit (See below), the terminal voltage is nothing but the voltage across R2, and R1 and R2 are in series with voltage $V_{CC}$ across the series resistors. So we can apply "voltage divider" to find the terminal voltage: $V_{th} = V_{CC} \cdot \frac{R_2}{R_1 + R_2}$




How about Thevenin resistor? Since we have only independent voltage source VCC, we apply the "Input resistance method" which gets the equivalent circuit at the terminals after deactivating the voltage source. Deactivation of a voltage source means shorting the voltage source, we have the two parallel resistors R1 and R2 at the terminals of B and GND. Therefore, Thevenin resistance is $R_{th} = \dfrac{R_1 \cdot R_2}{R_1 + R_2}$

Finally we have the following circuit which exactly corresponds to the initial biasing circuit we studied in the BJT 1 Lab.



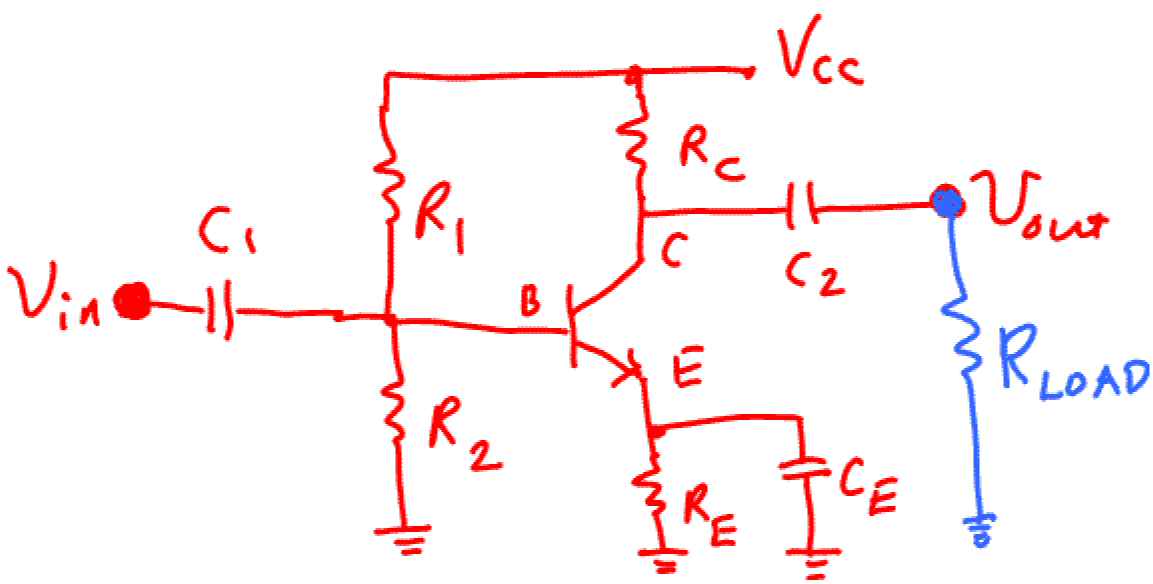

OK. Now it's time to consider a CE Amp circuit. By the way, when we say amplifier, we usually mean by amplifying AC signal. This means that the biased voltages are DC values and they are not to be disturbed. At the same time, AC wants to be riding over the DC and gets some boost. Also, the DC bias voltage should not interrupt the input AC signals and the amplified output AC signal. In other words, we can picture this way. A castle surrounded by circling high wall, with entrance and exit gates, is governed by a DC system. Whatever entered through the entrance gate is exiting the exit gate with amplification. What a great castle it must be! However, the DC system inside the castle cannot be leaked through the gates. It's a tightly controlled system. Therefore the gates' other function is to block any leakage from the castle to outside world. The castle here is the base voltage divider biased circuit. And the gates are realized by coupling capacitors. The size of the capacitor corresponds to the size of the gate. Smaller gates pass only smaller object, while larger gate passes through larger object.

Actually there is one more device inside the castle to nullify any effect of those foreign objects entering the castle, while keeping the DC system stable and intact. This in circuit formation is a bypass capacitor at the Emitter.

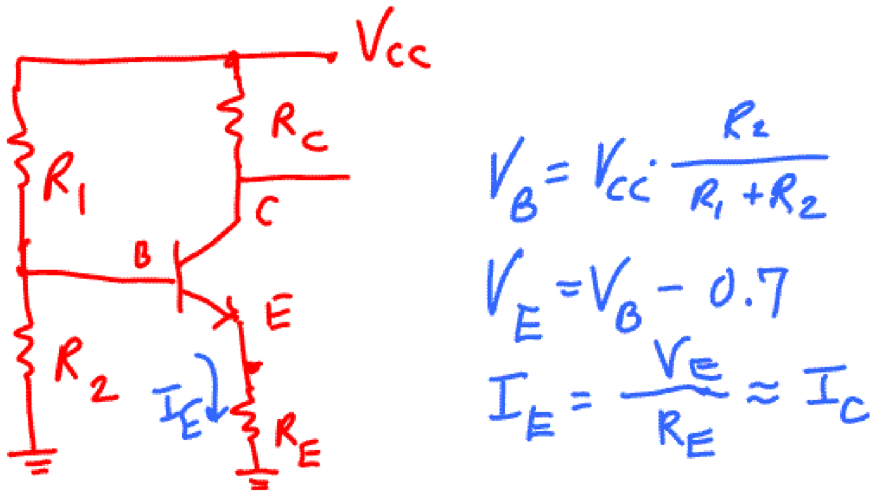
The circuit below is one of the popular AC Amp circuits. $C_1$ and $C_2$ are coupling capacitors, and $C_E$ is the bypass capacitor. As you can see, all other elements are exactly the same as the circuit we first discussed. The size, and its impact on frequency response of the whole circuit, of $C_1$, $C_2$, and $C_E$ will be discussed shortly.

**DC Analysis**

DC analysis of the circuit is very important in that (i) it makes sure DC biasing is all right and (ii) it finds $I_E$ which (indirectly) is used for voltage gain of the circuit.




In DC analysis, we assume that there are only DC sources. In the circuit above, when we assume that $V_{in}$ is a DC source, that DC source cannot cross coupling capacitor $C_1$. Why? Capacitor stores DC energy. In other words capacitor works as a open circuit for DC source. That means the DC-only circuit would look like this:



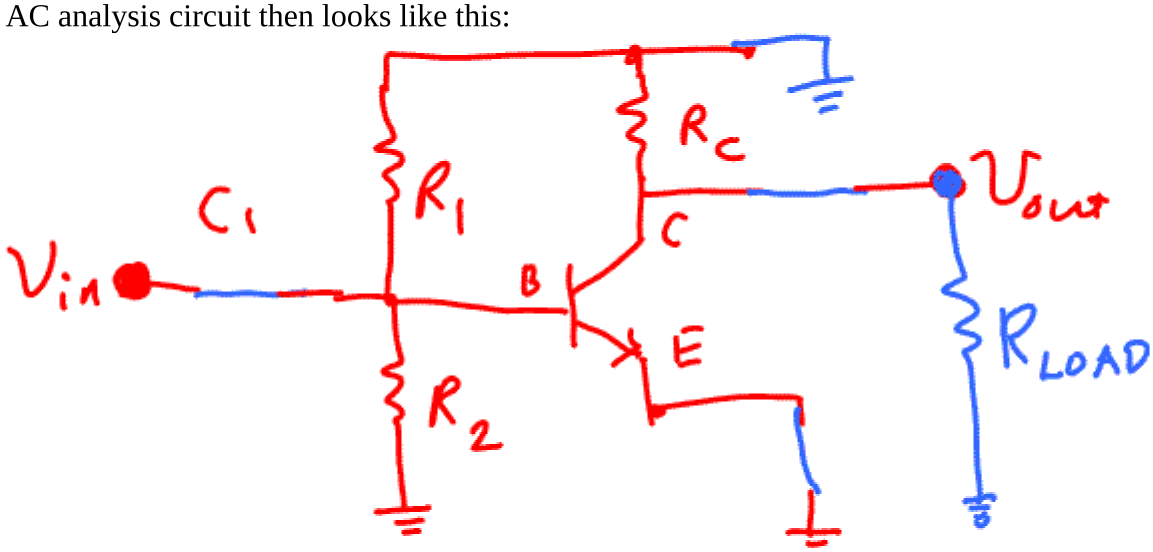

By the voltage divider rule, the Base voltage is $V_B = V_{CC} \cdot \dfrac{R_2}{R_1 + R_2}$

Then the voltage at the Emitter is 0.7 V lower than VB (typical silicon diode voltage drop), then the Emitter current $I_E$ is determined by $I_E = \dfrac{V_E}{R_E}$ . If we assume that Base current is negligible, then $I_C = I_E = \dfrac{V_E}{R_E}$

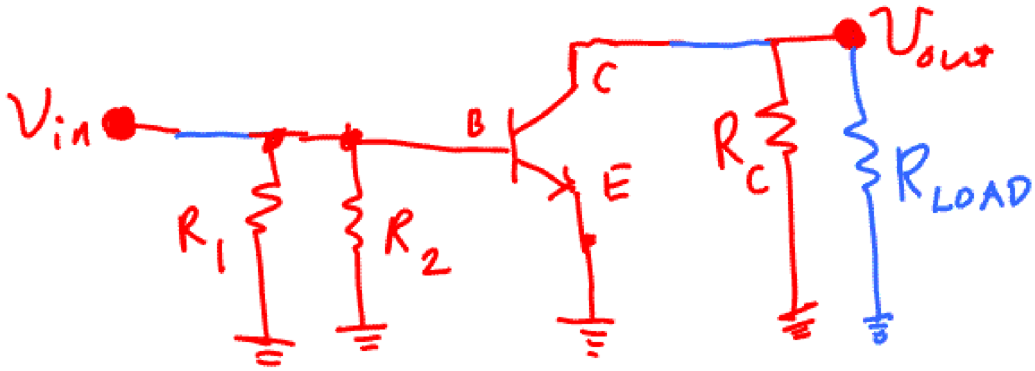
This $I_C$ is very important element in determining the AC voltage gain. Remember this. In AC voltage gain (amplification), the value of IC is an important factor to be included. This we will discuss in the AC Analysis of the circuit.

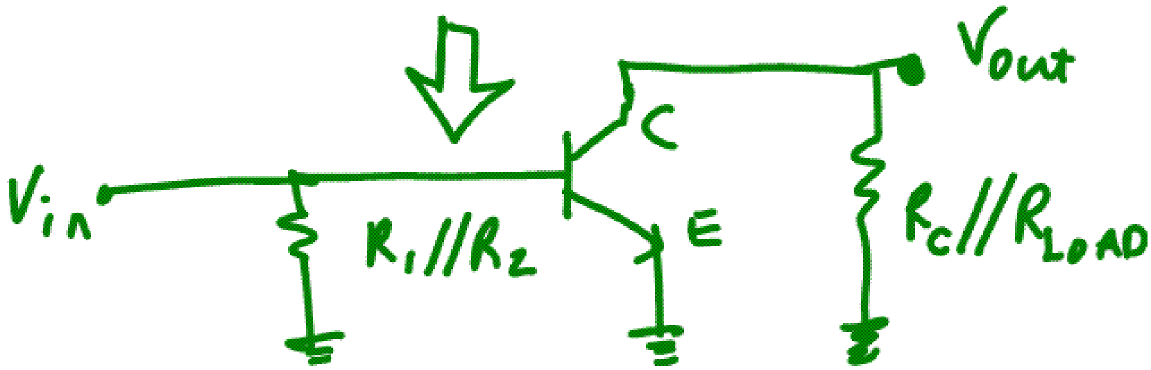
**AC Analysis**

In AC analysis, we assume there is no DC sources. All DC sources are deactivated. That means the DC source $V_{CC}$ will be grounded. Moreover, the capacitors are shorted. Why? The impedance of capacitor is reverse proportional to the capacitance and the frequency of AC signal. If we assume that the AC signal we provide is high frequency signal, then, we can safely say the impedance of capacitor is almost zero. And zero impedance means short circuit. The AC analysis circuit then looks like this:

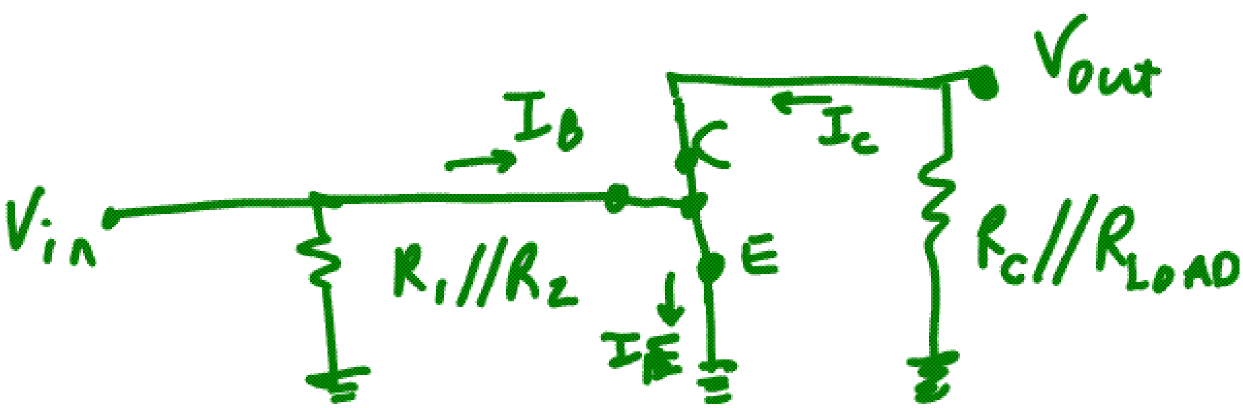



Since all three CE Amp resistors (R1, R2, and RC) are all connected to the GND, we can redraw the circuit as follows:



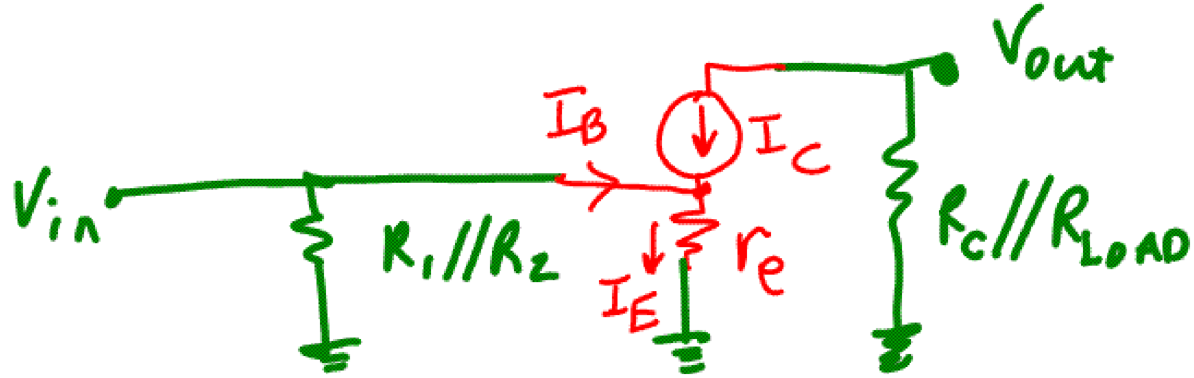




As we know the voltage gain is the ratio output voltage $V_{out}$ and the input voltage $V_{in}$. How do we get the ratio? If we blindly apply that the Emitter current is close to Collector current, at the same time Base current is zero, then, we would end up at the following "equivalent" circuit:




As you see the above approach has problem: the input voltage is tied to the ground. If you disconnect input circuit from Base (since Base current is zero), then there is no way to connect input and output.

Rescue: Have you heard about Ebers-Moll model of BJT? In the model, the small-signal impedance looking into the Emitter is found by the equation: $r_e = \frac{V_T}{I_c[mA]}$, where $V_T$=25.3[mV] at room temperature. (Here we learn that BJT performance is dependent upon temperature.) Now we can apply this Emitter resistance re (with simpler form of $25/I_C$[mA]) into the circuit. Then our final good equivalent circuit looks like:




$$V_{out} = -I_C \cdot [R_C // R_{LOAD}]$$

$$V_{in} = r_e I_E \doteq r_e I_C$$

$$A_v = \frac{V_{out}}{V_{in}} = \frac{-I_C [R_C // R_{LOAD}]}{r_e I_C} = -\frac{R_C // R_{LOAD}}{r_e}$$

Whew! After a long road to the final circuit, we have the following conclusion:

(1) The popular CE Amp circuit's voltage gain is dependent upon
- (a) $R_C$
- (b) Load resistor , and
- (c) the Emitter resistance.

(2) Since Emitter resistance is dependent on temperature, the voltage gain of the circuit can be unstable.

(3) Since the load resistor is also in the equation, load affects the voltage gain of the circuit. Remember this when you design your Common Emitter Amplifier.

Here I intentionally summarize the way we design for a common emitter amplifier because the above amplifier is not the best one I suggest. Design steps and consideration are discussed in the next Common Emitter Amplifier, so-called, swamped Common Emitter Amplifier. Here the idea is to add some bypassed emitter resistance for stable biasing with no change in gain at signal frequencies.

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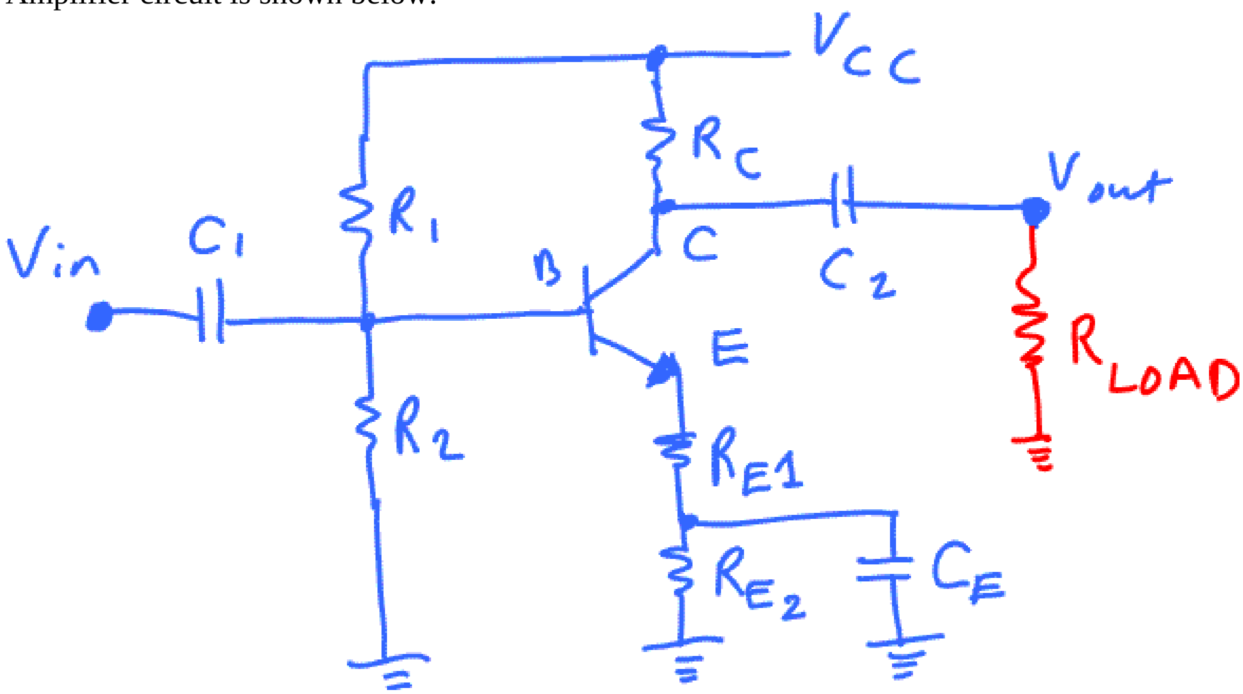
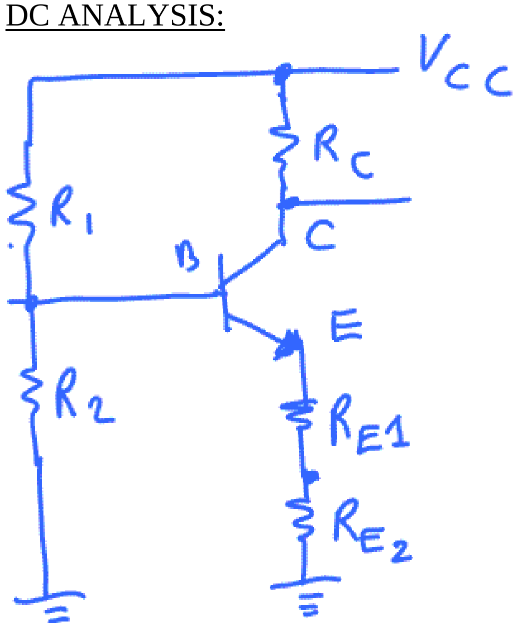
**Swamped Common Emitter Amplifier**

The only change here in the most popular Common Emitter Amplifier is that we increase the AC resistance of the Emitter circuit to reduce variations in voltage gain. The Common Emitter Amplifier circuit is shown below:




As you see above, part of the Emitter resistance is bypassed by the capacitor $C_E$.

DC ANALYSIS:



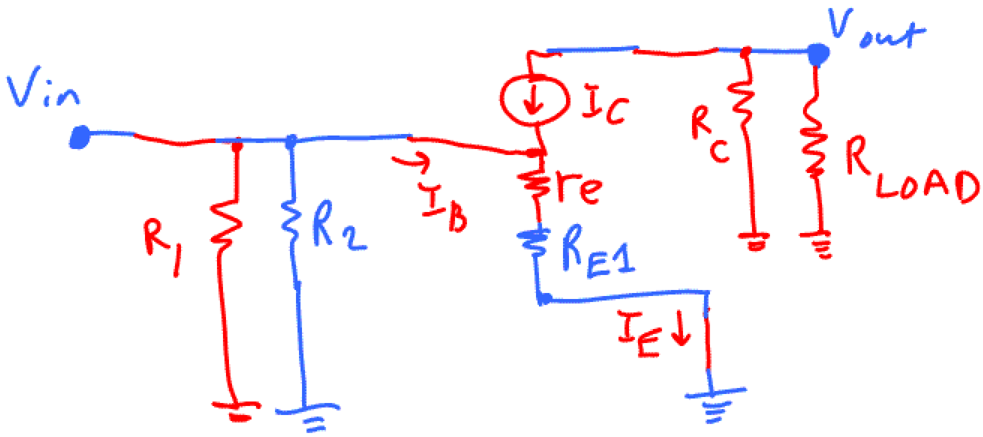

$$V_B = V_{CC} \cdot \frac{R_2}{R_1 + R_2}$$

$$V_E = V_B - 0.7$$

$$I_E = \frac{V_B - 0.7}{R_{E_1} + R_{E_2}}$$

$$r_e = \frac{25}{I_C} \approx \frac{25}{I_E[mA]}$$

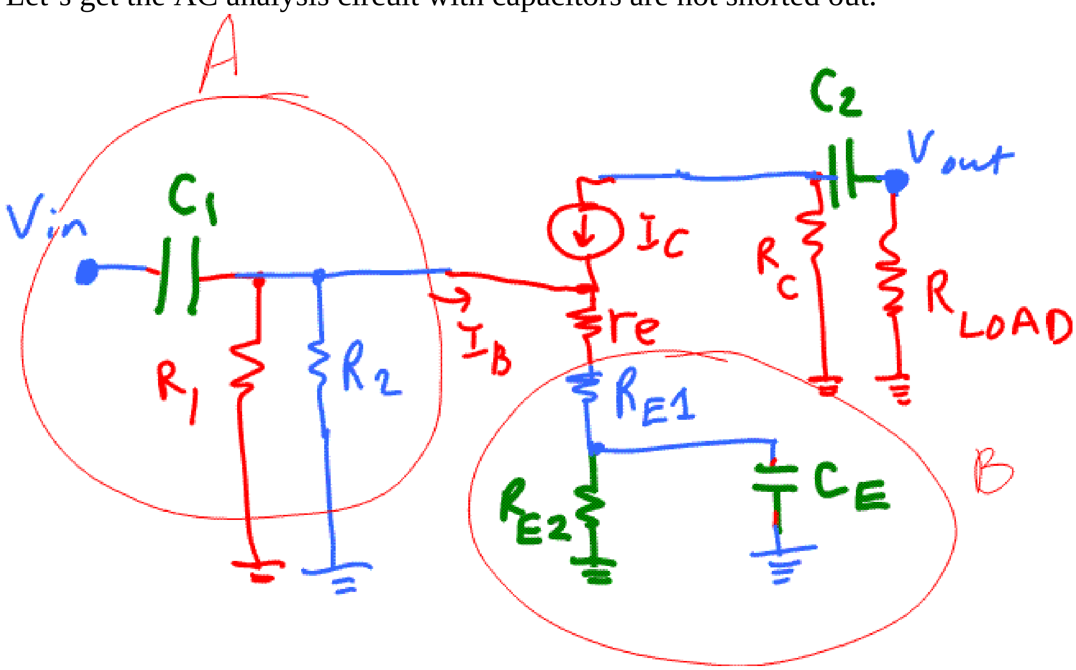
AC ANALYSIS:



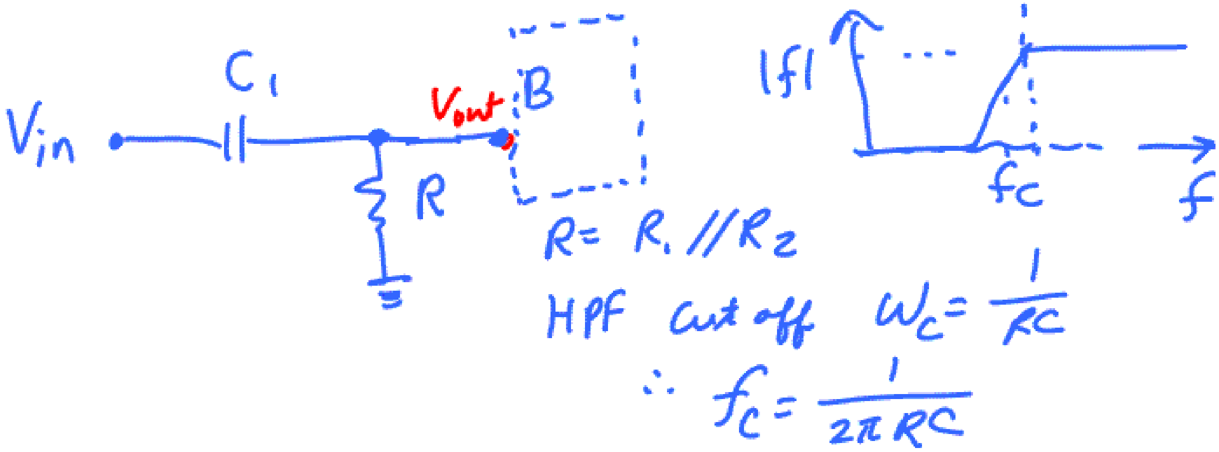

$$V_{out} = -I_C \cdot [R_C // R_{LOAD}]$$
$$V_{in} = I_E [R_{E1} + r_e]$$
$$\rightarrow A_v = \frac{V_{out}}{V_{in}} = -\frac{R_C // R_{LOAD}}{r_e + R_{E1}}$$
$$(I_C \approx I_E)$$

FREQUENCY ANALYSIS:

Well, we've run far and, thankfully, this is the last subject of the discussion. Before we said, in AC analysis, we short out capacitors when the AC signal frequency is high. This means that when AC signal frequency is low, the capacitor cannot be removed from the consideration. Then how "high" is high enough? This will answer the bandwidth of our Common Emitter Amplifier. Let's get the AC analysis circuit with capacitors are not shorted out.

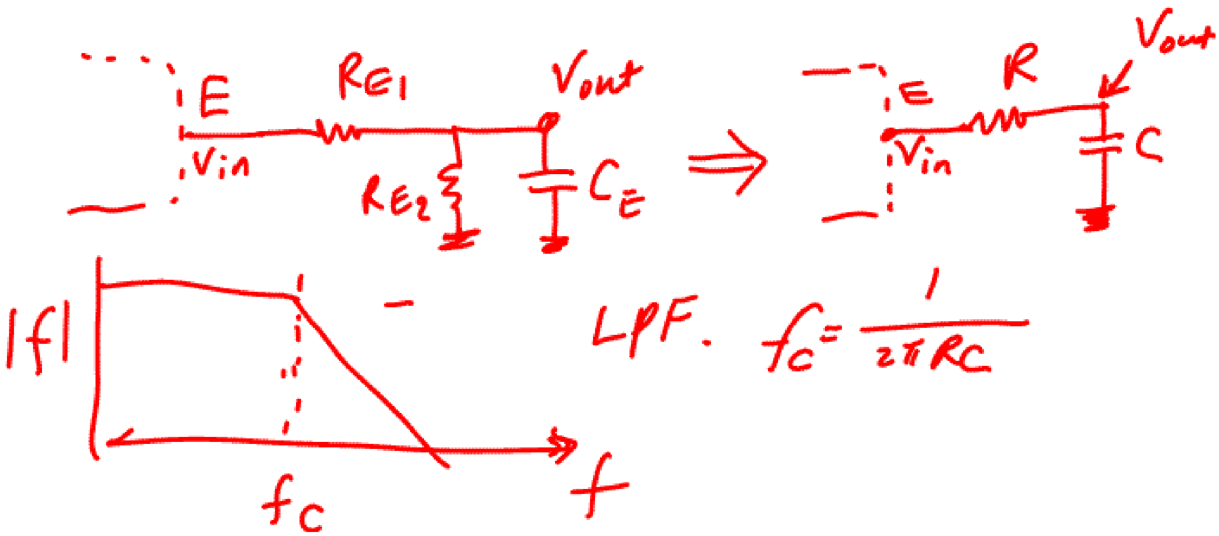



Let's look at the left circled circuit part, A. If we reduce the circuit A then, we can see the circuit from $V_{in}$ to the Base of the BJT (which is the input coupling circuit) forms a simple typical passive high pass filter circuit. It's cutoff frequency is determined by the capacitor and resistor.




From here we can guess (and use it in the design) what the lowest frequency it can pass without any reduction in the promised gain.

On the other hand, the circuit part at the bottom for bypassing, B, we can see this part is a simple typical passive low pass filter, with its cutoff frequency controlled by, again, capacitor and resistor.

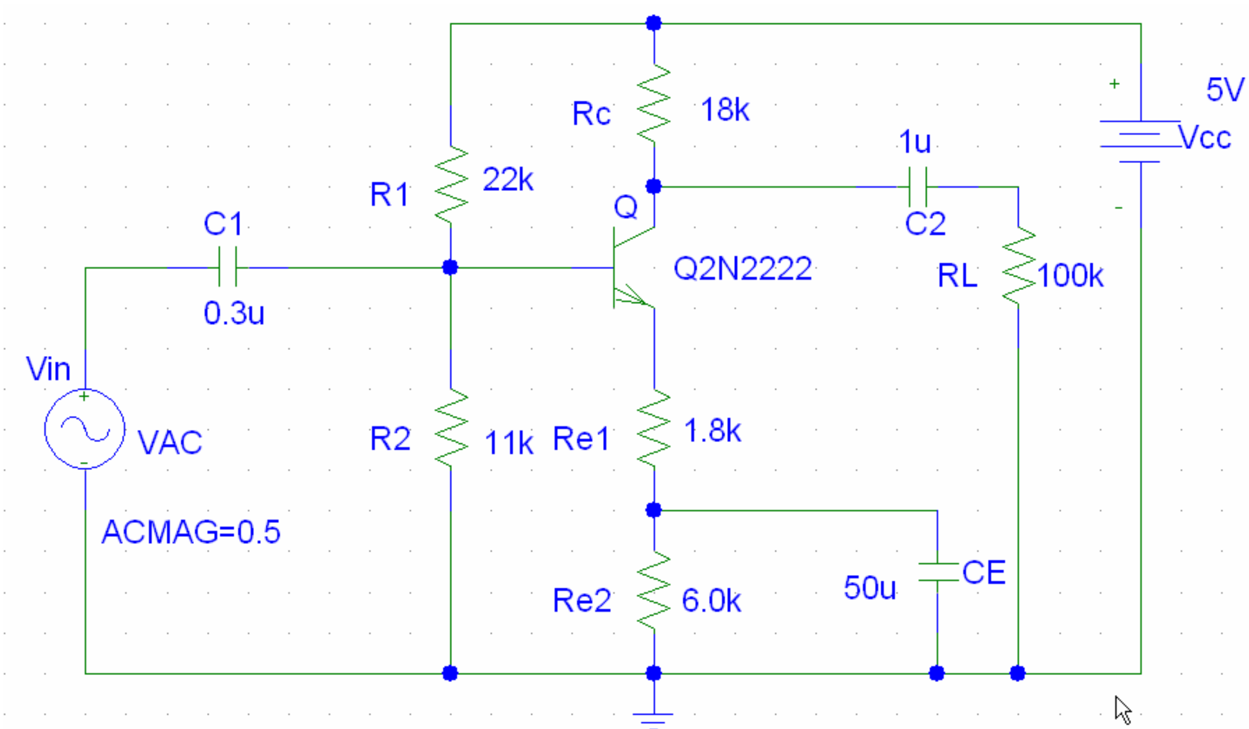



What about the output side capacitor? That part is again another high pass filter circuit. If you change the load, that means you change the frequency response of the circuit.

### *B.2 Simulation*

Since we spent enough time in Theory on Common Emitter Amplifier, we are now eager to design a circuit. But wait for a second. Let's do some simulation first. The circuit presented here may somewhat disappoint you mainly because this circuit does not satisfy the assignment, homework, or project of your class. Since I cannot satisfy everybody, and I do not intend to do so by the way, take the circuit presented here as a starter, but very important starter.

<u>Circuit Formation in PSPice</u>




Note that:

(a) Input signal is VAC (instead of usual VSIN) in the circuit since we need frequency response of the output voltage. AC Sweep is done only with VAC with only amplitude specified. Different frequency will be applied by the simulator.

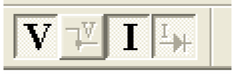
(b) To ease the limitation of power supply by IOBoard, $V_{CC}$ is supplied by 5V source.

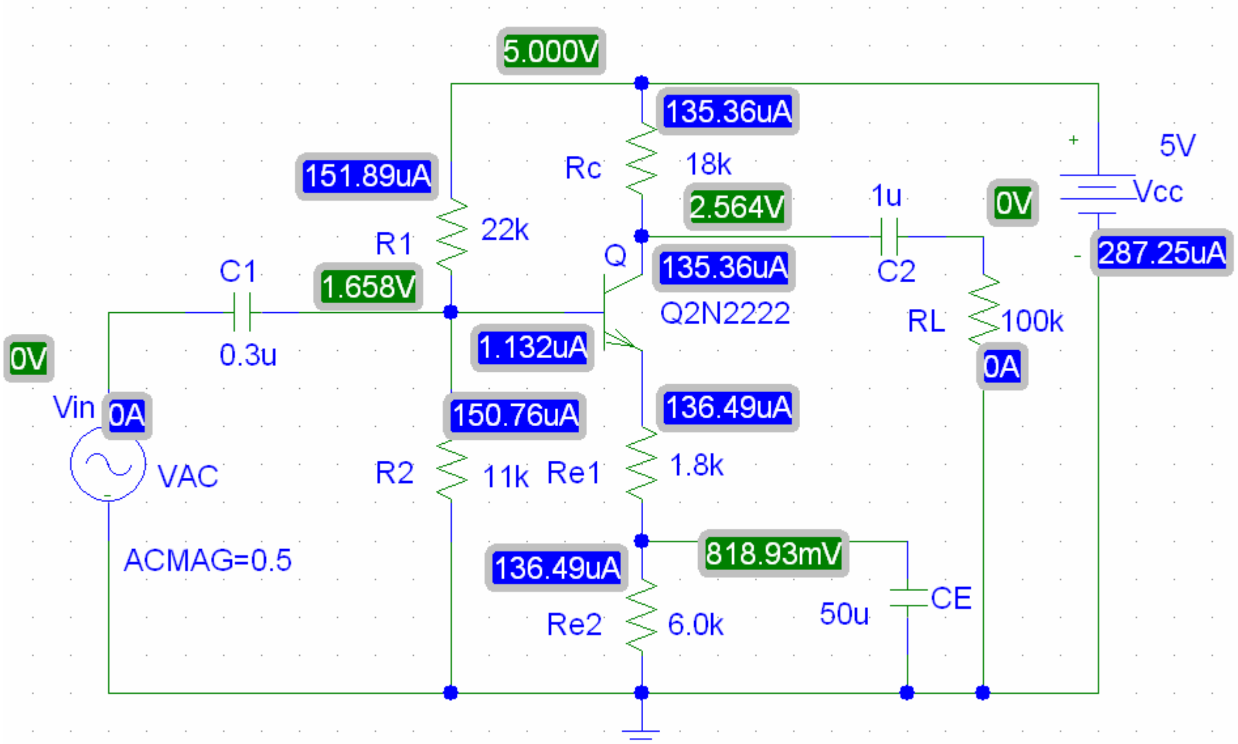
(c) The load resistance in the circuit is chosen 100kΩ. This value may be significantly different from your assigned work. You, I mean, you need to do some work too. Right?

(d) Why those values of resistors? Try to answer by DC analysis. Find expected voltage gain from the DC analysis.

(e) Why those values of capacitors? Perform AC analysis and find expected low and high cutoff frequencies.

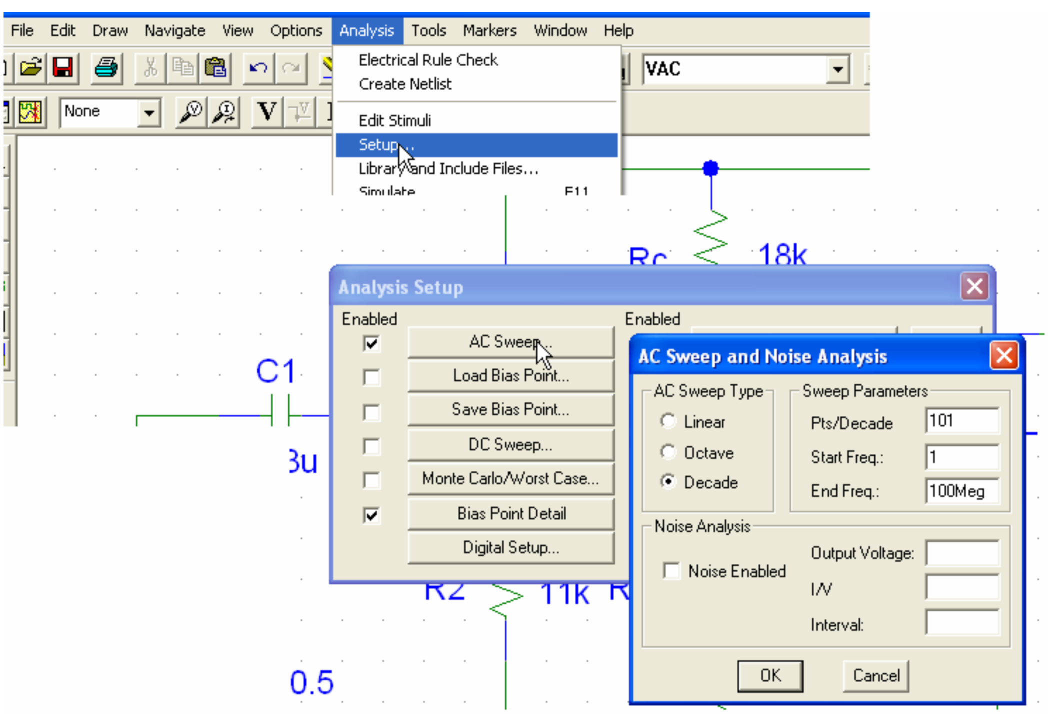
Getting Voltage and Current (all DC of course) gives you the pseudo-DC analysis of the circuit. From here you can get a lot of information.



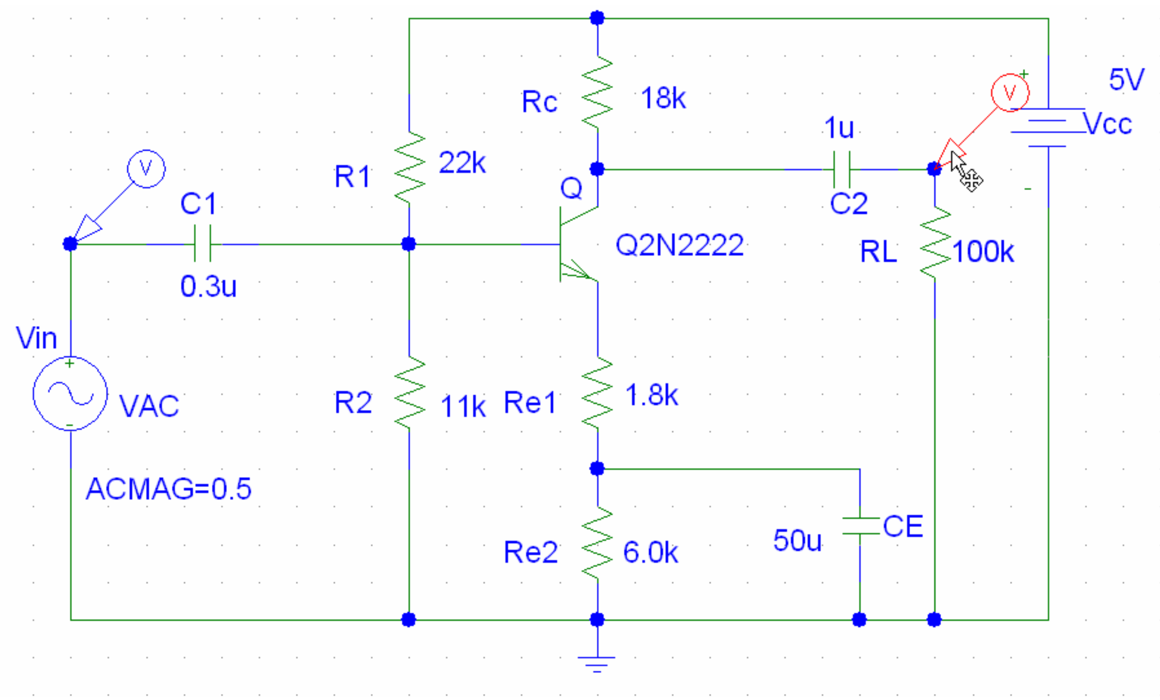




## AC Sweep

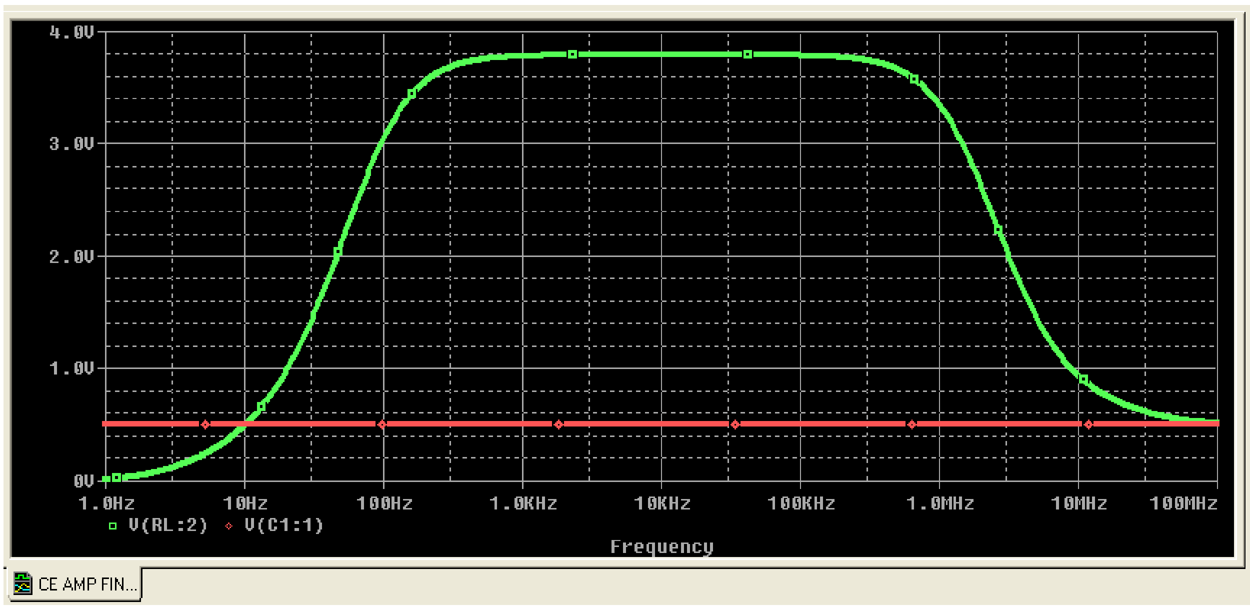
To do AC Sweep, your AC source must be VAC. You decide only ACMAG (AC magnitude), and I picked 0.5 in the circuit above. In the AC Sweep we have to assign our frequency band of interest. Here I set from 0 to 100MHz.



Then we place two voltage probes for frequency analysis:




Simulated Results (Frequency Response)




The green tracing is the voltage at the load and red, the input voltage, at each of the frequency at the range of 0 - 100MHz. What is the low cutoff frequency? What is the high cutoff frequency? What is the mid-band voltage gain?
How can you change the cutoff frequencies by changing capacitor values?
How do you change the gain by changing resistor values?
Do you see the influence of load, so called "load effect"?

**Bipolar Junction Transistor Circuits**

**Voltage and Power Amplifier Circuits**

Common Emitter Amplifier

The circuit shown on Figure 1 is called the common emitter amplifier circuit. The important subsystems of this circuit are:

1. The biasing resistor network made up of resistor $R_1$ and $R_2$ and the voltage supply $V_{CC}$.
2. The coupling capacitor $C_1$.
3. The balance of the circuit with the transistor and collector and emitter resistors.

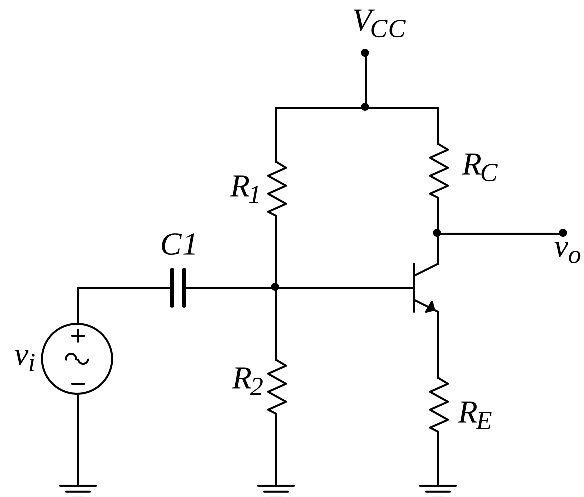



**Figure 1. Common Emitter Amplifier Circuit**

The common emitter amplifier circuit is the most often used transistor amplifier configuration.

The procedure to follow for the analysis of any amplifier circuit is as follows:

1. Perform the DC analysis and determine the conditions for the desired operating point (the Q-point)

2. Develop the AC analysis of the circuit. Obtain the voltage gain

DC Circuit Analysis

The biasing network ( $R_1$ and $R_2$ ) provides the Q-point of the circuit. The DC equivalent circuit is shown on Figure 2.

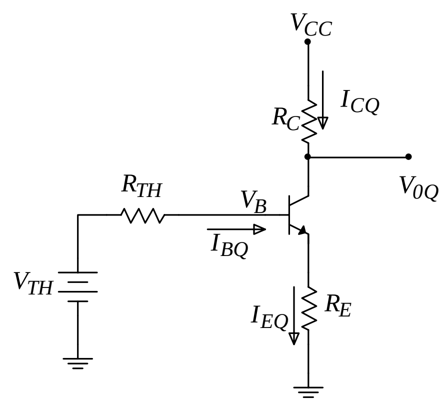



**Figure 2. DC equivalent circuit for the common emitter amplifier.**

The parameters $I_{CQ}$, $I_{BQ}$, $I_{EQ}$ and $V_{OQ}$ correspond to the values at the DC operating point- the Q-point

We may further simplify the circuit representation by considering the BJT model under DC conditions. This is shown on Figure 3. We are assuming that the BJT is properly biased and it is operating in the forward active region. The voltage $V_{BE(on)}$ corresponds to the forward drop of the diode junction, the 0.7 volts.

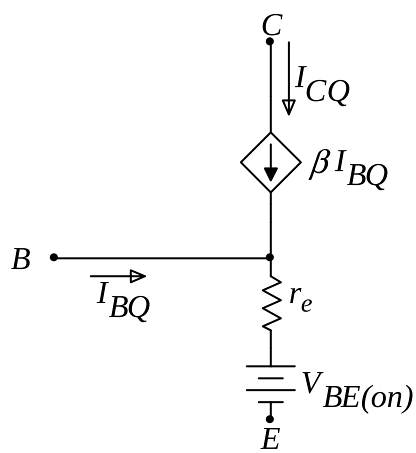



**Figure 3. DC model of an npn BJT**

For the B-E junction we are using the offset model shown on Figure 4. The resistance $r_e$ is equal to

$$r_e = \frac{V_T}{I_E} \tag{1.1}$$

Where $V_T$ is the thermal voltage, $V_T \equiv \frac{kT}{q}$, which at room temperature is $V_T = 26\text{ mV}$. $r_e$ is in general a small resistance in the range of a few Ohms.

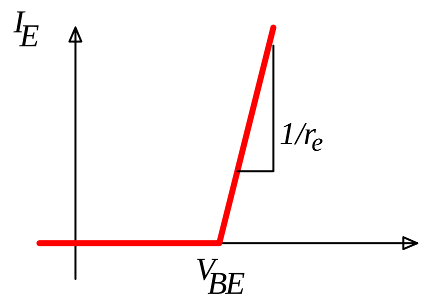



**Figure 4**

By incorporating the BJT DC model (Figure 3) the DC equivalent circuit of the common emitter amplifier becomes

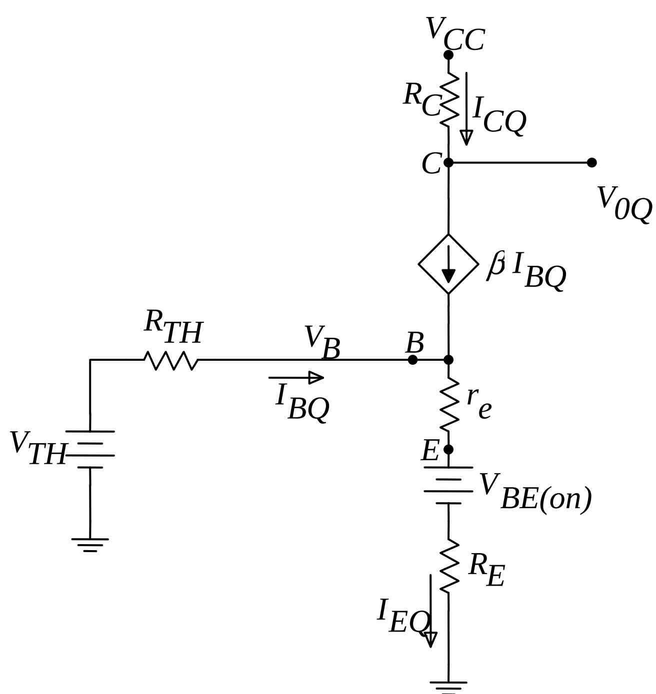



**Figure 5**

Recall that the transistor operates in the active (linear) region and the Q-point is determined by applying KVL to the B-E and C-E loops. The resulting expressions are:

$$\text{B-E Loop:} \Rightarrow \quad V_{TH} = I_{BQ}R_{TH} + V_{BE(on)} + I_{EQ}R_E \tag{1.2}$$

$$\text{C-E Loop:} \Rightarrow \quad V_{CEQ} = V_{CC} - I_{CQ}R_C - I_{EQ}R_E \tag{1.3}$$

Equations (1.2) and (1.3) define the Q-point

AC Circuit Analysis

If a small signal *vi* is superimposed on the input of the circuit the output signal is now a superposition of the Q-point and the signal due to *vi* as shown on Figure 6.

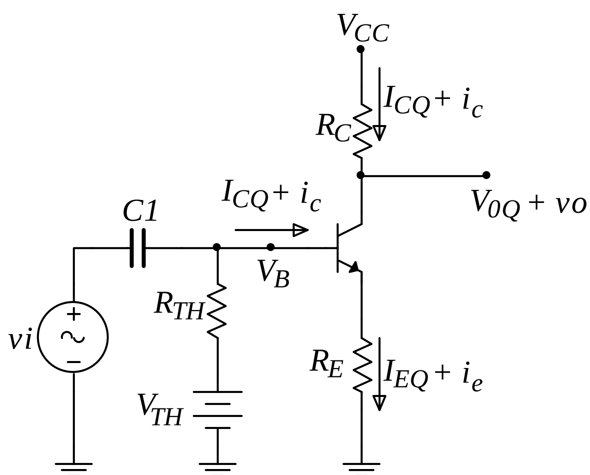



**Figure 6**

Using superposition, the voltage $V_B$ is found by:

1. Set $V_{TH} = 0$ and calculate the contribution due to *vi* ($V_{B1}$). In this case the capacitor *C1* along with resistor $R_{TH}$ form a high pass filter and for a very high value of *C1* the filter will pass all values of *vi* and $V_{B1} = vi$

2. Set *vi=0* and calculate the contribution due to $V_{TH}$ ($V_{B2}$). In this case the $V_{B2} = V_{TH}$

And therefore superposition gives

$$V_B = vi + V_{TH} \tag{1.4}$$

The AC equivalent circuit may now be obtained by setting all DC voltage sources to zero. The resulting circuit is shown on Figure 7 (a) and (b). Next by considering the AC model of the BJT (Figure 8), the AC equivalent circuit of the common emitter amplifier is shown on Figure 9.

