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](image)

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.](image)

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

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

(1.1)

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

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

![Figure 5](image)
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:

\[ \text{B-E Loop: } V_{TH} = I_{BQ} R_{TH} + V_{BE(on)} + I_{EQ} R_E \] (1.2)

\[ \text{C-E Loop: } V_{CEQ} = V_{CC} - I_{CQ} R_C - I_{EQ} R_E \] (1.3)

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

**AC Circuit Analysis**

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

![Figure 6](image)

Using superposition, the voltage \( V_B \) is found by:

1. Set \( V_{TH} = 0 \) and calculate the contribution due to \( v_i \) \( (V_{b1}) \). 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 \( v_i \) and \( V_{b1} = v_i \)

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

\[ V_B = v_i + V_{TH} \] (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

\[ A_v = \frac{v_o}{v_i} = \frac{-i_e R_C}{i_e (r_e + R_E)} = \frac{-\beta i_b R_C}{(1 + \beta)i_b(r_e + R_E)} = -\frac{\beta}{\beta + 1} \frac{R_C}{r_e + R_E} \]  \hspace{1cm} (1.5)

For \( \beta \gg 1 \) and \( r_e \ll R_E \) the gain reduces to

\[ A_v \cong -\frac{R_C}{R_E} \]  \hspace{1cm} (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.

![Common-emitter amplifier with bypass capacitor C2](image)

**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.

\[ \frac{1}{\omega C2} \ll r_e \]  \hspace{1cm} (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](image)

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

$$R_i = \frac{v_i}{i_i}$$  \hspace{1cm} (1.8)

Where the relevant parameters are shown on 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 $(1 + \beta)(r_e + R_E)$

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

Output Impedance

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

$$R_o = R_C$$  \hspace{1cm} (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.

![Common Collector Amplifier Circuit](attachment:image.png)

**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

\[
v_o = v_i \frac{R_E}{R_E + r_e}
\]  

And the gain becomes

\[
A_v = \frac{v_o}{v_i} = \frac{R_E}{R_E + r_e} \approx 1
\]
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

\[ R_{ib} = (1 + \beta)(r_e + R_E) \]  \hspace{1cm} (1.13)

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

\[ R_i = R_{TH} // (1 + \beta)(r_e + R_E) \]  \hspace{1cm} (1.14)

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

![Circuit Diagram](image)

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

\[ R_x = \frac{v_x}{i_x} \]  \hspace{1cm} (1.15)

KCL at the node \( A \) gives

\[ i_x = -i_b(1 + \beta) \]  \hspace{1cm} (1.16)

And KVL around the B-E loop gives

\[ i_b R_{TH} - i_x r_e + v_x = 0 \]  \hspace{1cm} (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

\[ R_o = R_{TH} \parallel \left( r_e + \frac{R_{TH}}{\beta + 1} \right) \tag{1.19} \]
Amplifier is a circuit that is used for amplifying a signal. The input signal to an amplifier will be a current or voltage and the output will be an amplified version of the input signal. An amplifier circuit which is purely based on a transistor or transistors is called a transistor amplifier. Transistors amplifiers are commonly used in applications like RF (radio frequency), audio, OFC (optic fibre communication) etc. Anyway the most common application we see in our day to day life is the usage of transistor as an audio amplifier. As you know there are three transistor configurations that are used commonly i.e. common base (CB), common collector (CC) and common emitter (CE). In common base configuration has a gain less than unity and common collector configuration (emitter follower) has a gain almost equal to unity). Common emitter follower has a gain that is positive and greater than unity. So, common emitter configuration is most commonly used in audio amplifier applications.

A good transistor amplifier must have the following parameters; high input impedance, high bandwidth, high gain, high slew rate, high linearity, high efficiency, high stability etc. The above given parameters are explained in the next section.

**Input impedance:** Input impedance is the impedance seen by the input voltage source when it is connected to the input of the transistor amplifier. In order to prevent the transistor amplifier circuit from loading the input voltage source, the transistor amplifier circuit must have high input impedance.

**Bandwidth.**

The range of frequency that an amplifier can amplify properly is called the bandwidth of that particular amplifier. Usually the bandwidth is measured based on the half power points i.e. the points where the output power becomes half the peak output power in the frequency Vs output graph. In simple words, bandwidth is the difference between the lower and upper half power points. The band width of a good audio amplifier must be from 20 Hz to 20 KHz because that is the frequency range that is audible to the human ear. The frequency response of a single stage RC coupled transistor is shown in the figure below (Fig 3). Points tagged P1 and P2 are the lower and upper half power points respectively.
Gain of an amplifier is the ratio of output power to the input power. It represents how much an amplifier can amplify a given signal. Gain can be simply expressed in numbers or in decibel (dB). Gain in number is expressed by the equation $G = \frac{P_{\text{out}}}{P_{\text{in}}}$. In decibel the gain is expressed by the equation $\text{Gain in dB} = 10 \log \left( \frac{P_{\text{out}}}{P_{\text{in}}} \right)$. Here $P_{\text{out}}$ is the power output and $P_{\text{in}}$ is the power input. Gain can be also expressed in terms of output voltage / input voltage or output current / input current. Voltage gain in decibel can be expressed using the equation, $A_v \text{ in dB} = 20 \log \left( \frac{V_{\text{out}}}{V_{\text{in}}} \right)$ and current gain in dB can be expressed using the equation $A_i = 20 \log \left( \frac{I_{\text{out}}}{I_{\text{in}}} \right)$.

**Derivation of gain.**

\[ G = 10 \log \left( \frac{P_{\text{out}}}{P_{\text{in}}} \right) \] \hspace{1cm} (1)

Let $P_{\text{out}} = V_{\text{out}} / R_{\text{out}}$ and $P_{\text{in}} = V_{\text{in}} / R_{\text{in}}$. Where $V_{\text{out}}$ is the output voltage $V_{\text{in}}$ is the input voltage, $P_{\text{out}}$ is the output power, $P_{\text{in}}$ is the input power, $R_{\text{in}}$ is the input voltage and $R_{\text{out}}$ is the output resistance. Substituting this in equation 1 we have

\[ G = 10 \log \left( \frac{V_{\text{out}}^2}{R_{\text{out}}} \right) / \left( V_{\text{in}}^2/R_{\text{in}} \right) \] \hspace{1cm} (2)
Let $R_{out} = R_{in}$, then the equation 2 becomes

$$G = 10 \log \left( \frac{V_{out}^2}{V_{in}^2} \right)$$
i.e.

$$G = 20 \log \left( \frac{V_{out}}{V_{in}} \right)$$

**Efficiency.**

Efficiency of an amplifier represents how efficiently the amplifier utilizes the power supply. In simple words it is a measure of how much power from the power supply is usefully converted to the output. Efficiency is usually expressed in percentage and the equation is $\zeta = \left( \frac{P_{out}}{P_{s}} \right) \times 100$. Where $\zeta$ is the efficiency, $P_{out}$ is the power output and $P_{s}$ is the power drawn from the power supply.

Class A transistor amplifiers have up to 25% efficiency, Class AB has up to 55% can class C has up to 90% efficiency. Class A provides excellent signal reproduction but the efficiency is very low while Class C has high efficiency but the signal reproduction is bad. Class AB stands in between them and so it is used commonly in audio amplifier applications.

**Stability.**

Stability is the capacity of an amplifier to resist oscillations. These oscillations may be high amplitude ones masking the useful signal or very low amplitude, high frequency oscillations in the spectrum. Usually stability problems occur during high frequency operations, close to 20KHz in case of audio amplifiers. Adding a Zobel network at the output, providing negative feedback etc improves the stability.

**Slew rate.**

Slew rate of an amplifier is the maximum rate of change of output per unit time. It represents how quickly the output of an amplifier can change in response to the input. In simple words, it represents the speed of an amplifier. Slew rate is usually represented in $V/\mu S$ and the equation is $SR = \frac{dV_{o}}{dt}$.

**Linearity.**

An amplifier is said to be linear if there is a linear relationship between the input power and the output power. It represents the flatness of the gain. 100% linearity is not possible practically as the amplifiers using active devices like BJTs, JFETs or MOSFETs tend to lose gain at high frequencies due to internal parasitic capacitance. In addition to this the input DC decoupling capacitors (seen in almost all practical audio amplifier circuits) sets a lower cutoff frequency.

**Noise.**

Noise refers to unwanted and random disturbances in a signal. In simple words, it can be said to be unwanted fluctuation or frequencies present in a signal. It may be due to design flaws,
component failures, external interference, due to the interaction of two or more signals present in a system, or by virtue of certain components used in the circuit.

**Output voltage swing.**

Output voltage swing is the maximum range up to which the output of an amplifier could swing. It is measured between the positive peak and negative peak and in single supply amplifiers it is measured from positive peak to the ground. It usually depends on the factors like supply voltage, biasing, and component rating.

