Introduction to the Amplifier

An amplifier is an electronic device or circuit which is used to increase the magnitude of the signal applied to its input.

Amplifier is the generic term used to describe a circuit which produces and increased version of its input signal. However, not all amplifier circuits are the same as they are classified according to their circuit configurations and modes of operation.

In "Electronics", small signal amplifiers are commonly used devices as they have the ability to amplify a relatively small input signal, for example from a Sensor such as a photo-device, into a much larger output signal to drive a relay, lamp or loudspeaker for example.

There are many forms of electronic circuits classed as amplifiers, from Operational Amplifiers and Small Signal Amplifiers up to Large Signal and Power Amplifiers. The classification of an amplifier depends upon the size of the signal, large or small, its physical configuration and how it processes the input signal, that is the relationship between input signal and current flowing in the load.

The type or classification of an Amplifier is given in the following table.

### Classification of Signal Amplifier

<table>
<thead>
<tr>
<th>Type of Signal</th>
<th>Type of Configuration</th>
<th>Classification</th>
<th>Frequency of Operation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Small Signal</td>
<td>Common Emitter</td>
<td>Class A Amplifier</td>
<td>Direct Current (DC)</td>
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<tr>
<td>Large Signal</td>
<td>Common Base</td>
<td>Class B Amplifier</td>
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<td></td>
<td>Common Collector</td>
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<td></td>
<td></td>
<td>Class C Amplifier</td>
<td>VHF, UHF and SHF Frequencies</td>
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</tbody>
</table>

Amplifiers can be thought of as a simple box or block containing the amplifying device, such as a Bipolar Transistor, Field Effect Transistor or Operational Amplifier, which has two input terminals and two output terminals (ground being common) with the output signal being much greater than that of the input signal as it has been “Amplified”.

https://www.electronics-tutorials.ws/amplifier/amp_1.html
An ideal signal amplifier will have three main properties: Input Resistance or \( R_{\text{IN}} \), Output Resistance or \( R_{\text{OUT}} \) and of course amplification known commonly as Gain or \( A \). No matter how complicated an amplifier circuit is, a general amplifier model can still be used to show the relationship of these three properties.

**Ideal Amplifier Model**

The amplified difference between the input and output signals is known as the Gain of the amplifier. Gain is basically a measure of how much an amplifier “amplifies” the input signal. For example, if we have an input signal of 1 volt and an output of 50 volts, then the gain of the amplifier would be “50”. In other words, the input signal has been increased by a factor of 50. This increase is called Gain.

Amplifier gain is simply the ratio of the output divided-by the input. Gain has no units as its a ratio, but in Electronics it is commonly given the symbol “A”, for Amplification. Then the gain of an amplifier is simply calculated as the “output signal divided by the input signal”.

**Amplifier Gain**

The introduction to the amplifier gain can be said to be the relationship that exists between the signal measured at the output with the signal measured at the input. There are three different kinds of amplifier gain which can be measured and these are: Voltage Gain \( \left( A_v \right) \), Current Gain \( \left( A_i \right) \) and Power Gain \( \left( A_p \right) \) depending upon the quantity being measured with examples of these different types of gains are given below.

**Amplifier Gain of the Input Signal**

\[
\text{Gain} \ (A) = \frac{\text{Output}}{\text{Input}}
\]

**Voltage Amplifier Gain**

\[
\text{Voltage Gain} \ (A_v) = \frac{\text{Output Voltage}}{\text{Input Voltage}} = \frac{V_{out}}{V_{in}}
\]
Current Amplifier Gain

\[ Current\ Gain\ (A_i) = \frac{Output\ Current}{Input\ Current} = \frac{I_{out}}{I_{in}} \]

Power Amplifier Gain

\[ Power\ Gain\ (A_p) = A_v \times A_i \]

Note that for the Power Gain you can also divide the power obtained at the output with the power obtained at the input. Also when calculating the gain of an amplifier, the subscripts \(v\), \(i\) and \(p\) are used to denote the type of signal gain being used.

The power gain \((A_p)\) or power level of the amplifier can also be expressed in Decibels, \((dB)\). The Bel \((B)\) is a logarithmic unit (base 10) of measurement that has no units. Since the Bel is too large a unit of measure, it is prefixed with \textit{deci} making it Decibels instead with one decibel being one tenth \((1/10\text{th})\) of a Bel. To calculate the gain of the amplifier in Decibels or dB, we can use the following expressions.

\[ \text{Voltage Gain in dB: } a_v = 20 \times \log(Av) \]
\[ \text{Current Gain in dB: } a_i = 20 \times \log(Ai) \]
\[ \text{Power Gain in dB: } a_p = 10 \times \log(Ap) \]

Note that the DC power gain of an amplifier is equal to ten times the common log of the output to input ratio, where as voltage and current gains are 20 times the common log of the ratio. Note however, that 20dB is not twice as much power as 10dB because of the log scale.

Also, a positive value of dB represents a \textit{Gain} and a negative value of dB represents a \textit{Loss} within the amplifier. For example, an amplifier gain of +3dB indicates that the amplifiers output signal has “doubled”, \((x2)\) while an amplifier gain of -3dB indicates that the signal has “halved”, \((x0.5)\) or in other words a loss.

The -3dB point of an amplifier is called the \textbf{half-power point} which is -3dB down from maximum, taking 0dB as the maximum output value.

Amplifier Example No1

Determine the Voltage, Current and Power Gain of an amplifier that has an input signal of 1mA at 10mV and a corresponding output signal of 10mA at 1V. Also, express all three gains in decibels, \((dB)\).

The Various Amplifier Gains:
Amplifier Gains given in Decibels (dB):

\[ a_v = 20 \log A_v = 20 \log 100 = 40 \text{ dB} \]

\[ a_i = 20 \log A_i = 20 \log 10 = 20 \text{ dB} \]

\[ a_p = 10 \log A_p = 10 \log 1000 = 30 \text{ dB} \]

Then the amplifier has a Voltage Gain, \( A_v \) of 100, a Current Gain, \( A_i \) of 10 and a Power Gain, \( A_p \) of 1,000

Generally, amplifiers can be sub-divided into two distinct types depending upon their power or voltage gain. One type is called the **Small Signal Amplifier** which include pre-amplifiers, instrumentation amplifiers etc. Small signal amplifies are designed to amplify very small signal voltage levels of only a few micro-volts (μV) from sensors or audio signals.

The other type are called **Large Signal Amplifiers** such as audio power amplifiers or power switching amplifiers. Large signal amplifiers are designed to amplify large input voltage signals or switch heavy load currents as you would find driving loudspeakers.

### Power Amplifiers

The **Small Signal Amplifier** is generally referred to as a “Voltage” amplifier because they usually convert a small input voltage into a much larger output voltage. Sometimes an amplifier circuit is required to drive a motor or feed a loudspeaker and for these types of applications where high switching currents are needed **Power Amplifiers** are required.

As their name suggests, the main job of a “Power Amplifier” (also known as a large signal amplifier), is to deliver power to the load, and as we know from above, is the product of the voltage and current applied to the load with the output signal power being greater than the input signal power. In other words, a power amplifier amplifies the power of the input signal which is why these types of amplifier circuits are used in audio amplifier output stages to drive loudspeakers.

The power amplifier works on the basic principle of converting the DC power drawn from the power supply into an AC voltage signal delivered to the load. Although the amplification is high the efficiency of the conversion from the DC power supply input to the AC voltage signal output is usually poor.

The perfect or ideal amplifier would give us an efficiency rating of 100% or at least the power “IN” would be equal to the power “OUT”. However, in reality this can never happen as some of the power is lost in the form of heat and also, the amplifier itself consumes power during the amplification.
process. Then the efficiency of an amplifier is given as:

**Amplifier Efficiency**

\[
\text{Efficiency} \ (\eta) = \frac{\text{Power delivered to the Load}}{\text{Power taken from the Supply}} = \frac{P_{\text{OUT}}}{P_{\text{IN}}}
\]

**Ideal Amplifier**

We can know specify the characteristics for an ideal amplifier from our discussion above with regards to its **Gain**, meaning voltage gain:

- The amplifiers gain, \( A \) should remain constant for varying values of input signal.
- Gain is not be affected by frequency. Signals of all frequencies must be amplified by exactly the same amount.
- The amplifiers gain must not add noise to the output signal. It should remove any noise that is already exists in the input signal.
- The amplifiers gain should not be affected by changes in temperature giving good temperature stability.
- The gain of the amplifier must remain stable over long periods of time.

**Electronic Amplifier Classes**

The classification of an amplifier as either a voltage or a power amplifier is made by comparing the characteristics of the input and output signals by measuring the amount of time in relation to the input signal that the current flows in the output circuit.

We saw in the *Common Emitter Transistor* tutorial that for the transistor to operate within its “Active Region” some form of “Base Biasing” was required. This small Base Bias voltage added to the input signal allowed the transistor to reproduce the full input waveform at its output with no loss of signal.

However, by altering the position of this Base bias voltage, it is possible to operate an amplifier in an amplification mode other than that for full waveform reproduction. With the introduction to the amplifier of a Base bias voltage, different operating ranges and modes of operation can be obtained which are categorized according to their classification. These various mode of operation are better known as **Amplifier Class**.

Audio power amplifiers are classified in an alphabetical order according to their circuit configurations and mode of operation. Amplifiers are designated by different classes of operation such as class “A”, class “B”, class “C”, class “AB”, etc. These different amplifier classes range from a near linear output but with low efficiency to a non-linear output but with a high efficiency.

No one class of operation is “better” or “worse” than any other class with the type of operation being determined by the use of the amplifying circuit. There are typical maximum conversion efficiencies for the various types or class of amplifier, with the most commonly used being:

- **Class A Amplifier** – has low efficiency of less than 40% but good signal reproduction and linearity.
- **Class B Amplifier** – is twice as efficient as class A amplifiers with a maximum theoretical efficiency of about 70% because the amplifying device only conducts (and uses power) for half of the input signal.

- **Class AB Amplifier** – has an efficiency rating between that of Class A and Class B but poorer signal reproduction than Class A amplifiers.

- **Class C Amplifier** – is the most efficient amplifier class but distortion is very high as only a small portion of the input signal is amplified therefore the output signal bears very little resemblance to the input signal. Class C amplifiers have the worst signal reproduction.

### Class A Amplifier Operation

**Class A Amplifier** operation is where the entire input signal waveform is faithfully reproduced at the amplifiers output terminal as the transistor is perfectly biased within its active region. This means that the switching transistor is never driven into its cut-off or saturation regions. The result is that the AC input signal is perfectly “centred” between the amplifiers upper and lower signal limits as shown below.

#### Class A Amplifier Output Waveform

A Class-A amplifier configuration uses the same switching transistor for both halves of the output waveform and due to its central biasing arrangement, the output transistor always has a constant DC biasing current, \(I_{CQ}\) flowing through it, even if there is no input signal present. In other words the output transistors never turns “OFF” and is in a permenant state of idle.

This results in the Class-A type of operation being somewhat inefficient as its conversion of the DC supply power to the AC signal power delivered to the load is usually very low.

Due to this centered biasing point, the output transistor of a Class-A amplifier can get very hot, even when there is no input signal present, so some form of heat sinking is required. The DC biasing current flowing through the collector of the transistor \(I_{CQ}\) is equal to the current flowing through the collector load. Thus a Class-A amplifier is very inefficient as most of this DC power is converted to heat.
Class B Amplifier Operation

Unlike the Class-A amplifier mode of operation above that uses a single transistor for its output power stage, the **Class-B Amplifier** uses two complimentary transistors (either an NPN and a PNP or a NMOS and a PMOS) to amplify each half of the output waveform.

One transistor conducts for only one-half of the signal waveform while the other conducts for the other or opposite half of the signal waveform. This means that each transistor spends half of its time in the active region and half its time in the cut-off region thereby amplifying only 50% of the input signal.

Class-B operation has no direct DC bias voltage unlike the class-A amplifier, but instead the transistor only conducts when the input signal is greater than the base-emitter voltage ($V_{BE}$) and for silicon transistors, this is about 0.7v. Therefore with zero input signal there is zero output. As only half the input signal is presented at the amplifiers output this improves the amplifier efficiency over the previous Class-A configuration as shown below.

Class B Amplifier Output Waveform

![Class B Amplifier Output Waveform](https://www.electronics-tutorials.ws/amplifier/amp_1.html)

In a Class-B amplifier, no DC voltage is used to bias the transistors, so for the output transistors to start to conduct each half of the waveform, both positive and negative, they need the base-emitter voltage $V_{BE}$ to be greater than the 0.7v forward voltage drop required for a standard bipolar transistor to start conducting.

Thus the lower part of the output waveform which is below this 0.7v window will not be reproduced accurately. This results in a distorted area of the output waveform as one transistor turns “OFF” waiting for the other to turn back “ON” once $V_{BE} > 0.7V$. The result is that there is a small part of the output waveform at the zero voltage cross over point which will be distorted. This type of distortion is called **Crossover Distortion** and is looked at later on in this section.

Class AB Amplifier Operation

The **Class-AB Amplifier** is a compromise between the Class-A and the Class-B configurations above. While Class-AB operation still uses two complementary transistors in its output stage a very small biasing voltage is applied to the Base of each transistor to bias them close to their cut-off region when no input signal is present.
An input signal will cause the transistor to operate as normal within its active region, eliminating any crossover distortion which is always present in the class-B configuration. A small biasing Collector current ($I_{CQ}$) will flow through the transistor when there is no input signal present, but generally it is much less than that for the Class-A amplifier configuration.

Thus each transistor is conducting, “ON” for a little more than half a cycle of the input waveform. The small biasing of the Class-AB amplifier configuration improves both the efficiency and linearity of the amplifier circuit compared to a pure Class-A configuration above.

**Class AB Amplifier Output Waveform**

![Class AB Amplifier Output Waveform Diagram]

When designing amplifier circuits, the class of operation of an amplifier is very important as it determines the amount of transistor biasing required for its operation as well as the maximum amplitude of the input signal.

Amplifier classification takes into account the portion of the input signal in which the output transistor conducts as well as determining both the efficiency and the amount of power that the switching transistor both consumes and dissipates in the form of wasted heat. Here we can make a comparison between the most common types of amplifier classifications in the following table.

### Power Amplifier Classes

<table>
<thead>
<tr>
<th>Class</th>
<th>A</th>
<th>B</th>
<th>C</th>
<th>AB</th>
</tr>
</thead>
<tbody>
<tr>
<td>Conduction Angle</td>
<td>360°</td>
<td>180°</td>
<td>Less than 90°</td>
<td>180 to 360°</td>
</tr>
<tr>
<td>Position of the Q-point</td>
<td>Centre Point of the Load Line</td>
<td>Exactly on the X-axis</td>
<td>Below the X-axis</td>
<td>In between the X-axis and the Centre Load Line</td>
</tr>
<tr>
<td>Overall Efficiency</td>
<td>Poor 25 to 30%</td>
<td>Better 70 to 80%</td>
<td>Higher than 80%</td>
<td>Better than A but less than B 50 to 70%</td>
</tr>
</tbody>
</table>
Badly designed amplifiers especially the Class “A” types may also require larger power transistors, more expensive heat sinks, cooling fans, or even an increase in the size of the power supply required to deliver the extra wasted power required by the amplifier. Power converted into heat from transistors, resistors or any other component for that matter, makes any electronic circuit inefficient and will result in the premature failure of the device.

So why use a Class A amplifier if its efficiency is less than 40% compared to a Class B amplifier that has a higher efficiency rating of over 70%. Basically, a Class A amplifier gives a much more linear output meaning that it has, **Linearity** over a larger frequency response even if it does consume large amounts of DC power.

In this **Introduction to the Amplifier** tutorial, we have seen that there are different types of amplifier circuit each with its own advantages and disadvantages. In the next tutorial about amplifiers, we will look at the most commonly connected type of transistor amplifier circuit, the common emitter amplifier. Most transistor amplifiers are of the Common Emitter or CE type circuit due to their large gains in voltage, current and power as well as their excellent input/output characteristics.
Common Emitter Amplifier

The most common amplifier configuration for an NPN transistor is that of the Common Emitter Amplifier circuit.

In the previous introduction to the amplifier tutorial, we saw that a family of curves known commonly as the **Output Characteristic Curves**, relate the transistors Collector Current \(I_c\), to its Collector Voltage \(V_{ce}\) for different values of the transistors Base Current \(I_b\).

All types of transistor amplifiers operate using AC signal inputs which alternate between a positive value and a negative value so some way of “presetting” the amplifier circuit to operate between these two maximum or peak values is required. This is achieved using a process known as **Biasing**. Biasing is very important in amplifier design as it establishes the correct operating point of the transistor amplifier ready to receive signals, thereby reducing any distortion to the output signal.

We also saw that a static or DC load line can be drawn onto these output characteristics curves to show all the possible operating points of the transistor from fully “ON” to fully “OFF”, and to which the quiescent operating point or **Q-point** of the amplifier can be found.

The aim of any small signal amplifier is to amplify all of the input signal with the minimum amount of distortion possible to the output signal, in other words, the output signal must be an exact reproduction of the input signal but only bigger (amplified).

To obtain low distortion when used as an amplifier the operating quiescent point needs to be correctly selected. This is in fact the DC operating point of the amplifier and its position may be established at any point along the load line by a suitable biasing arrangement.

The best possible position for this Q-point is as close to the center position of the load line as reasonably possible, thereby producing a Class A type amplifier operation, i.e. \(V_{ce} = \frac{1}{2}V_{cc}\). Consider the **Common Emitter Amplifier** circuit shown below.
The single stage common emitter amplifier circuit shown above uses what is commonly called “Voltage Divider Biasing”. This type of biasing arrangement uses two resistors as a potential divider network across the supply with their center point supplying the required Base bias voltage to the transistor. Voltage divider biasing is commonly used in the design of bipolar transistor amplifier circuits.

This method of biasing the transistor greatly reduces the effects of varying Beta, (β) by holding the Base bias at a constant steady voltage level allowing for best stability. The quiescent Base voltage (Vb) is determined by the potential divider network formed by the two resistors, R1, R2 and the power supply voltage Vcc as shown with the current flowing through both resistors.

Then the total resistance R_T will be equal to R1 + R2 giving the current as i = Vcc/R_T. The voltage level generated at the junction of resistors R1 and R2 holds the Base voltage (Vb) constant at a value below the supply voltage.

Then the potential divider network used in the common emitter amplifier circuit divides the supply voltage in proportion to the resistance. This bias reference voltage can be easily calculated using the simple voltage divider formula below:

**Transistor Bias Voltage**

\[ V_B = \frac{V_{CC} \cdot R_2}{R_1 + R_2} \]
The same supply voltage, \(V_{cc}\) also determines the maximum Collector current, \(I_c\) when the transistor is switched fully “ON” (saturation), \(V_{ce} = 0\). The Base current \(I_b\) for the transistor is found from the Collector current, \(I_c\) and the DC current gain Beta, \(\beta\) of the transistor.

**Beta Value**

\[
\beta = \frac{\Delta I_C}{\Delta I_B}
\]

Beta is sometimes referred to as \(h_{FE}\) which is the transistors forward current gain in the common emitter configuration. Beta has no units as it is a fixed ratio of the two currents, \(I_c\) and \(I_b\) so a small change in the Base current will cause a large change in the Collector current.

One final point about Beta. Transistors of the same type and part number will have large variations in their Beta value. For example, the *BC107 NPN Bipolar transistor* has a DC current gain Beta value of between 110 and 450 (data sheet value). So one BC107 may have a Beta value of 110, while another one may have a Beta value of 450, but they are both BC107 npn transistors. This is because Beta is a characteristic of the transistors construction and not of its operation.

As the Base/Emitter junction is forward-biased, the Emitter voltage, \(V_e\) will be one junction voltage drop different to the Base voltage. If the voltage across the Emitter resistor is known then the Emitter current, \(I_e\) can be easily calculated using Ohm’s Law. The Collector current, \(I_c\) can be approximated, since it is almost the same value as the Emitter current.

**Common Emitter Amplifier Example No1**

An common emitter amplifier circuit has a load resistance, \(R_L\) of 1.2kΩ and a supply voltage of 12v. Calculate the maximum Collector current (\(I_c\)) flowing through the load resistor when the transistor is switched fully “ON” (saturation), assume \(V_{ce} = 0\). Also find the value of the Emitter resistor, \(R_E\) if it has a voltage drop of 1v across it. Calculate the values of all the other circuit resistors assuming a standard NPN silicon transistor.

\[
I_{C(MAX)} = \frac{V_{CC} - V_{RE}}{R_L} = \frac{12 - 1}{1200} = 9.2\ mA
\]

\(V_{CE} = 0\) (Saturation)

This then establishes point “A” on the Collector current vertical axis of the characteristics curves and occurs when \(V_{ce} = 0\). When the transistor is switched fully “OFF”, their is no voltage drop across either resistor \(R_E\) or \(R_L\) as no current is flowing through them. Then the voltage drop across the transistor, \(V_{ce}\) is equal to the supply voltage, \(V_{cc}\). This establishes point “B” on the horizontal axis of the characteristics curves.
Generally, the quiescent Q-point of the amplifier is with zero input signal applied to the Base, so the Collector sits about half-way along the load line between zero volts and the supply voltage, \((V_{cc}/2)\). Therefore, the Collector current at the Q-point of the amplifier will be given as:

\[
I_{c(Q)} = \frac{12-1}{2} = \frac{5.5}{1200} = 4.58 \text{mA}
\]

This static DC load line produces a straight line equation whose slope is given as: \(-1/(R_L + R_E)\) and that it crosses the vertical \(I_c\) axis at a point equal to \(V_{cc}/(R_L + R_E)\). The actual position of the Q-point on the DC load line is determined by the mean value of \(I_b\).

As the Collector current, \(I_C\) of the transistor is also equal to the DC gain of the transistor (Beta), times the Base current \(\beta I_b\), if we assume a Beta \(\beta\) value for the transistor of say 100, (one hundred is a reasonable average value for low power signal transistors) the Base current \(I_b\) flowing into the transistor will be given as:

\[
\beta = \frac{I_C}{I_B}
\]

\[
\therefore I_B = \frac{I_C}{\beta} = \frac{4.58 \text{mA}}{100} = 45.8 \mu\text{A}
\]

Instead of using a separate Base bias supply, it is usual to provide the Base Bias Voltage from the main supply rail \((V_{cc})\) through a dropping resistor, \(R_1\). Resistors, \(R_1\) and \(R_2\) can now be chosen to give a suitable quiescent Base current of 45.8\(\mu\)A or 46\(\mu\)A rounded off to the nearest integer. The current flowing through the potential divider circuit has to be large compared to the actual Base current, \(I_b\), so that the voltage divider network is not loaded by the Base current flow.

A general rule of thumb is a value of at least 10 times \(I_b\) flowing through the resistor \(R_2\). Transistor Base/Emitter voltage, \(V_{be}\) is fixed at 0.7V (silicon transistor) then this gives the value of \(R_2\) as:

\[
R_2 = \frac{V_{(RE)} + V_{(BE)}}{10 \times I_B} = \frac{1 + 0.7}{458 \times 10^{-6}} = 3.71 \text{k}\Omega
\]

If the current flowing through resistor \(R_2\) is 10 times the value of the Base current, then the current flowing through resistor \(R_1\) in the divider network must be 11 times the value of the Base current. That is: \(I_{R2} + I_b\).

Thus the voltage across resistor \(R_1\) is equal to \(V_{cc} - 1.7V\) \((V_{RE} + 0.7\) for silicon transistor) which is equal to 10.3V, therefore \(R_1\) can be calculated as:
The value of the Emitter resistor, $R_E$ can be easily calculated using Ohm’s Law. The current flowing through $R_E$ is a combination of the Base current, $I_B$ and the Collector current $I_C$ and is given as:

$$I_E = I_C + I_B = 4.58\,mA + 45.8\,\mu\,A = 4.63\,mA$$

Resistor, $R_E$ is connected between the transistors Emitter terminal and ground, and we said previously that there is a voltage drop of 1 volt across it. Thus the value of the Emitter resistor, $R_E$ is calculated as:

$$R_E = \frac{V_{RE}}{I_E} = \frac{1\,v}{4.63\,mA} = 216\,\Omega$$

So, for our example above, the preferred values of the resistors chosen to give a tolerance of 5% (E24) are:

$$R_1 = 20\,k\,\Omega, \quad R_2 = 3.6\,k\,\Omega, \quad R_L = 1.2\,k\,\Omega, \quad R_E = 220\,\Omega$$

Then, our original Common Emitter Amplifier circuit above can be rewritten to include the values of the components that we have just calculated above.