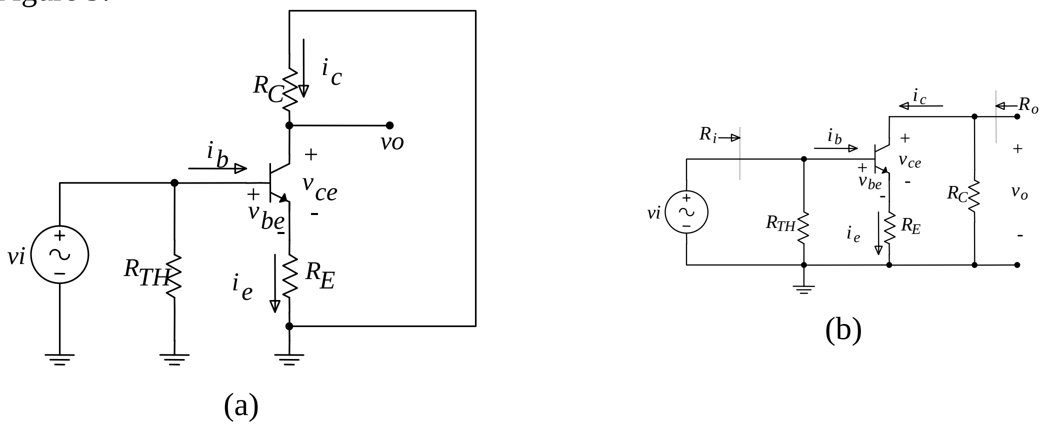



**Figure 7. AC equivalent circuit of common emitter amplifier**

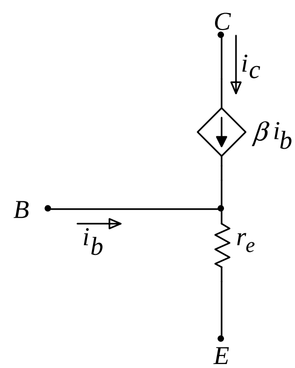



**Figure 8. AC model of a npn BJT (the T model)**

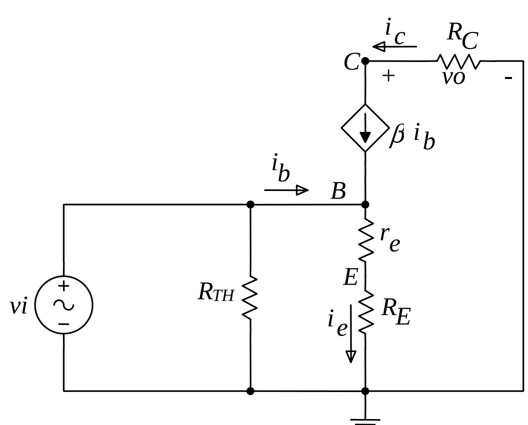



**Figure 9. AC equivalent circuit model of common emitter amplifier using the npn BJT AC model**

The gain of the amplifier of the circuit on Figure 9 is

$$A_v = \frac{vo}{vi} = \frac{-i_c R_C}{i_e(r_e + R_E)} = \frac{-\beta i_b R_C}{(1+\beta) i_b (r_e + R_E)} = -\frac{\beta}{\beta+1}\frac{R_C}{r_e + R_E} \tag{1.5}$$

For $\beta >> 1$ and $r_e << R_E$ the gain reduces to

$$A_v \cong -\frac{R_C}{R_E} \tag{1.6}$$

Let's now consider the effect of removing the emitter resistor $R_E$. First we see that the gain will dramatically increase since in general $r_e$ is small (a few Ohms). This might appear to be advantageous until we realize the importance of $R_E$ in generating a stable Q-point. By eliminating $R_E$ the Q-point is dependent solely on the small resistance $r_e$ which fluctuates with temperature resulting in an imprecise DC operating point. It is possible with a simple circuit modification to address both of these issues: increase the AC gain of the amplifier by eliminating $R_E$ in AC and stabilize the Q-point by incorporating $R_E$ when under DC conditions. This solution is implemented by adding capacitor *C2* as shown on the circuit of Figure 10. Capacitor *C2* is called a bypass capacitor.

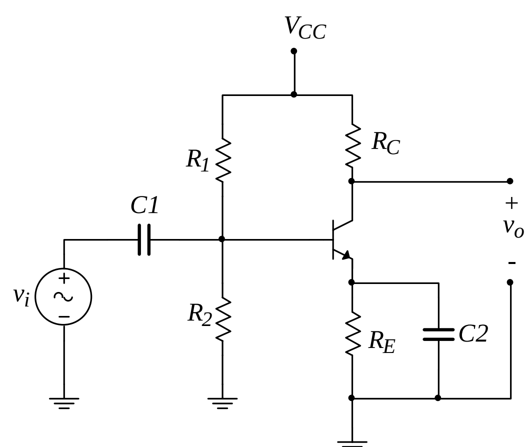



**Figure 10. Common-emitter amplifier with bypass capacitor C2**

Under DC conditions, capacitor *C2* acts as an open circuit and thus it does not affect the DC analysis and behavior of the circuit. Under AC conditions and for large values of *C2*, its effective resistance to AC signals is negligible and thus it presents a short to ground. This condition implies that the impedance magnitude of *C2* is much less than the resistance $r_e$ for all frequencies of interest.

$$\frac{1}{\omega C2} << r_e \tag{1.7}$$

Input Impedance

Besides the gain, the input, $R_i$, and the output, $R_o$, impedance seen by the source and the load respectively are the other two important parameters characterizing an amplifier. The general two port amplifier model is shown on Figure 11.

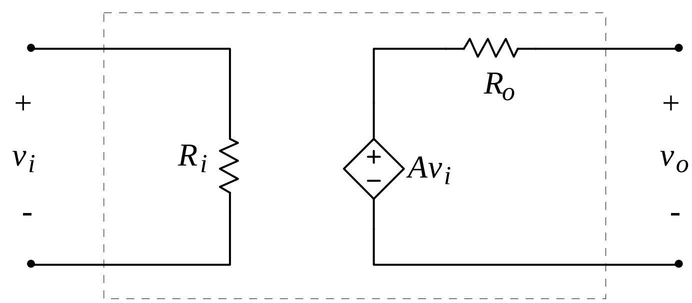



**Figure 11. General two port model of an amplifier**

For the common emitter amplifier the input impedance is calculated by calculating the ratio

$$R_i = \frac{v_i}{i_i} \tag{1.8}$$

Where the relevant parameters are shown on Figure 12 .

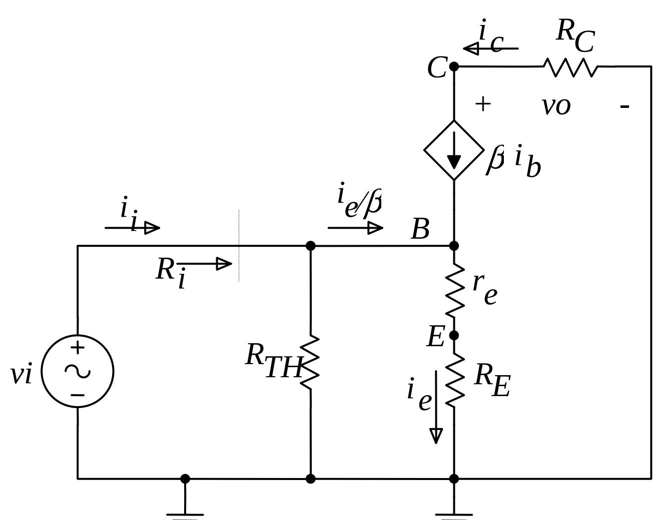



**Figure 12**

The input resistance is given by the parallel combination of $R_{TH}$ and the resistance seen at the base of the BJT which is equal to $(1+\beta)(r_e + R_E)$

$$R_i = R_{TH} // (1+\beta)(r_e + R_E) \tag{1.9}$$

Output Impedance

It is trivial to see that the output impedance of the amplifier is

$$R_o = R_C \tag{1.10}$$

Common Collector Amplifier: (Emitter Follower)

The common collector amplifier circuit is shown on Figure 13. Here the output is taken at the emitter node and it is measured between it and ground.

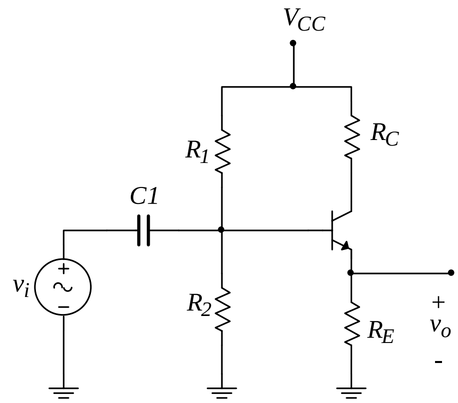



**Figure 13. Emitter Follower amplifier circuit**

Everything in this circuit is the same as the one we used in the analysis of the common emitter amplifier (Figure 1) except that in this case the output is sampled at the emitter.

The DC Q-point analysis is the same as developed for the common emitter configuration.

The AC model is shown on Figure 14. The output voltage is given by

$$v_o = v_i \frac{R_E}{R_E + r_e} \tag{1.11}$$

And the gain becomes

$$A_v = \frac{v_o}{v_i} = \frac{R_E}{R_E + r_e} \cong 1 \tag{1.12}$$

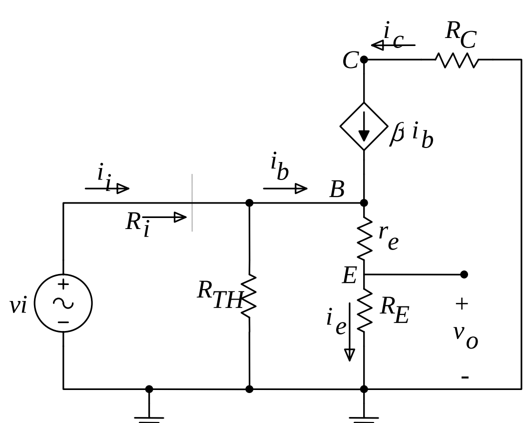



**Figure 14**

The importance of this configuration is not the trivial voltage gain result obtained above but rather the input impedance characteristics of the device.

The impedance looking at the base of the transistor is

$$R_{ib} = (1+\beta)(r_e + R_E) \tag{1.13}$$

And the input impedance seen by the source is again the parallel combination of $R_{TH}$ and $R_{ib}$

$$R_i = R_{TH} //(1+\beta)(r_e + R_E) \tag{1.14}$$

The output impedance may also be calculated by considering the circuit shown on Figure 15.

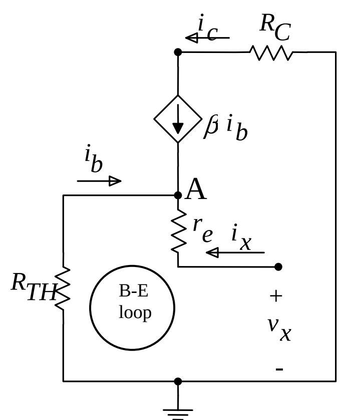



**Figure 15**

We have simplified the analysis by removing the emitter resistor $R_E$ in the circuit of Figure 15. So first we will calculate the impedance $R_x$ seen by $R_E$ and then the total output resistance will be the parallel combination of $R_E$ and $R_x$.
$R_x$ is given by

$$R_x = \frac{v_x}{i_x} \tag{1.15}$$

KCL at the node *A* gives

$$i_x = -i_b(1+\beta) \tag{1.16}$$

And KVL around the B-E loop gives

$$i_b R_{TH} - i_x r_e + v_x = 0 \tag{1.17}$$

And by combining Equations (1.15), (1.16) and (1.17) $R_x$ becomes

$$R_x = \frac{v_x}{i_x} = r_e + \frac{R_{TH}}{\beta + 1} \tag{1.18}$$

The total output impedance seen across resistor $R_E$ is

$$R_o = R_{TH} \,//\left( r_e + \frac{R_{TH}}{\beta + 1} \right) \tag{1.19}$$

# BJT Amplifier Circuits

As we have developed different models for DC signals (simple large-signal model) and AC signals (small-signal model), analysis of BJT circuits follows these steps:

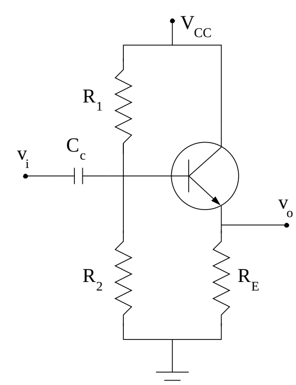
**DC biasing analysis:** Assume all capacitors are open circuit. Analyze the transistor circuit using the simple large signal mode as described in pp 57-58.

**AC analysis:**
1) Kill all DC sources
2) Assume coupling capacitors are short circuit. The effect of these capacitors is to set a lower cut-off frequency for the circuit. This is analyzed in the last step.
3) Inspect the circuit. If you identify the circuit as a prototype circuit, you can directly use the formulas for that circuit. Otherwise go to step 3. 3) Replace the BJT with its small signal model.
4) Solve for voltage and current transfer functions and input and output impedances (node-voltage method is the best).
5) Compute the cut-off frequency of the amplifier circuit.

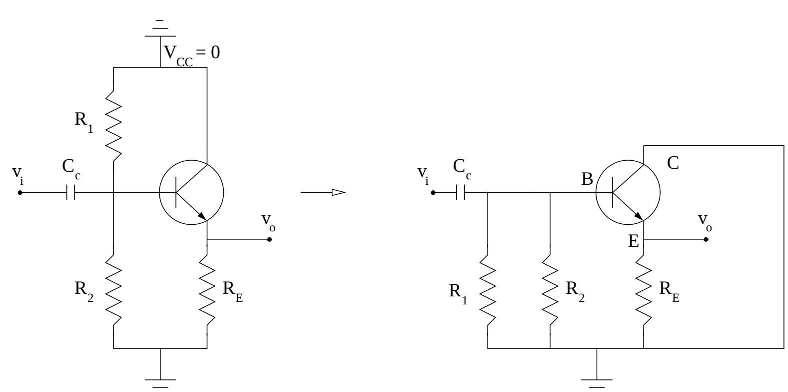
Several standard BJT amplifier configurations are discussed below and are analyzed. Because most manufacturer spec sheets quote BJT "h" parameters, I have used this notation for analysis. Conversion to notation used in most electronic text books ($r_\pi$, $r_o$, and $g_m$) is straight-forward.

**Common Collector Amplifier (Emitter Follower)**

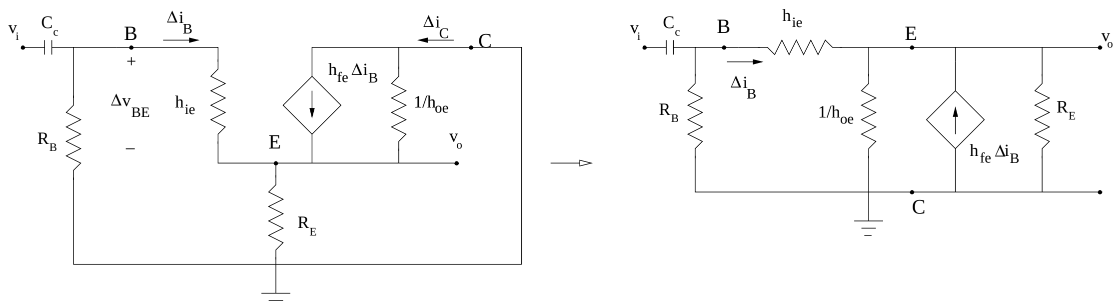
DC analysis: With the capacitors open circuit, this circuit is the same as our good biasing circuit of page 79 with $R_c = 0$. The bias point currents and voltages can be found using procedure of pages 78-81.




AC analysis: To start the analysis, we kill all DC sources:



We can combine $R_1$ and $R_2$ into $R_B$ (same resistance that we encountered in the biasing analysis) and replace the BJT with its small signal model:




The figure above shows why this is a common collector configuration: collector is shared between input and output AC signals. We can now proceed with the analysis. Node voltage method is usually the best approach to solve these circuits. For example, the above circuit will have only one node equation for node at point E with a voltage $v_o$:

$$\frac{v_o - v_i}{r_\pi} + \frac{v_o - 0}{r_o} - \beta \Delta i_B + \frac{v_o - 0}{R_E} = 0$$

Because of the controlled source, we need to write an "auxiliary" equation relating the control current ($\Delta i_B$) to node voltages:

$$\Delta i_B = \frac{v_i - v_o}{r_\pi}$$

Substituting the expression for $\Delta i_B$ in our node equation, multiplying both sides by $r_\pi$, and collecting terms, we get:

$$v_i(1+\beta) = v_o \left[ 1 + \beta + r_\pi \left( \frac{1}{r_o} + \frac{1}{R_E} \right) \right] = v_o \left[ 1 + \beta + \frac{r_\pi}{r_o \parallel R_E} \right]$$

Amplifier Gain can now be directly calculated:

$$A_v \equiv \frac{v_o}{v_i} = \frac{1}{1 + \dfrac{r_\pi}{(1+\beta)(r_o \parallel R_E)}}$$

Unless $R_E$ is very small (tens of $\Omega$), the fraction in the denominator is quite small compared to 1 and $A_v \approx 1$.

To find the input impedance, we calculate $i_i$ by KCL:

$$i_i = i_1 + \Delta i_B = \frac{v_i}{R_B} + \frac{v_i - v_o}{r_\pi}$$

Since $v_o \approx v_i$, we have $i_i = v_i/R_B$ or

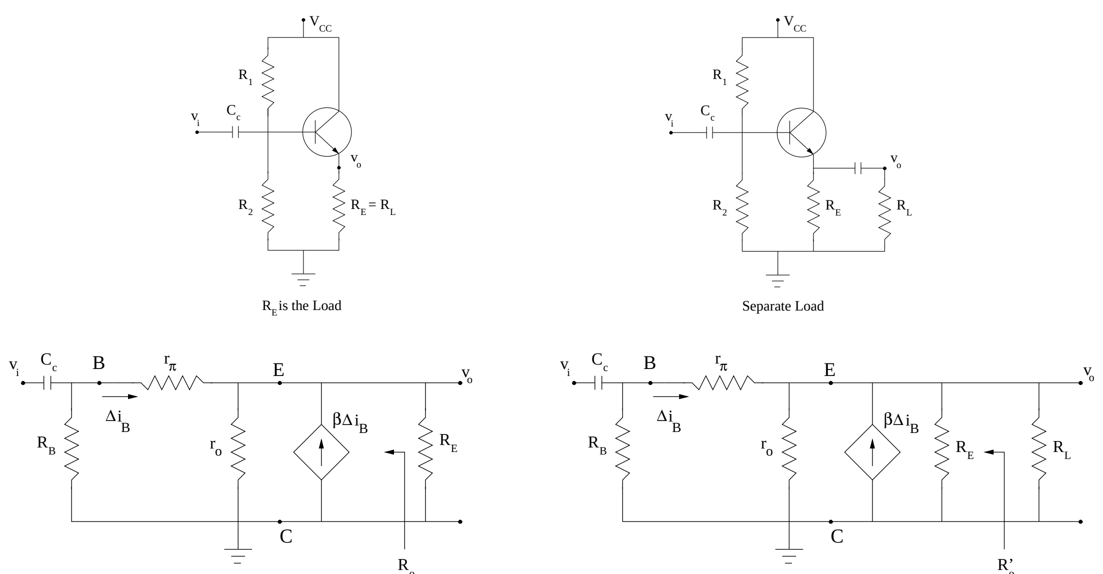
$$R_i \equiv \frac{v_i}{i_i} = R_B$$

Note that $R_B$ is the combination of our biasing resistors $R_1$ and $R_2$. With alternative biasing schemes which do not require $R_1$ and $R_2$, (and, therefore $R_B \to \infty$), the input resistance of the emitter follower circuit will become large. In this case, we cannot use $v_o \approx v_i$. Using the full expression for $v_o$ from above, the input resistance of the emitter follower circuit becomes:

$$R_i \equiv \frac{v_i}{i_i} = R_B \parallel [r_\pi + (R_E \parallel r_o)(1+\beta)]$$

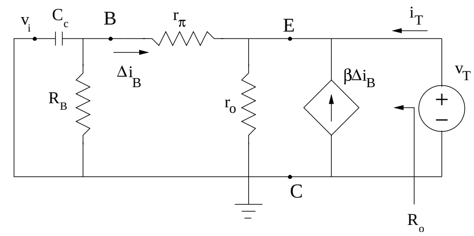
and it is quite large (hundreds of kΩ to several MΩ) for $R_B \to \infty$. Such a circuit is in fact the first stage of the 741 OpAmp.

The output resistance of the common collector amplifier (in fact for all transistor amplifiers) is somewhat complicated because the load can be configured in two ways (see figure): First, $R_E$, itself, is the load. This is the case when the common collector is used as a "current amplifier" to raise the power level and to drive the load. The output resistance of the circuit is $R_o$ as is shown in the circuit model. This is usually the case when values of $R_o$ and $A_i$ (current gain) is quoted in electronic text books.




Alternatively, the load can be placed in parallel to $R_E$. This is done when the common collector amplifier is used as a buffer ($A_v \approx 1$, $R_i$ large). In this case, the output resistance is denoted by $R_o'$ (see figure). For this circuit, BJT sees a resistance of $R_E \parallel R_L$. Obviously, if we want the load not to affect the emitter follower circuit, we should use $R_L$ to be much larger than $R_E$. In this case, little current flows in $R_L$ which is fine because we are using this configuration as a buffer and not to amplify the current and power. As such, value of $R'_o$ or $A_i$ does not have much use.

When $R_E$ is the load, the output resistance can be found by killing the source (short $v_i$) and finding the Thevenin resistance of the two-terminal network (using a test voltage source).




KCL: $i_T = -\Delta i_B + \frac{v_T}{r_o} - \beta \Delta i_B$

KVL (outside loop): $-r_\pi \Delta i_B = v_T$

Substituting for $\Delta i_B$ from the 2nd equation in the first and rearranging terms we get:

$$R_o \equiv \frac{v_T}{i_T} = \frac{(r_o)\, r_\pi}{(1+\beta)(r_o) + r_\pi} \approx \frac{(r_o)\, r_\pi}{(1+\beta)(r_o)} = \frac{r_\pi}{(1+\beta)} \approx \frac{r_\pi}{\beta} = r_e$$

where we have used the fact that $(1+\beta)(r_o) \gg r_\pi$.

When $R_E$ is the load, the current gain in this amplifier can be calculated by noting $i_o = v_o/R_E$ and $i_i \approx v_i/R_B$ as found above:

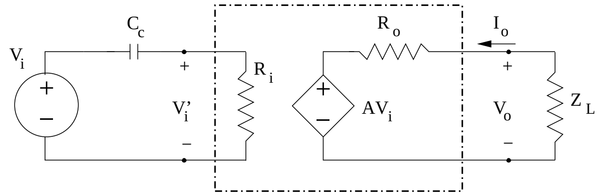
$$A_i \equiv \frac{i_o}{i_i} = \frac{R_B}{R_E}$$

In summary, the general properties of the common collector amplifier (emitter follower) include a voltage gain of unity ($A_v \approx 1$), a very large input resistance $R_i \approx R_B$ (and can be made much larger with alternate biasing schemes). This circuit can be used as buffer for matching impedance, at the first stage of an amplifier to provide very large input resistance (such in 741 OpAmp). As a buffer, we need to ensure that $R_L \gg R_E$. The common collector amplifier can be also used as the last stage of some amplifier system to amplify the current (and thus, power) and drive a load. In this case, $R_E$ is the load, $R_o$ is small: $R_o = r_e$ and current gain can be substantial: $A_i = R_B/R_E$.

**Impact of Coupling Capacitor:**

Up to now, we have neglected the impact of the coupling capacitor in the circuit (assumed it was a short circuit). This is not a correct assumption at low frequencies. The coupling capacitor results in a lower cut-off frequency for the transistor amplifiers. In order to find the cut-off frequency, we need to repeat the above analysis and include the coupling capacitor impedance in the calculation. In most cases, however, the impact of the coupling capacitor and the lower cut-off frequency can be deduced be examining the amplifier circuit model.

Consider our general model for any amplifier circuit. If we assume that coupling capacitor is short circuit (similar to our AC analysis of BJT amplifier), $v_i' = v_i$.



Voltage Amplifier Model

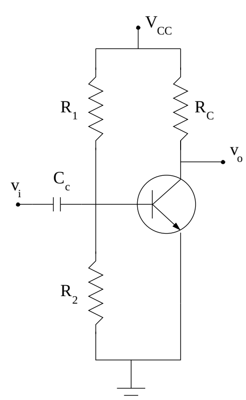
When we account for impedance of the capacitor, we have set up a high pass filter in the input part of the circuit (combination of the coupling capacitor and the input resistance of the amplifier). This combination introduces a lower cut-off frequency for our amplifier which is the same as the cut-off frequency of the high-pass filter:

$$\omega_l = 2\pi\, f_l = \frac{1}{R_i C_c}$$

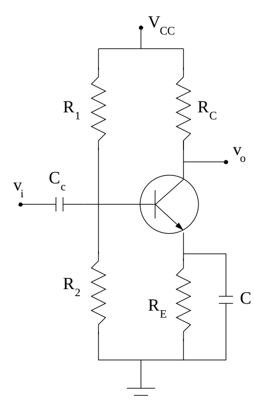
Lastly, our small signal model is a low-frequency model. As such, our analysis indicates that the amplifier has no upper cut-off frequency (which is not true). At high frequencies, the capacitance between BE , BC, CE layers become important and a high-frequency small-signal model for BJT should be used for analysis. You will see these models in upper division courses. Basically, these capacitances results in amplifier gain to drop at high frequencies. PSpice includes a high-frequency model for BJT, so your simulation should show the upper cut-off frequency for BJT amplifiers.

**Common Emitter Amplifier**

DC analysis: Recall that an emitter resistor is necessary to provide stability of the bias point. As such, the circuit configuration as is shown has as a poor bias. We need to include $R_E$ for good biasing (DC signals) and eliminate it for AC signals. The solution to include an emitter resistance and use a "bypass" capacitor to short it out for AC signals as is shown.



Poor Bias



Good Bias using a by−pass capacitor

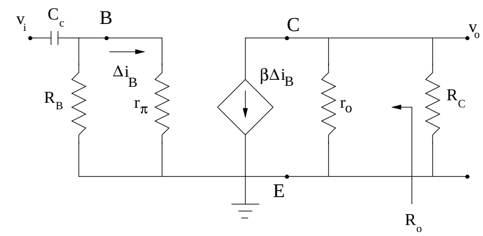
For this new circuit and with the capacitors open circuit, this circuit is the same as our good biasing circuit of page 78. The bias point currents and voltages can be found using procedure of pages 78-81.

AC analysis: To start the analysis, we kill all DC sources, combine $R_1$ and $R_2$ into $R_B$ and replace the BJT with its small signal model. We see that emitter is now common between input and output AC signals (thus, common emitter amplifier. Analysis of this circuit is straightforward. Examination of the circuit shows that:

$$v_i = r_\pi \Delta i_B \qquad v_o = -(R_c \parallel r_o)\,\beta \Delta i_B$$

$$A_v \equiv \frac{v_o}{v_i} = -\frac{\beta}{r_\pi}(R_c \parallel r_o) \approx -\frac{\beta}{r_\pi} R_c = -\frac{R_c}{r_e}$$

$$R_i = R_B \parallel r_\pi \qquad R_o = r_o$$




The negative sign in $A_v$ indicates 180° phase shift between input and output. The circuit has a large voltage gain but has medium value for input resistance.

As with the emitter follower circuit, the load can be configured in two ways: 1) $R_c$ is the load. Then $R_o = r_o$ and the circuit has a reasonable current gain. 2) Load is placed in parallel to $R_c$. In this case, we need to ensure that $R_L \gg R_c$. Little current will flow in $R_L$ and $R_o$ and $A_i$ values are of not much use.

**Lower cut-off frequency:** Both the coupling and bypass capacitors contribute to setting the lower cut-off frequency for this amplifier, both act as a low-pass filter with:

$$\omega_l(coupling) = 2\pi\, f_l = \frac{1}{R_i C_c}$$

$$\omega_l(bypass) = 2\pi\, f_l = \frac{1}{R'_E C_b}$$

$$\text{where} \quad R'_E \equiv R_E \parallel (r_e + \frac{R_B}{\beta})$$

In the case when these two frequencies are far apart, the cut-off frequency of the amplifier is set by the "larger" cut-off frequency. *i.e.,*

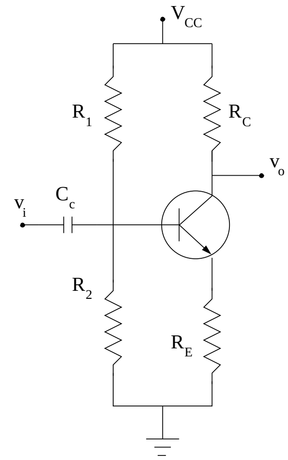
$$\omega_l(bypass) \ll \omega_l(coupling) \quad \rightarrow \quad \omega_l = 2\pi\, f_l = \frac{1}{R_i C_c}$$

$$\omega_l(coupling) \ll \omega_l(bypass) \quad \rightarrow \quad \omega_l = 2\pi\, f_l = \frac{1}{R'_E C_b}$$

When the two frequencies are close to each other, there is no exact analytical formulas, the cut-off frequency should be found from simulations. An approximate formula for the cut-off frequency (accurate within a factor of two and exact at the limits) is:

$$\omega_l = 2\pi\, f_l = \frac{1}{R_i C_c} + \frac{1}{R'_E C_b}$$

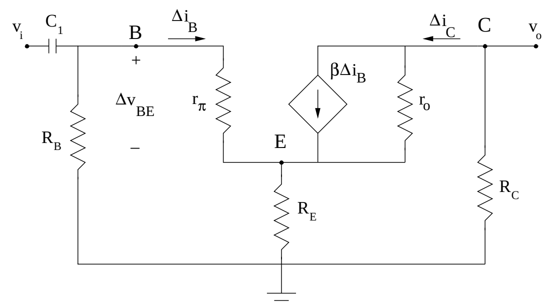
## Common Emitter Amplifier with Emitter resistance




A problem with the common emitter amplifier is that its gain depend on BJT parameters $A_v \approx (\beta/r_\pi) R_c$. Some form of feedback is necessary to ensure stable gain for this amplifier. One way to achieve this is to add an emitter resistance. Recall impact of negative feedback on OpAmp circuits: we traded gain for stability of the output. Same principles apply here.

DC analysis: With the capacitors open circuit, this circuit is the same as our good biasing circuit of page 78. The bias point currents and voltages can be found using procedure of pages 78-81.

AC analysis: To start the analysis, we kill all DC sources, combine $R_1$ and $R_2$ into $R_B$ and replace the BJT with its small signal model. Analysis is straight forward using node-voltage method.




$$\frac{v_E - v_i}{r_\pi} + \frac{v_E}{R_E} - \beta \Delta i_B + \frac{v_E - v_o}{r_o} = 0$$

$$\frac{v_o}{R_C} + \frac{v_o - v_E}{r_o} + \beta \Delta i_B = 0$$

$$\Delta i_B = \frac{v_i - v_E}{r_\pi} \quad \text{(Controlled source aux. Eq.)}$$

Substituting for $\Delta i_B$ in the node equations and noting $1 + \beta \approx \beta$, we get:

$$\frac{v_E}{R_E} + \beta \frac{v_E - v_i}{r_\pi} + \frac{v_E - v_o}{r_o} = 0$$

$$\frac{v_o}{R_C} + \frac{v_o - v_E}{r_o} - \beta \frac{v_E - v_i}{r_\pi} = 0$$

Above are two equations in two unknowns ($v_E$ and $v_o$). Adding the two equation together we get $v_E = -(R_E/R_C) v_o$ and substituting that in either equations we can find $v_o$.

Alternatively, we can find compact and simple solutions by noting that terms containing $r_o$ in the denominator are usually small as $r_o$ is quite large. In this case, the node equations simplify to (using $r_\pi/\beta = r_e$):

$$v_E \left( \frac{1}{R_E} + \frac{1}{r_e} \right) = \frac{v_i}{r_e} \quad \rightarrow \quad v_E = \frac{R_E}{R_E + r_e} v_i$$

$$v_o = \frac{R_C}{r_e} (v_E - v_i) = \frac{R_C}{r_e} \left( \frac{R_E}{R_E + r_e} - 1 \right) v_i = - \frac{R_C}{R_E + r_e} v_i$$

Then, the voltage gain and input and output resistance can also be easily calculated:

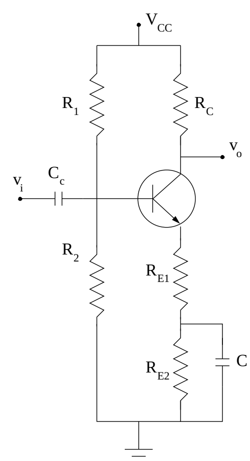
$$A_v = \frac{v_o}{v_i} = -\frac{R_C}{R_E + r_e} \approx -\frac{R_C}{R_E}$$
$$R_i = R_B \parallel [\beta(R_E + r_e)] \qquad R_o = r_e$$

As before the minus sign in $A_v$ indicates a 180° phase shift between input and output signals. Note the impact of negative feedback introduced by the emitter resistance. The voltage gain is independent of BJT parameters and is set by $R_C$ and $R_E$ as $R_E \gg r_e$ (recall OpAmp inverting amplifier!). The input resistance is increased dramatically.

**Lower cut-off frequency:** The coupling capacitor together with the input resistance of the amplifer lead to a lower cut-off freqnecy for this amplifer (similar to emitter follower). The lower cut-off freqncy is geivn by:

$$\omega_l = 2\pi\, f_l = \frac{1}{R_i C_c}$$

**A Possible Biasing Problem:** The gain of the common emitter amplifier with the emitter resistance is approximately $R_C/R_E$. For cases when a high gain (gains larger than 5-10) is needed, $R_E$ may be become so small that the necessary good biasing condition, $V_E = R_E I_E > 1$ V cannot be fulfilled. The solution is to use a by-pass capacitor as is shown. The AC signal sees an emitter resistance of $R_{E1}$ while for DC signal the emitter resistance is the larger value of $R_E = R_{E1} + R_{E2}$. Obviously formulas for common emitter amplifier with emitter resistance can be applied here by replacing $R_E$ with $R_{E1}$ as in deriving the amplifier gain, and input and output impedances, we "short" the bypass capacitor so $R_{E2}$ is effectively removed from the circuit.



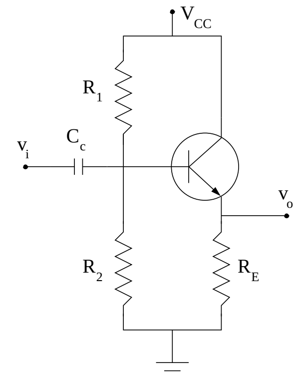

The addition of by-pass capacitor, however, modify the lower cut-off frequency of the circuit. Similar to a regular common emitter amplifier with no emitter resistance, both the coupling and bypass capacitors contribute to setting the lower cut-off frequency for this amplifier. Similarly we find that an approximate formula for the cut-off frequency (accurate within a factor of two and exact at the limits) is:

$$\omega_l = 2\pi\, f_l = \frac{1}{R_i C_c} + \frac{1}{R'_E C_b}$$

$$\text{where} \quad R'_E \equiv R_{E2} \parallel (R_{E1} + r_e + \frac{R_B}{\beta})$$

# Summary of BJT Amplifiers

**Common Collector (Emitter Follower):**



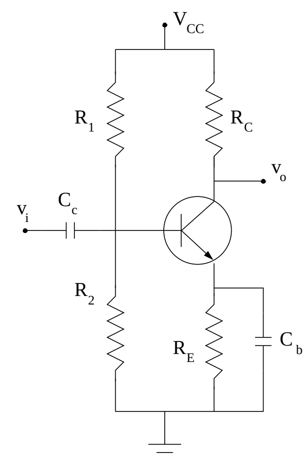

$$A_v = \frac{(R_E \parallel r_o)(1+\beta)}{r_\pi + (R_E \parallel r_o)(1+\beta)} \approx 1$$

$$R_i = R_B \parallel [r_\pi + (R_E \parallel r_o)(1+\beta)] \approx R_B$$

$$R_o = \frac{(r_o)\, r_\pi}{(1+\beta)(r_o) + r_\pi} \approx \frac{r_\pi}{\beta} = r_e$$

$$2\pi\, f_l = \frac{1}{R_i C_c}$$

**Common Emitter:**




$$A_v = -\frac{\beta}{r_\pi}(R_c \parallel r_o) \approx -\frac{\beta}{r_\pi} R_c = -\frac{R_c}{r_e}$$

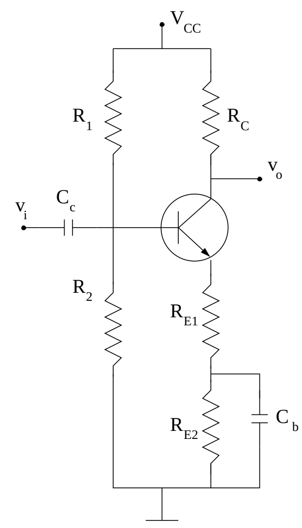
$$R_i = R_B \parallel r_\pi$$

$$R_o = r_o$$

$$2\pi\, f_l = \frac{1}{R_i C_c} + \frac{1}{R'_E C_b}$$

where $R'_E \equiv R_E \parallel (r_e + \frac{R_B}{\beta})$

**Common Emitter with Emitter Resistance:**




$$A_v = -\frac{R_C}{R_{E1} + r_e} \approx -\frac{R_C}{R_{E1}}$$

$$R_i = R_B \parallel [\beta(R_{E1} + r_e)]$$

$$R_o = r_e$$

If $R_{E2}$ and bypass capacitors are <u>not</u> present, replace $R_{E1}$ with $R_E$ in above formula and

$$2\pi\, f_l = \frac{1}{R_i C_c}$$

If $R_{E2}$ and bypass capacitor are present,

$$\omega_l = 2\pi\, f_l = \frac{1}{R_i C_c} + \frac{1}{R'_E C_b}$$

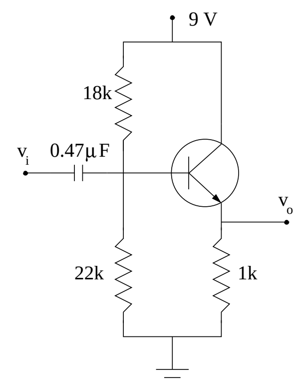
where $R'_E \equiv R_{E2} \parallel (R_{E1} + r_e + \frac{R_B}{\beta})$

**Examples of Analysis and Design of BJT Amplifiers**

**Example 1:** Find the bias point and AC amplifier parameters of this circuit (Manufacturers' spec sheets give: $h_{fe} = 200$, $h_{ie} = 5$ k$\Omega$, $h_{oe} = 10$ $\mu$S).

$$r_\pi = h_{ie} = 5 \text{ k}\Omega \qquad r_o = \frac{1}{h_{oe}} = 100 \text{ k}\Omega \qquad \beta = h_{fe} = 200 \qquad r_e = \frac{r_\pi}{\beta} = 25\ \Omega$$

DC analysis:



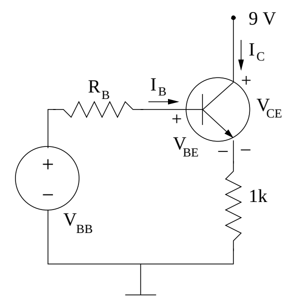

Replace $R_1$ and $R_2$ with their Thevenin equivalent and proceed with DC analysis (all DC current and voltages are denoted by capital letters):

$$R_B = 18 \text{ k} \parallel 22 \text{ k} = 9.9 \text{ k}\Omega$$

$$V_{BB} = \frac{22}{18+22} 9 = 4.95 \text{ V}$$

$$\text{KVL:} \quad V_{BB} = R_B I_B + V_{BE} + 10^3 I_E \qquad I_B = \frac{I_E}{1+\beta} = \frac{I_E}{201}$$

$$4.95 - 0.7 = I_E \left( \frac{9.9 \times 10^3}{2.1} + 10^3 \right)$$




$$I_E = 4 \text{ mA} \approx I_C, \qquad I_B = \frac{I_C}{\beta} = 20\ \mu\text{A}$$

$$\text{KVL:} \quad V_{CC} = V_{CE} + 10^3 I_E$$

$$V_{CE} = 9 - 10^3 \times 4 \times 10^{-3} = 5 \text{ V}$$

DC Bias summary: $I_E \approx I_C = 4$ mA, $I_B = 20$ $\mu$A, $V_{CE} = 5$ V

AC analysis: The circuit is a common collector amplifier. Using the formulas in page 98,

$$A_v \approx 1$$

$$R_i \approx R_B = 9.9\ k\Omega$$

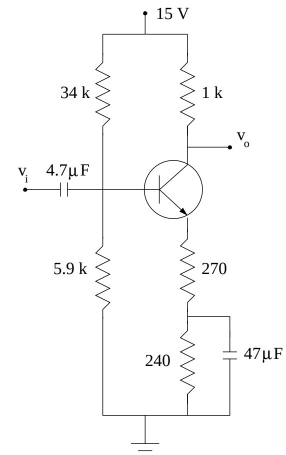
$$R_o \approx r_e = 25\ \Omega$$

$$f_l = \frac{\omega_l}{2\pi} = \frac{1}{2\pi R_B C_c} = \frac{1}{2\pi \times 9.9 \times 10^3 \times 0.47 \times 10^{-6}} = 36 \text{ Hz}$$

**Example 2:** Find the bias point and AC amplifier parameters of this circuit (Manufacturers' spec sheets give: $h_{fe} = 200$, $h_{ie} = 5$ kΩ, $h_{oe} = 10$ μS).

$$r_\pi = h_{ie} = 5 \text{ k}\Omega \qquad r_o = \frac{1}{h_{oe}} = 100 \text{ k}\Omega \qquad \beta = h_{fe} = 200 \qquad r_e = \frac{r_\pi}{\beta} = 25\ \Omega$$

DC analysis:




Replace $R_1$ and $R_2$ with their Thevenin equivalent and proceed with DC analysis (all DC current and voltages are denoted by capital letters). Since all capacitors are replaced with open circuit, the emitter resistance for DC analysis is $270+240 = 510\ \Omega$.

$$R_B = 5.9 \text{ k} \parallel 34 \text{ k} = 5.0 \text{ k}\Omega$$

$$V_{BB} = \frac{5.9}{5.9 + 34} 15 = 2.22 \text{ V}$$

$$\text{KVL:} \quad V_{BB} = R_B I_B + V_{BE} + 510 I_E \qquad I_B = \frac{I_E}{1+\beta} = \frac{I_E}{201}$$

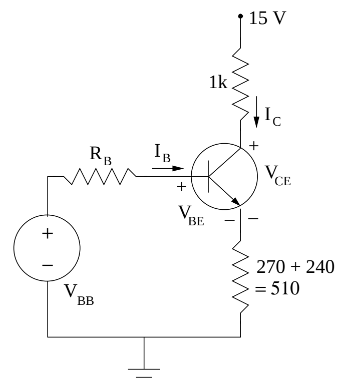
$$2.22 - 0.7 = I_E \left( \frac{5.0 \times 10^3}{2.1} + 510 \right)$$

$$I_E = 3 \text{ mA} \approx I_C, \qquad I_B = \frac{I_C}{\beta} = 15\ \mu\text{A}$$

$$\text{KVL:} \quad V_{CC} = 1000 I_C + V_{CE} + 510 I_E$$

$$V_{CE} = 15 - 1{,}510 \times 3 \times 10^{-3} = 10.5 \text{ V}$$

$$\text{DC Bias:} \quad I_E \approx I_C = 3 \text{ mA}, \quad I_B = 15\ \mu\text{A}, \quad V_{CE} = 10.5 \text{ V}$$




AC analysis: The circuit is a common collector amplifier with an emitter resistance. Note that the 240 Ω resistor is shorted out with the by-pass capacitor. It only enters the formula for the lower cut-off frequency. Using the formulas in page 98:

$$A_v = \frac{R_C}{R_{E1} + r_e} = \frac{1{,}000}{270 + 25} = 3.39$$

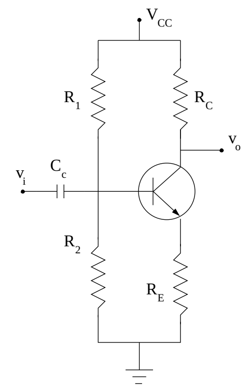
$$R_i \approx R_B = 5.0 \text{ k}\Omega \qquad\qquad R_o \approx r_e = 25\ \Omega$$

$$R'_E = \equiv R_{E2} \parallel (R_{E1} + r_e + \frac{R_B}{\beta}) = 240 \parallel (270 + 25 + \frac{5{,}000}{200}) = 137\ \Omega$$

$$f_l = \frac{\omega_l}{2\pi} = \frac{1}{2\pi R_i C_c} + \frac{1}{2\pi R'_E C_b} =$$

$$\frac{1}{2\pi \times 5{,}000 \times 4.7 \times 10^{-6}} + \frac{1}{2\pi \times 137 \times 47 \times 10^{-6}} = 31.5 \text{ Hz}$$

**Example 3:** Design a BJT amplifier with a gain of 4 and a lower cut-off frequency of 100 Hz. The Q point parameters should be $I_C = 3$ mA and $V_{CE} = 7.5$ V. (Manufacturers' spec sheets give: $\beta_{min} = 100$, $\beta = 200$, $h_{ie} = 5$ kΩ, $h_{oe} = 10$ μS).

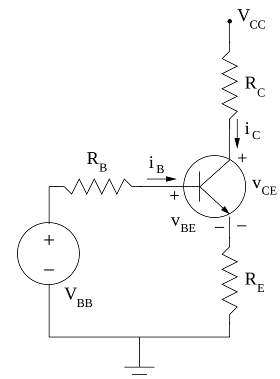



$$r_\pi = h_{ie} = 5 \text{ k}\Omega \qquad r_o = \frac{1}{h_{oe}} = 100 \text{ k}\Omega \qquad r_e = \frac{r_\pi}{\beta} = 25\ \Omega$$

The prototype of this circuit is a common emitter amplifier with an emitter resistance. Using formulas of page 98 ($r_e = r_\pi/h_{fe} = 25\ \Omega$),

$$|A_v| = \frac{R_C}{R_E + r_e} \approx \frac{R_C}{R_E} = 4$$

The lower cut-off frequency will set the value of $C_c$.




We start with the DC bias: As $V_{CC}$ is not given, we need to choose it. To set the Q-point in the middle of load line, set $V_{CC} = 2V_{CE} = 15$ V. Then, noting $I_C \approx I_E$,:

$$V_{CC} = R_C I_C + V_{CE} + R_E I_E$$

$$15 - 7.5 = 3 \times 10^{-3}(R_C + R_E) \quad \rightarrow \quad R_C + R_E = 2.5 \text{ k}\Omega$$

Values of $R_C$ and $R_E$ can be found from the above equation together with the AC gain of the amplifier, $A_V = 4$. Ignoring $r_e$ compared to $R_E$ (usually a good approximation), we get:

$$\frac{R_C}{R_E} = 4 \quad \rightarrow \quad 4R_E + R_E = 2.5 \text{ k}\Omega \quad \rightarrow \quad R_E = 500\ \Omega, R_C = 2.\ \text{k}\Omega$$

Commercial values are $R_E = 510\ \Omega$ and $R_C = 2$ kΩ. Use these commercial values for the rest of analysis.

We need to check if $V_E > 1$ V, the condition for good biasing. $V_E = R_E I_E = 510 \times 3 \times 10^{-3} = 1.5 > 1$, it is OK (See next example for the case when $V_E$ is smaller than 1 V).

We now proceed to find $R_B$ and $V_{BB}$. $R_B$ is found from good bias condition and $V_{BB}$ from a KVL in BE loop:

$$R_B \ll (\beta + 1)R_E \quad \rightarrow \quad R_B = 0.1(\beta_{min} + 1)R_E = 0.1 \times 101 \times 510 = 5.1 \text{ k}\Omega$$

$$\text{KVL:} \quad V_{BB} = R_B I_B + V_{BE} + R_E I_E$$

$$V_{BB} = 5.1 \times 10^3 \frac{3 \times 10^{-3}}{201} + 0.7 + 510 \times 3 \times 10^{-3} = 2.28 \text{ V}$$

Bias resistors $R_1$ and $R_2$ are now found from $R_B$ and $V_{BB}$:

$$R_B = R_1 \parallel R_2 = \frac{R_1 R_2}{R_1 + R_2} = 5 \text{ k}\Omega$$
$$\frac{V_{BB}}{V_{CC}} = \frac{R_2}{R_1 + R_2} = \frac{2.28}{15} = 0.152$$

$R_1$ can be found by dividing the two equations: $R_1 = 33$ k$\Omega$. $R_2$ is found from the equation for $V_{BB}$ to be $R_2 = 5.9$ k$\Omega$. Commercial values are $R_1 = 33$ k$\Omega$ and $R_2 = 6.2$ k$\Omega$.

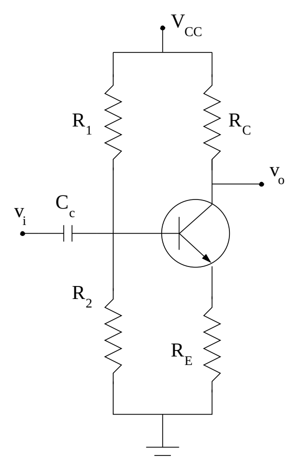
Lastly, we have to find the value of the coupling capacitor:

$$\omega_l = \frac{1}{R_i C_c} = 2\pi \times 100$$

Using $R_i \approx R_B = 5.1$ k$\Omega$, we find $C_c = 3 \times 10^{-7}$ F or a commercial values of $C_c = 300$ nF.

So, are design values are: $R_1 = 33$ k$\Omega$, $R_2 = 6.2$ k$\Omega$, $R_E = 510$ $\Omega$, $R_C = 2$ k$\Omega$. and $C_c = 300$ nF.

**Example 4:** Design a BJT amplifier with a gain of 10 and a lower cut-off frequency of 100 Hz. The Q point parameters should be $I_C = 3$ mA and $V_{CE} = 7.5$ V. A power supply of 15 V is available. Manufacturers' spec sheets give: $\beta_{min} = 100$, $h_{fe} = 200$, $r_\pi = 5$ k$\Omega$, $h_{oe} = 10$ $\mu$S.




$$r_\pi = h_{ie} = 5 \text{ k}\Omega \qquad r_o = \frac{1}{h_{oe}} = 100 \text{ k}\Omega \qquad r_e = \frac{r_\pi}{\beta} = 25\ \Omega$$

The prototype of this circuit is a common emitter amplifier with an emitter resistance. Using formulas of page 98:

$$|A_v| = \frac{R_C}{R_E + r_e} \approx \frac{R_C}{R_E} = 10$$

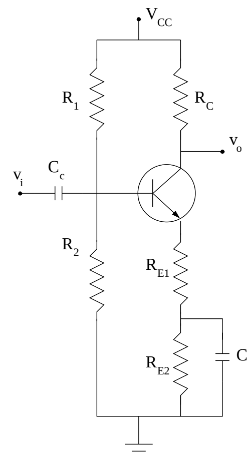
The lower cut-off frequency will set the value of $C_c$.

We start with the DC bias: As the power supply voltage is given, we set $V_{CC} = 15$ V. Then, noting $I_C \approx I_E$,:

$$V_{CC} = R_C I_C + V_{CE} + R_E I_E$$
$$15 - 7.5 = 3 \times 10^{-3}(R_C + R_E) \quad \rightarrow \quad R_C + R_E = 2.5 \text{ k}\Omega$$

Values of $R_C$ and $R_E$ can be found from the above equation together with the AC gain of the amplifier $A_V = 10$. Ignoring $r_e$ compared to $R_E$ (usually a good approximation), we get:

$$\frac{R_C}{R_E} = 10 \quad \rightarrow \quad 10R_E + R_E = 2.5 \text{ k}\Omega \quad \rightarrow \quad R_E = 227 \ \Omega, R_C = 2.27 \text{ k}\Omega$$



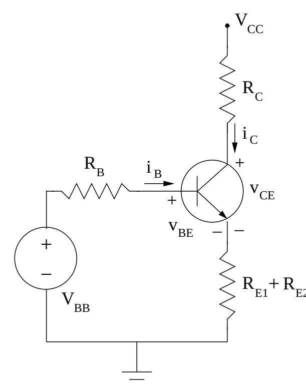

We need to check if $V_E > 1$ V which is the condition for good biasing: $V_E = R_E I_E = 227 \times 3 \times 10^{-3} = 0.69 < 1$. Therefore, we need to use a bypass capacitor and modify our circuits as is shown.

For DC analysis, the emitter resistance is $R_{E1} + R_{E2}$ while for AC analysis, the emitter resistance will be $R_{E1}$. Therefore:

$$\text{DC Bias:} \quad R_C + R_{E1} + R_{E2} = 2.5 \text{ k}\Omega$$

$$\text{AC gain:} \quad A_v = \frac{R_C}{R_{E1}} = 10$$

Above are two equations in three unknowns. A third equation is derived by setting $V_E = 1$ V to minimize the value of $R_{E1}+R_{E2}$.




$$V_E = (R_{E1} + R_{E2})I_E$$

$$R_{E1} + R_{E2} = \frac{1}{3 \times 10^{-3}} = 333$$

Now, solving for $R_C$, $R_{E1}$, and $R_{E2}$, we find $R_C = 2.2$ k$\Omega$, $R_{E1} = 220$ $\Omega$, and $R_{E2} = 110$ $\Omega$ (All commercial values).

We can now proceed to find $R_B$ and $V_{BB}$:

$$R_B \ll (\beta + 1)(R_{E1} + R_{E2})$$

$$R_B = 0.1(\beta_{min} + 1)(R_{E1} + R_{E2}) = 0.1 \times 101 \times 330 = 3.3 \text{ k}\Omega$$

$$\text{KVL:} \quad V_{BB} = R_B I_B + V_{BE} + R_E I_E$$

$$V_{BB} = 3.3 \times 10^3 \frac{3 \times 10^{-3}}{201} + 0.7 + 330 \times 3 \times 10^{-3} = 1.7 \text{ V}$$

Bias resistors $R_1$ and $R_2$ are now found from $R_B$ and $V_B B$:

$$R_B = R_1 \parallel R_2 = \frac{R_1 R_2}{R_1 + R_2} = 3.3 \text{ k}\Omega$$

$$\frac{V_{BB}}{V_{CC}} = \frac{R_2}{R_1 + R_2} = \frac{1}{15} = 0.066$$

$R_1$ can be found by dividing the two equations: $R_1 = 50$ k$\Omega$ and $R_2$ is found from the equation for $V_{BB}$ to be $R_2 = 3.6$k $\Omega$. Commercial values are $R_1 = 51$ k$\Omega$ and $R_2 = 3.6$k $\Omega$

Lastly, we have to find the value of the coupling and bypass capacitors:

$$R'_E == \equiv R_{E2} \parallel (R_{E1} + r_e + \frac{R_B}{\beta}) = 110 \parallel (220 + 25 + \frac{3,300}{200}) = 77.5\ \Omega$$

$$R_i \approx R_B = 3.3\ \text{k}\Omega$$

$$\omega_l = \frac{1}{R_i C_c} + \frac{1}{R'_E C_b} = 2\pi \times 100$$

This is one equation in two unknown ($C_c$ and $C_B$) so one can be chosen freely. Typically $C_b \gg C_c$ as $R_i \approx R_B \gg R_E \gg R'_E$. This means that unless we choose $C_c$ to be very small, the cut-off frequency is set by the bypass capacitor. The usual approach is the choose $C_b$ based on the cut-off frequency of the amplifier and choose $C_c$ such that cut-off frequency of the $R_i C_c$ filter is at least a factor of ten lower than that of the bypass capacitor. Note that in this case, our formula for the cut-off frequency is quite accurate (see discussion in page 95) and is

$$\omega_l \approx \frac{1}{R'_E C_b} = 2\pi \times 100$$

This gives $C_b = 20\ \mu$F. Then, setting

$$\frac{1}{R_i C_c} \ll \frac{1}{R'_E C_b}$$

$$\frac{1}{R_i C_c} = 0.1 \, \frac{1}{R'_E C_b}$$

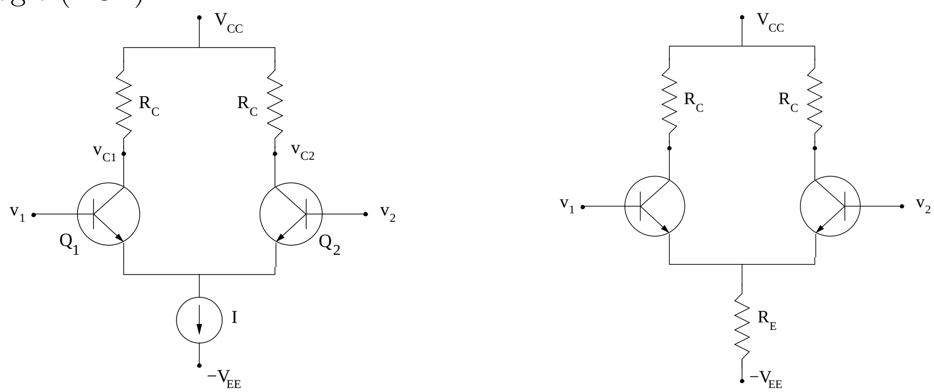
$$R_i C_c = 10 R'_E C_b \quad \rightarrow \quad C_c = 4.7^{-6} = 4.7\ \mu\text{F}$$

So, are design values are: $R_1 = 50$ k$\Omega$, $R_2 = 3.6$ k$\Omega$, $R_{E1} = 220\ \Omega$, $R_{E2} = 110\ \Omega$, $R_C = 2.2$ k$\Omega$, $C_b = 20\ \mu$F, and $C_c = 4.7\ \mu$F.

