**Course: Basic Electronics (EC21101)**

**Course Instructor: Prof. Kapil Debnath**

# Lecture 6: BJT Amplifier


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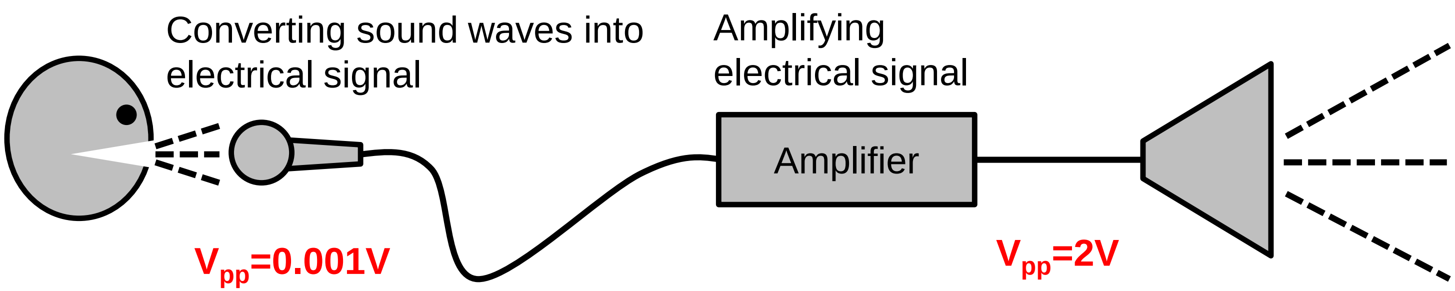
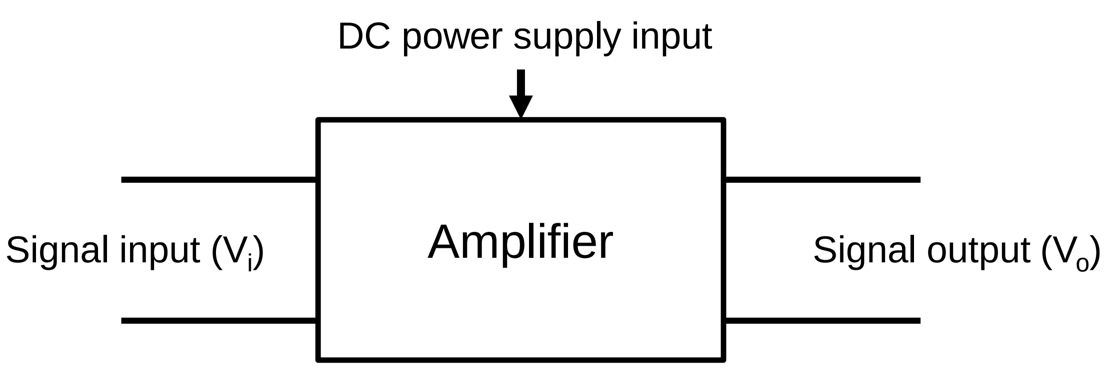
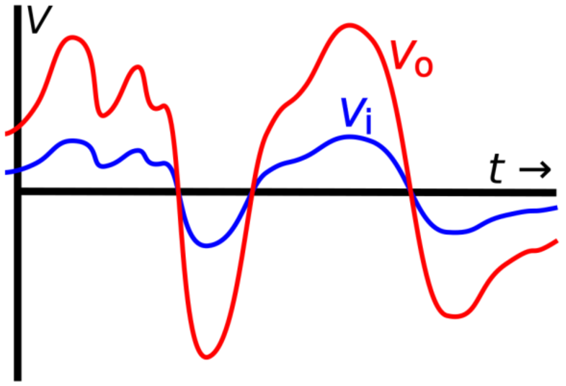
# Linear amplifier

The function of a linear amplifier is to increase the magnitude of an input signal without any distortion in the signal shape. Obviously we may get some phase shift in the process of amplification. As we have discussed in the previous lecture BJT can be used as an amplifier for voltage or current signals. Here we will study in details the design principle of a linear amplifier using BJTs.



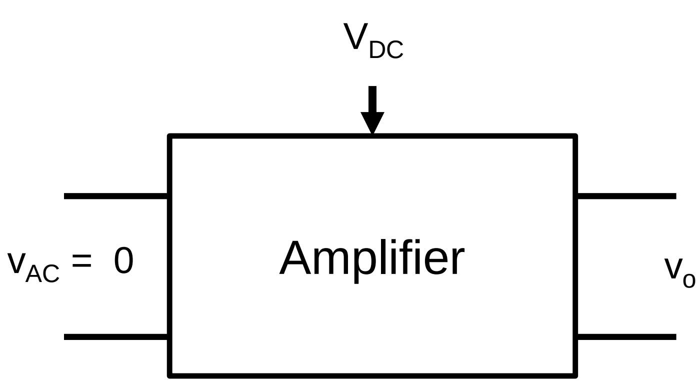
# Linear amplifier

In order to completely understand the behaviour of an amplifier we need to perform two analyses:

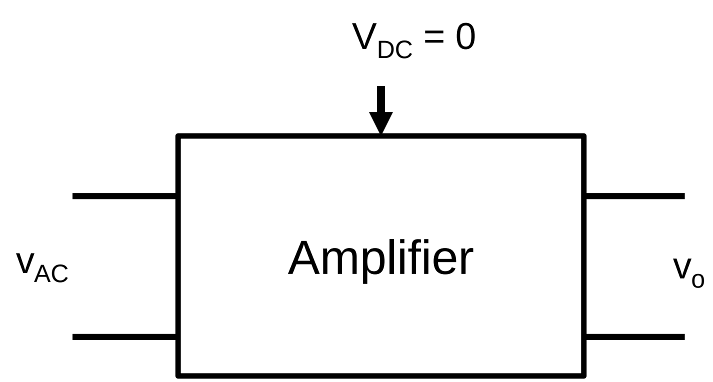
a) DC analysis or large signal analysis
b) AC analysis or small signal analysis

Since the circuit is considered to be linear, the superposition principle will apply. In order to perform DC analysis, we will set the AC source to zero. This analysis will establish the Q-point of the transistors in the amplifier. We have performed the Q-point analysis rigorously in the previous chapter. Once the Q-point of all the transistors in the circuit is established, we will then perform the AC analysis, also called small signal analysis. This will be done by setting the DC source to zero.
The total response of the amplifier is the sum of the two individual responses.
Later we will understand the reason behind calling the DC analysis as large signal analysis and the AC analysis as small signal analysis

First step: DC analysis

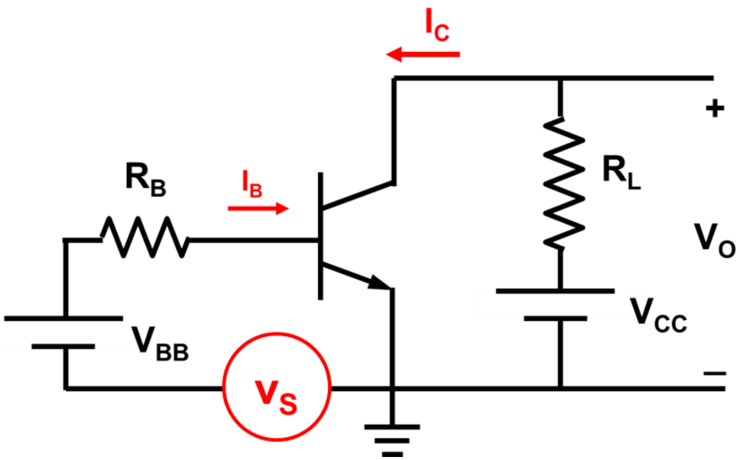


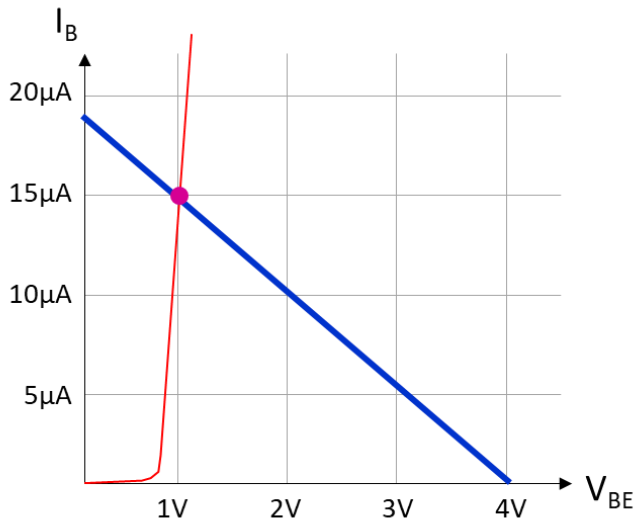

Second step: AC analysis

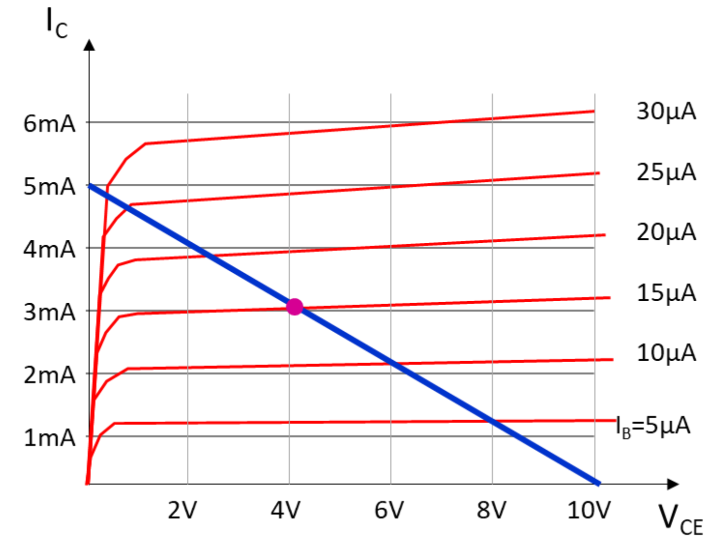


# A simple BJT amplifier circuit

In this circuit, a input signal $v_s$ is added to the base-emitter loop for amplification and the amplified output signal is taken out across the collector-emitter terminals. The input and output characteristic curves of the transistor along with the load lines are shown below.