**Completed Common Emitter Circuit**
Amplifier Coupling Capacitors

In Common Emitter Amplifier circuits, capacitors C1 and C2 are used as Coupling Capacitors to separate the AC signals from the DC biasing voltage. This ensures that the bias condition set up for the circuit to operate correctly is not affected by any additional amplifier stages, as the capacitors will only pass AC signals and block any DC component. The output AC signal is then superimposed on the biasing of the following stages. Also a bypass capacitor, $C_E$ is included in the Emitter leg circuit.

This capacitor is effectively an open circuit component for DC biasing conditions, which means that the biasing currents and voltages are not affected by the addition of the capacitor maintaining a good Q-point stability.

However, this parallel connected bypass capacitor effectively becomes a short circuit to the Emitter resistor at high frequency signals due to its reactance. Thus only $R_L$ plus a very small internal resistance acts as the transistors load increasing voltage gain to its maximum. Generally, the value of the bypass capacitor, $C_E$ is chosen to provide a reactance of at most, $1/10$th the value of $R_E$ at the lowest operating signal frequency.

Output Characteristics Curves

Ok, so far so good. We can now construct a series of curves that show the Collector current, $I_c$ against the Collector/Emitter voltage, $V_{ce}$ with different values of Base current, $I_b$ for our simple common emitter amplifier circuit.

These curves are known as the “Output Characteristic Curves” and are used to show how the transistor will operate over its dynamic range. A static or DC load line is drawn onto the curves for the load resistor $R_L$ of $1.2\, \text{k}\Omega$ to show all the transistors possible operating points.

When the transistor is switched “OFF”, $V_{ce}$ equals the supply voltage $V_{cc}$ and this is point “B” on the line. Likewise when the transistor is fully “ON” and saturated the Collector current is determined by the load resistor, $R_L$ and this is point “A” on the line.

We calculated before from the DC gain of the transistor that the Base current required for the mean position of the transistor was $45.8\, \mu\text{A}$ and this is marked as point $Q$ on the load line which represents the Quiescent point or Q-point of the amplifier. We could quite easily make life easy for ourselves and round off this value to $50\, \mu\text{A}$ exactly, without any effect to the operating point.
Point Q on the load line gives us the Base current Q-point of $I_b = 45.8\, \mu A$ or $46\, \mu A$. We need to find the maximum and minimum peak swings of Base current that will result in a proportional change to the Collector current, $I_c$ without any distortion to the output signal.

As the load line cuts through the different Base current values on the DC characteristics curves we can find the peak swings of Base current that are equally spaced along the load line. These values are marked as points “N” and “M” on the line, giving a minimum and a maximum Base current of $20\, \mu A$ and $80\, \mu A$ respectively.

These points, “N” and “M” can be anywhere along the load line that we choose as long as they are equally spaced from Q. This then gives us a theoretical maximum input signal to the Base terminal of $60\, \mu A$ peak-to-peak, $(30\, \mu A$ peak) without producing any distortion to the output signal.

Any input signal giving a Base current greater than this value will drive the transistor to go beyond point “N” and into its “cut-off” region or beyond point “M” and into its Saturation region thereby resulting in distortion to the output signal in the form of “clipping”.

Using points “N” and “M” as an example, the instantaneous values of Collector current and corresponding values of Collector-emitter voltage can be projected from the load line. It can be seen that the Collector-emitter voltage is in anti-phase (−180°) with the collector current.

As the Base current $I_b$ changes in a positive direction from $50\, \mu A$ to $80\, \mu A$, the Collector-emitter voltage, which is also the output voltage decreases from its steady state value of 5.8 volts to 2.0 volts.
Then a single stage **Common Emitter Amplifier** is also an “Inverting Amplifier” as an increase in Base voltage causes a decrease in Vout and a decrease in Base voltage produces an increase in Vout. In other words the output signal is 180° out-of-phase with the input signal.

**Common Emitter Voltage Gain**

The **Voltage Gain** of the common emitter amplifier is equal to the ratio of the change in the input voltage to the change in the amplifier’s output voltage. Then $\Delta V_L$ is Vout and $\Delta V_B$ is Vin. But voltage gain is also equal to the ratio of the signal resistance in the Collector to the signal resistance in the Emitter and is given as:

$$\text{Voltage Gain} = \frac{V_{out}}{V_{in}} = \frac{\Delta V_L}{\Delta V_B} = \frac{R_L}{R_E}$$

We mentioned earlier that as the signal frequency increases the bypass capacitor, $C_E$ starts to short out the Emitter resistor due to its reactance. Then at high frequencies $R_E = 0$, making the gain infinite.

However, bipolar transistors have a small internal resistance built into their Emitter region called $R_E$. The transistors semiconductor material offers an internal resistance to the flow of current through it and is generally represented by a small resistor symbol shown inside the main transistor symbol.

Transistor data sheets tell us that for a small signal bipolar transistors this internal resistance is the product of $25\text{mV} \div I_E$ ($25\text{mV}$ being the internal volt drop across the Emitter junction layer), then for our common Emitter amplifier circuit above this resistance value will be equal to:

$$R_E = \frac{25\text{mV}}{I_E} = \frac{25\text{mV}}{4.58\text{mA}} = 5.5\Omega$$

This internal Emitter leg resistance will be in series with the external Emitter resistor, $R_E$, then the equation for the transistor’s actual gain will be modified to include this internal resistance so will be:

$$\text{Voltage Gain} = -\frac{R_L}{(R_E + R_E)}$$

At low frequency signals the total resistance in the Emitter leg is equal to $R_E + R_E$. At high frequency, the bypass capacitor shorts out the Emitter resistor leaving only the internal resistance $R_E$ in the Emitter leg resulting in a high gain. Then for our common emitter amplifier circuit above, the gain of the circuit at both low and high signal frequencies is given as:

**Gain at Low Frequencies**
Gain at High Frequencies

\[
\text{Gain} = -\frac{R_L}{R_e} = -\frac{1200}{5.5} = -218
\]

One final point, the voltage gain is dependent only on the values of the Collector resistor, \( R_L \) and the Emitter resistance, \( R_e \), it is not affected by the current gain Beta, \( \beta (h_{FE}) \) of the transistor.

So, for our simple example above we can now summarise all the values we have calculated for our common emitter amplifier circuit and these are:

<table>
<thead>
<tr>
<th></th>
<th>Minimum</th>
<th>Mean</th>
<th>Maximum</th>
</tr>
</thead>
<tbody>
<tr>
<td>Base Current</td>
<td>20(\mu)A</td>
<td>50(\mu)A</td>
<td>80(\mu)A</td>
</tr>
<tr>
<td>Collector Current</td>
<td>2.0mA</td>
<td>4.8mA</td>
<td>7.7mA</td>
</tr>
<tr>
<td>Output Voltage Swing</td>
<td>2.0V</td>
<td>5.8V</td>
<td>9.3V</td>
</tr>
<tr>
<td>Amplifier Gain</td>
<td>-5.32</td>
<td></td>
<td>-218</td>
</tr>
</tbody>
</table>

Common Emitter Amplifier Summary

Then to summarise. The **Common Emitter Amplifier** circuit has a resistor in its Collector circuit. The current flowing through this resistor produces the voltage output of the amplifier. The value of this resistor is chosen so that at the amplifiers quiescent operating point, **Q-point** this output voltage lies half way along the transistors load line.

The Base of the transistor used in a common emitter amplifier is biased using two resistors as a potential divider network. This type of biasing arrangement is commonly used in the design of bipolar transistor amplifier circuits and greatly reduces the effects of varying Beta, \( \beta (h_{FE}) \) by holding the Base bias at a constant steady voltage. This type of biasing produces the greatest stability.

A resistor can be included in the emitter leg in which case the voltage gain becomes \(-R_L/R_e\). If there is no external Emitter resistance, the voltage gain of the amplifier is not infinite as there is a very small internal resistance, \( R_e \) in the Emitter leg. The value of this internal resistance is equal to \(25mV/I_E\)

In the next tutorial about transistor amplifiers we will look at the Junction Field Effect Amplifier commonly called the JFET Amplifier. Like the transistor, the JFET is used in a single stage amplifier circuit making it easier to understand. There are several different kinds of field effect transistor that we could use but the easiest to understand is the junction field effect transistor, or JFET which has a very high input impedance making it ideal for amplifier circuits.
Common Source JFET Amplifier

Common Source JFET Amplifier uses junction field effect transistors as its main active device offering high input impedance characteristics.

Transistor amplifier circuits such as the common emitter amplifier are made using Bipolar Transistors, but small signal amplifiers can also be made using Field Effect Transistors. These devices have the advantage over bipolar transistors of having an extremely high input impedance along with a low noise output making them ideal for use in amplifier circuits that have very small input signals.

The design of an amplifier circuit based around a junction field effect transistor or “JFET”, (N-channel FET for this tutorial) or even a metal oxide silicon FET or “MOSFET” is exactly the same principle as that for the bipolar transistor circuit used for a Class A amplifier circuit we looked at in the previous tutorial.

Firstly, a suitable quiescent point or “Q-point” needs to be found for the correct biasing of the JFET amplifier circuit with single amplifier configurations of Common-source (CS), Common-drain (CD) or Source-follower (SF) and the Common-gate (CG) available for most FET devices.

These three JFET amplifier configurations correspond to the common-emitter, emitter-follower and the common-base configurations using bipolar transistors. In this tutorial about FET amplifiers we will look at the popular Common Source JFET Amplifier as this is the most widely used JFET amplifier design.

Consider the Common Source JFET Amplifier circuit configuration below.

Common Source JFET Amplifier
The amplifier circuit consists of an N-channel JFET, but the device could also be an equivalent N-channel depletion-mode MOSFET as the circuit diagram would be the same just a change in the FET, connected in a common source configuration. The JFET gate voltage $V_g$ is biased through the potential divider network set up by resistors $R_1$ and $R_2$ and is biased to operate within its saturation region which is equivalent to the active region of the bipolar junction transistor.

Unlike a bipolar transistor circuit, the junction FET takes virtually no input gate current allowing the gate to be treated as an open circuit. Then no input characteristics curves are required. We can compare the JFET to the bipolar junction transistor (BJT) in the following table.

### JFET to BJT Comparison

<table>
<thead>
<tr>
<th>Junction FET</th>
<th>Bipolar Transistor</th>
</tr>
</thead>
<tbody>
<tr>
<td>Gate, (G)</td>
<td>Base, (B)</td>
</tr>
<tr>
<td>Drain, (D)</td>
<td>Collector, (C)</td>
</tr>
<tr>
<td>Source, (S)</td>
<td>Emitter, (E)</td>
</tr>
<tr>
<td>Gate Supply, ($V_G$)</td>
<td>Base Supply, ($V_B$)</td>
</tr>
<tr>
<td>Drain Supply, ($V_{DD}$)</td>
<td>Collector Supply, ($V_{CC}$)</td>
</tr>
<tr>
<td>Drain Current, ($I_D$)</td>
<td>Collector Current, ($I_C$)</td>
</tr>
</tbody>
</table>

Since the N-Channel JFET is a depletion mode device and is normally “ON”, a negative gate voltage with respect to the source is required to modulate or control the drain current. This negative voltage can be provided by biasing from a separate power supply voltage or by a self biasing arrangement as long as a steady current flows through the JFET even when there is no input signal present and $V_g$ maintains a reverse bias of the gate-source pn junction.

In our simple example, the biasing is provided from a potential divider network allowing the input signal to produce a voltage fall at the gate as well as voltage rise at the gate with a sinusoidal signal. Any suitable pair of resistor values in the correct proportions would produce the correct biasing voltage so the DC gate biasing voltage $V_g$ is given as:

\[ V_G = \frac{V_{DD} R_2}{R_1 + R_2} = V_{DD} \left( \frac{R_2}{R_1 + R_2} \right) \]

Note that this equation only determines the ratio of the resistors R1 and R2, but in order to take advantage of the very high input impedance of the JFET as well as reducing the power dissipation within the circuit, we need to make these resistor values as high as possible, with values in the order of 1MΩ to 10MΩ being common.

The input signal, \( V_{in} \) of the common source JFET amplifier is applied between the Gate terminal and the zero volts rail, (0v). With a constant value of gate voltage \( V_g \) applied the JFET operates within its “Ohmic region” acting like a linear resistive device. The drain circuit contains the load resistor, \( R_d \). The output voltage, \( V_{out} \) is developed across this load resistance.

The efficiency of the common source JFET amplifier can be improved by the addition of a resistor, \( R_s \) included in the source lead with the same drain current flowing through this resistor. Resistor, \( R_s \) is also used to set the JFET amplifiers “Q-point”.

When the JFET is switched fully “ON” a voltage drop equal to \( R_s \times I_d \) is developed across this resistor raising the potential of the source terminal above 0v or ground level. This voltage drop across \( R_s \) due to the drain current provides the necessary reverse biasing condition across the gate resistor, \( R_2 \) effectively generating negative feedback.

So in order to keep the gate-source junction reverse biased, the source voltage, \( V_s \) needs to be higher than the gate voltage, \( V_g \). This source voltage is therefore given as:

\[ V_s = I_D \times R_s = V_g - V_{GS} \]

Then the Drain current, \( I_d \) is also equal to the Source current, \( I_s \) as “No Current” enters the Gate terminal and this can be given as:

\[ I_D = \frac{V_s}{R_s} = \frac{V_{DD}}{R_D + R_s} \]

This potential divider biasing circuit improves the stability of the common source JFET amplifier circuit when being fed from a single DC supply compared to that of a fixed voltage biasing circuit. Both \( R_s \) and the source by-pass capacitor, \( C_s \) serve basically the same function as the emitter resistor and capacitor in the common emitter bipolar transistor amplifier circuit, namely to provide good stability and prevent a reduction in the loss of the voltage gain. However, the price paid for a stabilized quiescent gate voltage is that more of the supply voltage is dropped across \( R_s \).

The value in farads of the source by-pass capacitor is generally fairly high above 100μF and will be polarized. This gives the capacitor an impedance value much smaller, less than 10% of the transconductance, \( g_m \) (the transfer coefficient representing gain) value of the device. At high frequencies the by-pass capacitor acts essentially as a short-circuit and the source will be effectively connected directly to ground.
The basic circuit and characteristics of a **Common Source JFET Amplifier** are very similar to that of the common emitter amplifier. A DC load line is constructed by joining the two points relating to the drain current, \( I_d \) and the supply voltage, \( V_{dd} \) remembering that when \( I_d = 0 \): ( \( V_{dd} = V_{ds} \)) and when \( V_{ds} = 0 \): ( \( I_d = V_{dd}/R_L \)). The load line is therefore the intersection of the curves at the Q-point as follows.

**Common Source JFET Amplifier Characteristics Curves**

As with the common emitter bipolar circuit, the DC load line for the common source JFET amplifier produces a straight line equation whose gradient is given as: -1/(\( R_d + R_s \)) and that it crosses the vertical \( I_d \) axis at point A equal to \( V_{dd}/(R_d + R_s) \). The other end of the load line crosses the horizontal axis at point B which is equal to the supply voltage, \( V_{dd} \).

The actual position of the Q-point on the DC load line is generally positioned at the mid center point of the load line (for class-A operation) and is determined by the mean value of \( V_g \) which is biased negatively as the JFET is a depletion-mode device. Like the bipolar common emitter amplifier the output of the **Common Source JFET Amplifier** is 180° out of phase with the input signal.

One of the main disadvantages of using Depletion-mode JFET is that they need to be negatively biased. Should this bias fail for any reason the gate-source voltage may rise and become positive causing an increase in drain current resulting in failure of the drain voltage, \( V_d \).
Also the high channel resistance, $R_{ds(on)}$ of the junction FET, coupled with high quiescent steady state drain current makes these devices run hot so additional heatsink is required. However, most of the problems associated with using JFET's can be greatly reduced by using enhancement-mode MOSFET devices instead.

MOSFET's or Metal Oxide Semiconductor FET's have much higher input impedance's and low channel resistances compared to the equivalent JFET. Also the biasing arrangements for MOSFETs are different and unless we bias them positively for N-channel devices and negatively for P-channel devices no drain current will flow, then we have in effect a fail safe transistor.

### JFET Amplifier Current and Power Gains

We said previously that the input current, $I_g$ of a common source JFET amplifier is very small because of the extremely high gate impedance, $R_g$. A common source JFET amplifier therefore has a very good ratio between its input and output impedances and for any amount of output current, $I_{OUT}$ the JFET amplifier will have very high current gain $A_i$.

Because of this common source JFET amplifiers are extremely valuable as impedance matching circuits or are used as voltage amplifiers. Likewise, because: Power = Voltage x Current, $(P = V^I)$ and output voltages are usually several millivolts or even volts, the power gain, $A_p$ is also very high.

In the next tutorial we will look at how the incorrect biasing of the transistor amplifier can cause Distortion to the output signal in the form of amplitude distortion due to clipping and as well as the effect of phase and frequency distortion.
Amplifier Distortion

Amplifier Distortion can take on many forms such as Amplitude, Frequency and Phase Distortion due to Clipping

For a signal amplifier to operate correctly without any distortion to the output signal, it requires some form of DC Bias on its Base or Gate terminal. A DC bias is required so that the amplifier can amplify the input signal over its entire cycle with the bias “Q-point” set as near to the middle of the load line as possible.

The bias Q-point setting will give us a “Class-A” type amplification configuration with the most common arrangement being the “Common Emitter” for Bipolar transistors or the “Common Source” configuration for unipolar FET transistors.

The Power, Voltage or Current Gain, (amplification) provided by the amplifier is the ratio of the peak output value to its peak input value (Output ÷ Input).

However, if we incorrectly design our amplifier circuit and set the biasing Q-point at the wrong position on the load line or apply too large an input signal to the amplifier, the resultant output signal may not be an exact reproduction of the original input signal waveform. In other words the amplifier will suffer from what is commonly called Amplifier Distortion. Consider the common emitter amplifier circuit below.

Common Emitter Amplifier
Distortion of the output signal waveform may occur because:

- Amplification may not be taking place over the whole signal cycle due to incorrect biasing levels.
- The input signal may be too large, causing the amplifiers transistors to be limited by the supply voltage.
- The amplification may not be a linear signal over the entire frequency range of inputs.

This means then that during the amplification process of the signal waveform, some form of Amplifier Distortion has occurred.

Amplifiers are basically designed to amplify small voltage input signals into much larger output signals and this means that the output signal is constantly changing by some factor or value, called gain, multiplied by the input signal for all input frequencies. We saw previously that this multiplication factor is called the Beta, $\beta$ value of the transistor.

Common emitter or even common source type transistor circuits work fine for small AC input signals but suffer from one major disadvantage, the calculated position of the bias Q-point of a bipolar amplifier depends on the same Beta value for all transistors. However, this Beta value will vary from transistors of the same type, in other words, the Q-point for one transistor is not necessarily the same as the Q-point for another transistor of the same type due to the inherent manufacturing tolerances.

Then amplifier distortion occurs because the amplifier is not linear and a type of amplifier distortion called Amplitude Distortion will result. Careful choice of the transistor and biasing components can help minimise the effect of amplifier distortion.

**Amplitude Distortion**

Amplitude distortion occurs when the peak values of the frequency waveform are attenuated causing distortion due to a shift in the Q-point and amplification may not take place over the whole signal cycle. This non-linearity of the output waveform is shown below.

**Amplitude Distortion due to Incorrect Biasing**
If the transistors biasing point is correct, the output waveform should have the same shape as that of the input waveform only bigger, (amplified). If there is insufficient bias and the Q-point lies in the lower half of the load line, then the output waveform will look like the one on the right with the negative half of the output waveform “cut-off” or clipped. Likewise, if there is too much bias and the Q-point lies in the upper half of the load line, then the output waveform will look like the one on the left with the positive half “cut-off” or clipped.

Also, when the bias voltage is set too small, during the negative half of the cycle the transistor does not fully conduct so the output is set by the supply voltage. When the bias is too great the positive half of the cycle saturates the transistor and the output drops almost to zero.

Even with the correct biasing voltage level set, it is still possible for the output waveform to become distorted due to a large input signal being amplified by the circuits gain. The output voltage signal becomes clipped in both the positive and negative parts of the waveform an no longer resembles a sine wave, even when the bias is correct. This type of amplitude distortion is called **Clipping** and is the result of “over-driving” the input of the amplifier.

When the input amplitude becomes too large, the clipping becomes substantial and forces the output waveform signal to exceed the power supply voltage rails with the peak (+ve half) and the trough (-ve half) parts of the waveform signal becoming flattened or “Clipped-off”. To avoid this the maximum value of the input signal must be limited to a level that will prevent this clipping effect as shown above.

**Amplitude Distortion due to Clipping**
Amplifier Distortion in Transistor Amplifiers

Amplitude Distortion greatly reduces the efficiency of an amplifier circuit. These “flat tops” of the distorted output waveform either due to incorrect biasing or over driving the input do not contribute anything to the strength of the output signal at the desired frequency.

Having said all that, some well known guitarist and rock bands actually prefer that their distinctive sound is highly distorted or “overdriven” by heavily clipping the output waveform to both the +ve and -ve power supply rails. Also, increasing the amounts of clipping on a sinusoid will produce so much amplifier distortion that it will eventually produce an output waveform which resembles that of a “square wave” shape which can then be used in electronic or digital synthesizer circuits.

We have seen that with a DC signal the level of gain of the amplifier can vary with signal amplitude, but as well as Amplitude Distortion, other types of amplifier distortion can occur with AC signals in amplifier circuits, such as Frequency Distortion and Phase Distortion.

Frequency Distortion

Frequency Distortion is another type of amplifier distortion which occurs in a transistor amplifier when the level of amplification varies with frequency. Many of the input signals that a practical amplifier will amplify consist of the required signal waveform called the “Fundamental Frequency” plus a number of different frequencies called “Harmonics” superimposed onto it.

Normally, the amplitude of these harmonics are a fraction of the fundamental amplitude and therefore have very little or no effect on the output waveform. However, the output waveform can become distorted if these harmonic frequencies increase in amplitude with regards to the fundamental frequency. For example, consider the waveform below:

**Frequency Distortion due to Harmonics**

![Frequency Distortion due to Harmonics](image)

In the example above, the input waveform consists a the fundamental frequency plus a second harmonic signal. The resultant output waveform is shown on the right hand side. The frequency distortion occurs when the fundamental frequency combines with the second harmonic to distort the output signal. Harmonics are therefore multiples of the fundamental frequency and in our simple example a second harmonic was used.

Therefore, the frequency of the harmonic is twice the fundamental, $2f$ or $2f$. Then a third harmonic would be $3f$, a fourth, $4f$, and so on. Frequency distortion due to harmonics is always a possibility in amplifier circuits containing reactive elements such as capacitance or inductance.

Phase Distortion

https://www.electronics-tutorials.ws/amplifier/amp_4.html
**Phase Distortion** or **Delay Distortion** is a type of amplifier distortion which occurs in a non-linear transistor amplifier when there is a time delay between the input signal and its appearance at the output.

If we say that the phase change between the input and the output is zero at the fundamental frequency, the resultant phase angle delay will be the difference between the harmonic and the fundamental. This time delay will depend on the construction of the amplifier and will increase progressively with frequency within the bandwidth of the amplifier. For example, consider the waveform below:

**Phase Distortion due to Delay**

![Diagram showing phase distortion due to delay](image)

Other than high end audio amplifiers, most practical amplifiers will have some form of **Amplifier Distortion** being a combination of both “Frequency Distortion” and “Phase Distortion”, together with amplitude distortion. In most applications such as in audio amplifiers or power amplifiers, unless the amplifiers distortion is excessive or severe it will not generally affect the operation or output sound of the amplifier.

In the next tutorial about amplifiers, we will look at the **Class A Amplifier**. Class A amplifiers are the most common type of amplifier output stage making them ideal for use in audio power amplifiers.
Class A Amplifier

Common emitter amplifiers are the most commonly used type of amplifier as they can have a very large voltage gain.

Common Emitter (CE) amplifiers are designed to produce a large output voltage swing from a relatively small input signal voltage of only a few millivolt's and are used mainly as “small signal amplifiers” as we saw in the previous tutorials.

However, sometimes an amplifier is required to drive large resistive loads such as a loudspeaker or to drive a motor in a robot and for these types of applications where high switching currents are needed Power Amplifiers are required.

The main function of the power amplifier, which are also known as a “large signal amplifier” is to deliver power, which is the product of voltage and current to the load. Basically a power amplifier is also a voltage amplifier the difference being that the load resistance connected to the output is relatively low, for example a loudspeaker of 4Ω or 8Ω resulting in high currents flowing through the collector of the transistor.

Because of these high load currents the output transistor(s) used for power amplifier output stages such as the 2N3055 need to have higher voltage and power ratings than the general ones used for small signal amplifiers such as the BC107.