An alternative approach is to choose $C_b$ (or $C_c$) and compute the value of the other from the formula for the cut-off frequency. For example, if we choose $C_b = 47\ \mu$F, we find $C_c = 0.86\ \mu$F.

# BJT Differential Pairs: Emitter-Coupled Logic and Difference Amplifiers

The differential pairs are the most widely used circuit building block in analog ICs. They are made from both BJT and variant of Field-effect transistors (FET). In addition, BJT differential pairs are the basis for the very-high-speed logic circuit family called Emitter-Coupled Logic (ECL).




The circuit above (on the left) shows the basic BJT differential-pair configuration. It consists of two matched BJTs with emitters coupled together. On ICs, the differential pairs are typically biased by a current source as is shown (using a variant of current mirror circuit). The differential pair can be also biased by using an emitter resistor as is shown on the circuit above right. This variant is typically used when simple circuits are built from individual components (it is not very often utilized in modern circuits). Here we focus on the differential pairs that are biased with a current source.

The circuit has two inputs, $v_1$ and $v_2$ and the output signals can be extracted from the collector of both BJTs ($v_{C1}$ and $v_{C2}$). Inspection of the circuit reveal certain properties. By KCL we find that $i_{C1} + i_{C2} \approx i_{E1} + i_{E2} = I$. That is the two BJTs share the current $I$ between them. So, in general, $i_{C1} \approx i_{E1} \leq I$ and $i_{C2} \approx i_{E2} \leq I$. It is clear that at least one of the BJT pair should be ON (*i.e.,* not in cut-off) in order to satisfy the above equation (both $i_{E1}$ and $i_{E2}$ cannot be zero). Value of $R_C$ is chosen such that either BJT will be in active-linear if its collector current reaches its maximum value of $I$.

$$V_{CC} = R_C i_{C1} + v_{CE1} + V_{ICS} - V_{EE}$$

$$v_{CE1} = V_{CC} + V_{EE} + V_{ICS} - R_C i_{C1} > v_\gamma$$

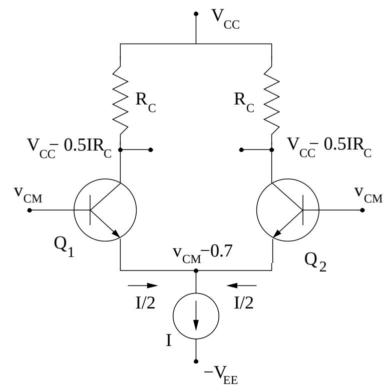
$$R_C < \frac{V_{CC} + V_{EE} + V_{ICS} - V_\gamma}{I} < \frac{V_{CC} + V_{EE} - V_\gamma}{I}$$

With this choice for $R_C$, both BJTs will either be in cut-off or active-linear (and never in saturation).

Lastly, if we write a KVL through a loop that contains the input voltage sources and both base-emitter junctions, we will have:

$$\text{KVL:} \quad -v_1 + v_{BE1} - v_{BE2} + v_2 = 0 \quad \rightarrow \quad v_{BE1} - v_{BE2} = v_1 - v_2$$

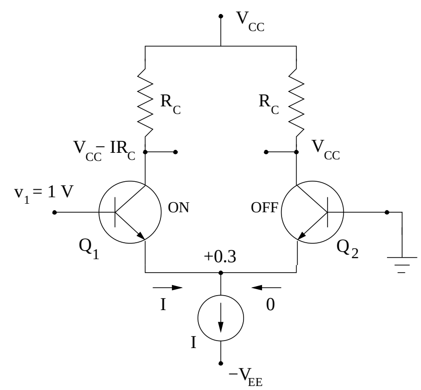
To understand the behavior of the circuit, let's assume that a common voltage of $v_{CM}$ is applied to both inputs: $v_1 = v_2 = v_{CM}$ (CM stands for Common Mode). Then, $v_{BE1} - v_{BE2} = v_1 - v_2 = 0$ or $v_{BE1} = v_{BE2}$. Because identical BJTs are biased with same $v_{BE}$, we should have $i_{E1} = i_{E2}$ and current $I$ is divided equally between the pair:




$$\text{KCL:} \quad i_{C1} \approx i_{E1} = 0.5I \quad \text{and} \quad i_{C2} \approx i_{E2} = 0.5I.$$

As such, both BJTs will be in active linear, $v_{BE1} = v_{BE2} = 0.7$ V and the output voltages of $v_{C1} = v_{C2} = v_{CC} - 0.5IR_C$ will appear at both collectors.

Now, let's assume $v_1 = 1$ V and $v_2 = 0$. Writing KVL on a loop that contains both input voltage sources, we get:




$$\text{KVL:} \quad v_{BE1} - v_{BE2} = v_1 - v_2 = 1 \text{ V}$$

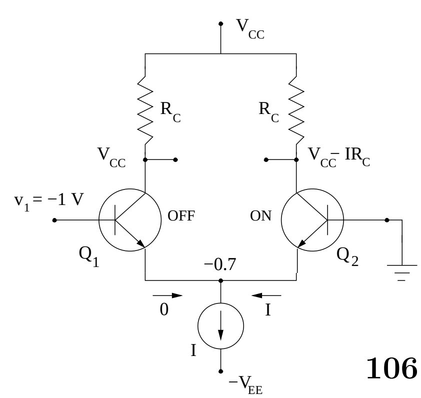
Because $v_{BE} \leq v_\gamma = 0.7$ V, the only way that the above equation can be satisfied is for $v_{BE2}$ to be negative: $Q_2$ is in cut-off and $i_{E2} = 0$. Because of the current sharing properties, $Q_1$ should be on and carry current $I$. Thus:

$$v_{BE1} = 0.7 \text{ V}, \quad v_{BE2} = v_{BE1} - 1 = -0.3 \text{ V}$$

$$i_{C1} = i_{E1} = I, \quad i_{C2} = i_{E2} = 0$$

And voltages of $v_{C1} = V_{CC} - IR_C$ and $v_{C2} = V_{CC}$ will develop at the collectors of the BJT pair. One can easily show that for any $v_1 - v_2 > v_\gamma = 0.7$ V, $Q_1$ will be ON with $i_{C1} = i_{E1} = I$ and $v_{C1} = V_{CC} - IR_C$; and $Q_2$ will be OFF with $i_{C2} = i_{E2} = 0$ and $v_{C2} = V_{CC}$.

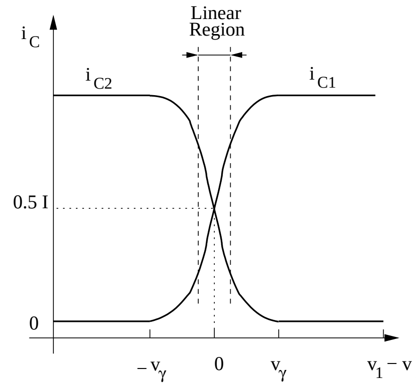
If we now apply $v_1 = -1$ V and $v_2 = 0$, the reverse of the above occurs:




$$\text{KVL:} \quad v_{BE1} - v_{BE2} = v_1 - v_2 = -1 \text{ V}$$

In this case, $Q_2$ will be ON and carry current $I$ and $Q_1$ will be OFF. Again, it is easy to show that this is true for any $v_1 - v_2 < -v_\gamma = -0.7$ V.

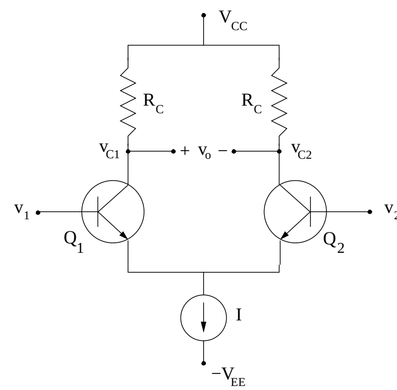
The response of the BJT differential pair to a pair of input signals with $v_d = v_1 - v_2$ is summarized in this graph. When $v_d$ is large, the collector voltages switch from one state $v_{CC}$ to another state $v_{CC} - IR_C$ depending on the sign $v_d$. As such, the differential pair can be used as a logic gate and a family of logic circuits, emitter-coupled logic, is based on differential pairs. In fact, because a BJT can switch very rapidly between cut-off and active-linear regimes, ECL circuits are the basis for very fast logic circuits today.




For small $v_d$ (typically $\leq 0.2$ V), the circuit behaves as a linear amplifier. In this case, the circuit is called a differential amplifier and is the most popular building block of analog ICs.

**Differential Amplifiers**

The properties of the differential amplifier above (case of $v_d$ small) can be found in a straight-forward manner. The input signals $v_1$ and $v_2$ can be written in terms of their difference $v_d = v_1 - v_2$ and their average (common-mode voltage $v_{CM}$) as:




$$v_{CM} = \frac{v_1 + v_2}{2} \quad \text{and} \quad v_d = v_1 - v_2$$

$$v_1 = v_{CM} + 0.5 v_d$$

$$v_2 = v_{CM} - 0.5 v_d$$

The response of the circuit can now be found using superposition principle by considering the response to: case 1) $v_1 = v_{CM}$ and $v_2 = v_{CM}$ and case 2) $v_1 = 0.5v_d$ and $v_2 = -0.5v_d$. The response of the circuit to case 1, $v_1 = v_2 = v_{CM}$, was found in page 108. Effectively, $v_{CM}$ sets the bias point for both BJTs with $i_{C1} = i_{E1} = i_{C2} = i_{E2} = 0.5I$, collector voltages of $v_{C1} = v_{C2} = v_{CC} - 0.5IR_C$, and a difference of zero between to collector voltages, $v_o = v_{C1} - v_{C2} = 0$.

To find the response of the circuit to case 2, $v_1 = 0.5v_d$ and $v_2 = -0.5v_d$, we can use our small signal model (since $v_d$ is small). Examination of the circuit reveals that each of the BJTs form a common emitter amplifier configuration (with no emitter resistor). Using our analysis of common emitter amplifiers ($A_v = R_C/r_e$), we have:

$$v_{c1} = A_v v_i = \frac{R_C}{r_e}(0.5v_d) \quad \text{and} \quad v_{c2} = A_v v_i = \frac{R_C}{r_e}(-0.5v_d)$$

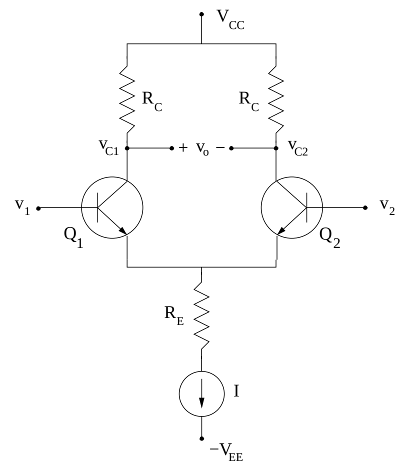
$$v_o = v_{c1} - v_{c2} = \frac{R_C}{r_e} v_d$$

Summing the responses for case 1 and 2, we find that the output voltage of this amplifier is

$$v_o = 0 + \frac{R_C}{r_e}\, v_d = \frac{R_C}{r_e}\, v_d \quad \rightarrow \quad A_v = \frac{R_C}{r_e}$$

similar to a common emitter amplifier. The additional complexity of this circuit compared to our standard common emitter amplifier results in three distinct improvements:
1) This is a "DC" amplifier and does not require a coupling capacitor.
2) Absence of biasing resistors ($R_b \rightarrow \infty$) leads to a higher input resistance, $R_i = r_\pi \parallel R_B = r_\pi$.
3) Elimination of biasing resistors makes it more suitable for IC implementation.

It should be obvious that a differential amplifier configuration can be developed which is similar to a common emitter amplifier with a emitter resistor (to stabilize the gain and increase the input resistance dramatically). Such a circuit is shown. Note that $R_E$ in this circuit is not used to provide stable DC biasing (current source does that). Its function is to provide negative feedback for amplification of small signal, $v_d$. Following the above procedure, one can show that the gain of this amplifier configuration is:




$$v_o = \frac{R_C}{R_E + r_e}\, v_d \quad \rightarrow \quad A_v = \frac{R_C}{R_E + r_e}$$

As with standard CE amplifer with emitter resistance, the input impdenace is also increased dramatically by negative feedback of $R_E$ (and absence of biasing resistors, $R_b \rightarrow \infty$):

$$R_i = R_B \parallel [\beta(R_{E1} + r_e)] = \beta(R_{E1} + r_e)$$

# Lecture 22

## Frequency Response of Amplifiers (II)

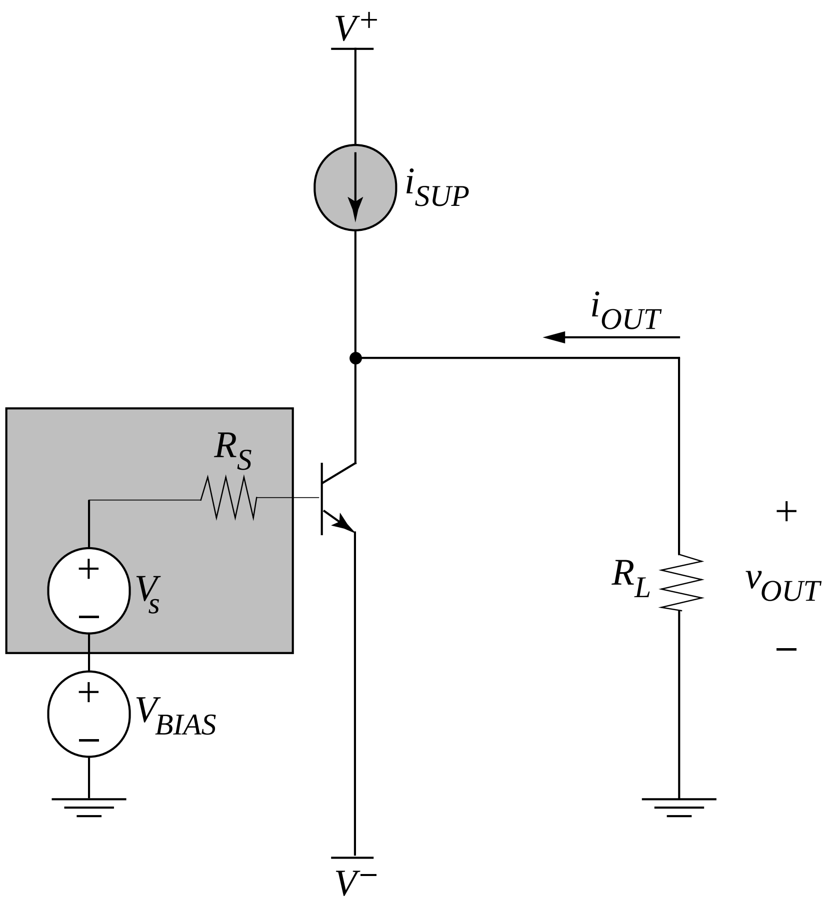
**VOLTAGE AMPLIFIERS**

## Outline

1. Full Analysis
2. Miller Approximation
3. Open Circuit Time Constant

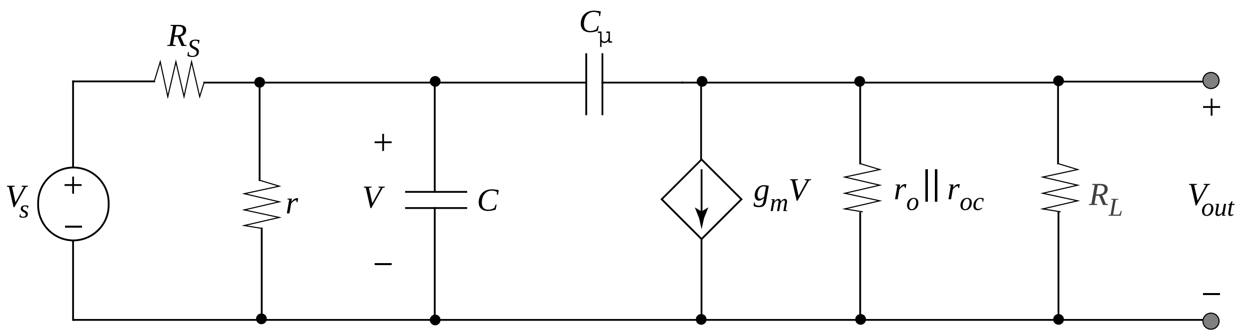
**Reading Assignment:**
Howe and Sodini, Chapter 10, Sections 10.1-10.4

# Common Emitter Amplifier



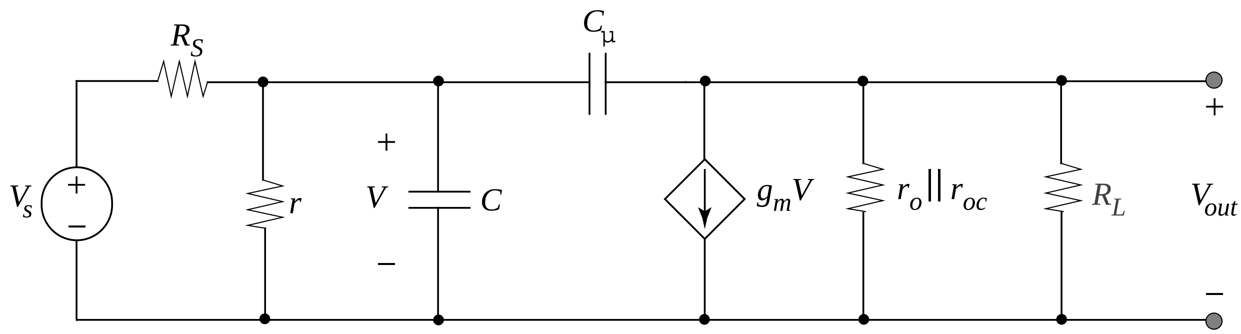

- Operating Point Analysis
  - $v_s$=0, $R_S$ = 0, $r_o \rightarrow \infty$, $r_{oc} \rightarrow \infty$, $R_L \rightarrow \infty$
  - Find $V_{BIAS}$ such that $I_C$=$I_{SUP}$ with the BJT in the forward active region

# Frequency Response Analysis of the Common Emitter Amplifier

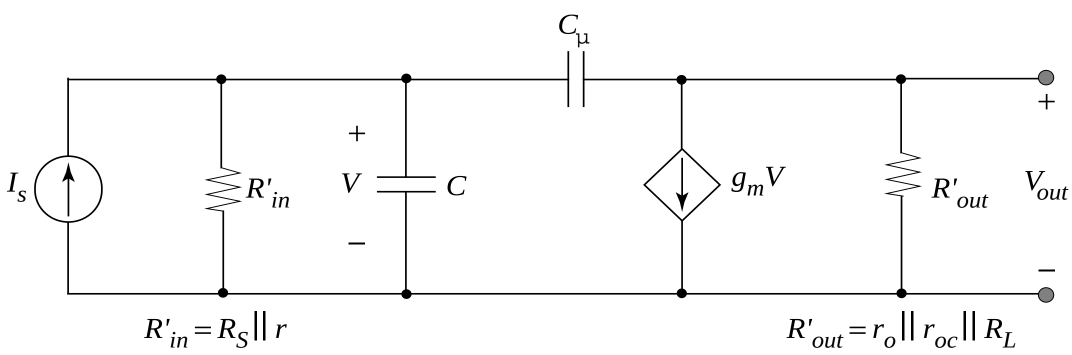



- Frequency Response
  - Set $V_{BIAS} = 0$.
  - Substitute BJT small signal model (with capacitors) including $R_S$, $R_L$, $r_o$, $r_{oc}$
  - Perform impedance analysis

# 1. Full Analysis of CE Voltage Amplifier




Replace voltage source and resistance with current source and resistance using Norton Equivalent




**Node 1:**

$$\mathbf{I_s = \frac{V_\pi}{R'_{in}} + j\omega C_\pi V_\pi + j\omega C_\mu \left(V_\pi - V_{out}\right)}$$

**Node 2:**

$$\mathbf{g_m V_\pi + \frac{V_{out}}{R'_{out}} = j\omega C_\mu \left(V_\pi - V_{out}\right)}$$

# Full Frequency Response Analysis (contd.)

- Re-arrange **2** and obtain an expression for $V_\pi$
- Substituting it into **1** and with some manipulation, we can obtain an expression for $V_{out} / I_s$:

$$\frac{V_{out}}{I_s} = \frac{-R'_{in}R'_{out}\left(g_m - j\omega C_\mu\right)}{1 + j\omega\left(R'_{out}C_\mu + R'_{in}C_\mu + R'_{in}C_\pi + g_m R'_{out}R'_{in}C_\mu\right) - \omega^2 R'_{out}R'_{in}C_\mu C_\pi}$$

Changing input current source back to a voltage source:

$$\frac{V_{out}}{V_s} = \frac{-g_m R'_{out}\left(\frac{r_\pi}{R_S + r_\pi}\right)\left(1 - j\omega\frac{C_\mu}{g_m}\right)}{1 + j\omega\left(R'_{out}C_\mu + R'_{in}C_\mu\left(1 + g_m R'_{out}\right) + R'_{in}C_\pi\right) - \omega^2 R'_{out}R'_{in}C_\mu C_\pi}$$

where $R'_{in} = \mathbf{R_S} \,\|\, \mathbf{r_\pi}$ and $R'_{out} = \mathbf{r_o} \,\|\, \mathbf{r_{oc}} \,\|\, \mathbf{R_L}$

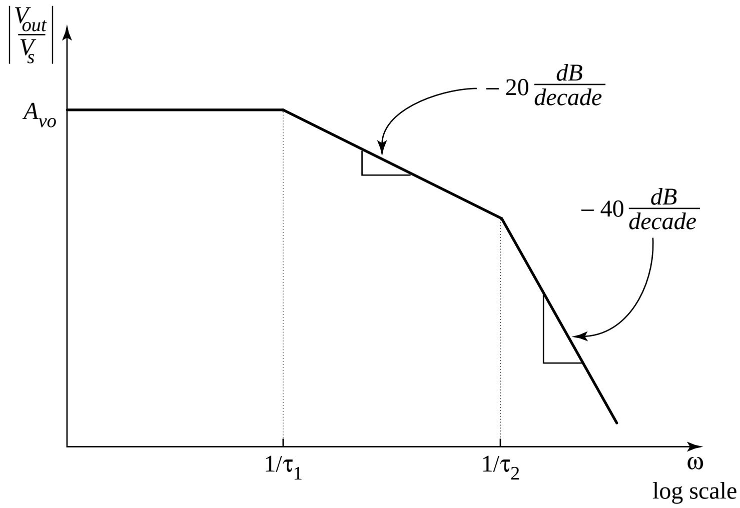
We can ignore zero at $g_m/C_\mu$ because it is higher than $\omega_T$.

The gain can be expressed as:

$$\frac{V_{out}}{V_s} = \frac{A_{vo}}{\left(1 + j\omega\tau_1\right)\left(1 + j\omega\tau_2\right)} = \frac{A_{vo}}{1 - j\omega\left(\tau_1 + \tau_2\right) - \omega^2\tau_1\tau_2}$$

where $A_{vo}$ is the gain at low frequency and $\tau_1$ and $\tau_2$ are the two time constants associated with the capacitors

# Denominator of the System Transfer Function




$$\tau_1 + \tau_2 = R'_{out}C_\mu + R'_{in}C_\mu(1 + g_m R'_{out}) + R'_{in}C_\pi$$

$$\tau_1 \bullet \tau_2 = R'_{out}R'_{in}C_\mu C_\pi$$

We could solve for $\tau_1$ and $\tau_2$ but is algebraically complex.

- However, if we assume that $\tau_1 >> \tau_2$ ,$\Rightarrow$ $\tau_1 + \tau_2 \approx \tau_1$.
- This is a conservative estimate since the *true* $\tau_1$ is actually smaller and hence the *true* bandwidth is actually larger than:

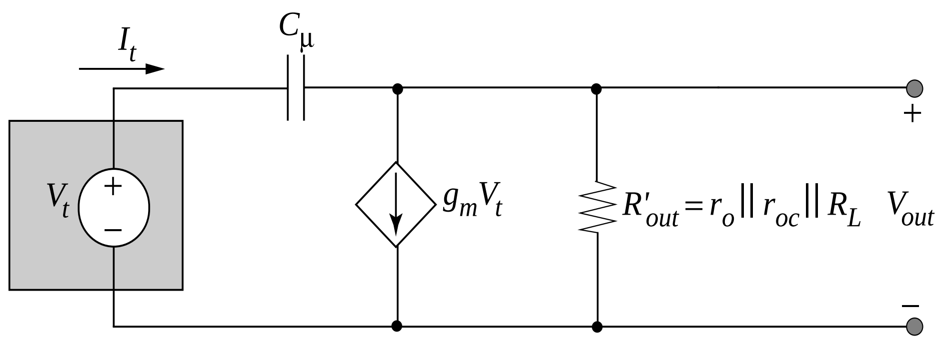
$$\tau_1 \approx R'_{in}\left[C_\pi + C_\mu(1 + g_m R'_{out})\right] + R'_{out}C_\mu$$

Then:

$$\omega_{3dB} = \frac{1}{\tau_1} = \frac{1}{R'_{in}\left[C_\pi + C_\mu(1 + g_m R'_{out})\right] + R'_{out}C_\mu}$$

# 2. The Miller Approximation

**Effect of $C_\mu$ on the Input Impedance:**




The input impedance $Z_i$ is determined by applying a test voltage $V_t$ to the input and measuring $I_t$:

$$V_{out} = -g_m V_t R'_{out} + I_t R'_{out}$$

The Miller Approximation assumes that current through $C_\mu$ is small compared to the transconductance generator

$$I_t << |g_m V_t|$$

$$V_{out} \approx -g_m V_t R'_{out}$$

We can relate $V_t$ and $V_{out}$ by

$$V_t - V_{out} = \frac{I_t}{j\omega C_\mu}$$

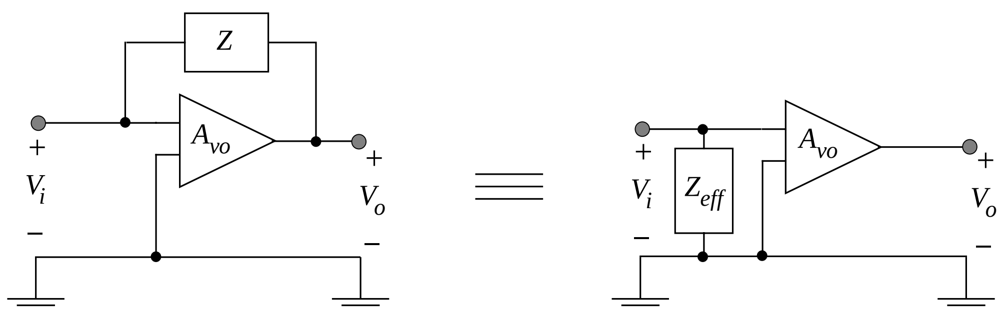
# The Miller Approximation (contd.)

After some Algebra:

$$\frac{V_t}{I_t} = Z_{eff} = \frac{1}{j\omega C_\mu (1 + g_m R'_{out})} = \frac{1}{j\omega C_\mu \left(1 - A_{vC_\mu}\right)}$$

The effect of $C_\mu$ at input is that $C_\mu$ is "Miller multiplied" by $(1-A_{vC\mu})$

## Generalized "Miller Effect"

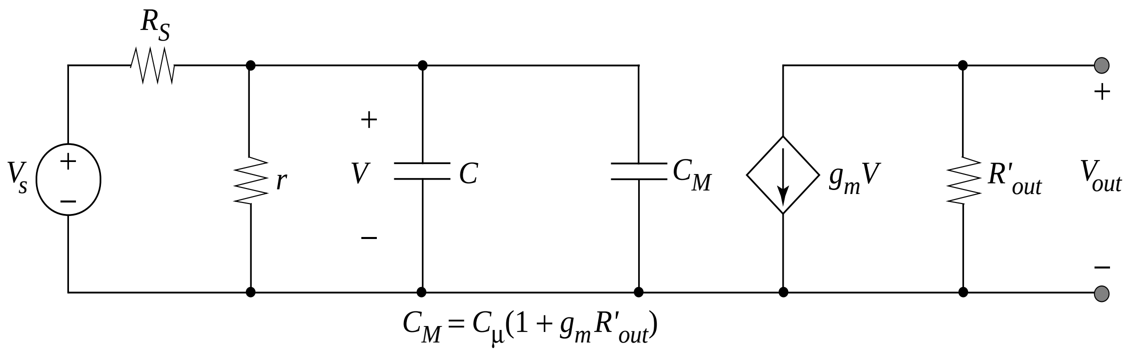



$Z_{eff} = Z/(1 - A_{vo})$

- An impedance connected across an amplifier with voltage gain $A_{vo}$ can be replaced by an an impedance to ground … divided by $(1-A_{vo})$
- $A_{vo}$ is large and negative for common-emitter and common-source amplifiers
- Capacitance at input is magnified.

$$Z_{eff} = \frac{Z}{(1 - A_{vo})}$$

# Frequency Response of the CE Voltage Amplifier Using Miller Approximation




- The Miller capacitance is lumped together with $C_\pi$, which results in a single pole low pass filter at the input

$$\frac{V_{out}}{V_s} = -g_m\left(\frac{r_\pi}{r_\pi + R_S}\right)R'_{out}\left[\frac{1}{1 + j\omega(C_\pi + C_M)(R_S \parallel r_\pi)}\right]$$

- At low frequency (DC) the small signal voltage gain is

$$\frac{V_{out}}{V_s} = -g_m\left(\frac{r_\pi}{r_\pi + R_S}\right)R'_{out}$$

- The frequency at which the magnitude of the voltage gain is reduced by $1/\sqrt{2}$ is

$$\omega_{3dB} = \frac{1}{(R_s \parallel r_\pi)(C_\pi + C_M)} = \left[\frac{1}{(R_s \parallel r_\pi)}\right]\left[\frac{1}{C_\pi + (1 + g_m R'_{out})C_\mu}\right]$$

# 3. Open Circuit Time Constant Analysis

**Assumptions**:

- No zeros
- One "dominant" pole ($1/\tau_1 << 1/\tau_2 , 1/\tau_3 \ldots 1/\tau_n$ )
- N capacitors

$$\frac{V_{out}}{V_s} = \frac{A_{vo}}{(1 + j\omega\tau_1)(1 + j\omega\tau_2)(1 + j\omega\tau_n)}$$

The example shows a voltage gain; however, it could be $I_{out}/V_s$ or $V_{out}/I_s$.

Multiplying out the denominator:

$$\frac{V_{out}}{V_s} = \frac{A_{vo}}{1 + b_1(j\omega) + b_2(j\omega)^2 + \ldots + b_n(j\omega)^n}$$

where $b_1 = \tau_1 + \tau_2 + \tau_3 + \ldots. + \tau_n$

It can be shown that the coefficient $b_1$ can be found exactly [see Gray & Meyer, 3rd Edition, pp. 502-506]

$$b_1 = \left( \sum_{i=1}^{N} R_{Ti} C_i \right) = \left( \sum_{i}^{N} \tau_{C_{io}} \right)$$

- $\tau_{Cio}$ is the open-circuit time constant for capacitor $C_i$
- $C_i$ is the $i^{th}$ capacitor and $R_{Ti}$ is the Thevenin resistance across the $i^{th}$ capacitor terminals (with all capacitors open-circuited)

# Open Circuit Time Constant Analysis

## Estimating the Dominant Pole

The dominant pole of the system can be estimated by:

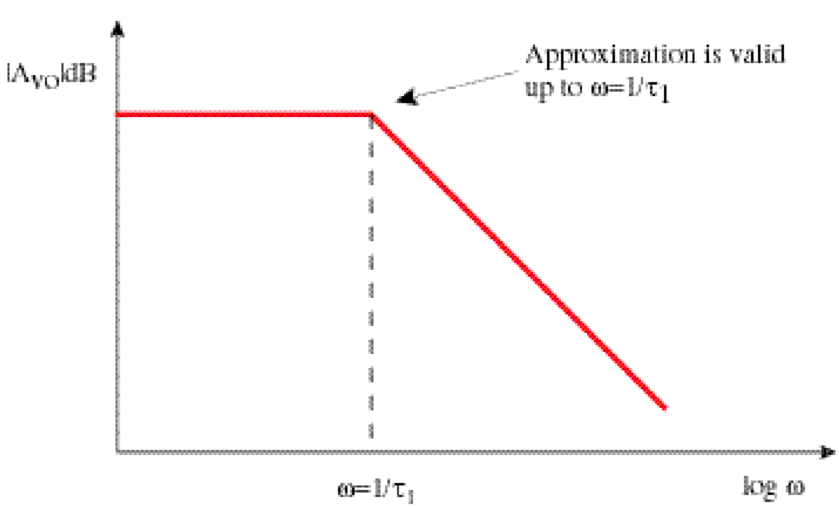
$b_1 = \tau_1 + \tau_2 + \tau_3 + \ldots + \tau_n$

$$b_1 = \left( \sum_{i=1}^{N} R_{Ti} C_i \right) \approx \tau_1 = \frac{1}{\omega_1}$$

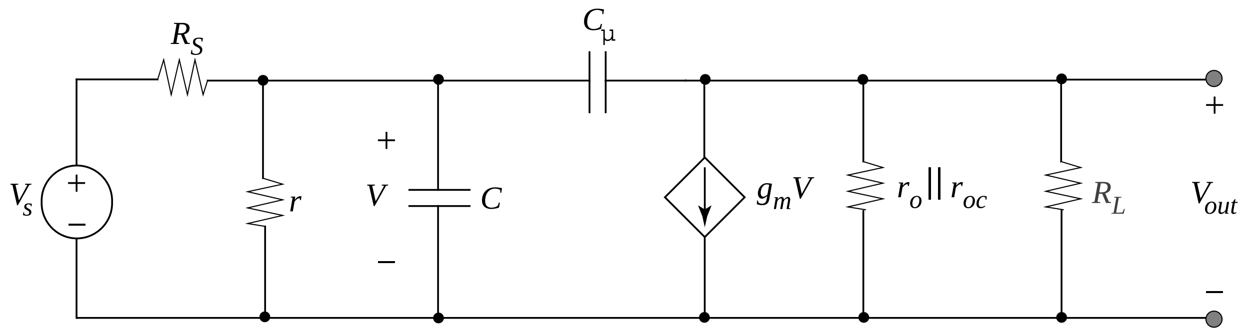
$R_{Ti}C_i$ is the **open-circuit time constant** for capacitor $C_i$

## Power of the Technique:

- Estimates the contribution of each capacitor to the dominant pole frequency separately
- Enables the designer to understand what part of a complicated circuit is responsible for limiting the bandwidth of amplifier
- The approximate magnitude of the Bode Plot is



# Common Emitter Amplifier Analysis Using OCT




From the Full Analysis

$$\frac{V_{out}}{V_s} = \frac{-g_m R'_{out}\left(\frac{r_\pi}{R_S + r_\pi}\right)\left(1 - j\omega\frac{C_\mu}{g_m}\right)}{1 + j\omega\left(R'_{out}C_\mu + R'_{in}C_\mu\left(1 + g_m R'_{out}\right) + R'_{in}C_\pi\right) - \omega^2 R'_{out}R'_{in}C_\mu C_\pi}$$

where $R'_{in} = R_S \,||\, r_\pi$ and $R'_{out} = r_o \,||\, r_{oc} \,||\, R_L$

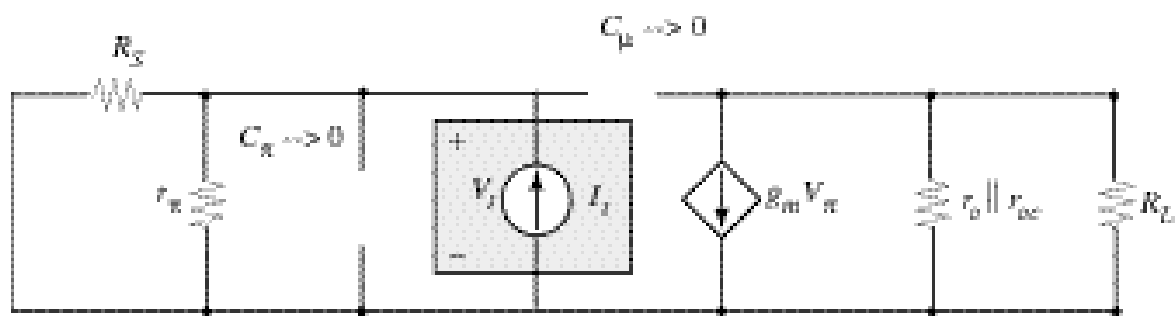
$$b_1 = R'_{out}C_\mu + R'_{in}C_\mu\left(1 + g_m R'_{out}\right) + R'_{in}C_\pi$$

$$\omega_{3dB} \approx \frac{1}{b_1} = \frac{1}{R'_{out}C_\mu + R'_{in}C_\mu\left(1 + +g_m R'_{out}\right) + R'_{in}C_\pi}$$

# Common Emitter Amplifier Analysis Using OCT—Procedure

1. Eliminate all independent sources [e.g. $V_s \rightarrow 0$]
2. Open-circuit all capacitors
3. Find the Thevenin resistance by applying $i_t$ and measuring $v_t$.

## Time Constant for $C_\pi$



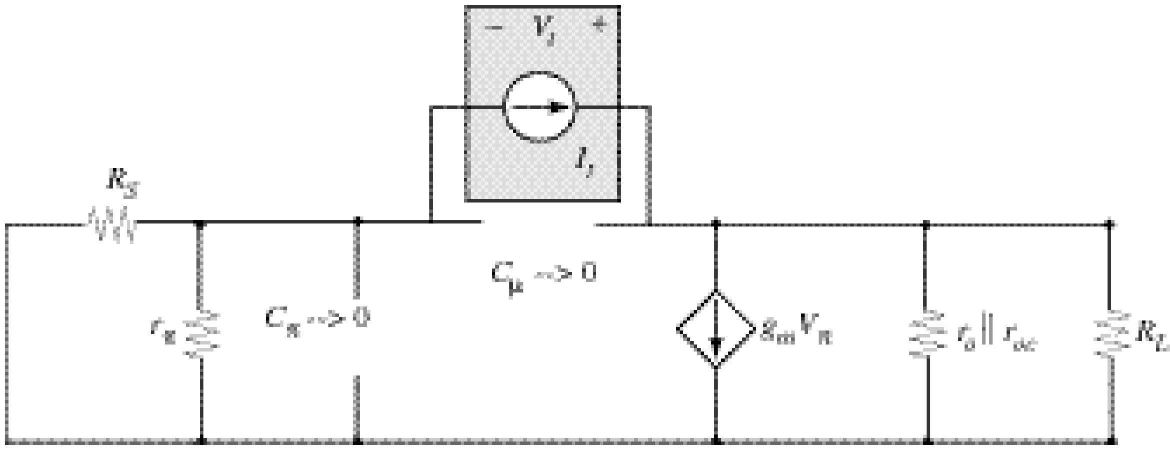
Result obtained by inspection

$$R_{T\pi} = R_S \,||\, r_\pi$$

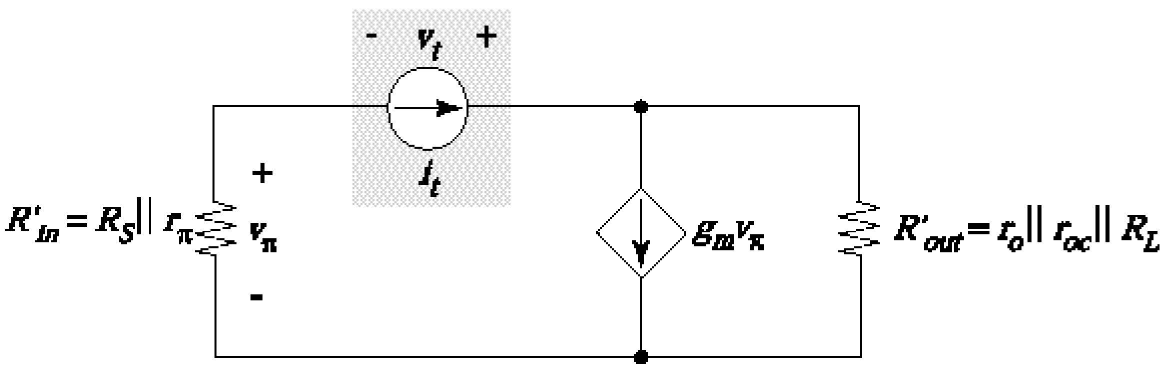
$$\tau_{C_{\pi o}} = R_{T\pi} C_\pi$$

# Common Emitter Amplifier Analysis Using OCT—Time Constant for $C_\mu$

Using the same procedure




Let $R'_{in} = R_S \parallel r_\pi$ and $R'_{out} = r_o \parallel r_{oc} \parallel R_L$




$$-i_t = \frac{v_\pi}{R'_{in}} \qquad i_t = \frac{v_t + v_\pi}{R'_{out}} + g_m v_\pi$$

Eliminate $v_\pi$:

$$\frac{v_t}{i_t} = R_{T\mu} = R'_{out} + R'_{in}\left(1 + g_m R'_{out}\right)$$

$$\tau_{C_{\mu o}} = R_{T\mu} C_\mu = \left[R'_{out} + R'_{in}\left(1 + g_m R'_{out}\right)\right] C_\mu$$

# Common Emitter Amplifier Analysis Using OCT—Dominant Pole

Summing individual time constants

$$b_1 = R_{T\pi} C_\pi + R_{T\mu} C_\mu$$

$$b_1 = R'_{out} C_\mu + R'_{in} C_\mu \left(1 + g_m R'_{out}\right) + R'_{in} C_\pi$$

Assume $\tau_1 >> \tau_2$

$$b_1 = \tau_1 + \tau_2 \approx \tau_1$$

$$b_1 = R'_{out} C_\mu + R'_{in} C_\mu \left(1 + g_m R'_{out}\right) + R'_{in} C_\pi$$

$$\omega_{3dB} \approx \frac{1}{b_1} = \frac{1}{R'_{out} C_\mu + R'_{in} C_\mu \left(1 + g_m R'_{out}\right) + R'_{in} C_\pi}$$

This result is very similar to the Miller Effect calculation
Additional term $R'_{out}C_\mu$ taken into account

# Compare the Three Methods of Analyzing the Frequency Response of CE Amplifier

**Full Analysis—**

$$\omega_{3dB} \approx \frac{1}{\tau_1} = \frac{1}{R'_{out}C_\mu + R'_{in}C_\mu\left(1 + g_m R'_{out}\right) + R'_{in}C_\pi}$$

**Miller Approximation—**

$$\omega_{3dB} = \left[\frac{1}{R'_{in}}\right]\left[\frac{1}{C_\pi + \left(1 + g_m R'_{out}\right)C_\mu}\right]$$

**Open Circuit Time Constant—**

$$\omega_{3dB} \approx \frac{1}{b_1} = \frac{1}{R'_{out}C_\mu + R'_{in}C_\mu\left(1 + g_m R'_{out}\right) + R'_{in}C_\pi}$$

# What did we learn today?

## Summary of Key Concepts

- Full Analysis
  - Assumes that $\tau_1 + \tau_2 \approx \tau_1$

$$\omega_{3dB} \approx \frac{1}{\tau_1} = \frac{1}{R'_{out}C_\mu + R'_{in}C_\mu\left(1 + g_m R'_{out}\right) + R'_{in}C_\pi}$$

- Miller Approximation
  - Does not take into account $R'_{out}$

$$\omega_{3dB} = \left[\frac{1}{R'_{in}}\right]\left[\frac{1}{C_\pi + \left(1 + g_m R'_{out}\right)C_\mu}\right]$$

- Open Circuit Time Constant (OCT)
  - Assumes a dominant pole as full analysis

$$\omega_{3dB} \approx \frac{1}{b_1} = \frac{1}{R'_{out}C_\mu + R'_{in}C_\mu\left(1 + g_m R'_{out}\right) + R'_{in}C_\pi}$$

# Physics lecture notes on Electronics

*Lecture-7*

## BJT Amplifiers

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Physics lecture notes on Electronics, 2010-2011 Ranjdar M. Abdullah

***Outline:***

- Transistor AC Equivalent Circuits
  - r-parameters
  - Comparison of the AC ($\beta_{ac}$) to the DC ($\beta_{DC}$)
- Bipolar Transistor Amplifier Configurations
  1. The Common Emitter Amplifier Configuration
  2. The Common Collector Amplifier Configuration
  3. The Common Base Amplifier Configuration
- Darlington Pair
- Sziklai pair
- Multistage Amplifiers Gain

# Transistor AC Equivalent Circuits

- To visualize the operation of a transistor in an amplifier circuit, it is often useful to represent the device by an equivalent circuit.

## r-Parameters

- There are five **r Parameters** are given in table below.
- An r-parameter equivalent circuit for a bipolar junction transistor .

| r Parameter | Description |
|---|---|
| $\alpha_{ac}$ | Ac alpha ($I_c/I_e$) |
| $\beta_{ac}$ | Ac beta ($I_c/I_b$) |
| $r'_e$ | Ac emitter resistance |
| $r'_b$ | Ac base resistance |
| $r'_c$ | Ac collector resistance |

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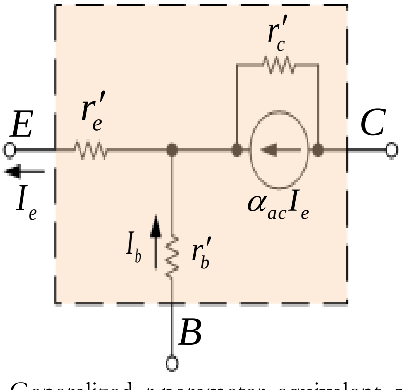
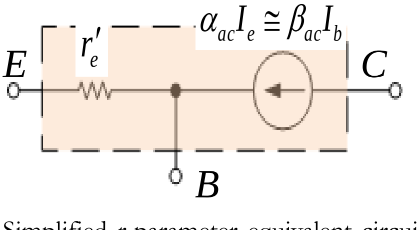
# Transistor AC Equivalent Circuits

## r-Parameters

- The effect of the ac base resistance ( $r'_b$ ) is usually small enough to neglect, so it can be replaced by a short.
- The ac collector resistance ( $r'_c$ ) is usually several hundred kilohms and can be replaced by an open.




- Generalized r-parameter equivalent circuit for a bipolar junction transistor




- Simplified r-parameter equivalent circuit for a bipolar junction transistor

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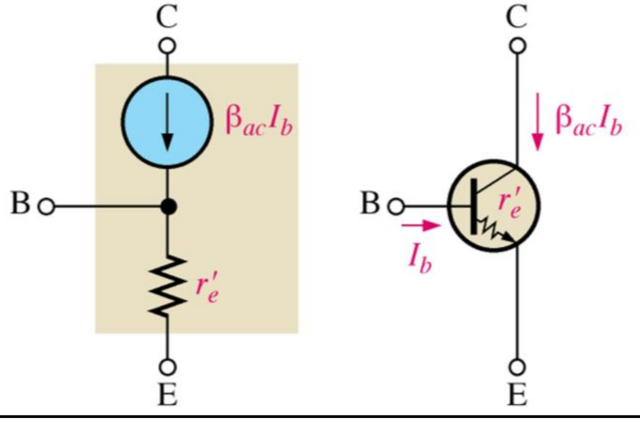
# Transistor AC Equivalent Circuits

## r-Parameter

- These factors are shown in transistor symbol in the figure below.
- For amplifier analysis, the ac emitter resistance, $r'_e$ , is the most important of the r parameters.

$$r'_e \cong \frac{25mV}{I_E}$$

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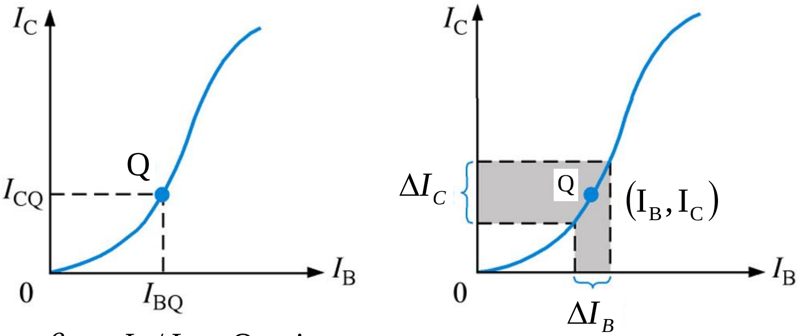
# Transistor AC Equivalent Circuits

## Comparison of the AC ($\beta_{ac}$) to the DC ($\beta_{DC}$)

- For a typical transistor, a graph of $I_C$ versus $I_B$ is nonlinear, as shown in figure (a).
- If you pick a **Q-point** on the curve and cause the base current to vary an amount $\Delta I_B$, then collector current will vary an amount $\Delta I_C$ as shown in part (b). At different points on the nonlinear curve, the ratio $\Delta I_C/\Delta I_B$ will be different, and it may also differ from the $I_C/I_B$ ratio at the **Q-point**. Since $\beta_{DC}=I_C/I_B$ and $\beta_{ac}= \Delta I_C/\Delta I_B$, the values of these two quantities can differ slightly.




$\beta_{DC} = I_C / I_B$ at Q point

$\beta_{ac} = \Delta I_C / \Delta I_B$

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# Bipolar Transistor Amplifier Configurations

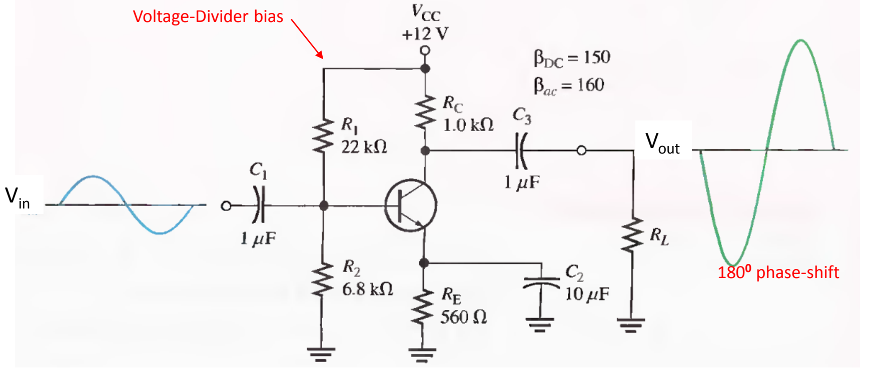
- As the BJT is a **3** terminal device, there are basically **3** possible way to connect it within an electronic circuit with one terminal being common to both the input and output.
- Each method of connection responding differently to its input signal within a circuit as the static characteristics of the transistor vary with each circuit arrangement.

1. The Common **Emitter** Amplifier Configuration
2. The Common **Collector** Amplifier Configuration
3. The Common **Base** Amplifier Configuration



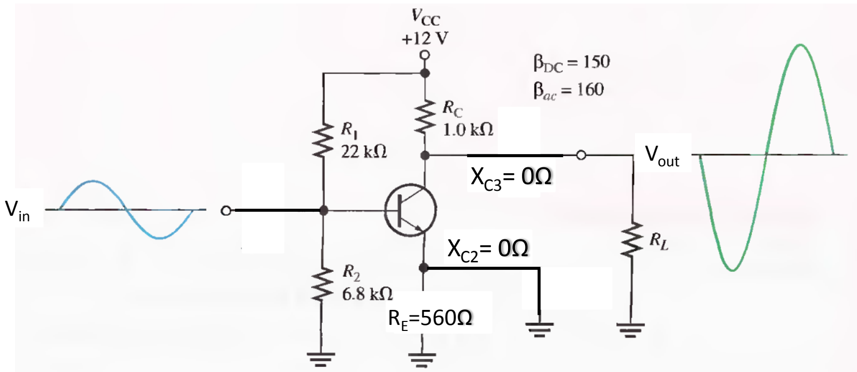
# The Common-Emitter Amplifier

- Input is at the base. Output is at the collector.
- There is a phase inversion from input to output, the amplified output is 180° out of phase with the input. When the voltage on the input starts to go positive, the device is forward biased. As forward bias increases, collector current increases. That's how the device works. Turn it on more, and more current flows through it. As collector current increases, collector voltage decreases. There's the key. Increasing base voltage causes increasing collector current and decreases collector voltage. Increasing base voltage causes decreasing collector voltage. And the opposite is true.



# The Common-Emitter Amplifier

- $C_1$ and $C_3$ are coupling capacitors for the input and output signals.
- $C_2$ is the emitter-bypass capacitor ($X_{C2} \approx 0\Omega$ for the AC signal current). The emitter bypass capacitor helps increase the gain by allowing the ac signal to pass more easily.
- All capacitors must have a negligible reactance at the frequency of operation
- Emitter is at ac ground due to the bypass capacitor.
- The $X_{C2(bypass)}$ should be about ten times less than $R_E$.
- The AC equivalent circuit is shown in the following:

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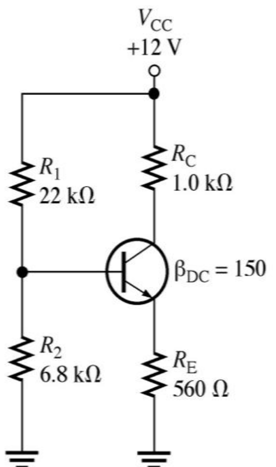
# The Common-Emitter Amplifier

## DC Equivalent Circuit Analysis

- To analyze the amplifier, the dc bias values must first be determined. To do this, a dc equivalent circuit is developed by replacing the coupling and bypass capacitors with open (remember, a capacitor appears open to dc).
- The dc component of the circuit "sees" only the part of the circuit that is within the boundaries of $C_1$, $C_2$, and $C_3$ as the dc will not pass through these components. The equivalent circuit for dc analysis is shown.
- The methods for dc analysis are just are the same as dealing with a voltage-divider circuit.