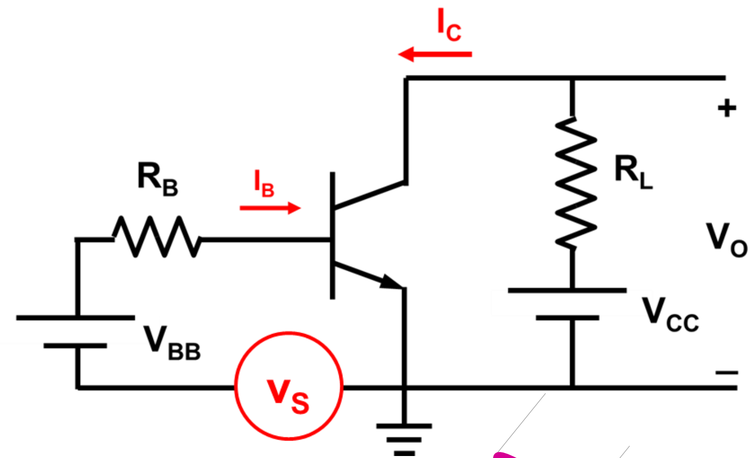


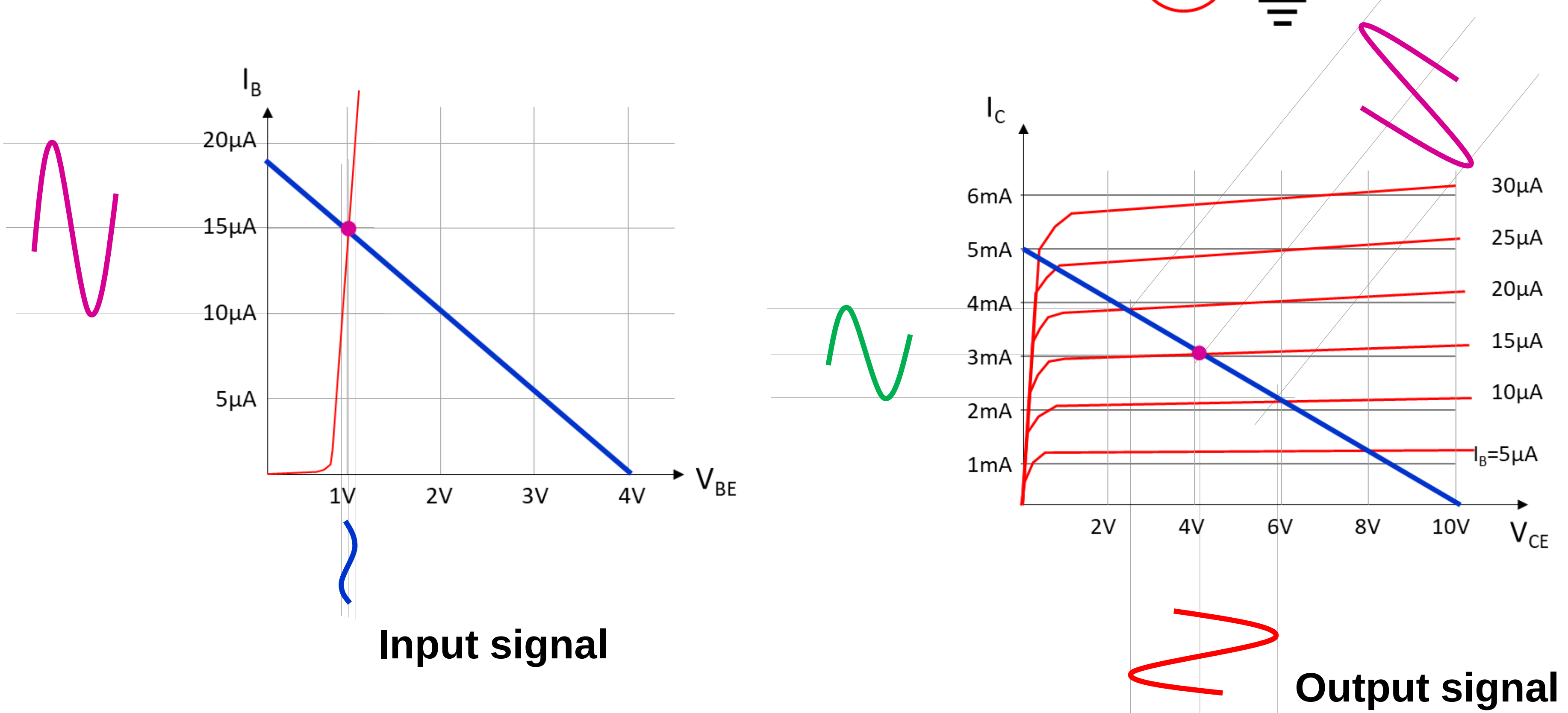



# A simple BJT amplifier circuit

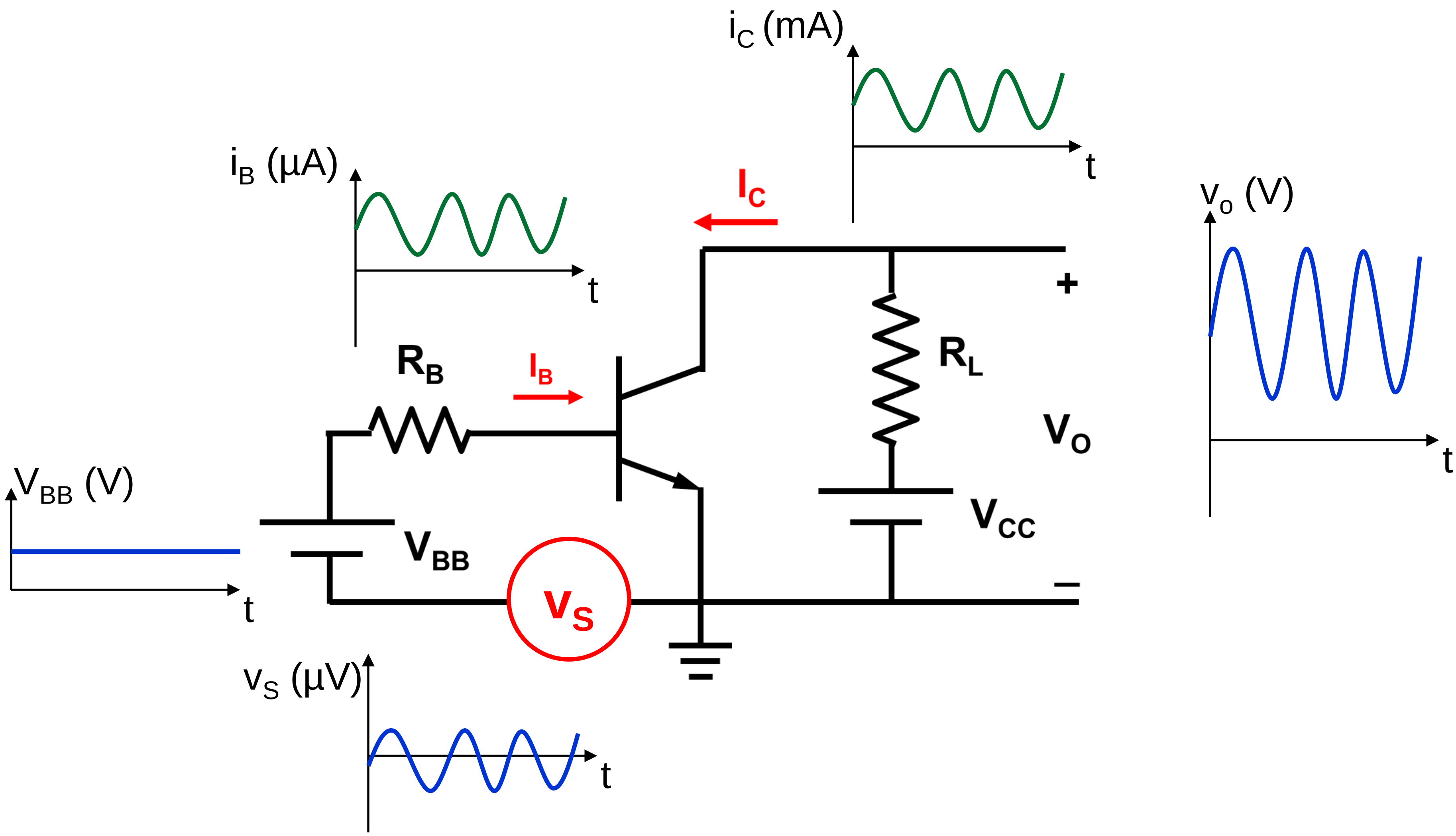
If the Q-point is chosen to be at the center of the active region, we can get linear amplification over a wide range of input signal.



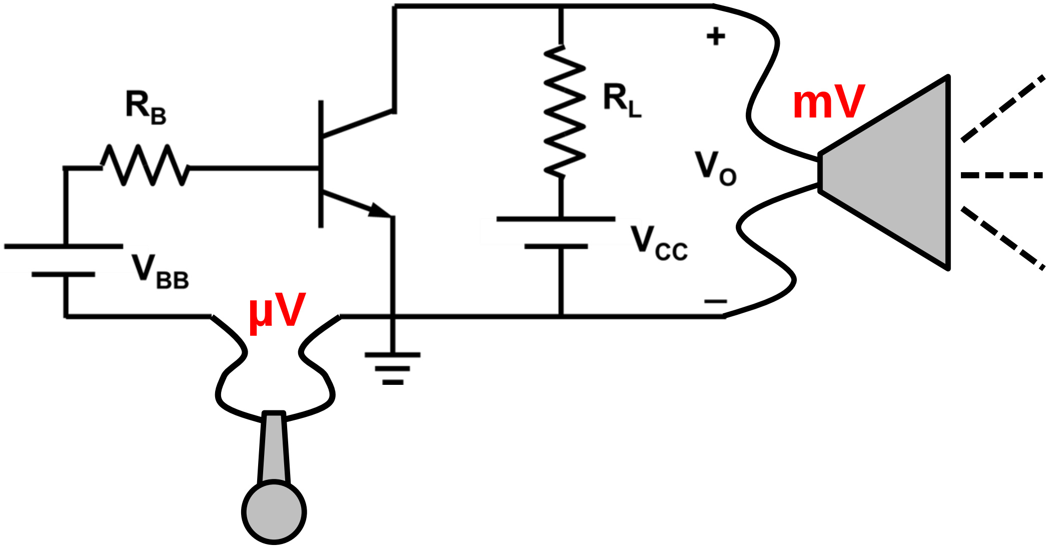
# A simple BJT amplifier circuit

**Various voltage and current components:**



# A simple BJT amplifier circuit

*Lets say that the circuit is used to amplify a voice signal from a microphone and the load is a speaker*



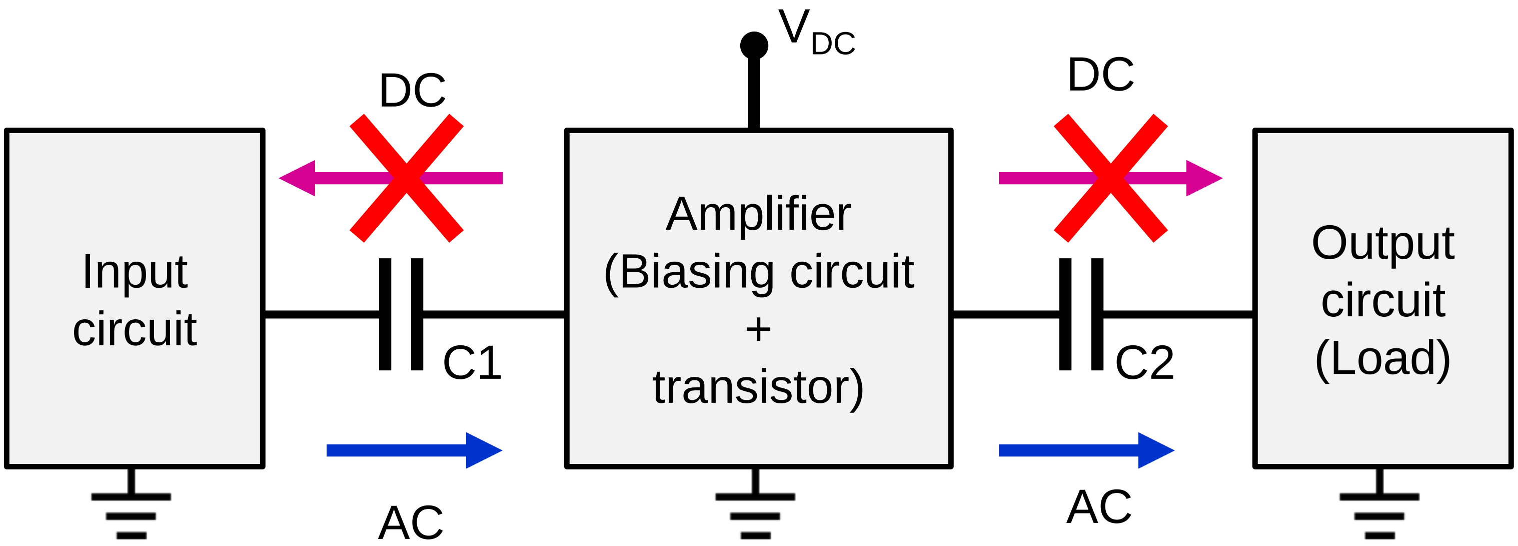

**Observations**:

- In order to create a linear amplifier, we must keep the transistor in the forward-active mode, establish a Q-point near the center of the load line and couple the time varying input signal to the base.
- The design that we have used in the previous slide has some issues:
  - The voltage output is an amplified version of the input signal along with some DC voltage. This may cause issue at the load.
  - The signal source is not grounded
  - There may be situations where you do not want a DC base current flowing through the signal source.