Since we are interested in delivering maximum AC power to the load, while consuming the minimum DC power possible from the supply we are mostly concerned with the “conversion efficiency” of the amplifier.

However, one of the main disadvantage of power amplifiers and especially the Class A amplifier is that their overall conversion efficiency is very low as large currents mean that a considerable amount of power is lost in the form of heat. Percentage efficiency in amplifiers is defined as the r.m.s. output...
power dissipated in the load divided by the total DC power taken from the supply source as shown below.

**Power Amplifier Efficiency**

![Power Amplifier Efficiency Diagram](https://www.electronics-tutorials.ws/amplifier/amp_5.html)

\[
\eta\% = \frac{P_{OUT}}{P_{DC}} \times 100
\]

Where:
- \( \eta\% \) is the efficiency of the amplifier.
- \( P_{out} \) is the amplifier's output power delivered to the load.
- \( P_{dc} \) is the DC power taken from the supply.

For a power amplifier it is very important that the amplifier's power supply is well designed to provide the maximum available continuous power to the output signal.

**Class A Amplifier**

The most commonly used type of power amplifier configuration is the **Class A Amplifier**. The Class A amplifier is the simplest form of power amplifier that uses a single switching transistor in the standard common emitter circuit configuration as seen previously to produce an inverted output. The transistor is always biased “ON” so that it conducts during one complete cycle of the input signal waveform producing minimum distortion and maximum amplitude of the output signal.

This means then that the **Class A Amplifier** configuration is the ideal operating mode, because there can be no crossover or switch-off distortion to the output waveform even during the negative half of the cycle. Class A power amplifier output stages may use a single power transistor or pairs of transistors connected together to share the high load current. Consider the **Class A amplifier** circuit below.

**Single Stage Amplifier Circuit**

[Diagram of Single Stage Amplifier Circuit](https://www.electronics-tutorials.ws/amplifier/amp_5.html)
This is the simplest type of Class A power amplifier circuit. It uses a single-ended transistor for its output stage with the resistive load connected directly to the Collector terminal. When the transistor switches “ON” it sinks the output current through the Collector resulting in an inevitable voltage drop across the Emitter resistance thereby limiting the negative output capability.

The efficiency of this type of circuit is very low (less than 30%) and delivers small power outputs for a large drain on the DC power supply. A Class A amplifier stage passes the same load current even when no input signal is applied so large heatsinks are needed for the output transistors.

However, another simple way to increase the current handling capacity of the circuit while at the same time obtain a greater power gain is to replace the single output transistor with a **Darlington Transistor**. These types of devices are basically two transistors within a single package, one small “pilot” transistor and another larger “switching” transistor. The big advantage of these devices are that the input impedance is suitably large while the output impedance is relatively low, thereby reducing the power loss and therefore the heat within the switching device.

**Darlington Transistor Configurations**

https://www.electronics-tutorials.ws/amplifier/amp_5.html
The overall current gain Beta ($\beta$) or $h_{fe}$ value of a Darlington device is the product of the two individual gains of the transistors multiplied together and very high $\beta$ values along with high Collector currents are possible compared to a single transistor circuit.

To improve the full power efficiency of the Class A amplifier it is possible to design the circuit with a transformer connected directly in the Collector circuit to form a circuit called a Transformer Coupled Amplifier. The transformer improves the efficiency of the amplifier by matching the impedance of the load with that of the amplifiers output using the turns ratio ($n$) of the transformer and an example of this is given below.

**Transformer-coupled Amplifier Circuit**
As the Collector current, \( I_c \), is reduced to below the quiescent Q-point set up by the base bias voltage, due to variations in the base current, the magnetic flux in the transformer core collapses causing an induced emf in the transformer primary windings. This causes an instantaneous collector voltage to rise to a value of twice the supply voltage \( 2V_{cc} \) giving a maximum collector current of twice \( I_c \) when the Collector voltage is at its minimum. Then the efficiency of this type of Class A amplifier configuration can be calculated as follows.

The r.m.s. Collector voltage is given as:

\[
V_{CE} = \frac{V_{C(max)} - V_{C(min)}}{2\sqrt{2}} = \frac{2V_{cc} - 0}{2\sqrt{2}}
\]

The r.m.s. Collector current is given as:

\[
I_{CE} = \frac{I_{C(max)} - I_{C(min)}}{2\sqrt{2}} = \frac{2I_c - 0}{2\sqrt{2}}
\]

The r.m.s. Power delivered to the load (\( P_{ac} \)) is therefore given as:

\[
P_{ac} = V_{CE} \times I_{CE} = \frac{2V_{cc}}{2\sqrt{2}} \times \frac{2I_c}{2\sqrt{2}} = \frac{2V_{cc} \times 2I_c}{8}
\]

The average power drawn from the supply (\( P_{dc} \)) is given by:

\[
P_{dc} = V_{cc} \times I_c
\]

and therefore the efficiency of a Transformer-coupled Class A amplifier is given as:

\[
\eta_{(max)} = \frac{P_{ac}}{P_{dc}} = \frac{2V_{cc} \times 2I_c}{8V_{cc} \times I_c} \times 100\%
\]

An output transformer improves the efficiency of the amplifier by matching the impedance of the load with that of the amplifiers output impedance. By using an output or signal transformer with a suitable turns ratio, class-A amplifier efficiencies reaching 40% are possible with most commercially available Class-A type power amplifiers being of this type of configuration.

However, the transformer is an inductive device due to its windings and core so the use of inductive components in amplifier switching circuits is best avoided as any back emf’s generated may damage the transistor without adequate protection.

Also another big disadvantage of this type of transformer coupled class A amplifier circuit is the additional cost and size of the audio transformer required.

https://www.electronics-tutorials.ws/amplifier/amp_5.html
The type of “Class” or classification that an amplifier is given really depends upon the conduction angle, the portion of the 360° of the input waveform cycle, in which the transistor is conducting. In the Class A amplifier the conduction angle is a full 360° or 100% of the input signal while in other amplifier classes the transistor conducts during a lesser conduction angle.

It is possible to obtain greater power output and efficiency than that of the Class A amplifier by using two complementary transistors in the output stage with one transistor being an NPN or N-channel type while the other transistor is a PNP or P-channel (the complement) type connected in what is called a “push-pull” configuration.

This type of power amplifier configuration is generally called a Class B Amplifier and is another type of audio amplifier circuit that we will look at in the next tutorial.
Class B Amplifier

Class-B Amplifiers use two or more transistors biased in such a way so that each transistor only conducts during one half cycle of the input waveform.

To improve the full power efficiency of the previous Class A amplifier by reducing the wasted power in the form of heat, it is possible to design the power amplifier circuit with two transistors in its output stage producing what is commonly termed as a Class B Amplifier also known as a push-pull amplifier configuration.

Push-pull amplifiers use two “complementary” or matching transistors, one being an NPN-type and the other being a PNP-type with both power transistors receiving the same input signal together that is equal in magnitude, but in opposite phase to each other. This results in one transistor only amplifying one half or 180° of the input waveform cycle while the other transistor amplifies the other half or remaining 180° of the input waveform cycle with the resulting “two-halves” being put back together again at the output terminal.

Then the conduction angle for this type of amplifier circuit is only 180° or 50% of the input signal. This pushing and pulling effect of the alternating half cycles by the transistors gives this type of circuit its amusing "push-pull" name, but are more generally known as the Class B Amplifier as shown below.

Class B Push-pull Transformer Amplifier Circuit
The circuit above shows a standard **Class B Amplifier** circuit that uses a balanced center-tapped input transformer, which splits the incoming waveform signal into two equal halves and which are 180° out of phase with each other. Another center-tapped transformer on the output is used to recombined the two signals providing the increased power to the load. The transistors used for this type of transformer push-pull amplifier circuit are both NPN transistors with their emitter terminals connected together.

Here, the load current is shared between the two power transistor devices as it decreases in one device and increases in the other throughout the signal cycle reducing the output voltage and current to zero. The result is that both halves of the output waveform now swings from zero to twice the quiescent current thereby reducing dissipation. This has the effect of almost doubling the efficiency of the amplifier to around 70%.

Assuming that no input signal is present, then each transistor carries the normal quiescent collector current, the value of which is determined by the base bias which is at the cut-off point. If the transformer is accurately center tapped, then the two collector currents will flow in opposite directions (ideal condition) and there will be no magnetization of the transformer core, thus minimizing the possibility of distortion.

When an input signal is present across the secondary of the driver transformer T1, the transistor base inputs are in “anti-phase” to each other as shown, thus if TR1 base goes positive driving the transistor into heavy conduction, its collector current will increase but at the same time the base current of TR2 will go negative further into cut-off and the collector current of this transistor decreases by an equal amount and vice versa. Hence negative halves are amplified by one transistor and positive halves by the other transistor giving this push-pull effect.

Unlike the DC condition, these alternating currents are **ADDITIVE** resulting in the two output half-cycles being combined to reform the sine-wave in the output transformers primary winding which then appears across the load.
**Class B Amplifier** operation has zero DC bias as the transistors are biased at the cut-off, so each transistor only conducts when the input signal is greater than the Base-emitter voltage. Therefore, at zero input there is zero output and no power is being consumed. This then means that the actual Q-point of a Class B amplifier is on the $V_{ce}$ part of the load line as shown below.

Class B Output Characteristics Curves

The **Class B Amplifier** has the big advantage over their Class A amplifier cousins in that no current flows through the transistors when they are in their quiescent state (ie, with no input signal), therefore no power is dissipated in the output transistors or transformer when there is no signal present unlike Class A amplifier stages that require significant base bias thereby dissipating lots of heat – even with no input signal present.

So the overall conversion efficiency ($\eta$) of the amplifier is greater than that of the equivalent Class A with efficiencies reaching as high as 70% possible resulting in nearly all modern types of push-pull amplifiers operated in this Class B mode.

**Transformerless Class B Push-Pull Amplifier**

One of the main disadvantages of the Class B amplifier circuit above is that it uses balanced center-tapped transformers in its design, making it expensive to construct. However, there is another type of Class B amplifier called a **Complementary-Symmetry Class B Amplifier** that does not use transformers in its design therefore, it is transformerless using instead complementary or matching pairs of power transistors.

As transformers are not needed this makes the amplifier circuit much smaller for the same amount of output, also there are no stray magnetic effects or transformer distortion to effect the quality of the output signal. An example of a “transformerless” Class B amplifier circuit is given below.

Class B Transformerless Output Stage

The Class B amplifier circuit above uses complimentary transistors for each half of the waveform and while Class B amplifiers have a much high gain than the Class A types, one of the main disadvantages of class B type push-pull amplifiers is that they suffer from an effect known commonly as Crossover Distortion.

Hopefully we remember from our tutorials about Transistors that it takes approximately 0.7 volts (measured from base to emitter) to get a bipolar transistor to start conducting. In a pure class B amplifier, the output transistors are not “pre-biased” to an “ON” state of operation.

This means that the part of the output waveform which falls below this 0.7 volt window will not be reproduced accurately as the transition between the two transistors (when they are switching over from one transistor to the other), the transistors do not stop or start conducting exactly at the zero crossover point even if they are specially matched pairs.

The output transistors for each half of the waveform (positive and negative) will each have a 0.7 volt area in which they are not conducting. The result is that both transistors are turned “OFF” at exactly the same time.

A simple way to eliminate crossover distortion in a Class B amplifier is to add two small voltage sources to the circuit to bias both the transistors at a point slightly above their cut-off point. This then would give us what is commonly called an **Class AB Amplifier** circuit. However, it is impractical to add additional voltage sources to the amplifier circuit so PN-junctions are used to provide the additional bias in the form of silicon diodes.

### The Class AB Amplifier

We know that we need the base-emitter voltage to be greater than 0.7v for a silicon bipolar transistor to start conducting, so if we were to replace the two voltage divider biasing resistors connected to the base terminals of the transistors with two silicon Diodes. The biasing voltage applied to the transistors would now be equal to the forward voltage drop of these diodes. These two diodes are generally called **Biasing Diodes** or **Compensating Diodes** and are chosen to match the characteristics of the matching transistors. The circuit below shows diode biasing.
The **Class AB Amplifier** circuit is a compromise between the Class A and the Class B configurations. This very small diode biasing voltage causes both transistors to slightly conduct even when no input signal is present. An input signal waveform will cause the transistors to operate as normal in their active region thereby eliminating any crossover distortion present in pure Class B amplifier designs.

A small collector current will flow when there is no input signal but it is much less than that for the Class A amplifier configuration. This means then that the transistor will be “ON” for more than half a cycle of the waveform but much less than a full cycle giving a conduction angle of between 180° to 360° or 50% to 100% of the input signal depending upon the amount of additional biasing used. The amount of diode biasing voltage present at the base terminal of the transistor can be increased in multiples by adding additional diodes in series.

**Class B amplifiers** are greatly preferred over Class A designs for high-power applications such as audio power amplifiers and PA systems. Like the class-A amplifier circuit, one way to greatly boost the current gain \( A_i \) of a Class B push-pull amplifier is to use Darlington transistors pairs instead of single transistors in its output circuitry.

In the next tutorial about amplifiers we will look more closely at the effects of Crossover Distortion in Class B amplifier circuits and ways to reduce its effect.
Crossover Distortion in Amplifiers

Crossover Distortion is a common feature of Class-B amplifiers where the non-linearities of the two switching transistors do not vary linearly with the input signal.

We have seen that one of the main disadvantages of the **Class-A Amplifier** configuration is its low full power efficiency rating due to being biased around its central Q-point.

But we also know that we can improve the amplifier and almost double its efficiency simply by changing the output stage of the amplifier to a Class B push-pull type configuration. However, this is great from an efficiency point of view, but most modern Class B amplifiers are transformerless or complementary types with two transistors in their output stage.

This results in one main fundamental problem with push-pull amplifiers in that the two transistors do not combine together fully at the output both halves of the waveform due to their unique zero cut-off biasing arrangement. As this problem occurs when the signal changes or “crosses-over” from one transistor to the other at the zero voltage point it produces an amount of “distortion” to the output wave shape. This results in a condition that is commonly called **Crossover Distortion**.

**Crossover Distortion** produces a zero voltage “flat spot” or “deadband” on the output wave shape as it crosses over from one half of the waveform to the other. The reason for this is that the transition period when the transistors are switching over from one to the other, does not stop or start exactly at the zero crossover point thus causing a small delay between the first transistor turning “OFF” and the second transistor turning “ON”. This delay results in both transistors being switched “OFF” at the same instant in time producing an output wave shape as shown below.

**Crossover Distortion Waveform**
In order that there should be no distortion of the output waveform we must assume that each transistor starts conducting when its base to emitter voltage rises just above zero, but we know that this is not true because for silicon bipolar transistors, the base-emitter voltage must reach at least 0.7v before the transistor starts to conduct due to the forward diode voltage drop of the base-emitter pn-junction, thereby producing this flat spot. This crossover distortion effect also reduces the overall peak to peak value of the output waveform causing the maximum power output to be reduced as shown below.

Non-Linear Transfer Characteristics

This effect is less pronounced for large input signals as the input voltage is usually quite large but for smaller input signals it can be more severe causing audio distortion to the amplifier.

Pre-biasing the Output

https://www.electronics-tutorials.ws/amplifier/amp_7.html
The problem of **Crossover Distortion** can be reduced considerably by applying a slight forward base bias voltage (same idea as seen in the Transistor tutorial) to the bases of the two transistors via the center-tap of the input transformer, thus the transistors are no longer biased at the zero cut-off point but instead are “Pre-biased” at a level determined by this new biasing voltage.

### Push-pull Amplifier with Pre-biasing

This type of resistor pre-biasing causes one transistor to turn “ON” exactly at the same time as the other transistor turns “OFF” as both transistors are now biased slightly above their original cut-off point. However, to achieve this the bias voltage must be at least twice that of the normal base to emitter voltage to turn “ON” the transistors. This pre-biasing can also be implemented in transformerless amplifiers that use complementary transistors by simply replacing the two potential divider resistors with **Biasing Diodes** as shown below.

### Pre-biasing with Diodes
This pre-biasing voltage either for a transformer or transformerless amplifier circuit, has the effect of moving the amplifiers Q-point past the original cut-off point thus allowing each transistor to operate within its active region for slightly more than half or 180° of each half cycle. In other words, \(180° + \text{Bias}\). The amount of diode biasing voltage present at the base terminal of the transistor can be increased in multiples by adding additional diodes in series. This then produces an amplifier circuit commonly called a **Class AB Amplifier** and its biasing arrangement is given below.

### Class AB Output Characteristics

![Class AB Output Characteristics Diagram](image)

### Crossover Distortion Summary

Then to summarise, **Crossover Distortion** occurs in Class B amplifiers because the amplifier is biased at its cut-off point. This then results in BOTH transistors being switched “OFF” at the same instant in time as the waveform crosses the zero axis. By applying a small base bias voltage either by using a resistive potential divider circuit or diode biasing this crossover distortion can be greatly reduced or even eliminated completely by bringing the transistors to the point of being just switched “ON”.

The application of a biasing voltage produces another type or class of amplifier circuit commonly called a **Class AB Amplifier**. Then the difference between a pure Class B amplifier and an improved Class AB amplifier is in the biasing level applied to the output transistors. One major advantage of using diodes over resistors is that their PN-junctions compensate for variations in the temperature of the transistors.

Therefore, we can correctly say that the Class AB amplifier is effectively a Class B amplifier with added “Bias” and we can summarise this as follows:
Class A Amplifiers – No Crossover Distortion as they are biased in the center of the load line.

Class B Amplifiers – Large amounts of Crossover Distortion due to biasing at the cut-off point.

Class AB Amplifiers – Some Crossover Distortion if the biasing level is set too low.

As well as the three amplifier classes above, there are a number of high efficiency Amplifier Classes relating to switching amplifier designs that use different switching techniques to reduce power loss and increase efficiency. Some of these amplifier designs use RLC resonators or multiple power-supply voltages to help reduce power loss and distortion.
Amplifiers Summary

Amplifiers are used extensively in electronic circuits to make an electronic signal bigger without affecting it in any other way.

Generally we think of Amplifiers as audio amplifiers in the radios, CD players and stereo’s we use around the home. In this amplifier tutorial section we looked at the amplifier circuit based on a single bipolar transistor as shown below, but there are several different kinds of transistor amplifier circuits that we could use.

Typical Single Stage Amplifier Circuit
Small Signal Amplifiers

- Small Signal Amplifiers are also known as Voltage Amplifiers.
- Voltage Amplifiers have 3 main properties, Input Resistance, Output Resistance and Gain.
- The Gain of a small signal amplifier is the amount by which the amplifier “Amplifies” the input signal.
- Gain is a ratio of output divided by input, therefore it has no units but is given the symbol (A) with the most common types of transistor gain being, Voltage Gain (Av), Current Gain (Ai) and Power Gain (Ap)
- The power Gain of the amplifier can also be expressed in Decibels or simply dB.
- In order to amplify all of the input signal distortion free in a Class A type amplifier, DC Base Biasing is required.
- DC Bias sets the Q-point of the amplifier half way along the load line.
- This DC Base biasing means that the amplifier consumes power even if there is no input signal present.
- The transistor amplifier is non-linear and an incorrect bias setting will produce large amounts of distortion to the output waveform.
- Too large an input signal will produce large amounts of distortion due to clipping, which is also a form of amplitude distortion.
- Incorrect positioning of the Q-point on the load line will produce either Saturation Clipping or Cut-off Clipping.
- The Common Emitter Amplifier configuration is the most common form of all the general purpose voltage amplifier circuit using a Bipolar Junction Transistor.
- The Common Source Amplifier configuration is the most common form of all the general purpose voltage amplifier circuit using a Junction Field Effect Transistor.
BJT Amplifier to JFET Amplifier Comparison

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Common Emitter Amplifier</th>
<th>Common Source Amplifier</th>
</tr>
</thead>
<tbody>
<tr>
<td>Voltage Gain, ( A_v )</td>
<td>Medium/High</td>
<td>Medium/High</td>
</tr>
<tr>
<td>Current Gain, ( A_I )</td>
<td>High</td>
<td>Very High</td>
</tr>
<tr>
<td>Power Gain, ( A_P )</td>
<td>High</td>
<td>Very High</td>
</tr>
<tr>
<td>Input Resistance, ( R_{in} )</td>
<td>Medium</td>
<td>Very High</td>
</tr>
<tr>
<td>Output Resistance, ( R_{out} )</td>
<td>Medium/High</td>
<td>Medium/High</td>
</tr>
<tr>
<td>Phase Shift</td>
<td>180°</td>
<td>180°</td>
</tr>
</tbody>
</table>

Large Signal Amplifiers

- Large Signal Amplifiers are also known as **Power Amplifiers**.
- Power Amplifiers can be sub-divided into different Classes, for example:
  - **Class A Amplifiers** – where the output device conducts for all of the input cycle.
  - **Class B Amplifiers** – where the output device conducts for only 50% of the input cycle.
  - **Class AB Amplifiers** – where the output device conducts for more than 50% but less than 100% of the input cycle.

- An ideal Power Amplifier would deliver 100% of the available DC power to the load.
- Class A amplifiers are the most common form of power amplifier but only have an efficiency rating of less than 40%.
- Class B amplifiers are more efficient than Class A amplifiers at around 70% but produce high amounts of distortion.
- Class B amplifiers consume very little power when there is no input signal present.
- By using the “Push-pull” output stage configuration, distortion can be greatly reduced.
- However, simple push-pull Class B Power amplifiers can produce high levels of **Crossover Distortion** due to their cut-off point biasing.
- Pre-biasing resistors or diodes will help eliminate this crossover distortion.
- Class B Power Amplifiers can be made using Transformers or Complementary Transistors in its output stage.
Emitter Resistance

Emitter Resistance connected to the emitter terminal of a transistor amplifier can be used to increases the amplifiers bias stabilisation

The aim of an AC signal amplifier circuit is to stabilise the DC biased input voltage to the amplifier and thus only amplify the required AC signal.

This stabilisation is achieved by the use of an Emitter Resistance which provides the required amount of automatic biasing needed for a common emitter amplifier. To explain this a little further, consider the following basic amplifier circuit below.

Basic Common Emitter Amplifier Circuit

The common emitter amplifier circuit shown uses a voltage divider network to bias the transistors base and the common emitter configuration is a very popular way of designing bipolar transistor amplifier circuits. An important feature of this circuit is that an appreciable amount of current flows into the base of the transistor.

The voltage at the junction of the two biasing resistors, R1 and R2, holds the transistors base voltage, $V_B$, at a constant voltage and proportional to the supply voltage, $V_{cc}$. Note that $V_B$ is the voltage measured from base to ground, which is the actual voltage drop across R2.

This “class-A” type amplifier circuit is always designed so that the base current ($I_B$) is less than 10% of the current flowing through the biasing resistor R2. So for example, if we require a quiescent collector current of 1mA, the base current, $I_B$ will be about one hundredth of this, or 10μA. Therefore the current flowing through resistor R2 of the potential divider network must be at least 10 times this amount, or 100μA.

The advantage of using a voltage divider lies in its stability. Since the voltage divider formed by R1 and R2 is lightly loaded, the base voltage, $V_B$ can be easily calculated by using the simple voltage divider formula as shown.
Voltage Divider Equation

\[
V_{out} = V_{in} \left( \frac{R_2}{R_1 + R_2} \right)
\]

Therefore:

\[
V_B = V_{CC} \left( \frac{R_2}{R_1 + R_2} \right)
\]

However, with this type of biasing arrangement the voltage divider network is not loaded by the base current as it is too small, so if there are any changes in the supply voltage \(V_{CC}\), then the voltage level on the base will also change by a proportional amount. Then some form of voltage stabilisation of the transistors base bias or Q-point is required.

Emitter Resistance Stabilisation

The amplifiers bias voltage can be stabilised by placing a single resistor in the transistors emitter circuit as shown. This resistance is known as the **Emitter Resistance**, \(R_E\). The addition of this *emitter resistor* means that the transistors emitter terminal is no longer grounded or at zero volt potential but sits at a small potential above it given by the Ohms Law equation of: \(V_E = I_E \times R_E\). Where: \(I_E\) is the actual emitter current.

Now if the supply voltage \(V_{CC}\) increases, the transistors collector current \(I_C\) also increases for a given load resistance. If the collector current increases, the corresponding emitter current must also increase causing the voltage drop across \(R_E\) to increase. This action results in a proportional increase in base voltage because \(V_B = V_E + V_{BE}\).

Since the base voltage is held constant by the divider resistors \(R_1\) and \(R_2\), the DC voltage on the base relative to the emitter \(V_{BE}\) is lowered by a proportional amount thus reducing the base current drive and keeping the collector current from increasing further. A similar action occurs if the supply voltage and collector current try to decrease in value.