**Common emitter RC coupled amplifier.**

The common emitter RC coupled amplifier is one of the simplest and elementary transistor amplifier that can be made. Don’t expect much boom from this little circuit, the main purpose of this circuit is pre-amplification i.e. to make weak signals strong enough for further processing or amplification. If designed properly, this amplifier can provide excellent signal characteristics. The circuit diagram of a single stage common emitter RC coupled amplifier using transistor is shown in Fig1.
Capacitor Cin is the input DC decoupling capacitor which blocks any DC component if present in the input signal from reaching the Q1 base. If any external DC voltage reaches the base of Q1, it will alter the biasing conditions and affects the performance of the amplifier.

R1 and R2 are the biasing resistors. This network provides the transistor Q1’s base with the necessary bias voltage to drive it into the active region. The region of operation where the transistor is completely switched off is called cut-off region and the region of operation where the transistor is completely switched ON (like a closed switch) is called saturation region. The region in between cut-off and saturation is called active region. Refer Fig 2 for better understanding. For a transistor amplifier to function properly, it should operate in the active region. Let us consider this simple situation where there is no biasing for the transistor. As we all know, a silicon transistor requires 0.7 volts for switch ON and surely this 0.7 V will be taken from the input audio signal by the transistor. So all parts of there input waveform with amplitude ≤ 0.7V will be absent in the output waveform. In the other hand if the transistor is given with a heavy bias at the base , it will enter into saturation (fully ON) and behaves like a closed switch so that any further change in the base current due to the input audio signal will not cause any change in the output. The voltage across collector and emitter will be 0.2V at this condition (Vce sat = 0.2V). That is why proper biasing is required for the proper operation of a transistor amplifier.

![BJT output characteristics](image)
Cout is the output DC decoupling capacitor. It prevents any DC voltage from entering into the succeeding stage from the present stage. If this capacitor is not used the output of the amplifier (Vout) will be clamped by the DC level present at the transistors collector.

Rc is the collector resistor and Re is the emitter resistor. Values of Rc and Re are so selected that 50% of Vcc gets dropped across the collector & emitter of the transistor. This is done to ensure that the operating point is positioned at the center of the load line. 40% of Vcc is dropped across Rc and 10% of Vcc is dropped across Re. A higher voltage drop across Re will reduce the output voltage swing and so it is a common practice to keep the voltage drop across Re = 10%Vcc. Ce is the emitter by-pass capacitor. At zero signal condition (i.e, no input) only the quiescent current (set by the biasing resistors R1 and R2 flows through the Re). This current is a direct current of magnitude few milli amperes and Ce does nothing. When input signal is applied, the transistor amplifies it and as a result a corresponding alternating current flows through the Re. The job of Ce is to bypass this alternating component of the emitter current. If Ce is not there, the entire emitter current will flow through Re and that causes a large voltage drop across it. This voltage drop gets added to the Vbe of the transistor and the bias settings will be altered. In reality, it is just like giving a heavy negative feedback and so it drastically reduces the gain.

**Design of RC coupled amplifier.**

The design of a single stage RC coupled amplifier is shown below.

The nominal value of collector current Ic and hfe can be obtained from the datasheet of the transistor.

**Design of Re and Ce.**

Let voltage across Re; \( V_{Re} = 10\% V_{cc} \) ............(1)

Voltage across Rc; \( V_{Rc} = 40\% V_{cc} \). ..................(2)

The remaining 50% will drop across the collector-emitter.

From (1) and (2) \( Rc = 0.4 \frac{(Vcc/Ic)}{} \) and \( Re = 0.1(Vcc/Ic) \).

**Design of R1 and R2.**

Base current \( I_b = \frac{I_c}{hfe} \).

Let \( I_c = I_e \).

Let current through R1; \( IR1 = 10I_b \).

Also voltage across R2 ; \( VR2 \) must be equal to \( V_{be} + V_{Re} \). From this \( VR2 \) can be found.

Therefore \( VR1 = V_{cc}-VR2 \). Since \( VR1 \),\( VR2 \) and \( IR1 \) are found we can find R1 and R2 using the following
equations.

R1 = VR1/IR1 and R2 = VR2/IR1.

**Finding Ce.**

Impedance of emitter by-pass capacitor should be one by tenth of Re.

i.e, XCe = 1/10 (Re).

Also XCe = 1/2πF Ce.

F can be selected to be 100Hz.

From this Ce can be found.

**Finding Cin.**

Impedance of the input capacitor (Cin) should be one by tenth of the transistors input impedance (Rin).

i.e, XCin = 1/10 (Rin)

Rin = R1 parallel R2 parallel (1 + (hfe re))

re = 25mV/le.

Xcin = 1/2πF Cin.

From this Cin can be found.

**Finding Cout.**

Impedance of the output capacitor (Cout) must be one by tenth of the circuit’s output resistance (Rout).

i.e, XCout = 1/10 (Rout).

Rout = Rc.

XCout = 1/2πF Cout.

From this Cout can be found.

**Setting the gain.**

Introducing a suitable load resistor RL across the transistor’s collector and ground will set the gain. This is not shown in Fig1.

Expression for the voltage gain (Av) of a common emitter transistor amplifier is as follows.
\[ A_v = -\frac{r_c}{r_e} \]

\[ r_e = 25\text{mV/}\text{i}e \]

and \( r_c = R_c \text{ parallel } R_L \)

From this RL can be found.
COMMON BASE AMPLIFIERS
Overview

This topic covers the identification and operation of the common base transistor amplifier configuration.
Topic Learning Outcome

LO 3 Describe the operation of a Common Base transistor amplifier.

Assessment Criteria

LO 3.1 Identify the circuit layout of a common base transistor amplifier.

LO 3.2 Describe the operating characteristics of a common base transistor amplifier.

LO 3.3 Describe the operation of a common base transistor amplifier.
Common Base Amplifier

The common base (CB) amplifier is configured with the base terminal common to both the input voltage and the output voltage.

Figure 3—1 illustrates a CB amplifier circuit.

![Figure 3—1](image)

*Figure 3—1*
*Common Base Amplifier*

Figure 3—2 shows a simplified AC equivalent circuit for the CB amplifier.

![Figure 3—2](image)

*Figure 3—2*
*Equivalent Circuit Common Base Amplifier*

Note that the input voltage is applied between the emitter and base terminal and the output is taken across the collector and base terminals.
Capacitor $C_1$ in Figure 3—1 effectively removes the voltage divider resistors $R_{B1}$ and $R_{B2}$ by placing an AC ground at the base of the transistor.

Note that for an AC signal, the load resistor $R_L$ and collector resistor $R_C$ are in parallel at the output.

This results in an equivalent output resistance $R_{OUT}$ of:

$$R_{OUT} = \frac{10\,k \times 500}{10\,k + 500} \approx 476\,\Omega$$

**DC operation**

DC operation of the CB amplifier shown in Figure 3—3 is determined in a similar manner to that of the CE amplifier.

![Common Base Amplifier Diagram](image)

**Figure 3—3**

*Common Base Amplifier*

Capacitors $C_{IN}$, $C_{OUT}$ and $C_1$ have no effect on the DC operation of the circuit.
Referring to Figure 3—3, the output of the CB amplifier is derived across the collector base terminals of the transistor. The output voltage will vary with variations in the input or emitter current (I_E).

Therefore, the collector characteristic curve of the CB amplifier will be a plot of I_E versus I_C and V_CB.

The Q point of the common base amplifier is located at the intersection of the collector current I_C, emitter current I_E and the collector base voltage V_CB.

In a CB amplifier the input current is the emitter current and the output current is the collector current.

Current gain for a CB amplifier is therefore determined by the ratio of the DC collector current to the DC emitter current. It is known as alpha (α).

For the CB amplifier shown in Figure 3—3, the quiescent DC conditions are:

\[
V_{\text{BASE}} = \frac{R_{b2}}{R_{b1} + R_{b2}} \times V_{CC}
\]

\[
V_{\text{BASE}} = 5.7 \text{ V}
\]

\[
V_E = V_{\text{BASE}} - V_{BE}
\]

\[
V_E = 5.7 - 0.7
\]

\[
V_E = 5.0 \text{ V}
\]

\[
I_E = \frac{V_E}{R_E}
\]

\[
I_E = 1 \text{ mA}
\]

Assuming that the emitter current is the same as the collector current:

\[
V_C = V_{CC} \cdot (I_C \times R_C)
\]

\[
V_C = 10 \text{ V}
\]

Therefore, the collector base voltage V_CB is:

\[
V_{CB} = V_C - V_B
\]

\[
V_{CB} = 4.3 \text{ V}
\]
The Q point of the circuit is therefore located at the co-ordinates:

- \( I_E = 1 \text{ mA} \),
- \( I_C = 1 \text{ mA} \), and
- \( V_{CB} = 4.3 \text{ V} \).

The cut-off and saturation points of the CB amplifier are also determined differently than previously learnt for the CE amplifier.