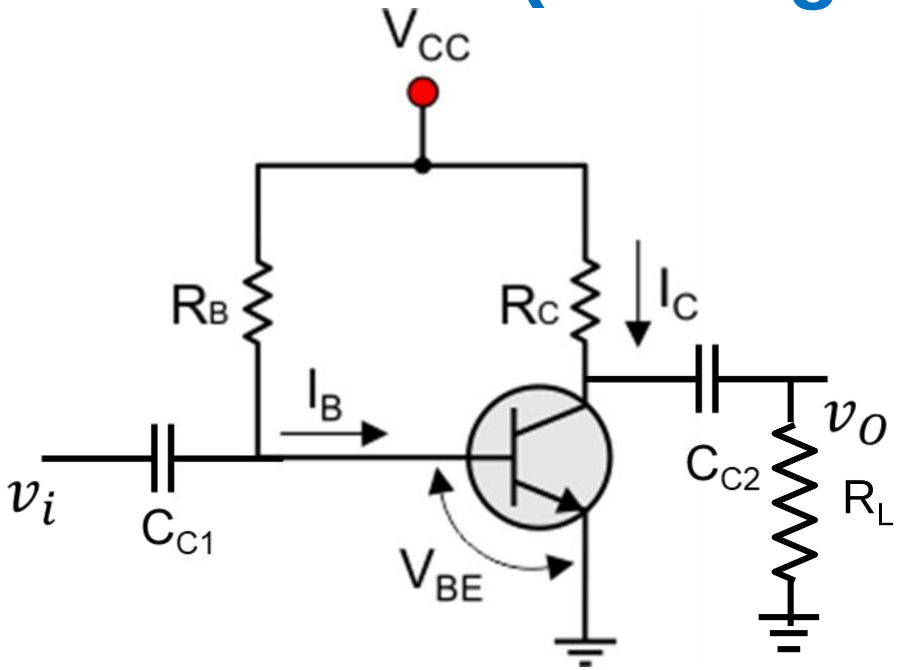
***Therefore, we need a circuit configuration where we can apply and extract the AC signals without being affected by the DC biasing circuit.***

# Capacitive coupling

*We can avoid the DC biasing circuit interference on the input and output AC signals by using coupling capacitors as shown below. A coupling capacitor only allows ac signal to pass through but completely blocks any DC signal.*



# Fixed base (or Single base) resistor biasing

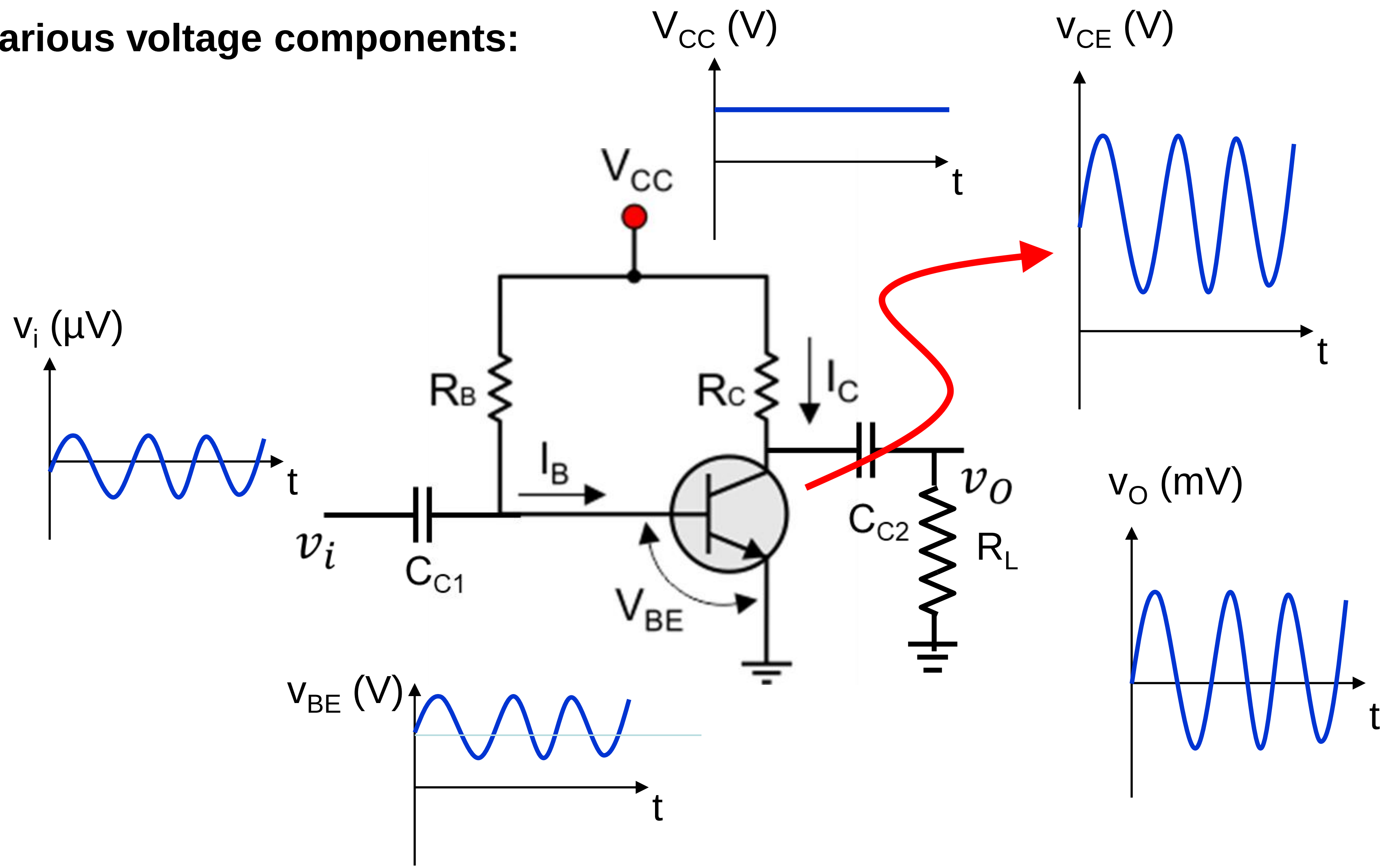



Notice:

- $C_{C1}$ and $C_{C2}$ are called coupling capacitors (typical values range between 1-10µF). These are called coupling capacitors. They act as open circuit for DC voltages. $C_{C1}$ isolates the signal source from the DC base current. $C_{C2}$ removes any DC component from the output voltage.
- If the frequency of the input signal is large enough and $C_{C1}$ and $C_{C2}$ are large enough, the input signal can be coupled to the base through $C_{C1}$ and amplified AC signal can be transferred to the load with little attenuation.
- Here only one DC bias source $V_{CC}$ is used. By choosing correct values of $R_B$ and $R_C$ we can control the junction voltages.

# Fixed base (or Single base) resistor biasing

**Various voltage components:**



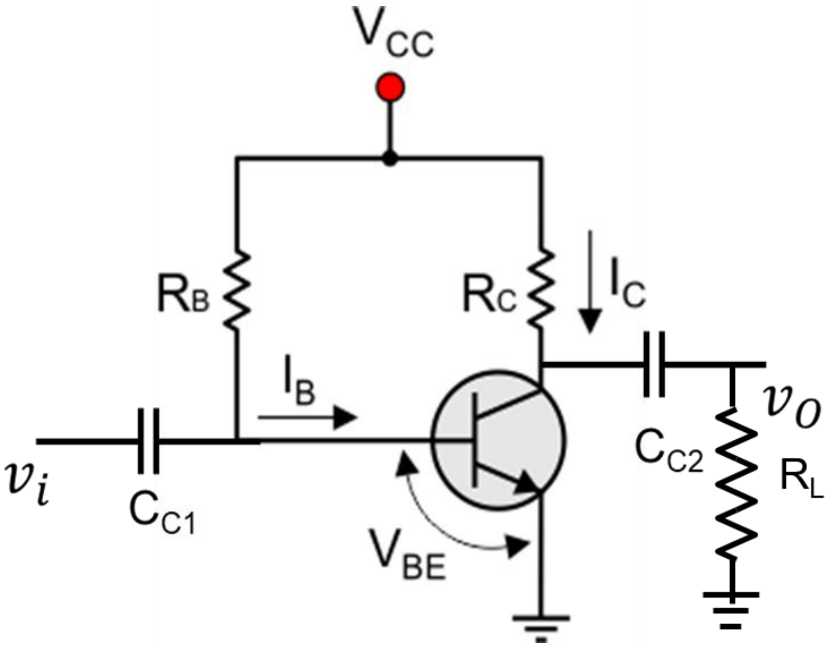

**Compare the output waveform with slide 5**

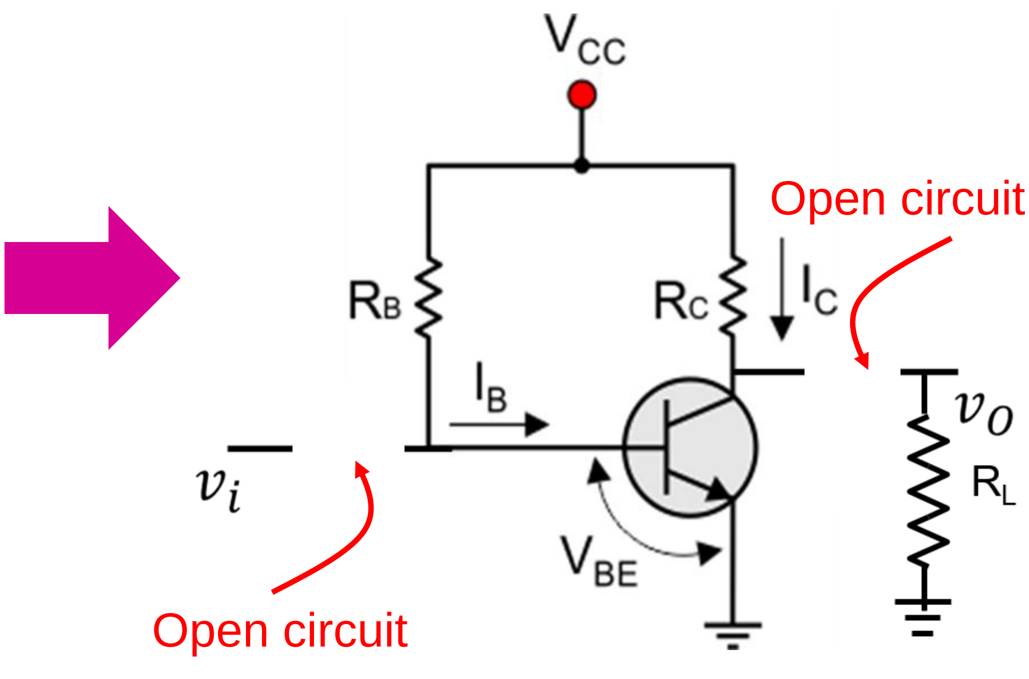
# Fixed base (or Single base) resistor biasing

## DC analysis

The amplifier circuit is now designed in such a way that the DC biasing components only provide a set of currents and voltages which fall within the forward-active region, however the DC components of these currents and voltages does get pass through to the load. Before we analyse the AC behaviour of the circuit, we need to ensure that the DC biasing circuit is providing an optimum Q-point for the desired operation (i.e. amplification). Therefore, we will study the DC behaviour of the circuit first before moving into AC responses.