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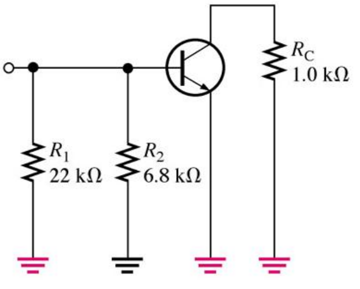
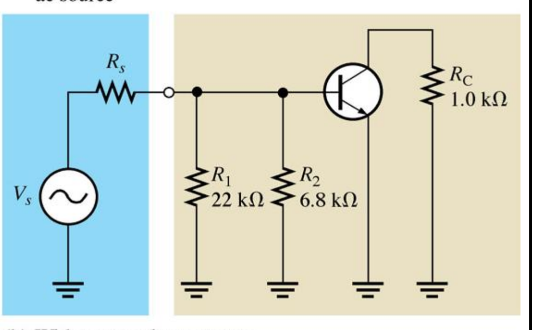
# The Common-Emitter Amplifier

## The AC Equivalent Circuit Analysis

- The ac equivalent circuit basically replaces the capacitors($X_C \approx 0\Omega$) with shorts, being that ac passes through easily through them.
- The power supplies are also effectively shorts to ground for ac analysis at the signal frequency ($R_{int}=0\Omega$ of the battery).




(a) Without an ac voltage source.
AC ground is shown in red.




(b) With an ac voltage source

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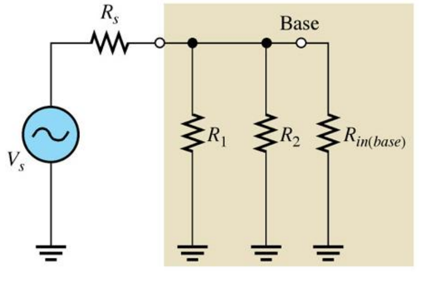
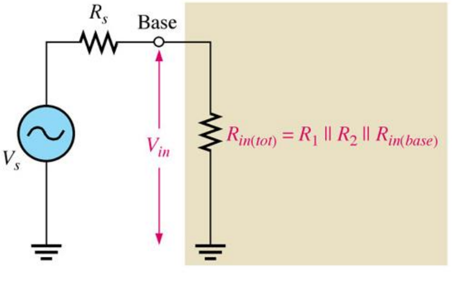
# The Common-Emitter Amplifier

## The AC Equivalent Circuit Analysis

- We can look at the input voltage in terms of the equivalent base circuit (ignore the other components from the previous diagram).
- Note the use of simple series-parallel analysis skills for determining Vin.

$$V_{in} = \frac{R_{in}}{R_S + R_{in}} V_S$$

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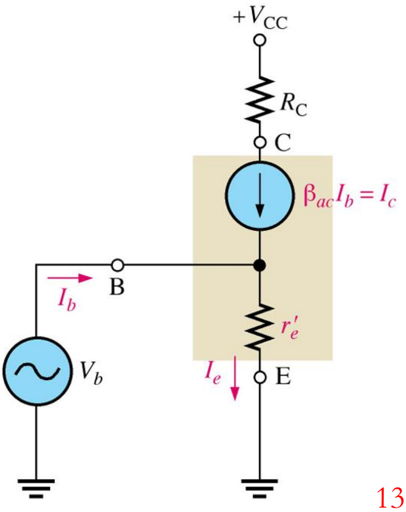
# The Common-Emitter Amplifier

## The AC Equivalent Circuit Analysis

- The **input resistance** as seen by the input voltage can be illustrated by the **r parameter** equivalent circuit. The simplified formula below is used.

$$R_{IN(Base)} \cong \beta_{DC} R_E$$

$$R_{in(Base)} \cong \beta_{ac} r'_e$$

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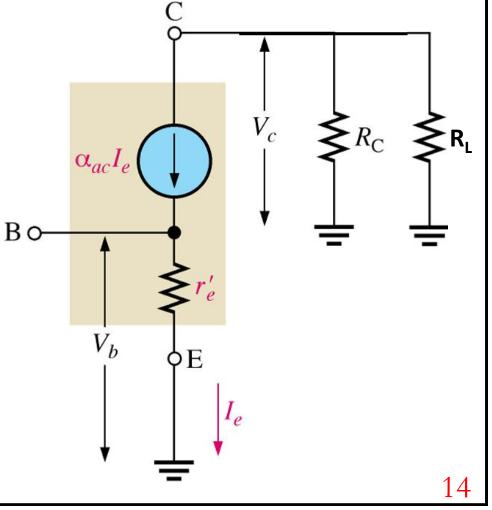
# The Common-Emitter Amplifier

## The AC Equivalent Circuit Analysis

- The **output resistance** is for all practical purposes the value of

$$R_c \cong R_C \parallel R_L$$

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# The Common-Emitter Amplifier

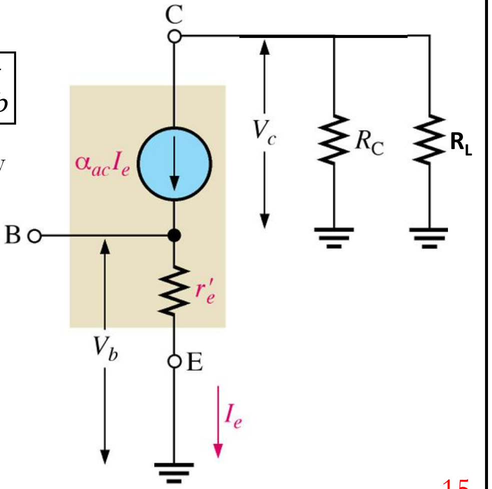
## The AC Equivalent Circuit Analysis

- **Voltage gain** can be easily determined by dividing the ac output voltage by the ac input voltage.

$$A_v = V_{out} / V_{in} = V_c / V_b$$

- **Voltage gain** can also be determined by the simplified formula below.

$$A_v = R_c / r'_e$$

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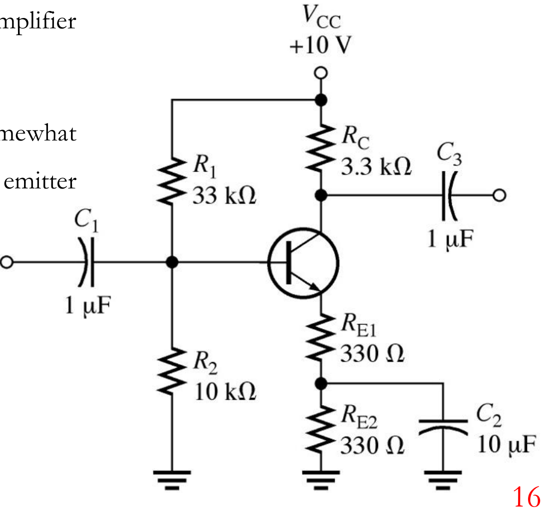
# The Common-Emitter Amplifier

## The AC Equivalent Circuit Analysis

- The bypass capacitor makes the gain unstable since transistor amplifier becomes more dependent on $\mathbf{I_E}$.
- This effect can be swamped or somewhat improved by adding another emitter resistor($\mathbf{R_{E1}}$).

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# The Common-Emitter Amplifier

## The AC Equivalent Circuit Analysis

- Taking the **attenuation** from the ac supply internal resistance and input resistance into consideration is included in the overall gain

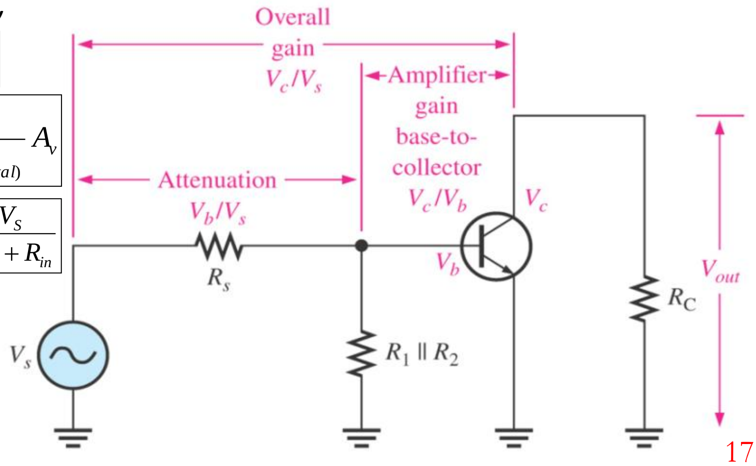
***A'$_v$ = (V$_b$/V$_s$)A$_v$***

$$A_v = V_c / V_b$$

$$A_v^{'} = \frac{R_{in(total)}}{R_s + R_{in(total)}} A_v$$

$$A_i = \frac{I_C}{I_S},\ I_S = \frac{V_S}{R_S + R_{in}}$$

$$A_p = A_v A_i$$

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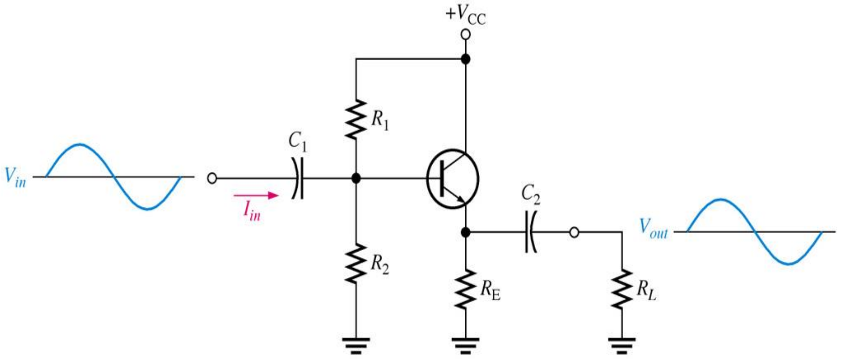
# The Common-Collector Amplifier

- The **Common-Collector** circuit with voltage-divider bias is shown figure below.
- Notice that the input signal is capacitively coupled to the base, the output signal is capacitively coupled from the emitter, and the collector is at ac ground.
- The CC amplifier is usually referred as the **emitter follower** (since the output voltage at the emitter follows the input voltage at the base.

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# The Common-Collector Amplifier

**Input and Output Resistance**

$$R_{in(Base)} = \frac{V_{in}}{I_{in}} = \frac{V_b}{I_b} = \frac{Ie(r'_e + R_e)}{I_b}$$

since $I_e \cong I_c = \beta_{ac} I_b$,

$$R_{in(Base)} \cong \frac{\beta_{ac} I_b (r'_e + R_e)}{I_b}$$

The $I_b$ terms cancel; therefore,

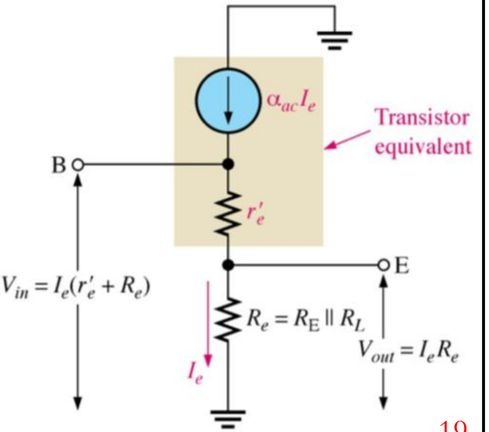
$$R_{in(Base)} \cong \beta_{ac}(r'_e + R_e)$$

If $R_e >> \beta_{ac} r'_e$

$$R_{in(Base)} \cong \beta_{ac}(r'_e + R_e)$$

$$R_{in(Base)} \cong \beta_{ac} R_e$$

$$R_{in(tot)} = R_1 \parallel R_2 \parallel R_{in(Base)}$$

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# The Common-Collector Amplifier

**Input and Output Resistance**

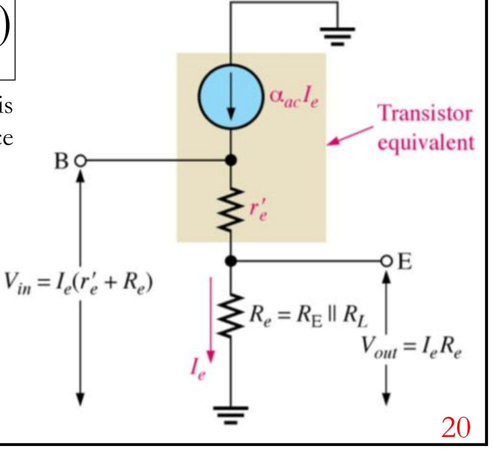
- The prime function of this circuit is to connect a high resistance source to a low resistance load (**"a buffer amplifier"**).

- The input resistance can be determined by the simplified formula below.

$$R_{in(Base)} = \frac{V_{in}}{I_b} \cong \beta_{ac}(r'_e + R_e)$$

- The output resistance is very low. This makes it useful for driving low impedance loads (**"a buffer amplifier"**).

$$R_{out} = \frac{V_{out}}{-I_e} = \frac{I_e R_e}{I_e} = Low$$

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# The Common-Collector Amplifier

**Voltage gain**

- As in all amplifiers, the voltage gain is $A_v = V_{out}/V_{in}$.

$$V_{out} = I_e R_e$$

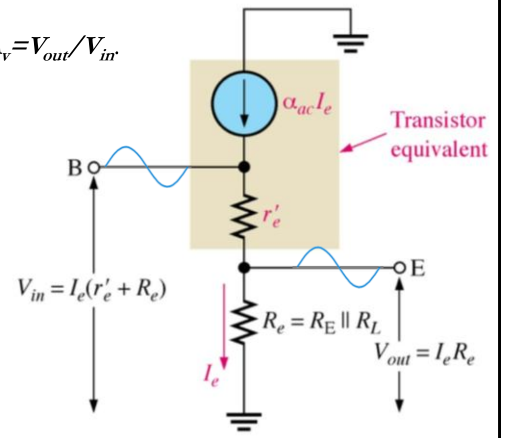
Where : $R_e$ is $R_E \parallel R_L$

$$V_{in} = I_e(r'_e + R_e)$$

$$A_v = \frac{I_e R_e}{I_e(r'_e + R_e)}$$

$$A_v = \frac{R_e}{r'_e + R_e}$$

$$A_v \cong 1$$




- Since the output is at the emitter, it is ***in phase*** with the base voltage, so there is ***no inversion*** from input to output. Because there is no inversion and because the voltage gain is approximately **1**, the output voltage closely ***follows*** the input voltage in both phase and amplitude; thus the term ***emitter-follower***.

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# The Common-Collector Amplifier

**Current gain**

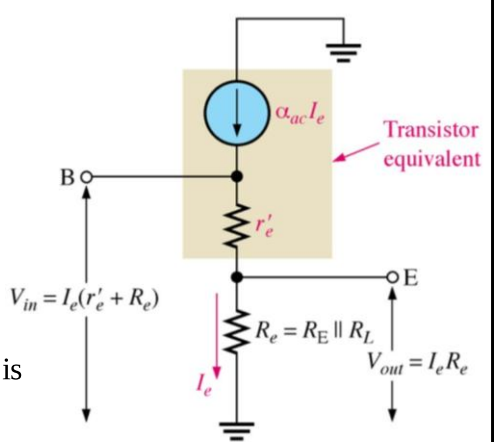
$$A_i = \frac{I_e}{I_{in}}$$

**Power gain**

$$A_p = A_v A_i$$

since $A_v \cong 1$, the overall power gain is

$$A_p \cong A_i$$

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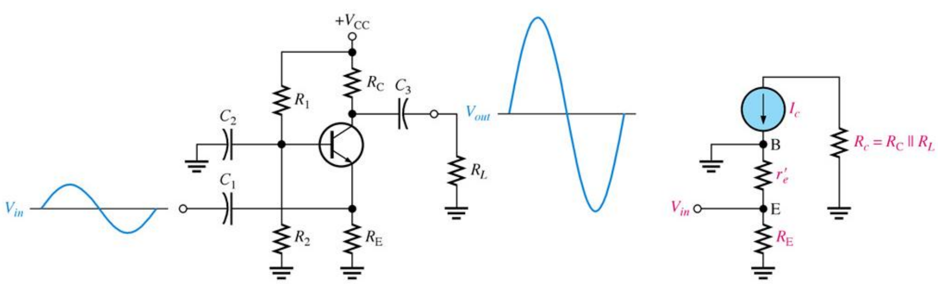
## The Common-Base Amplifier

- A typical **common-base** amplifier is shown in figure below.
- The **base** is the common terminal and is **at ac ground** because of capacitor $\mathbf{C_2}$.
- The input signal is capacitively coupled to the **emitter**.
- The output is capacitively coupled from the **collector** to a load resistor.




(a) Complete circuit with load

(b) AC equivalent model

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## The Common-Base Amplifier

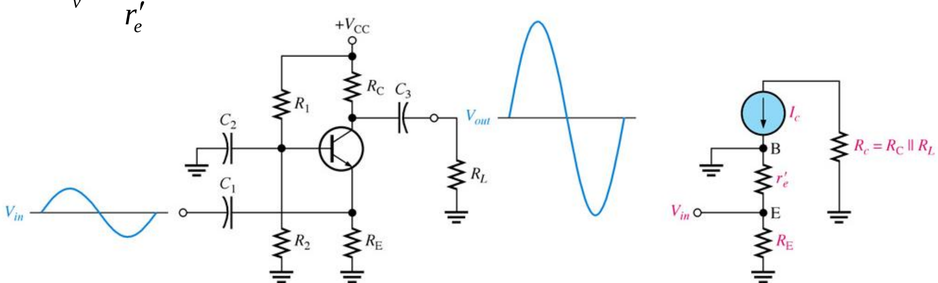
**Voltage Gain**

The voltage gain from emitter to collector is developed as follows ($\mathbf{V_{in}=V_e}$, $\mathbf{V_{out}=V_c}$).

$$A_v = \frac{V_{out}}{V_{in}} = \frac{V_c}{V_e} = \frac{I_c R_c}{Ie(r'_e \parallel R_E)} \cong \frac{I_e R_c}{Ie(r'_e \parallel R_E)}$$

if $R_E >> r'_e$, then

$$A_v \cong \frac{R_c}{r'_e}$$




(a) Complete circuit with load

(b) AC equivalent model

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# The Common-Base Amplifier

**Input Resistance**

The resistance, looking in at the emitter, is

$$R_{in(emitter)} = \frac{V_{in}}{I_{in}} = \frac{V_e}{I_e} = \frac{I_e(r_e' \parallel R_E)}{I_e}$$

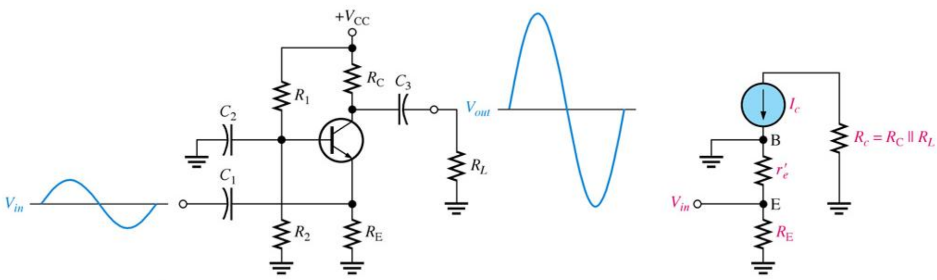
if $R_E >> r_e'$, then

$$R_{in(emitter)} \cong r_e'$$

**Output Resistance**

Looking into the collector the ac collector resistance, appears in parallel with $R_C$. But typically much larger than $R_C$, so a good approximation for the output resistance is:

$$R_{out} \cong R_C$$




(a) Complete circuit with load (b) AC equivalent model

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# The Common-Base Amplifier

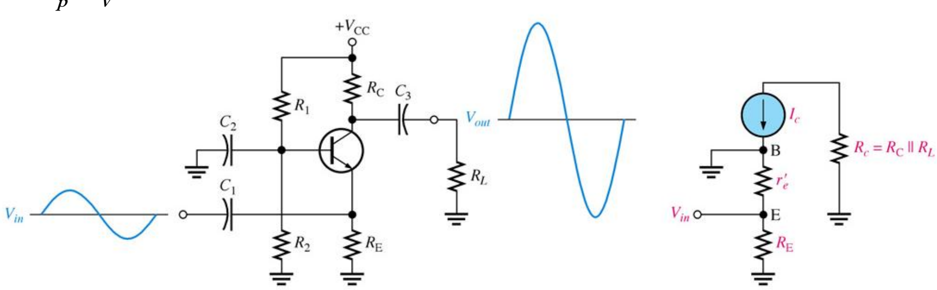
**Current Gain**

- The current gain is the output current divided by the input current. $I_c$ is the ac output current, and $I_e$ is the ac input current. Since $I_c \approx I_e$, the current gain is approximately **1**.

**Power Gain**

- Since the current gain is approximately **1** for the common-base amplifier and $A_p = A_v A_i$ the power gain is approximately equal to the voltage gain.

$A_p \approx A_v$




(a) Complete circuit with load (b) AC equivalent model

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## Relative Comparison of Amplifier Configuration

| | CE | CC | CB |
|---|---|---|---|
| Voltage gain, $A_v$ | High<br>$R_C/r'_e$ | Low<br>$\cong 1$ | High<br>$R_C/r'_e$ |
| Current gain, $A_{i(max)}$ | High<br>$\beta_{ac}$ | High<br>$\beta_{ac}$ | Low<br>$\cong 1$ |
| Power gain, $A_p$ | Very high<br>$A_iA_v$ | High<br>$\cong A_i$ | High<br>$\cong A_v$ |
| Input resistance, $R_{in(max)}$ | Low<br>$\beta_{ac}r'_e$ | High<br>$\beta_{ac}R_E$ | Very low<br>$r'_e$ |
| Output resistance, $R_{out}$ | High<br>$R_C$ | Very low<br>$(R_s/\beta_{ac}) \parallel R_E$ | High<br>$R_C$ |



## Darlington Transistor

- The ***Darlington transistor*** (***Darlington pair***) is a compound structure consisting of two bipolar transistors (either integrated or separated devices) connected in such a way that the current amplified by the first transistor is amplified further by the second one.
- The collectors are joined together and the emitter of the input transistor is connected to the base of the output transistor as shown in figure below:

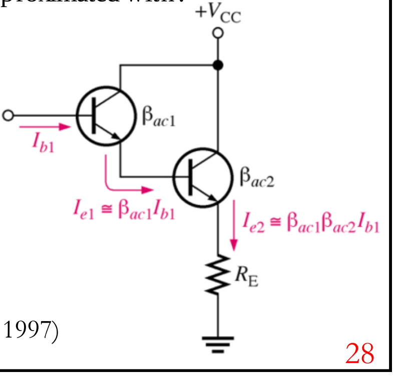
$$\beta_{Darlington} = \beta_1 \cdot \beta_2 + \beta_1 + \beta_2$$

if $\beta_1$ and $\beta_2$ are high enough, this relation can be approximated with:

$$\beta_{Darlington} \approx \beta_1 \cdot \beta_2$$

- The current gain is high so it can be used to amplify weak signal.

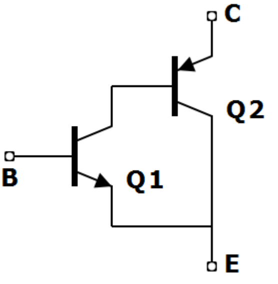
**Sidney Darlington**
(July 18, 1906 – October 31, 1997)



## Sziklai pair

- ***The Sziklai pair*** is a configuration of two bipolar transistors, similar to a ***Darlington pair***. But the ***Sziklai pair*** has one NPN and one PNP transistor, and so it is sometimes called the "***complementary Darlington***".
- Current gain is similar to that of a Darlington pair, which is the product of the gains of the two transistors.

**George Clifford Sziklai**
(July 9, 1909– September 9, 1998)

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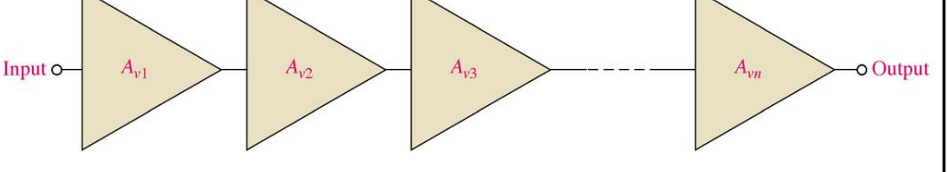
## Multistage Amplifiers Gain

- Two or more amplifiers can be connected to increase the gain of an ac signal. The overall gain can be calculated by simply multiplying each gain together.

$$A'_v = A_{v1} A_{v2} A_{v3} \ldots\ldots$$

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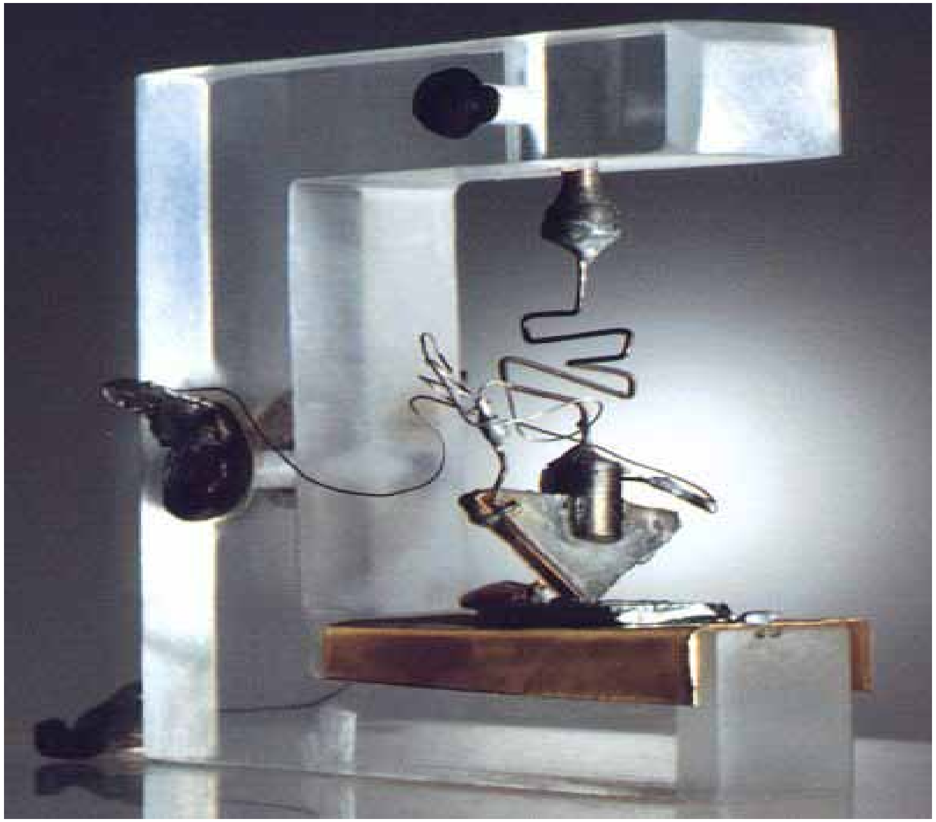
# TRANSISTOR AMPLIFIERS
# AET 8



First Transistor developed at Bell Labs on December 16, 1947

# TRANSISTOR AMPLIFIERS

## Objective 1a

Identify Bipolar Transistor Amplifier Operating Principles

# TRANSISTOR AMPLIFIERS

## Overview

(1) Dynamic Operation

(2) Configurations

(3) Common Emitter

(4) Common Collector

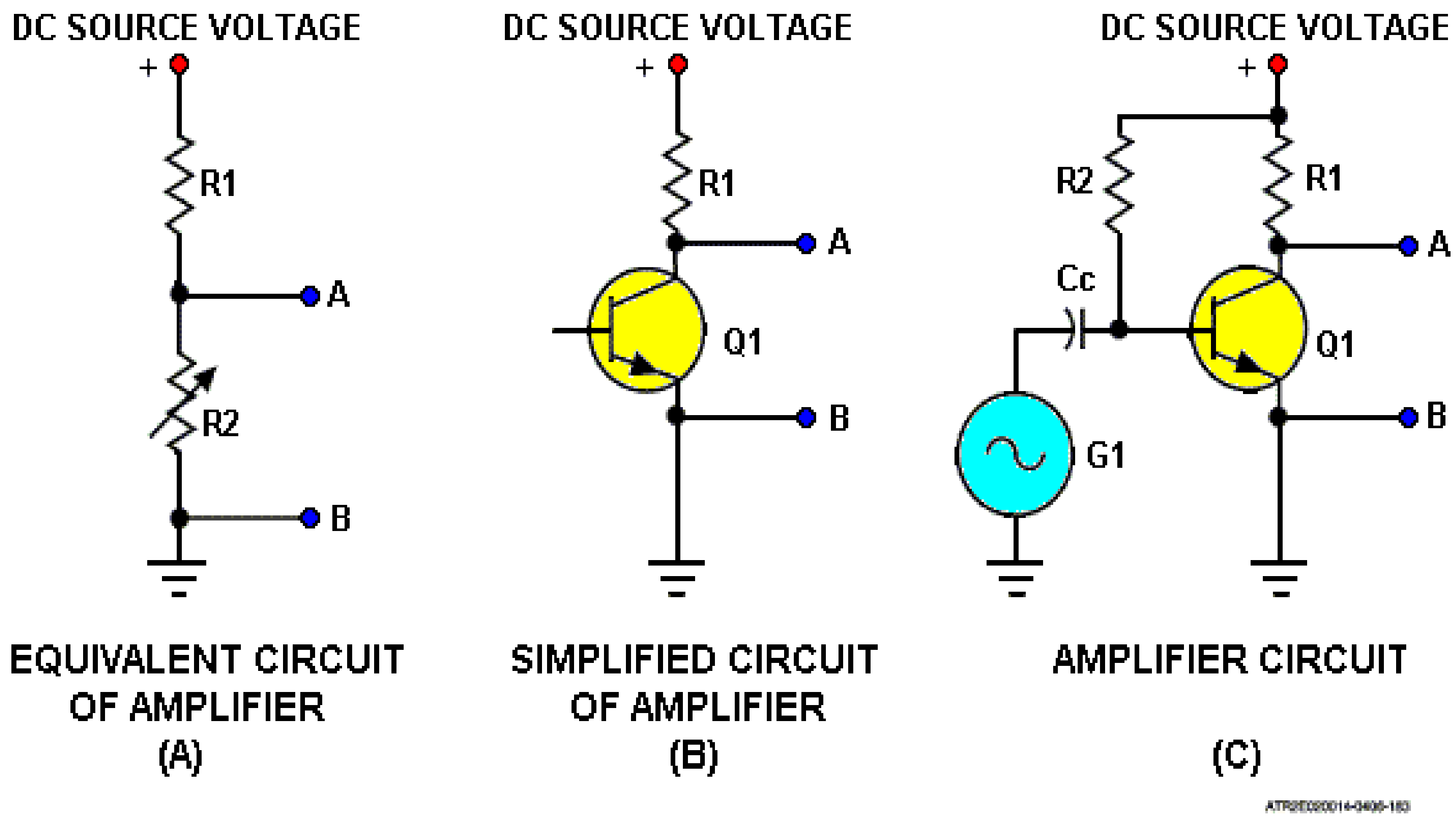
(5) Common Base

(6) Temperature Stabilization

(7) Coupling

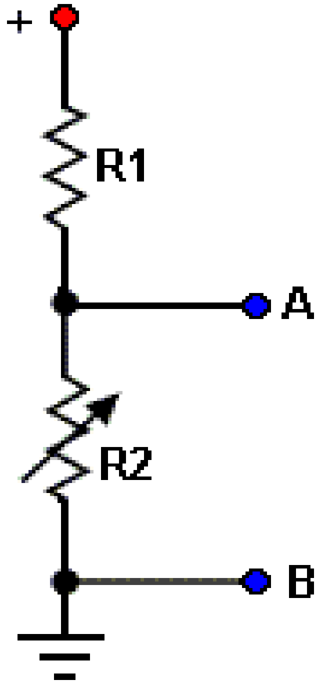
# TRANSISTOR AMPLIFIERS

## Typical Amplifier



# TRANSISTOR AMPLIFIERS

## Typical Amplifier




EQUIVALENT CIRCUIT
OF AMPLIFIER
(A)

**(A). Output taken from A to B:**

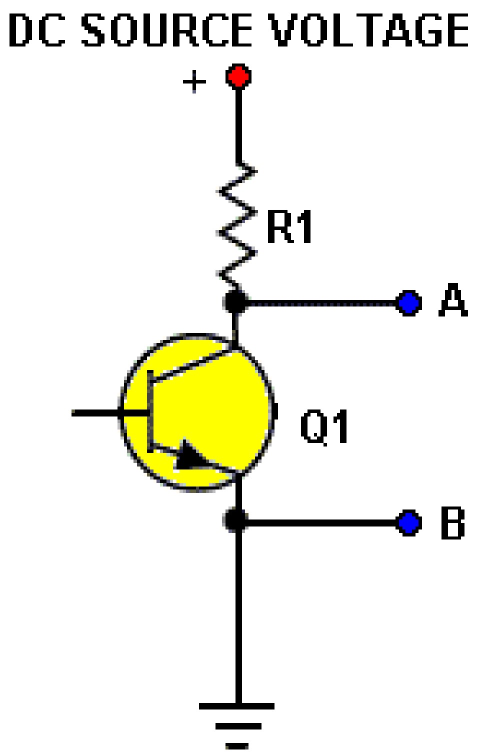
**Reduce the resistance of R2, voltage from A to B decreases.**

**Increase the resistance of R2, voltage from A to B increases.**

**(Voltage follows resistance)!**

# TRANSISTOR AMPLIFIERS

## Typical Amplifier




SIMPLIFIED CIRCUIT OF AMPLIFIER (B)

Resistor (R2) is replaced with transistor (Q1)

(B). Output taken from A to B:

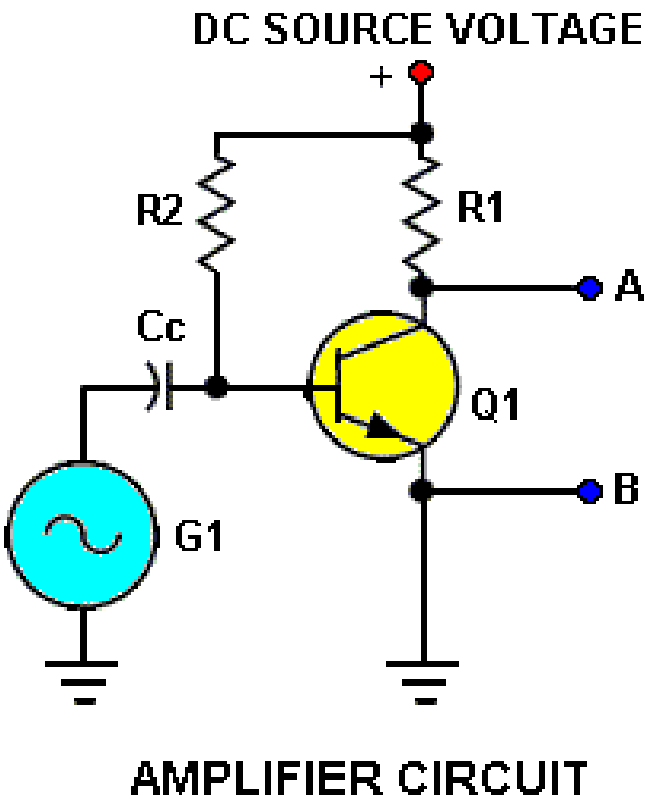
Reduce the resistance of Q1, voltage from A to B decreases.

Increase the resistance of Q1, voltage from A to B increases.

(Voltage follows resistance)!

# TRANSISTOR AMPLIFIERS

## Typical Amplifier




(C)

**(C) An input signal from G1 is applied to the base through $C_C$. The input signal changes the Bias on the base of the transistor controlling the current flow through the transistor.**

**The output, taken from A to B, will be a reproduction of the input signal only much larger.**

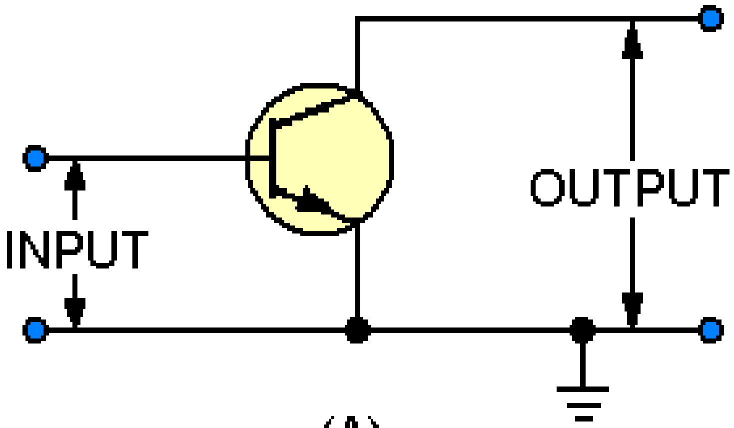
# TRANSISTOR AMPLIFIERS

**Amplification:** **The ability of a circuit to receive a small change of input voltage or current (signal) and produce a large change in the output voltage or current (signal).**

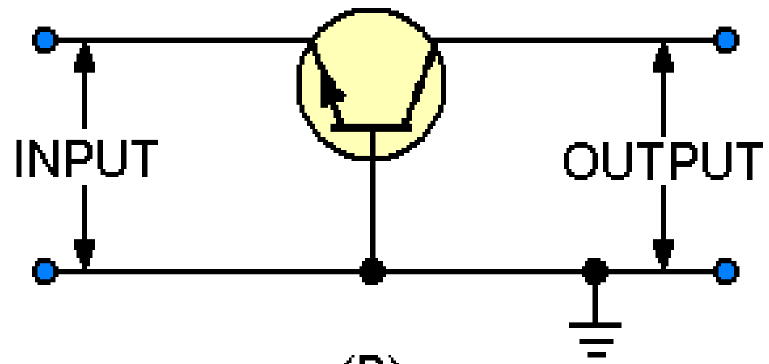
**Amplification depends on the change in the transistor’s resistance caused by an input signal.**

# TRANSISTOR AMPLIFIERS

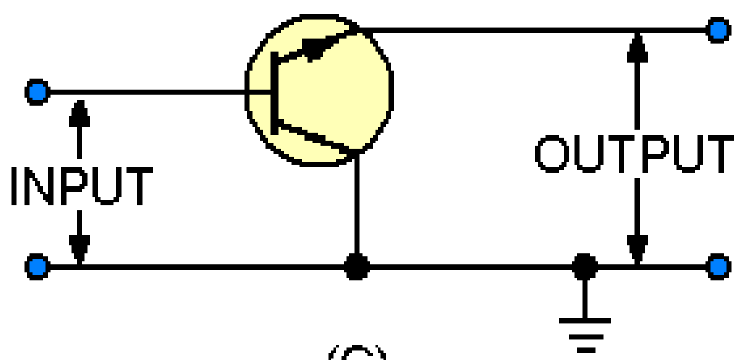
## CONFIGURATIONS



(A)
COMMON EMITTER



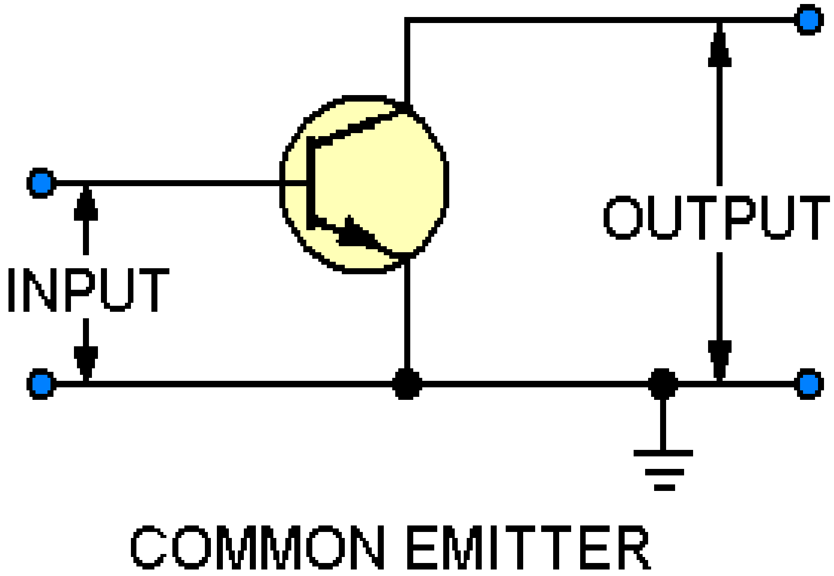
(B)
COMMON BASE



(C)
COMMON COLLECTOR

# TRANSISTOR AMPLIFIERS

## Common Emitter




**Common Emitter is sometimes called the Grounded Emitter.**

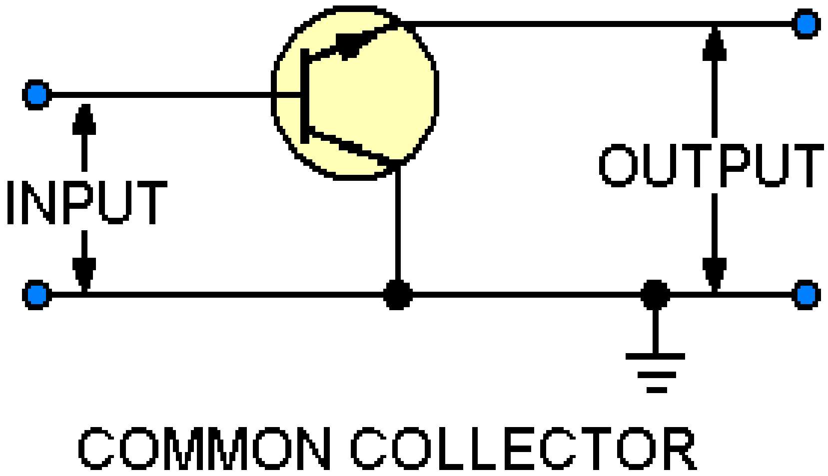
**Input signal is applied to the base.**

**Output signal is taken from the collector.**

**The common line, (not used for signal) is connected to the emitter.**

# TRANSISTOR AMPLIFIERS

## Common Collector




**Common Collector (CC) is sometimes called Grounded Collector.**

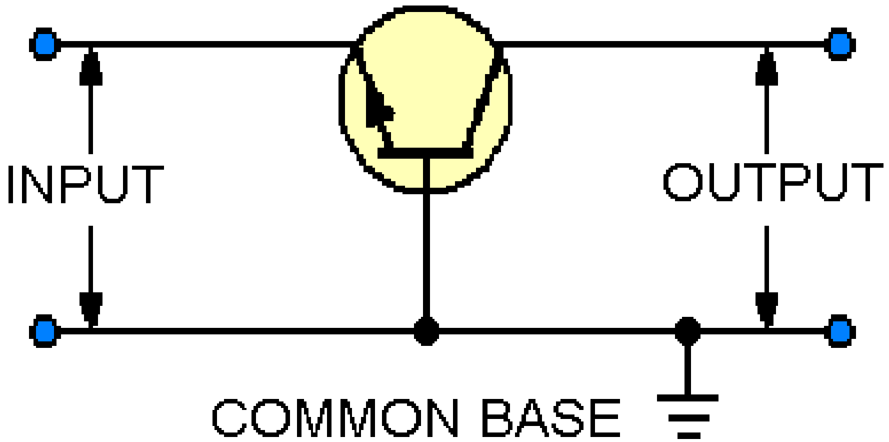
**The input signal is applied to the base.**

**The output signal is taken from the emitter.**

**The common line, (not used for signal) is connected to the collector.**

# TRANSISTOR AMPLIFIERS

## Common Base




**Common Base (CB) is sometimes called Grounded Base.**

**The input signal is applied to the emitter.**

**The output signal is taken from the collector.**

**The common line, (not used for signal) is connected to the base.**

# TRANSISTOR AMPLIFIERS

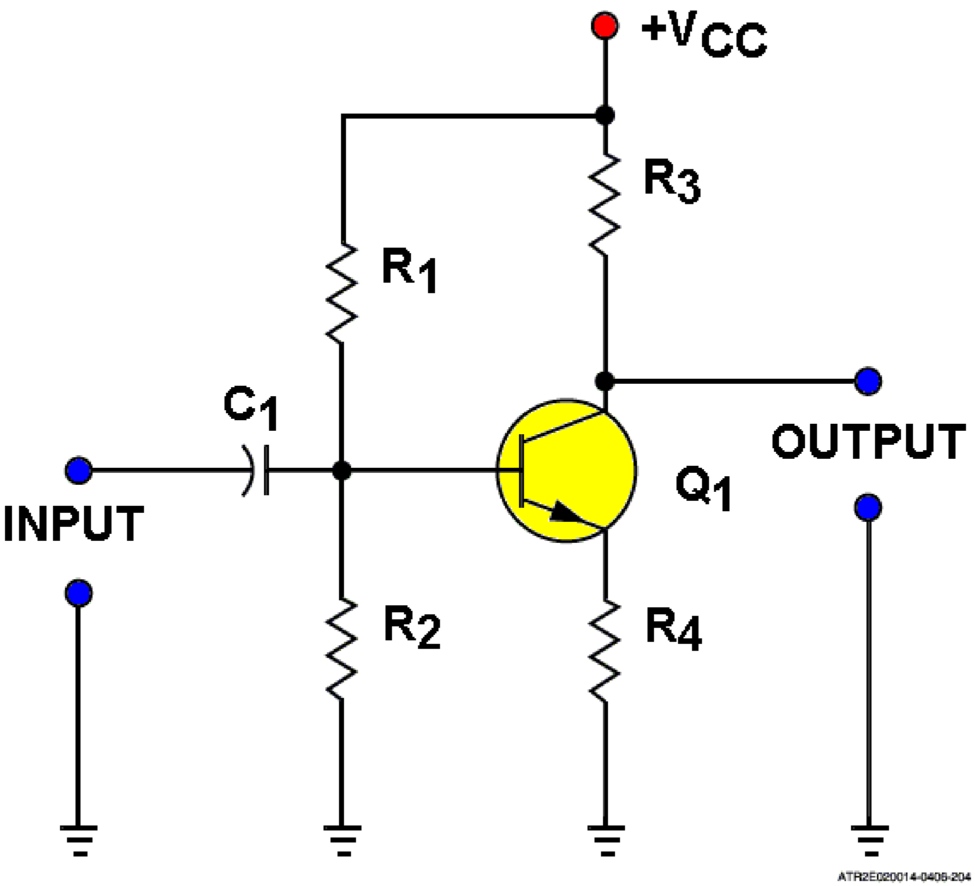
## Common Emitter Amplifier

- **The purpose of the common emitter amplifier is to provide good current, voltage, and power gain.**

- **180° phase shift**

# TRANSISTOR AMPLIFIERS

## Common Emitter Amplifier Components




$R_1$ determines forward bias

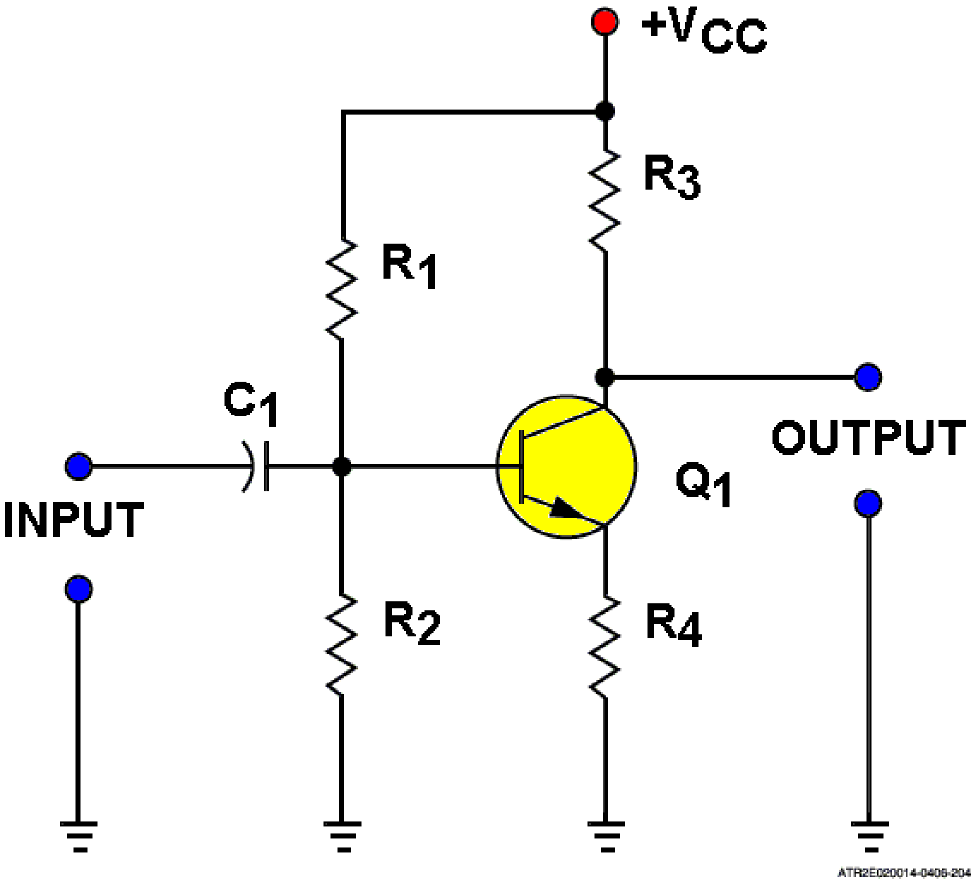
$R_2$ aids in developing bias

$R_3$ is the collector load resistor used to develop the output signal

$R_4$ is the emitter resistor used for thermal stability

# TRANSISTOR AMPLIFIERS

## Common Emitter Amplifier Components

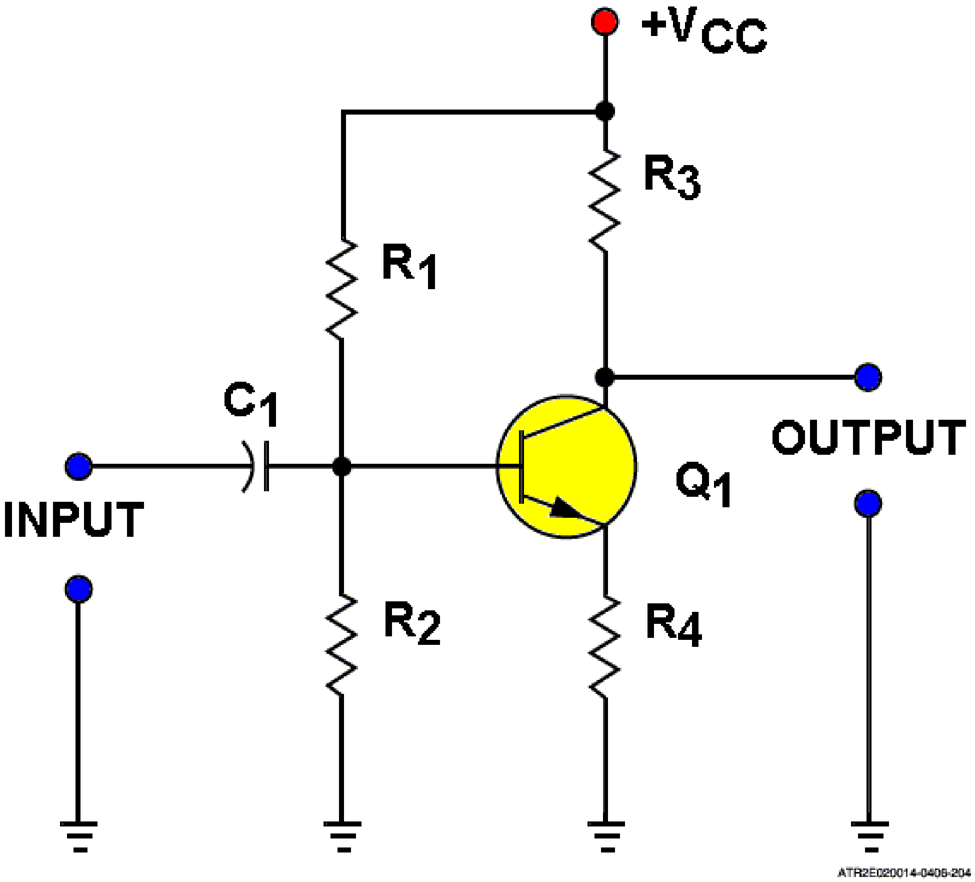



**$Q_1$ - transistor**

**$C_1$ is the input coupling capacitor**

# TRANSISTOR AMPLIFIERS

## Common Emitter Amplifier




Current paths and percentage of flow

- $I_E$ = 100%, $I_C$ = 95%, $I_B$ = 5%
- NPN – Current flows from Ground to +VCC

# TRANSISTOR AMPLIFIERS

## Common Emitter Amplifier

**Signal path: When a signal is applied to an amplifier, four things occur.**

- **Base, emitter & collector currents change at the rate of the input signal**
- **Collector voltage changes at the rate of the input signal**
- **Phase shift of 180°**
- **There will be signal gain!**

# TRANSISTOR AMPLIFIERS

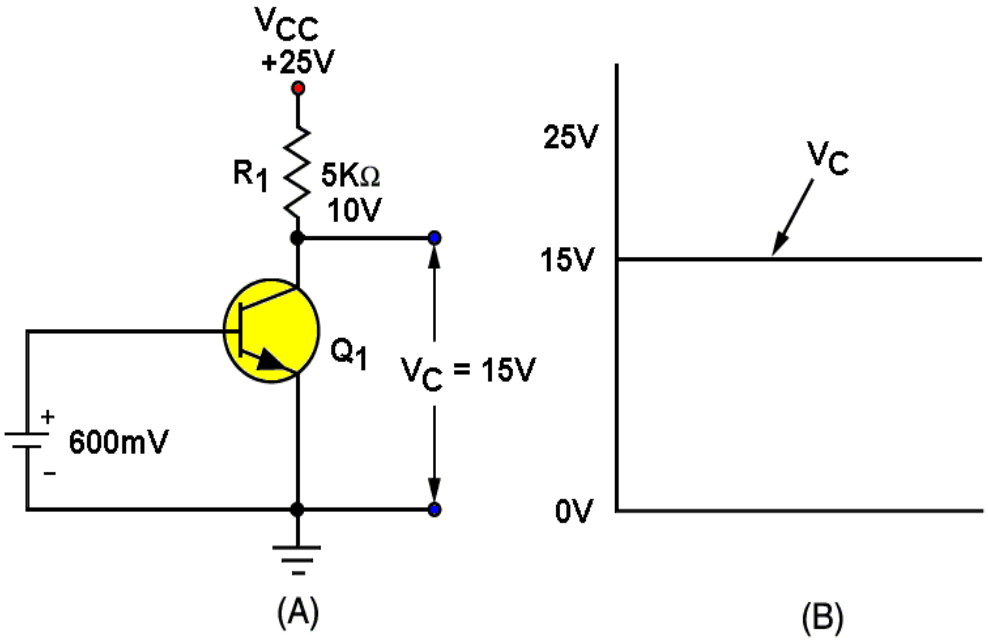
## Common Emitter Amplifier

### Static or Quiescent Operation

**By definition, bias is defined as the average DC voltage (or current) used to establish the operating point in transistor circuits for a static or quiescent condition. A static condition means the circuit does not have an input signal and is fixed in a non-varying condition.**

# TRANSISTOR AMPLIFIERS

## Typical Amplifier with Bias - Static Condition

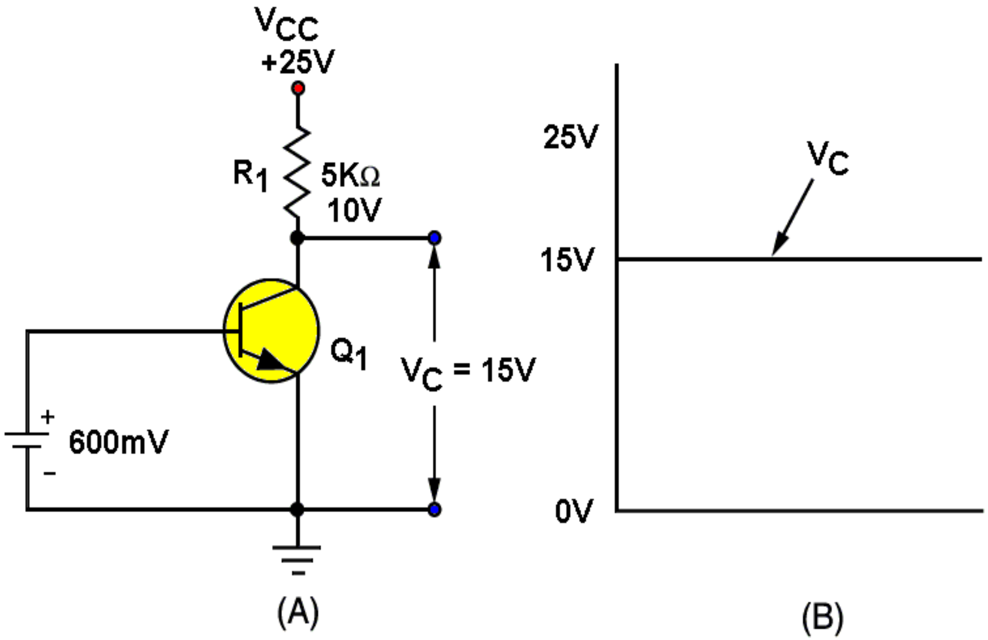



**Transistor Current Path**

**600mv (.6v) Bias (emitter to base voltage) causes emitter current (IE), base current (IB), and collector current (IC) to flow.**

# TRANSISTOR AMPLIFIERS

## Typical Amplifier with Bias - Static Condition




**Current enters the emitter and exits the base.**

**Current enters the emitter and exits the collector through R1 to $V_{CC}$.**

# TRANSISTOR AMPLIFIERS

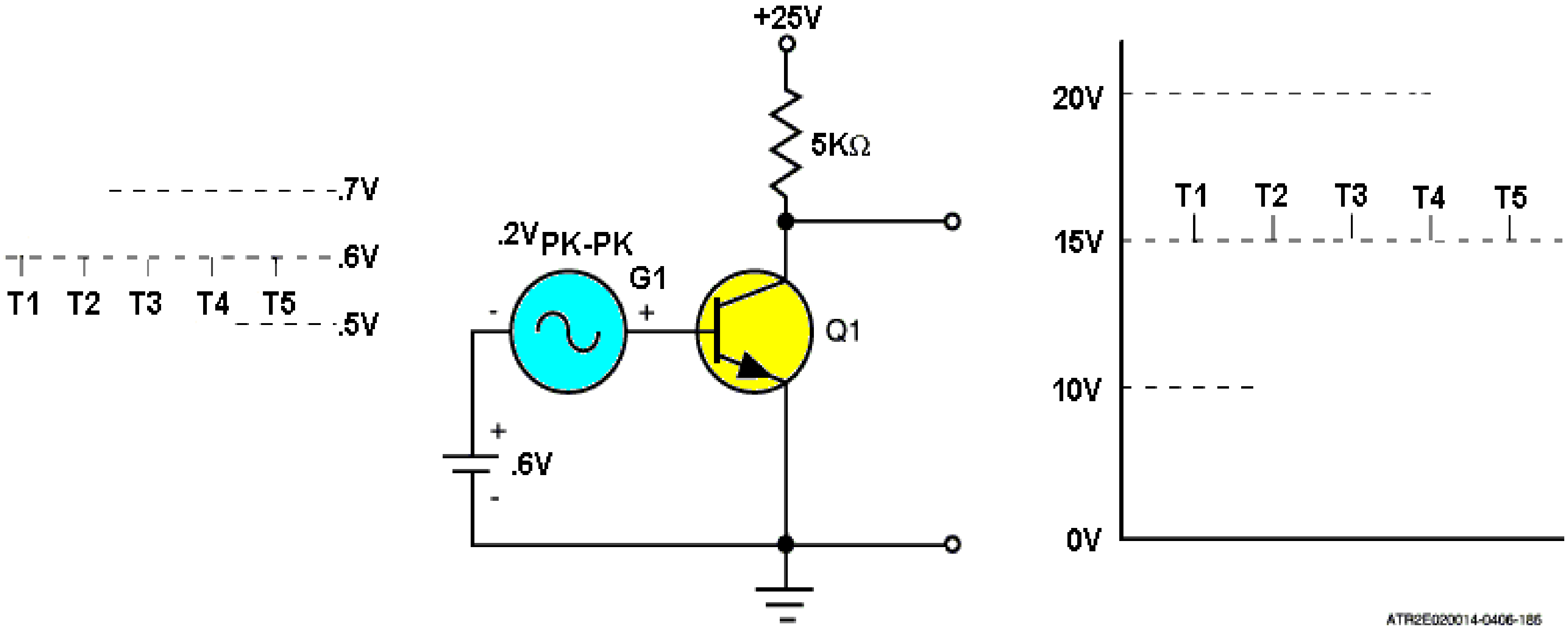
## Common Emitter Amplifier

### Dynamic Operation

The varying condition of a circuit is called its dynamic condition or operating condition. This occurs whenever an input signal is applied.