In other words, the addition of this emitter terminal resistance helps control the transistors base biasing using negative feedback, which negates any attempted change in collector current with an opposing change in the base bias voltage and so the circuit tends to be stabilised at a fixed level.

Also, since part of the supply is dropped across \(R_E\), its value should be as small as possible so that the largest possible voltage can be developed across the load resistance, \(R_L\) and therefore the output. However, its value cannot be too small or once again the instability of the circuit will suffer.

Then the current flowing through the emitter resistor is calculated as:

**Emitter Resistor Current**
Emitter Resistance and the Transistor Emitter Resistor

As a general rule of thumb, the voltage drop across this emitter resistance is generally taken to be: \( V_B - V_{BE} \), or one-tenth \((1/10\text{th})\) of the value of the supply voltage, \( V_{cc} \). A common figure for the emitter resistor voltage is between 1 to 2 volts, whichever is the lower. The value of the emitter resistance, \( R_E \) can also be found from the gain as now the AC voltage gain is equal to: \( R_L / R_E \)

**Emitter Resistance Example No1**

A common emitter amplifier has the following characteristics, \( \beta = 100 \), \( V_{cc} = 30V \) and \( R_L = 1k\Omega \). If the amplifier circuit uses an emitter resistance to improve its stability, calculate its resistance.

The amplifier's quiescent current, \( I_{CQ} \) is given as:

\[
I_{CQ} = \frac{1}{2} \frac{V_{cc}}{R_L} = \frac{15V}{1k\Omega} = 15\text{mA}
\]

\[
I_B = \frac{I_{CQ}}{\beta} = \frac{15\text{mA}}{100} = 150\mu\text{A}
\]

The voltage drop across the emitter resistance is generally between 1 and 2 volts, so let's assume a voltage drop, \( V_E \) of 1.5 volts.

\[
V_B = V_E + V_{BE} = 1.5V + 0.7V = 2.2\text{Volts}
\]

\[
R_2 = \frac{V_E}{10 \times I_B} = \frac{2.2}{10 \times 150\mu\text{A}} = 1.47k\Omega
\]

\[
R_1 = \frac{V_{cc} - V_B}{11 \times I_B} = \frac{30 - 2.2}{11 \times 150\mu\text{A}} = 16.67k\Omega
\]

\[
I_E = I_{CQ} + I_B = 15\text{mA} + 150\mu\text{A} = 15.15\text{mA}
\]

\[
R_E = \frac{V_E}{I_E} = \frac{1.5V}{15.15\text{mA}} = 100\Omega
\]
Then the value of the **Emitter Resistance** required for the amplifier circuit is given as: \(100\Omega\), and the final common emitter circuit is given as:

### Final Common Emitter Amplifier

![Final Common Emitter Amplifier Diagram]

The gain of the amplifier stage can also be found if so required and is given as:

\[
\text{Gain, (A)} = \frac{R_L}{R_E} = \frac{1k\Omega}{100\Omega} = 10
\]

### Emitter By-pass Capacitor

In the basic series feedback circuit above, the emitter resistor, \(R_E\) performs two functions: DC negative feedback for stable biasing and AC negative feedback for signal transconductance and voltage gain specification. But as the emitter resistance is a feedback resistor, it will also reduce the amplifiers gain due to fluctuations in the emitter current \(I_E\) owing to the AC input signal.

To overcome this problem a capacitor, called an “Emitter Bypass Capacitor”, \(C_E\) is connected across the emitter resistance as shown. This bypass capacitor causes the frequency response of the amplifier to break at a designated cut-off frequency, \(f_c\), bypassing (hence its name) signal currents to ground.

Being a capacitor it appears as an open circuit for the for DC bias and therefore, the biased currents and voltages are unaffected by the addition of the bypass capacitor. Over the amplifiers operating range of frequencies, the capacitors reactance, \(X_C\) will be extremely high at low frequencies producing a negative feedback effect, reducing the amplifiers gain.

https://www.electronics-tutorials.ws/amplifier/emitter-resistance.html
The value of this bypass capacitor $C_E$ is generally chosen to provide a capacitive reactance of, at most one-tenth (1/10th) of the value of the emitter resistor $R_E$ at the lowest cut-off frequency point. Then assuming that the lowest signal frequency to be amplified is 100 Hz. The value of the bypass capacitor $C_E$ is calculated as:

**Emitter Bypass Capacitor**

$$X_C = \frac{1}{1/10th} R_E \text{ at } f_{3dB} = 0.1 \times 100 \Omega = 10 \Omega$$

$$C_E = \frac{1}{2\pi f_{3dB} X_C} = \frac{1}{2\pi \times 100 \times 10} = 160 \mu F$$

Then for our simple common emitter amplifier above the value of the emitter bypass capacitor connected in parallel with the emitter resistance is: $160 \mu F$

**Split Emitter Amplifier**

While the addition of the bypass capacitor, $C_E$ helps to control the amplifiers gain by counteracting the effects of the uncertainty of beta, ($\beta$), one of its main disadvantages is that at high frequencies the capacitors reactance becomes so low that it effectively shorts out the emitter resistance, $R_E$ as the frequency increases.

The result is that at high frequencies the reactance of the capacitor allows very little AC feedback control because $R_E$ is shorted out which also means that the AC voltage gain of the transistor is greatly increased driving the amplifier into saturation.

One easy way of controlling the amplifiers gain over the whole operating frequency range is to split the emitter resistance into two parts as shown.

**Split Emitter Resistors**

The resistor in the emitter leg has been split into two parts: $R_{E1}$ and $R_{E2}$ forming a voltage divider network within the emitter leg with the by-pass capacitor connected in parallel across the lower resistor.

The upper resistor, $R_{E1}$ is the same value as before but is unbypassed by the capacitor so must be considered when calculating signal parameters. The lower resistor $R_{E2}$ is connected in parallel with the capacitor and is considered to be zero ohms when calculating signal parameters as it becomes shorted out at high frequencies.

The advantage here is that we can control the AC gain of the amplifier over the full range of input frequencies. At DC the total value of the emitter resistance is equal to $R_{E1} + R_{E2}$ while at higher AC frequencies the emitter resistance is just: $R_{E1}$, the same as it was in the original unbypassed circuit above.

So what value is resistor, $R_{E2}$. Well that will depend upon the DC voltage gain required at the lower frequency cut-off point. We said earlier that the gain of the above circuit was equal to: $R_{1} / R_{E}$ which for our common emitter circuit above was calculated at 10 (1kΩ/100Ω). But now at DC the gain will be
equal to: $R_L / (R_{E1} + R_{E2})$

Therefore if we choose a DC gain of say 1 (one) the value of emitter resistor, $R_{E2}$ is given as:

**Split-emitter Resistor, $R_{E2}$**

$$ DC \text{ Gain, } (A_{dc}) = \frac{R_L}{(R_{E1} + R_{E2})} = \frac{1k\Omega}{100 + R_{E2}} = 1 $$

$$ \therefore R_{E2} = \frac{R_L}{A_{dc}} - R_{E1} = \frac{1k\Omega}{1} - 100 = 900\Omega $$

Then for a DC gain of 1 (one), $R_{E1} = 100\Omega$ and $R_{E2} = 900\Omega$. Note that the AC gain will be the same at 10.

Then a split-emitter amplifier has values of voltage gain and input impedance somewhere between those of a fully bypassed emitter amplifier and an unbypassed emitter amplifier depending upon the operating frequency.

**Emitter Resistance Summary**

Then to summarise, the current amplification parameter, $\beta$ of a transistor can vary considerably from one device to another of the same type and part number because of manufacturing tolerances, and also due to variations in supply voltage and operating temperature.

Then for a common emitter class-A amplifier circuit it is necessary to use a biasing circuit that will stabilize the operating Q-point making the DC collector current, $I_C$ independent of beta. The influence of $\beta$ on the value of the emitter current can be reduced by the addition of an **Emitter Resistance**, $R_E$ in the emitter leg to provide stabilisation.

The voltage drop across this emitter resistance is usually given as between 1 to 2 volts. The emitter resistor can be fully bypassed by a suitable bypass capacitor, $C_E$ connected in parallel with the emitter resistor to achieve a higher AC gain or partly bypassed, using a split-emitter voltage divider network which reduces the DC gain and distortion. The value of this capacitor is determined from its capacitive reactance ($X_C$) value at the lowest signal frequency.
Amplifier Classes

Amplifiers are classified into classes according to their construction and operating characteristics.

Not all amplifiers are the same and there is a clear distinction made between the way their output stages are configured and operate. The main operating characteristics of an ideal amplifier are linearity, signal gain, efficiency and power output but in real world amplifiers there is always a trade off between these different characteristics.

Generally, large signal or power amplifiers are used in the output stages of audio amplifier systems to drive a loudspeaker load. A typical loudspeaker has an impedance of between 4Ω and 8Ω, thus a power amplifier must be able to supply the high peak currents required to drive the low impedance speaker.

One method used to distinguish the electrical characteristics of different types of amplifiers is by “class”, and as such amplifiers are classified according to their circuit configuration and method of operation. Then Amplifier Classes is the term used to differentiate between the different amplifier types.

Amplifier Classes represent the amount of the output signal which varies within the amplifier circuit over one cycle of operation when excited by a sinusoidal input signal. The classification of amplifiers range from entirely linear operation (for use in high-fidelity signal amplification) with very low efficiency, to entirely non-linear (where a faithful signal reproduction is not so important) operation but with a much higher efficiency, while others are a compromise between the two.

Amplifier classes are mainly lumped into two basic groups. The first are the classically controlled conduction angle amplifiers forming the more common amplifier classes of A, B, AB and C, which are defined by the length of their conduction state over some portion of the output waveform, such that the output stage transistor operation lies somewhere between being “fully-ON” and “fully-OFF”.

https://www.electronics-tutorials.ws/amplifier/amplifier-classes.html
The second set of amplifiers are the newer so-called “switching” amplifier classes of D, E, F, G, S, T etc, which use digital circuits and pulse width modulation (PWM) to constantly switch the signal between “fully-ON” and “fully-OFF” driving the output hard into the transistors saturation and cut-off regions.

The most commonly constructed amplifier classes are those that are used as audio amplifiers, mainly class A, B, AB and C and to keep things simple, it is these types of amplifier classes we will look at here in more detail.

Class A Amplifier

Class A Amplifiers are the most common type of amplifier topology as they use just one output switching transistor (Bipolar, FET, IGBT, etc) within their amplifier design. This single output transistor is biased around the Q-point within the middle of its load line and so is never driven into its cut-off or saturation regions thus allowing it to conduct current over the full 360 degrees of the input cycle. Then the output transistor of a class-A topology never turns “OFF” which is one of its main disadvantages.

Class “A” amplifiers are considered the best class of amplifier design due mainly to their excellent linearity, high gain and low signal distortion levels when designed correctly. Although seldom used in high power amplifier applications due to thermal power supply considerations, class-A amplifiers are probably the best sounding of all the amplifier classes mentioned here and as such are used in high-fidelity audio amplifier designs.

Class A Amplifier

To achieve high linearity and gain, the output stage of a class A amplifier is biased “ON” (conducting) all the time. Then for an amplifier to be classified as “Class A” the zero signal idle current in the output stage must be equal to or greater than the maximum load current (usually a loudspeaker) required to produce the largest output signal.

As a class A amplifier operates in the linear portion of its characteristic curves, the single output device conducts through a full 360 degrees of the output waveform. Then the class A amplifier is equivalent to a current source.

Since a class A amplifier operates in the linear region, the transistors base (or gate) DC biasing voltage should by chosen properly to ensure correct operation and low distortion. However, as the output device is “ON” at all times, it is constantly carrying current, which represents a continuous loss of power in the amplifier.
Due to this continuous loss of power class A amplifiers create tremendous amounts of heat adding to their very low efficiency at around 30%, making them impractical for high-power amplifications. Also due to the high idling current of the amplifier, the power supply must be sized accordingly and be well filtered to avoid any amplifier hum and noise. Therefore, due to the low efficiency and over heating problems of Class A amplifiers, more efficient amplifier classes have been developed.

Class B Amplifier

Class B amplifiers were invented as a solution to the efficiency and heating problems associated with the previous class A amplifier. The basic class B amplifier uses two complimentary transistors either bipolar or FET for each half of the waveform with its output stage configured in a “push-pull" type arrangement, so that each transistor device amplifies only half of the output waveform.

In the class B amplifier, there is no DC base bias current as its quiescent current is zero, so that the dc power is small and therefore its efficiency is much higher than that of the class A amplifier. However, the price paid for the improvement in the efficiency is in the linearity of the switching device.

Class B Amplifier

When the input signal goes positive, the positive biased transistor conducts while the negative transistor is switched “OFF”. Likewise, when the input signal goes negative, the positive transistor switches “OFF” while the negative biased transistor turns “ON" and conducts the negative portion of the signal. Thus the transistor conducts only half of the time, either on positive or negative half cycle of the input signal.

Then we can see that each transistor device of the class B amplifier only conducts through one half or 180 degrees of the output waveform in strict time alternation, but as the output stage has devices for both halves of the signal waveform the two halves are combined together to produce the full linear output waveform.

This push-pull design of amplifier is obviously more efficient than Class A, at about 50%, but the problem with the class B amplifier design is that it can create distortion at the zero-crossing point of the waveform due to the transistors dead band of input base voltages from -0.7V to +0.7.

We remember from the Transistor tutorial that it takes a base-emitter voltage of about 0.7 volts to get a bipolar transistor to start conducting. Then in a class B amplifier, the output transistor is not “biased” to an "ON" state of operation until this voltage is exceeded.
This means that the part of the waveform which falls within this 0.7 volt window will not be reproduced accurately making the class B amplifier unsuitable for precision audio amplifier applications.

To overcome this zero-crossing distortion (also known as Crossover Distortion) class AB amplifiers were developed.

**Class AB Amplifier**

As its name suggests, the **Class AB Amplifier** is a combination of the “Class A” and the “Class B” type amplifiers we have looked at above. The AB classification of amplifier is currently one of the most common used types of audio power amplifier design. The class AB amplifier is a variation of a class B amplifier as described above, except that both devices are allowed to conduct at the same time around the waveforms crossover point eliminating the crossover distortion problems of the previous class B amplifier.

The two transistors have a very small bias voltage, typically at 5 to 10% of the quiescent current to bias the transistors just above its cut-off point. Then the conducting device, either bipolar or FET, will be “ON” for more than one half cycle, but much less than one full cycle of the input signal. Therefore, in a class AB amplifier design each of the push-pull transistors is conducting for slightly more than the half cycle of conduction in class B, but much less than the full cycle of conduction of class A.

In other words, the conduction angle of a class AB amplifier is somewhere between 180° and 360° depending upon the chosen bias point as shown.

**Class C Amplifier**

The **Class C Amplifier** design has the greatest efficiency but the poorest linearity of the classes of amplifiers mentioned here. The previous classes, A, B and AB are considered linear amplifiers, as the output signals amplitude and phase are linearly related to the input signals amplitude and phase.
However, the class C amplifier is heavily biased so that the output current is zero for more than one half of an input sinusoidal signal cycle with the transistor idling at its cut-off point. In other words, the conduction angle for the transistor is significantly less than 180 degrees, and is generally around the 90 degrees area.

While this form of transistor biasing gives a much improved efficiency of around 80% to the amplifier, it introduces a very heavy distortion of the output signal. Therefore, class C amplifiers are not suitable for use as audio amplifiers.

### Class C Amplifier

![Class C Amplifier Diagram]

Due to its heavy audio distortion, class C amplifiers are commonly used in high frequency sine wave oscillators and certain types of radio frequency amplifiers, where the pulses of current produced at the amplifiers output can be converted to complete sine waves of a particular frequency by the use of LC resonant circuits in its collector circuit.

### Amplifier Classes Summary

Then we have seen that the quiescent DC operating point (Q-point) of an amplifier determines the amplifier classification. By setting the position of the Q-point at half way on the load line of the amplifiers characteristics curve, the amplifier will operate as a class A amplifier. By moving the Q-point lower down the load line changes the amplifier into a class AB, B or C amplifier.

Then the class of operation of the amplifier with regards to its DC operating point can be given as:

### Amplifier Classes and Efficiency

https://www.electronics-tutorials.ws/amplifier/amplifier-classes.html
As well as audio amplifiers there are a number of high efficiency Amplifier Classes relating to switching amplifier designs that use different switching techniques to reduce power loss and increase efficiency. Some amplifier class designs listed below use RLC resonators or multiple power-supply voltages to reduce power loss, or are digital DSP (digital signal processing) type amplifiers which use pulse width modulation (PWM) switching techniques.

Other Common Amplifier Classes

- **Class D Amplifier** – A Class D audio amplifier is basically a non-linear switching amplifier or PWM amplifier. Class-D amplifiers theoretically can reach 100% efficiency, as there is no period during a cycle were the voltage and current waveforms overlap as current is drawn only through the transistor that is on.

- **Class F Amplifier** – Class-F amplifiers boost both efficiency and output by using harmonic resonators in the output network to shape the output waveform into a square wave. Class-F amplifiers are capable of high efficiencies of more than 90% if infinite harmonic tuning is used.

- **Class G Amplifier** – Class G offers enhancements to the basic class AB amplifier design. Class G uses multiple power supply rails of various voltages and automatically switches between these supply rails as the input signal changes. This constant switching reduces the average power consumption, and therefore power loss caused by wasted heat.

- **Class I Amplifier** – The class I amplifier has two sets of complementary output switching devices arranged in a parallel push-pull configuration with both sets of switching devices sampling the same input waveform. One device switches the positive half of the waveform, while the other switches the negative half similar to a class B amplifier. With no input signal applied, or when a signal reaches the zero crossing point, the switching devices are both turned ON and OFF simultaneously with a 50% PWM duty cycle cancelling out any high frequency signals.

To produce the positive half of the output signal, the output of the positive switching device is increased in duty cycle while the negative switching device is decreased by the same and vice versa. The two switching signal currents are said to be interleaved at the output, giving the class I amplifier the named of: “interleaved PWM amplifier” operating at switching frequencies in excess of 250kHz.
- **Class S Amplifier** – A class S power amplifier is a non-linear switching mode amplifier similar in operation to the class D amplifier. The class S amplifier converts analogue input signals into digital square wave pulses by a delta-sigma modulator, and amplifies them to increases the output power before finally being demodulated by a band pass filter. As the digital signal of this switching amplifier is always either fully “ON” or “OFF” (theoretically zero power dissipation), efficiencies reaching 100% are possible.

- **Class T Amplifier** – The class T amplifier is another type of digital switching amplifier design. Class T amplifiers are starting to become more popular these days as an audio amplifier design due to the existence of digital signal processing (DSP) chips and multi-channel surround sound amplifiers as it converts analogue signals into digital pulse width modulated (PWM) signals for amplification increasing the amplifiers efficiency. Class T amplifier designs combine both the low distortion signal levels of class AB amplifier and the power efficiency of a class D amplifier.

We have seen here a number of classification of amplifiers ranging from linear power amplifiers to non-linear switching amplifiers, and have seen how an amplifier class differs along the amplifiers load line. The class AB, B and C amplifiers can be defined in terms of the conduction angle, $\theta$ as follows:

### Amplifier Class by Conduction Angle

<table>
<thead>
<tr>
<th>Amplifier Class</th>
<th>Description</th>
<th>Conduction Angle</th>
</tr>
</thead>
<tbody>
<tr>
<td>Class-A</td>
<td>Full cycle 360° of Conduction</td>
<td>$\theta = 2\pi$</td>
</tr>
<tr>
<td>Class-B</td>
<td>Half cycle 180° of Conduction</td>
<td>$\theta = \pi$</td>
</tr>
<tr>
<td>Class-AB</td>
<td>Slightly more than 180° of conduction</td>
<td>$\pi &lt; \theta &lt; 2\pi$</td>
</tr>
<tr>
<td>Class-C</td>
<td>Slightly less than 180° of conduction</td>
<td>$\theta &lt; \pi$</td>
</tr>
<tr>
<td>Class-D to T</td>
<td>ON-OFF non-linear switching</td>
<td>$\theta = 0$</td>
</tr>
</tbody>
</table>
Transistor Biasing

Transistor Biasing is the process of setting a transistor's DC operating voltage or current conditions to the correct level so that any AC input signal can be amplified correctly by the transistor.

The steady state operation of a transistor depends a great deal on its base current, collector voltage, and collector current values and therefore, if the transistor is to operate correctly as a linear amplifier, it must be properly biased around its operating point.

Establishing the correct operating point requires the selection of bias resistors and load resistors to provide the appropriate input current and collector voltage conditions. The correct biasing point for a bipolar transistor, either NPN or PNP, generally lies somewhere between the two extremes of operation with respect to it being either “fully-ON” or “fully-OFF” along its DC load line. This central operating point is called the “Quiescent Operating Point”, or Q-point for short.

When a bipolar transistor is biased so that the Q-point is near the middle of its operating range, that is approximately halfway between cut-off and saturation, it is said to be operating as a Class-A amplifier. This mode of operation allows the output voltage to increase and decrease around the amplifiers Q-point without distortion as the input signal swings through one complete cycle. In other words, the output is available for the full 360° of the input cycle.

So how do we set this Q-point biasing of a transistor? – The correct biasing of the transistor is achieved using a process known commonly as Base Bias.

But before we start looking at the possible different transistor biasing arrangements, lets first remind ourselves of a basic single transistor circuit along with its voltages and currents as shown on the left.

The function of the “DC Bias level" is to correctly set the transistors Q-point by setting its Collector current (I_C) to a constant and steady state value without any external input signal applied to the transistors Base.

This steady-state or DC operating point is set by the values of the circuits DC supply voltage (Vcc) and the value of any biasing resistors connected the transistors Base terminal.

Since the transistors Base bias currents are steady-state DC currents, the appropriate use of coupling and bypass capacitors will help block any biasing currents from other transistor stage affecting the bias conditions of the transistor.
the next. Base bias networks can be used for Common-base (CB), common-collector (CC) or common-emitter (CE) transistor configurations. In this simple transistor biasing tutorial we will look at the different biasing arrangements available for a Common Emitter Amplifier.

**Base Biasing a Common Emitter Amplifier**

One of the most frequently used biasing circuits for a transistor circuit is with the self-biasing of the emitter-bias circuit were one or more biasing resistors are used to set up the initial DC values for the three transistor currents, \( I_B \), \( I_C \) and \( I_E \).

The two most common forms of bipolar transistor biasing are: *Beta Dependent* and *Beta Independent*. Transistor bias voltages are largely dependent on transistor beta, \( \beta \) so the biasing set up for one transistor may not necessarily be the same for another transistor as their beta values may be different. Transistor biasing can be achieved either by using a single feedback resistor or by using a simple voltage divider network to provide the required biasing voltage.

The following are five examples of transistor Base bias configurations from a single supply (\( V_{cc} \)).

**Fixed Base Biasing a Transistor**

The circuit shown is called as a “fixed base bias circuit”, because the transistors base current, \( I_B \) remains constant for given values of \( V_{cc} \), and therefore the transistors operating point must also remain fixed. This two resistor biasing network is used to establish the initial operating region of the transistor using a fixed current bias.

This type of transistor biasing arrangement is also beta dependent biasing as the steady-state condition of operation is a function of the transistors beta \( \beta \) value, so the biasing point will vary over a wide range for transistors of the same type as the characteristics of the transistors will not be exactly the same.

The emitter diode of the transistor is forward biased by applying the required positive base bias voltage via the current limiting resistor \( R_B \). Assuming a standard bipolar transistor, the forward base-emitter voltage drop would be 0.7V. Then the value of \( R_B \) is simply: \( (V_{cc} - V_{BE})/I_B \) where \( I_B \) is defined as \( I_C/\beta \).

With this single resistor type of biasing arrangement the biasing voltages and currents do not remain stable during transistor operation and can vary enormously. Also the operating temperature of the transistor can adversely effect the operating point.
Collector Feedback Biasing a Transistor

This self biasing collector feedback configuration is another beta dependent biasing method which requires two resistors to provide the necessary DC bias for the transistor. The collector to base feedback configuration ensures that the transistor is always biased in the active region regardless of the value of Beta ($\beta$). The DC base bias voltage is derived from the collector voltage $V_C$, thus providing good stability.

In this circuit, the base bias resistor, $R_B$ is connected to the transistors collector $C$, instead of to the supply voltage rail, $V_{CC}$. Now if the collector current increases, the collector voltage drops, reducing the base drive and thereby automatically reducing the collector current to keep the transistors Q-point fixed. Therefore this method of collector feedback biasing produces negative feedback round the transistor as there is a direct feedback from the output terminal to the input terminal via resistor, $R_B$.