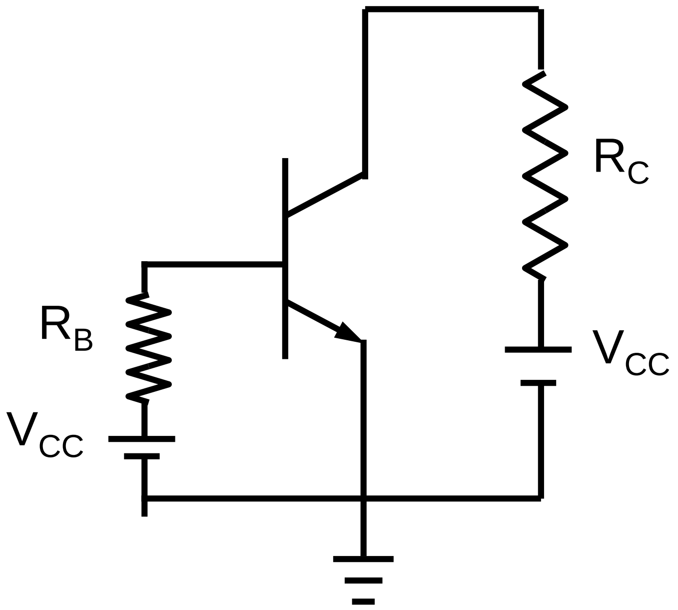
**Under only DC condition**



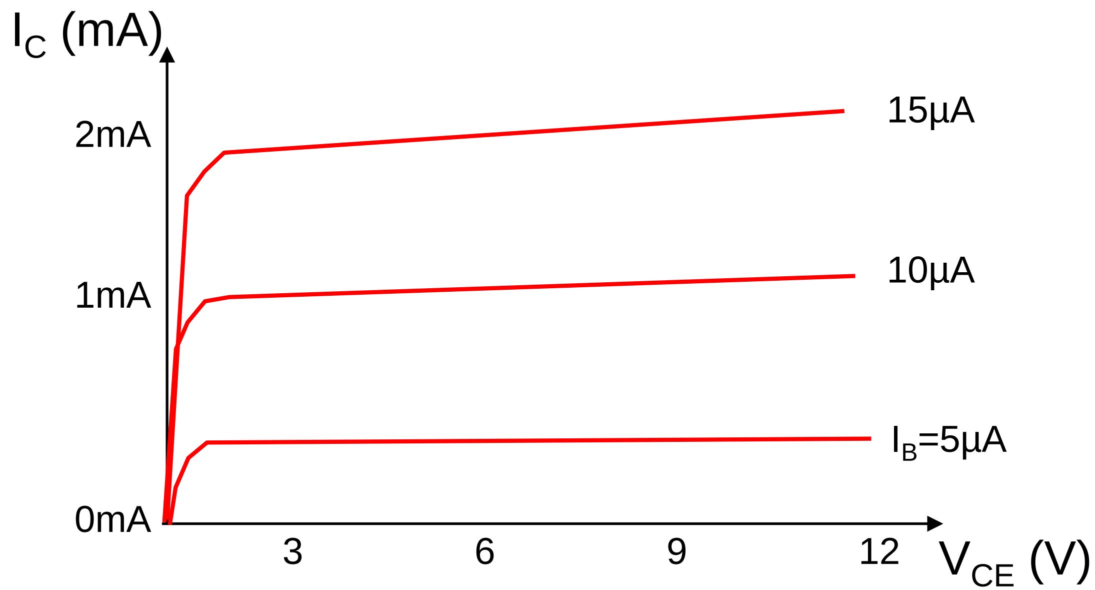



# Fixed base (or Single base) resistor biasing

## DC equivalent circuit




**Transistor output characteristic**




If $V_{CC}$ = 12 V and the Q-point need to be $I_C$ = 1mA and $V_{CEQ}$ = 6V, find the values of $R_B$ and $R_C$. Assume $\beta$ = 100 and $V_{BE(ON)}$ = 0.7V.

# Fixed base (or Single base) resistor biasing

From the output circuit we can find the value of $R_C$

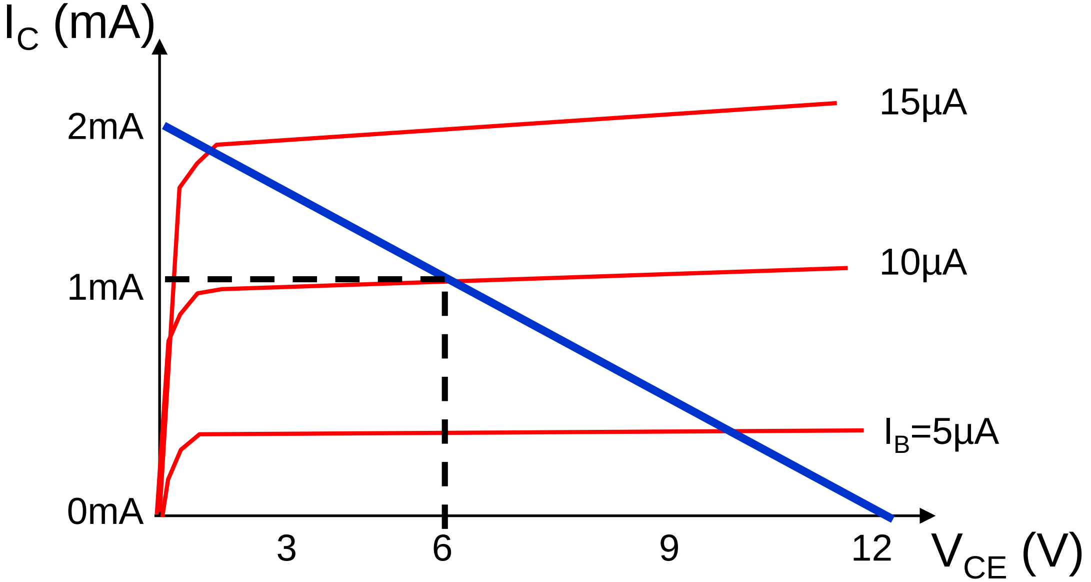
$$R_C = \frac{V_{CC} - V_{CEQ}}{I_{CQ}} = 6\text{k}\Omega$$

The base current:

$$I_B = \frac{I_{CQ}}{\beta} = 10\mu A$$

The base resistance:

$$R_B = \frac{V_{CC} - V_{BE(ON)}}{I_{BQ}} = 1.13\text{M}\Omega$$



# Fixed base (or Single base) resistor biasing

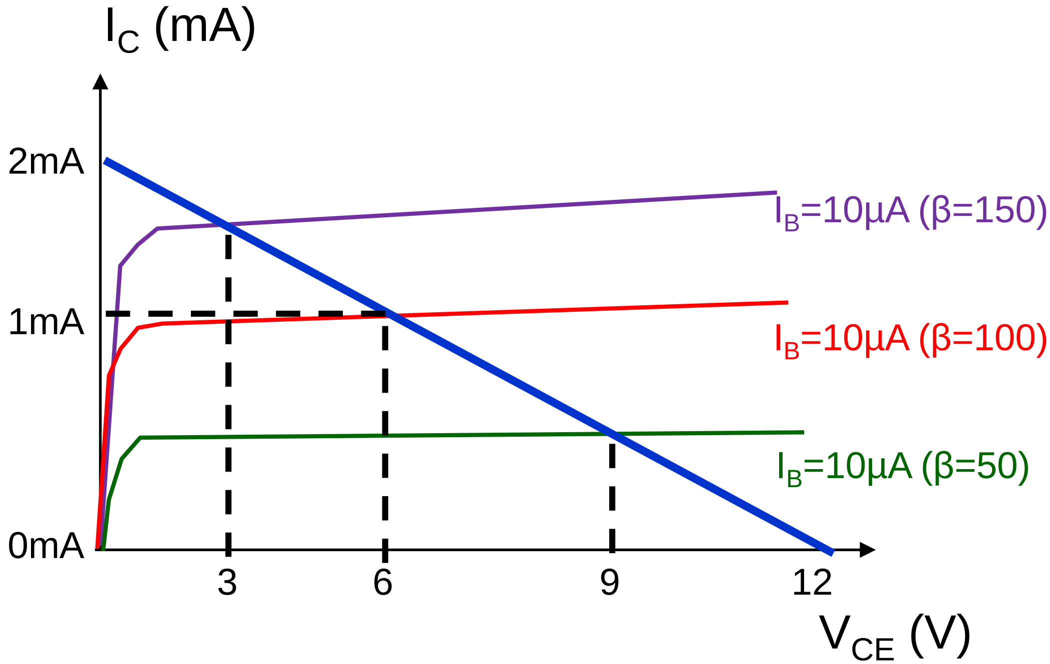
This fixed base biasing configuration although simple, has two major draw backs:

1. **Large base resistance**: In order to keep the base current in the range of few μA, the base resistance value lies in the range of MΩ. This resistance is too large to be used in integrated circuits.
2. **Bias instability**: in this configuration the Q-point is not stable against any variation in the β value.

**Change in Q-point as β changes:**

β of a transistor may change for various reasons. For the transistor used in this example, although the nominal value of β is considered to be 100, the β value may vary in the range of 50-150.

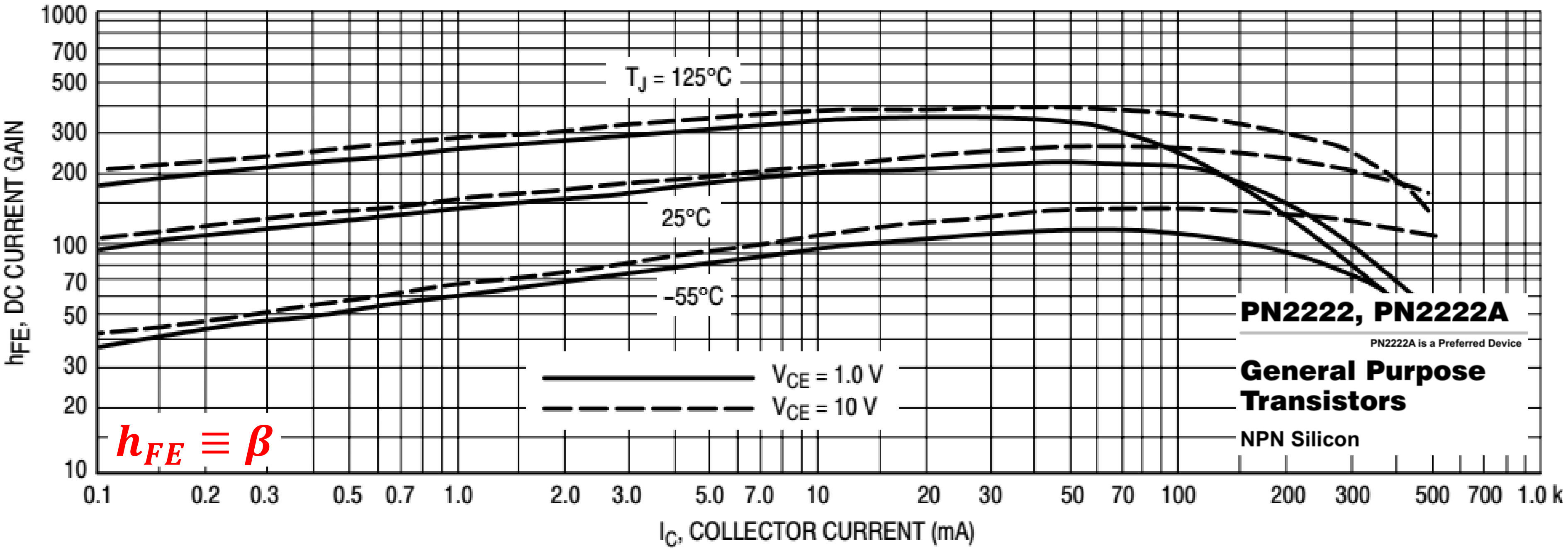
Since the base current does not depend on β, rather on $V_{CC}$ and $R_B$, it remains constant against any fluctuation of β. However the output characteristic curve will change as the β value changes. As a result the Q-point will vary accordingly.




| β | | 50 | 100 | 150 |
|---|---|---|---|---|
| Q-point values | $I_{CQ}$ | 0.5mA | 1mA | 1.5mA |
| | $V_{CEQ}$ | 9V | 6V | 3V |