# TRANSISTOR AMPLIFIERS

## Typical Amplifier with Bias - Dynamic

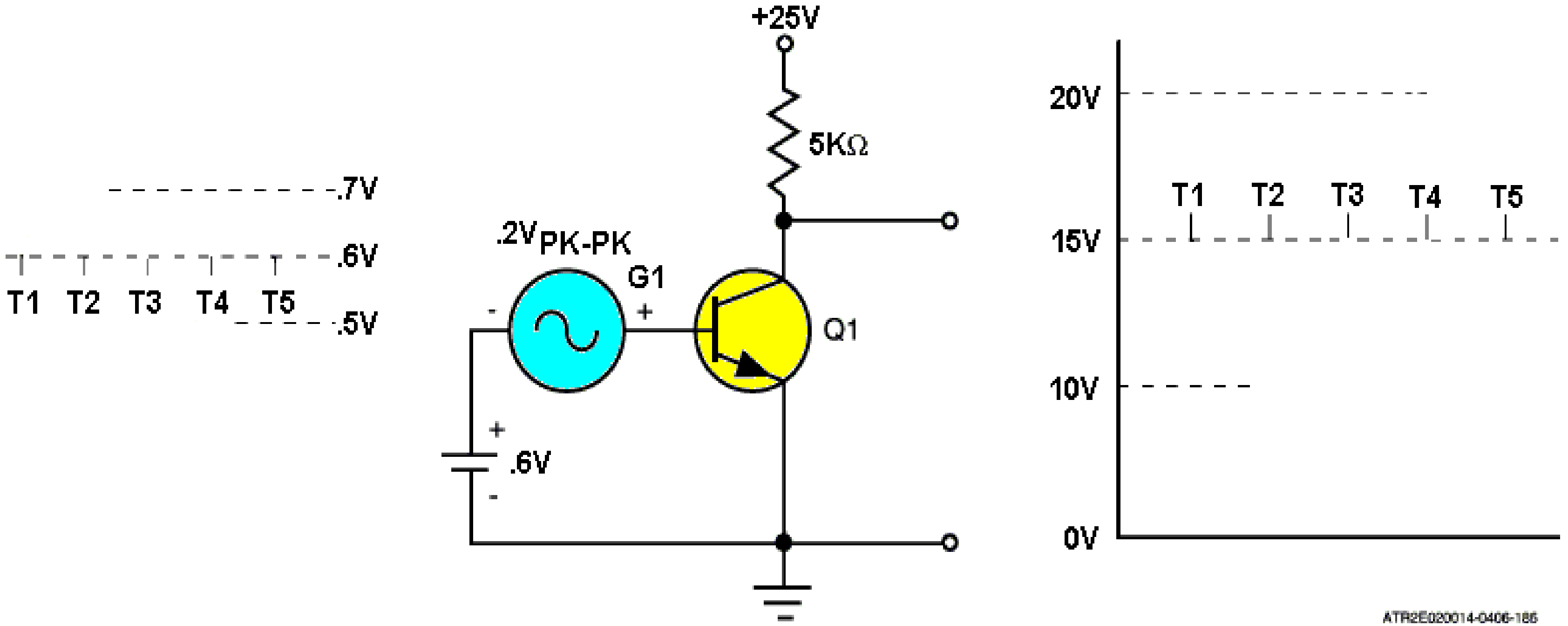



**Dynamic condition:** **DC Bias with signal added (Varying condition)**

**The output voltage has a much larger voltage change than the input.**

# TRANSISTOR AMPLIFIERS

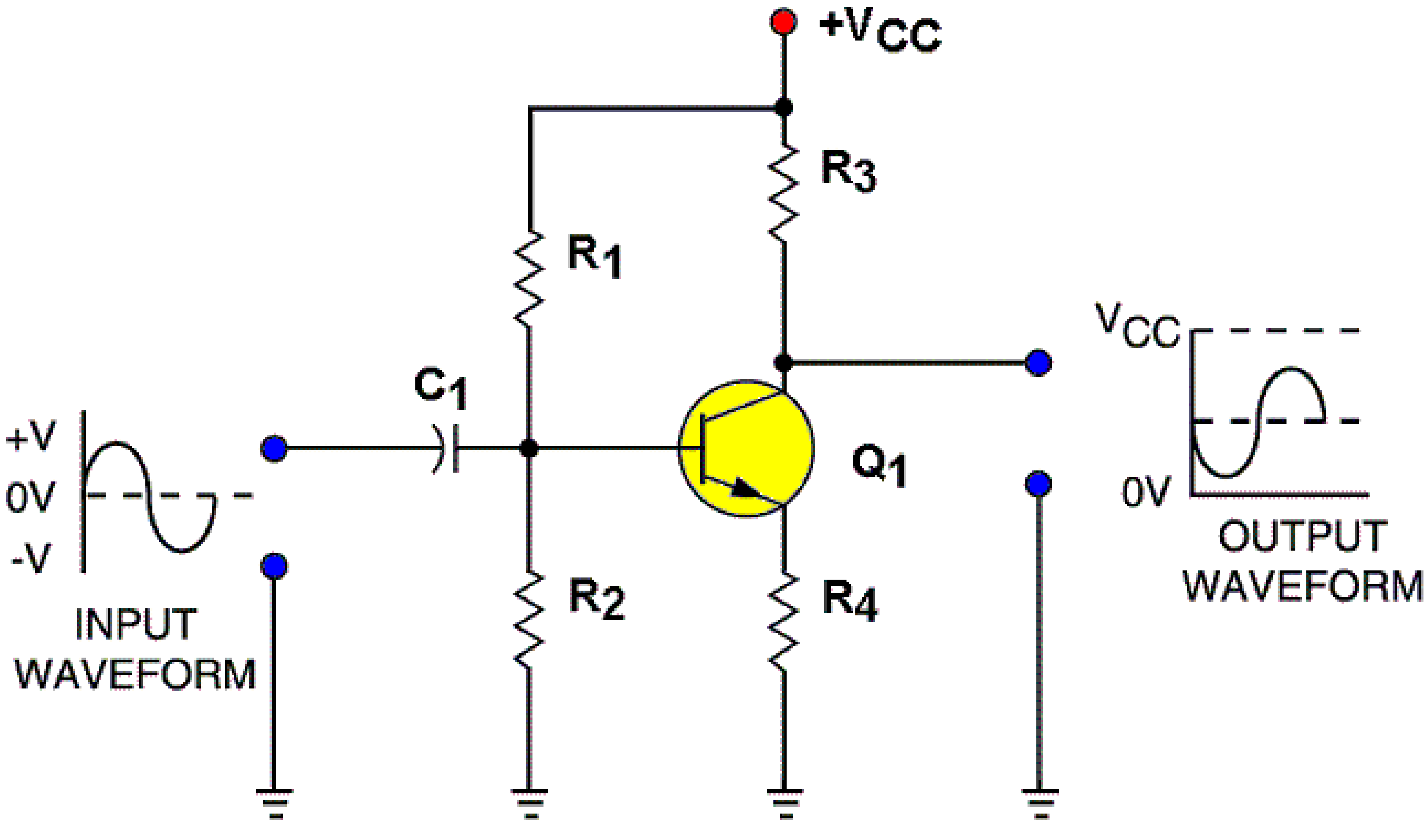
## Typical Amplifier with Bias - Dynamic




**Notice the .2V Pk-Pk signal at the input is using the .6v DC as its reference and the output 10V Pk-Pk signal is using the 15V DC as its reference.**

# TRANSISTOR AMPLIFIERS

## Common Emitter Amplifier



# TRANSISTOR AMPLIFIERS

## NPN Common Emitter Amplifier Operation

**The negative alternation of the input signal applied to the base of the transistor causes forward bias to decrease and collector current to decrease.**

**The voltage drop across $R_3$ decreases because $I_C$ decreased**

**The collector voltage ($V_C$) increases**

**The bias decrease caused an increase in output voltage and produced a 180 phase inversion**

# TRANSISTOR AMPLIFIERS

## NPN Common Emitter Amplifier Operation

The positive alternation of the input signal applied to the base causes forward bias to increase and collector current to increase

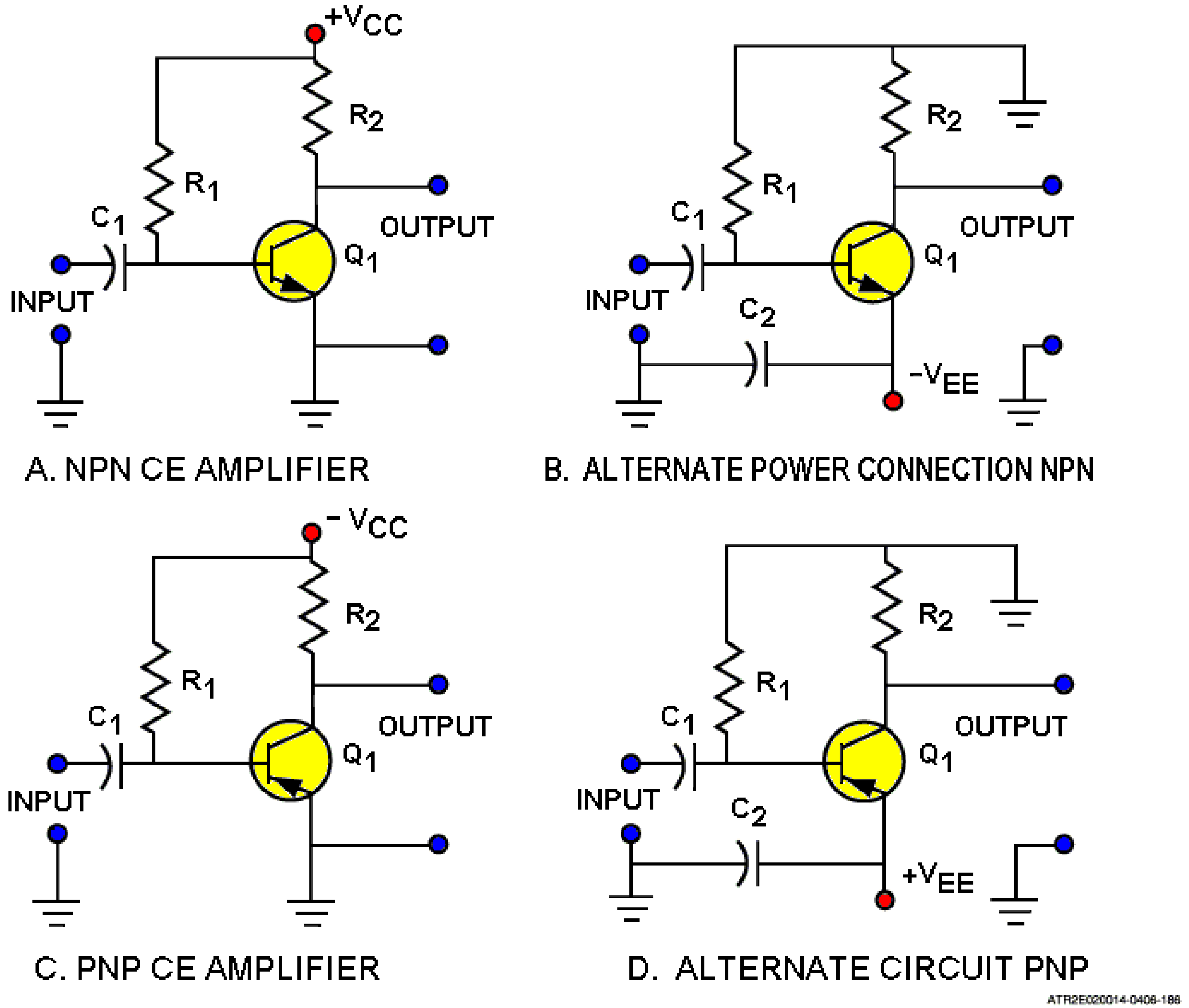
The voltage drop across $R_3$ increases because $I_C$ increased

The collector voltage ($V_C$) decreases

The bias increase caused a decrease in output voltage and produced a 180 phase inversion

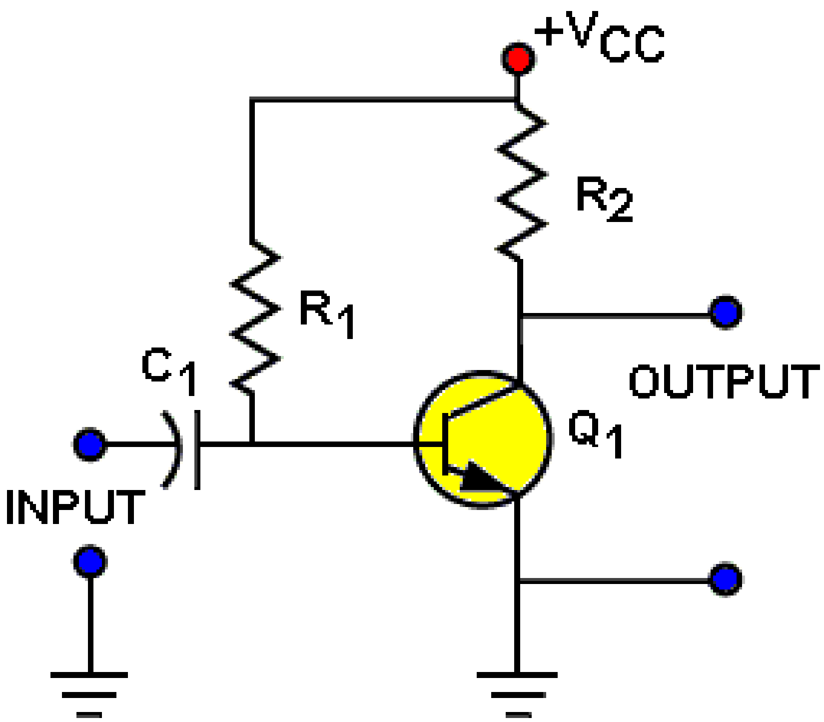
# TRANSISTOR AMPLIFIERS

## Common Emitter Amplifier



# TRANSISTOR AMPLIFIERS

## Common Emitter Amplifier

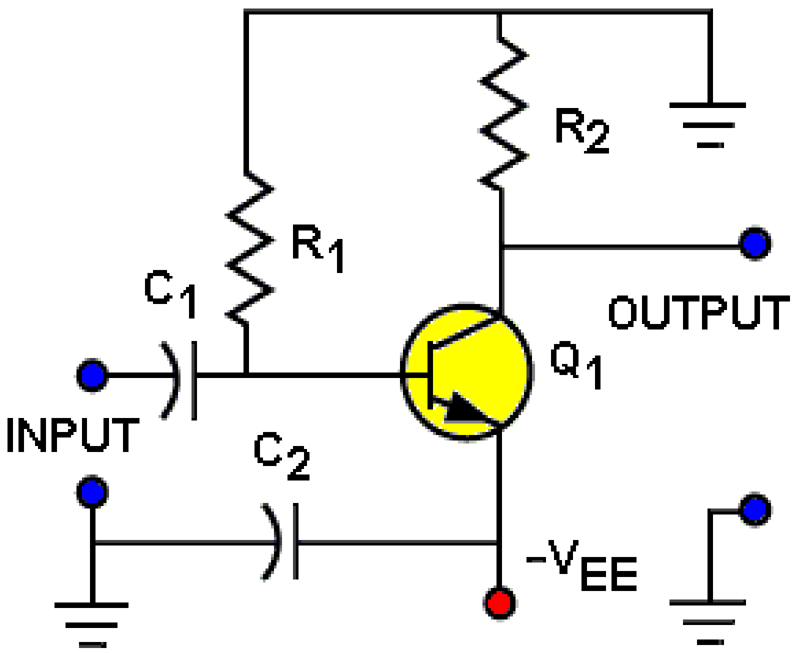



A. NPN CE AMPLIFIER

**NPN with conventional power connection $V_{CC}$ to base and collector using respective resistors ($R_1$ & $R_2$).**

# TRANSISTOR AMPLIFIERS

## Common Emitter Amplifier

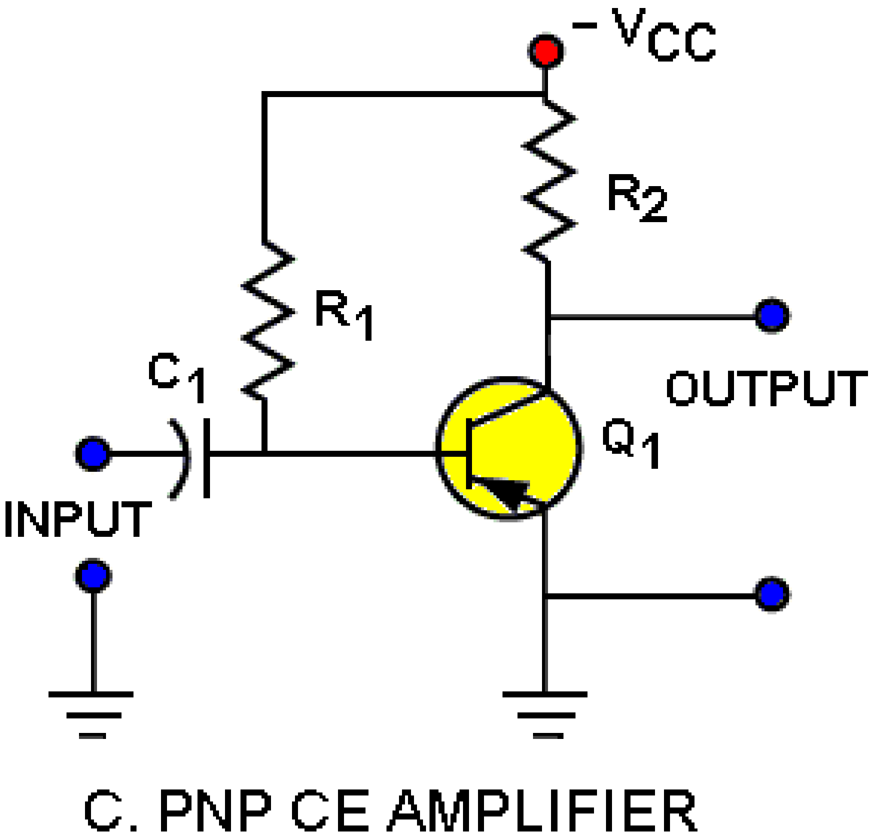



B. ALTERNATE POWER CONNECTION NPN

**NPN with alternate power connection $V_{EE}$ to emitter with current path through $Q_1$ out the base and collector through $R_1$ & $R_2$ to ground.**

# TRANSISTOR AMPLIFIERS

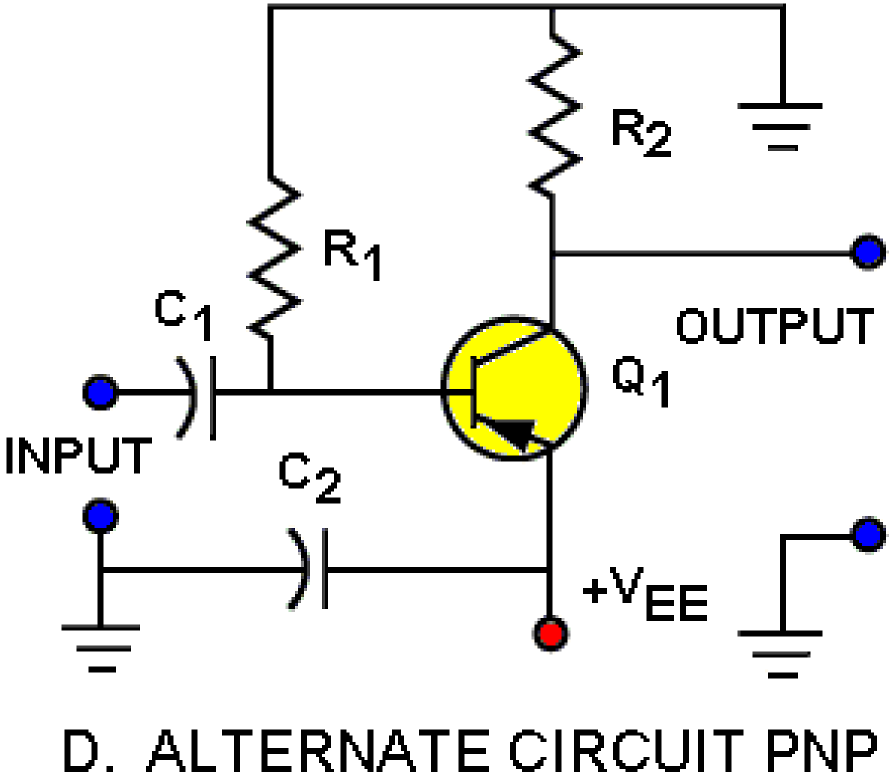
## Common Emitter Amplifier




**PNP with conventional power connection $-V_{CC}$ to base and collector using respective resistors ($R_1$ & $R_2$).**

# TRANSISTOR AMPLIFIERS

## Common Emitter Amplifier




**PNP with alternate power connection $+V_{EE}$ to emitter with current path in the base and collector through $R_1$ & $R_2$ out the emitter to ground.**

# TRANSISTOR AMPLIFIERS

## Common Emitter Amplifier

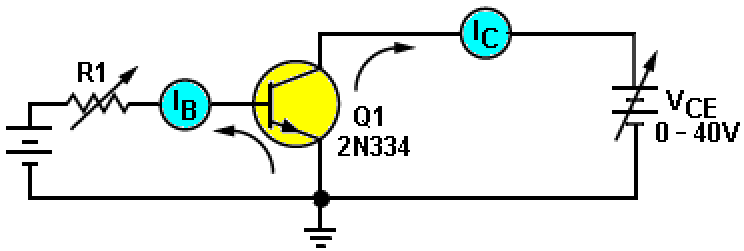
### Characteristic Curve Graph

**A transistor CHARACTERISTIC CURVE is a graph plotting of the relationships between currents and voltages in a transistor circuit.**

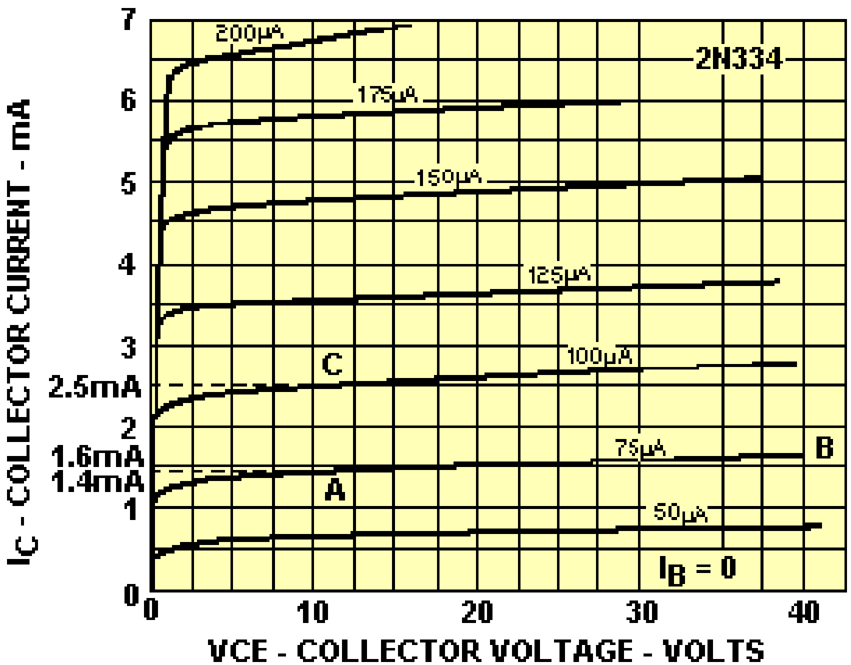
**The graph is then called a FAMILY of curves.**

# TRANSISTOR AMPLIFIERS

## Common Emitter Amplifier



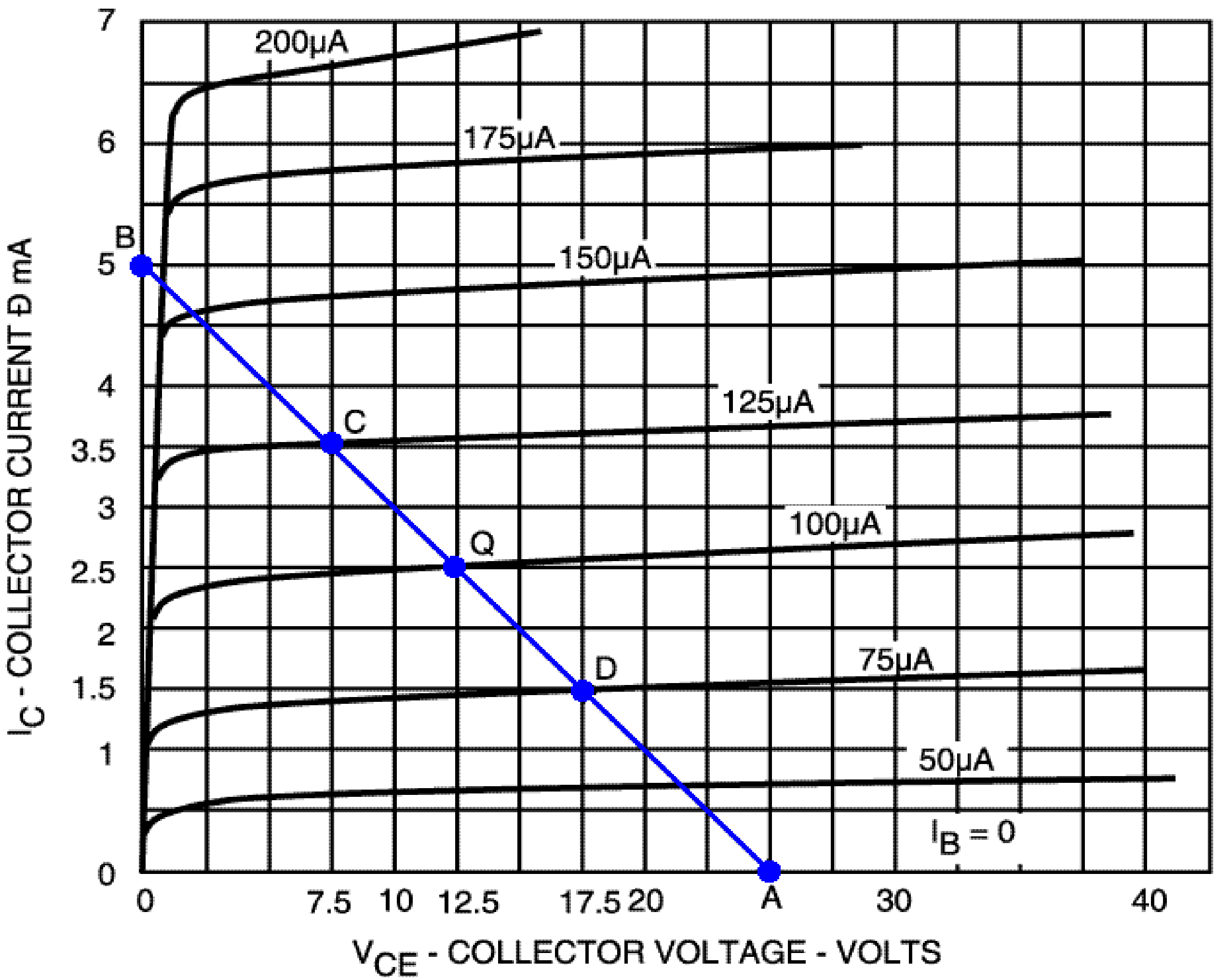

A. SCHEMATIC




**Characteristic Curve Graph**

**Graph shows base current ($I_B$) changes vs. collector current ($I_C$).**

**Graph shows a change in $V_{CC}$ vs. $I_C$**




## Point A -Cutoff

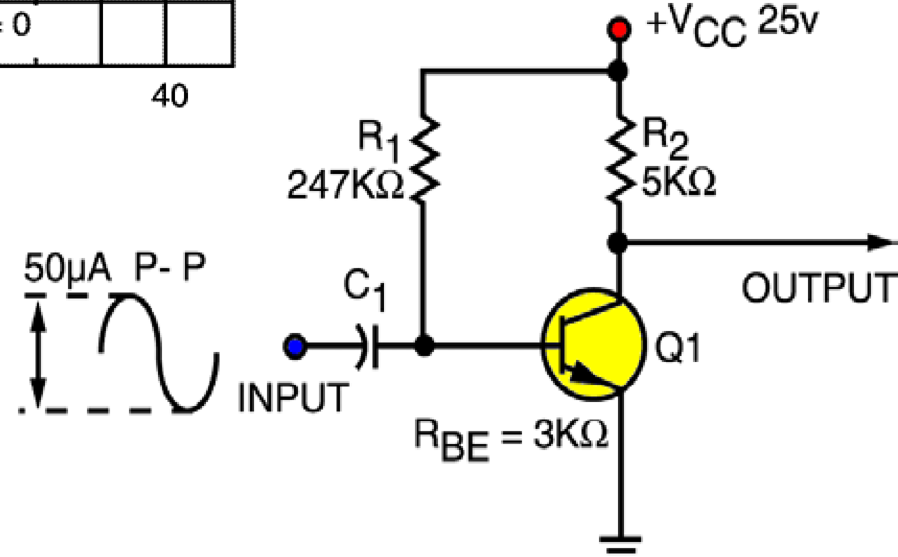
**Applied Voltage = 25V**

## Point B -Saturation

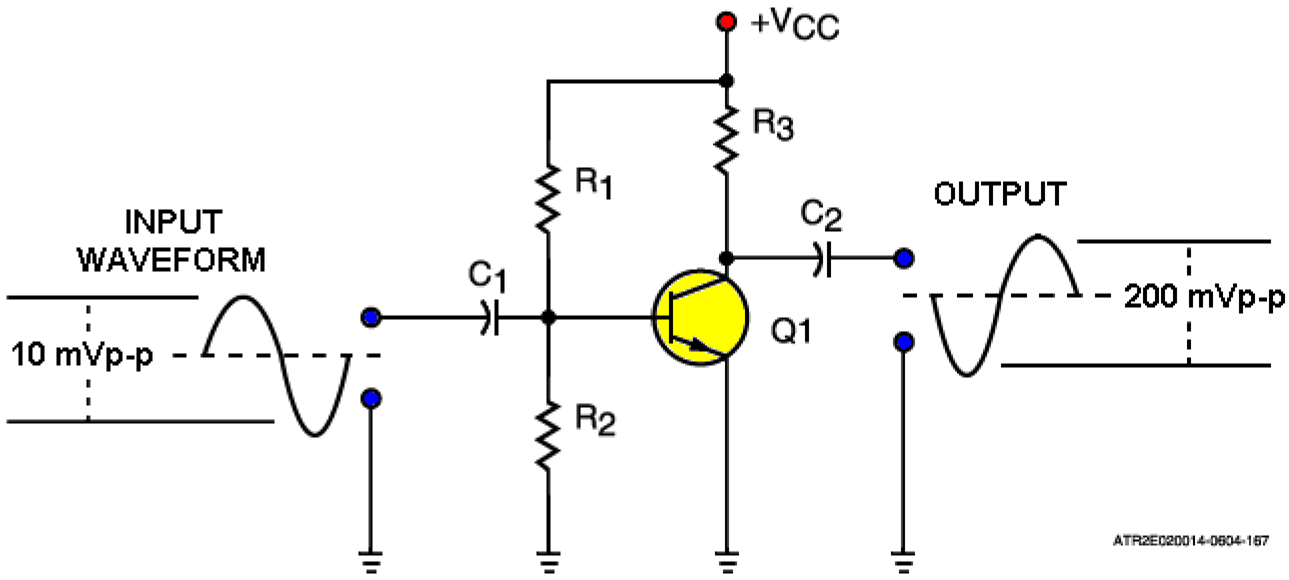
$$I_C = \frac{V_{cc}}{R2} = \frac{25\ \text{volts}}{5K\Omega} = 5\ \text{mA}$$

## Base current - $I_B$

$$I_B = \frac{V_{cc}}{R_t} = \frac{25\ \text{Volts}}{250K\Omega} = 100\mu A$$



# TRANSISTOR AMPLIFIERS

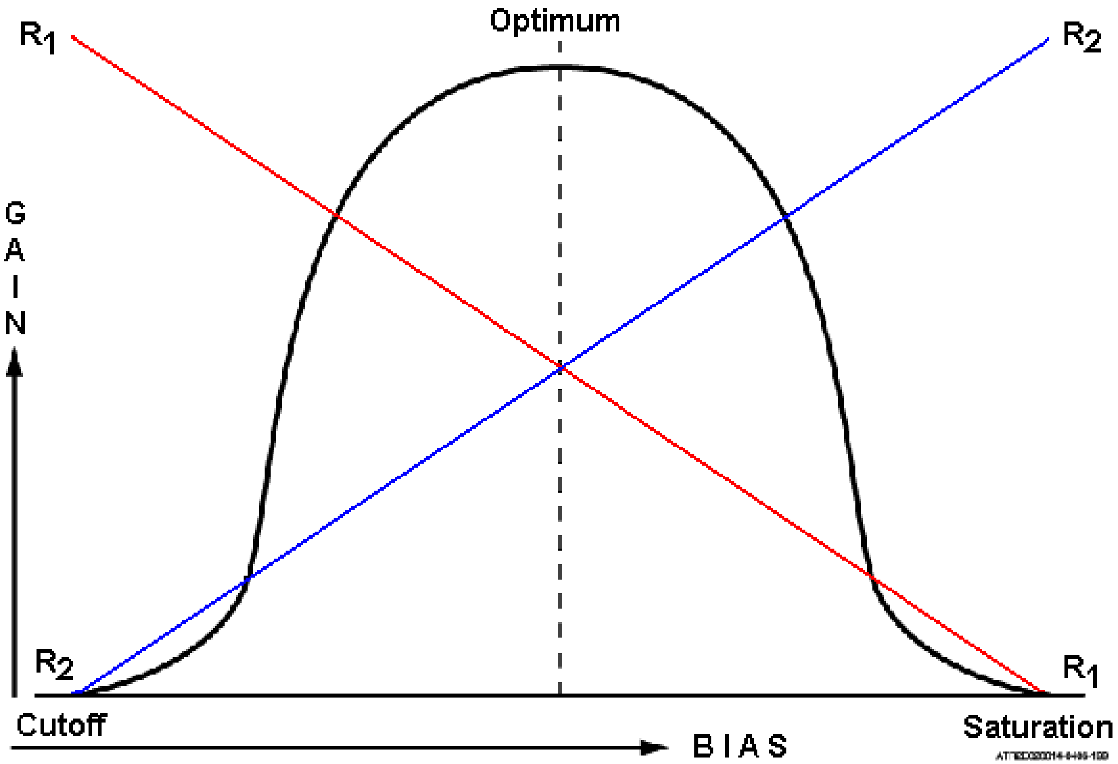



Amplifier Gain – A ratio of the change in output to the change in input expressed as a formula:

$$\text{Gain} = \frac{\Delta \text{Output}}{\Delta \text{Input}} = \frac{200 \text{ mV}}{10 \text{ mV}} = 20$$

# TRANSISTOR AMPLIFIERS

## Common Emitter Amplifier



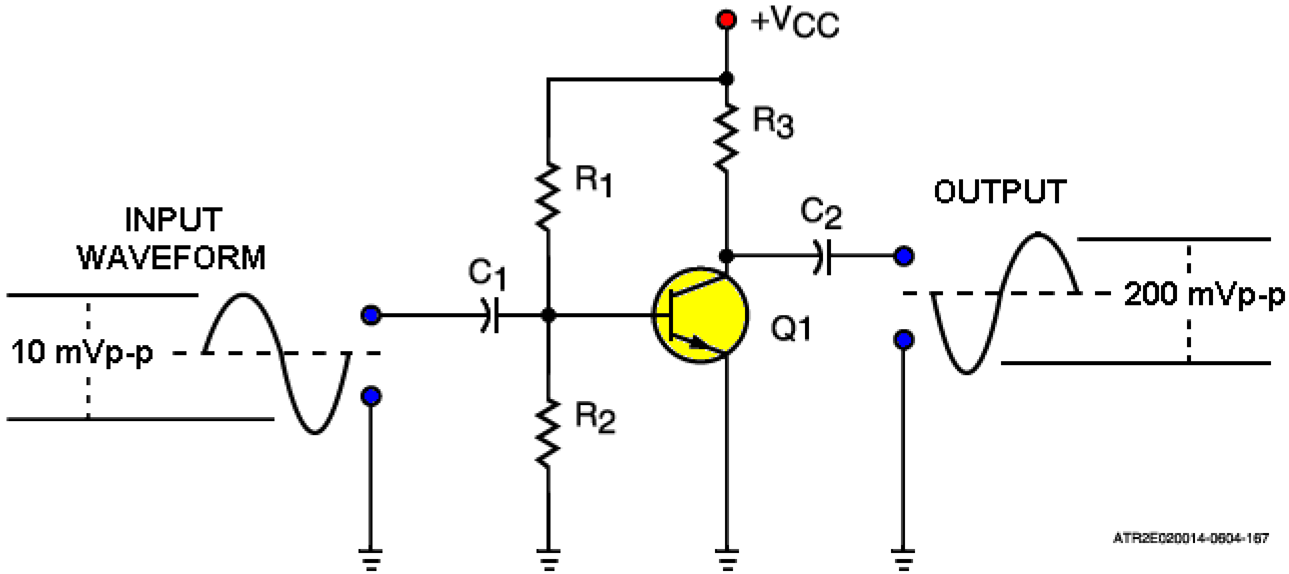

**Bias vs. Gain Characteristics**

**Optimum has the best gain**

**$R_2$ is directly proportional to bias, resistance increases forward bias increases**

**$R_1$ is inversely proportional to bias**

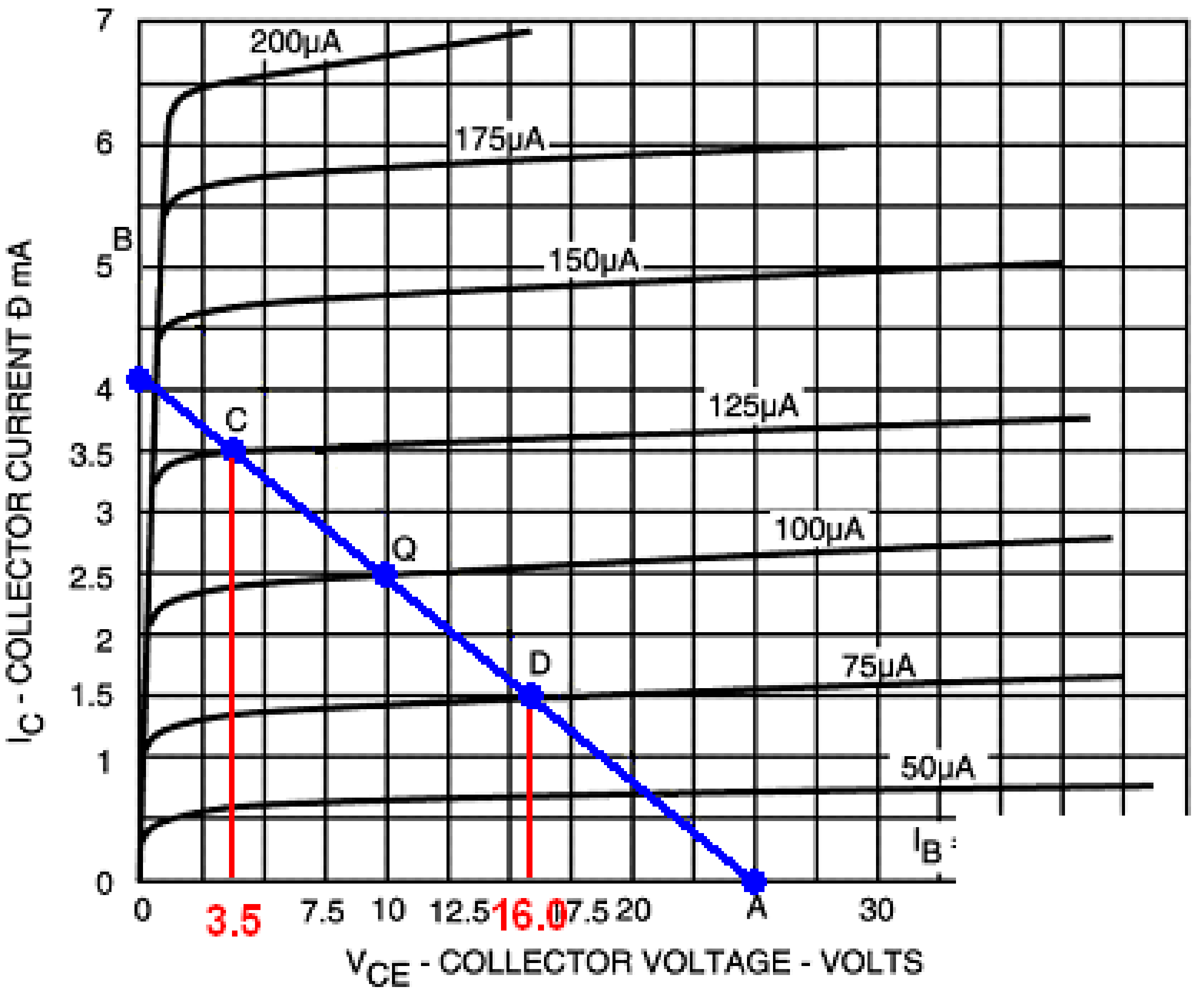
# TRANSISTOR AMPLIFIERS




## Collector Load Resistor Changes

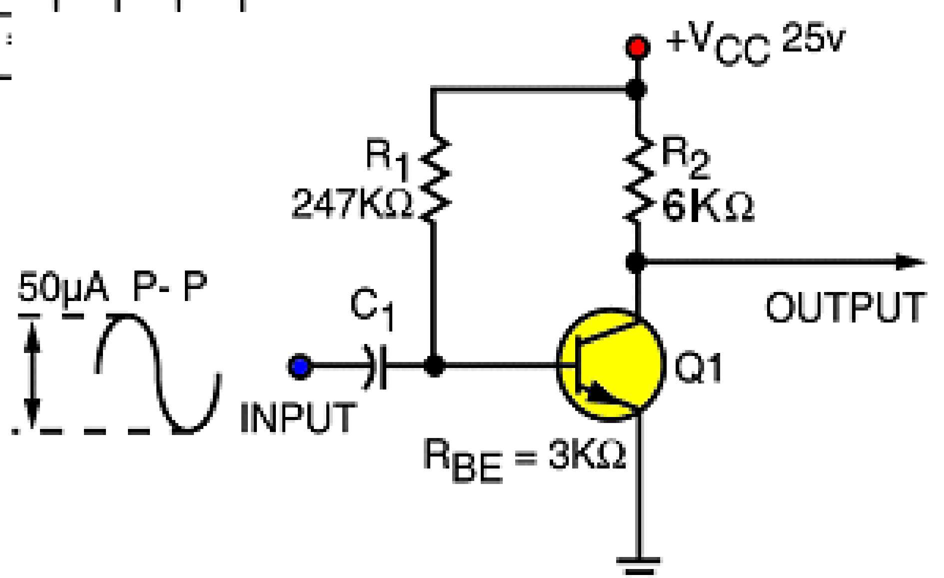
**Increasing the resistance of R3 will cause a corresponding increase in the amount of change in collector voltage and increase in voltage gain.**

**Gain is directly proportional to the resistance value of R3.**




# Point B-Saturation

$$I_C = \frac{V_{cc}}{R2} = \frac{25 \text{ volts}}{6K\Omega} = 4.17 \text{ mA}$$




**Increasing R2 to 6KΩ changes the load line and gain increases from 10V to 12.5 volts.**

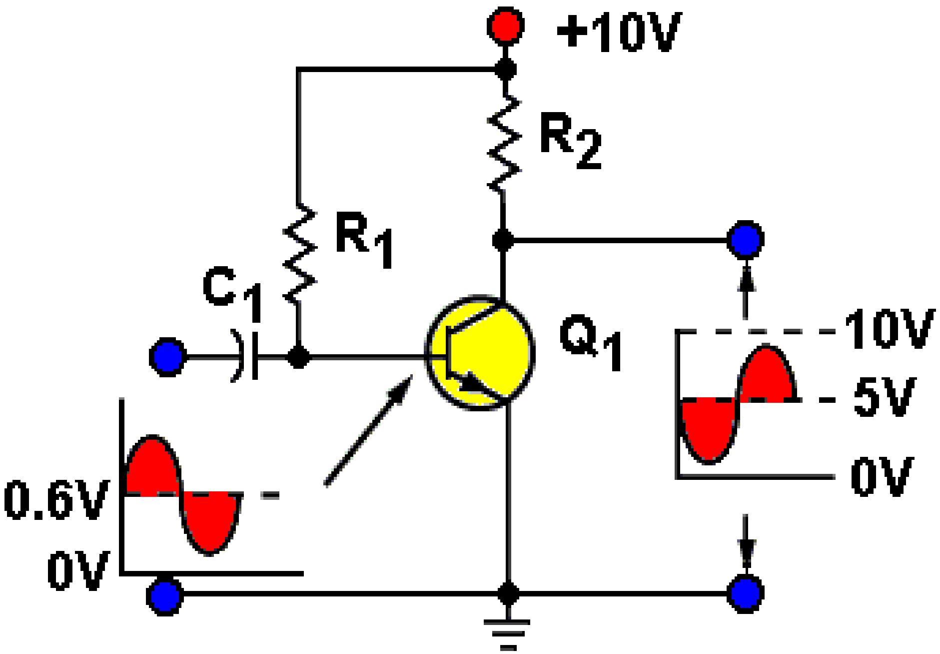
# TRANSISTOR AMPLIFIERS

## Class of Operation

- There are four classes of operation for amplifiers: A, AB, B and C
- The class of operation is determined by the amount of forward bias.