The cut-off point is defined as the collector base voltage when the collector current is zero.

Therefore:

\[
\text{Cut-off} = V_C - V_B \\
\text{Cut-off} = 20 \text{ V} - 5.7 \text{ V} \\
\text{Cut-off} = 14.3 \text{ V}
\]

The base voltage does not change at the cut-off point because of the voltage divider resistors \( R_{B1} \) and \( R_{B2} \). The collector voltage is equal to \( V_{CC} \) when \( I_C = 0 \).

The saturation point is determined when the collector base junction of the transistor comes out of reverse bias. At the saturation point, \( V_{CB} \) is considered to be zero (or shorted) and the collector current is maximum.

The saturation point is therefore determined as:

\[
I_{(SAT)} = \frac{V_{CC} - V_B}{R_C} \\
I_{(SAT)} = \frac{20 \text{ V} - 5.7 \text{ V}}{10 \text{ k}} \\
I_{(SAT)} = 1.43 \text{ mA}
\]
Figure 3—4 shows the collector characteristic curve for the CB amplifier.
AC Operation

With capacitor $C_1$ at the base of the transistor, resistors $R_{B1}$ and $R_{B2}$ hold the base at a constant DC potential.

The introduction of the AC input signal at the emitter of the transistor causes the base emitter voltage to vary. This change in the base emitter voltage causes the base current and therefore, the collector current to vary.

For example, a positive going AC signal will reduce the forward bias of the base emitter junction. This reduces the base current thereby reducing the collector current.

A decrease in $I_C$ results in the collector voltage increasing due to the decreased voltage drop across $R_C$. This change is then passed through $C_{OUT}$ to the output.

A positive going input voltage has produced a positive going change in the output voltage. The operation for a negative going AC input signal is opposite to that just described.

The output voltage is, in both cases, in phase with the input voltage.

Figure 3—5 shows the circuit wave forms for the CB amplifier.

![CB Amplifier Waveforms](image-url)
Input Impedance

In Figure 3—6, the input impedance of our CB amplifier is equal to:

\[ Z_{in} = R_E || r_e \]

\[ r_e = \frac{25\text{mV}}{I_E} \]

= 25Ω for this example

A major disadvantage of the CB amplifier is that the input impedance is extremely low.
Output Impedance

The output impedance (Figure 3—7) of the CB amplifier is determined as:

\[ Z_{OUT} = r_c || R_C \]

\( r_c \) is very high \( \therefore Z_{OUT} \approx R_C \)

Typically, the output impedance remains approximately equal to the collector resistance.

*Figure 3—7
CB Amplifier Output Impedance*
Current Gain

Current gain is defined as the ratio of the output current to the input current.

For the CB amplifier, the input current is the emitter current and the output current is the collector current.

The ratio of collector current to emitter current for the CB amplifier is Alpha (α) and is given by:

\[ \frac{I_C}{I_E} \]

The relationship between transistor emitter, base and collector currents is:

\[ I_E = I_B + I_C \]

As \( I_C \) is always smaller than \( I_E \), the current gain (α) of the CB amplifier will always be less than one.

Voltage Gain

The voltage gain of the CB amplifier can be expressed as:

\[ A_v = \frac{V_{out}}{V_{in}} \]

\[ A_v = \frac{V_C}{V_E} \]

\[ = \frac{I_C R_C}{I_c r_e} \quad I_C \approx I_c \]

\[ \therefore \quad A_v = \frac{R_C}{r_e} \]

This is the formula for unloaded Voltage gain, the gain with a load is determined by:

\[ A_v = \frac{R_C \| R_L}{r_e} \]
CB Amplifier Summary

The characteristics of CB amplifier are:

- output voltage is in phase with the applied input voltage;
- high voltage gain (greater than unity, typically 300-400);
- low current gain (less than unity);
- good power gain ($A_V \times A_I$, typically 300-400);
- high output impedance (typically 100 kΩ);
- extremely low input impedance (typically 50Ω).

The CB amplifier provides voltage gain and power gain, but no current gain.

A disadvantage of this configuration is the very low input impedance. This low input impedance has the effect of 'loading down' most voltage sources, making it difficult to develop an AC signal across the input.
Practical Exercise

Common Base Amplifier

Overview

The following practical exercises will reinforce the theory on common base amplifiers and will form part of your performance assessment for this module.

Procedure

Your Instructor will nominate which of the following Lab-Volt practical exercises you are to carry out:

<table>
<thead>
<tr>
<th></th>
<th>Transistor Amplifier Circuits, Common Base Circuits Exercise 1</th>
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</thead>
<tbody>
<tr>
<td>1</td>
<td>Transistor Amplifier Circuits, Common Base Circuits Exercise 2</td>
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Equipment

LabVolt Classroom Equipment
Trainee Activity

1. For the above circuit determine:
   (Assume $I_C = I_E$)
   A. the saturation and cut-off points.
   B. the biasing configuration.
   C. the Q point.
   D. the phase relationship between $V_C$ and $V_E$. 

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2. Draw the AC equivalent circuit for the above circuit.
3. Using the circuit shown in Question 2, calculate:
(Assume $R_{CB} = 1\, \text{M}\Omega$ and $R_{BE} = 1.5\, \text{k}\Omega$

A. $Z_{IN}$

B. $Z_{OUT}$

C. DC Load Line.
4. List the characteristics of a Common Base (CB) amplifier.

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End of Topic Text
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:

![BJT Diagram](image-url)

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:

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

Amplifier Gain can now be directly calculated:

$$A_v \equiv \frac{v_o}{v_i} = \frac{1}{1 + \frac{1}{(1 + \beta)(r_o || R_E)}}$$

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 $R_B \rightarrow \infty$), 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 $R_B \rightarrow \infty$. 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).

\[
\text{KCL:} \quad i_T = -\Delta i_B + \frac{v_T}{r_o} - \beta \Delta i_B
\]

\[
\text{KVL (outside loop):} \quad -r_\pi \Delta i_B = v_T
\]

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 by 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), \( v_i' = v_i \).

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 result 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.

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:

\[
\begin{align*}
  v_i &= r_\pi \Delta i_B \\
  v_o &= -(R_c \parallel r_o) \beta \Delta i_B \\
  A_v &= \frac{v_o}{v_i} = -\frac{\beta}{r_\pi} (R_c \parallel r_o) \approx -\frac{\beta}{r_\pi} R_c = -\frac{R_c}{r_e} \\
  R_i &= R_B \parallel r_\pi \\
  R_o &= r_o
\end{align*}
\]

The negative sign in $A_v$ indicates $180^\circ$ 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:

\[
\begin{align*}
  \omega_l(\text{coupling}) &= 2\pi f_l = \frac{1}{R_i C_c} \\
  \omega_l(\text{bypass}) &= 2\pi f_l = \frac{1}{R'_E C_b} \\
  \text{where} \quad R'_E &= R_E \parallel (r_e + \frac{R_B}{\beta})
\end{align*}
\]

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.,

\[
\begin{align*}
  \omega_l(\text{bypass}) &\ll \omega_l(\text{coupling}) \quad \rightarrow \quad \omega_l = 2\pi f_l = \frac{1}{R_i C_c} \\
  \omega_l(\text{coupling}) &\ll \omega_l(\text{bypass}) \quad \rightarrow \quad \omega_l = 2\pi f_l = \frac{1}{R'_E C_b}
\end{align*}
\]

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.

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

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

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

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

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:

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

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 amplifier lead to a lower cut-off frequency for this amplifier (similar to emitter follower). The lower cut-off frequency is given 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, \( V_E = R_E I_E > 1 \text{ V} \) 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:

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

where \( R'_E \equiv R_{E2} \parallel (R_{E1} + r_e + \frac{R_B}{\beta}) \)
Summary of BJT Amplifiers

Common Collector (Emitter Follower):

\[ A_v = \frac{(R_e \parallel r_o)(1 + \beta)}{r_\pi + (R_E \parallel r_o)(1 + \beta)} \approx 1 \]
\[ R_i = R_B \parallel [r_\pi + (R_E \parallel r_o)(1 + \beta)] \approx R_B \]
\[ R_o = \frac{(r_o) r_\pi}{(1 + \beta)(r_\pi) + r_\pi} \approx \frac{r_\pi}{\beta} = r_e \]
\[ 2\pi f_l = \frac{1}{R_i C_c} \]

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 not 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: \( h_{fe} = 200 \), \( h_{ie} = 5 \text{ k}\Omega \), \( h_{oe} = 10 \mu\text{S} \)).