# Transistor datasheet: variation of β with temperature

## β changes with temperature

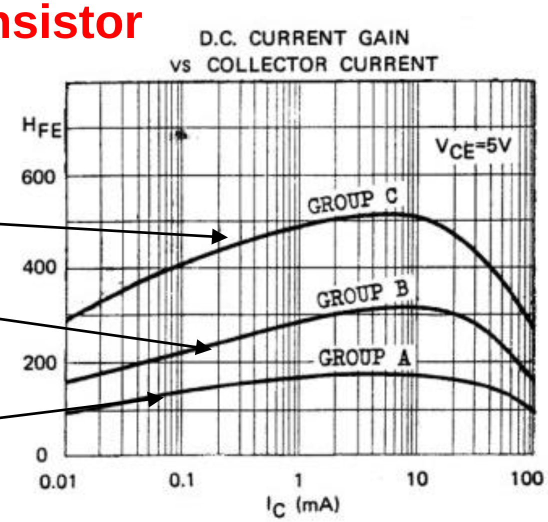



## β may vary between transistor to transistor

Transistors with high β

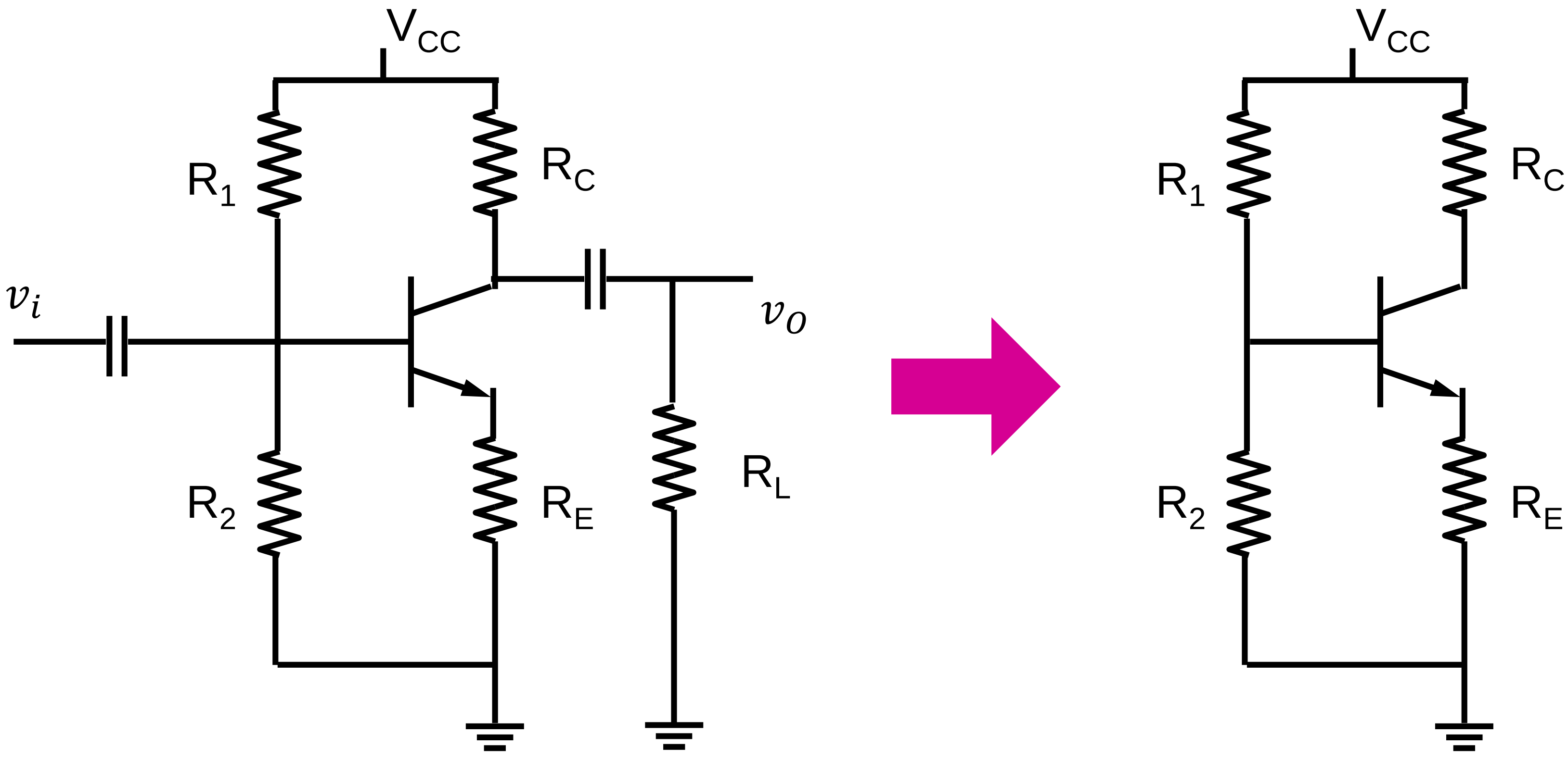
Transistors with nominal β

Transistors with low β



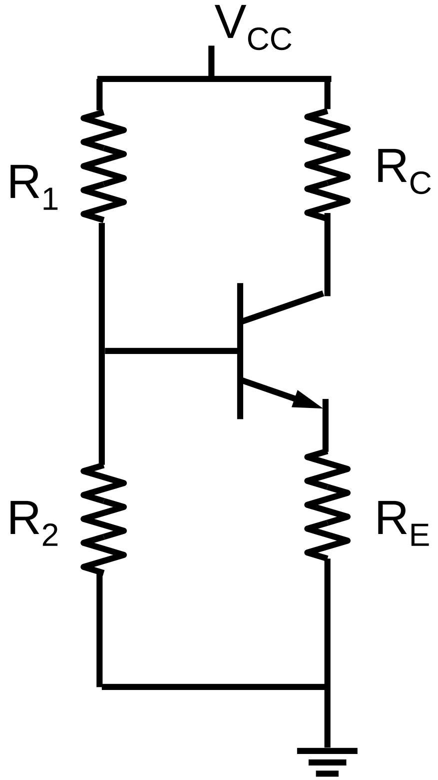
# Voltage divider biasing for bias stability

**DC equivalent circuit**

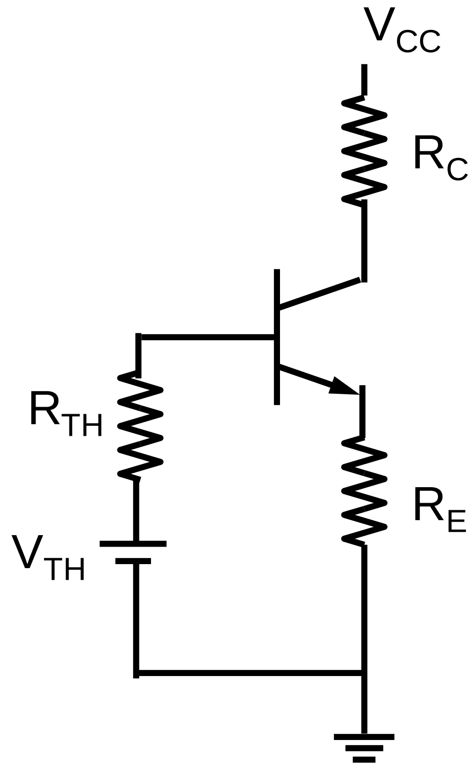


# Voltage divider biasing for bias stability

## DC equivalent circuit




## Thevenin equivalent circuit

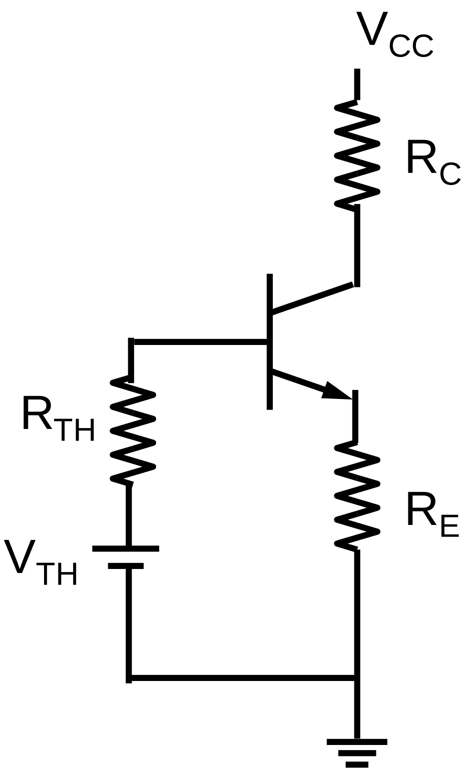



$$V_{TH} = \frac{R_2}{R_1 + R_2} V_{CC}$$

$$R_{TH} = \frac{R_1 R_2}{R_1 + R_2}$$

**Notice here since the voltage applied to the base depends on the ratio between $R_1$ and $R_2$ rather than their individual values, we have complete flexibility in choosing the values of $R_1$ and $R_2$.**

# Voltage divider biasing for bias stability




Apply KCL in B-E loop:

$$V_{TH} = I_{BQ}R_{TH} + V_{BE(ON)} + I_{EQ}R_E$$

If the transistor is biased in the forward-active mode, then

$$I_{EQ} = (1+\beta)I_{BQ}$$

Therefore the base current becomes

$$I_{BQ} = \frac{V_{TH} - V_{BE(ON)}}{R_{TH} + (1+\beta)R_E}$$

Hence the collector current becomes

$$I_{CQ} = \beta I_{BQ} = \frac{\beta(V_{TH} - V_{BE(ON)})}{R_{TH} + (1+\beta)R_E}$$

If $R_{TH} \ll (1+\beta)R_E$

$I_{CQ} \approx \frac{\beta(V_{TH} - V_{BE(ON)})}{(1+\beta)R_E}$ and normally $\beta \gg 1$

Therefore $I_{CQ}$ becomes

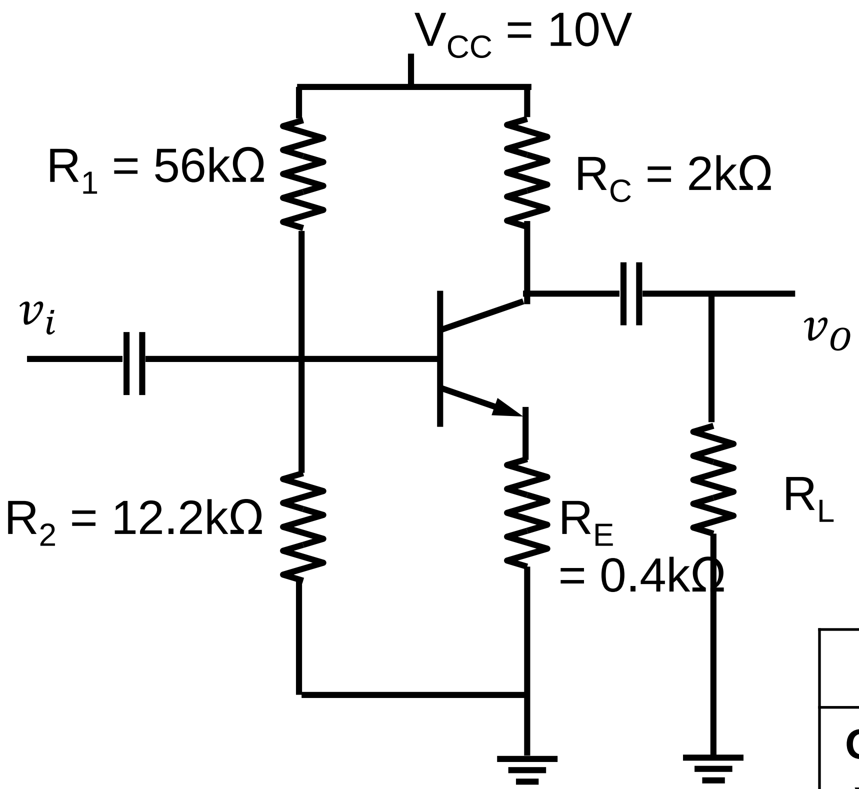
$$I_{CQ} \cong \frac{(V_{TH} - V_{BE(ON)})}{R_E}$$

**Notice here that the quiescent collector current has essentially become a function of the bias voltage ($V_{CC}$) and the emitter resistance $R_E$. Hence any variation in $\beta$ will have minimum effect on the Q-point**

In practice $R_{TH} = 0.1(1+\beta)R_E$ is considered to avoid excessive power dissipation in $R_1$ and $R_2$

# Voltage divider biasing for bias stability

**Example:**




Assume $\beta$ = 100 and $V_{BE(ON)}$ = 0.7V.