Since the biasing voltage is derived from the voltage drop across the load resistor, $R_L$, if the load current increases there will be a larger voltage drop across $R_L$, and a corresponding reduced collector voltage, $V_C$. This effect will cause a corresponding drop in the base current, $I_B$ which in turn, brings $I_C$ back to normal.

The opposite reaction will also occur when the transistors collector current reduces. Then this method of biasing is called self-biasing with the transistors stability using this type of feedback bias network being generally good for most amplifier designs.

Dual Feedback Transistor Biasing
Adding an additional resistor to the base bias network of the previous configuration improves stability even more with respect to variations in Beta, ($\beta$) by increasing the current flowing through the base biasing resistors.

The current flowing through $R_{B1}$ is generally set at a value equal to about 10% of collector current, $I_C$. Obviously it must also be greater than the base current required for the minimum value of Beta, $\beta$.

One of the advantages of this type of self biasing configuration is that the two resistors provide both automatic biasing and $R_f$ feedback at the same time.

**Transistor Biasing with Emitter Feedback**

This type of transistor biasing configuration, often called self-emitter biasing, uses both emitter and base-collector feedback to stabilize the collector current even further. This is because resistors $R_{B1}$ and $R_E$ as well as the base-emitter junction of the transistor are all effectively connected in series with the supply voltage, $V_{CC}$.

The downside of this emitter feedback configuration is that it reduces the output gain due to the base resistor connection. The collector voltage determines the current flowing through the feedback resistor, $R_{B1}$ producing what is called “degenerative feedback”.
The current flowing from the emitter, $I_E$ (which is a combination of $I_C + I_B$) causes a voltage drop to appear across $R_E$ in such a direction, that it reverse biases the base-emitter junction.

So if the emitter current increases, due to an increase in collector current, voltage drop $I_E R_E$ also increases. Since the polarity of this voltage reverse biases the base-emitter junction, $I_B$ automatically decrease. Therefore the emitter current increase less than it would have done had there been no self biasing resistor.

Generally, resistor values are set so that the voltage dropped across the emitter resistor $R_E$ is approximately 10% of $V_{CC}$ and the current flowing through resistor $R_{B1}$ is 10% of the collector current $I_C$.

Thus this type of transistor biasing configuration works best at relatively low power supply voltages.

### Voltage Divider Transistor Biasing

Here the common emitter transistor configuration is biased using a voltage divider network to increase stability. The name of this biasing configuration comes from the fact that the two resistors $R_{B1}$ and $R_{B2}$ form a voltage or potential divider network across the supply with their center point junction connected the transistors base terminal as shown.

This voltage divider biasing configuration is the most widely used transistor biasing method. The emitter diode of the transistor is forward biased by the voltage value developed across resistor $R_{B2}$. Also, voltage divider network biasing makes the transistor circuit independent of changes in beta as the biasing voltages set at the transistors base, emitter, and collector terminals are not dependant on external circuit values.

To calculate the voltage developed across resistor $R_{B2}$ and therefore the voltage applied to the base terminal we simply use the voltage divider formula for resistors in series.

Generally the voltage drop across resistor $R_{B2}$ is much less than for resistor $R_{B1}$. Clearly the transistors base voltage $V_B$ with respect to ground, will be equal to the voltage across $R_{B2}$.

The amount of biasing current flowing through resistor $R_{B2}$ is generally set to 10 times the value of the required base current $I_B$ so that it is sufficiently high enough to have no effect on the voltage divider current or changes in Beta.
The goal of Transistor Biasing is to establish a known quiescent operating point, or Q-point for the bipolar transistor to work efficiently and produce an undistorted output signal. Correct DC biasing of the transistor also establishes its initial AC operating region with practical biasing circuits using either a two or four-resistor bias network.

In bipolar transistor circuits, the Q-point is represented by \((V_{CE}, I_C)\) for the NPN transistors or \((V_{EC}, I_C)\) for PNP transistors. The stability of the base bias network and therefore the Q-point is generally assessed by considering the collector current as a function of both Beta \((\beta)\) and temperature.

Here we have looked briefly at five different configurations for “biasing a transistor” using resistive networks. But we can also bias a transistor using either silicon diodes, zener diodes or active networks all connected to the transistors base terminal. We could also correctly bias the transistor from a dual voltage power supply if so wished.
Input Impedance of an Amplifier

The Input Impedance of an amplifier defines its input characteristics with regards to current and voltage looking into an amplifier's input terminals.

**Input Impedance**, $Z_{IN}$ or *Input Resistance* as it is often called, is an important parameter in the design of a transistor amplifier and as such allows amplifiers to be characterized according to their effective input and output impedances as well as their power and current ratings.

An amplifier's impedance value is particularly important for analysis especially when cascading individual amplifier stages together one after another to minimize distortion of the signal.

The *input impedance of an amplifier* is the input impedance “seen” by the source driving the input of the amplifier. If it is too low, it can have an adverse loading effect on the previous stage and possibly affecting the frequency response and output signal level of that stage. But in most applications, common emitter and common collector amplifier circuits generally have high input impedances.

Some types of amplifier designs, such as the common collector amplifier circuit automatically have high input impedance and low output impedance by the very nature of their design. Amplifiers can have high input impedance, low output impedance, and virtually any arbitrary gain, but were an amplifier's input impedance is lower than desired, the output impedance of the previous stage can be adjusted to compensate or if this is not possible then buffer amplifier stages may be needed.

In addition to voltage amplification ($A_V$), an amplifier circuit must also have current amplification ($A_I$). Power amplification ($A_P$) can also be expected from an amplifier circuit. But as well as having these three important characteristics, an amplifier circuit must also have other characteristics like high input impedance ($Z_{IN}$), low output impedance ($Z_{OUT}$) and some degree of bandwidth, ($B_w$). Either way, the “perfect” amplifier will have infinite input impedance and zero output impedance.

**Input and Output Impedance**

In many ways, an amplifier can be thought of as a type of “black box” which has two input terminals and two output terminals as shown. This idea provides a simple *h-parameter model* of the transistor that we can use to find the DC set point and operating parameters of an amplifier. In reality one of the terminals is common between the input and output representing ground or zero volts.

When looking from the outside in, these terminals have an input impedance, $Z_{IN}$, and an output impedance, $Z_{OUT}$. The input and output impedance of an amplifier is the ratio of voltage to current flowing in or out of these terminals. The input impedance may depend upon the source supply feeding the amplifier while the output impedance may also vary according to the load impedance, $R_L$ across the output terminals.

The input signals being amplified are usually alternating currents (AC) with the amplifier circuit representing a load, $Z$ to the source. The input impedance of an amplifier can be tens of ohms, (Ohms $\Omega$) to a few thousand ohms, (kilo-ohms $k\Omega$) for bipolar based transistor circuits up to millions of ohms, (Mega-ohms $M\Omega$) for FET based transistor circuits.

When a signal source and load are connected to an amplifier, the corresponding electrical properties of the amplifier circuit can be modelled as shown.

**Output and Input Impedance Model**

![Output and Input Impedance Model](image)

Where, $V_S$ is the signal voltage, $R_S$ is the internal resistance of the signal source, and $R_L$ is the load resistance connected across the output. We can expand this idea further by looking at how the amplifier is connected to the source and load.

When an amplifier is connected to a signal source, the source “sees” the input impedance, $Z_{IN}$ of the amplifier as a load. Likewise, the input voltage, $V_{IN}$ is what the amplifier sees across the input impedance, $Z_{IN}$. Then the amplifiers input can be modelled as a simple voltage divider circuit as shown.

**Amplifier Input Circuit Model**

![Amplifier Input Circuit Model](image)

The same idea applies for the output impedance of the amplifier. When a load resistance, $R_L$ is connected to the output of the amplifier, the amplifier becomes the source feeding the load. Therefore, the output voltage and impedance automatically becomes the source voltage and source impedance for the load as shown.
Amplifier Output Circuit Model

Then we can see that the input and output characteristics of an amplifier can both be modelled as a simple voltage divider network. The amplifier itself can be connected in Common Emitter (emitter grounded), Common Collector (emitter follower) or in Common Base configurations. In this tutorial we will look at the bipolar transistor connected in a common emitter configuration seen previously.

Common Emitter Amplifier

The so called classic common emitter configuration uses a potential divider network to bias the transistors Base. Power supply \( V_{cc} \) and the biasing resistors set the transistor operating point to conduct in the forward active mode. With no signal current flow into the Base, no Collector current flows, (transistor in cut-off) and the voltage on the Collector is the same as the supply voltage, \( V_{cc} \). A signal current into the Base causes a current to flow in the Collector resistor, \( R_c \) generating a voltage drop across it which causes the Collector voltage to drop.

Then the direction of change of the Collector voltage is opposite to the direction of change on the Base, in other words, the polarity is reversed. Thus the common emitter configuration produces a large voltage amplification and a well defined DC voltage level by taking the output voltage from across the collector as shown with resistor \( R_L \) representing the load across the output.

Single Stage Common Emitter Amplifier

Hopefully by now we are able to calculate the values of the resistors required for the transistor to operate in the middle of its linear active region, called the quiescent point or Q point, but a quick refresher will help us understand better how the amplifiers values were obtained so that we can use the above circuit to find the input impedance of the amplifier.

Firstly lets start by making a few simple assumptions about the single stage common emitter amplifier circuit above to define the operating point of the transistor. The voltage drop across the the Emitter resistor, $V_{RE} = 1.5V$, the quiescent current, $I_Q = 1mA$, the current gain (Beta) of the NPN transistor is 100 ($\beta = 100$), and the corner or breakpoint frequency of the amplifier is given as: $f_{-3dB} = 40Hz$.

As the quiescent current with no input signal flows through the Collector and Emitter of the transistor, then we can say that: $I_C = I_E = I_Q = 1mA$. So by using Ohms Law:

$$R_E = \frac{V_{RE}}{I_E} = \frac{1.5V}{1mA} = 1500\Omega \text{ or } 1.5k\Omega$$

With the transistor switched fully-ON (saturation), the voltage drop across the Collector resistor, $R_C$ will be half of $V_{CC} - V_{RE}$ to allow for maximum output signal swing from peak-to-peak around the center point without clipping of the output signal.

$$V_{RC} = \frac{V_{CC} - V_{RE}}{2} = \frac{12 - 1.5}{2} \equiv 5V$$

$$\therefore R_C = \frac{V_{RC}}{I_C} = \frac{5}{1mA} = 5k\Omega$$

Note that the DC no signal voltage gain of the amplifier can be found from $-R_C/R_E$. Also notice that the voltage gain is negative in value due to the fact that the output signal has been inverted with respect to the original input signal.

As the NPN transistor is forward biased, the Base-Emitter junction acts like a forward biased diode so the Base will be 0.7 volts more positive than the Emitter voltage ( $V_e + 0.7V$ ), therefore the voltage across the Base resistor $R_2$ will be:

$$V_{R2} = V_{RE} + V_{BE} = 1.5 + 0.7 = 2.2V$$

If the two biasing resistors are already given, we can also use the following standard voltage divider formula to find the Base voltage $V_{b}$ across $R_2$.

$$V_{R2} = V_{CC} \left[ \frac{R_2}{R_1 + R_2} \right]$$

The information given stated that the quiescent current is 1mA. Thus the transistor is biased with a Collector current of 1mA across the 12 volt supply, $V_{CC}$. This Collector current is proportional to the Base current as $I_C = \beta I_B$. The DC current gain, Beta ($\beta$) of the transistor was given as 100, then
the Base current flowing into the transistor will be:

\[ \beta = 100 = \frac{I_c}{I_b} \quad \therefore \quad I_b = \frac{I_c}{\beta} = \frac{1mA}{100} = 10\mu A \]

The DC bias circuit formed by the voltage divider network of \( R_1 \) and \( R_2 \) sets the DC operating point. The Base voltage was previously calculated at 2.2 volts then we need to establish the proper ratio of \( R_1 \) to \( R_2 \) to produce this voltage value across the 12 volt supply, \( V_{cc} \).

Generally, for a standard voltage divider DC biasing network of a common emitter amplifier circuit, the current flowing through the lower resistor, \( R_2 \) is ten times greater than the DC current flowing into the Base. Then the value of resistor, \( R_2 \) can be calculated as:

\[ I_{R_2} = 10 \times I_b = 10 \times 10\mu A = 100\mu A \]

\[ R_2 = \frac{V_{R_2}}{I_{R_2}} = \frac{2.2V}{100\mu A} = 22k\Omega \]

The voltage dropped across resistor \( R_1 \) will be the supply voltage minus the Base bias voltage. Also if resistor \( R_2 \) carries 10 times the Base current, upper resistor \( R_1 \) of the series chain must pass the current of \( R_2 \) plus the transistors actual Base current, \( I_b \). In other words, 11 times the Base current as shown.

\[ V_{R_1} = V_{cc} - V_B = 12 - 2.2 = 9.8V \]

\[ I_{R_1} = I_{R_2} + I_B = 100\mu A + 10\mu A = 110\mu A \]

\[ \therefore \quad R_1 = \frac{V_{R_1}}{I_{R_1}} = \frac{9.8V}{110\mu A} = 90k\Omega \]

For a common emitter amplifier, the reactance \( X_c \) of the Emitter bypass capacitor is usually one tenth (1/10th) the value of the Emitter resistor, \( R_E \) at the cut-off frequency point. The amplifiers specifications gave a -3dB corner frequency of 40Hz, then the value of capacitor \( C_E \) is calculated as:

\[ \text{at } 40Hz, \quad X_C = \frac{1}{10} \times R_E = \frac{1500}{10} = 150\Omega \]

\[ C_E = \frac{1}{2\pi f X_C} = \frac{1}{2\pi \times 40 \times 150} = 27\mu F \]
Now we have the values established for our common emitter amplifier circuit above, we can now look at calculating its input and output impedance of amplifier as well as the values of the coupling capacitors C1 and C2.

**Basic Emitter Amplifier Model**

The generalised formula for the input impedance of any circuit is $Z_{IN} = V_{IN}/I_{IN}$. The DC bias circuit sets the DC operating “Q” point of the transistor and as the input capacitor, C1 acts as an open circuit and blocks any DC voltage, at DC (0Hz) the input impedance ($Z_{IN}$) of the circuit will be extremely high. However when an AC signal is applied to the input, the characteristics of the circuit changes as capacitors act as short circuits at high frequencies and pass AC signals.

The generalised formula for the AC input impedance of an amplifier looking into the Base is given as $Z_{IN} = R_{EQ}||\beta(R_E + r_e)$. Where $R_{EQ}$ is the equivalent resistance to ground (0v) of the biasing network across the Base, and $r_e$ is the internal signal resistance of the forward biased Emitter layer.

Then if we short out the 12 volt power supply, $V_{CC}$ to ground because $V_{CC}$ appears as a short to AC signals, we can redraw the common emitter circuit above as follows:

**Amplifier Circuit Model**

Then we can see that with the supply voltage shorted, there are a number of resistors connected in parallel across the transistor. By taking the input side of the transistor amplifier only and treating capacitor C1 as a short circuit to AC signals, we can redraw the above circuit to define the input impedance of the amplifier as:

**Input Impedance of Amplifier**

![Input Impedance of Amplifier Diagram](https://www.electronics-tutorials.ws/amplifier/input-impedance-of-an-amplifier.html)
We said in the previous Common Emitter Amplifier tutorial that the internal signal resistance of the Emitter layer was equal to the product of \( 25\text{mV} \div I_e \) with this \( 25\text{mV} \) value being the internal volt drop and \( I_E = I_Q \). Then for our amplifier circuit above the equivalent AC resistance value \( r_E \) of the Emitter diode is given as:

**Emitter Leg Signal Resistance**

\[
    r_E = \frac{25\text{mV}}{I_E} = \frac{25\text{mV}}{1\text{mA}} = 25\Omega
\]

Where \( r_E \) represents a small internal resistor in series with the Emitter. Since \( I_c/I_b = \beta \), then the value of the transistors Base impedance will be equal to \( \beta \cdot r_E \). Note that if bypass capacitor \( C_E \) is not included within the amplifiers design, then the value becomes: \( \beta (R_E + r_E) \) significantly increasing the input impedance of the amplifier.

In our example bypass capacitor, \( C_E \) is included, therefore the input impedance, \( Z_{IN} \) of the common Emitter amplifier is the input impedance “seen” by the AC source driving the amplifier and is calculated as:

**Input Impedance Equation**

\[
    Z_{IN} = R_1 || R_2 || \beta (r_E)
\]

\[
    \frac{1}{Z_{IN}} = \frac{1}{R_1} + \frac{1}{R_2} + \frac{1}{\beta (r_E)}
\]

\[
    \frac{1}{Z_{IN}} = \frac{1}{90k} + \frac{1}{22k} + \frac{1}{100 \times 25}
\]

\[\therefore Z_{IN} = 2190\Omega, \text{ or } 2.2k\Omega\]

This 2.2\(k\Omega \) is the input impedance looking into the input terminal of the amplifier. If the impedance value of the source signal is known, and in our simple example above it is given as 1\(k\Omega \), then this value can be added or summed with \( Z_{IN} \) if required.

But lets assume for one minute that our circuit has no bypass capacitor, \( C_E \) connected. What would be the input impedance of the amplifier without it. The equation would still be the same except for the addition of \( R_E \) in the \( \beta (R_E + r_E) \) part of the equation as the resistor will no longer be shorted at high frequencies. Then the unbypassed input impedance of our amplifier circuit without \( C_E \) will be:

**Input Impedance without Bypass Capacitor**
Then we can see that the inclusion of the Emitter leg bypass capacitor makes a huge difference to the input impedance of the circuit as the impedance goes down from 15.8kΩ without it to 2.2kΩ with it in our example circuit. We will see later that the addition of this bypass capacitor, \( C_E \) also increases the amplifiers gain.

In our calculations to find the input impedance of the amplifier, we have assumed that the capacitors in the circuit have zero impedance (\( X_c = 0 \)) for AC signal currents, as well as infinite impedance (\( X_c = \infty \)) for DC biasing currents. Now that we know the bypassed input impedance of the amplifier circuit, we can use this value of 2.2kΩ to find the value of the input coupling capacitor, \( C_1 \) required at the specified cut-off frequency point which was given previously as 40Hz. Therefore:

\[
\frac{1}{Z_{in}} = \frac{1}{90k} + \frac{1}{22k} + \frac{1}{100(1500+25)}
\]

\[
\therefore Z_{in} = 15842\Omega, \text{ or } 15.8k\Omega
\]

**Input Coupling Capacitor Equation**

\[
C_1 = \frac{1}{2\pi f_{3dB} Z_{in}} = \frac{1}{2\pi(40Hz)(2.2k\Omega)} = 1.8\mu F
\]

Now that we have a value for the input impedance of our single stage common Emitter amplifier circuit above, we can also obtain an expression for the output impedance of the amplifier in a similar fashion.

**Output Impedance of an Amplifier**

The **Output Impedance** of an amplifier can be thought of as being the impedance (or resistance) that the load sees “looking back” into the amplifier when the input is zero. Working on the same principle as we did for the input impedance, the generalised formula for the output impedance can be given as: \( Z_{out} = V_{CE}/I_C \).

But the signal current flowing in the Collector resistor, \( R_C \) also flows in the load resistor, \( R_L \) as the two are connected in series across \( V_{cc} \). Then again, by taking the output side of the transistor amplifier only and treating the output coupling capacitor \( C_2 \) as a short circuit to AC signals, we can redraw the above circuit to define the output impedance of the amplifier as:

**Output Impedance of Amplifier**

\[
Z_{in} = R_1 || R_2 || \beta(R_E + re)
\]

\[
\frac{1}{Z_{in}} = \frac{1}{R_1} + \frac{1}{R_2} + \frac{1}{\beta(R_E + re)}
\]

\[
\frac{1}{Z_{in}} = \frac{1}{90k} + \frac{1}{22k} + \frac{1}{100(1500+25)}
\]

\[
\therefore Z_{in} = 15842\Omega, \text{ or } 15.8k\Omega
\]
Then we can see that the output signal resistance is equal to $R_C$ in parallel with $R_L$ giving us an output resistance of:

**Output Impedance Equation**

$$Z_{OUT} = R_C \parallel R_L$$

$$\frac{1}{Z_{OUT}} = \frac{1}{R_C} + \frac{1}{R_L}$$

$$\frac{1}{Z_{OUT}} = \frac{1}{5k} + \frac{1}{1k} = 833\Omega$$

Note that this value of 833Ω results from the fact that the load resistance is connected across the transistor. If $R_L$ is omitted, then the output impedance of the amplifier would be equal to the Collector resistor, $R_C$ only.

Now that we have a value for the output impedance of our amplifier circuit above, we can calculate the value of the output coupling capacitor, $C_2$ as before at the 40Hz cut-off frequency point.

**Output Coupling Capacitor Equation**

$$C_2 = \frac{1}{2\pi f_{3dB} Z_{OUT}} = \frac{1}{2\pi(40Hz)(833\Omega)} = 4.7\mu F$$

Again the value of coupling capacitor $C_2$ can be calculated either with or without the inclusion of load resistor $R_L$.

**Common Emitter Voltage Gain**

The voltage gain of a common emitter circuit is given as $Av = R_{OUT}/R_{EMITTER}$ where $R_{OUT}$ represents the output impedance as seen in the Collector leg and $R_{EMITTER}$ is equal the the equivalent resistance in the Emitter leg either with or without the
bypass capacitor connected.

Without the bypass capacitor \( C_E \) connected, \((R_E + re)\).

\[
A_v = \frac{R_{OUT}}{R_E + re} = \frac{833\Omega}{1.5k\Omega + 25\Omega} = 0.546
\]

and with the bypass capacitor \( C_E \) connected, \((re)\) only.

\[
A_v = \frac{R_{OUT}}{re} = \frac{833\Omega}{25\Omega} = 33.3
\]

Then we can see that the inclusion of the bypass capacitor within the amplifier design makes a dramatic change to the voltage gain, \( A_v \) of our common emitter circuit from 0.5 to 33. It also shows that the common emitter gain does not go to infinity when the external emitter resistor is shorted by the bypass capacitor at high frequencies but instead the gain goes to the finite value of \( \frac{R_{OUT}}{re} \).

We have also seen that as the gain goes up the input impedance goes down from 15.8k\( \Omega \) without it to 2.2k\( \Omega \) with it. The increase in voltage gain can be considered an advantage in most amplifier circuits at the expense of a lower input impedance.

**Input Impedance Summary**

In this tutorial we have seen that the input impedance of a common emitter amplifier can be found by shorting out the supply voltage and treating the voltage divider biasing circuit as resistors in parallel. The impedance “seen” looking into the divider network \((R1||R2)\) is generally much less that the impedance looking directly into the transistors Base, \( \beta(R_E + re) \) as the AC input signal changes the bias on the Base of the transistor controlling the current flow through the transistor.

There are many ways to bias the transistor. Thus, there are many practical single transistor amplifier circuits each with their own input impedance equations and values. If you require the input impedance of the whole stage plus source impedance, then you will need to consider \( Rs \) in series with the base bias resistors as well, \((Rs + R1||R2)\).

The output impedance of a common emitter stage is just equal to the collector resistor in parallel with the load resistor \((R_C||R_L)\) if connected otherwise its just \( R_C \). The voltage gain, \( A_v \) of the amplifier is dependant upon \( R_C/R_E \).

The emitter bypass capacitor, \( C_E \) can provide an AC ground path for the Emitter, shorting out the emitter resistor, \( R_E \) leaving only the signal Emitter resistance, \( re \) in the Emitter leg. The effect of this is an increase in the gain of the amplifier (from 0.5 to 33) at high frequencies but also a decrease in the amplifiers input impedance value, (from 18.5k\( \Omega \) to 2.2k\( \Omega \)).

With this bypass capacitor removed, the amplifiers voltage gain, \( A_v \) decreases and \( Z_{IN} \) increases. One way to maintain a fixed amount of gain and input impedance is to include an additional resistor in series with \( C_E \) to create what is called a “split-emitter” amplifier circuit that is a trade-off between an unbypassed and a fully bypassed amplifier circuit. Note that the addition or removal of this bypass capacitor has no effect on the amplifiers output impedance.
Then we can see that the input and output impedances of an amplifier can play an important role in defining the transfer characteristics of an amplifier with regards to the relationship between the output current, $I_c$ and the input current, $I_b$. Knowing an amplifiers input impedance can help to graphically construct a set of output characteristics curves for the amplifier.
**Frequency Response**

Frequency Response of an amplifier or filter shows how the gain of the output responds to input signals at different frequencies.

Amplifiers and filters are widely used electronic circuits that have the properties of amplification and filtration, hence their names.

Amplifiers produce gain while filters alter the amplitude and/or phase characteristics of an electrical signal with respect to its frequency. As these amplifiers and filters use resistors, inductors, or capacitor networks (RLC) within their design, there is an important relationship between the use of these reactive components and the circuits frequency response characteristics.