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

**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):

\[
R_B = 18 \text{ k} \| 22 \text{ k} = 9.9 \text{ k}\Omega
\]

\[
V_{BB} = \frac{22}{18 + 22} \cdot 9 = 4.95 \text{ V}
\]

**KVL:**

\[
V_{BB} = R_B I_B + V_{BE} + 10^3 I_E \quad I_B = \frac{I_E}{1 + \beta} = \frac{I_E}{201}
\]

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

\[
I_E = 4 \text{ mA} \approx I_C, \quad I_B = \frac{I_C}{\beta} = 20 \mu\text{A}
\]

**KVL:**

\[
V_{CC} = V_{CE} + 10^3 I_E
\]

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

**DC Bias summary:** \( I_E \approx I_C = 4 \text{ mA}, \quad I_B = 20 \mu\text{A}, \quad V_{CE} = 5 \text{ V} \)

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

\[
A_v \approx 1
\]

\[
R_i \approx R_B = 9.9 \text{ k}\Omega
\]

\[
R_o \approx r_e = 25 \text{ }\Omega
\]

\[
f_l = \frac{\omega_l}{2\pi} = \frac{1}{2\pi R_B C_c} = \frac{1}{2\pi \times 9.9 \times 10^3 \times 0.47 \times 10^{-6}} = 36 \text{ Hz}
\]
Example 2: Find the bias point and AC amplifier parameters of this circuit (Manufacturers’ spec sheets give: \(h_{fe} = 200\), \(h_{ie} = 5 \text{k} \Omega\), \(h_{oe} = 10 \mu S\)).

\[
\begin{align*}
    r_\pi &= h_{ie} = 5 \text{k} \Omega \\
    r_o &= \frac{1}{h_{oe}} = 100 \text{k} \Omega \\
    \beta &= h_{fe} = 200 \\
    r_e &= \frac{r_\pi}{\beta} = 25 \text{ } \Omega 
\end{align*}
\]

**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 \(270 + 240 = 510 \Omega\).

\[
\begin{align*}
    R_B &= 5.9 \text{k} \Omega \parallel 34 \text{k} = 5.0 \text{k} \Omega \\
    V_{BB} &= \frac{5.9}{5.9 + 34} \times 15 = 2.22 \text{ } \text{V} \\
    \text{KVL: } V_{BB} &= R_B I_B + V_{BE} + 510 I_E \\
    I_B &= \frac{I_E}{1 + \beta} = \frac{I_E}{201} \\
    2.22 - 0.7 &= I_E \left( \frac{5.0 \times 10^3}{2.1} + 510 \right) \\
    I_E &= 3 \text{ mA} \approx I_C, \quad I_B = \frac{I_C}{\beta} = 15 \mu \text{A} \\
    \text{KVL: } V_{CC} &= 1000 I_C + V_{CE} + 510 I_E \\
    V_{CE} &= 15 - 1,510 \times 3 \times 10^{-3} = 10.5 \text{ V} \\
    \text{DC Bias: } I_E \approx I_C = 3 \text{ mA}, \quad I_B = 15 \mu \text{A}, \quad V_{CE} = 10.5 \text{ V}
\end{align*}
\]

**AC analysis:** The circuit is a common collector amplifier with an emitter resistance. Note that the 240 \text{ } \Omega\ 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:

\[
\begin{align*}
    A_v &= \frac{R_C}{R_{E1} + r_e} = \frac{1,000}{270 + 25} = 3.39 \\
    R_i &\approx R_B = 5.0 \text{k} \Omega \\
    R_o &\approx r_e = 25 \text{ } \Omega \\
    R'_E &= (R_{E1} + r_e + \frac{R_B}{\beta}) = 240 \parallel (270 + 25 + \frac{5,000}{200}) = 137 \text{ } \Omega \\
    f_l &= \frac{\omega_l}{2\pi} = \frac{1}{2\pi R_o C_c} + \frac{1}{2\pi R'_E C_b} = \frac{1}{2\pi \times 5,000 \times 4.7 \times 10^{-6}} + \frac{1}{2\pi \times 137 \times 47 \times 10^{-6}} = 31.5 \text{ Hz}
\end{align*}
\]
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: $\beta_{min} = 100$, $\beta = 200$, $h_{ie} = 5 \text{ k}\Omega$, $h_{oe} = 10 \text{ \mu S}$).

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

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

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

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 $I_C \approx I_E$:

\[ V_{CC} = R_CI_C + V_{CE} + R_EI_E \]
\[ 15 - 7.5 = 3 \times 10^{-3}(R_C + R_E) \quad \rightarrow \quad R_C + R_E = 2.5 \text{ k}\Omega \]

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:

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

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

We need to check if $V_E > 1$ V, the condition for good biasing. $V_E = R_EI_E = 510 \times 3 \times 10^{-3} = 1.5 > 1$, 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:

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

KVL: \[ V_{BB} = R_BI_B + V_{BE} + R_EI_E \]
\[ V_{BB} = 5.1 \times 10^{-3} \times \frac{3 \times 10^{-3}}{201} + 0.7 + 510 \times 3 \times 10^{-3} = 2.28 \text{ V} \]
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: $R_1 = 33 \, \text{k}\Omega$. $R_2$ is found from the equation for $V_{BB}$ to be $R_2 = 5.9 \, \text{k}\Omega$. Commercial values are $R_1 = 33 \, \text{k}\Omega$ and $R_2 = 6.2 \, \text{k}\Omega$.

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

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

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

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

**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 $I_C = 3 \, \text{mA}$ and $V_{CE} = 7.5 \, \text{V}$. A power supply of 15 V is available. Manufacturers’ spec sheets give: $\beta_{min} = 100$, $h_{fe} = 200$, $r_\pi = 5 \, \text{k}\Omega$, $h_{oe} = 10 \, \mu\text{S}$.

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

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 $V_{CC} = 15 \, \text{V}$. 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:

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

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:

- **DC Bias**: $R_C + R_{E1} + R_{E2} = 2.5 \text{ k}\Omega$
- **AC gain**: $A_v = \frac{R_C}{R_{E1}} = 10$

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 $R_C = 2.2 \text{ k}\Omega$, $R_{E1} = 220 \text{ } \Omega$, and $R_{E2} = 110 \text{ } \Omega$ (All commercial values).

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

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

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

**KVL**: $V_{BB} = R_B I_B + V_{BE} + R_E I_E$

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

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

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

$$\frac{V_{BB}}{V_{CC}} = \frac{R_2}{R_1 + R_2} = \frac{1}{15} = 0.066$$
$R_1$ can be found by dividing the two equations: $R_1 = 50 \, \text{k}\Omega$ and $R_2$ is found from the equation for $V_{BB}$ to be $R_2 = 3.6 \, \text{k}\Omega$. Commercial values are $R_1 = 51 \, \text{k}\Omega$ and $R_2 = 3.6 \, \text{k}\Omega$.

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

\[
R' \equiv R_{E2} \parallel (R_{E1} + r_c + \frac{R_B}{\beta}) = 110 \parallel (220 + 25 + \frac{3.300}{200}) = 77.5 \, \text{\Omega}
\]

\[
R_i \approx R_B = 3.3 \, \text{\k}\Omega
\]

\[
\omega_l = \frac{1}{R_i C_c} + \frac{1}{R'E C_b} = 2\pi \times 100
\]

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 $C_b = 20 \, \mu\text{F}$. Then, setting

\[
\frac{1}{R_i C_c} \ll \frac{1}{R'E C_b}
\]

\[
\frac{1}{R_i C_c} = 0.1 \frac{1}{R'E C_b}
\]

\[
R_i C_c = 10R'E C_b \quad \rightarrow \quad C_c = 4.7^{-6} = 4.7 \, \mu\text{F}
\]

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

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 $C_b = 47 \, \mu\text{F}$, we find $C_c = 0.86 \, \mu\text{F}$. 


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).

![Diagram of BJT differential pair](image)

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:

KVL: \(-v_1 + v_{BE1} - v_{BE2} + v_2 = 0 \rightarrow v_{BE1} - v_{BE2} = v_1 - v_2\)

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:

KCL: \(i_{C1} \approx i_{E1} = 0.5I\) and \(i_{C2} \approx i_{E2} = 0.5I\).

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:

KVL: \(v_{BE1} - v_{BE2} = v_1 - v_2 = 1\) 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:

KVL: \(v_{BE1} - v_{BE2} = v_1 - v_2 = -1\) 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 straightforward 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:

\[
\begin{align*}
  v_{CM} &= \frac{v_1 + v_2}{2} \\
  v_1 &= v_{CM} + 0.5v_d \\
  v_2 &= v_{CM} - 0.5v_d
\end{align*}
\]

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 \( i_C = i_{E1} = i_{C2} = i_{E2} = 0.5I \), 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:

\[
\begin{align*}
  v_{c1} &= A_v v_i = \frac{R_C}{r_e} (0.5v_d) \\
  v_{c2} &= A_v v_i = \frac{R_C}{r_e} (-0.5v_d) \\
  v_o &= v_{c1} - v_{c2} = \frac{R_C}{r_e} v_d
\end{align*}
\]
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 amplifier with emitter resistance, the input impedance is also increased dramatically by negative feedback of \(R_E\) (and absence of biasing resistors, \(R_b \rightarrow \infty\)):

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

**Amplification:** Amplification is the process in which the strength (voltage, current, or power) of a weak signal increases when it is passed through a circuit called "AMPLIFIER".