**Effect of β**

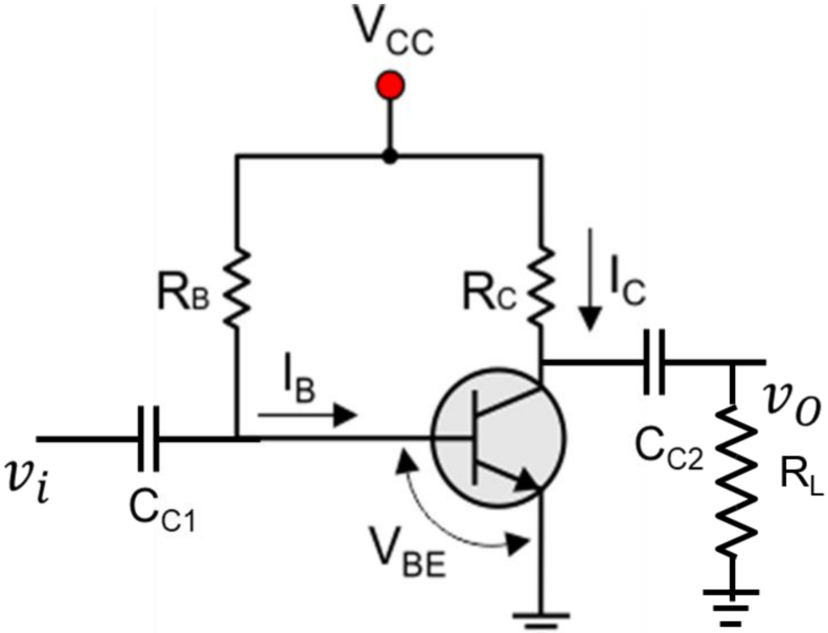
| **β** | | 50 | 100 | 150 |
|---|---|---|---|---|
| **Q-point values** | **$I_{CQ}$** | 1.8mA | 2.16mA | 2.32mA |
| | **$V_{CEQ}$** | 4.4V | 4.81V | 4.4V |

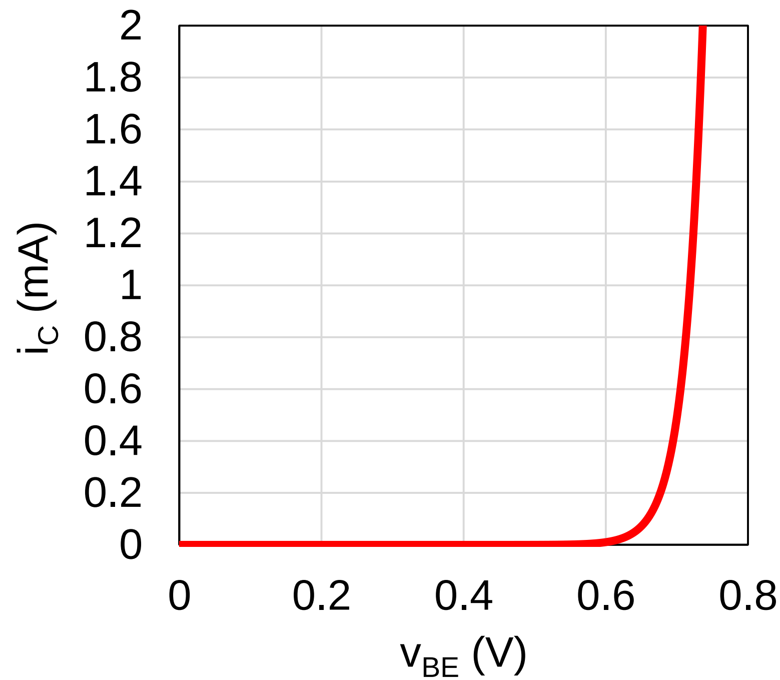
**Effect of β is much smaller than the fixed base resistor biasing circuit**

# Linear amplification and signal strength

We have so far argued that if the Q-point is located around the center of the forward active region, we can get linear operation over a large input signal range. However, this statement is true under the assumption that the transistor behaves linearly within the entire active region and single gets distorted only when it moves into the cut-off or saturation region. Because of exponential dependence of the output current $i_C$ on base-emitter voltage ($V_{BE}$) we expect to get nonlinear dependence of output signal on input signal.

Lets consider a fixed base resistance basing circuit. The current $i_C$ will have an exponential dependence on the base-emitter voltage.

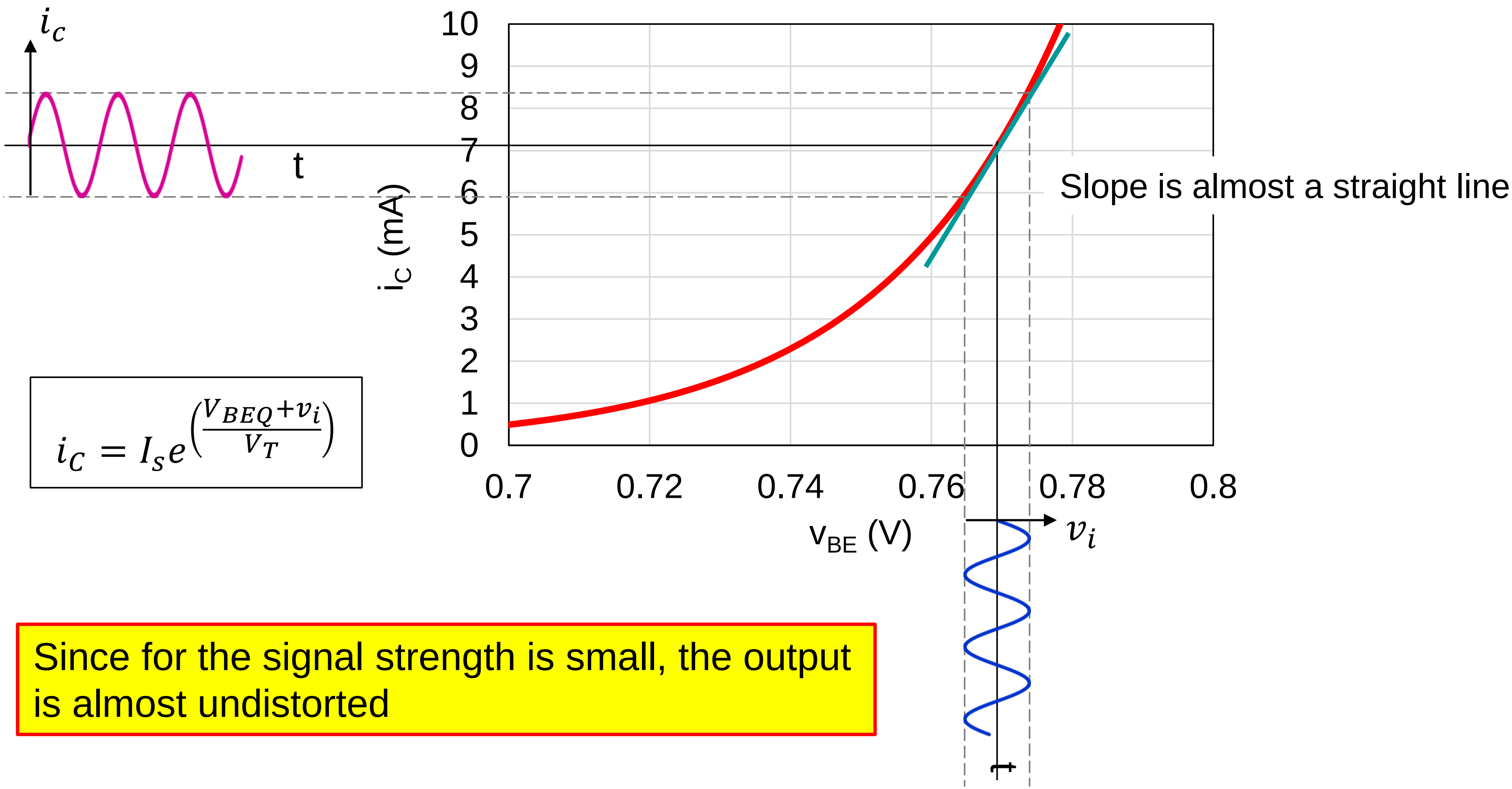


# Linear amplification and signal strength

Let us assume that the Q-point is at $V_{BEQ}$ = 0.77V and $I_{CQ}$ = 7.1mA

Case 1: $v_i = 5mV$



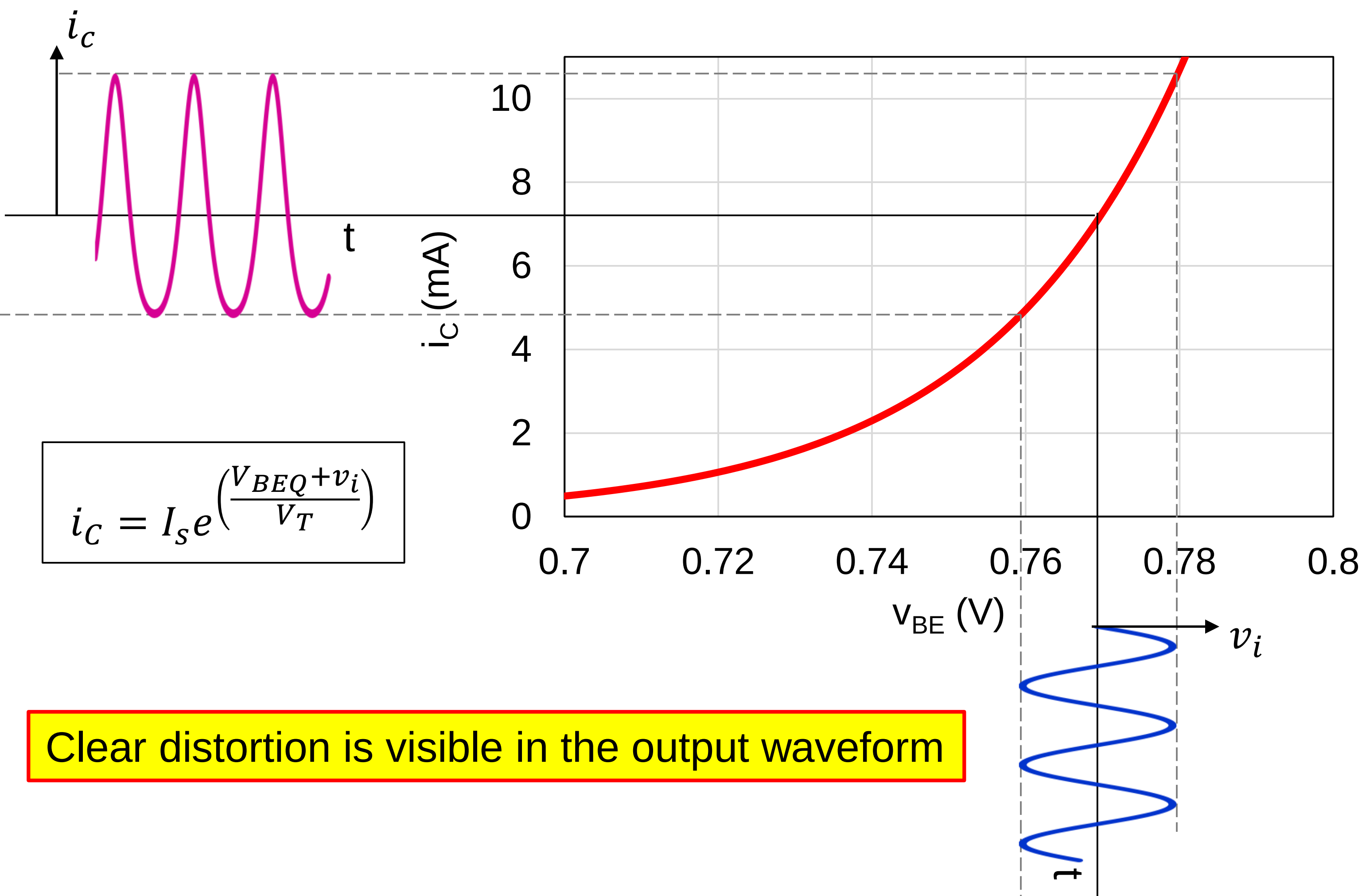

$$i_C = I_s e^{\left(\frac{V_{BEQ}+v_i}{V_T}\right)}$$

Since for the signal strength is small, the output is almost undistorted

# Linear amplification and signal strength

Let us assume that the Q-point is at $V_{BEQ} = 0.77V$ and $I_{CQ} = 7.1mA$

Case 1: $v_i = 20mV$




$$i_C = I_s e^{\left(\frac{V_{BEQ}+v_i}{V_T}\right)}$$

Clear distortion is visible in the output waveform

# Linear amplification and signal strength

From the previous discussion we see that

When $V_{BEQ}$ = 770mV and ICQ = 7.1mA

a. For input voltage vi = 5mA, no significant distortion is visible
b. For input voltage vi = 20mA, significant distortion is visible.