When dealing with AC circuits it is assumed that they operate at a fixed frequency, for example either 50 Hz or 60 Hz. But the response of a linear AC circuit can also be examined with an AC or sinusoidal input signal of a constant magnitude but with a varying frequency such as those found in amplifier and filter circuits. This then allows such circuits to be studied using frequency response analysis.

**Frequency Response** of an electric or electronics circuit allows us to see exactly how the output gain (known as the magnitude response) and the phase (known as the phase response) changes at a particular single frequency, or over a whole range of different frequencies from 0Hz, (d.c.) to many thousands of mega-hertz, (MHz) depending upon the design characteristics of the circuit.

Generally, the frequency response analysis of a circuit or system is shown by plotting its gain, that is the size of its output signal to its input signal, Output/Input against a frequency scale over which the circuit or system is expected to operate. Then by knowing the circuits gain, (or loss) at each frequency point helps us to understand how well (or badly) the circuit can distinguish between signals of different frequencies.

The frequency response of a given frequency dependent circuit can be displayed as a graphical sketch of magnitude (gain) against frequency \( f \). The horizontal frequency axis is usually plotted on a logarithmic scale while the vertical axis representing the voltage output or gain, is usually drawn as a
linear scale in decimal divisions. Since a system's gain can be both positive or negative, the y-axis can therefore have both positive and negative values.

In Electronics, the Logarithm, or “log” for short is defined as the power to which the base number must be raised to get that number. Then on a Bode plot, the logarithmic x-axis scale is graduated in \( \log_{10} \) divisions, so every decade of frequency (e.g., 0.01, 0.1, 1, 10, 100, 1000, etc.) is equally spaced onto the x-axis. The opposite of the logarithm is the antilogarithm or “antilog”.

Graphical representations of frequency response curves are called **Bode Plots** and as such Bode plots are generally said to be a semi-logarithmic graphs because one scale (x-axis) is logarithmic and the other (y-axis) is linear (log-lin plot) as shown.

**Frequency Response Curve**

Then we can see that the frequency response of any given circuit is the variation in its behaviour with changes in the input signal frequency as it shows the band of frequencies over which the output (and the gain) remains fairly constant. The range of frequencies either big or small between \( f_L \) and \( f_H \) is called the circuit's bandwidth. So from this we are able to determine at a glance the voltage gain (in dB) for any sinusoidal input within a given frequency range.

As mentioned above, the Bode diagram is a logarithmic presentation of the frequency response. Most modern audio amplifiers have a flat frequency response as shown above over the whole audio range of frequencies from 20 Hz to 20 kHz. This range of frequencies, for an audio amplifier is called its Bandwidth, (BW) and is primarily determined by the frequency response of the circuit.

Frequency points \( f_L \) and \( f_H \) relate to the lower corner or cut-off frequency and the upper corner or cut-off frequency points respectively were the circuits gain falls off at high and low frequencies. These points on a frequency response curve are known commonly as the -3dB (decibel) points. So the bandwidth is simply given as:

\[
\text{Bandwidth, (BW)} = f_H - f_L
\]

The decibel, (dB) which is \( 1/10^{th} \) of a bel (B), is a common non-linear unit for measuring gain and is defined as \( 20 \log_{10}(A) \) where A is the decimal gain, being plotted on the y-axis. Zero decibels, (0dB) corresponds to a magnitude function of unity giving the maximum output. In other words, 0dB occurs when \( V_{out} = V_{in} \) as there is no attenuation at this frequency level and is given as:

\[
V_{out} = V_{in}
\]
We see from the Bode plot above that at the two corner or cut-off frequency points, the output drops from 0dB to -3dB and continues to fall at a fixed rate. This fall or reduction in gain is known commonly as the roll-off region of the frequency response curve. In all basic single order amplifier and filter circuits this roll-off rate is defined as 20dB/decade, which is an equivalent to a rate of 6dB/octave. These values are multiplied by the order of the circuit.

These -3dB corner frequency points define the frequency at which the output gain is reduced to 70.71% of its maximum value. Then we can correctly say that the -3dB point is also the frequency at which the systems gain has reduced to 0.707 of its maximum value.

**Frequency Response -3dB Point**

\[
-3\, \text{dB} = 20 \log_{10}(0.7071)
\]

The -3dB point is also know as the half-power points since the output power at this corner frequencies will be half that of its maximum 0dB value as shown.

\[
P = \frac{V^2}{R} = I^2 \times R
\]

At \( f_L \) or \( f_H \),

\( V \) or \( I \) = 70.71\% of maximum or 0.7071\( \text{max} \)

If \( R = 1 \), then \( P = \frac{(0.7071 \times V)^2}{1} \) or \( (0.7071 \times I)^2 \times 1 \)

\[
\therefore P = 0.5V \ or \ 0.5I
\]

Therefore the amount of output power delivered to the load is effectively “halved” at the cut-off frequency and as such the bandwidth (BW) of the frequency response curve can also be defined as the range of frequencies between these two half-power points.

While for voltage gain we use \( 20 \log_{10}(Av) \), and for current gain \( 20 \log_{10}(Ai) \), for power gain we use \( 10 \log_{10}(Ap) \). Note that the multiplying factor of 20 does not mean that it is twice as much as 10 as the decibel is a unit of the power ratio and not a measure of the actual power level. Also gain in dB can be either positive or negative with a positive value indicating gain and a negative value attenuation.

Then we can present the relationship between voltage, current and power gain in the following table.
<table>
<thead>
<tr>
<th>dB Gain</th>
<th>Voltage or Current Gain $\frac{20\log_{10}(A)}{}$</th>
<th>Power Gain $10\log_{10}(A)$</th>
</tr>
</thead>
<tbody>
<tr>
<td>-6</td>
<td>0.5</td>
<td>0.25</td>
</tr>
<tr>
<td>-3</td>
<td>0.7071 or $\frac{1}{\sqrt{2}}$</td>
<td>0.5</td>
</tr>
<tr>
<td>0</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>3</td>
<td>1.414 or $\sqrt{2}$</td>
<td>2</td>
</tr>
<tr>
<td>6</td>
<td>2</td>
<td>4</td>
</tr>
<tr>
<td>10</td>
<td>3.2</td>
<td>10</td>
</tr>
<tr>
<td>20</td>
<td>10</td>
<td>100</td>
</tr>
<tr>
<td>30</td>
<td>32</td>
<td>1,000</td>
</tr>
<tr>
<td>40</td>
<td>100</td>
<td>10,000</td>
</tr>
<tr>
<td>60</td>
<td>1,000</td>
<td>1,000,000</td>
</tr>
</tbody>
</table>

Operational amplifiers can have open-loop voltage gains, $(A_{VO})$ in excess of 1,000,000 or 100dB.

**Decibels Example No1**

If an electronic system produces a 24mV output voltage when a 12mV signal is applied, calculate the decibel value of the systems output voltage.

\[
A_V \text{ dB} = 20 \log_{10} (A_V)
\]

\[
A_V \text{ dB} = 20 \log_{10} \left( \frac{V_{\text{OUT}}}{V_{\text{IN}}} \right) = 20 \log_{10} \left( \frac{24 \text{mV}}{12 \text{mV}} \right) = 20 \log_{10} (2)
\]

\[
\therefore \quad A_V \text{ dB} = 6 \text{ dB}
\]

**Decibels Example No2**

If the output power from an audio amplifier is measured at 10W when the signal frequency is 1kHz, and 1W when the signal frequency is 10kHz. Calculate the dB change in power.

\[
A_P \text{ dB} = 10 \log_{10} \left( \frac{P_{\text{OUT}}}{P_{\text{IN}}} \right)
\]

\[
A_P \text{ dB} = 10 \log_{10} \left( \frac{10W}{1W} \right) = 10 \log_{10} (10)
\]

\[
\therefore \quad A_P \text{ dB} = 10 \text{ dB}
\]
In this tutorial we have seen how the range of frequencies over which an electronic circuit operates is determined by its **frequency response**. The frequency response of a device or a circuit describes its operation over a specified range of signal frequencies by showing how its gain, or the amount of signal it lets through changes with frequency.

Bode plots are graphical representations of the circuits frequency response characteristics and as such can be used in solving design problems. Generally, the circuits gain magnitude and phase functions are shown on separate graphs using logarithmic frequency scale along the x-axis.

Bandwidth is the range of frequencies that a circuit operates at in between its upper and lower cut-off frequency points. These cut-off or corner frequency points indicate the frequencies at which the power associated with the output falls to half its maximum value. These half power points corresponds to a fall in gain of 3dB (0.7071) relative to its maximum dB value.

Most amplifiers and filters have a flat frequency response characteristic in which the bandwidth or passband section of the circuit is flat and constant over a wide range of frequencies. Resonant circuits are designed to pass a range of frequencies and block others. They are constructed using resistors, inductors, and capacitors whose reactances vary with the frequency, their frequency response curves can look like a sharp rise or point as their bandwidth is affected by resonance which depends on the Q of the circuit, as a higher Q provides a narrower bandwidth.

\[
A_F \text{ dB} = 10 \log_{10}(A_P)
\]

\[
A_F \text{ dB} = 10 \log_{10}\left(\frac{P_{\text{OUT}}}{P_{\text{IN}}}ight) = 10 \log_{10}\left(\frac{1W}{10W}\right) = 10 \log_{10}(0.1)
\]

\[\therefore A_P \text{ dB} = -10 \text{ dB}\]
MOSFET Amplifier

MOSFET Amplifier uses a metal-oxide silicon transistor connected in the common source configuration.

In our previous tutorial about FET amplifiers, we saw that simple single stage amplifiers can be made using junction field effect transistors, or JFET’s. But there are other types of field effect transistors available which can be used to construct and amplifier, and in this tutorial we will look at the MOSFET Amplifier.

Metal Oxide Semiconductor Field Effect Transistor, or MOSFET for short, is an excellent choice for small signal linear amplifiers as their input impedance is extremely high making them easy to bias. But for a mosfet to produce linear amplification, it has to operate in its saturation region, unlike the Bipolar Junction Transistor. But just like the BJT, it too needs to be biased around a centrally fixed Q-point.

MOSFETS conduct through a conductive region or path called “the channel”. We can make this conductive channel wider or smaller by applying a suitable gate potential. An electric field induced around the gate terminal by the application of this gate voltage affects the electrical characteristics of the channel, thus the name field-effect transistor.

In other words, we can control how the mosfet operates by creating or “enhancing” its conductive channel between the source and drain regions producing a type of mosfet commonly called an n-channel Enhancement-mode MOSFET, which simply means that unless we bias them positively on the gate (negatively for the p-channel), no channel current will flow.

There are large variations in the characteristics of different types of mosfets, and hence the biasing of a mosfet must be done individually. As with the bipolar transistor common emitter configuration, the common source mosfet amplifier
needs to be biased at a suitable quiescent value. But first let’s remind ourselves of the mosfets basic characteristics and configuration.

Enhancement N-channel MOSFET

Note that the fundamental differences between a Bipolar Junction Transistor and a FET are that a BJT has terminals labelled Collector, Emitter and Base, while a MOSFET has terminals labelled Drain, Source and Gate respectively.

Also the MOSFET differs from the BJT in that there is no direct connection between the gate and channel, unlike the base-emitter junction of the BJT, as the metal gate electrode is electrically insulated from the conductive channel giving it the secondary name of Insulated Gate Field Effect Transistor, or IGFET.

We can see that for the n-channel MOSFET (NMOS) above the substrate semiconductor material is p-type, while the source and drain electrodes are n-type. The supply voltage will be positive. Biasing the gate terminal positive attracts electrons within the p-type semiconductor substrate under the gate region towards it.

This over abundance of free electrons within the p-type substrate causes a conductive channel to appear or grow as the electrical properties of the p-type region invert, effectively changing the p-type substrate into a n-type material allowing channel current to flow.

The reverse is also true for the p-channel MOSFET (PMOS), where a negative gate potential causes a build of holes under the gate region as they are attracted to the electrons on the outer side of the metal gate electrode. The result is that the n-type substrate creates a p-type conductive channel.

So for our n-type MOS transistor, the more positive potential we put on the gate the greater the build-up of electrons around the gate region and the wider the conductive channel becomes. This enhances the electron flow through the channel allowing more channel current to flow from drain to source leading to the name of **Enhancement MOSFET**.

Enhancement MOSFET Amplifier

Enhancement MOSFET, or eMOSFET, can be classed as normally-off (non-conducting) devices, that is they only conduct when a suitable gate-to-source positive voltage is applied, unlike Depletion type mosfets which are normally-on devices conducting when the gate voltage is zero.
However, due to the construction and physics of an enhancement type mosfet, there is a minimum gate-to-source voltage, called the threshold voltage $V_{TH}$ that must be applied to the gate before it starts to conduct allowing drain current to flow.

In other words, an enhancement mosfet does not conduct when the gate-source voltage, $V_{GS}$ is less than the threshold voltage, $V_{TH}$ but as the gates forward bias increases, the drain current, $I_D$ (also known as drain-source current $I_{DS}$) will also increase, similar to a bipolar transistor, making the eMOSFET ideal for use in mosfet amplifier circuits.

The characteristics of the MOS conductive channel can be thought of as a variable resistor that is controlled by the gate. The amount of drain current that flows through this n-channel therefore depends on the gate-source voltage and one of the many measurements we can take using a mosfet is to plot a transfer characteristics graph to show the i-v relationship between the drain current and the gate voltage as shown.

**N-channel eMOSFET I-V Characteristics**

With a fixed $V_{DS}$ drain-source voltage connected across the eMOSFET we can plot the values of drain current, $I_D$ with varying values of $V_{GS}$ to obtain a graph of the mosfets forward DC characteristics. These characteristics give the transconductance, $g_m$ of the transistor.

This transconductance relates the output current to the input voltage representing the gain of the transistor. The slope of the transconductance curve at any point along it is therefore given as: $g_m = \frac{I_D}{V_{GS}}$ for a constant value of $V_{DS}$.

So for example, assume a MOS transistor passes a drain current of 2mA when $V_{GS} = 3v$ and a drain current of 14mA when $V_{GS} = 7v$. Then:

$$g_m = \frac{\Delta I_D}{\Delta V_{GS}} = \frac{(14 - 2)\times 10^{-3}}{7-3} = 3 mS$$

This ratio is called the transistors static or DC transconductance which is short for “transfer conductance” and is given the unit of Siemens (S), as its amps per volt. Voltage gain of a mosfet amplifier is directly proportional to the transconductance and to the value of the drain resistor.
At $V_{GS} = 0$, no current flows through the MOS transistors channel because the field effect around the gate is insufficient to create or “open” the n-type channel. Then the transistor is in its cut-off region acting as an open switch. In other words, with zero gate voltage applied the n-channel eMOSFET is said to be normally-off and this “OFF” condition is represented by the broken channel line in the eMOSFET symbol (unlike the depletion types that have a continuous channel line).

As we now gradually increase the positive gate-source voltage $V_{GS}$, the field effect begins to enhance the channel regions conductivity and there becomes a point where the channel starts to conduct. This point is known as the threshold voltage $V_{TH}$. As we increase $V_{GS}$ more positive, the conductive channel becomes wider (less resistance) with the amount of drain current, $I_D$ increases as a result. Remember that the gate never conducts any current as its electrical isolated from the channel giving a mosfet amplifier an extremely high input impedance.

Therefore the n-channel enhancement mosfet will be in its cut-off mode when the gate-source voltage, $V_{GS}$ is less than its threshold voltage level, $V_{TH}$ and its channel conducts or saturates when $V_{GS}$ is above this threshold level. When the eMOS transistor is operating in the saturation region the drain current, $I_D$ is given by:

**eMOSFET Drain Current**

$$I_D = k(V_{GS} - V_{TH})^2$$

Note that the values of $k$ (conduction parameter) and $V_{TH}$ (threshold voltage) vary from one eMOSFET to the next and can not be physically changed. This is because they are specific specification relating to the material and device geometry which are in-built during the fabrication of the transistor.

The static transfer characteristics curve on the right is generally parabolic (square law) in shape and then linear. The increase in drain current, $I_D$ for a given increase in gate-source voltage, $V_{GS}$ determines the slope or gradient of the curve for constant values of $V_{DS}$.

Then we can see that turning an enhancement MOS transistor “ON” is a gradual process and in order for us to use the MOSFET as an amplifier we must bias its gate terminal at some point above its threshold level.

There are many different ways we can do this from using two separate voltage supplies, to drain feedback biasing, to zener diode biasing, etc, etc. But whichever biasing method we use, we must make sure that the gate voltage is more positive than the source by an amount greater than $V_{TH}$. In this mosfet amplifier tutorial we will use the now familiar universal voltage divider biasing circuit.

**DC Biasing the MOSFET**

The universal voltage divider biasing circuit is a popular biasing technique used to establish a desired DC operating condition of bipolar transistor amplifiers as well as mosfet amplifiers. The advantage of the voltage divider biasing network is that the MOSFET, or indeed a bipolar transistor, can be biased from a single DC supply. But first we need to know where to bias the gate for our mosfet amplifier.

A mosfet device has three different regions of operation. These regions are called the: **Ohmic/Triode region**, **Saturation/Linear region** and **Pinch-off point**. For a mosfet to operate as a linear amplifier, we need to establish a well-defined quiescent operating point, or Q-point, so it must be biased to operate...
in its saturation region. The Q-point for the mosfet is represented by the DC values, \( I_D \) and \( V_{GS} \) that position the operating point centrally on the mosfets output characteristics curve.

As we have seen above, the saturation region begins when \( V_{GS} \) is above the \( V_{TH} \) threshold level. Therefore if we apply a small AC signal which is superimposed on to this DC bias at the gate input, then the MOSFET will act as a linear amplifier as shown.

**eMOSFET DC Bias Point**

![Diagram](https://www.electronics-tutorials.ws/amplifier/mosfet-amplifier.html)

The common-source NMOS circuit above shows that the sinusoidal input voltage, \( V_I \) is in series with a DC source. This DC gate voltage will be set by the bias circuit. Then the total gate-source voltage will be the sum of \( V_{GS} \) and \( V_I \).

The DC characteristics and therefore Q-point (quiescent point) are all functions of gate voltage \( V_{GS} \), supply voltage \( V_{DD} \) and load resistance \( R_D \).

The MOS transistor is biased within the saturation region to establish the desired drain current which will define the transistors Q-point. As the instantaneous value of \( V_{GS} \) increases, the bias point moves up the curve as shown allowing a larger drain current to flow as \( V_{DS} \) decreases.

Likewise, as the instantaneous value of \( V_{GS} \) decreases (during the negative half of the input sine wave), the bias point moves down the curve and a smaller \( V_{GS} \) results in a smaller drain current and increased \( V_{DS} \).

Then in order to establish a large output swing we must bias the transistor well above threshold level to ensure that the transistor stays in saturation over the full sinusoidal input cycle. However, there is a limit on the amount of gate bias and drain current we can use. To allow for maximum voltage swing of the output, the Q-point should be positioned approximately halfway between the supply voltage \( V_{DD} \) and the threshold voltage \( V_{TH} \).

So for example, lets assume we want to construct a single stage NMOS common-source amplifier. The threshold voltage, \( V_{TH} \) of the eMOSFET is 2.5 volts and the supply voltage, \( V_{DD} \) is +15 volts. Then the DC bias point will be \( 15 - 2.5 = 12.5 \) volts or 6 volts to the nearest integer value.

**The MOSFETS \( I_D \) – \( V_{DS} \) Characteristics**

We have seen above that we can construct a graph of the mosfets forward DC characteristics by keeping the supply voltage, \( V_{DD} \) constant and increasing the gate voltage, \( V_G \). But in order to get a complete picture of the operation of the n-type enhancement MOS transistor to use within a mosfet
amplifier circuit, we need to display the output characteristics for different values of both \( V_{DD} \) and \( V_{GS} \).

As with the NPN Bipolar Junction Transistor, we can construct a set of output characteristics curves showing the drain current, \( I_D \) for increasing positive values of \( V_G \) for an n-channel enhancement-mode MOS transistor as shown.

N-type eMOSFET Characteristics Curves

Note that a p-channel eMOSFET device would have a very similar set of drain current characteristics curves but the polarity of the gate voltage would be reversed.

Basic Common Source MOSFET Amplifier

Previously we look at how to establish the desired DC operating condition to bias the n-type eMOSFET. If we apply a small time-varying signal to the input, then under the right circumstances the mosfet circuit can act as a linear amplifier providing the transistors Q-point is somewhere near the center of the saturation region, and the input signal is small enough for the output to remain linear. Consider the basic mosfet amplifier circuit below.

Basic MOSFET Amplifier
This simple enhancement-mode common source mosfet amplifier configuration uses a single supply at the drain and generates the required gate voltage, $V_G$, using a resistor divider. We remember that for a MOSFET, no current flows into the gate terminal and from this we can make the following basic assumptions about the MOSFET amplifiers DC operating conditions.

\[ V_{DD} = I_D R_D + V_{DS} + I_D R_S \]
\[ = I_D (R_D + R_S) + V_{DS} \]

\[ \therefore R_D + R_S = \frac{V_{DD} - V_{DS}}{I_D} \]

Then from this we can say that:

\[ R_D = \frac{V_{DD} - V_D}{I_D} \quad \text{and} \quad R_S = \frac{V_S}{I_D} \]

and the mosfets gate-to-source voltage, $V_{GS}$ is given as:

\[ V_{GS} = V_G - I_S R_S \]

As we have seen above, for proper operation of the mosfet, this gate-source voltage must be greater than the threshold voltage of the mosfet, that is $V_{GS} > V_{TH}$. Since $I_S = I_D$, the gate voltage, $V_G$ is therefore equal too:
To set the mosfet amplifier gate voltage to this value we select the values of the resistors, \( R1 \) and \( R2 \) within the voltage divider network to the correct values. As we know from above, “no current” flows into the gate terminal of a mosfet device so the formula for voltage division is given as:

**MOSFET Amplifier Gate Bias Voltage**

\[
V_G = V_{DD} \left( \frac{R_2}{R_1 + R_2} \right)
\]

Note that this voltage divider equation only determines the ratio of the two bias resistors, \( R1 \) and \( R2 \) and not their actual values. Also it is desirable to make the values of these two resistors as large as possible to reduce their \( I^2R \) power loss and increase the mosfet amplifiers input resistance.

**MOSFET Amplifier Example No1**

An common source mosfet amplifier is to be constructed using a n-channel eMOSFET which has a conduction parameter of 50mA/V\(^2\) and a threshold voltage of 2.0 volts. If the supply voltage is +15 volts and the load resistor is 470 Ohms, calculate the values of the resistors required to bias the MOSFET amplifier at 1/3\( (V_{DD}) \). Draw the circuit diagram.

Values given: \( V_{DD} = +15 \text{v} \), \( V_{TH} = +2.0 \text{v} \), \( k = 50 \text{mA/V}^2 \) and \( R_D = 470 \Omega \).

1. Drain Current, \( I_D \)

\[
V_D = \frac{V_{DD}}{2} = \frac{15}{2} = 7.5 \text{v}
\]

\[
I_D = \frac{V_D}{R_D} = \frac{7.5}{470} = 16 \text{mA}
\]

2. Gate-source Voltage, \( V_{GS} \)

https://www.electronics-tutorials.ws/amplifier/mosfet-amplifier.html
\[ I_D = k(V_{GS} - V_{TH})^2 \]

\[ \therefore V_{GS} = \sqrt{\frac{I_D}{k}} + V_{TH} = \sqrt{\frac{0.016}{0.05}} + 2.0 = 2.6\text{v} \]

3. Gate Voltage, \( V_G \)

\[ V_G = \frac{1}{3}V_{DD} = \frac{15}{3} = 5\text{v} \]

\[ V_G = V_{GS} + V_S \]

\[ \therefore V_S = V_G - V_{GS} = 5 - 2.6 = 2.4\text{v} \]

Thus applying KVL across the mosfet, the drain-source voltage, \( V_{DS} \) is given as:

\[ V_{DD} = V_D + V_{DS} + V_S = 15\text{v} \]

\[ \therefore V_{DS} = V_{DD} - V_D - V_S = 15 - 7.5 - 2.4 = 5.1\text{v} \]

4. Source Resistance, \( R_S \)

\[ R_S = \frac{V_S}{I_D} = \frac{2.4}{0.016} = 150\Omega \]

The ratio of the voltage divider resistors, \( R_1 \) and \( R_2 \) required to give \( 1/3V_{DD} \) is calculated as:

\[ V_G = V_{DD}\left(\frac{R_2}{R_1 + R_2}\right) = 15\left(\frac{1}{3}\right) \]

If we choose: \( R_1 = 200k\Omega \) and \( R_2 = 100k\Omega \) this will satisfy the condition of: \( V_G = 1/3V_{DD} \). Also this combination of bias resistors will give an input resistance to the mosfet amplifier of approximately 67k\( \Omega \).
We can take this design one step further by calculating the values of the input and output coupling capacitors. If we assume a lower cut-off frequency for our mosfet amplifier of say, 20Hz, then the values of the two capacitors taking into account the input impedance of the gate biasing network is calculated as:

\[
R_{\text{in}} = \frac{R_1 \times R_2}{R_1 + R_2} = \frac{200k \times 100k}{100k + 200k} \approx 67k\Omega
\]

\[
f_{(-3\text{dB})} = 20\text{Hz} = \frac{1}{2\pi R_{\text{in}}C} \quad \therefore \quad C = \frac{1}{2\pi f R_{\text{in}}}
\]

\[
C = \frac{1}{2\pi \times 20 \times 67000} = 0.12\mu\text{F}
\]

Then the final circuit for the single stage **MOSFET Amplifier** circuit is given as:

**Single Stage MOSFET Amplifier**

![Single Stage MOSFET Amplifier Diagram](https://www.electronics-tutorials.ws/amplifier/mosfet-amplifier.html)

**MOSFET Amplifier Summary**

The main goal of a MOSFET amplifier, or any amplifier for that matter, is to produce an output signal that is a faithful reproduction of its input signal but amplified in magnitude. This input signal could be a current or a voltage, but for a mosfet device to operate as an amplifier it must be biased to operate within its saturation region.