**Faithful amplification:** Amplification in which the shape of the electrical signal remains the same, only the magnitude (voltage, current, or power) of the signal increases is called faithful amplification.

**Transistor amplifier:** If the amplification is achieved by using a Bipolar junction transistor and associated biasing circuit, then the amplifier is called "transistor amplifier". For faithful amplification, the transistor should always be operated in the linear region (active region) of its output characteristics. Therefore, the biasing circuit should be designed in such a way that during all the instants of the input signal,

i) Emitter-Base junction remains under forward bias and

ii) Collector-Base junction remains under reverse bias.

Amplifiers are classified under various criteria's as follows.

1. Based on transistor configuration:
   a. Common-emitter (CE) amplifier
   b. Common-base (CB) amplifier
   c. Common-collector (CC) amplifier

2. Based on the strength of input signal,
   a. Small-signal amplifier (voltage amplifier)
   b. Large signal amplifier (power amplifier)

3. Based on biasing conditions,
   a. Class A amplifiers
   b. Class B amplifiers
   c. Class C amplifiers
   d. Class AB amplifiers

4. Based on frequency response,
   a. DC amplifier (from zero frequency)
   b. Audio frequency amplifiers (20 Hz - 20kHz)
   c. Intermediate frequency amplifiers (IF)
   d. Radio frequency amplifiers (20kHz to MHz)
      i) Very high frequency amplifiers (VHF)
      ii) Ultra high frequency amplifiers (UHF)
   e. Microwave frequency amplifiers (μwF)

5. Based on the bandwidth,
   a. Narrow band amplifiers (Tuned amplifiers)
   b. Wide band amplifiers.

6. Based on the number of stages,
   a. Single stage amplifiers
   b. Two stage amplifiers
   c. Multistage amplifiers.

7. Based on the type of coupling
a. RC coupled amplifiers  
b. Inductive coupled amplifiers  
c. Transformer coupled amplifiers and  
d. Direct coupled amplifiers.

8. Based on the output  
a. Voltage amplifiers  
b. Power amplifiers  

In general, the different types of amplifiers can be designed using any of the three transistor configurations i.e., CE, CB and CC. Each of these configurations can be used for certain specific application based on their characteristic features.

**Characteristics of amplifiers:** To choose a right kind of amplifier for a purpose it is necessary to know the general characteristics of amplifiers. They are: Current gain, Voltage gain, Power gain, Input impedance, Output impedance, Bandwidth.

1. **Voltage gain:**  
Voltage gain of an amplifier is the ratio of the change in output voltage to the corresponding change in the input voltage. Since amplifiers handle ac signals, the instantaneous output voltage $V_o$ and instantaneous input voltage $V_i$ can replace $\Delta V_o$ and $\Delta V_i$ respectively.

Hence, $A_v = \frac{V_o}{V_i}$

2. **Current gain:** Current gain of an amplifier is the ratio of the change in output current to the corresponding change in the input current. i.e., $A_i = \frac{i_o}{i_i}$, where $i_o$ and $i_i$ are the ac values of output current and input current respectively.

3. **Power gain:** Power gain of an amplifier is the ratio of the change in output power to the corresponding change in the input power. 
Since power $p = v \times i$, The power gain

\[ A_p = \frac{p_o}{p_i} \]

\[ A_p = \frac{V_o \cdot i_o}{V_i \cdot i_i} = A_v \times A_i \]

(Power amplification of the input signal takes place at the expense of the d.c. energy.)
4. **Input impedance** \((Z_i)\): Input impedance of an amplifier is the impedance offered by the amplifier circuit as seen through the input terminals and is given by the ratio of the input voltage \((v_i)\) to the input current \((i_i)\). i.e.,
\[
Z_i = \frac{v_i}{i_i}
\]

5. **Output impedance** \((Z_0)\): Output impedance of an amplifier is the impedance offered by the amplifier circuit as seen through the output terminals and is given by the ratio of the output voltage \((v_o)\) to the output current \((i_o)\).
\[
Z_0 = \frac{v_o}{i_o}
\]

6. **Bandwidth (BW)**: The range of frequencies over which the gain (voltage gain or current gain) of an amplifier is equal to and greater than 0.707 times the maximum gain is called the bandwidth.

In figure shown, \(f_1\) and \(f_2\) are the lower and upper cutoff frequencies where the voltage or the current gain falls to 70.7% of the maximum gain. ∴ Bandwidth \(BW=(f_2-f_1)\).

**Gain in decibels:**
Often it is convenient to consider the gain of an amplifier on a logarithmic scale than on a linear scale. Such a unit, of the logarithmic scale is called the ‘bel’. The power gain of an amplifier in bel is
written as \( \text{Gain in bel} = \log_{10} \left( \frac{p_o}{p_i} \right) \) where, \( p_i \) and \( p_o \) are input and output powers respectively.

Since bel is too large a unit for most practical purposes, a smaller unit called decibel (dB) which is \((1/10)\)th of bel is used.

\[ \therefore \text{Gain in dB} = 10 \log_{10} \left( \frac{p_o}{p_i} \right) \]

Decibel voltage gain and Decibel current gain:
The power in a resistive branch is proportional to square of the voltage or current, therefore, expressing the power ratio \((P_o/P_i)\) in terms of a voltage ratio or a current ratio,

\[ 10 \log_{10} \left( \frac{v_o}{v_i} \right)^2 = 20 \log A_v \]

where \( v_i \) is the input voltage and \( v_o \), the output voltage assuming the same input and output resistances.

Similarly, Current gain in dB = \( 20 \log A_i \).

Graph showing the frequency response in dB gain

The cutoff frequencies are also defined as the frequencies where the gain of the amplifier falls by 3 dB from the maximum gain

**Common Emitter Amplifier:**

Figure shows the circuit of a single stage common emitter (CE) amplifier using an NPN transistor. The input signal \( v_s \) is applied between the base and the emitter (since the bypass capacitor \( C_E \) keeps the Emitter ac potential at zero). The output is taken across the load resistance \( R_L \). The resistors \( R_1 \) and \( R_2 \) provide the necessary d.c. bias to the transistor.
The Resistor $R_C$ is generally of a large value compared to the input resistance of the transistor which acts as a collector load. Coupling capacitors $C_B$ and $C_C$ block the dc and allow the a.c. $C_E$ is called the bypass capacitor. It grounds the emitter for ac signals and thereby avoids the negative feedback for a.c. However the Resistor $R_E$ stabilises the operating point since the emitter dc potential is unaffected. Without $C_E$, the alternating voltage across $R_E$ results in reduced $i_b$ and hence $i_c$. This reduces the gain of the amplifier.

**Circuit operation:**
During the positive half cycles of input signal, base emitter junction is more forward biased and hence the base current increases. This will increases collector current $i_C$ by a large amount. Therefore, the voltage across resistance $R_C$ (i.e., $i_C R_C$) increases. Which reduces the output voltage. Similarly, during negative half cycles of the input signal, collector current decreases by a large amount producing a decreased voltage across $R_C$. This increases the output voltage.

Output across the transistor is given by $v_o=V_{CC} - i_c R_C$.

Thus the output voltage in CE amplifier is $180^\circ$ out of phase with the input signal as shown in the figure.

**Characteristics of CE amplifier:**
- Current gain and voltage gain are high.
- Power gain is very high
- Input and output impedances are moderate as compared to CB and CC amplifiers. (The typical values of input and output impedances are $1 \, k\Omega$ and $10 \, k\Omega$ respectively. Therefore, the input impedance is low and the output impedance is high)
- The effective input capacitance is large and hence the frequency response though good, is not as good as of CB or CC amplifiers.
- There will be $180^\circ$ phase shift between the input and output voltages.

**Applications:**
- CE amplifier configurations are basically used as voltage amplifiers viz. Preamplifiers driving the power amplifiers. CE amplifiers are called as small signal amplifiers since the small amplitude of the input signal is required to drive such amplifiers unlike the power amplifiers, which require signal of large amplitude.
- Despite its large power gain, CE amplifier cannot be used as a power amplifier. This is because; it cannot drive the low impedance load due to its high output impedance.
Frequency response of CE amplifier:

At low frequencies, the capacitive reactance of the coupling capacitor $C_B$ will be high. Therefore, a small fraction of the input voltage appears across the input terminals. This decreases the output voltage and hence the overall voltage gain is low. With increase in frequency, the capacitive reactance decreases and the input to the amplifier increases. Therefore, the voltage gain increases. At high frequencies, the capacitive reactance of the coupling capacitor $C_C$ will be very low and it behaves as a short circuit. Hence the loading effect of the resistance $R_C$ with $R_L$ increases. This decreases the output voltage and hence the overall voltage gain decreases. Further, the decrease in capacitive reactance of the base emitter junction and the stray capacitance at the output section will lead to the decrease in voltage gain at high frequencies.