# TRANSISTOR AMPLIFIERS

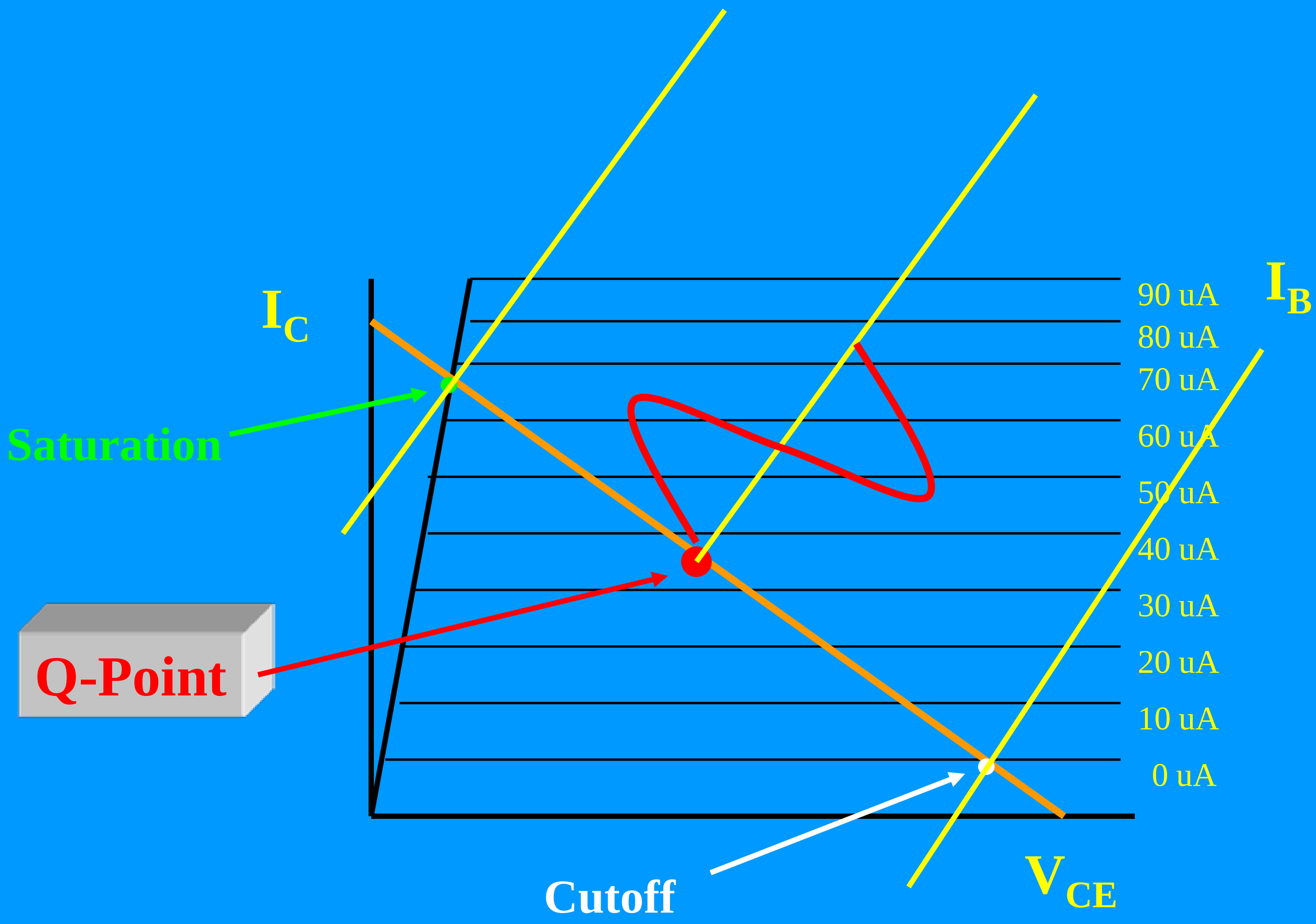
## Common Emitter Amplifier – Class A




**Class A amplifiers have an exact reproduction of the input in the output. Conducts 100 % of the time**

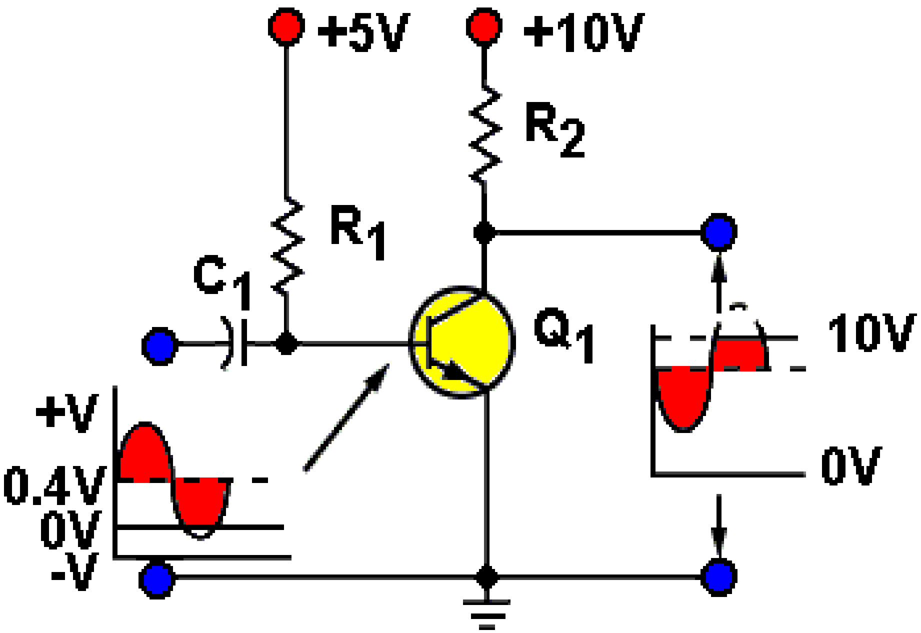
**The collector current will flow for 360 degrees of the input signal**

# Class ‘A’ Amplifier Curve



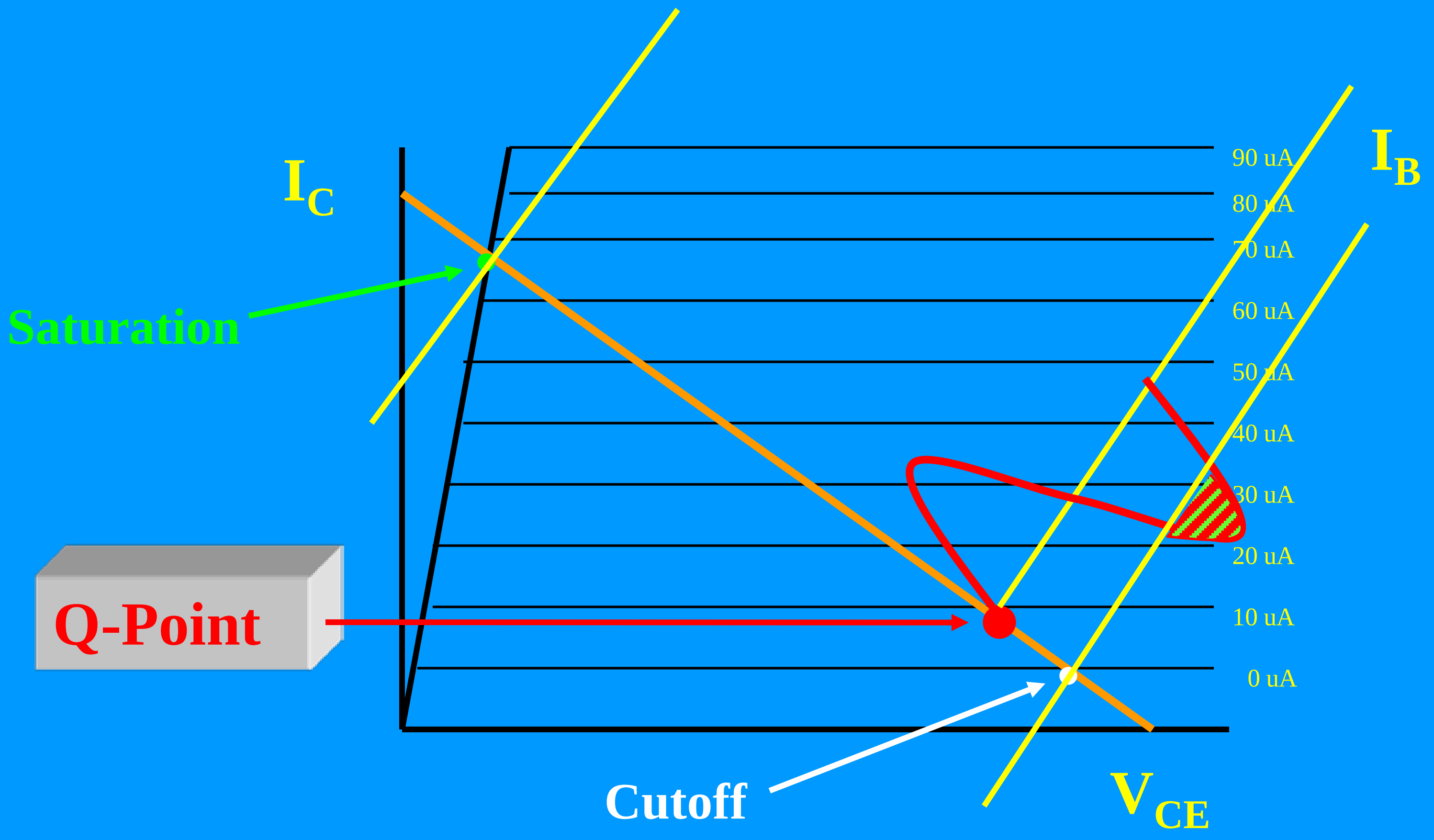
# TRANSISTOR AMPLIFIERS

## Common Emitter Amplifier – Class AB



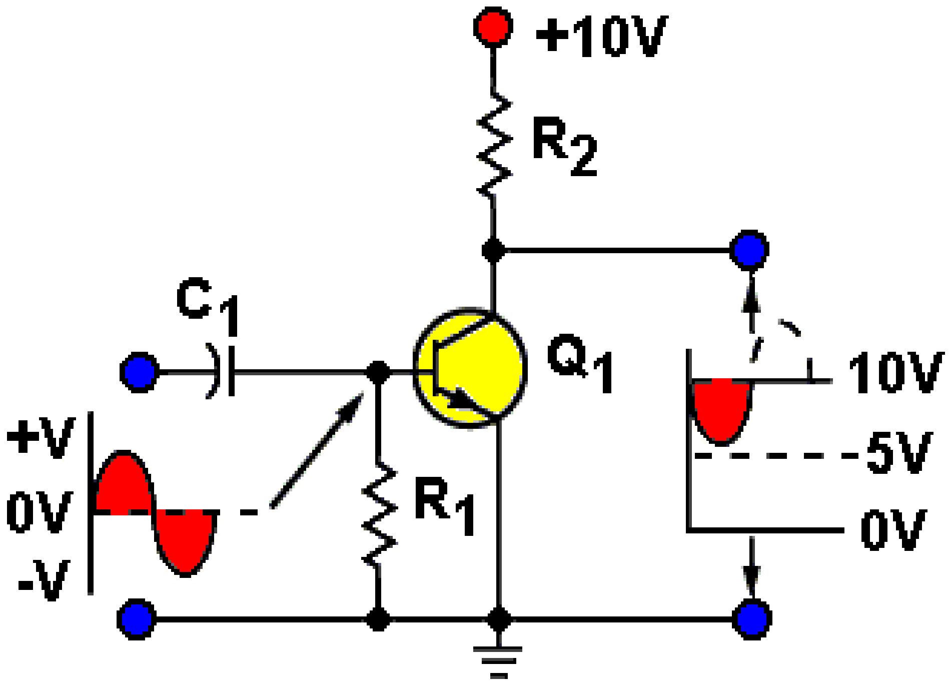

**Class AB amplifiers has some amplitude distortion and conducts 51% to 99% of the time.**

# Class ‘AB’ Amplifier Curve



# TRANSISTOR AMPLIFIERS

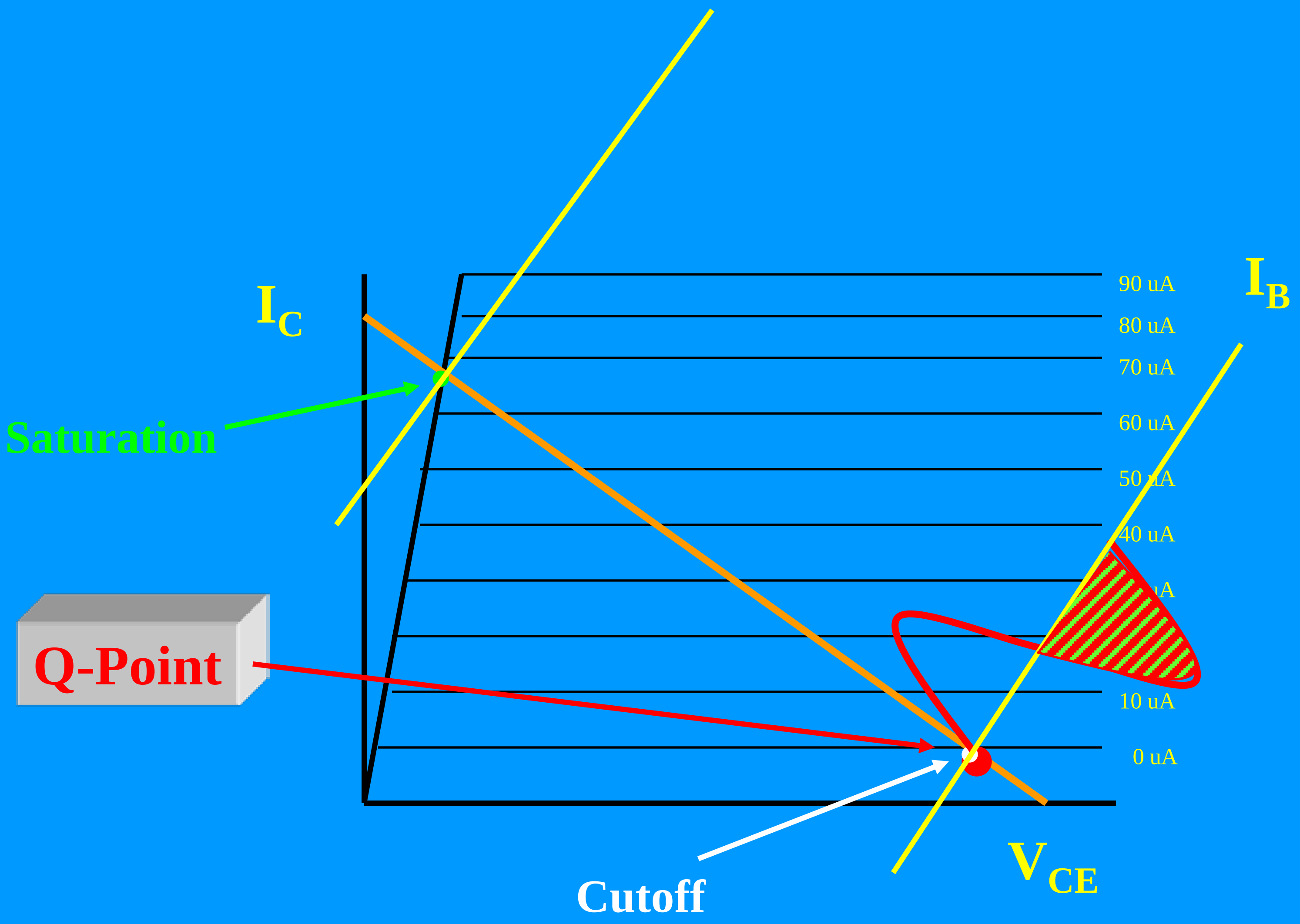
## Common Emitter Amplifier – Class B




**Class B amplifiers has amplitude and crossover distortion. Conducts 50 % of the time.**

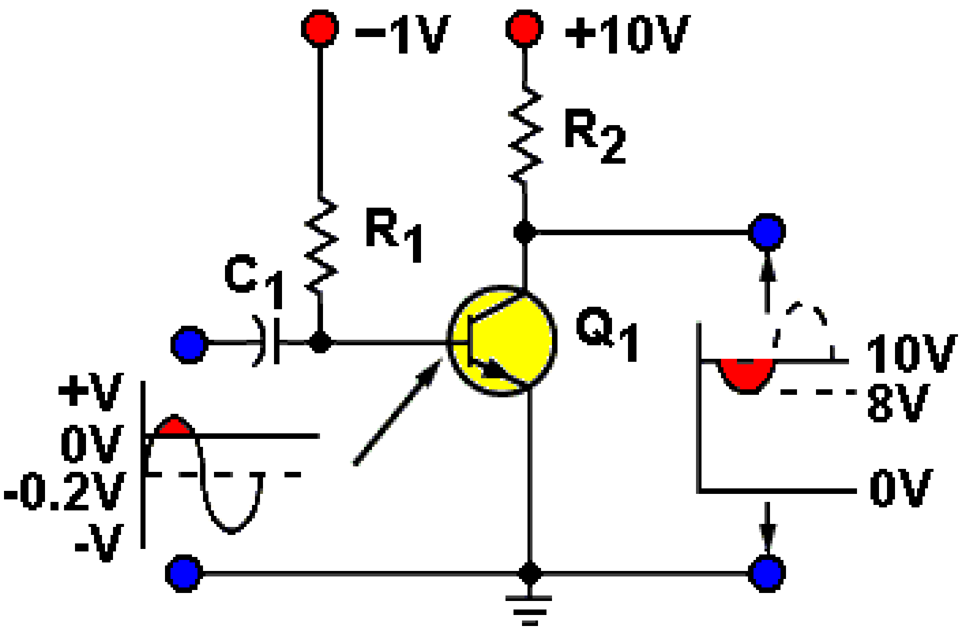
**The collector current will flow for 180 degrees of the input signal.**

# Class 'B' Amplifier Curve



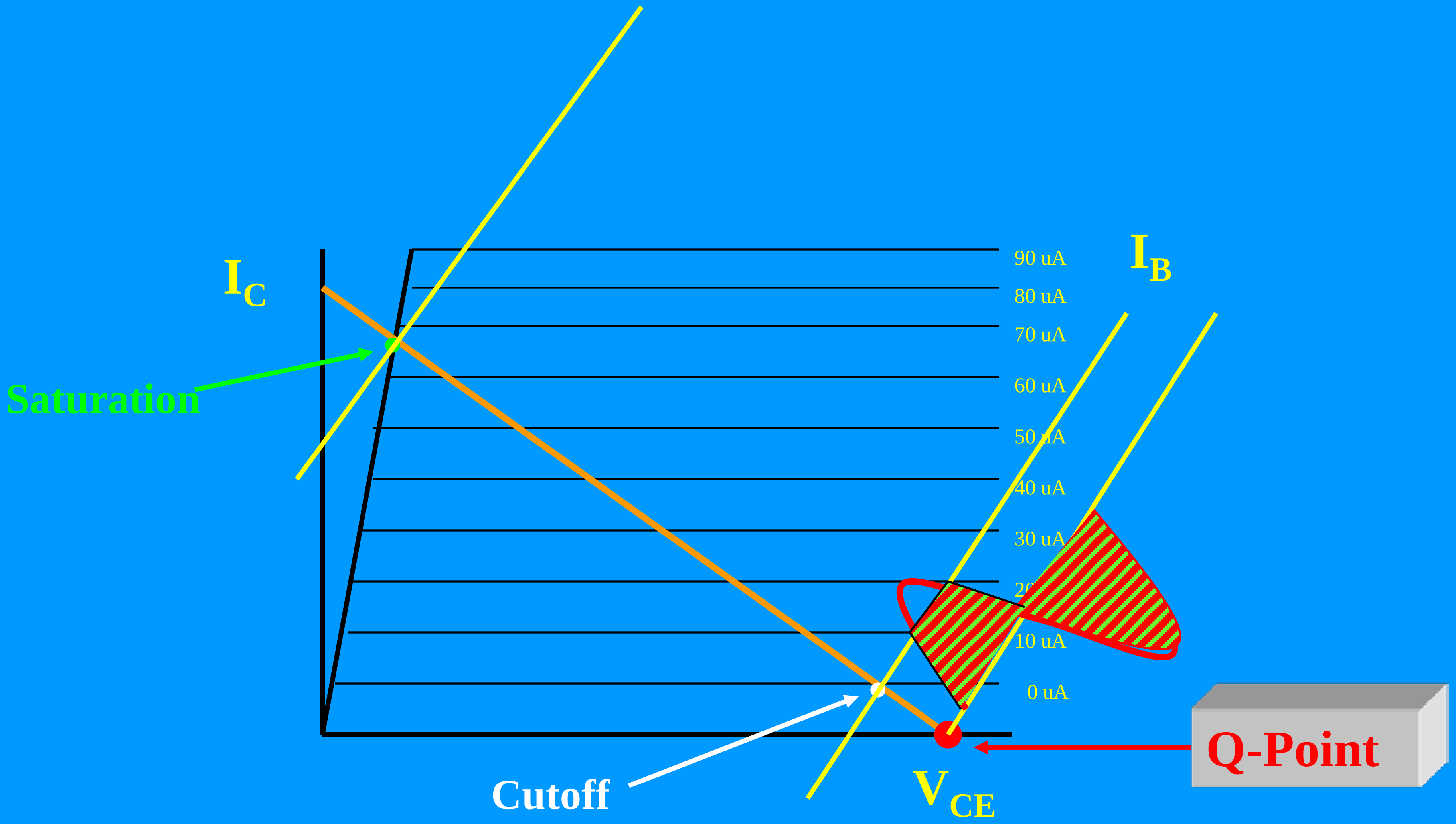
# TRANSISTOR AMPLIFIERS

## Common Emitter Amplifier – Class C




**Class C amplifiers have amplitude and crossover distortion on both alternations. Conducts < 50 %**

# Class 'C' Amplifier Curve



# TRANSISTOR AMPLIFIERS

**Fidelity – The degree to which a device accurately reproduces at its output the characteristics of its input signal.**

**Class A has the best fidelity**

**Efficiency – The ratio between the output signal power and the total input power.**

**Class C has the best efficiency.**

# TRANSISTOR AMPLIFIERS

**Amplitude Distortion – The result of changing a waveshape so its amplitude is no longer proportional to the original amplitude.**

**Amplitude distortion caused by too large input signal, excessive bias, or insufficient forward bias.**

# TRANSISTOR AMPLIFIERS

## Class of Operation Chart

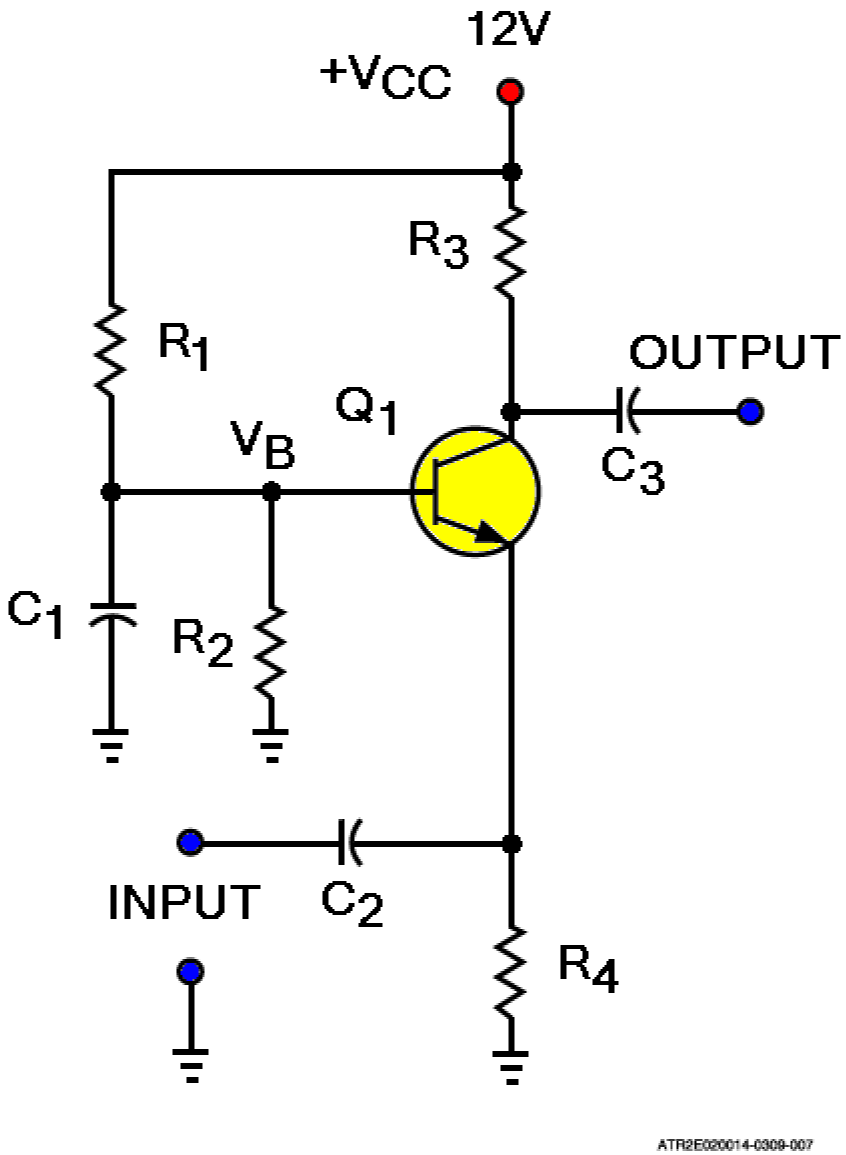
| CLASS | FIDELITY | EFFICIENCY | CONDUCTS | WAVESHAPE | BIAS "E" |
|---|---|---|---|---|---|
| A | Excellent | Worst | 360°<br>100% TIME | | AT OR NEAR OPTIMUM |
| B | Poor | Good | 180°<br>50% Conducts | | AT CUT OFF |
| AB | Average | Poor | MORE THAN 180°/ LESS THAN 360° Conducts: 50% LESS THAN 100% | | Below OPTIMUM Above Cutoff |
| C | Worst | Excellent | LESS THAN 180° Conducts: LESS THAN 50% | | BELOW CUTOFF |
| OVERDRIVEN | Poor | Poor | LESS THAN 360° Conducts LESS THAN 100% | | INPUT TOO LARGE |

# TRANSISTOR AMPLIFIERS

## Common Base Amplifier

- The common base amplifier is also known as the grounded base amplifier.
- The common base amplifier has a voltage gain greater than one, but it has a current gain less than one.
- It is normally characterized by a very small input impedance and a high output impedance like the common emitter amplifier.
- The input signal is in phase with the output signal.

# TRANSISTOR AMPLIFIERS




## Common Base Amplifier

**$R_1$ provides forward bias for the emitter-base junction**

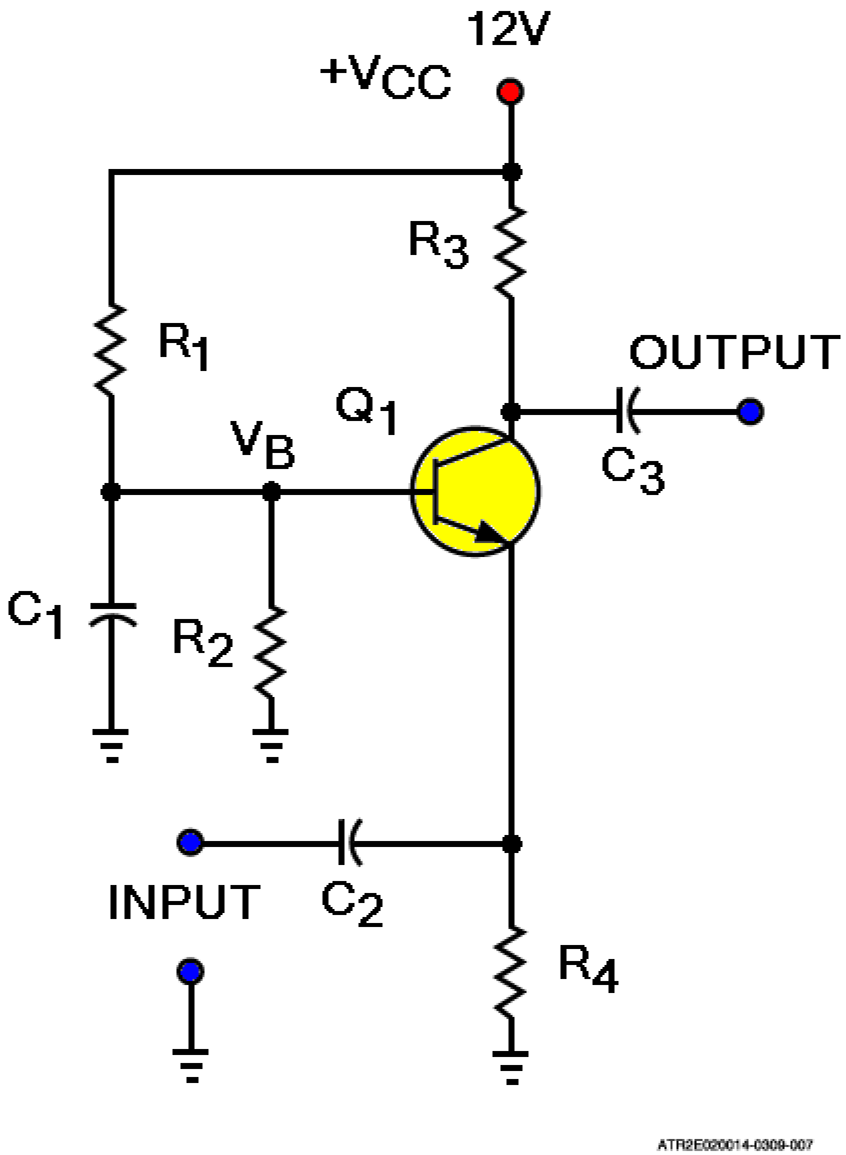
**$R_2$ aids in developing forward bias**

**$R_3$ is the collector load resistor**

**$R_4$ develops the input signal**

# TRANSISTOR AMPLIFIERS

## Common Base Amplifier



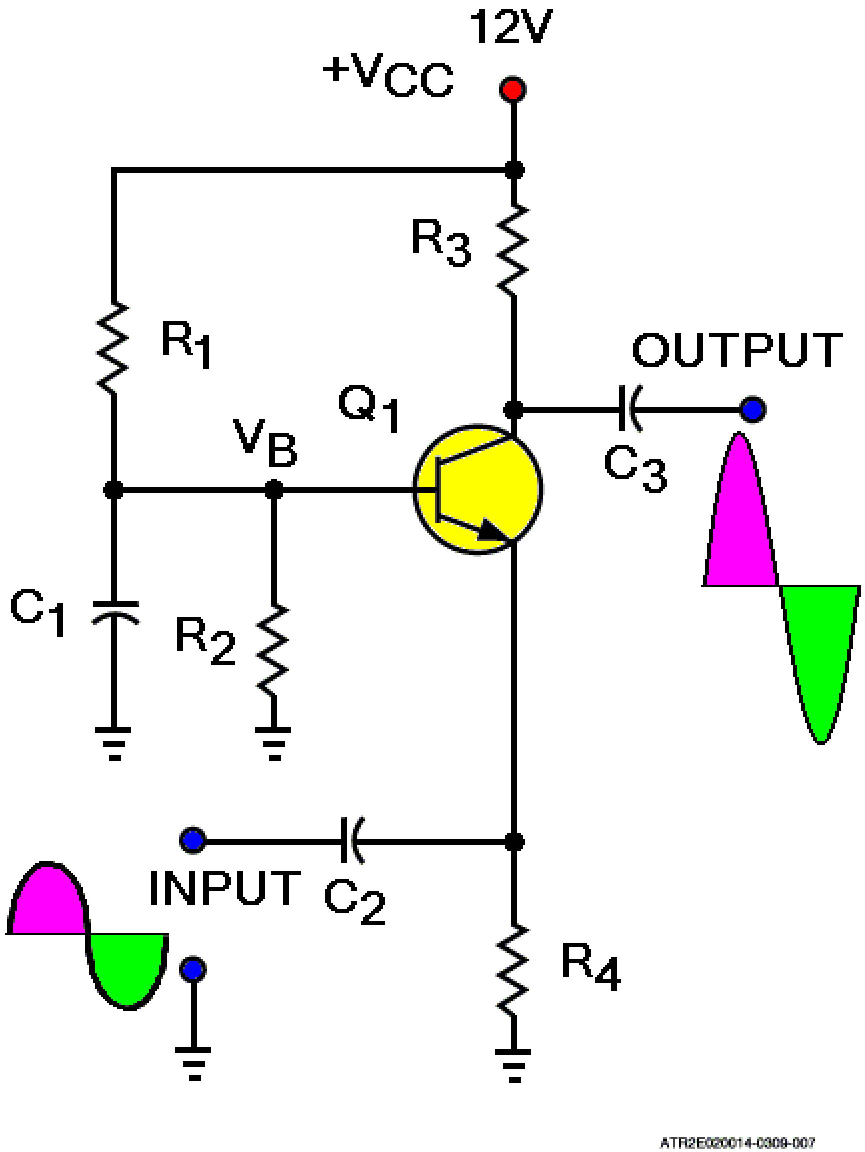

$C_1$ places the base at AC ground

$C_2$ is the input coupling capacitor

$C_3$ is the Output coupling capacitor

$Q_1$ NPN transistor

# TRANSISTOR AMPLIFIERS




## Common Base Amplifier

**A positive alternation applied to the emitter of the transistor decreases forward bias and causes emitter current to decrease. A decrease in emitter current results in a decrease in collector current. A decrease in $I_C$ decreases $E_{R3}$, causing $V_C$ to become more positive. The collector waveform is an amplified reproduction of the positive input alternation.**

# TRANSISTOR AMPLIFIERS

## Common Collector Amplifier

- The common collector amplifier is also called the *emitter follower* amplifier because the output voltage signal at the emitter is approximately equal to the input signal on the base.
- Amplifier's voltage gain is always less than the input signal voltage.
- Used to match a high-impedance source to a low-impedance load

# TRANSISTOR AMPLIFIERS

## Common Collector Amplifier

- Common collector amplifier has a large current and power gain, excellent stability and frequency response.
- The output impedance of this circuit is equal to the value of the emitter resistor, this circuit is used for impedance matching.
- The input and output signals are in phase.

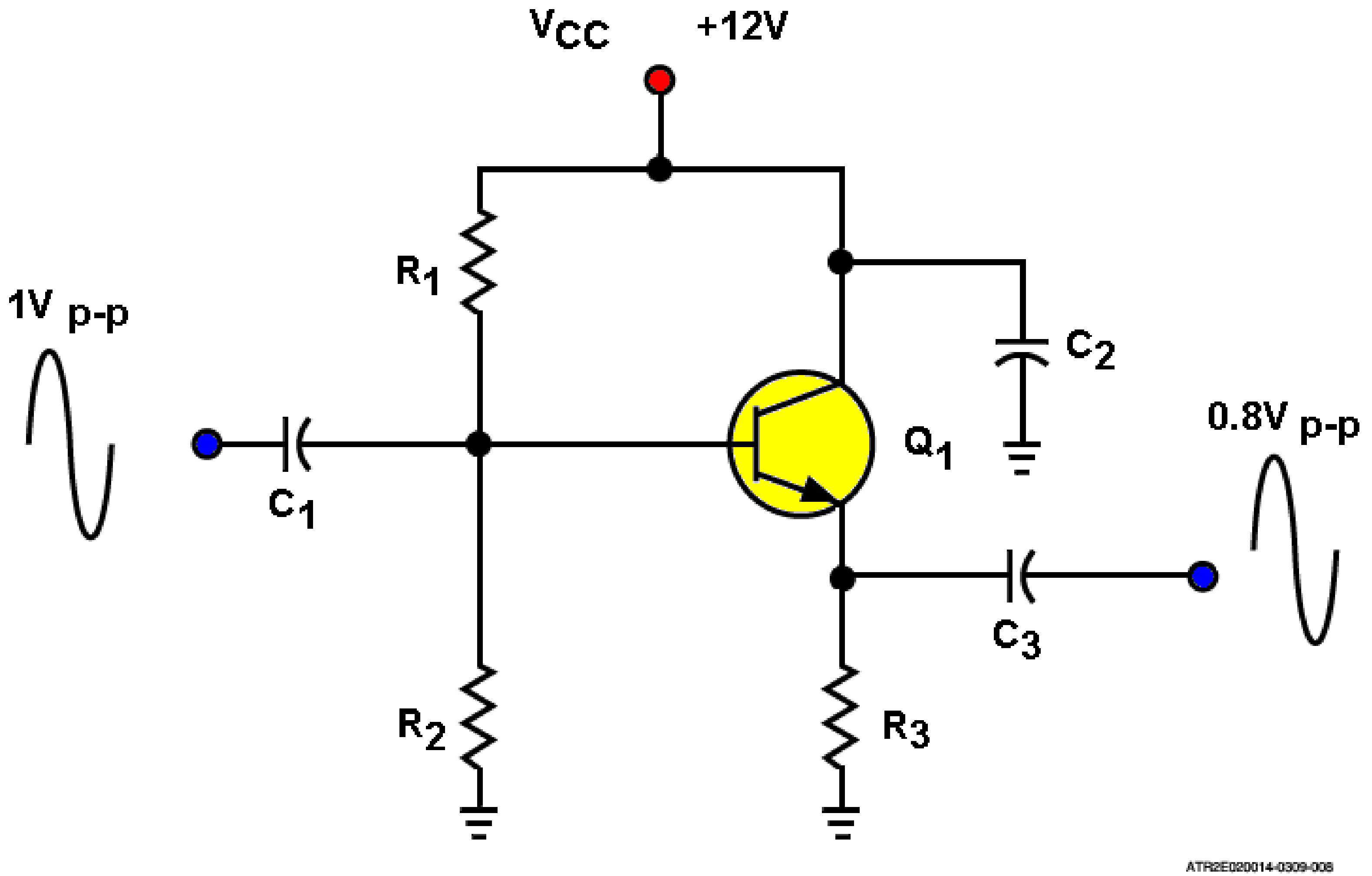
# TRANSISTOR AMPLIFIERS

## Common Collector Amplifier

- Uses degenerative or negative feedback.
- Degenerative feedback is the process of returning a part of the output of an amplifier to its input in such a manner that it cancels part of the input signal.
- As a result, the common collector amplifier has a voltage gain of less than 1.

# TRANSISTOR AMPLIFIERS

## Common Collector Amplifier



# TRANSISTOR AMPLIFIERS

## Common Collector Amplifier

**R1 – Determines amplifier forward bias**

**R2 – Aids in determining forward bias**

**R3 – Emitter load resistor-develops the output signal & degenerative feedback**

**C1 – Input coupling capacitor**

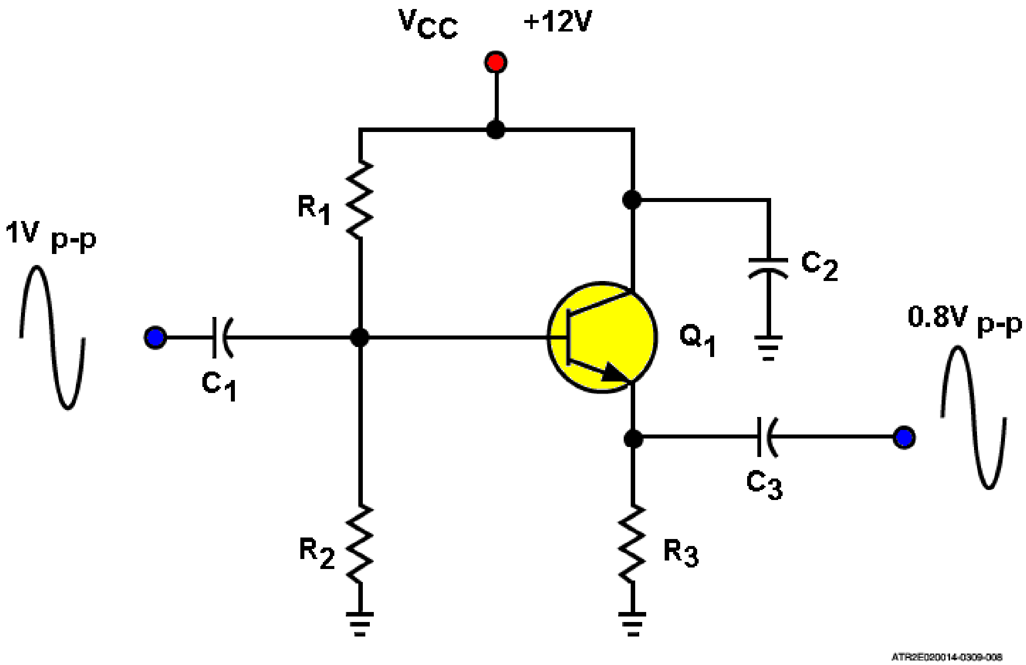
**C2 – By-pass capacitor, places collector at AC ground**

**C3 – Output coupling capacitor**

**Q1 – Transistor amplifier**

# TRANSISTOR AMPLIFIERS

## Common Collector Amplifier

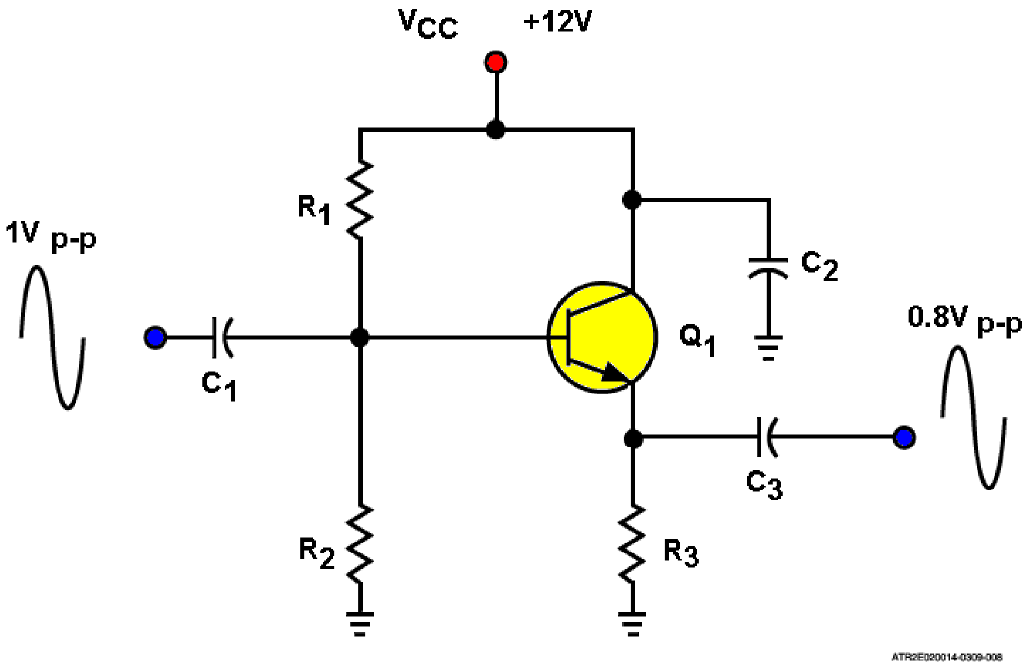



**As the voltage on the base goes in a positive direction, the voltage on the emitter goes in a positive direction.**

**This positive voltage reverse biases the transistor decreasing $I_C$ resulting in an increase voltage drop across the transistor.**

# TRANSISTOR AMPLIFIERS

## Common Collector Amplifier




**As the voltage drop across the transistor increases the voltage drop across the load resistor $R_3$ decreases, thus gain less than one.**

# TRANSISTOR AMPLIFIERS

## Appraisal

# TRANSISTOR AMPLIFIERS

**1. In the common emitter configuration, the input is applied to the ________ and the output is taken from the _______ .**

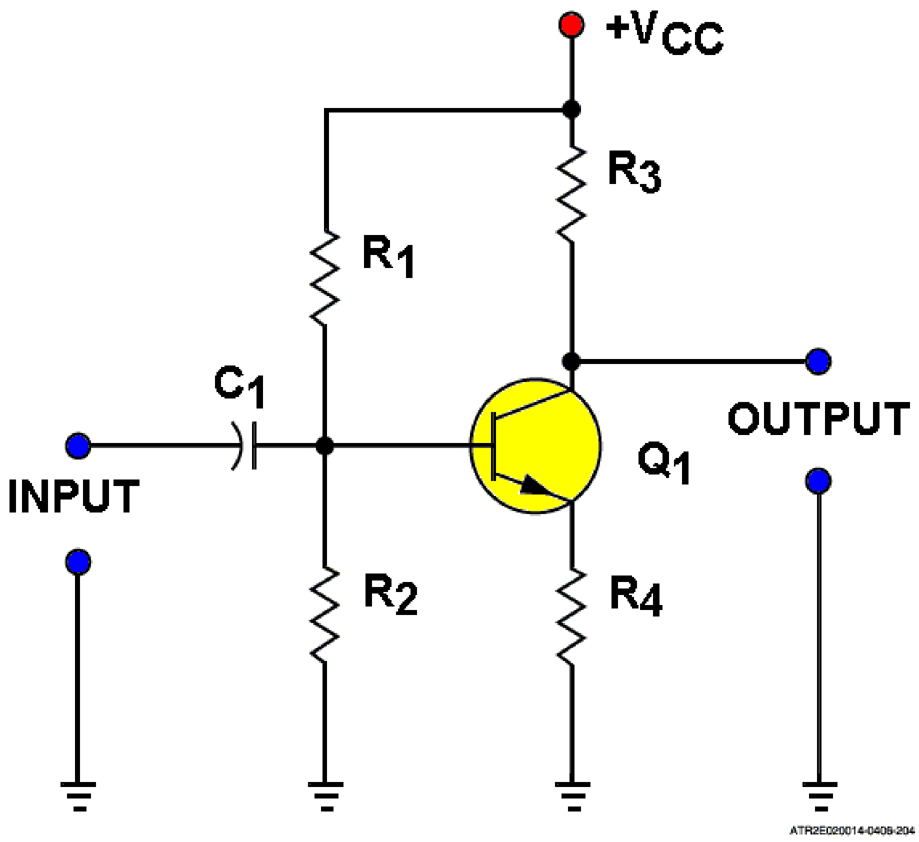
**a. emitter; collector**

**b. base; collector**

**c. emitter; base**

**d. base; emitter**

# TRANSISTOR AMPLIFIERS




**2. What is the purpose of resistors R1 and R2?**

**a. Amplify the input signal**

**b. Develop the output signal**

**c. Develop forward bias voltage for Q1**

**d. Block DC from the base of Q1**

# TRANSISTOR AMPLIFIERS

**3. In a common collector amplifier, degenerative feedback is _______ out of phase with the input signal.**

**a. 0 degrees**

**b. 90 degrees**

**c. 180 degrees**

**d. 270 degrees**

# TRANSISTOR AMPLIFIERS

**4.** **The common base amplifier has a voltage gain _______, but a current gain _______ .**

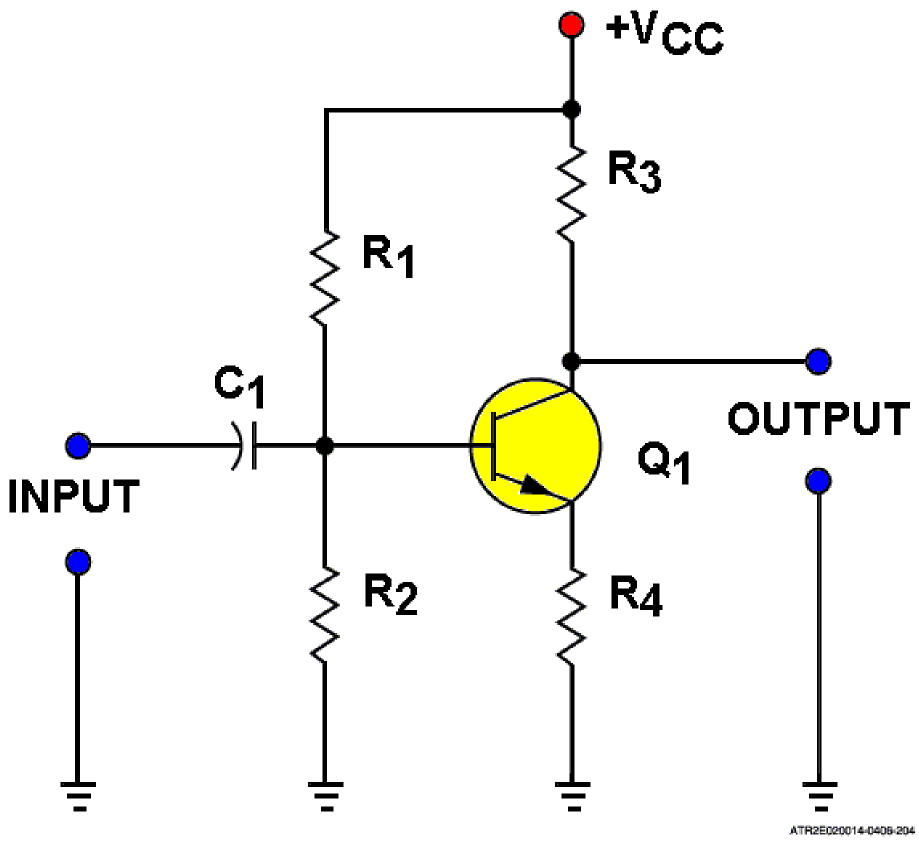
**a. less than one, less than one**

**b. greater than one, less than one**

**c. less than one, greater than one**

**d. greater than one, greater than one**

# TRANSISTOR AMPLIFIERS




**5. In the common emitter configuration, R3 primarily affects**

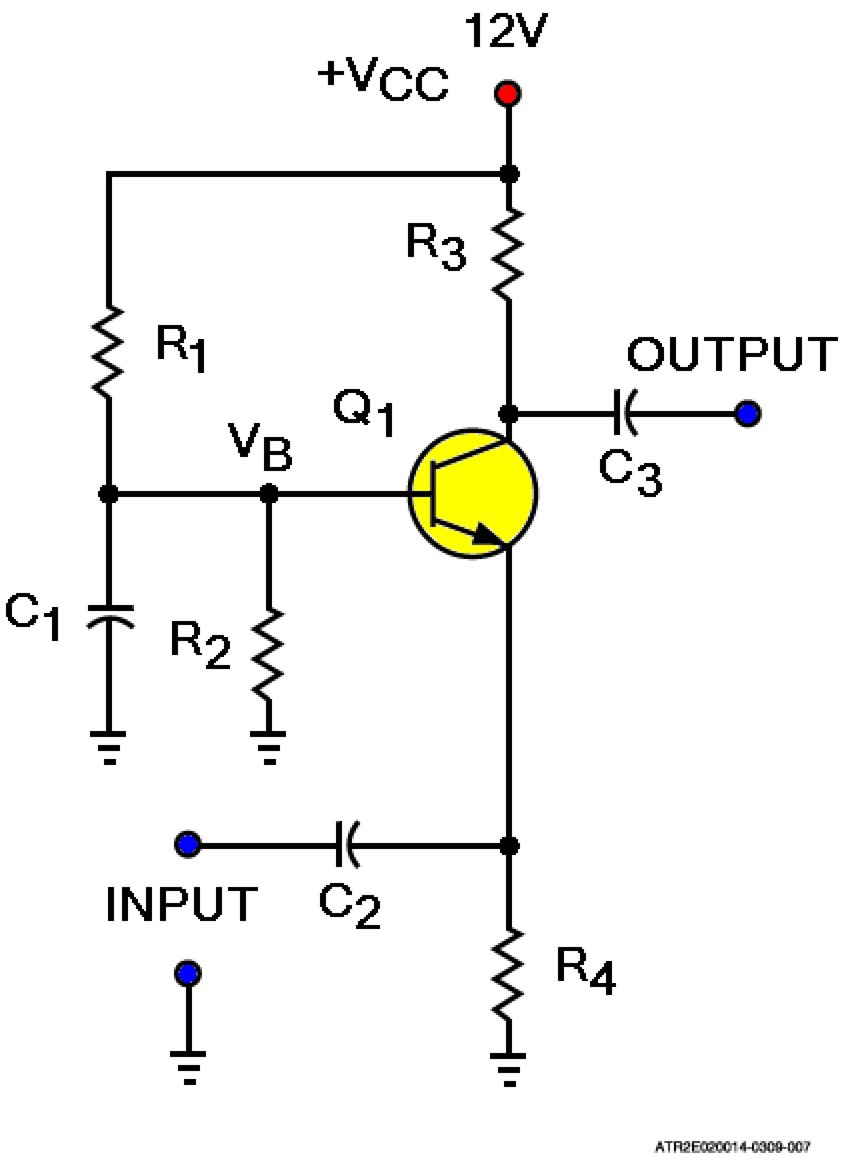
**a. gain.**

**b. forward bias.**

**c. degeneration.**

**d. temperature stabilization.**

# TRANSISTOR AMPLIFIERS




**6. What is the purpose of R4 in the common base amplifier?**

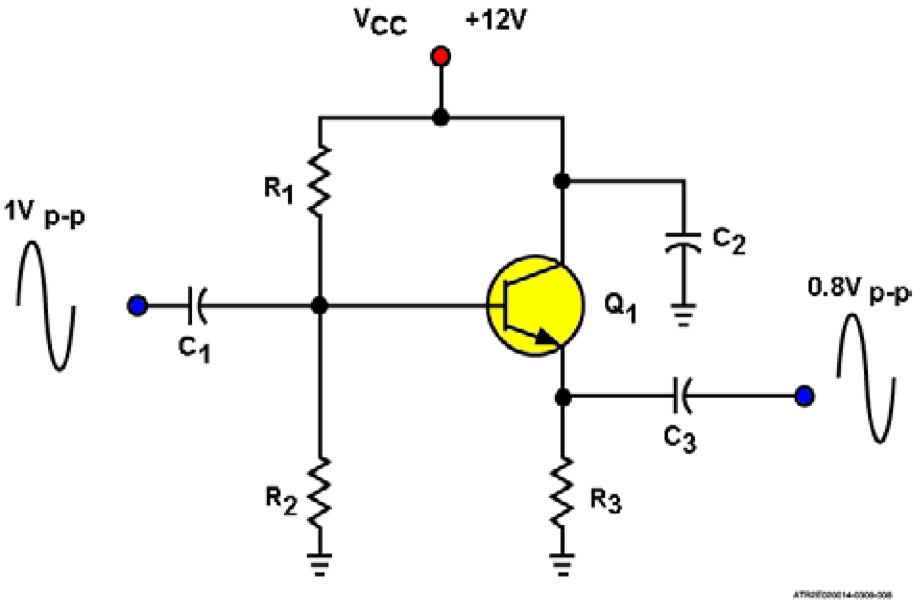
**a. Couple the output signal**

**b. Develop the input signal**

**c. Develop the output signal**

**d. Keep the base at AC ground**

# TRANSISTOR AMPLIFIERS




**7.** **In the amplifier circuit shown, the purpose of C2 is to**

**a. couple the output signal.**

**b. develop the output signal.**

**c. place the collector at AC ground.**

**d. provide regenerative feeback.**

# TRANSISTOR AMPLIFIERS

**8. The amplifiers class of operation is determined by**

**a. fidelity.**

**b. efficiency.**

**c. output waveform.**

**d. amount of forward bias.**

# TRANSISTOR AMPLIFIERS

**9. With a transistor amplifier operating in class B, the collector current will flow for _____ of the input signal.**

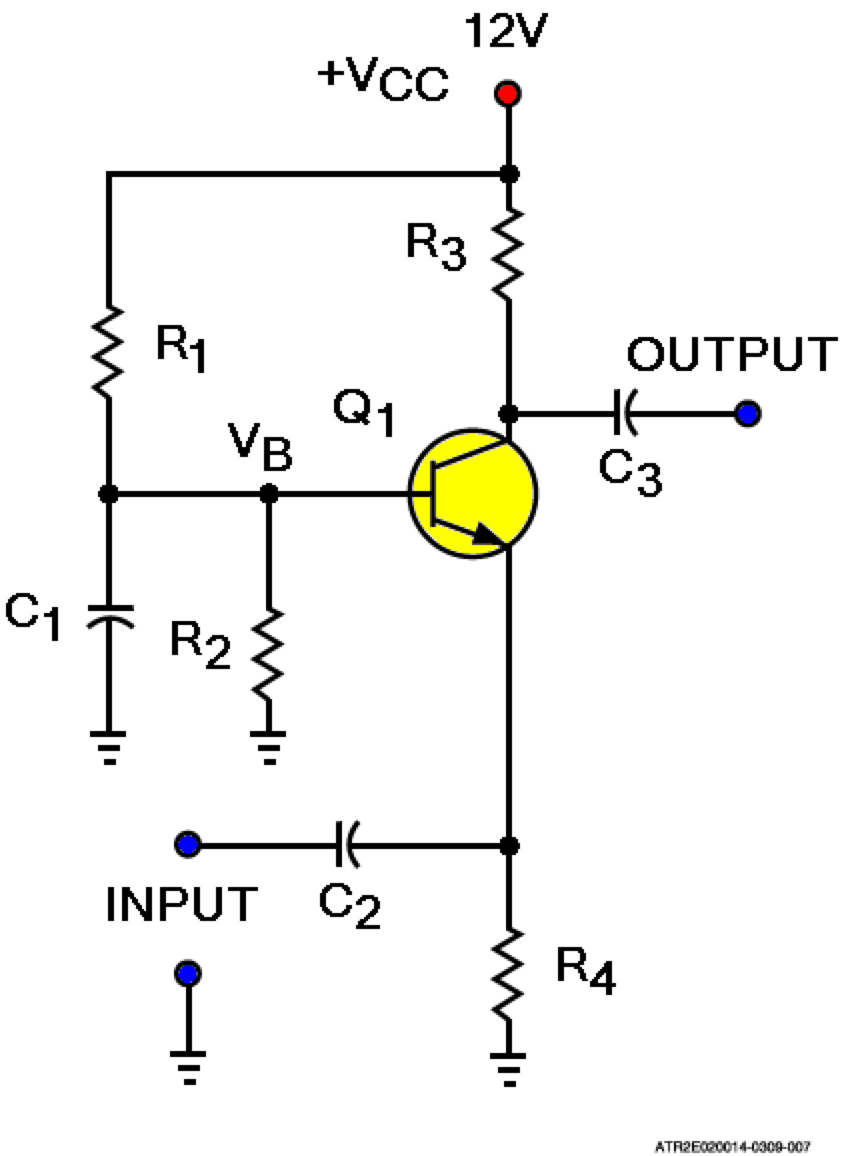
**a. 90 degrees**

**b. 180 degrees**

**c. 360 degrees**

**d. more than 180 degrees but less than 360 degrees**

# TRANSISTOR AMPLIFIERS




**10.** **In the transistor amplifier shown, what is the phase relationship between the input and output signals?**

**a. 0 degree phase shift**

**b. 90 degree phase shift**

**c. 180 degree phase shift**

**d. 270 degree phase shift**

# TRANSISTOR AMPLIFIER TEMPERATURE STABALIZATION

# TEMPERATURE STABALIZATION

## PURPOSE

**The process of minimizing undesired changes in a transistor circuit caused by heat is called temperature stabilization.**