It is clear that the AC signal strength should be much smaller than the DC bias voltage, so that the $I_C$-$V_{CE}$ relationship can be approximated to be linear. So the condition for linear amplifier operation is that the AC signals very small in comparison to the DC signals.

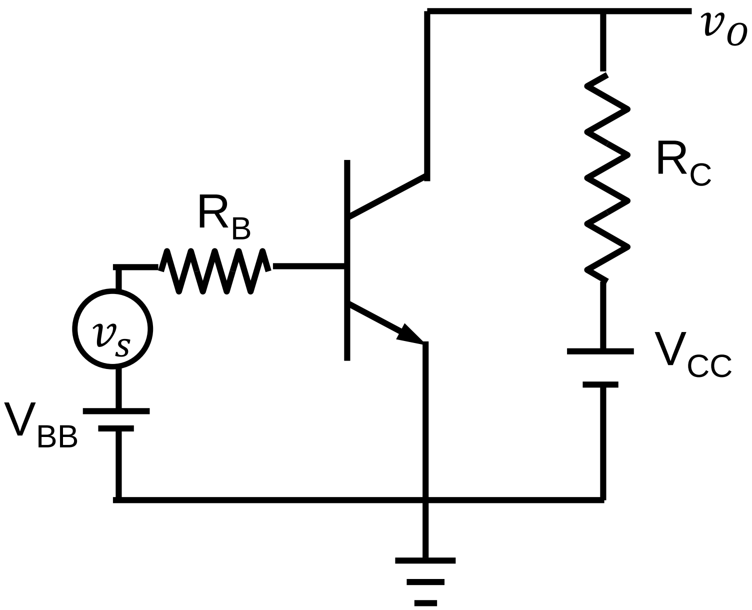
That is why the DC analysis is called “large signal analysis” and the AC analysis is called “small signal analysis”.

# Small signal analysis

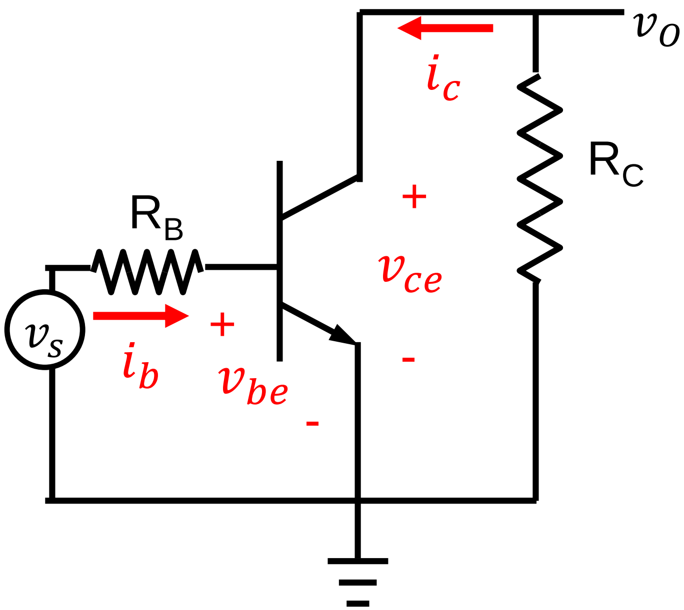
Here we will only analyse the amplifier circuit considering the input signal strength to be much smaller than the DC bias signals. So that we can approximate the voltage-current relationships to be linear. For AC analysis or small signal analysis we will set the DC sources to be zero and analyse the circuit only for the AC sources.

Lets consider a simple amplifier circuit considered in the last chapter.

**Actual amplifier circuit**




**Circuit for small signal analysis**




Notice that all the AC signals are written in small letters

# Small signal model for AC analysis

Similar to DC analysis where we have used input and output characteristics along with load lines to determine the relationships between the DC values of terminal voltages and currents of a transistor within an amplifier circuit, now we need to develop similar relationships between the AC voltage and current components for the transistor.
To do so it will be very useful to replace the transistor with some linear components, such as resistances, capacitances and voltage or current sources etc. (known as equivalent circuit model) and then we can use linear circuit analysis tools (KVL, KCL etc) to develop relationships between different current and voltage components.

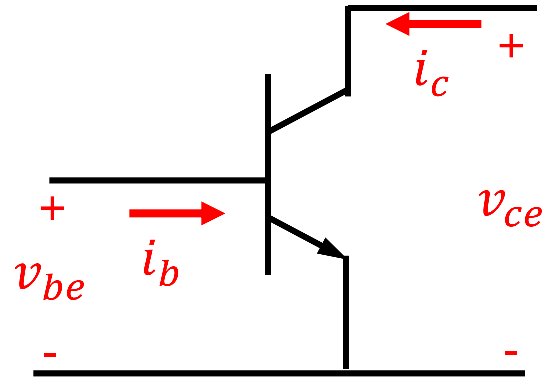
Here we will develop small signal equivalent circuit model for the transistor under the following assumption:

a) The transistor is always in forward-active mode
b) The AC signals is much smaller than the DC bias voltages and currents.
c) Relationships between all the AC current and voltage components are linear

There are various small signal equivalent circuit models available, but we will use one particular model known as Hybrid-π model.

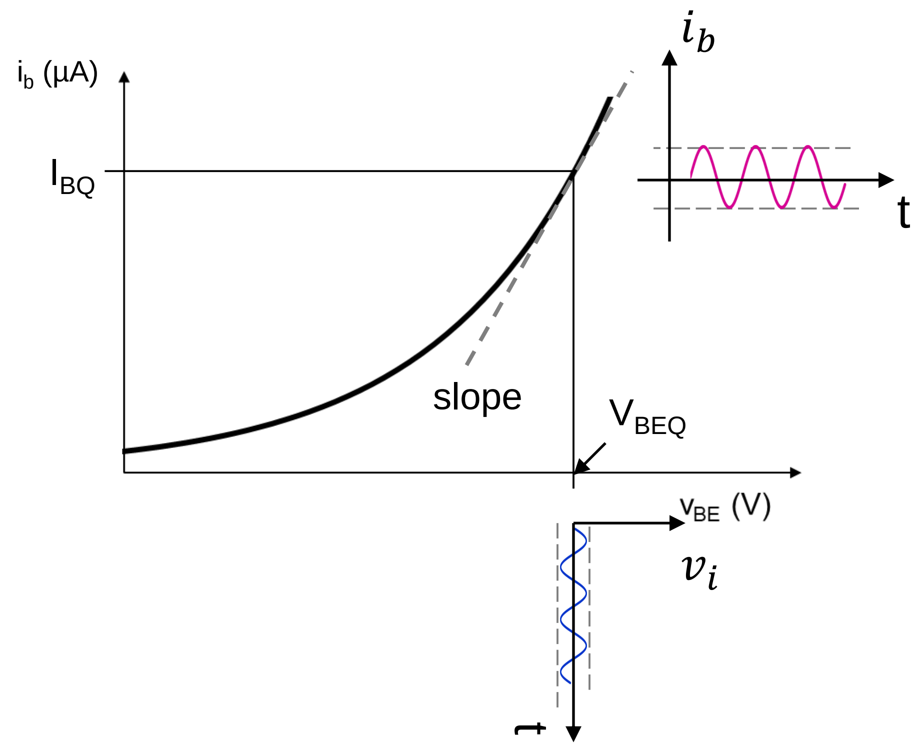
# Hybrid-π for AC analysis

Here we are interested in developing an equivalent circuit to replace the transistor. In the input loop of the transistor we have voltage $v_{be}$ and current $i_b$ and in the output loop we have voltage $v_{ce}$ and current $i_c$.




Within the linear region of operation, $i_b$ can be approximated to vary linearly with $v_{be}$.
The slope of this section of the curve can be expressed as:

$$\text{Slope} \equiv \left.\frac{\partial i_B}{\partial v_{BE}}\right|_{Q-point} = \frac{1}{r_\pi}$$




This slope gives the conductance of the input port of the transistor and $r_\pi$ is the small signal input resistance. It is important to note here that since the slope of the $i_b$-$v_{be}$ curve changes so $r_\pi$ is a function of the Q-point parameters.
Now we know

$$i_B = \frac{i_C}{\beta} = \frac{I_S}{\beta} e^{\frac{v_{BE}}{V_T}}$$

Therefore:

$$\frac{1}{r_\pi} = \left.\frac{\partial i_B}{\partial v_{BE}}\right|_{Q-point} = \left.\frac{\partial}{\partial v_{BE}}\left[\frac{I_S}{\beta} e^{\frac{v_{BE}}{V_T}}\right]\right|_{Q-point}$$

# Hybrid-π for AC analysis

or

$$\frac{1}{r_\pi} = \frac{1}{V_T}\left[\frac{I_S}{\beta}e^{\frac{v_{BE}}{V_T}}\right]\Bigg|_{Q-point} = \frac{I_{BQ}}{V_T}$$

Therefore

$$r_\pi = \frac{V_T}{I_{BQ}} = \frac{\beta V_T}{I_{CQ}}$$

If we ignore the early effect, then the output current of the transistor, $i_C$, is only a function of the input voltage, $v_{BE}$.

$$i_C = I_S e^{\frac{v_{BE}}{V_T}}$$

Within the liner region of operation, we can write:

slope$\equiv$ $g_m = \frac{\partial i_C}{\partial v_{BE}}\Big|_{Q-point}$

Similar analysis as above gives us:

$$g_m = \frac{I_{CQ}}{V_T}$$

$g_m$ is known as the transconductance, since it relates the input voltage to the output current. $g_m$ is also a function of the the Q-point parameters.

# Hybrid-π for AC analysis

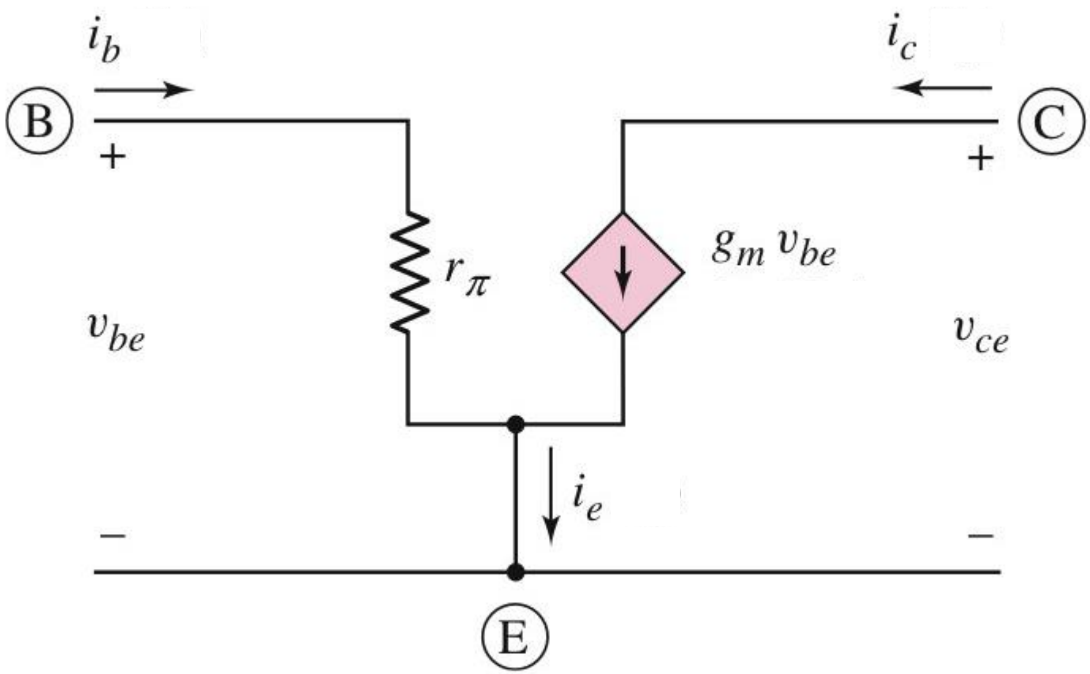
With these information we are now ready to develop the small signal hybrid-π model. For input port we have,

$$v_{be} = r_\pi i_b$$

And for the output port we have,

$$i_c = g_m v_{be}$$

We can represent the input relationship using a resistance and the trans conductance as a dependent current source.