In the mid frequency range, voltage gain of the amplifier is constant. As the frequency increases, the reactance of $C_C$ decreases which tends to increase the gain. At the same time, the loading effect of the $R_C$ with $R_L$ increases and tends to decrease the voltage gain. These two factors almost cancel each other resulting in a constant gain in the mid frequency range.

Common Base Amplifier:

Fig. shows the circuit of a common base amplifier. Here, the resistors $R_E$, $R_C$ along with the supply voltages $+V_{CC}$ and $-V_{EE}$ bias the transistor to work in its active region. The input signal $v_s$ is applied across emitter base junction through the capacitor $C_C$ and the amplified output is taken across the collector base junction. i.e., $v_o=v_{cb}$. Capacitors $C_C$ and $C_B$ block the d.c component and allow only ac signal to pass through.


**Circuit operation:** During the positive half cycles of the input signal, forward bias on the emitter-base junction decreases. This results in decrease of the emitter current $i_e$ thereby decreasing the collector current $i_c$. Applying KVL to the output section,

$$v_o = v_{cb} = V_{CC} - i_c R_C.$$  

Therefore, the decrease in $i_c$ causes the voltage drop $i_c R_C$ to decrease. This increases $v_{cb}$, i.e., $v_o$ increases.

Similarly, during the negative half cycles of the input signal, forward bias on the emitter-base junction increases resulting in increase of the emitter current $i_e$ and the collector current $i_c$. Therefore, the voltage drop across $R_C$ increases. Thus, $v_{cb}$ or $v_o$ decreases. Therefore, the input and output voltages are in phase.

Since $I_C < I_E$, there is no current gain in CB amplifier. By selecting a resistance of large value at the output (i.e., $R_C$), the magnitude of the output voltage will be much greater than the magnitude of input voltage. Therefore, the voltage gain is high.

**Characteristics of CB amplifier:**

- The voltage gain is fairly high (200-300)
- The current gain $\alpha$ is less than 1.
- The power gain is also fairly large and is nearly equal to voltage gain.
- The input impedance is very low (20Ω to 200Ω).
- The output impedance is very high (50kΩ to several MΩ).
- It is suitable for amplifying high frequencies (VHF).

(This is because, in the low frequency region, the input resistance between the base and the emitter is very low compared to capacitive reactance of the capacitor. Therefore, more input voltage appears across the coupling capacitor $C_b$ and a negligible fraction of the input signal appears across the EB junction. Therefore, the voltage gain is very low at low frequencies.

Further at high frequencies, especially in the VHF range, the reactance of the input capacitor will be negligibly small allowing whole
of the input signal to appear at the EB junction leading to increased output).
There is no phase shift between the input and the output signals.

**Applications:**

- It is used as voltage amplifier in RF circuits
- It is used as a constant current source
- It is used to match low Output impedance circuit with that of a high impedance load.

Despite its fairly large power gain (equal to voltage gain), CB amplifier is never used as a Power amplifier because of very high Output impedance.

**Common Collector Amplifier:**

![Common Collector Amplifier Diagram]

Figure shows the transistor in CC configuration with voltage divider bias. Here the resistors R₁, R₂, Rₑ along with the supply voltage Vcc forms the biasing and stabilisation network. In this circuit, since Rₑ = 0Ω, the potential at collector is The input voltage is applied to base with respect to collector and the output is taken at emitter with respect to collector.

**Circuit operation:**

Since the output is taken at the emitter, vₑ = iₑRₑ & vₒ = iₑRₑ.

Applying KVL to the input loop we get

\[ vₛ = v_{BE} + iₑRₑ \]  (1)

During the positive half cycles of the input voltage, forward bias on the base emitter base junction increases. This increases base current and hence the emitter current. Therefore, the voltage drop iₑRₑ increases.

Since vₒ = iₑRₑ, vₒ also increases. Similarly, any decrease in the input voltage causes the output voltage to decrease. i.e., any variation at the input causes the same variation at the output. Thus the input and the output signals are in phase.

But, from eq.(1),

\[ vₛ = v_{BE} + iₑRₑ \]

i.e., \[ vₑ = iₑRₑ = vₛ - v_{BE} \]

or \[ vₒ = vₛ - v_{be} \]
This means that the output voltage is always slightly less than the input voltage. Therefore, the voltage gain is always less than unity.

Since the output voltage (emitter voltage) follows the input voltage without any phase change, the circuit is also called as EMITTER FOLLOWER.

**Characteristics of CC amplifier:**
The input impedance is very high (>450 kΩ)
The output impedance is very low (around 50Ω)
The voltage gain is less than unity (typical values are 0.99, 0.98, --)
Provides high current gain (typical values are 101, 202, ----)
There is no phase shift between the input and the output waveforms.

**Applications:**
i) Since the CC amplifier circuit provides very high input impedance and very low output impedance, it is used for impedance matching purposes (i.e., to match high Output impedance circuit with that of a low impedance load)
ii) It is used as a power amplifier.

**Comparison of CE, CB and CC amplifiers:**
A study of the different amplifier configurations provide valuable information, which can help in making the right choice for a specific purpose.

For example, a power amplifier requires a large input signal and a signal source may be very weak. In this case, the signal is first amplified using a CE amplifier and the amplified voltage is used as the input for the power amplifier.

Consider a low impedance load (a device such as speaker). To deliver maximum power to the load, the output impedance of amplifier should be low. Common collector amplifier satisfies this requirement. Though the voltage gain of a CC amplifier is less than 1, it is still useful as power amplifier because of its large current gain. Further, due to its low output impedance, it delivers large power to the low impedance loads.

**Commonly used transistor configuration:**
Amongst the three transistor configurations, the CE circuit is used in most of the transistor applications due to the following reasons.
1. Current gain is very high. It may range from 20 to 500
2. Voltage gain is high
3. Power gain is high
4. Moderate output to input impedance ratio (50). However this configuration cannot be used for impedance matching purpose like CC configuration.
Comparison of CB, CE and CC amplifiers:

<table>
<thead>
<tr>
<th>Parameters</th>
<th>CB</th>
<th>CE</th>
<th>CC</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. Current gain</td>
<td>Less than 1 ($\alpha \approx 1$)</td>
<td>High ($\beta &gt; 1$)</td>
<td>Highest ($\gamma &gt; 1$) ($\gamma = \beta + 1$)</td>
</tr>
<tr>
<td>2. Voltage gain</td>
<td>High</td>
<td>Very high</td>
<td>Less than 1</td>
</tr>
<tr>
<td>3. Power gain</td>
<td>High</td>
<td>Highest</td>
<td>$&gt;1$ (low when compared to CB &amp; CE amplifiers)</td>
</tr>
<tr>
<td>4. Input impedance</td>
<td>Lowest</td>
<td>Moderate</td>
<td>Highest</td>
</tr>
<tr>
<td>5. Output impedance</td>
<td>Highest</td>
<td>Moderate</td>
<td>Lowest</td>
</tr>
<tr>
<td>6. Phase difference</td>
<td>$0^0$ or $2\pi$</td>
<td>$180^0$ or $(2n+1)\pi$</td>
<td>$0^0$ or $2\pi$</td>
</tr>
<tr>
<td>7. Applications</td>
<td>Used mainly as HF amplifier</td>
<td>Used as a (voltage amplifier)</td>
<td>Used as a Buffer amplifier, impedance matching unit</td>
</tr>
</tbody>
</table>

AC and DC equivalent circuits

A transistor amplifier circuit has certain dc conditions for its operation. These dc conditions are provided by the biasing arrangement. The ac signal to be amplified is superposed on the dc values of voltage and current. Hence in an amplifier circuit in action both ac and dc conditions prevail simultaneously.

The analysis of a transistor amplifier circuit becomes easier by analysing the dc and ac behavior of the circuit separately.

This is done by using the appropriate "Equivalent circuits". i.e., D.C equivalent circuit and A.C equivalent circuit.

D.C equivalent circuit:

The dc equivalent circuit of a transistor amplifier is the configuration of only those circuit elements, which are responsible for the dc conditions of the circuit.

A.C equivalent circuit:

The ac equivalent circuit of a transistor amplifier is the configuration of only those circuit elements, which are responsible for ac conditions of the circuit.

Steps involved in writing D.C equivalent circuit:

1. All a.c. sources are to be reduced to zero
2. Since the capacitors offer infinite reactance to the flow of d.c., all the capacitors are to be treated as open circuits.
3. Inductors if any appear in the circuits, they are to be replaced by short circuit equivalents since the inductive reactance is zero for d.c.