# TEMPERATURE STABALIZATION

## Negative Temperature Coefficient

- **Transistors have a negative temperature coefficient**
- **This means that as temperature increases the resistance of the transistor decreases.**

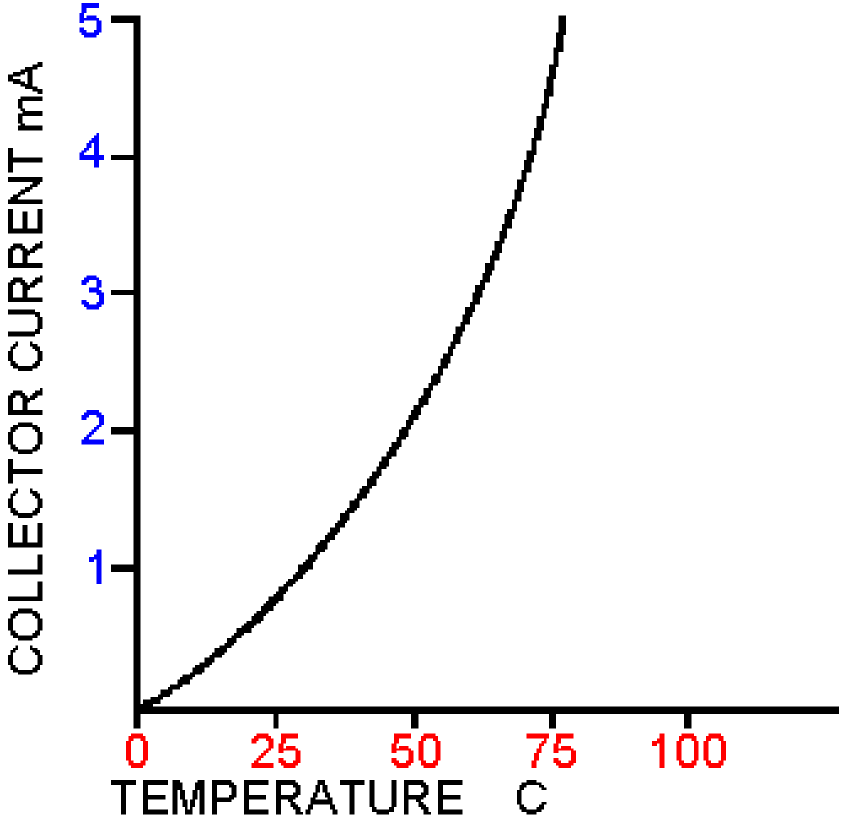
# TEMPERATURE STABALIZATION

## Negative Temperature Coefficient

**To compensate for temperature changes, all thermal stabilization circuits do the opposite to the transistor. As temperature increases, the thermal stabilization circuits reduce forward bias of the transistor, increasing its resistance.**

# TEMPERATURE STABALIZATION

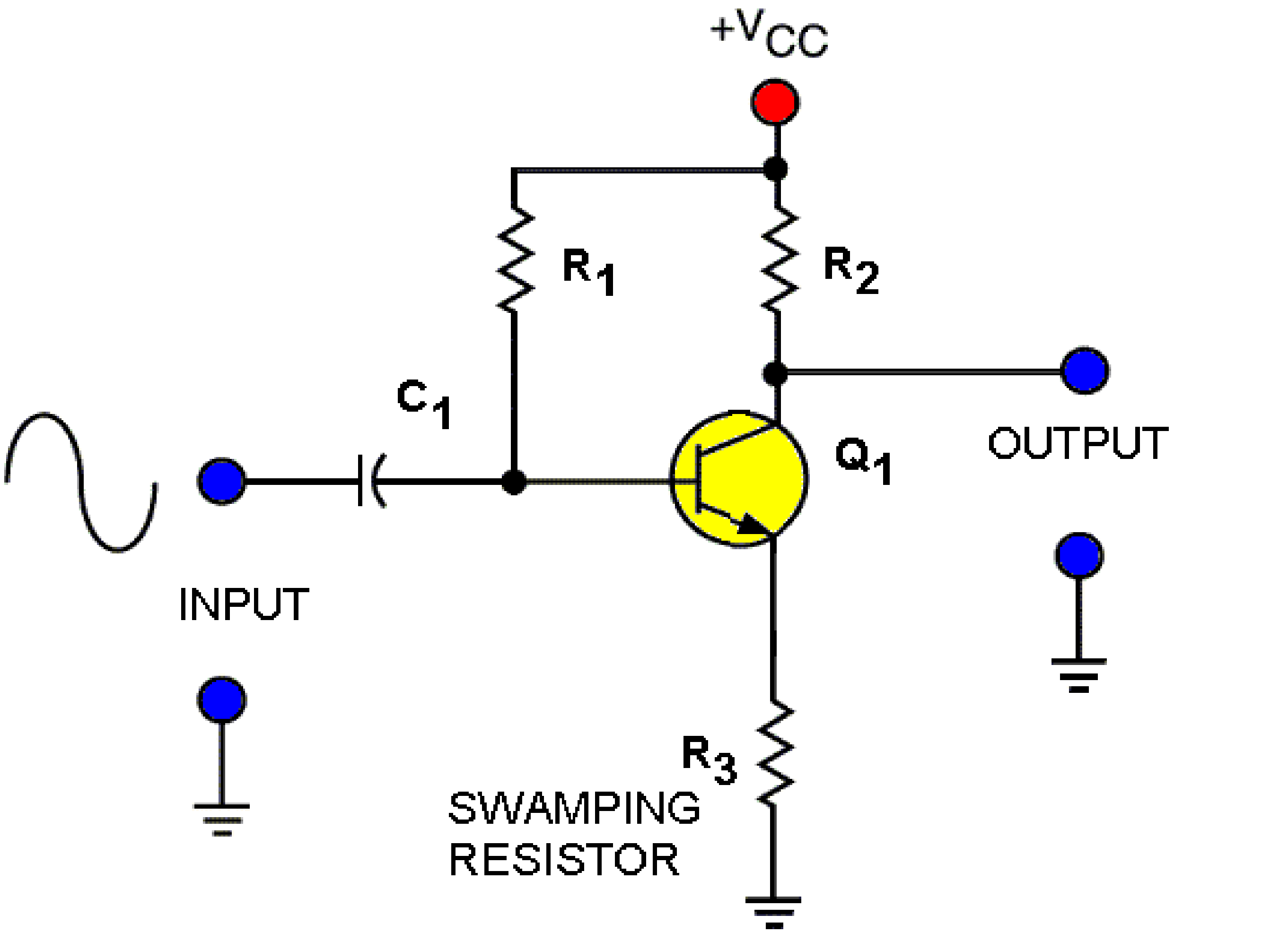
**Collector Current ($I_C$) vs.Temperature Graph**
**Non-stabilized circuits**




- As temperature increases $I_C$ increases due to the resistance of the transistor decreasing.
- This causes the transistor $I_C$ to move above its operating point.

# TEMPERATURE STABALIZATION

## Swamping Resistor Stabilization



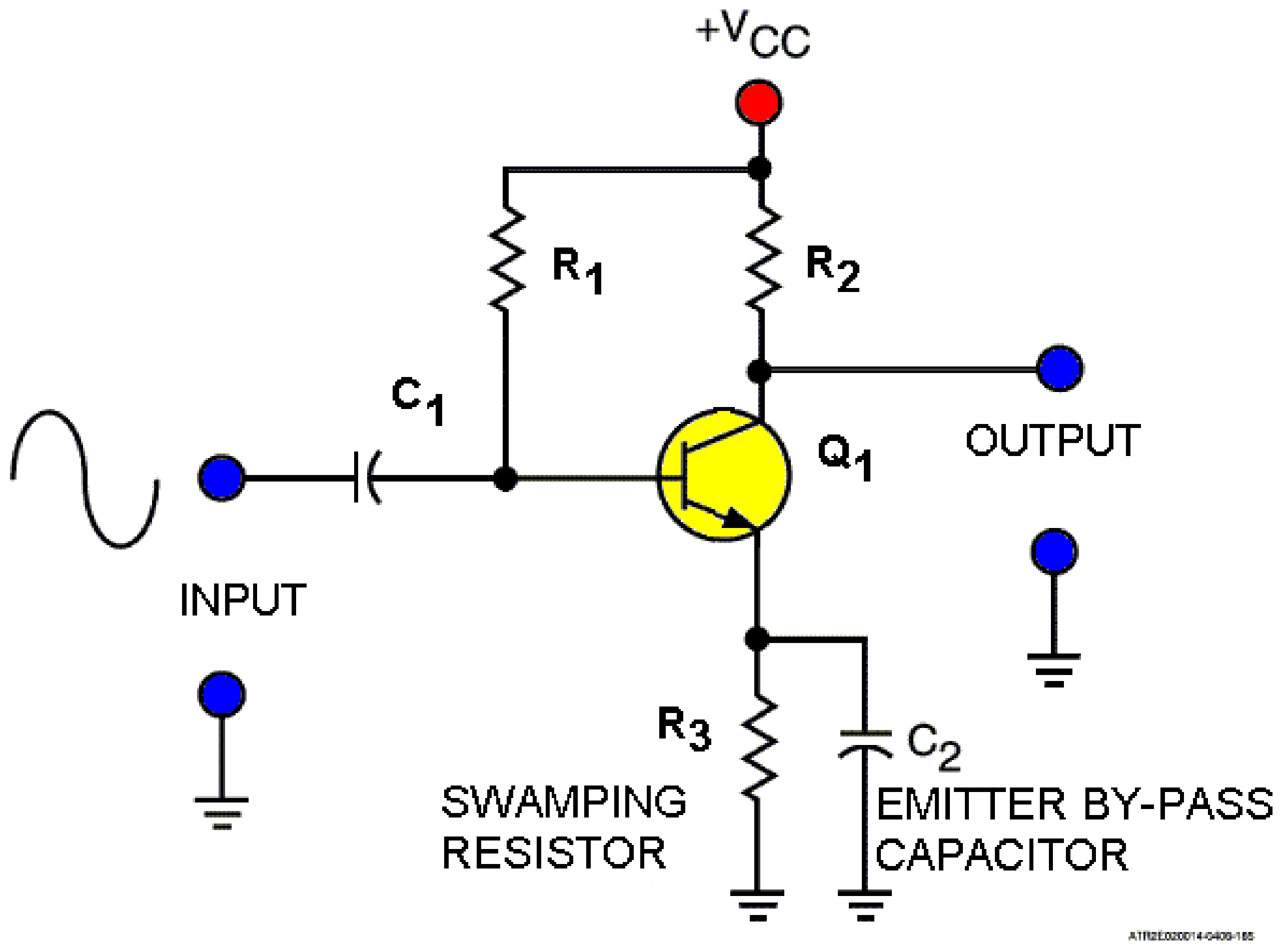
# TEMPERATURE STABALIZATION

## Swamping Resistor Stabilization

- Placing a resistor ($R_3$) in the emitter for temperature stabilization is referred to as a "Swamping" resistor. Using swamping resistor ($R_3$) for temperature stabilization results in degeneration feedback.
- An increase in $I_C$ flows through the emitter resistor and develops an increase in voltage on the emitter.
- This voltage opposes forward bias and reduces $I_B$ and $I_C$.

# TEMPERATURE STABALIZATION

## Swamping Resistor with Bypass Capacitor



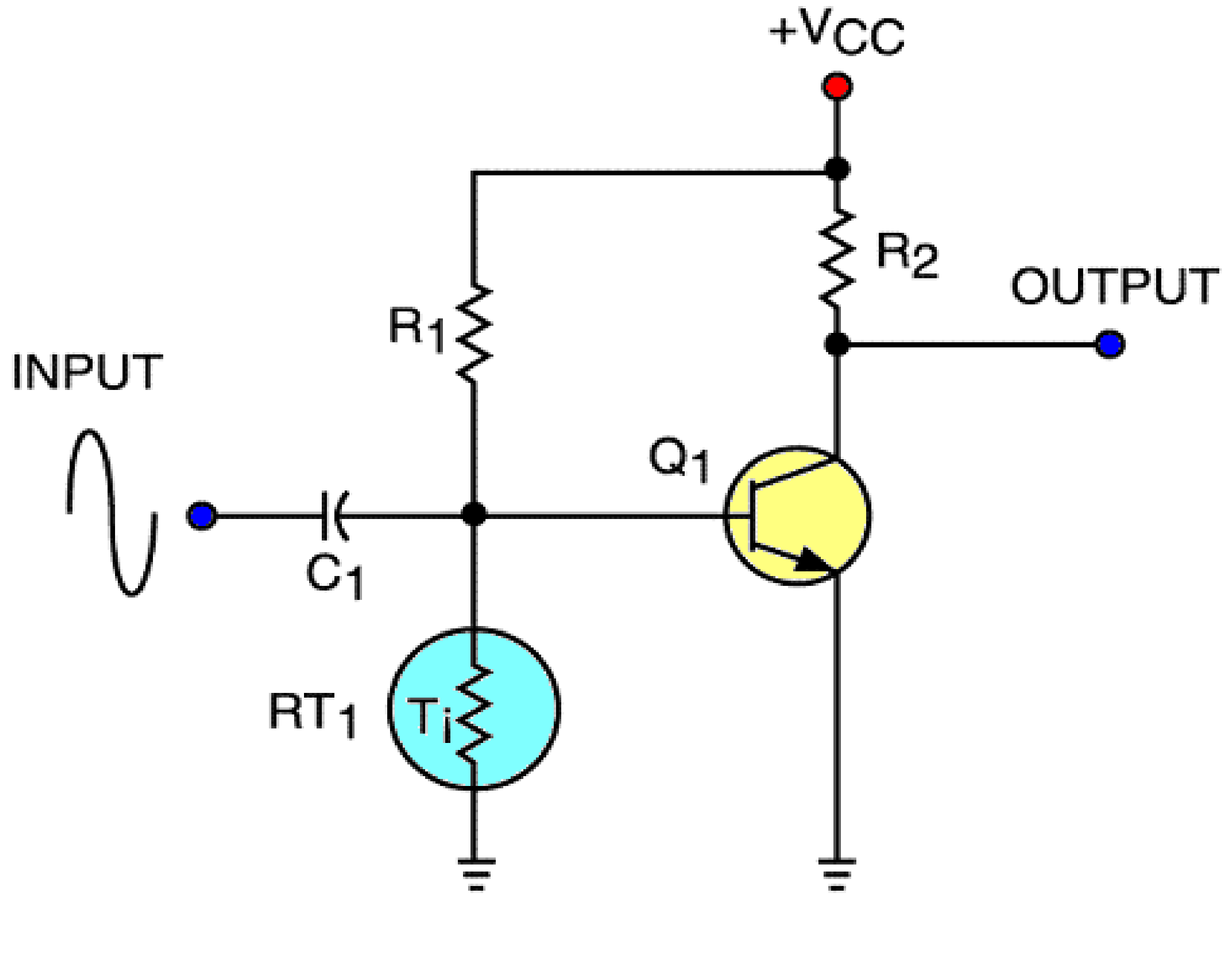
# TEMPERATURE STABALIZATION

## Swamping Resistor with Bypass Capacitor

- $C_2$ is referred to as the “emitter bypass capacitor”.
- By placing a large capacitor ($C_2$) across $R_3$, a signal ground is established and compensates for signal degeneration

# TEMPERATURE STABALIZATION

## Thermistor Stabilization



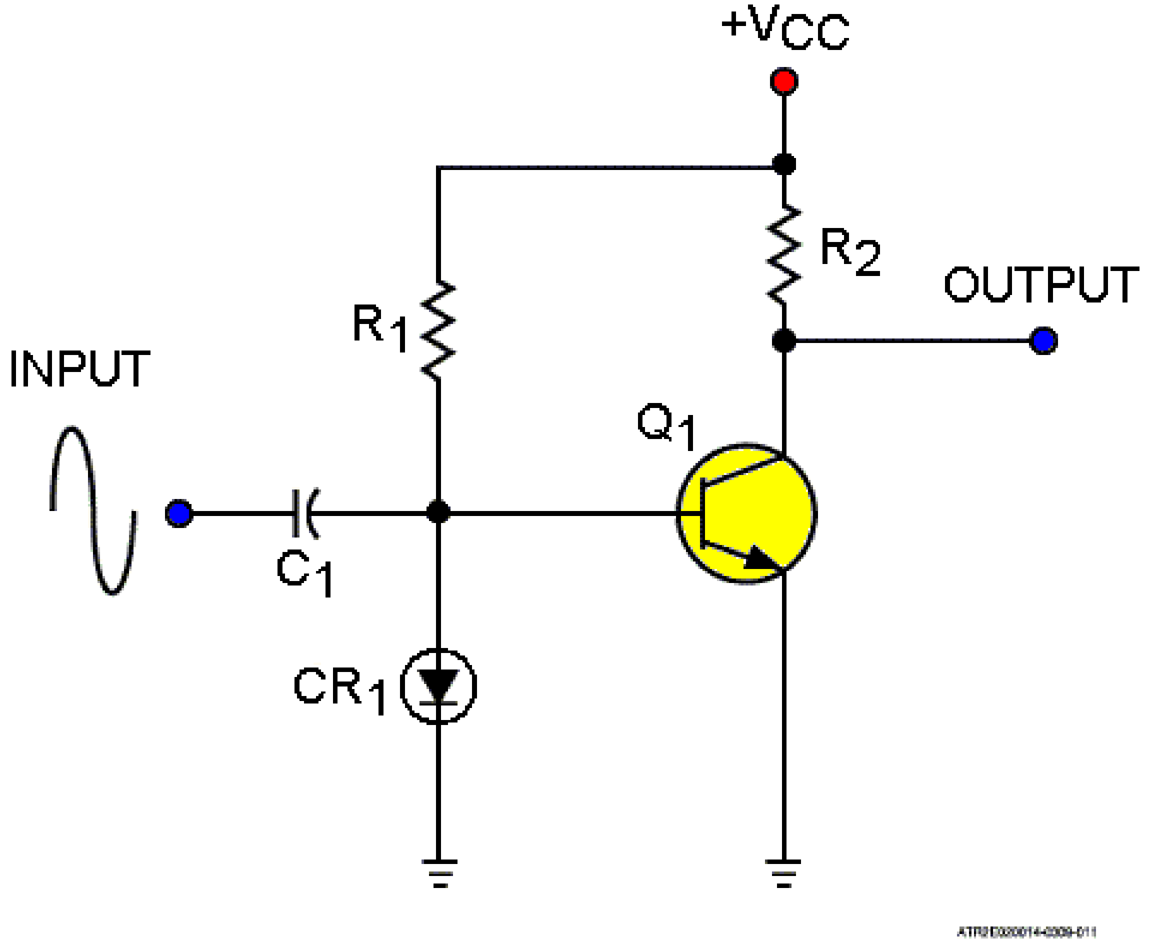
# TEMPERATURE STABALIZATION

## Thermistor Stabilization

- A thermistor has a negative temperature coefficient of resistance.
- Bias is established by $R_1$ and $R_{T1}$ the thermistor.
- As temp. increases, resistance of $R_{T1}$ decreases, causing bias and $I_C$ to decrease
- This compensates for the change in $I_C$ due to temp. variations.

# TEMPERATURE STABALIZATION

## Forward Bias Diode Stabilization



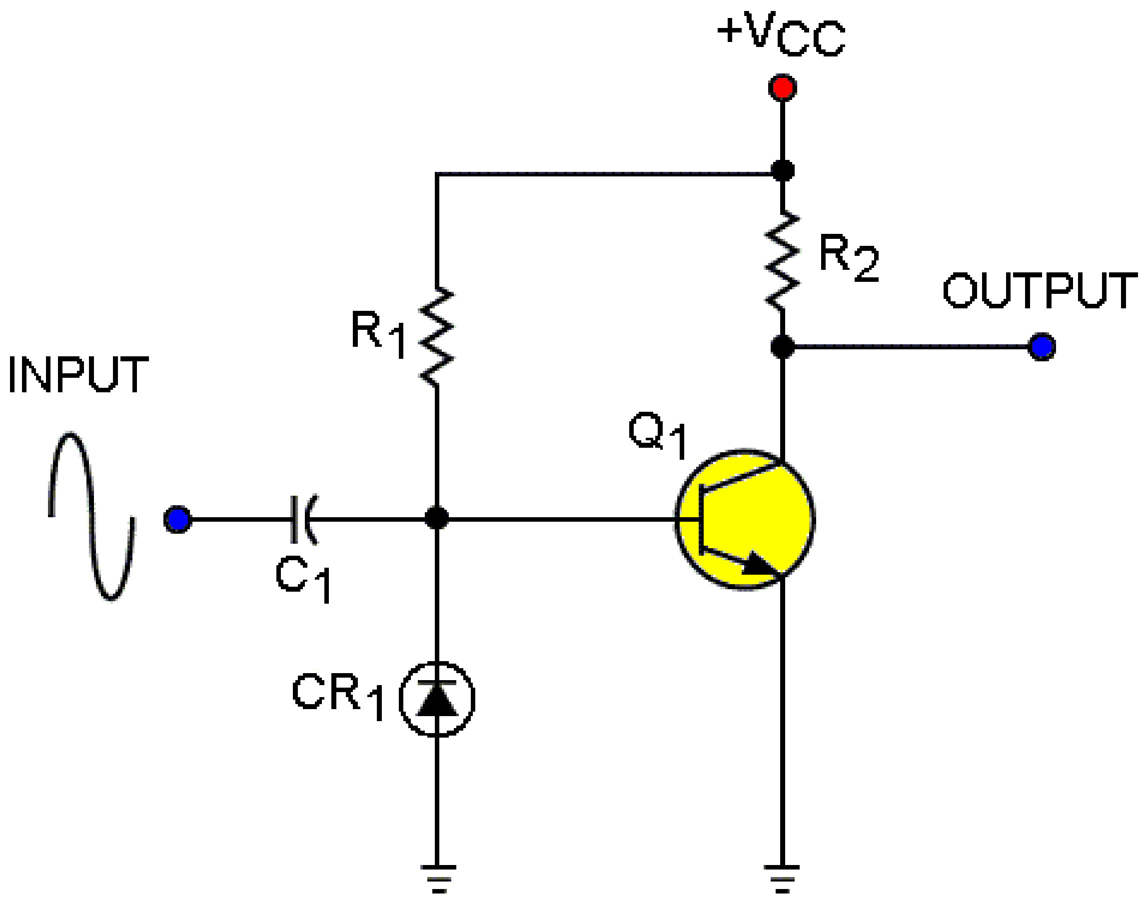
# TEMPERATURE STABALIZATION

## Forward Bias Diode Stabilization

- To more closely follow resistance changes of the transistor, replace the thermistor with a diode.
- Diodes and transistors are made of the same materials, therefore, closely follow temperature changes.
- As the amplifiers forward biased diode temperature increases its resistance decreases, thus forward bias decreases.

# TEMPERATURE STABALIZATION

## Reverse Bias Diode Stabilization



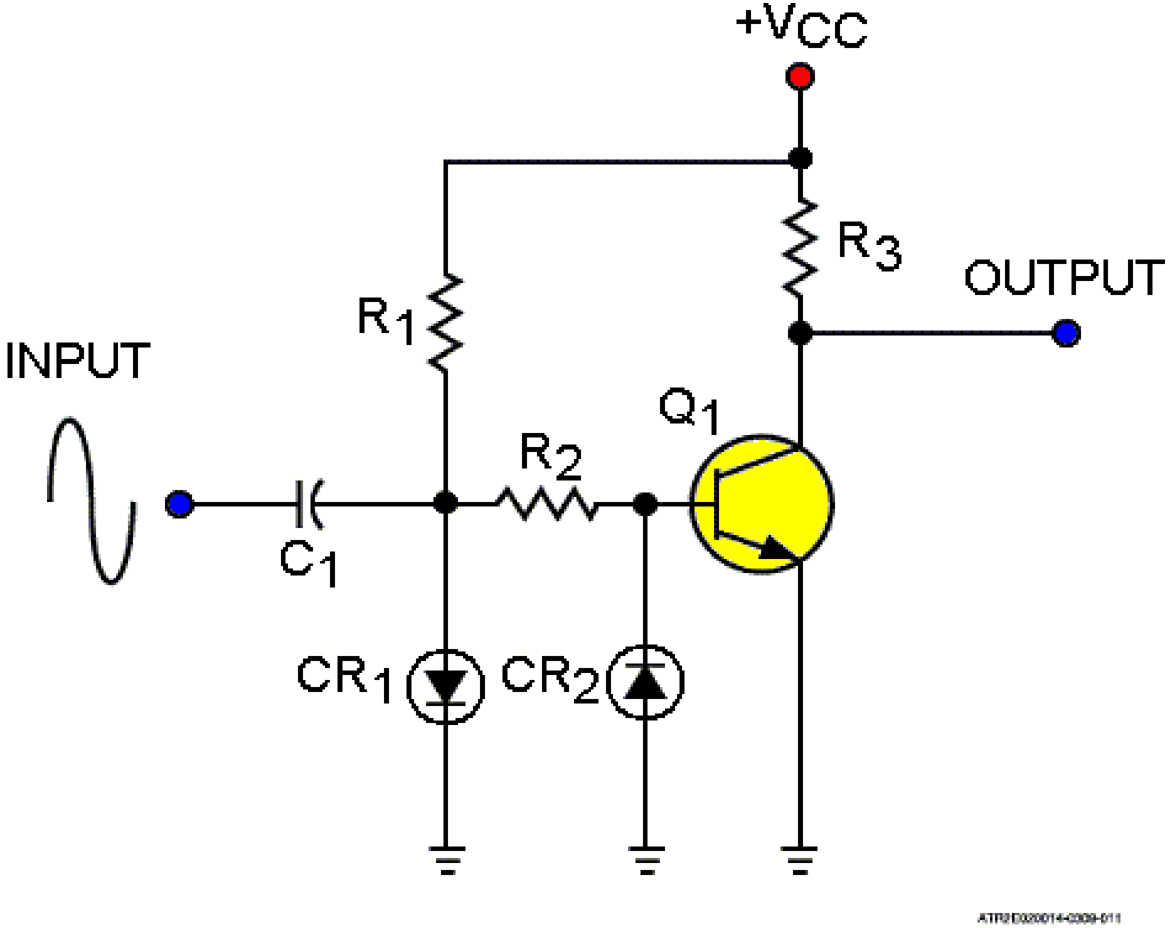
# TEMPERATURE STABALIZATION

## Reverse Bias Diode Stabilization

- Used to reduce the effects of $I_{CB}$ on collector current.
- As the reverse current of $CR_1$ increases, it will cause a larger voltage drop across $R_1$.
- This will reduce the voltage across the base-emitter junction ($V_{EB}$), causing base current to decrease, causing collector current will decrease.

# TEMPERATURE STABALIZATION

## Double Diode Stabilization



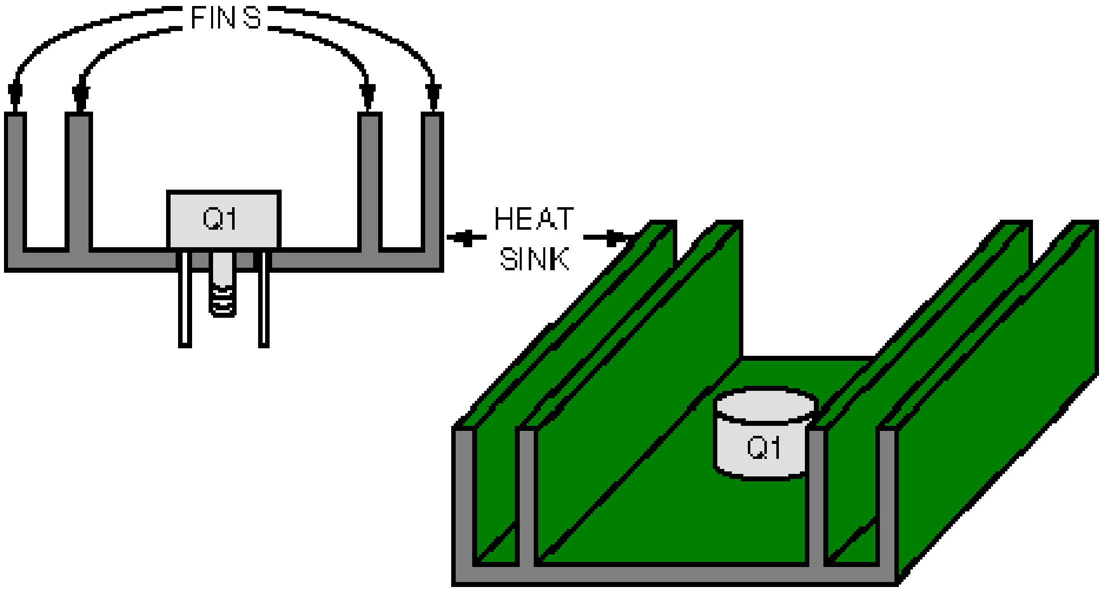
# TEMPERATURE STABALIZATION

## Double Diode Stabilization

- **Forward biased diode $CR_1$ compensates for changes in the resistance of the forward biased emitter-base junction due to temperature.**
- **The reverse biased diode $CR_2$ compensates for the effects of $I_{CB}$ in the reverse biased collector-base junction.**

# TEMPERATURE STABALIZATION

## Heat Sink




**Heat sinks dissipate heat generated by high current through transistors**

**The transistor is connected directly to the heat sink and the fins dissipate the heat away from the junctions.**

# TEMPERATURE STABILIZATION

## Appraisal

# TEMPERATURE STABILIZATION

**11. The "negative temperature coefficient" of a thermistor means that as temperature increases resistance _________ .**

**a. increases**

**b. decreases**

**c. Remains the same**

# TEMPERATURE STABILIZATION

**12. Using the swamping resistor for thermal stability, what type of feedback is developed to control the amplifier?**

**a. Regenerative**

**b. Degenerative**

**c. Positive feedback**

# TEMPERATURE STABILIZATION

**13. Which of the following devices is used to dissipate heat into the air?**

**a. Heat sink**

**b. Circuit board**

**c. Swamping resistor**

**d. Coupling capacitor**

# TRANSISTOR AMPLIFIER COUPLING

# TRANSISTOR AMPLIFIER COUPLING

## Purpose:

**To achieve the high gain needed by most circuits, amplifiers are connected in series (or cascaded together) to form cascade amplifiers. The signal is couple from one amplifier stage to another.**

# TRANSISTOR AMPLIFIER COUPLING

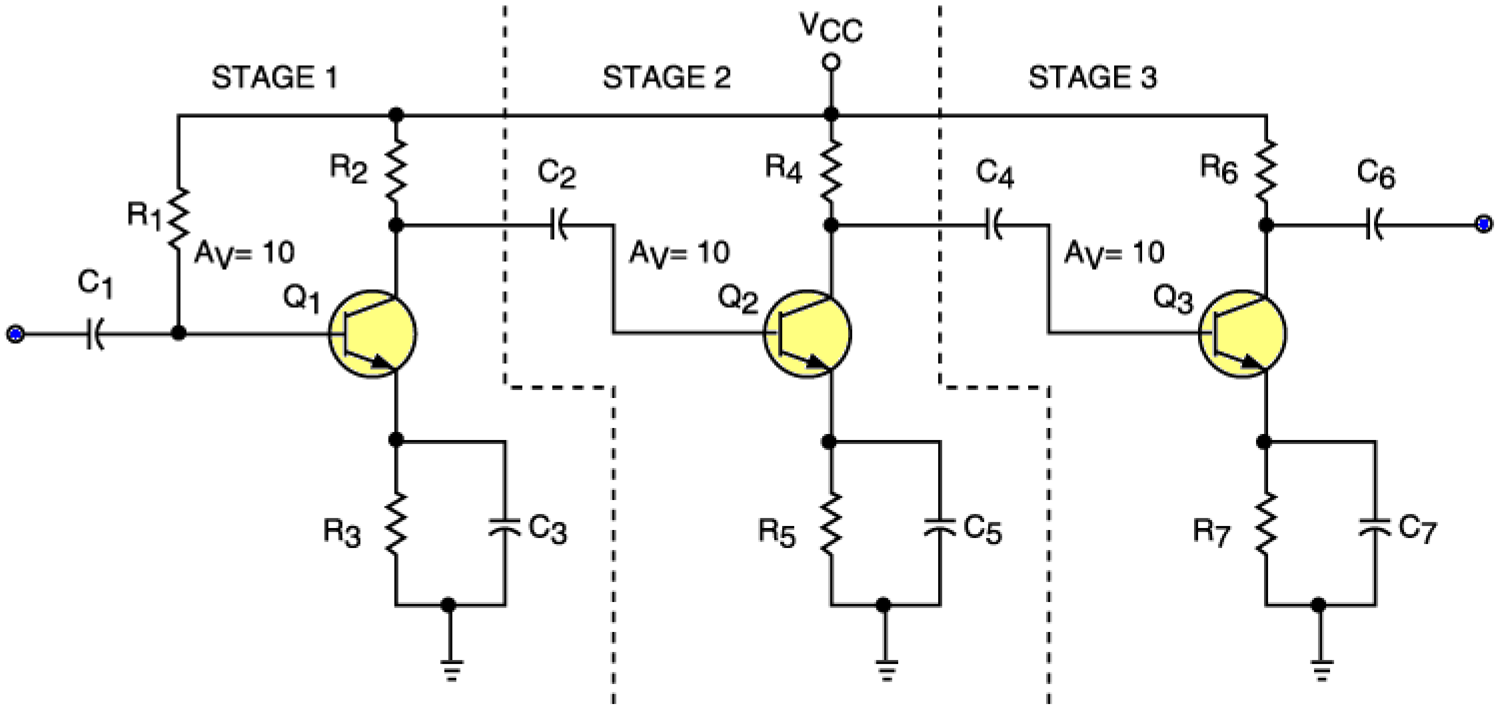
## Cascade Amplifier Voltage Gain

**Low gain amplifiers do not amplify the input signal enough to be of practical use. Using cascade amplifiers, high gain is achieved without incurring distortion.**

**The overall gain of a cascade amplifier is equal to the product of the individual gains, or:** $A_{V(TOTAL)} = A_{V1} \times A_{V2} \times A_{V3}$

# TRANSISTOR AMPLIFIER COUPLING

## Cascade Amplifier Voltage Gain



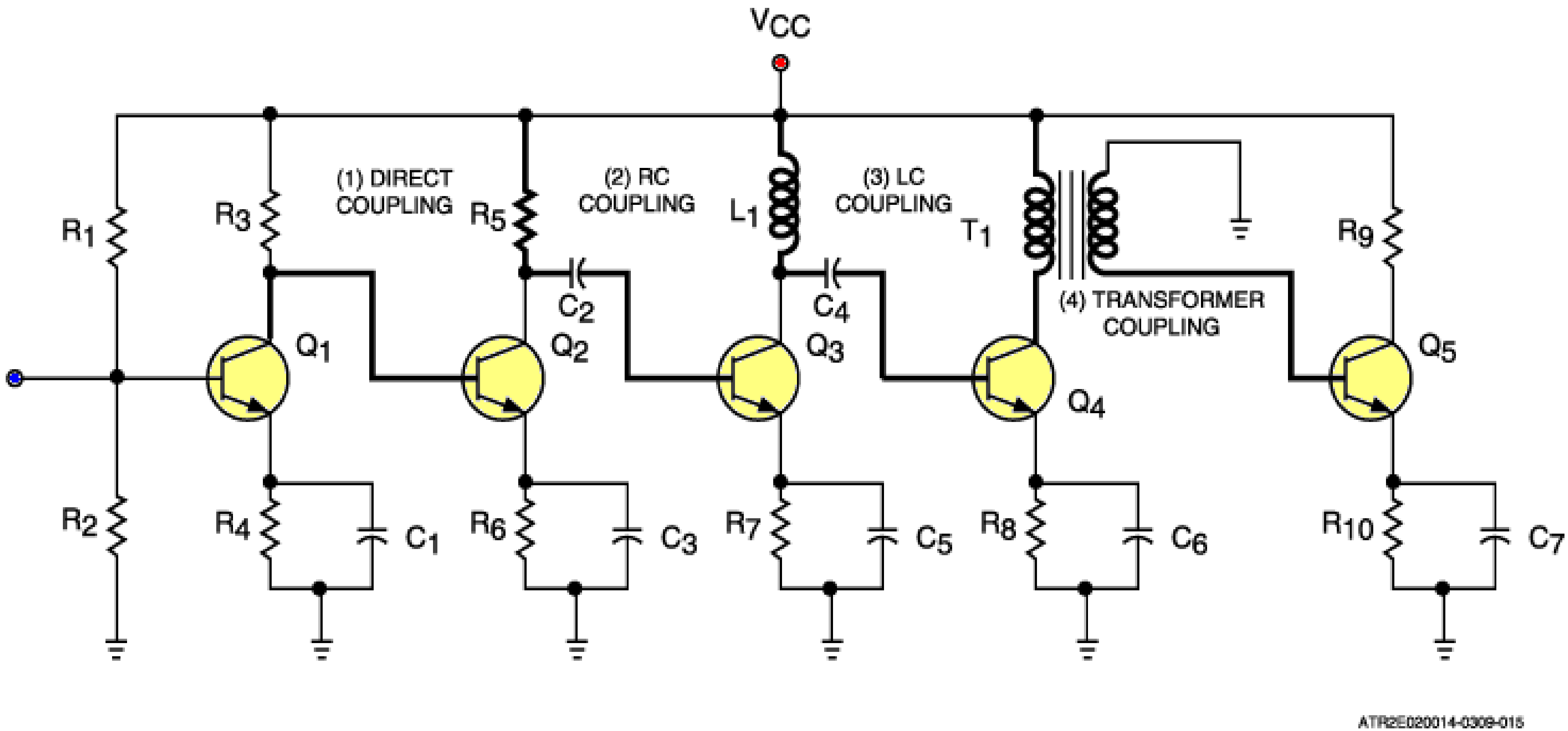

**The overall gain for this cascade amplifier, however, is 1000 ($A_{V(TOTAL)} = A_{V1} \times A_{V2} \times A_{V3} = 10 \times 10 \times 10 = 1000$).**

# TRANSISTOR AMPLIFIER COUPLING

There are numerous types of circuits used to connect (or couple) one amplifier to another. The most commonly used are:

- Direct Coupling
- RC Coupling
- LC Coupling
- Transformer Coupling

# Direct, RC, LC, and Transformer Coupling



# LOW FREQUENCY GAIN LOSS

**Three types of components cause low frequency gain loss in a cascade amplifier: coupling capacitors, inductors and transformers.**

Coupling Capacitors cause low frequency gain loss because of their high capacitive reactance at low frequencies.

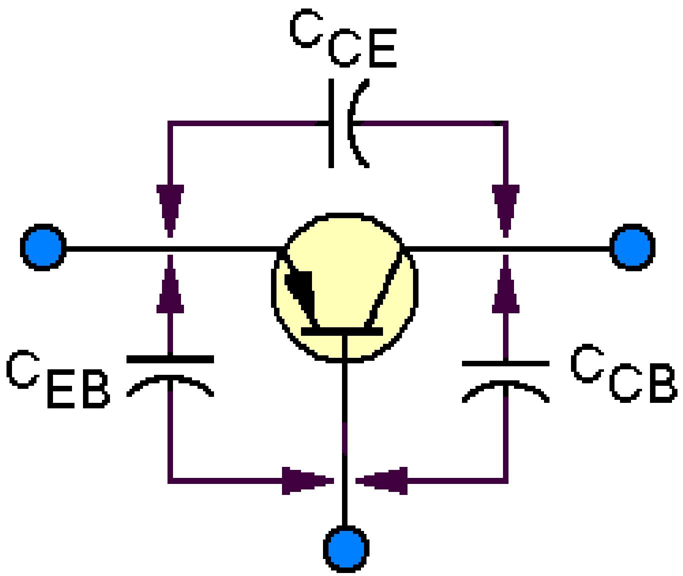
Inductors and Transformers cause low frequency gain loss at low frequencies for the opposite reason. They have low reactance at low frequencies.

# HIGH FREQUENCY GAIN LOSS

- Ø Components that cause high frequency gain loss are transistors, inductors and transformers.
- Ø Stray capacitance caused by various wires and components will also cause high frequency gain loss.

# HIGH FREQUENCY GAIN LOSS

## Transistors - Interelement Capacitance



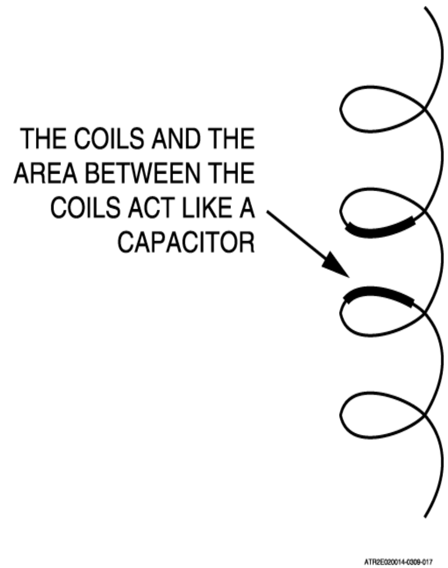

**The emitter-base and collector-base junctions form an effective capacitance at high frequencies.**

**The signal bypasses the transistor thus preventing amplification.**

**Interelement capacitance causes loss of signal at high frequencies.**

# HIGH FREQUENCY GAIN LOSS

## Inter-winding Capacitance



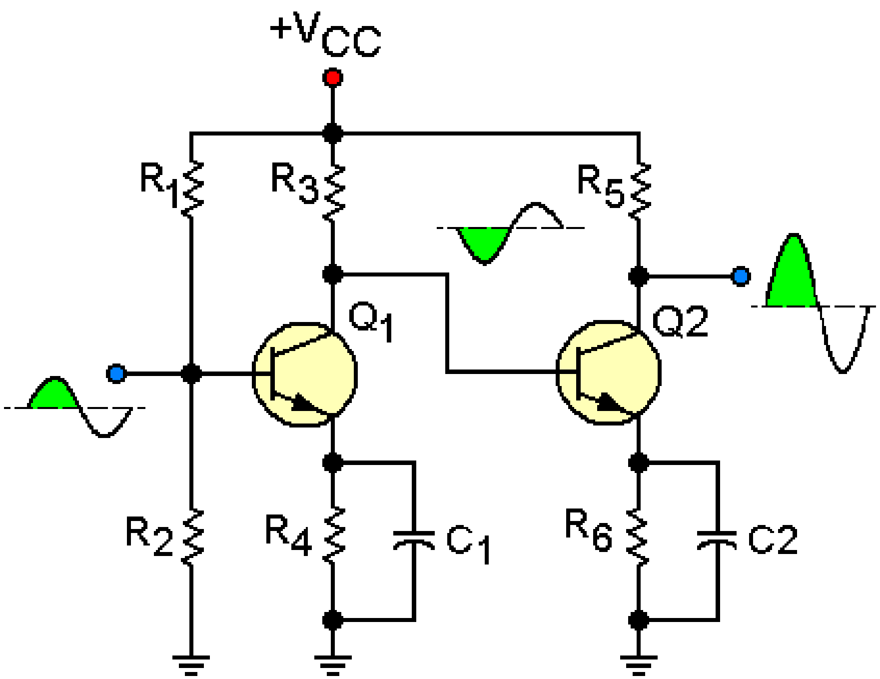

- **High frequency loss is due to <u>inter-winding capacitance</u> in which the individual coils can act as capacitors.**
- **Only occurs at very high frequencies.**

# HIGH FREQUENCY GAIN LOSS

## Stray Capacitance

- **Capacitance which exists between circuit components and wiring. The stray capacitance between two conductors could cause output signal amplitude to decrease.**
- **Stray capacitance is not normally a problem in audio amplifiers. The highest frequency involved is about 20kHz and the capacitive reactance is still high.**

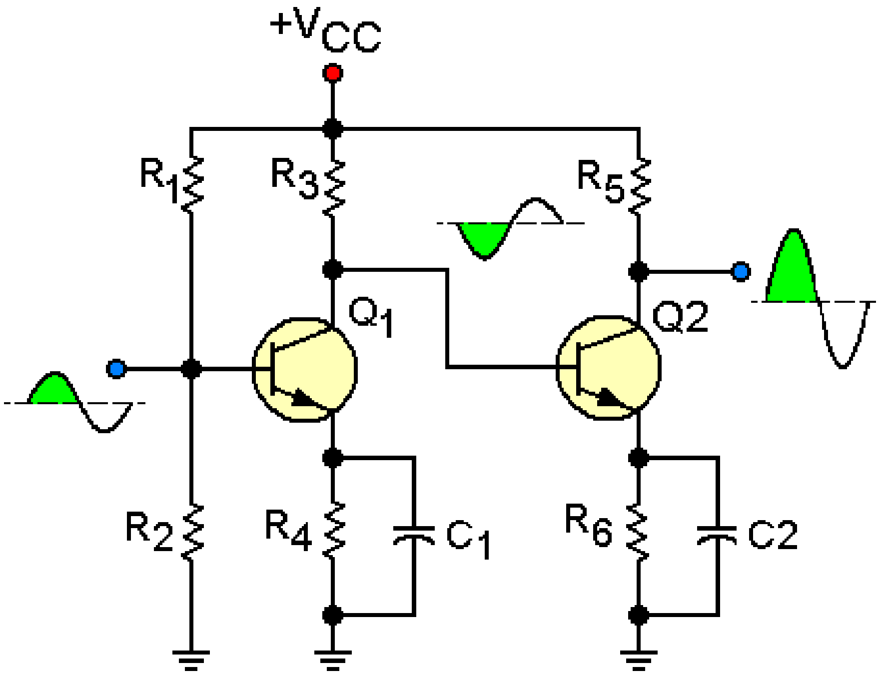
# DIRECT COUPLING




**Note: The line connected between $Q_1$ collector and $Q_2$ base enables AC and DC to be transferred from $Q_1$ to $Q_2$.**

**Direct coupling is the only type of coupling that can amplify DC voltages as well as AC signals.**

# DIRECT COUPLING

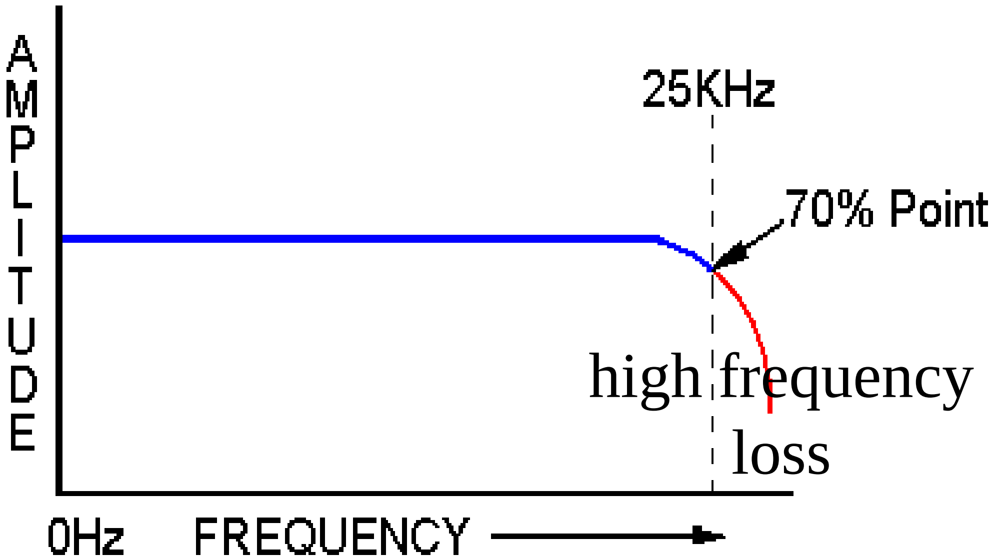



**Has a poor high frequency response due to interelement capacitance of transistors.**

**R3 - Collector load resistor for $Q_1$ and the base bias resistor for $Q_2$.**

# DIRECT COUPLING

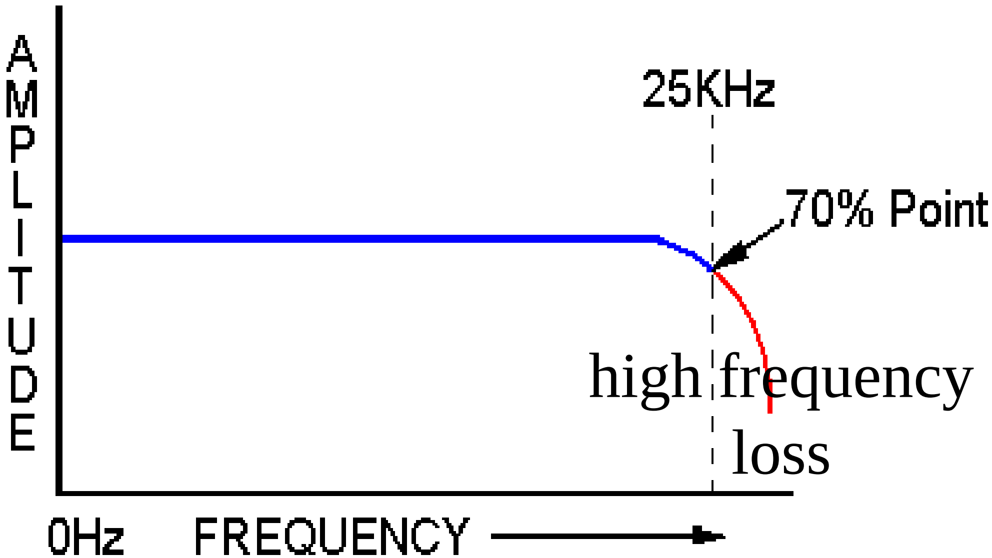
Frequency Response Graph




**Observe the loss of signal at the high frequencies which is due to the transistor's inter-element capacitance.**

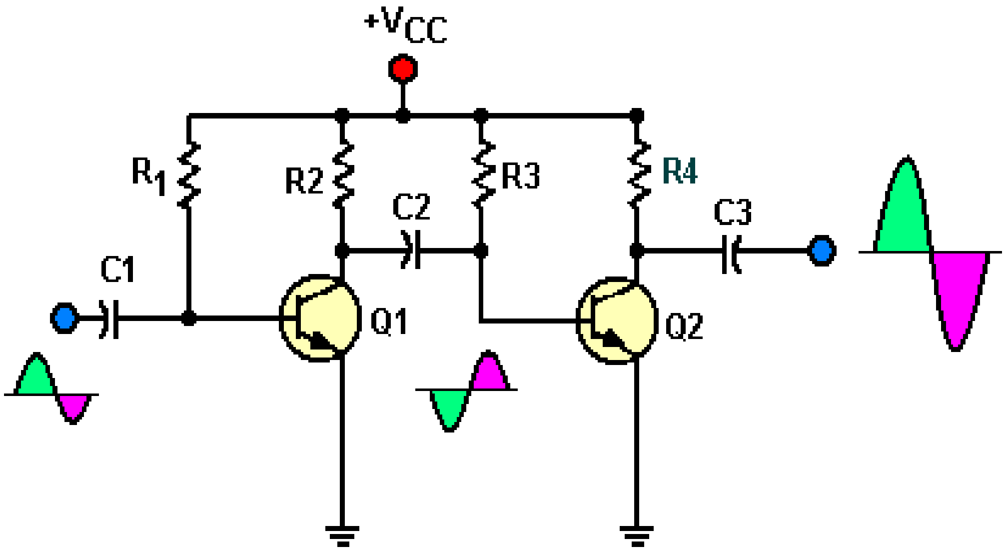
# DIRECT COUPLING

Frequency Response Graph




**When amplifying AC signals, direct coupling is normally used to amplify the audio range of frequencies (20Hz to 20kHz).**

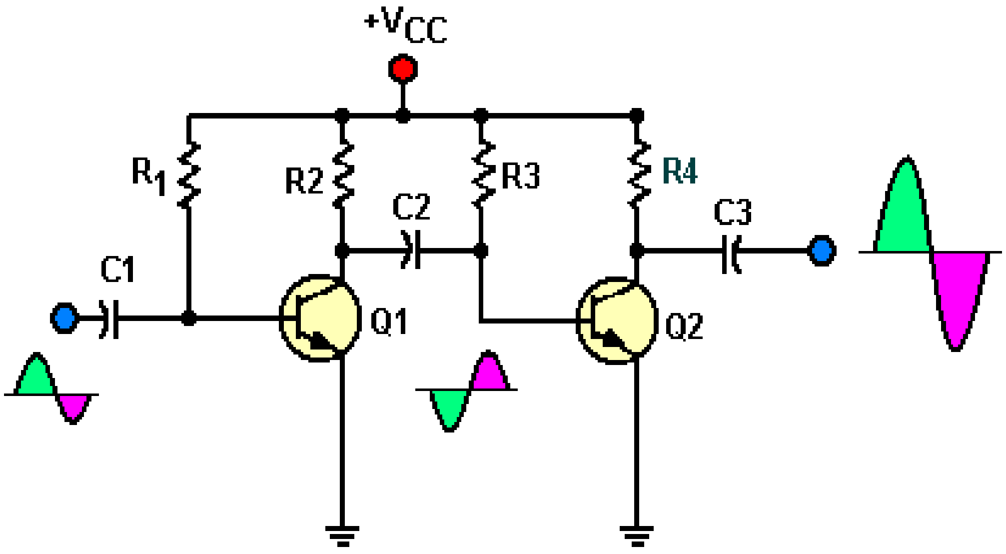
# Resistive-Capacitive (RC)




**RC coupling uses a capacitor to couple the signal between stages.**

**$C_2$ – Passes AC and blocks (isolates) direct current between stages.**

# Resistive-Capacitive (RC)

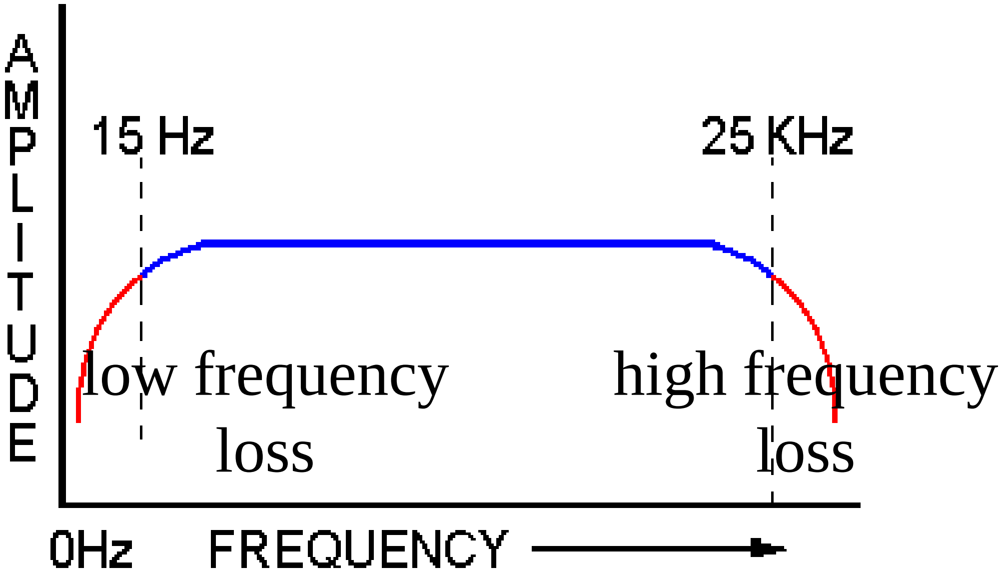



Has a poor high frequency response due to transistor interelement capacitance.