There are two basic types of enhancement-mode MOSFETs, n-channel and p-channel and in this mosfet amplifier tutorial we have looked at the n-channel enhancement MOSFET is often referred to as an NMOS, as it can be operated with positive gate and drain voltages relative to the source as opposed to the p-channel PMOS which is operated with negative gate and drain voltages relative to the source.

https://www.electronics-tutorials.ws/amplifier/mosfet-amplifier.html
The saturation region of a mosfet device is its constant-current region above its threshold voltage, $V_{TH}$. Once correctly biased in the saturation region the drain current, $I_D$ varies as a result of the gate-to-source voltage, $V_{GS}$ and not by the drain-to-source voltage, $V_{DS}$ since the drain current is called saturated.

In an enhancement-mode MOSFET, the electrostatic field created by the application of a gate voltage enhances the conductivity of the channel, rather than deplete the channel as in the case of a depletion-mode MOSFET.

The threshold voltage is the minimum gate bias required to enable the formation of the channel between the source and the drain. Above this value the drain current increases in proportion to $(V_{GS} - V_{TH})^2$ in the saturation region allowing it to operate as an amplifier.
Class AB Amplifier

Class AB amplifier output stage combines the advantages of the Class A amplifier and the Class B amplifier producing a better amplifier design.

The purpose of any amplifier is to produce an output which follows the characteristics of the input signal but is sufficiently large enough to supply the needs of the load connected to it.

We have seen that the power output of an amplifier is the product of the voltage and current, \( P = V \times I \) applied to the load, while the power input is the product of the DC voltage and current taken from the power supply.

Although the amplification of a Class A amplifier, (where the output transistor conducts 100% of the time) can be high, the efficiency of the conversion from the DC power supply to an AC power output is generally poor at less than 50%. However if we modify the Class A amplifier circuit to operate in Class B mode, (where each transistor conducts for only 50% of the time) the collector current flows in each transistor for only 180° of the cycle. The advantage here is that the DC-to-AC conversion efficiency is much higher at about 75%, but this Class B configuration results in distortion of the output signal which can be unacceptable.

One way to produce an amplifier with the high efficiency output of the Class B configuration along with the low distortion of the Class A configuration is to create an amplifier circuit which is a combination of the previous two classes resulting in a new type of amplifier circuit called a Class AB Amplifier. Then the Class AB amplifier output stage combines the advantages of the Class A amplifier and the Class B amplifier while minimising the problems of low efficiency and distortion associated with them.

As we said above, the Class AB Amplifier is a combination of Classes A and B in that for small power outputs the amplifier operates as a class A amplifier but changes to a class B amplifier for larger current outputs. This action is achieved by pre-biasing the two transistors in the amplifiers output stage. Then each transistor will conduct between 180° and 360° of the time depending on the amount of current output and pre-biasing. Thus the amplifier output stage operates as a Class AB amplifier.

First lets look at a comparison of output signals for the different amplifier classes of operation.

Comparison of the Different Amplifier Classes
Then the amplifier classes are always defined as follows:

- **Class A**: The amplifiers single output transistor conducts for the full 360° of the cycle of the input waveform.
- **Class B**: The amplifiers two output transistors only conduct for one-half, that is, 180° of the input waveform.
- **Class AB**: The amplifiers two output transistors conduct somewhere between 180° and 360° of the input waveform.

### Class A Amplifier Operation

For Class A amplifier operation the switching transistors Q-point is located near to the centre of the output characteristic load line of the transistor and within the linear region. This allows the transistor to conduct for the complete 360° so the output signal varies over the full cycle of the input signal.

The main advantage of Class A is that the output signal will always be an exact reproduction of the input signal reducing distortion. However it suffers from poor efficiency, because to bias the transistor in the center of the load line there must always be a suitable DC quiescent current flowing through the switching transistor even if there is no input signal to amplify.

### Class B Amplifier Operation

For Class B amplifier operation, two complimentary switching transistors are used with the Q-point (that is its biasing point) of each transistor located at its cut-off point.

This allows for one transistor to amplify the signal over one half of the input waveform, while the other transistor amplifies the other half. These two amplified halves are then combined together at the load to produce one full waveform cycle. This NPN-PNP complimentary pair is also known as a push-pull configuration.

Because of the cut-off biasing, the quiescent current is zero when there is no input signal, therefore no power is dissipated or wasted when the transistors are in the quiescent condition, increasing the overall efficiency of a Class B amplifier with respect to Class A.

However, as the Class B amplifier is biased so that the output current flows through each transistor for only half of the input cycle, the output waveform is therefore not an exact replica of the input waveform since the output signal is distorted. This distortion occurs at every zero-crossing of the input.
signal producing what is generally called cross-over distortion as the two transistors switch “ON” between themselves.

This distortion problem can be easily overcome by locating the biasing point of the transistor slightly above cut-off. By biasing the transistor slightly above its cut-off point but much below the centre Q-point of the class A amplifier, we can create a Class AB amplifier circuit. Then the basic purpose of a Class AB amplifier is to preserve the basic Class B configuration while at the same time improving its linearity by biasing each switching transistor slightly above threshold.

**Biasing A Class AB Amplifier**

So how do we do this. A Class AB amplifier can be made from a standard Class B push–pull stage by biasing both switching transistors into slight conduction, even when no input signal is present. This small biasing arrangement ensures that both transistors conduct simultaneously during a very small part of the input waveform by more than 50 per cent of the input cycle, but less than 100 per cent.

The 0.6 to 0.7V (one forward diode volt drop) dead band that produces the crossover distortion effect in Class B amplifiers is greatly reduced by the use of suitable biasing. The pre-biasing of the transistor devices can be achieved in a number of different ways using either a preset voltage bias, a voltage divider network, or by using a series connected diode arrangement.

**Class AB Amplifier Voltage Biasing**

Here the biasing of the transistors is achieved by using a suitable fixed bias voltage applied the bases of TR1 and TR2. Then there is a region where both transistors are conducting and the small quiescent collector current flowing through TR1 combines with the small quiescent collector current flowing through TR2 and into the load.

When the input signal goes positive, the voltage at the base of TR1 increases producing a positive output of a similar amount which increases the collector current flowing through TR1 sourcing current to the load, $R_L$. However, because the voltage between the two bases is fixed and constant, any increase in the conduction of TR1 will cause an equal and opposite decrease in the conduction of TR2 during the positive half cycle.

As a result, transistor TR2 eventually turns off leaving the forward biased transistor, TR1 to supply all the current gain to the load. Likewise, for the negative half of the input voltage the opposite occurs. That is, TR2 conducts sinking the load current while TR1 turns off as the input signal becomes more negative.
Then we can see that when the input voltage, $V_{IN}$ is zero, both transistors are slightly conducting due to their voltage biasing, but as the input voltage becomes more positive or negative, one of the two transistors conducts more either sinking or sourcing the load current. As the switching between the two transistors occurs nearly instantly and is a smooth one, the crossover distortion which affects the Class B configuration is greatly reduced. However, incorrect biasing can cause sharp crossover distortion spikes as the two transistor switch over.

The use of a fixed biasing voltage allows each transistor to conduct for more than one-half of the input cycle, (Class AB operation). However, it is not very practical to have extra batteries within the amplifiers output stage design. One very simple and easy way of producing two fixed biasing voltages to set a stable Q-point near to the transistors cut-off, is to use a resistive voltage divider network.

**Class AB Amplifier Resistor Biasing**

![Class AB Amplifier Resistor Biasing Diagram](image)

When a current passes through a resistor, a voltage drop is developed across the resistor as defined by Ohm's law. So by placing two or more resistors in series across a supply voltage we can create a voltage divider network that produces a set of fixed voltages at the values of our choosing.

The basic circuit is similar to the above voltage biasing circuit in that transistors, $TR_1$ and $TR_2$ conduct during the opposite half cycles of the input waveform. That is, when $V_{IN}$ is positive, $TR_1$ conducts and when $V_{IN}$ is negative, $TR_2$ conducts.

The four resistances $R_1$ to $R_4$ are connected across the supply voltage $V_{CC}$ to provide the required resistive biasing. The two resistors, $R_1$ and $R_4$ are chosen to set the Q-point slightly above cut-off with the correct value of $V_{BE}$ being set at about 0.6V so that the voltage drops across the resistive network brings the base of $TR_1$ to about 0.6V, and that of $TR_2$ to about –0.6V.

Then the total voltage drop across biasing resistors $R_2$ and $R_3$ is approximately 1.2 volts, which is just below the value required to turn each transistor fully-on. By biasing the transistors just above cut-off, the value of the quiescent collector current, $I_{CQ}$, should be zero. Also, since both switching transistors are effectively connected in series across the supply, the $V_{CEQ}$ volt drop across each transistor will be approximately one-half of $V_{CC}$.

While the resistive biasing of a Class AB amplifier works in theory, a transistors collector current is very sensitive to changes in its base biasing voltage, $V_{BE}$. Also, the cut-off point of the two complimentary transistors may not be the same, so finding the correct resistor combination within the
voltage divider network may be troublesome. One way to overcome this is to use an adjustable resistor to set the correct Q-point as shown.

**Adjustable Amplifier Biasing**

![Adjustable Amplifier Biasing Diagram]

An adjustable resistor, or potentiometer can be used to bias both transistors onto the verge of conduction. Then transistors TR1 and TR2 are biased via \( R_{B1} \) - \( V_R1 \) - \( R_{B2} \) so that their outputs are balanced and zero quiescent current flows into the load.

The input signal which is applied via capacitors C1 and C2 is superimposed onto the biasing voltages and applied to the bases of both transistors. Note that both the signals applied to each base has the same frequency and amplitude as they originated from \( V_{IN} \).

The advantage of this adjustable biasing arrangement is that the basic amplifier circuit does not require the use of complimentary transistors with closely matched electrical characteristics or and exact resistor ratio within the voltage divider network as the potentiometer can be adjusted to compensate.

As resistors are passive devices that convert electrical power into heat due to its power rating, the resistive biasing of a Class AB amplifier, either fixed or adjustable, can be very sensitive to changes in temperature. Any small changes in the operating temperature of the biasing resistors (or transistors) may affect their value producing undesirable changes in the quiescent collector current of each transistor. One way to overcome this temperature related problem is to replace the resistors with diodes to use diode biasing.

**Class AB Amplifier Diode Biasing**
While the use of biasing resistors may not solve the temperature problem, one way to compensate for any temperature related variation in the base-emitter voltage, $V_{BE}$, is to use a pair of normal forward biased diodes within the amplifier's biasing arrangement as shown.

A small constant current flows through the series circuit of R1-D1-D2-R2, producing voltage drops which are symmetrical either side of the input. With no input signal voltage applied, the point between the two diodes is zero volts. As current flows through the chain, there is a forward bias voltage drop of approximately 0.7V across the diodes which is applied to the base-emitter junctions of the switching transistors.

Therefore the voltage drop across the diodes, biases the base of transistor TR1 to about 0.7 volts, and the base of transistor TR2 to about –0.7 volts. Thus the two silicon diodes provide a constant voltage drop of approximately 1.4 volts between the two bases biasing them above cut-off.

As the temperature of the circuit rises, so too does that of the diodes as they are located next to the transistors. The voltage across the PN junction of the diode thus decreases diverting some of the transistors base current stabilising the transistors collector current.

If the electrical characteristics of the diodes are closely matched to that of the transistors base-emitter junction, the current flowing in the diodes and the current in the transistors will be the same creating what is called a current mirror. The effect of this current mirror compensates for variations in temperature producing the required Class AB operation thereby eliminating any crossover distortion.

In practice, diode biasing is easily accomplished in modern day integrated circuit amplifiers as both the diode and switching transistor are fabricated onto the same chip, such as in the popular LM386 audio power amplifier IC. This means that they both have identical characteristics curves over a wide temperature change providing thermal stabilisation of the quiescent current.

The biasing of a Class AB amplifier output stage is generally adjusted to suit a particular amplifier application. The amplifiers quiescent current is adjusted to zero to minimise power consumption, as in Class B operation, or adjusted for a very small quiescent current to flow that minimises crossover distortion producing a true Class AB amplifier operation.

In the above Class AB biasing examples, the input signal is coupled directly to the switching transistors bases by using capacitors. But we can improve the output stage of a Class AB amplifier a little more by the addition of a simple common-emitter driver stage as shown.
Transistor TR3 acts as a current source that sets up the required DC biasing current flowing through the diodes. This sets the quiescent output voltage as \( \frac{V_{cc}}{2} \). As the input signal drives the base of TR3, it acts as an amplifier stage driving the bases of TR1 and TR2 with the positive half of the input cycle driving TR1 while TR2 is off and the negative half of the input cycle driving TR2 while TR1 is off, the same as before.

Like with most electronic circuits, there are many different ways to design a power amplifiers output stage as many variations and modifications can be made to a basic amplifier output circuit. The job of a power amplifier is to deliver an appreciable level of output power (both current as well as voltage) to the connected load with a reasonable degree of efficiency. This can be achieved by operating the transistor(s) in one of of two basic operating modes, Class A or Class B.

One way of operating an amplifier with a reasonable level of efficiency is to use a symmetrical Class B output stage based on complementary NPN and PNP transistors. With a suitable level of forward biasing its possible to reduce any crossover distortion as a result of the two transistors being both cut-off for a brief period of each cycle, and as we have seen above, such a circuit is known as a Class AB amplifier.

Then putting it all together, we can now design a simple Class AB power amplifier circuit as shown, producing about one watt into 16 ohms with a frequency response of about 20Hz to 20kHz.

**Class AB Amplifier**
Class AB Amplifier Summary

We have seen here that a Class AB amplifier is biased so that output current flows for less than one full-cycle of the input waveform but more than a half cycle. The implementation of Class AB amplifiers is very similar to the standard Class B configurations in that it uses two switching transistors as part of a complementary output stage with each transistor conducting on opposite half-cycles of the input waveform before being combined at the load.

Thus by allowing both switching transistors to conduct current at the same time for a very short period, the output waveform during the zero crossover period can be substantially smoothed reducing the crossover distortion associated with the Class B amplifier design. Then the conduction angle is greater than $180^\circ$ but much smaller than $360^\circ$.

We have also seen that a Class AB amplifier configuration is more efficient than a Class A amplifier but slightly less efficient than that of a Class B because of the small quiescent current needed to bias the transistors just above cut-off. However, the use of incorrect biasing can cause crossover distortion spikes producing a worse condition.

Having said that, Class AB amplifiers are one of the most preferred audio power amplifier designs due to their combination of reasonably good efficiency and high-quality output as they have low crossover distortion and a high linearity similar to the Class A amplifier design.
Common Collector Amplifier

Common Collector Amplifiers produce an output voltage across its emitter load which is in-phase with the input signal.

The **Common Collector Amplifier** is another type of bipolar junction transistor, (BJT) configuration where the input signal is applied to the base terminal and the output signal taken from the emitter terminal. Thus the collector terminal is common to both the input and output circuits. This type of configuration is called Common Collector, (CC) because the collector terminal is effectively “grounded” or “earthed” through the power supply.

In many ways the common collector configuration (CC) is the reverse of the common emitter (CE) configuration as the connected load resistor is changed from the collector terminal for $R_C$ to the emitter terminal for $R_E$.

The common collector or grounded collector configuration is commonly used where a high impedance input source needs to be connected to a low impedance output load requiring a high current gain. Consider the common collector amplifier circuit below.

**Common Collector Amplifier using an NPN Transistor**
Resistors $R_1$ and $R_2$ form a simple voltage divider network used to bias the NPN transistor into conduction. Since this voltage divider lightly loads the transistor, the base voltage, $V_B$ can be easily calculated by using the simple voltage divider formula as shown.

**Voltage Divider Network**

With the collector terminal of the transistor connected directly to $V_{CC}$ and no collector resistance, ($R_C = 0$) any collector current will generate a voltage drop across the emitter resistor $R_E$. However, in the common collector amplifier circuit, the same voltage drop, $V_E$ also represents the output voltage, $V_{OUT}$.

Ideally we would want the DC voltage drop across $R_E$ to be equal to half the supply voltage, $V_{CC}$ to make the transistors quiescent output voltage sit somewhere in the middle of the characteristics curves allowing for a maximum unclipped output signal. Thus the choice of $R_E$ depends greatly on $I_B$ and the transistors current gain Beta, $\beta$.

As the base-emitter pn-junction is forward biased, base current flows through the junction to the emitter encouraging transistor action causing a much larger collector current, $I_C$ to flow. Thus the emitter current is a combination of base current and collector current as: $I_E = I_B + I_C$. However, as the base current is extremely small compared to the collector current, the emitter current is therefore approximately equal to the collector current. Thus $I_E \approx I_C$.

As with the common emitter (CE) amplifier configuration, the input signal is applied to the transistors base terminal, and as we said previously, the amplifiers output signal is taken from the emitter emitter terminal. However, as there is only one forward biased pn-junction between the transistors base and its emitter terminal, any input signal applied to the base passes directly through the junction to the emitter. Therefore the output signal present at the emitter is in-phase with the applied input signal at the base.

As the amplifiers output signal is taken from across the emitter load this type of transistor configuration is also known as an Emitter Follower circuit as the emitter output “follows” or tracks any voltage changes to the base input signal, except that it remains about 0.7 volts ($V_{BE}$) below the base voltage. Thus $V_{IN}$ and $V_{OUT}$ are in-phase producing zero phase difference between the input and output signals.
Having said that, the emitters pn-junction effectively acts as a forward biased diode and for small AC input signals this emitter diode junction has a resistance given by: \( r'_e = \frac{25 \text{mV}}{I_e} \) where the 25mV is the thermal voltage of the junction at room temperature (25°C) and \( I_e \) is the emitter current. So as the emitter current increases, the emitter resistance decreases by a proportional amount.

The base current which flows through this internal base-emitter junction resistance also flows out and through the externally connected emitter resistor, \( R_E \). These two resistances are series connected thus acting as a potential divider network creating a voltage drop. Since the value of \( r'_e \) is very small, and \( R_E \) is much larger, usually in the kilohms (kΩ) range, the magnitude of the amplifiers output voltage is therefore less than its input voltage.

However, in reality the magnitude of the output voltage (peak-to-peak) is generally in the 98 to 99% value of the input voltage which is close enough in most cases to be considered as unity gain.

We can calculate the voltage gain, \( V_A \) of the common collector amplifier by using the voltage divider formula as shown assuming that the base voltage, \( V_B \) is actually the input voltage, \( V_{IN} \).

**Common Collector Amplifier Voltage Gain**

\[
V_{OUT} = \frac{V_{IN} \times R_E}{r'_e + R_E}
\]

Thus:

\[
A_V = \frac{V_{OUT}}{V_{IN}} = \frac{I_e \times R_E}{I_e \left( r'_e + R_E \right)}
\]

Since \( R_E \) is much greater than \( r'_e \) \( (r'_e + R_E) \approx R_E \)

and the two emitter currents, \( I_e \) cancel, thus:

\[
A_V = \frac{V_{OUT}}{V_{IN}} = \frac{R_E}{R_E} \approx 1
\]

So the common collector amplifier cannot provide voltage amplification and another expression used to describe the common collector amplifier circuit is as a *Voltage Follower Circuit* for obvious reasons. Thus since the output signal closely follows the input and is in-phase with the input the common collector circuit is therefore a non-inverting unity voltage gain amplifier.

**Common Collector Amplifier Example No1**

A common collector amplifier is constructed using an NPN bipolar transistor and a voltage divider biasing network. If \( R_1 = 5k\Omega \), \( R_2 = 6k\Omega \) and the supply voltage is 12 volts. Calculate the values of: \( V_B \), \( V_C \) and \( V_E \), the emitter current \( I_e \), the internal emitter resistance \( r'_e \) and the amplifiers voltage gain \( A_V \) when a load resistance of 4k7Ω is used. Also draw the final circuit and corresponding characteristics curve with load line.

1. Base biasing voltage, \( V_B \)
2. Collector voltage, \( V_C \): As there is no collector load resistance, the transistors collector terminal is connected directly to the DC supply rail, so \( V_C = V_{CC} = 12 \) volts.

3. Emitter biasing voltage, \( V_E \)

\[
V_E = V_B - V_{BE} = 6.5 - 0.7 = 5.8 \text{V}
\]

Thus:

\[
V_{CE(\text{OFF})} = V_{CC} - V_E = 12 - 5.8 = 6.2 \text{V}
\]

4. Emitter Current, \( I_E \)

\[
I_E = \frac{V_E}{R_E} = \frac{5.8}{4700} = 0.00123 = 1.23 \text{mA}
\]

5. AC Emitter Resistance, \( r'_e \)

\[
r'_e = \frac{25 \text{mV}}{I_E} = \frac{25 \text{mV}}{1.23 \text{mA}} = 20.3 \Omega
\]

6. Voltage gain, \( A_V \)

\[
A_V = \frac{R_E}{r'_e + R_E} = \frac{4700}{20.3 + 4700} = 0.996 \text{ or } 99.6\%
\]

Common Collector Amplifier Circuit with Load Line
Common Collector Input Impedance

Although the common collector amplifier is not very good at being a voltage amplifier, because as we have seen, its small signal voltage gain is approximately equal to one ($A_V \approx 1$), it does however make a very good voltage buffer circuit due to its high input ($Z_{IN}$) and low output ($Z_{OUT}$) impedances, providing isolation between an input signal source from a load impedance load.

Another useful feature of the common collector amplifier is that it provides current gain ($A_I$) as long as it is conducting. That is it can pass a large current flowing from the collector to the emitter, in response to a small change to its base current, $I_B$. Remember that this DC current only sees $R_E$ as there is no $R_C$. Then the DC current is simply: $V_{CC}/R_E$ which can be large if $R_E$ is small.

Consider the basic common collector amplifier or emitter follower configuration below.

Common Collector Amplifier Configuration
For AC analysis of the circuit, the capacitors are shorted and $V_{CC}$ is shorted (zero impedance). Thus the equivalent circuit is given as shown with the biasing currents and voltages given as:

\[ R_B = R_1 \parallel R_2 \]

\[ R_E = R_E \parallel R_L \]

\[ \beta = \frac{I_C}{I_B} \quad \therefore I_C = \beta I_B \]

\[ I_E \approx I_C = \beta I_B \]

\[ V_{IN} = V_B = V_{BE} + V_E \]

The Input Impedance, $Z_{IN}$ of the common collector configuration looking into the base is given as:
But as Beta, \( \beta \) is generally much greater than 1 (usually above 100), the expression of: \( \beta + 1 \) can be reduced to just Beta, \( \beta \) as multiplication by 100 is virtually the same as multiplying by 101. Thus:

**Common Collector Amplifier Base Impedance**

\[
Z_{\text{base}} = \beta (R_e + r_e')
\]

Where: \( \beta \) is the transistors current gain, \( R_e \) is the equivalent emitter resistance, and \( r_e' \) is the ac resistance of the emitter-base diode. Note that since the combined value of \( R_e \) is generally much greater than the diodes equivalent resistance, \( r_e' \) (kilo-ohms compared to a few ohms) the transistors base impedance can be given as simply: \( \beta R_e \).

An interesting point to notice here is that the transistors input base impedance, \( Z_{\text{IN(base)}} \) can be controlled by the value of either the emitter leg resistor, \( R_E \) or the load resistor \( R_L \) as they are parallel connected.