**D.C analysis of a CE amplifier with voltage divider bias using D.C equivalent circuit:**

For a single stage CE amplifier with voltage divider bias, applying the steps 1 to 3, the d.c equivalent circuit can be written as follows.

\[
\begin{align*}
&V_{\text{cc}} \\
&\leftarrow R_1 \\
&\leftarrow R_2 \\
&\leftarrow R_C \\
&\leftarrow R_E \\
&\leftarrow C_E \\
&\leftarrow C_B \\
&V_v \\
&\leftarrow v_o \\
&\rightarrow +V_{\text{cc}}
\end{align*}
\]

**Single stage CE amplifier**

**d.c equivalent circuit**

To find the Operating point \((V_{\text{CEQ}} \text{ & } I_{\text{CQ}})\) using D.C equivalent circuit:

Voltage across \(R_2\) is given by,

\[
V_2 = \frac{R_2}{R_1 + R_2} \times V_{\text{cc}}
\]

From KVL,

\[
V_2 = V_{\text{BE}} + V_E \quad \text{i.e., } V_2 = V_{\text{BE}} + I_E R_E
\]

\[
I_E = \frac{V_2 - V_{\text{BE}}}{R_E} \cong I_C \quad \rightarrow 1
\]

\(V_{\text{BE}}\) is 0.7V for silicon transistors and is 0.3V for Germanium transistors.

Applying KVL to the output section,

\[
V_{\text{CE}} = V_{\text{cc}} - I_C (R_C + R_E) \quad \rightarrow 2
\]

Equations (1) and (2) give the coordinates of operating point.

To draw the d.c load line:

End points of the d.c load line are given by substituting the limiting conditions in equation (2).

i) When \(I_C = 0\), then

\[
V_{\text{CE(max)}} = V_{\text{cc}} \quad \text{(point B)}
\]
ii) When $V_{CE} = 0$, then

$$I_{C(\text{max})} = \frac{V_{CC}}{(R_C + R_E)}$$ (point A)

By joining these two points a line is drawn which gives the d.c. load line as in fig.

**A.C equivalent circuit:**

**Steps involved in writing a.c equivalent circuit:**
1. All d.c. sources are to be reduced to zero
2. Since the capacitors offer minimum reactance to the flow of a.c., all the capacitors are replaced by their short circuit equivalents.
3. Inductors if any appear in the circuits, they are to be replaced by open circuit equivalents since the inductive reactance is very high for a.c.
4. The transistor is to be replaced by one of its a.c equivalent models like $r_e$ model or hybrid equivalent model.

The most commonly used transistor ac equivalent models are,

1. $r_e$ Model and (2) Hybrid equivalent model.

The $r_e$ model is derived from the diode equivalent circuit.

**Diode Equivalent circuit:** From the input characteristics of a transistor, it is found that the input section (i.e., Emitter-Base junction) behaves like a semiconductor diode. Therefore, the E-B junction can be replaced by a semiconductor diode. Similarly, from the output characteristics of a transistor, it is clear that the output section (i.e., Collector-Base junction) behaves like a constant current source. Therefore, the C-B or C-E terminals can be replaced by a constant current source as shown in fig.

$r_e$ Model: Since the Emitter-Base junction is always forward biased, for small a.c. signals, the semiconductor diode representing the input section can be replaced by its equivalent resistance $r_e$. 

![Diode Equivalent Circuit](image-url)
called a.c Emittor resistance and is given by 
\[ r_E = \frac{25 \text{ mV}}{I_E} \]
where \( I_E \) is the d.c emitter current. The directions of the currents shown in the circuits here may not be the actual directions in which the currents flow. As a matter of standardisation, all the currents are considered such that they flow into the transistor.

**AC equivalent circuit (\( r_e \) model) of transistor in CE mode:**

Since \( I_E \cong \beta I_B \), from equation 1, we get, \( r_e = \frac{25 \text{ mV}}{\beta I_B} \). Therefore, the diode resistance in CE mode is given by,

where \( I_B \) is the d.c current through base. \( \beta r_e \) is also called as \( r_{in(base)} \). Analysis of a single stage CE amplifier using \( r_e \) model:

The ac equivalent circuit using the \( r_e \) model is as follows.

Replacing \( R_1 \parallel R_2 \) by \( R_B \) and \( R_C \parallel R_L \) by \( R_{ac} \), the above circuit can be simplified as follows.
Let $v_s$, $i_s$, $v_o$, and $i_o$ be the input voltage, input current, output voltage and output current respectively for a single stage CE amplifier as shown in the circuit.

1. Input impedance ($Z_i$) or $r_{in(stage)}$:

We know that

$$Z_i = \frac{v_s}{i_s}$$

Also, $v_s = i_s \times (R_1 \parallel R_2 \parallel \beta r_e)$.

Therefore,

$$Z_i = \frac{i_s \times (R_1 \parallel R_2 \parallel \beta r_e)}{i_s}$$

i.e, $Z_i = (R_1 \parallel R_2 \parallel \beta r_e) \rightarrow 1$

Input impedance at the base is $Z_{in(base)} = \beta r_e$

2. Output impedance ($Z_O$) or $r_{o(stage)}$:

We know that

$$Z_O = \frac{v_o}{i_o}$$

Also, $v_o = i_o \times (R_C \parallel R_L)$

Therefore,

$$Z_O = \frac{i_o \times (R_C \parallel R_L)}{i_o}$$

i.e, $Z_O = (R_C \parallel R_L) \rightarrow 2$

3. Voltage Gain ($A_v$):

The general equation for the Voltage gain of the amplifier is

$$A_v = \frac{v_o}{v_s}$$

where, $v_o$ and $v_s$ are the input and the output voltages respectively.

Also, $v_o = -i_o \times (R_C \parallel R_L)$.

Since $i_o \equiv i_c$, the output voltage is given by,

$$v_o = -i_c \times (R_C \parallel R_L).$$

The input signal voltage can also be expressed as $v_s = i_b \times \beta r_e$

Substituting the values of output voltage and signal voltage, we get,

$$A_v = -\frac{i_c \times (R_C \parallel R_L)}{i_b \times \beta r_e}$$

But $i_c = \beta i_b$.

$$A_v = \frac{\beta i_b \times (R_C \parallel R_L)}{i_b \times \beta r_e} \Rightarrow 3$$

i.e.,

$$A_v = -\frac{(R_C \parallel R_L)}{r_e} \Rightarrow 3$$

The current gain of an amplifier is given by,

$$A_i = \frac{i_o}{i_s}$$

Since $i_o \approx i_c$ and $i_s \approx i_B^{**}$, the current gain is given by,

$$A_i = \frac{i_c}{i_B} = \beta$$

** If the biasing resistance $R_B$ is much greater than $\beta r_c$, neglecting the current through $R_B$, $i_s \approx i_B$.

5. Power Gain ($A_p$): It is the product of voltage gain and the current gain. i.e., $A_p = A_v \times A_i$.

$$A_p = \frac{\beta (R_C \parallel R_L)}{r_c}$$

Frequency response of a single stage CE amplifier:

It is the plot of gain of the amplifier for various values of applied frequency. It is observed that the gain is not constant at all the frequencies. The gain decreases both at low and at high frequencies.

The frequency of a single stage CE amplifier is shown in the fig. The gain remains more or less constant over a certain range of frequencies. It falls when the frequency is below $f_1$ or above $f_2$. These are called cutoff frequencies.

The response of the amplifier is studied under three conditions namely, Low Frequency, High Frequency and Mid Frequency response.

1. Low frequency response: At low frequencies the reactance of the capacitor is considerable. Hence, all the capacitors ($C_B$, $C_C$ and $C_E$) introduce considerable reactance to the applied signal. This reduces
the strength of the signal available at the base emitter junction (input). This reduces the output signal and hence the gain.

2. High frequency response: At very high frequencies, the reactance of the capacitor is very low. They act like short circuit. The interjunction capacitance also behaves like short circuit. This introduces negative feedback and hence the gain decreases. Also, the variation of current amplification factor $\beta$ decreases at high frequencies. Stray wire capacitance also behaves like short circuit. Due to all these reasons gain decreases even at high frequency.

3. Mid frequency response: In the mid frequency region, the coupling capacitors and bypass capacitor behave like short circuit. The gain of the amplifier does not depend on the reactance value in this region. Hence, it almost remains constant.

**Cascade amplifiers or Multi stage amplifiers:**

An amplifier is the building block of most electronic systems. A single stage amplifier cannot supply enough signal output. For example, the RF signal at the antenna of a radio receiver is generally in microvolt. Audio signal required for a microphone or tape recorders is in the order of millivolt range. The voltage or current needed to operate a speaker is however much greater than the signal input in the amplifier. The louder the sound we want to hear, the greater the audio power output needed.