Poor low frequency response due to $X_C$ of the capacitor.

# Resistive-Capacitive (RC)

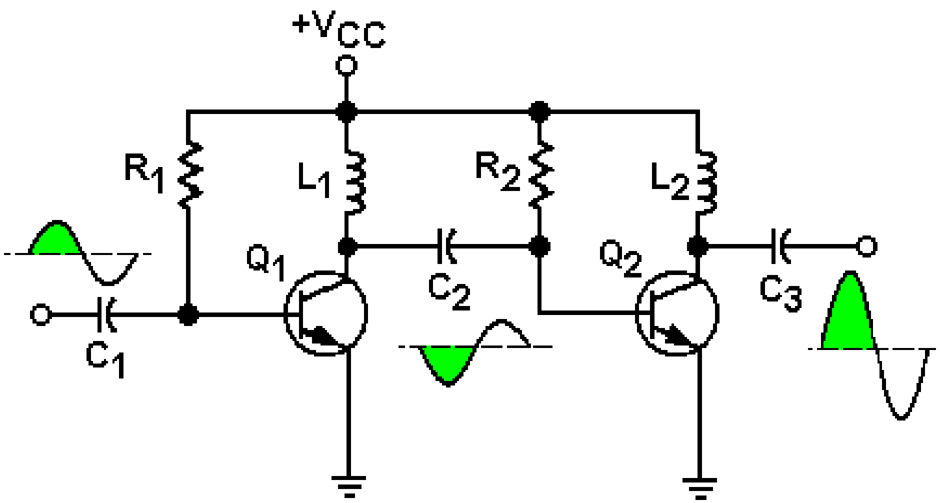
Frequency Response Curve




**Low frequency loss due to the high reactance of $C_1$, $C_2$ and $C_3$**

**High frequency loss due to the interelement capacitance of $Q_1$ and $Q_2$**

# Impedance Coupling (LC)

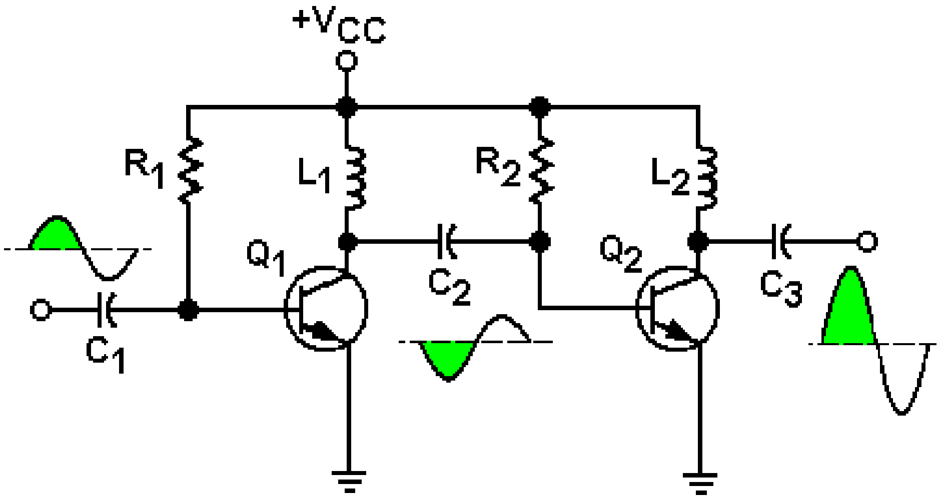



LC coupling is used to amplify much higher frequencies.

$R_L$ is replaced with an inductor.

The gain of the amplifier is now determined by the inductor's inductive reactance ($X_L$).

# Impedance Coupling (LC)

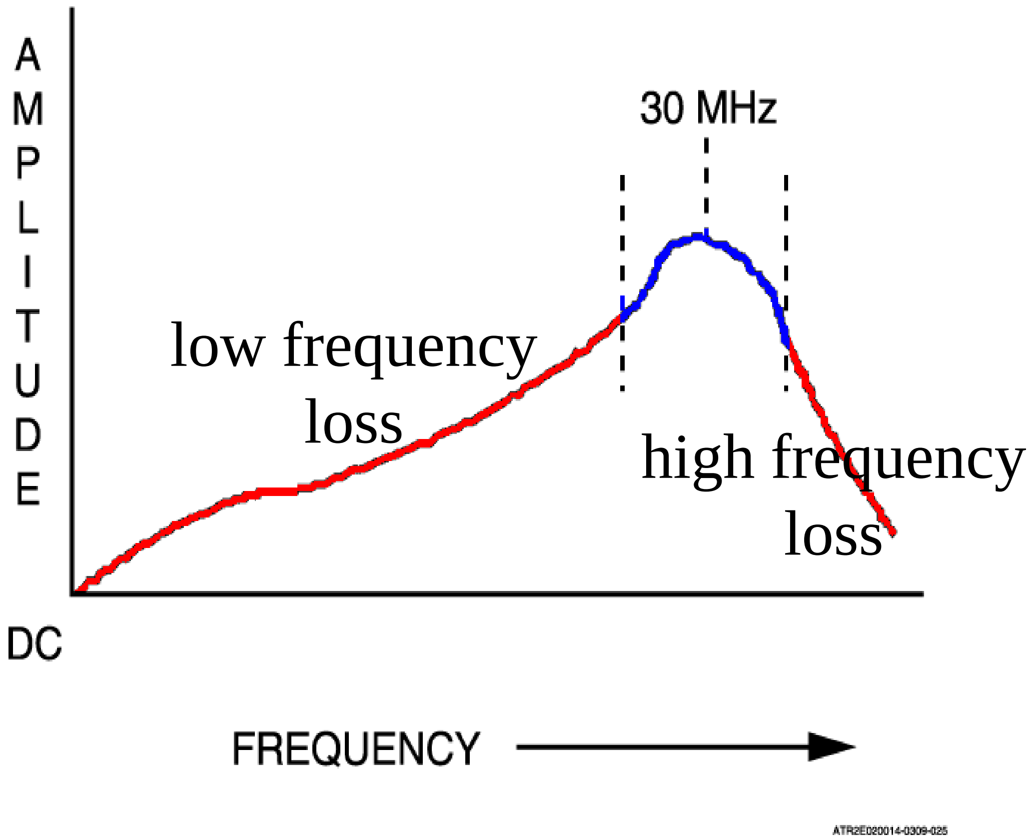



**The main disadvantage of impedance coupling is that it is limited to high frequency use.**

**The reactance of the inductor at low frequencies is not large enough to produce good voltage gain.**

# Impedance Coupling (LC)

Frequency Response Curve

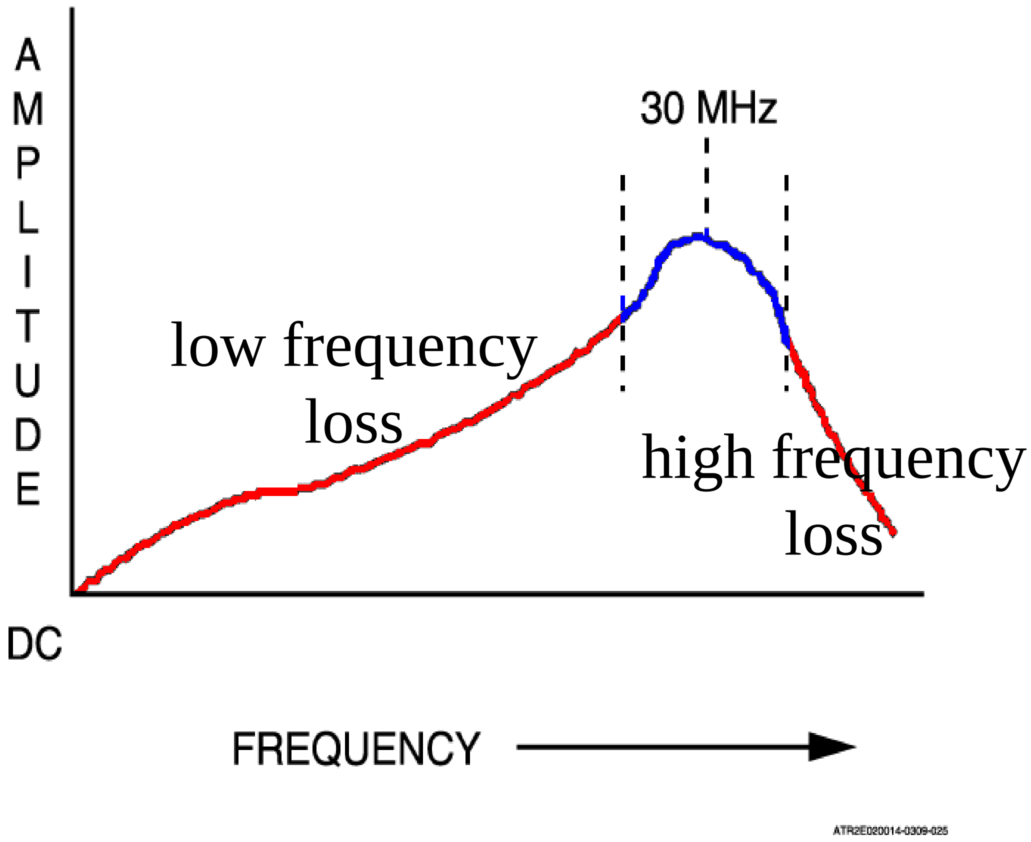



**Loss of amplitude at low frequency is due to low reactance of the inductor.**

**Loss of amplitude at high frequency is due to inter-element capacitance of $Q_1$ and $Q_2$.**

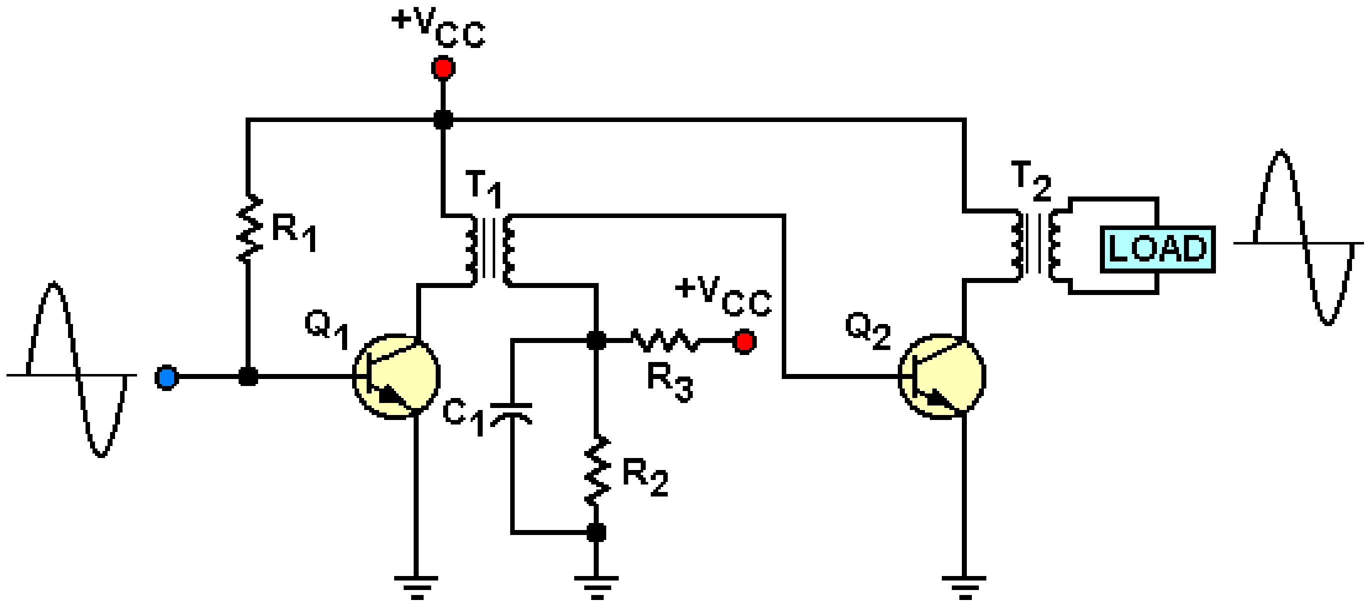
# Impedance Coupling (LC)

Frequency Response Curve




**The specific point (in this case 30MHz) that the amplifier will peak at is determined by the <u>resonant frequency</u> of the LC circuit.**

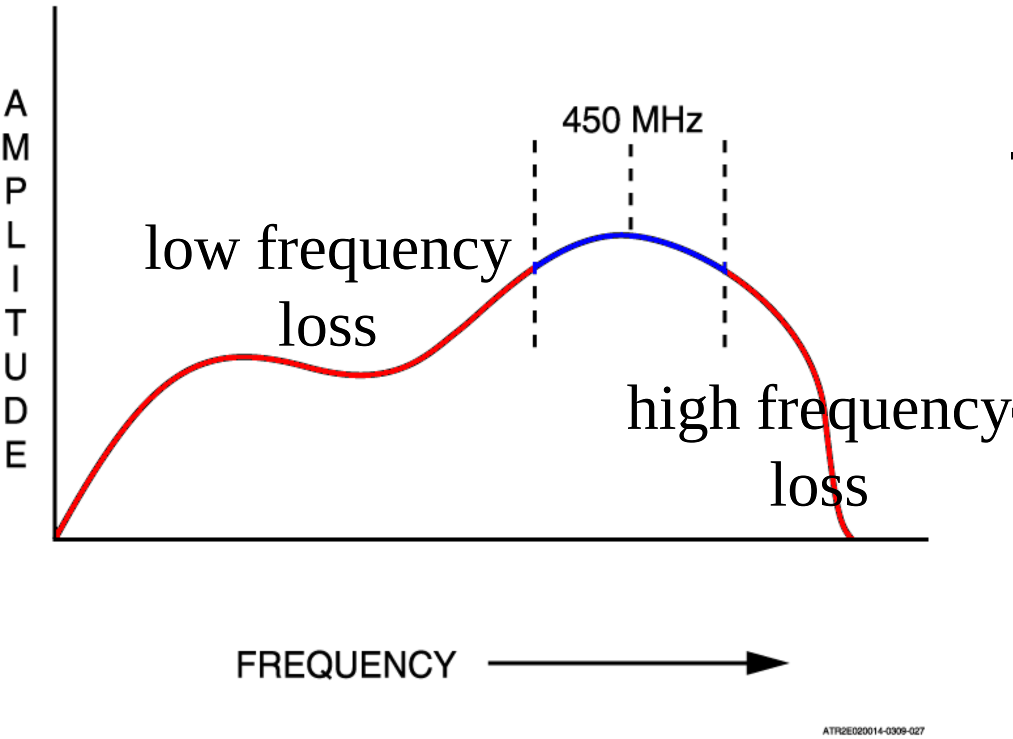
# Transformer Coupling




The advantages of transformer coupling is that it provides isolation between stages so that one stage does not feedback and interfere with another stages, and is also used for impedance matching between stages.

# Transformer Coupling

Frequency Response Curve




**Has a poor <u>low frequency</u> response due to low XL of transformer windings.**

**Transistor interelement capacitance and inter-winding capacitance of the transformer causes high frequency loss.**

# TRANSISTOR AMPLIFIER COUPLING

## Appraisal

# TRANSISTOR AMPLIFIER COUPLING

**14. What type of amplifier coupling is used that can amplify DC voltages as well as AC signals?**

**a. LC**

**b. RC**

**c. Direct**

**d. Transformer**

# TRANSISTOR AMPLIFIER COUPLING

**15. What type of amplifier coupling is used for impedance matching and circuit isolation?**

**a. LC**

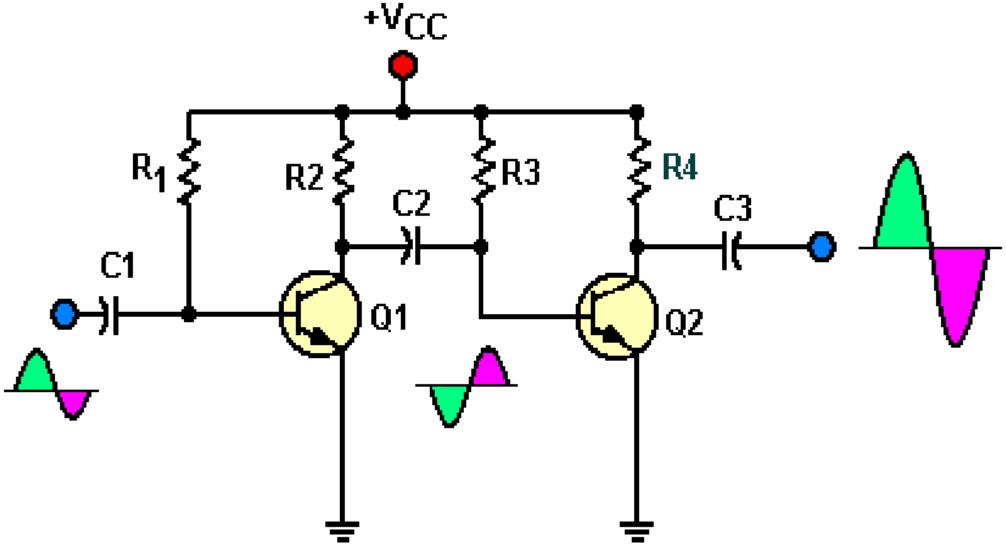
**b. RC**

**c. Direct**

**d. Transformer**

# TRANSISTOR AMPLIFIER COUPLING

**16. In the RC coupled amplifier, the low frequency gain loss is due to the reactance of components**




**a. C1, C2, and C3**

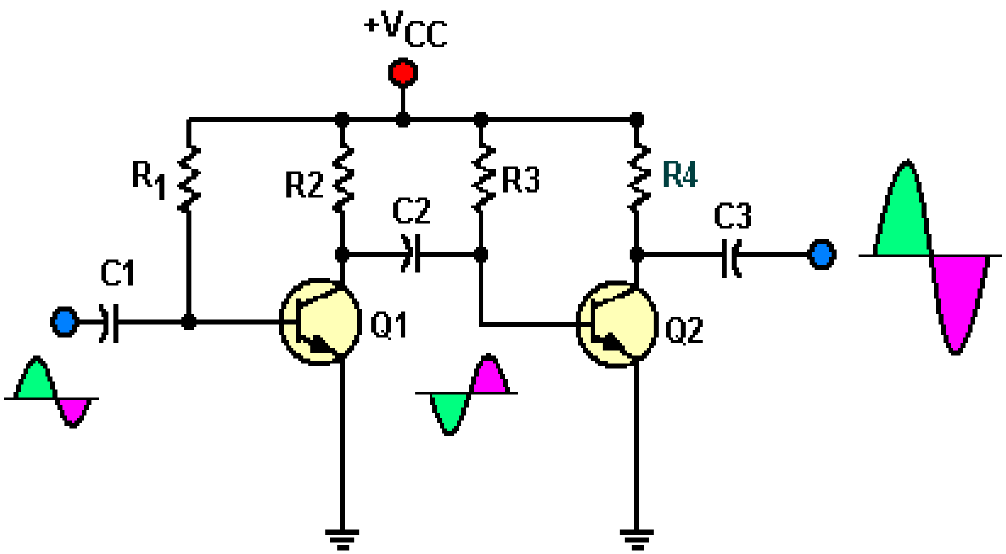
**b. R1 and R4**

**c. R2 and R5**

**d. Q1 and Q2**

# TRANSISTOR AMPLIFIER COUPLING

**17.** **In the RC coupled amplifier, the high frequency gain loss is due to the inter-element capacitance of components**




**a. C1, C2, and C3**

**b. R1 and R4**

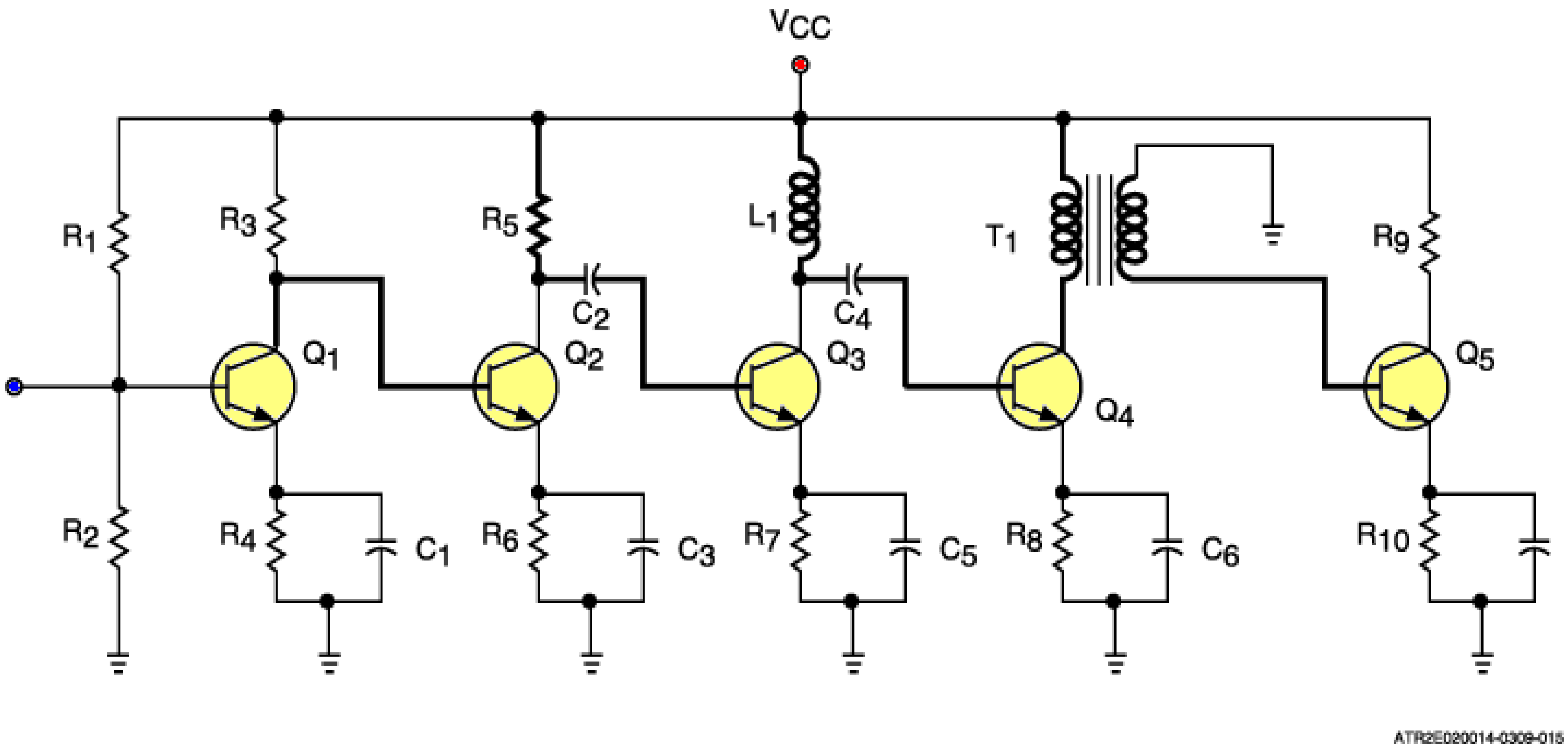
**c. R2 and R5**

**d. Q1 and Q2**

# TRANSISTOR AMPLIFIER COUPLING

**18.** **In the following figure, what type of coupling is used between Q3 and Q4?**

**a. LC** **b. RC** **c. Direct** **d. Transformer**



# Appraisal Answers

| | |
|---|---|
| 1. B | 10. A |
| 2. C | 11. B |
| 3. C | 12. B |
| 4. B | 13. A |
| 5. A | 14. C |
| 6. B | 15. D |
| 7. C | 16. A |
| 8. D | 17. D |
| 9. B | 18. A |

The End

# Transistor Amplifiers

## Purpose

The aim of this experiment is to develop a bipolar transistor amplifier with a voltage gain of minus 25. The amplifier must accept input signals from a source impedance of 1 kΩ and provide an undistorted output amplitude of 5 V when driving a 560 Ω load. The bandwidth should extend from below 100 Hz to above 1 MHz.

## Introduction

An electrical signal can be amplified by using a device which allows a small current or voltage to control the flow of a much larger current from a dc power source. Transistors are the basic device providing control of this kind. There are two general types of transistors, bipolar and field-effect. Very roughly, the difference between these two types is that for bipolar devices an input current controls the large current flow through the device, while for field-effect transistors an input voltage provides the control. In this experiment we will build a two-stage amplifier using two bipolar transistors.

In most practical applications it is better to use an op-amp as a source of gain rather than to build an amplifier from discrete transistors. A good understanding of transistor fundamentals is nevertheless essential. Because op-amps are built from transistors, a detailed understanding of op-amp behavior, particularly input and output characteristics, must be based on an understanding of transistors. We will learn in Experiments #9 and #10 about logic devices, which are the basic elements of computers and other digital devices. These integrated circuits are also made from transistors, and so the behavior of logic devices depends upon the behavior of transistors. In addition to the importance of transistors as components of op-amps, logic circuits, and an enormous variety of other integrated circuits, single transistors are still important in many applications. For experiments they are especially useful as interface devices between integrated circuits and sensors, indicators, and other devices used to communicate with the outside world.

The three terminals of a bipolar transistor are called the emitter, base, and collector (Figure 7.1). A small current into the base controls a large current flow from the collector to the emitter. The current at the base is typically one hundredth of the collector-emitter current. Moreover, the large current flow is almost independent of the voltage across the transistor from collector to emitter. This makes it possible to obtain a large amplification of voltage by taking the output voltage from a resistor in series with the collector. We will begin by constructing a common emitter amplifier, which operates on this principle.

A major fault of a single-stage common emitter amplifier is its high output impedance.  This can be cured by adding an emitter follower as a second stage.  In this circuit the control signal is again applied at the base, but the output is taken from the emitter.  The emitter voltage precisely follows the base voltage but more current is available from the emitter.  The common emitter stage and the emitter follower stage are by far the most common transistor circuit configurations.

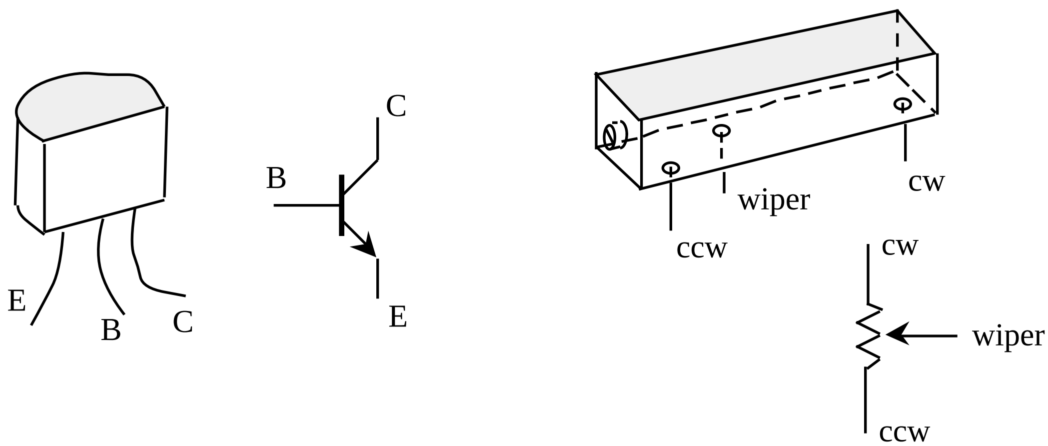



Figure 7.1   Pin-out of 2N3904 and 1 k trimpot

## Readings

D&H Chapter 8.1 through 8.6 on bipolar transistors.

Horowitz and Hill, Chapter 2 also may be helpful, especially 2.01–2.03, 2.05, the first page of 2.06, 2.07, 2.09–2.12, and the part of 2.13 on page 84 and 85. Table 2.1 and Figure 2.78 give summaries of the specifications of some real devices.

## Theory

CURRENT AMPLIFIER MODEL OF BIPOLAR TRANSISTOR

From the simplest point of view a bipolar transistor is a current amplifier.  The current flowing from collector to emitter is equal to the base current multiplied by a factor.  An NPN transistor operates with the collector voltage at least a few tenths of a volt above the emitter voltage, and with a current flowing *into* the base.  The base-emitter junction then acts like a forward-biased diode with an 0.6 V drop:  $V_B \approx V_E + 0.6V$.  Under these conditions, the collector current is proportional to the base current:  $I_C = h_{FE}\, I_B$.  The constant of proportionality is called $h_{FE}$ because it is one of the "h-parameters,"  a set of numbers that give a complete description of the small-signal properties of a transistor (see Bugg Section 17.4).  It is important to keep in mind that $h_{FE}$ is not really a constant. It depends on collector current (see H&H Fig. 2.78), and it varies by 50% or more from device to device. If you want to know the emitter current rather than the collector current you can find it by current conservation: $I_E = I_B + I_C = (1/h_{FE} + 1)\, I_C$. The difference between $I_C$ and $I_E$ is almost never important since $h_{FE}$ is normally in the range 100 – 1000. Another way to say this is that the base current is very small compared to the collector and emitter currents.

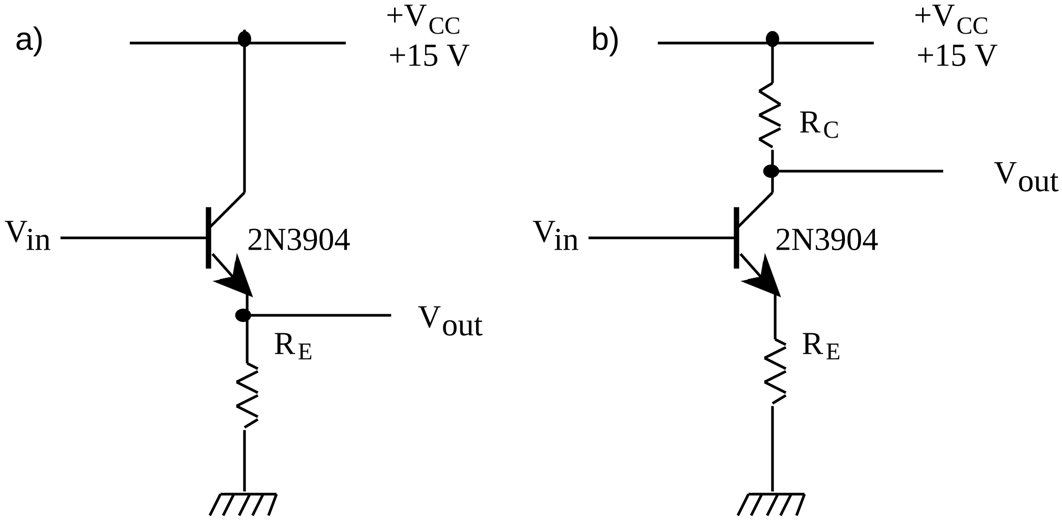



Figure 7.2 a) Emitter follower stage b) Common Emitter Stage

Figure 7.2 shows the two main transistor-based circuits we will consider. In the emitter-follower stage the output (emitter) voltage is simply related to the input (base) voltage by a diode drop of about .6 eV. An ac signal of 1 volt amplitude on the input will therefore give an AC signal of 1 volt on the output, i.e. the output just “follows” the input. As we will see later, the advantage of this circuit is as a buffer due to a relatively high input and low output impedance.

In the common emitter stage of figure 7.2b, a 1 volt ac signal at the input will again cause a 1 volt ac signal at the emitter. This will cause an ac current of $1\text{volt}/R_E$ from the emitter to ground, and hence also through $R_c$. $V_{out}$ is therefore $15 - R_c(1\text{volt}/R_E)$ and we see that there is an ac voltage gain of $-R_c/R_E$.

Although we are only looking to amplify the AC signal, it is nonetheless very important to set up proper dc bias conditions or quiescent points. The first step is to fix the dc voltage of the base with a voltage divider ($R_1$ and $R_2$ in Figure 7.3). The emitter voltage will then be 0.6 V less than the base voltage. With the emitter voltage known, the current flowing from the emitter is determined by the emitter resistor: $I_E = V_E/R_E$. For an emitter follower, the collector is usually tied to the positive supply voltage $V_{CC}$. The only difference between biasing the emitter follower and biasing the common emitter circuit is that the common emitter circuit always has a collector resistor. The collector resistor does not change the base or emitter voltage, but the drop across the collector resistor does determine the collector voltage: $V_C = V_{CC} - I_C R_C$.

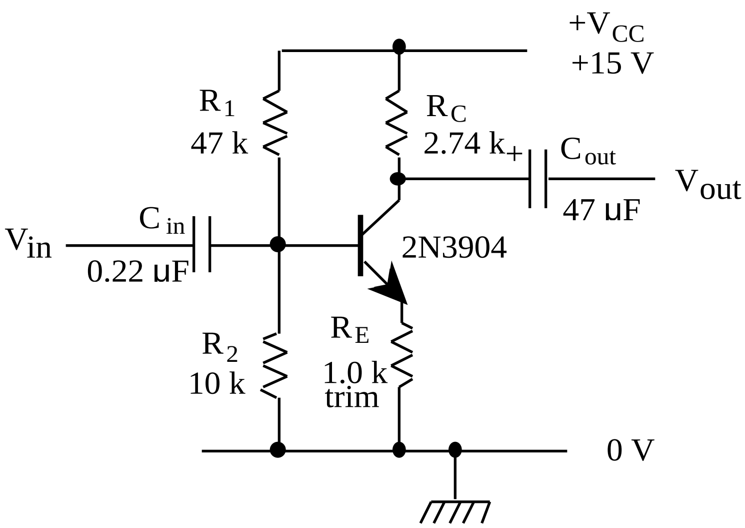



Figure 7.3 Biased Common Emitter Amplifier

There are three subtleties to keep in mind when biasing common-emitter or emitter-follower circuits. First of all, the base bias voltage must be fixed by a low enough impedance so that changes in the base current do not alter the base voltage. This is essential because the base current depends on $h_{FE}$ and so is not a well determined quantity. If the base voltage is determined by a divider (as in Figure 7.3), the divider impedance will be low enough when:

$$R_1 \| R_2 = \frac{R_1 R_2}{R_1 + R_2} << h_{FE} R_E . \qquad (1)$$

As we will see in a moment, this equation just says that the impedance seen looking into the divider (The Thevenin equivalent or $R_1||R_2$) should be much less that the impedance looking into the base. Another point to keep in mind is that when you fix the quiescent point by choosing the base divider ratio and the resistors $R_E$ and $R_C$, you are also fixing the dc power dissipation in the transistor: P = $(V_C – V_E)\ I_E$. Be careful that you do not exceed the maximum allowed power dissipation $P_{max}$. Finally, the quiescent point determines the voltages at which the output will clip. For a common emitter stage the maximum output voltage will be close to the positive supply voltage $V_{CC}$. The minimum output voltage occurs when the transistor <u>saturates</u>, which happens when the collector voltage is no longer at least a few tenths of a volt above the emitter voltage. We usually try to design common emitter stages for <u>symmetrical clipping</u>, which means that the output can swing equal amounts above and below the quiescent point.

The voltage gain of the emitter follower stage is very close to unity. The common emitter stage, in contrast, can have a large voltage gain:

$$A = -\frac{R_C}{R_E}. \quad (2)$$

If we are interested in the ac gain, then $R_C$ and $R_E$ stand for the ac impedances attached to the collector and emitter, which may be different from the dc resistances. In our circuit we use $C_E$ to bypass part of the emitter resistor at the signal frequency.

INPUT AND OUTPUT IMPEDANCES

The input impedance is the same for both emitter followers and common emitter stages. The input impedance looking into the base is

$$r_{in} = (h_{FE} + 1)R. \quad (3)$$

In this expression R is whatever impedance is connected to the emitter. For a common emitter, R would usually just be the emitter resistor, but for an emitter follower R might be the emitter resistor in parallel with the input impedance of the next stage. If you want the input impedance of the whole stage, rather than just that looking into the base, you will have to consider $r_{in}$ in parallel with the base bias resistors.

The output impedance of a common emitter stage is just equal to the collector resistor.

The output impedance looking into the emitter of an emitter follower is given by

$$r_{out} = \frac{R}{h_{FE} + 1}. \quad (4)$$

Now R stands for whatever impedance is connected to the base. For our two-stage amplifier shown in Figure 7.5, the emitter-follower base is connected to the collector of a common emitter stage, and so R is the output impedance of that stage, which is equal to $R_C$.

EBERS-MOLL MODEL OF BIPOLAR TRANSISTOR

A slightly more detailed picture of the bipolar transistor is required to understand what happens when the emitter resistor is very small. Instead of using the current amplifier model, one can take the view that the collector current $I_C$ is controlled by the base-emitter voltage $V_{BE}$. The dependence of $I_C$ on $V_{BE}$ is definitely not linear, rather it is a very rapid exponential function. The formula relating $I_C$ and $V_{BE}$ is called the Ebers-Moll equation, and it is discussed in H&H Section 2.10.

For our purposes, the Ebers-Moll model only modifies our current amplifier model in one important way. For small variations about the quiescent point, the transistor now acts as if it has a small internal resistor $r_e$ in series with the emitter

$$r_e = 25\,\Omega\left(\frac{1\ mA}{I_C}\right).$$

The magnitude of the intrinsic emitter resistance $r_e$ dependes on the collector current $I_C$.

The presence of the intrinsic emitter resistance $r_e$ modifies the above Equations (1) – (4). In Equations (1) and (2) we should substitute $R_E \rightarrow R_E + r_e$, and for Equation (3) we need to substitute $R \rightarrow R + r_e$. Equation (4) is modified to read

$$r_{out} = \frac{R}{h_{FE}+1} + r_e. \qquad (4')$$

The most important of these results is the modified Equation (2)

$$A = -\frac{R_C}{R_E + r_e}. \qquad (2')$$

which shows that the common emitter gain does not go to infinity when the external emitter resistor goes to zero. Instead the gain goes to the finite value $A = -R_C / r_e$.

## Problems

1. Calculate the quiescent voltages $V_B$, $V_E$, and $V_C$, and the currents $I_E$ and $I_C$ for the common emitter circuit in Figure 7.4. How much power is dissipated in the transistor itself? Is the power safely below $P_{max}$? (See Appendix for 2N3904 Data Sheet.)

2. Find the ac voltage gain of the circuit in Figure 7.4 for 10 kHz sine waves with the emitter bypass capacitor $C_E$ removed. Estimate the maximum amplitude of the output before clipping occurs. (The maximum output voltage is limited by the positive supply voltage, and the minimum is determined by the requirement that the collector voltage must be at least a few tenths of a volt above the emitter voltage.)

3. The emitter bypass capacitor can provide an AC ground path for the emitter, increasing the gain of the amplifier at high frequency. Considering the effects of the intrinsic emitter resistance $r_e$, what is the maximum possible AC voltage gain of the amplifier in Figure 7.4? Will this gain likely be realized for 10 kHz sine waves? Why or why not?

4. What setting of the emitter trimpot is needed to give the required gain of –25? For the single stage in Figure 7.4, what are the input and output impedances $r_{in}$ and $r_{out}$ at 10 kHz

and a gain of –25? (Note that $r_{in}$ is the impedance looking into the base in parallel with the base divider impedance.) Calculate the fraction of the original amplitude obtained when a 560 Ω load is connected to the output via a coupling capacitor.

5. Calculate the output impedance for the emitter follower circuit shown in Figure 7.5. What fraction of the original output amplitude do you expect to obtain when you attach the 560 Ω load to the emitter follower output?

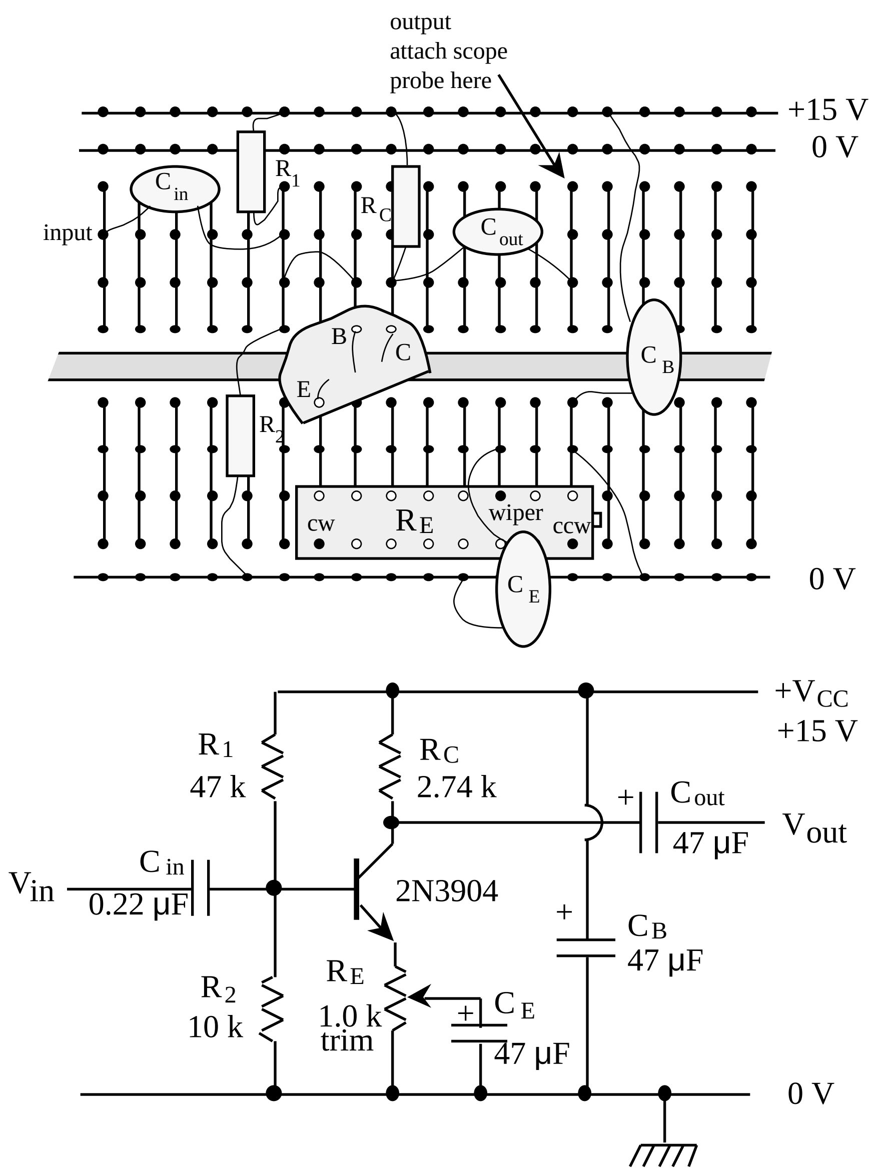



Figure 7.4 Common Emitter Stage Layout and Schematic

## New Apparatus and Methods

A drawing to help you identify the leads of the 2N3904 transistor and the trimpot is shown in Figure 7.1. The 2N3904 is an NPN device, as indicated by its symbol with an outward pointing arrow. The arrow for a PNP device points in. To keep the convention straight, remember Not Pointing iN for NPN. Your trimpot may not look exactly like the one shown, but it will have the three leads wiper, cw, and ccw. The wiper moves toward the cw lead when the screw is turned clockwise.

The transistor amplifier uses dc power at +15 V only. Use just the positive section of the dc power supply. Disconnect the negative line from your circuit board.

In Figure 7.4 we show the first amplifier stage and a suggested circuit board layout. Your circuit will be easier to understand if you try to keep the physical layout looking like the schematic diagram. Use the wiring color code given in Experiment #4.

Use the oscilloscope 10x probe to observe the amplifier outputs. This minimizes capacitive loading and reduces the risk of spontaneous oscillations.

## Outline of the Experiment

1 Verify that the 2N3904 is an NPN transistor using the digital multimeter. Is the 2N3906 a PNP or an NPN transistor?

2. Construct a common emitter transistor bias circuit. Confirm that the quiescent voltages are correct. Add coupling capacitors to the circuit to make an ac amplifier, and measure the ac voltage gain for 10 kHz sine waves. Verify that the gain has the expected value, and confirm that the output amplitude can reach 5 V before the extremes of the sine waves are clipped.

3. Make a variable gain amplifier by bypassing part of the emitter resistance with a capacitor. Find the maximum possible voltage gain and compare with your prediction.

4. Adjust the gain to the required value of –25. Find the effect on the output amplitude of placing a source impedance of 1 kΩ in series with the signal source. Also observe what happens when you place a 560 Ω load between the output and ground.

5. Now build an emitter follower stage as an impedance buffer between the amplifier and the

load. Verify that the emitter follower alone has unit voltage gain. What happens now when you connect the load to the emitter follower output?

6. Test the performance of the complete circuit under the specified conditions: 1 kΩ source impedance and 560 Ω load. First reset the overall gain to –25 if it has changed. Check that the 5 V undistorted output amplitude is still available. Measure the gain versus frequency from 1 Hz to 10 Mhz.

## Detailed Procedure

POLARITY CHECK

Determine the polarities of the emitter-base and base-collector diode junctions of a 2N3904 using the diode tester on your digital multimeter. Now check the polarities for a 2N3906. Is it an NPN or a PNP transistor? The pin-out for a 2N3906 is the same as for a 2N3904.

COMMON EMITTER AMPLIFIER: QUIESCENT STATE

The first step is to construct the bias network and check that the correct dc levels (quiescent voltages) are established. Assemble the common emitter stage as shown in Figure 7.4, but without the input and output coupling capacitors or the emitter capacitor (without $C_{in}$, $C_{out}$, and $C_E$). The wiper contact on the emitter resistor $R_E$ should not be connected to anything yet. Measure the resistors before putting them in the circuit, and if they differ from the values used in your calculations, recalculate the quiescent voltages. Before turning on the power, disconnect the power supply from the circuit board for a moment and check that it is set to +15 V. Then turn on the power, and check the dc levels $V_B$ (at the transistor base), $V_E$ (at the emitter) and $V_C$ (at the collector).

The quiescent levels should agree with your calculations to within 10%. If they do not, there is something wrong that must be corrected before you can go on.

COMMON EMITTER AMPLIFIER: FIXED GAIN

Convert the previous circuit to an ac amplifier by adding the coupling capacitors $C_{in}$ and $C_{out}$. Be sure to observe the polarity of polarized capacitors. The capacitors will transmit ac signals but block dc signals. This allows you to connect signals without disturbing the quiescent conditions.

When you switch on the power, you may see high frequency spontaneous oscillations. These must be suppressed before you can proceed.

Assemble a test set-up to observe the input and output of the amplifier with 10 kHz sine waves, using the 10x scope probe for the output. You may need to add a 220 kΩ resistor to ground after $C_{out}$ to keep the dc level at the scope input near ground. Vary the input amplitude to find the output amplitude at which clipping begins. Can you get a 5 V undistorted output amplitude (10 V p-p)?

Measure the gain of the amplifier for 10 kHz sine waves at an amplitude about half the clipping level. While you are at the bench, compare the measured gain with that predicted from the measured values of components:

$$A = -\frac{R_c}{R_E + r_e}.$$

If they differ by more than 5% find the cause and correct the problem before you go ahead.

COMMON EMITTER AMPLIFIER–VARIABLE GAIN

Connect the wiper of the 1.0 k trimpot $R_E$ through the bypass capacitor $C_E$ to ground. Verify that the quiescent point has not changed significantly.

Observe the change in gain as you traverse the full range of the trimpot using 10 kHz sine waves. Start with the contact at ground (bottom of diagram) and move it up until $C_E$ bypasses all of $R_E$. When approaching maximum gain turn down the input amplitude (a long way) so that the output signals are still well shaped sine waves. If the output is distorted the amplifier is not in its linear regime, and our formulas for the ac gain are not correct.

Compare the measured maximum gain with the value predicted in the homework for several output amplitudes going down by factors of two. Do theory and experiment tend to converge as $V_{out}$ tends to zero?

COMMON EMITTER AMPLIFIER: INPUT AND OUTPUT IMPEDANCE

Set the amplifier gain to –25 for 10 kHz sine waves. What trimpot setting gives a gain of –25?. (To see where the trimpot is set, remove it from the circuit and measure the resistance from cw to wiper or from ccw to wiper.)

Simulate the required source impedance by inserting a 1 kΩ resistor in series with the input. What fraction of the original output amplitude do you see? Is this as expected? Remove the 1 kΩ resistor before the next test so that you test only one thing at a time.

Connect a 560 Ω load from the output to ground. What fraction of the original output do you now see? Is this as expected?

EMITTER FOLLOWER OUTPUT STAGE

In the emitter follower circuit, the input signal is applied to the base of the transistor, but the output is taken from the emitter. The emitter follower has unit gain, *i.e.* the emitter "follows" the base voltage. The input impedance is high and the output impedance is low.

Ordinarily the quiescent base voltage is determined by a bias circuit. In the present case the collector voltage $V_C$ of the previous circuit already has a value suitable for biasing the follower, so a direct dc connection can be made between the two circuits.

Assemble the emitter follower circuit shown in Figure 7.5. Do not connect the 560 Ω load to the output yet.

Carry out appropriate dc diagnostic tests. This time we expect the collector to be at +15 V, the base to be at the collector voltage of the first stage, and the emitter to be about 0.6 V below the collector. Correct any problems before moving on.

Confirm that the voltage gain of the emitter follower is unity. Drive the complete system with the function generator. Observe the ac amplitudes at the input of the emitter follower and at the output. Measure the ac gain of the emitter follower stage. (Again you may need to add a 220 kΩ resistor to ground after $C_{out}$ to keep the dc level at the scope input near ground.) You may want to put the scope on ac coupling when you probe points with large dc offsets.

Attach a 560 Ω load from the output to ground. What fraction of the unloaded output do you now see? Compare with your calculations.

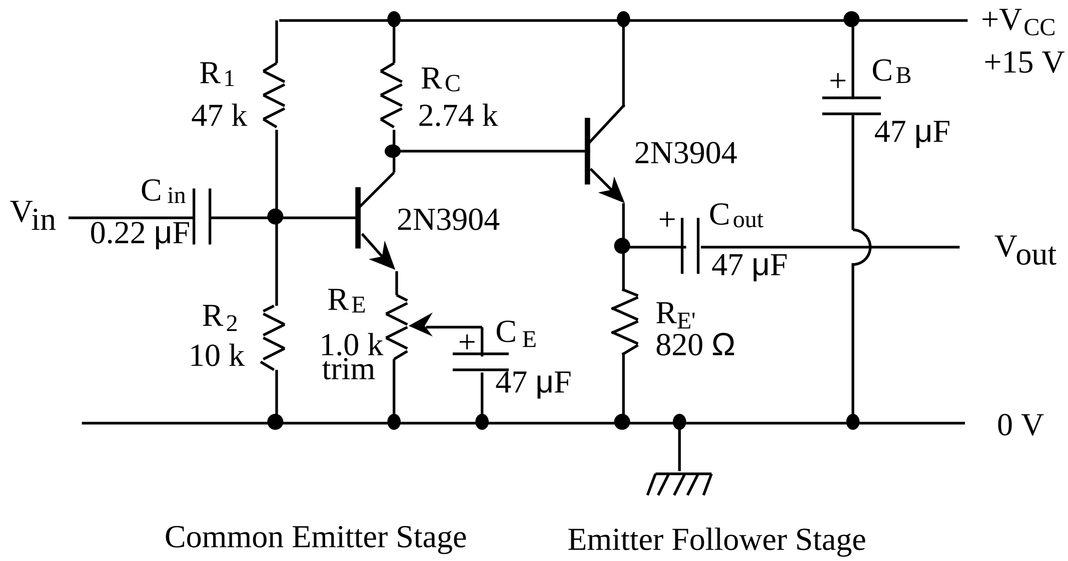



Figure 7.5 Complete Two-stage Amplifier Circuit

FINAL TESTS

Reset the gain to –25 with the 1 kΩ source resistor and the 560 Ω output load in place. Check the linearity of the amplifier for 10 kHz sine waves by measuring the output amplitude at several input amplitudes, extending up into the clipped regime. Graph $V_{out}$ versus $V_{in}$. The slope should equal the gain in the linear region of the graph.

Set the amplitude to be about one half the clipped value, and then determine the upper and lower cut-off frequencies $f_+$ and $f_–$ by varying the frequency of the sine waves. Can you understand the origin of these frequency cutoffs?

## Appendix

Data sheet for the 2N3904. (See also Horowitz and Hill, Table 2.1)

The 2N3904 is an NPN silicon bipolar junction transistor.

ABSOLUTE MAXIMUM RATINGS

| | | |
|---|---|---|
| $V_{CE}$ | 40 V | (collector to emitter voltage) |
| $V_{EB}$ | 6 V | (emitter to base voltage) |
| $I_C$ | 200 mA | (collector current) |
| $P_{max}$ | 300 mW | (power dissipation) |

TYPICAL CHARACTERISTICS

| | | |
|---|---|---|
| $h_{FE}$ | 200 | (current gain. See H&H Figure 2.78 for typical dependence on $I_C$.) |
| $f_T$ | 300 MHz | (frequency where internal capacitances cause gain to be reduced to unity) |
| $C_{EB}$ | 10 pF | (internal emitter-base capacitance) |
| $C_{BC}$ | 3 pF | (internal base-collector capacitance) |