While the equation above gives us the input impedance looking into the base of the transistor, it does not give us the true input impedance that the source signal would see looking into the complete amplifier circuit. For that we need to consider the two resistors which make up the voltage divider biasing network. Thus:

**Common Collector Amplifier Input Impedance**

\[
Z_{\text{IN}} = R_{\text{BIAS}} \parallel Z_{\text{base}}
\]

Where: \( R_{\text{BIAS}} = R_B = R_1 \parallel R_2 \)

\[
\therefore Z_{\text{IN}} = R_B \parallel \beta (R_e + r_e')
\]
**Common Collector Example No2**

Using the previous common collector amplifier circuit above, calculate the input impedances of the transistors base and amplifier stage if the load resistance, $R_L$ is 10kΩ and the NPN transistors current gain is 100.

1. **AC Emitter Resistance, $r'_e$**

   $$r'_e = \frac{25 \text{mV}}{I_e} = \frac{25 \text{mV}}{1.23 \text{mA}} = 20.3 \Omega$$

2. **Equivalent Load Resistance, $R_e$**

   $$R_e = R_E \parallel R_L$$

   $$R_e = \frac{R_E \times R_L}{R_E + R_L} = \frac{4700 \times 10000}{4700 + 10000} = 3197 \Omega \text{ or } 3.2 \text{kΩ}$$

3. **Transistors Base Impedance, $Z_{\text{BASE}}$**

   $$Z_{\text{BASE}} = \beta (R_e + r'_e)$$

   $$r'_e = \frac{25 \text{mV}}{I_e} = \frac{25 \text{mV}}{1.23 \text{mA}} = 20.3 \Omega$$

   $$\therefore Z_{\text{BASE}} = 100 (3200 + 20.3) = 322 \text{kΩ}$$

2. **Amplifier Input Impedance, $Z_{\text{IN(STAGE)}}$**

   $$Z_{\text{IN}} = R_{\text{BIAS}} \parallel Z_{\text{BASE}}$$

   $$R_{\text{BIAS}} = \frac{R_1 \times R_2}{R_1 + R_2} = \frac{5600 \times 6800}{5600 + 6800} = 3070 \Omega$$

   $$\therefore Z_{\text{IN}} = \frac{R_{\text{BIAS}} \times Z_{\text{BASE}}}{R_{\text{BIAS}} + Z_{\text{BASE}}} = \frac{3070 \times 32000}{3070 + 32000} = 2800 \Omega \text{ or } 2.8 \text{kΩ}$$

As the transistors base impedance of 322kΩ is much higher than the amplifiers input impedance of only 2.8kΩ, thus the input impedance of the common collector amplifier is determined by the ratio of the two biasing resistors, $R_1$ and $R_2$.

**Common Collector Output Impedance**

https://www.electronics-tutorials.ws/amplifier/common-collector-amplifier.html
To determine the CC amplifiers output impedance $Z_{OUT}$ looking from the load back into the amplifiers emitter terminal, we must first remove the load as we want to see the effective resistance of the amplifier that is driving the load. Thus the AC equivalent circuit looking into the amplifiers output is given as:

![Common Collector Amplifier Circuit Diagram]

From above, the input impedance of the base circuit is given as: $R_B = R_1 || R_2$. The current gain of the transistor is given as: $\beta$. Thus the output equation is given as:

$$Z_{OUT} = R_E || \left( r_e' + \frac{R_1 || R_2}{\beta + 1} \right)$$

We can see then that the emitter resistor, $R_E$ is effectively in parallel with the whole impedance of the transistor looking back into its emitter terminal.

If we calculate the output impedance of our common emitter amplifier circuit using the component values from above, it would give an output impedance $Z_{OUT}$ of less than 50Ω (49.5Ω) which is much smaller than the higher input impedance, $Z_{IN(BASE)}$ calculated previously.

Thus we can see then that the **Common Collector Amplifier** configuration has, from calculation, a very high input impedance and a very low output impedance allowing it to drive a low impedance load. In fact due to the CC amplifiers relatively high input impedance and very low output impedance it is commonly used as a unity gain buffer amplifier.

Having determined that the output impedance, $Z_{OUT}$ of our example amplifier above is approximately 50Ω by calculation, if we now connect the 10kΩ load resistor back into the circuit, the resulting output impedance will be:

$$Z_{OUT(LOAD)} = Z_{OUT} || R_L$$

$$Z_{OUT(LOAD)} = \frac{49.5 \times 10000}{49.5 + 10000} = 49.3\Omega$$

Although the load resistance is 10kΩ, the equivalent output resistance is still low at 49.3Ω. This is because $R_L$ is large compared with $Z_{OUT}$, thus for maximum power transfer, $R_L$ must equal $Z_{OUT}$. As the voltage gain of the common collector amplifier is considered to be unity (1), the amplifiers power gain must be equal to its current gain, as $P = V*I$.

Since the common collector current gain is defined as the ratio of the emitter current to the base current, $\gamma = \frac{I_E}{I_B} = \beta + 1$, it therefore follows that the amplifiers current gain must be approximately equal to Beta ($\beta$) as $\beta + 1$ is virtually the same as Beta.

**Common Collector Summary**

We have seen in this tutorial about the **Common Collector Amplifier** that it gets its name because the collector terminal of the BJT is common to both the input and output circuits as there is no collector resistance, $R_C$.  

https://www.electronics-tutorials.ws/amplifier/common-collector-amplifier.html
The voltage gain of the common collector amplifier is approximately equal to unity ($A_v \approx 1$) and that its current gain, $A_i$ is approximately equal to Beta, ($A_i \approx \beta$) which depending on the value of the particular transistors Beta value can be quiet high.

We have also seen through calculation, that the input impedance, $Z_{IN}$ is high while its output impedance, $Z_{OUT}$ is low making it useful for impedance matching (or resistance-matching) purposes or as a buffer circuit between a voltage source and a low impedance load.

As the the common collector (CC) amplifier receives its input signal to the base with the output voltage taken from across the emitter load, the input and output voltages are “in-phase” (0° phase difference) thus the common collector configuration goes by the secondary name of *Emitter Follower* as the output voltage (emitter voltage) follows the input base voltage.
The **Common Base Amplifier** is another type of bipolar junction transistor, (BJT) configuration where the base terminal of the transistor is a common terminal to both the input and output signals, hence its name *common base* (CB). The common base configuration is less common as an amplifier than compared to the more popular *common emitter*, (CE) or *common collector*, (CC) configurations but is still used due to its unique input/output characteristics.

For the common base configuration to operate as an amplifier, the input signal is applied to the emitter terminal and the output is taken from the collector terminal. Thus the emitter current is also the input current, and the collector current is also the output current, but as the transistor is a three layer, two pn-junction device, it must be correctly biased for it to work as a *common base amplifier*. That is the base-emitter junction is forward-biased.

Consider the basic common base amplifier configuration below.

**Common Base Amplifier using an NPN Transistor**
Then we can see from the basic common base configuration that the input variables relate to the emitter current $I_E$ and the base-emitter voltage, $V_{BE}$, while the output variables relate to the collector current $I_C$ and the collector-base voltage, $V_{CB}$.

Since the emitter current, $I_E$ is also the input current, any changes to the input current will create a corresponding change in the collector current, $I_C$. For a common base amplifier configuration, current gain, $A_i$ is given as $i_{OUT}/i_{IN}$ which itself is determined by the formula $I_C/I_E$. The current gain for a CB configuration is called Alpha, ($\alpha$).

In a BJT amplifier the emitter current is always greater than the collector current as $I_E = I_B + I_C$, the current gain ($\alpha$) of the amplifier must therefore be less than one (unity) as $I_C$ is always less than $I_E$ by the value of $I_B$. Thus the CB amplifier attenuates the current, with typical values of alpha ranging from between 0.980 to 0.995.

The electrical relationship between the three transistor currents can be shown to give the expressions for alpha, $\alpha$ and Beta, $\beta$ as shown.

\[
I_E = I_B + I_C
\]

\[
\text{Alpha} (\alpha) = \frac{I_C}{I_E} \quad \text{and} \quad \text{Beta} (\beta) = \frac{I_C}{I_B}
\]

\[
\therefore I_C = \alpha \times I_E = \beta \times I_B
\]

\[
\text{thus:} \quad \alpha = \frac{\beta}{\beta + 1} \quad \beta = \frac{\alpha}{1 - \alpha}
\]

Common Base Amplifier Current Gain
Therefore if the Beta value of a standard bipolar junction transistor is 100, then the value of Alpha would be given as: 100/101 = 0.99.

**Common Base Amplifier Voltage Gain**

Since the common base amplifier can not operate as a current amplifier \((A_i \equiv 1)\), it must therefore have the ability to operate as a voltage amplifier. The voltage gain for the common base amplifier is the ratio of \(V_{OUT}/V_{IN}\), that is the collector voltage \(V_C\) to the emitter voltage \(V_E\). In other words, \(V_{OUT} = V_C\) and \(V_{IN} = V_E\).

As the output voltage \(V_{OUT}\) is developed across the collector resistance, \(R_C\), the output voltage must therefore be a function of \(I_C\) as from Ohms Law, \(V_{RC} = I_C \times R_C\). So any change in \(I_E\) will have a corresponding change in \(I_C\).

Then we can say for a common base amplifier configuration that:

\[
A_V = \frac{V_{OUT}}{V_{IN}} = \frac{V_C}{V_E} \approx \frac{I_C \times R_C}{I_E \times R_E}
\]

As \(I_C/I_E\) is alpha, we can present the amplifiers voltage gain as:

\[
A_V = \alpha \frac{R_C}{R_E} = A_i \left[ \frac{R_C}{R_E} \right]
\]

Therefore the voltage gain is more or less equal to ratio of the collector resistance to the emitter resistance. However, there is a single pn-diode junction within a bipolar junction transistor between the base and emitter terminals giving rise to what is called the transistors dynamic emitter resistance, \(r'e\).

For AC input signals the emitter diode junction has an effective small-signal resistance given by: \(r'e = 25mV/I_E\), where the 25mV is the thermal voltage of the pn-junction and \(I_E\) is the emitter current. So as the current flowing through the emitter increases, the emitter resistance will decrease by a proportional amount.

Some of the input current flows through this internal base-emitter junction resistance to the base as well as through the externally connected emitter resistor, \(R_E\). For small-signal analysis these two resistances are connected in parallel with each other.

Since the value of \(r'e\) is very small, and \(R_E\) is generally much larger, usually in the kilohms (kΩ) range, the magnitude of the amplifiers voltage gain changes dynamically with different levels of emitter current.

Thus if \(R_E \gg r'e\) then the true voltage gain of the common base amplifier will be:
Because the current gain is approximately equal to one as \( I_C \approx I_E \), then the voltage gain equation simplifies to just:

\[
A_V = \alpha \frac{R_C}{r'e} = A_i \left[ \frac{R_C}{r'e} \right]
\]

So if for example, 1mA of current is flowing through the emitter-base junction, its dynamic impedance would be 25mV/1mA = 25\( \Omega \). The volt gain, \( A_V \) for a collector load resistance of 10k\( \Omega \) would be: 10,000/25 = 400, and the more current which flows through the junction, the lower becomes its dynamic resistance and the higher the voltage gain.

Likewise, the higher the value of load resistance the greater the amplifiers voltage gain. However, a practical common base amplifier circuit would be unlikely to use a load resistor greater than about 20k\( \Omega \) with typical values of voltage gain range from about 100 to 2000 depending on the value of \( R_C \).

Note that the amplifiers power gain is about the same as its voltage gain.

As the voltage gain of the common base amplifier is dependent on the ratio of two resistive values, it therefore follows that there is no phase inversion between the emitter and the collector. Thus the input and output waveforms are “in-phase” with each other showing that the common base amplifier is non-inverting amplifier configuration.

**Common Collector Amplifier Resistance Gain**

One of the interesting characteristics of the common base amplifier circuit is the ratio of its input and output impedances giving rise to what is known as the amplifiers Resistance Gain, the fundamental property which makes amplification possible. We have seen above that the input is connected to the emitter and the output taken from the collector.

Between the input and ground terminal there are two possible parallel resistive paths. One through the emitter resistance, \( R_E \) to ground and the other through \( r'e \) and the base terminal to ground. Thus we can say looking into the emitter with the base grounded that: 

\[
Z_{IN} = R_E || r'e
\]

But as the dynamic emitter resistance, \( r'e \) is very small compared to \( R_E (r'e \ll R_E) \), the internal dynamic emitter resistance, \( r'e \) dominates the equation resulting in a low input impedance approximately equal to \( r'e \)

So for the common base configuration the input impedance is very low and depending on the value of the source impedance, \( R_S \) connected to emitter terminal, input impedance values can range from between 10\( \Omega \) and 200\( \Omega \). The low input impedance of the common base amplifier circuit is one of the main reason for its limited applications as a single stage amplifier.

The output impedance of the CB amplifier however, can be high depending on the collector resistance used to control the voltage gain and the connected external load resistance, \( R_L \). If a load resistance is connected across the amplifiers output terminal, it is effectively connected in parallel with the collector resistance, then 

\[
Z_{OUT} = R_C || R_L
\]
But if $R_E$ is very large compared to $R_C$ then the emitter resistance will dominate the equation resulting in a moderate output impedance approximately equal to $R_C$, so the output impedance looking back into the collector terminal would be simply: $Z_{OUT} = R_C$.

As the output impedance of the amplifier looking back into the collector terminal can be very large, the common base circuit operates almost like an ideal current source taking the input current from the low input impedance side and sending the current to the high output impedance side. The common base circuit is therefore also referred to as a current buffer or current follower.

**Common Base Amplifier Summary**

We have seen here in this tutorial about the **Common Base Amplifier** that it has a current gain (alpha) of approximately one (unity), but also a voltage gain that can be very high with typical values ranging from 100 to over 2000 depending on the value of the collector resistor $R_L$ used.

We have also seen that the input impedance of the amplifier circuit is very low, but the output impedance can be very high. We also said that the common base amplifier does not invert the input signal as it is a non-inverting amplifier configuration.

Due to its input-output impedance characteristics, the common base amplifier arrangement is extremely useful in audio and radio frequency applications as a current buffer to match a low-impedance source to a high-impedance load or as a single stage amplifier as part of a cascaded or multi-stage configuration where one amplifier stage is used to drive another.
Phase Splitter

A phase splitter circuit produces two output signals that are equal in amplitude but opposite in phase from each other from a single input signal.

The Phase Splitter is another type of bipolar junction transistor, (BJT) configuration where a single sinusoidal input signal is split into two separate outputs that differ in phase from each other by 180 electrical degrees.

The input signal of a transistor phase splitter is applied to the base terminal with one output signal taken from the collector terminal and the second output signal taken from the emitter terminal. Thus the transistor phase splitter is a dual output amplifier producing complementary outputs from its collector and emitter terminals which are out-of-phase by 180°.

A single-transistor phase splitter circuit is nothing new as we have seen its basic building blocks in previous tutorials. the phase splitter, phase-inverter circuit combines the characteristics of a common emitter amplifier with that of a common collector amplifier. As with the CE amplifier and CC amplifier circuits, the phase splitter circuit is forward biased to operated as a linear class-A amplifier to reduce output signal distortion.

But first let's refresh our knowledge of the common emitter (CE) amplifier circuit and the common collector (CC) amplifier circuit configurations.

Common Emitter Amplifier

The common emitter circuit with voltage divider biasing is the most widely used linear amplifier configuration as its easy to bias and understand.
The input signal is applied to the base terminal, and the output signal is taken from across the load resistance, $R_L$ connected between the collector and the positive supply rail, $V_{CC}$ as shown. Thus the emitter is common to both the input and output circuits.

As well as providing voltage amplification determined by the ratio of: $R_L/R_E$, the main characteristic of the Common Emitter (CE) configuration is that it is an inverting amplifier producing a phase reversal of 180° between the input and the output signals.

To operate as a class-A amplifier the circuit is biased so that the quiescent current fed into the base, $I_B$ positions the collector terminal voltage at approximately half the supply voltage value. The ratio of resistors $R_1$ and $R_2$ is chosen so that the transistor is correctly biased providing maximum undistorted output signal.

**Common Collector Amplifier**

The *common collector amplifier* uses the single transistor in the common collector configuration with the collector being common to both the input and output circuits. The input signal is applied to the transistors base terminal and the output is taken from the emitter terminal as shown.

As the output signal is taken from across the emitter resistor, $R_E$ no collector resistor is used so the collector terminal is connected directly to the supply rail, $V_{CC}$. This type of amplifier configuration is also known as a voltage follower or more commonly an *emitter follower* as the output signal follows the input signal.

The main characteristic of the Common Collector (CC) configuration is that it is a non-inverting amplifier as the input signal passes directly through the base-emitter junction to the output. Hence the output is “in-phase” with the input. Due to this it has a voltage gain of slightly less than one (unity).

As with the previous common emitter configuration, the transistor of the common collector amplifier is biased using a voltage divider network to half the supply voltage to give good stabilisation for its DC operating conditions.

**Phase Splitter Configuration**

If we combine the configuration of the common emitter amplifier with that of the common collector amplifier and take the outputs from both the collector and the emitter terminals at the same time, we can create a transistor circuit that produces two output signals which are equal in magnitude but inverted with respect to each other.

The **Phase Splitter** uses a single transistor to produce inverting and non-inverting outputs as shown.

**Phase Splitter using an NPN Transistor**
We said previously that the voltage gain of the common emitter amplifier is the ratio of $R_L$ to $R_E$, that is $-R_L/R_E$ (the minus sign indicates an inverting amplifier). If we were to make these two resistors equal in value ($R_L = R_E$), then the voltage gain of the common emitter stage would be equal to -1 or unity.

As the common collector, emitter follower amplifier circuit naturally has a non-inverting voltage gain of near unity (+1), the two output signals, one from the collector and one from the emitter, will be equal in amplitude but 180° out-of-phase. This makes the unity gain transistor phase splitter circuit very useful to provide complementary or anti-phase inputs to another amplifier stage, such as a class-B push-pull power amplifier.

For proper operation, the voltage divider network connected across the supply rail and ground must be chosen to produce the correct stabilising of the DC conditions for the output voltage swing from both the collector and emitter terminals producing symmetrical outputs.

### Phase Splitter Example No1

A single transistor phase splitter circuit is required to drive a push-pull power amplifier stage. Design a suitable circuit if the supply voltage is 9 volts, the Beta value of the NPN 2N3904 transistor used is 100, and the quiescent collector current is 1mA and the input signal has an amplitude of 1V peak.

To prevent distortion of the emitter terminal output signal, the d.c. biasing voltage of the emitter terminal must be greater than the maximum value of the input signal, in this case 1 volt peak. If we set the DC quiescent emitter terminal voltage at twice the input value to ensure a distortion free output swing, the $V_E$ will equal 2 volts.

As $V_E$ is set at 2 volts and the emitter current, which is also the collector quiescent current, flowing through it is given as 1mA, the value of emitter resistance, $R_E$ is calculated as:

$$R_E = \frac{V_E}{I_E} = \frac{2\text{V}}{1\text{mA}} = \frac{2}{0.001} = 2,000\Omega \text{ or } 2k\Omega$$

For the voltage gain of the common emitter side of the phase splitter circuit to equal -1 (unity), the collector load resistance $R_L$ must be equal to $R_E$. That is $R_L = R_E = 2k\Omega$. Thus the voltage dropped across the collector load resistance is calculated as:

https://www.electronics-tutorials.ws/amplifier/phase-splitter.html
\[ R_L = R_E = 2.0k\Omega \]

\[ V_C = I_C \times R_L = 1mA \times 2k\Omega = 2.0\text{Volts} \]

\[ \therefore V_{C(Q)} = V_{CC} - V_C = 9 - 2 = 7.0\text{Volts} \]

As \[ V_{E(Q)} = 2.0V, \] and \[ V_{C(Q)} = 7.0V, \]

\[ V_{CE(Q)} = V_{C(Q)} - V_{E(Q)} = 7.0 - 2.0 = 5.0\text{Volts} \]

Applying Kirchhoff’s Voltage Law, \[ V_{CC} - V_C - V_{CE} - V_E = 0. \] Thus \[ 9 - 2 - 5 - 2 = 0. \] We would expect to see this because as \( R_L = R_E \) and the current flowing through both resistors is approximately the same value, so the \( I \times R \) voltage drop across each resistor would therefore be the same at 2.0 volts.

This means then that the DC bias voltage for the non-inverting output (emitter terminal) is 2.0 volts (0 + 2), and the DC bias voltage for the inverting output (collector terminal) is 7.0 volts (9 – 2). In other words, the DC quiescent output voltages of the two outputs are at different values.

The transistors DC current gain, Beta is given as being 100. As for a common emitter amplifier, Beta is the ratio of collector current to base current, that is; \( \beta = \frac{I_C}{I_B} \), the value of the base biasing current required is calculated as:

\[ \beta = \frac{I_C}{I_B} = 100 \]

\[ \therefore I_B = \frac{I_C}{\beta} = \frac{1mA}{100} = 10\mu A \]

Then for a DC current gain of 100, the quiescent base current, \( I_{B(Q)} \) is given as 10uA. It is common practice that the value of the quiescent current flowing through the base-to-ground resistor of the voltage divider network is ten times (x10) greater than the base current. Thus the current flowing through \( R_2 \) will be \( 10 \times I_B = 10 \times 10uA = 100uA \).

The base voltage, \( V_B \) is equal to the emitter voltage \( V_E \) plus the 0.7 volt forward voltage drop of the base-emitter pn-junction, that is: \( 2.0 + 0.7 = 2.7 \text{ volts} \). Therefore the value of \( R_2 \) is calculated as:

\[ R_2 = \frac{V_B}{I_{R2}} = \frac{2.7V}{100\mu A} = 27,000 \Omega \text{ or } 27k\Omega \]

As there is 100uA flowing through \( R_2 \) and 10uA flowing into the transistors base terminal, it must therefore follow that there is 110uA \( (100uA + 10uA) \) flowing through the top resistor, \( R_1 \) of the voltage divider network. If the supply voltage is 9 volts and the transistors base voltage is 2.7 volts. The value of resistor \( R_1 \) is calculated as:
Thus the voltage divider network used for the DC biasing of the splitter circuit consists of $R_1 = 57.3\,\text{k}\Omega$ and $R_2 = 27\,\text{k}\Omega$.

Putting the above calculated values together gives us the single transistor phase splitter circuit of:

Transistor Phase Splitter Circuit

As a single transistor phase splitter circuit produces two output versions of the input signal, a non-inverted version identical in phase to the input signal, and an $180^\circ$ phase inverted version of the input signal with both outputs having a similar amplitude. This would make the phase splitter circuit ideal for use in driving *push-pull* or *totem-pole* configured outputs for amplification or DC motor control.

Consider the circuit below.

Totem-pole Output Stage
As the complementary outputs are taken from the collector and the emitter of the transistor Q1, when the upper transistor Q2 is forward biased and conducting on the negative half-cycle (due to the inversion), the lower transistor Q3 is OFF, so the negative half of the waveform is passed to the load resistor, $R_L$.

On the positive half-cycle of the input waveform, the lower transistor Q3 is forward biased and conducting, while the upper transistor, Q2 is OFF, so the positive half of the waveform is passed to the load resistor, $R_L$.

Thus at any one time only one of the output transistors, Q2 or Q3 is sufficiently forward biased and conducting only one half of the input signal waveform. The two output transistors alternate conduction from one to the other as determined by Q1, with both halves of the input signal being combined together to produce an inverted output waveform across $R_L$. Load resistor $R_L$ has a DC biasing voltage centered around the difference between $V_C$ and $V_E$. Resistor $R_S$ is used to limit the maximum current flow.

Transistor Phase Splitter Summary

We have seen here in this tutorial that by combining a common emitter circuit with a common collector circuit, we can create another type of single transistor circuit which is not really a CE amplifier nor a CC amplifier but instead a phase splitter circuit that produces two voltages of the same amplitude but of opposite phase.

Sometimes it is necessary to have two signals which are both equal in amplitude but are $180^\circ$ out-of-phase with each other and there are different ways to create a dual output phase splitter circuit, including the use of differential amplifiers and operational amplifiers. But the single transistor phase splitter circuit configuration is the easiest to build and understand.

The single transistor phase splitter circuit is biased to operate as a class A amplifier with the two complementary (inverted and non-inverted) outputs taken from the collector and the emitter terminals respectively of the transistor. To operate correctly the gain of each output must be set to 1, unity gain.

Single transistor phase splitter circuits are useful for driving Class-B push-pull amplifiers, center-tapped transformer for inverters or totem-pole outputs for motor control, as when one transistor is ON the other transistor is OFF.