A single stage that operates with a low level signal does not have enough output power. Hence, two or more stages are cascaded to provide a greater signal. This is achieved by coupling a number of amplifier stages such that the output of first stage drives the input of the second, output of second drives the input of the third, and so on through coupling device. This type of connection is called multistage or Cascade and the amplifier is called multi stage amplifier or Cascade amplifier. Fig shows the representation of multistage amplifier.

```
Input A_{V1} A_{V2} A_{V3} A_{V4} A_{V5} Output
```

In the representation, since the amplifiers are cascaded the overall gain of the amplifier will be given by,

$$ A_{V} = (A_{V1}) \times (A_{V2}) \times (A_{V3}) \times (A_{V4}) \times (A_{V5}) $$

If the gains are represented in dB the overall gain is the sum of the individual gains. $ A_{V} = (A_{V1}) + (A_{V2}) + (A_{V3}) + (A_{V4}) + (A_{V5})$

The purpose of coupling device is to transfer ac output of first stage to the input of the next stage to isolate the dc conditions of one stage from the next.
The name of the multistage amplifier is usually given after the type of coupling used as:
- RC coupled amplifier
- Inductive coupled amplifier
- Transformer coupled amplifier
- Direct coupled amplifier

**RC coupled amplifier**: This is the most popular type of coupling because it is cheap and provides excellent audio fidelity over a wide range of frequency. It is usually employed for voltage amplification.

Fig shows two-stage RC coupled amplifier. A coupling capacitor $C_C$ is used to connect the output of the first stage to the input of the second (base). As the coupling from one stage to the next is achieved by a coupling capacitor followed by a shunt resistor, hence such amplifiers are called RC coupled amplifiers.

The resistance $R_1$, $R_2$, and $R_E$ form a biasing and stabilisation network. The emitter bypass capacitor $C_E$ offers low reactance path to the signal. Without this capacitor, the gain of each stage would be very low due to negative feedback. The coupling capacitor $C_C$ transmits AC signal and blocks the DC thereby prevents the DC interference between various stages.

**Circuit operation**: When an AC signal is applied to the base of first transistor, it appears in the amplified form across the collector load $R_C$. The amplified signal across $R_C$ is given to the base of the next stage through a coupling capacitor $C_C$. The second stage further amplifies the signal and overall gain considerably increases. The overall gain is less than the product of the individual gains. This is because when a second stage is made to follow the first stage, the effective load resistance of the first stage is reduced due to the shunting effect of the input resistance of the second stage. This reduces the gain of the stage which is loaded by the next stage.
Frequency response of RC coupled amplifier: The frequency response of a typical RC coupled amplifiers is shown in the fig. It is clear from the graph that the voltage gain drops off at low frequencies and high frequencies.

While it remains constant in the mid frequency range. This behavior of the amplifier is explained as follows:

**At low frequencies:** The coupling capacitors $C_C$ offer a high reactance. Hence it will allow only a part of the signal to pass from one stage to the next stage. In addition to this, the emitter bypass capacitor $C_E$ cannot shunt the emitter resistor $R_E$ effectively, because of its large reactance at low frequencies. Due to these reasons, the gain of the amplifier drops at low frequencies.

**At high frequencies:** The coupling capacitor $C_C$ offers a low reactance and it acts as a short circuit. As a result of this, the loading effect of the next stage increases, which reduces the voltage gain. Moreover, at high frequencies, capacitive reactance of base emitter junction is low which increases the base current. This in turn reduces the current amplification factor $\beta$. As a result of these two factors, gain drops at high frequencies.

**At mid frequency:** In the mid frequency range, the effect of coupling capacitor is such that it maintains a constant gain. Thus, as the frequency increases, the reactance of capacitor $C_C$ decreases, which tends to increase the gain. However, at the same time, lower capacitive reactance increases the loading effect of first stage to which the gain reduces. These two factors cancel each other. Thus the constant gain is maintained.

**Advantages of RC coupled amplifiers:**
it requires components like resistors and capacitors. Hence, it is small, light and inexpensive.
It has a wide frequency response. The gain is constant over audio
frequency range which is the region of most importance for speech
and music.
It provides less frequency distortion.
Its overall amplification is higher than that of other coupling
combinations.

Disadvantages of RC coupled amplifiers:
The overall gain of the amplifier is comparatively small because of the
loading effect.
RC coupled amplifiers have tendency to become noisy with age,
especially in moist climate.
The impedance matching is poor as the output impedance is several
hundred ohms, where as that of a speaker is only few ohms. Hence,
small amount of power will be transferred to the speaker.

Applications:
RC coupled amplifiers have excellent audio frequency fidelity over a
wide range of frequency i.e., they are widely used as voltage
amplifiers. This property makes it very useful in the initial stages of
public address system. However, it may be noted that a coupled
amplifier cannot be used as a final stage of the amplifier because of
its poor impedance matching.

Direct coupled amplifier:
The circuit diagram of direct coupling using two identical transistors
is shown in the fig. In this method, the ac output signal is fed directly
to the next stage. This type of coupling is used where low frequency
signals are to be amplified. The coupling devices such as capacitors,
inductors and transformers cannot be used at low frequencies because
there size becomes very large. The amplifiers using this coupling are
called direct coupled amplifiers or dc amplifiers.

Advantages
The circuit arrangement is simple because of minimum number of components.
The circuit can amplify even very low frequency signals as well as direct current signals.
No bypass and coupling capacitors are required.

**Disadvantages**
1. It cannot be used for amplifying high frequencies.
2. The operating point is shifted due to temperature variations.

**Applications**: Direct coupled amplifiers find applications in regulator circuits of electronic power supplies, differential amplifiers, pulse amplifiers, electronic instruments and computers.

**Differential amplifier**: Differential amplifier is a very high gain direct coupled amplifier with two input terminals. It amplifies the difference of the two input signals. It is the building block of operational amplifier which is a monolithic IC used to perform number of mathematical operations.

Fig. shows the circuit of a differential amplifier. $v_{i1}, v_{i2}$ are the input terminals and $v_{o1}, v_{o2}$ are the output terminals. Transistors $Q_1$ and $Q_2$ are the matched transistors.

If the transistor $Q_1$ conducts heavily, it draws more current from the transistor $Q_2$ which conducts less such that the net current supplied remains constant under all conditions. Output can be taken between two collectors (called the Balanced output) or at each collector with respect to ground (called the Unbalanced output).
Circuit operation: Consider the input signal applied to the input $V_{i1}$ alone by grounding the other input as shown in fig. The output $V_{o1}$ is amplified and inverted version of $v_{i1}$ whereas the output at $v_{o2}$ is the amplified and in phase version of the input $v_{i1}$. This is because, during the positive half cycle of the input signal, the transistor $Q_1$ conducts more and hence the current $I_{E1}$ increases. Since the current supplied by the constant current source remains same at all instances, i.e., $I_E=I_{E1}+I_{E2}$, the increase in $I_{E1}$ is followed by decrease in $I_{E2}$ by the same amount. Therefore, the transistor $Q_2$ conducts less and the voltage drop across the resistor $R_{C2}$ decreases and the voltage at $v_{O2}$ with respect to ground increases. Therefore, a single input at $v_{i1}$ develops the output at both collectors with opposite polarities and of same magnitude.

If the output is taken at any one collector with respect to other collector (double ended or balanced output), the amplitude of the amplified signal will be double that of the single ended (or unbalanced) output.

Similarly, the outputs of same magnitude but of opposite polarities will be obtained by applying the signal at input $v_{i2}$ alone grounding the input terminal $v_{i1}$. If the input signals are applied simultaneously to both inputs, the outputs can be analysed by applying superposition theorem.

Different modes of operation are,

Common mode operation: If the input signals are such that they are of same frequency, same phase and of same amplitude, they are called as common mode signals and the operation is called common mode operation. Figure shows the circuit for common mode operation wherein both the inputs receive the signals of same frequency, same
phase and of same amplitude. If the two sections of the differential amplifier are matched type then the output due to common mode signals is zero, i.e., $v_{i2} - v_{i1} = 0$. The common mode gain $A_C$ is hence zero in ideal case.

The typical value of Common mode gain is very low but not zero due to the slight imbalance in the two sections of the differential amplifier.

Differential gain: If the input signals are of different amplitude or of different phase, or different frequency, then the difference of the inputs at all instances will not be zero and such type of operation is called differential operation. Generally the signals which are of different amplitude or different phase (commonly, out of phase) are used as differential input signals.

Figure shows the circuit of a differential mode operation. The differential gain $A_d$ is ideally equal to infinity. Typically, it is very high of the order of $10^6$ but not infinity.

Common Mode Rejection Ratio: It is defined as the absolute value of ratio of differential gain $A_d$ to the common mode gain $A_C$. C.M.R.R is expressed in decibel.
The factor C.M.R.R is the ability of the differential amplifier to reject the common mode signals and to amplify only the differential signals.

If $A_d$ is the gain of the differential amplifier,

$$A_d = \frac{V_0}{V_1 - V_2} \quad \text{or} \quad V_0 = A_d(V_1 - V_2)$$

For an ideal differential amplifier, the differential gain is infinity and the common mode gain is zero.

Therefore, the common mode rejection ratio is infinity for an ideal differential amplifier.