$$g_m = \frac{I_{CQ}}{V_T}$$

$$r_\pi = \frac{\beta V_T}{I_{CQ}}$$

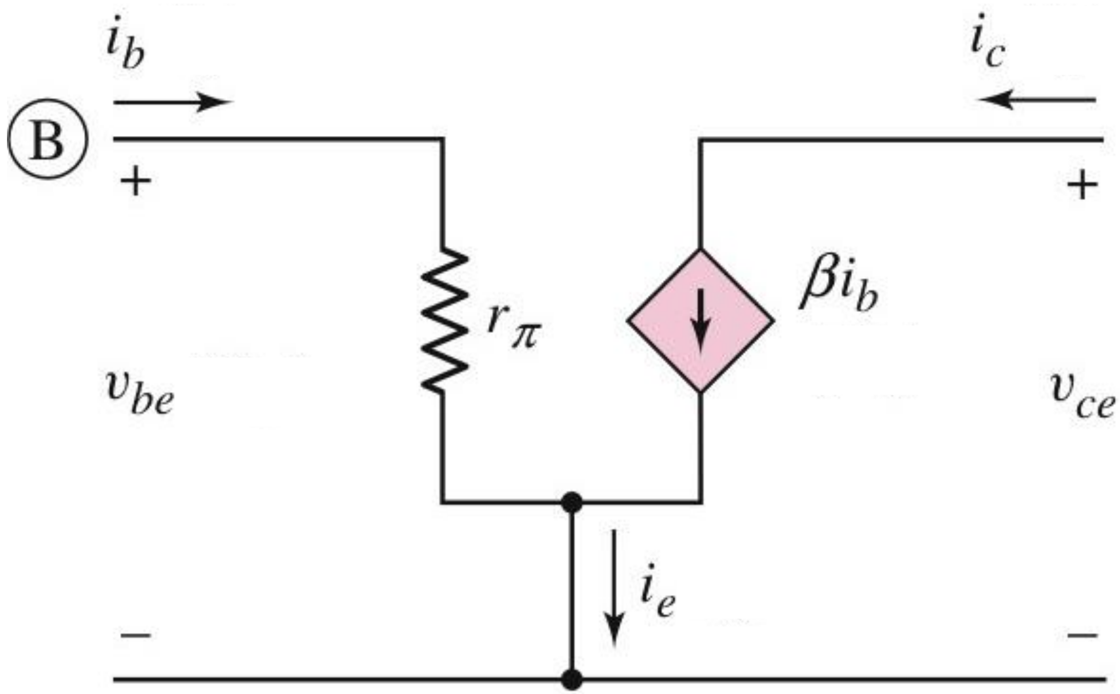
$$g_m r_\pi = \beta$$

# Hybrid-π for AC analysis

The magnitude of the dependent current source can also be represented in terms of β, where

$$\beta = \left.\frac{\partial i_C}{\partial i_B}\right|_{Q-point}$$

Also called AC common emitter current gain.



# Hybrid-π for AC analysis

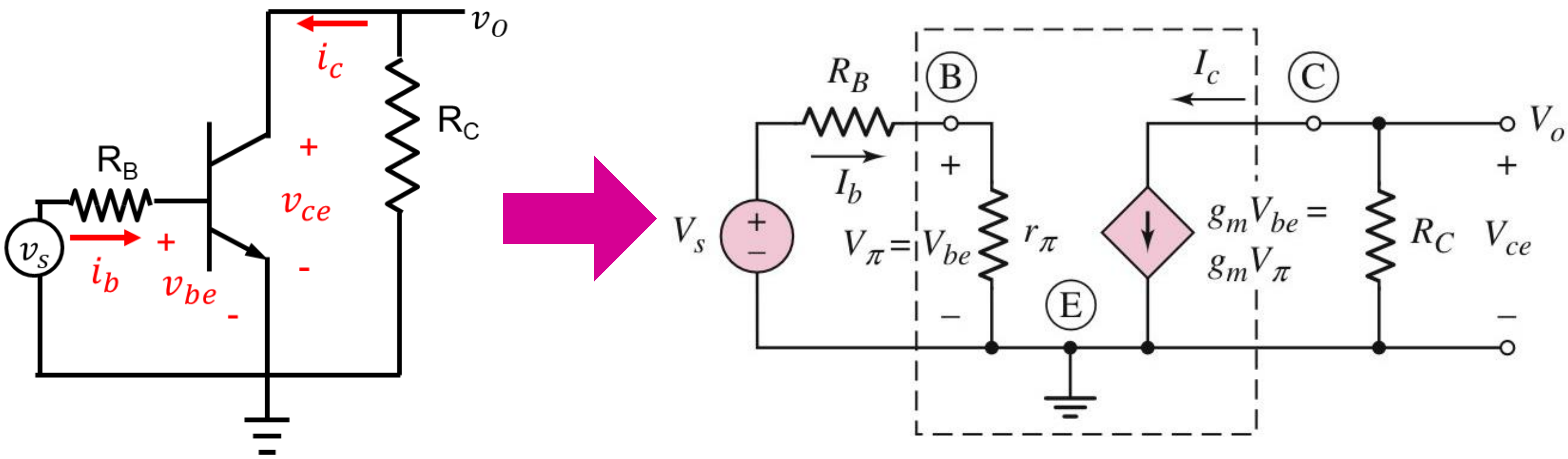
**Small signal current gain (CE configuration)**:

In CE configuration the current gain is simply:

$$\frac{i_c}{i_b} = \frac{g_m v_{be}}{i_b} = g_m r_\pi = \beta$$

**Small signal voltage gain (CE configuration)**:

We can now replace the transistor with the hybrid-π model in the amplifier circuit

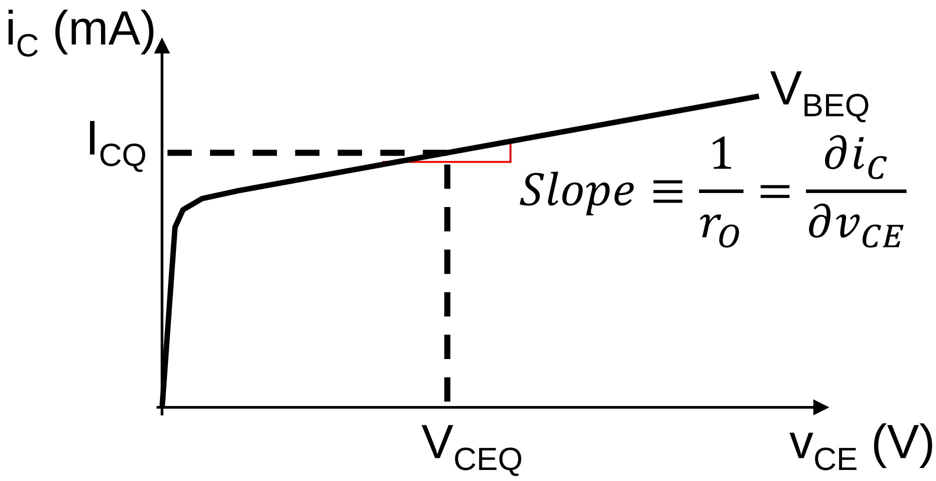



$$A_v = -(g_m R_C)\left(\frac{r_\pi}{r_\pi + R_B}\right)$$

# Effect of Early voltage

The model that we developed in the previous slide does not take into account the Early effect. Let us now also include the dependence of $i_C$ on $v_{CE}$.

$$Slope \equiv \frac{1}{r_O} = \frac{\partial i_C}{\partial v_{CE}}\bigg|_{Q-point}$$




With Early effect

$$i_C = I_S e^{\frac{v_{BE}}{V_T}}\left(1 + \frac{v_{CE}}{V_A}\right)$$

$$\frac{1}{r_O} = \frac{\partial}{\partial v_{CE}} I_S e^{\frac{v_{BE}}{V_T}}\left(1 + \frac{v_{CE}}{V_A}\right)\bigg|_{Q-point}$$

$$\frac{1}{r_O} \cong \frac{I_{CQ}}{V_A}$$

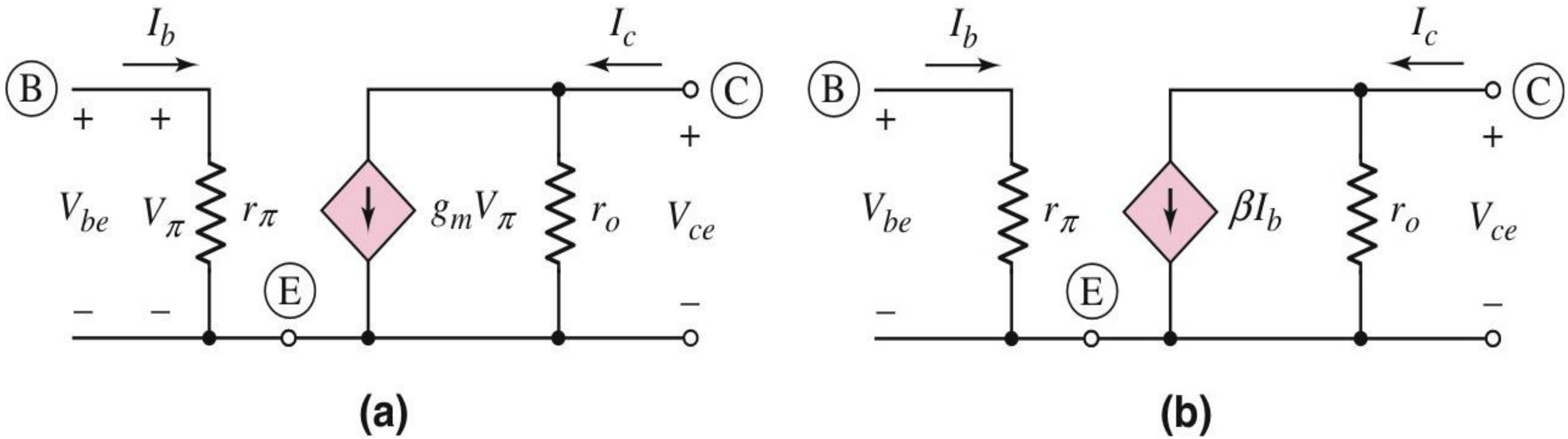
Or

$$r_O \cong \frac{V_A}{I_{CQ}}$$

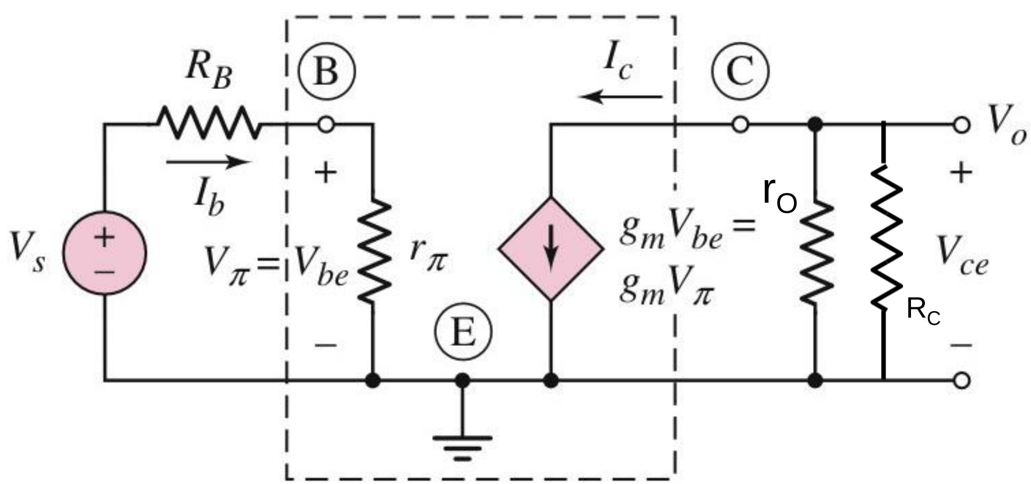
$r_O \equiv$ small-signal transistor output resistance

# Effect of Early voltage

With output resistance the hybrid-π model becomes:




**Small signal voltage gain with output resistance (CE configuration)**:



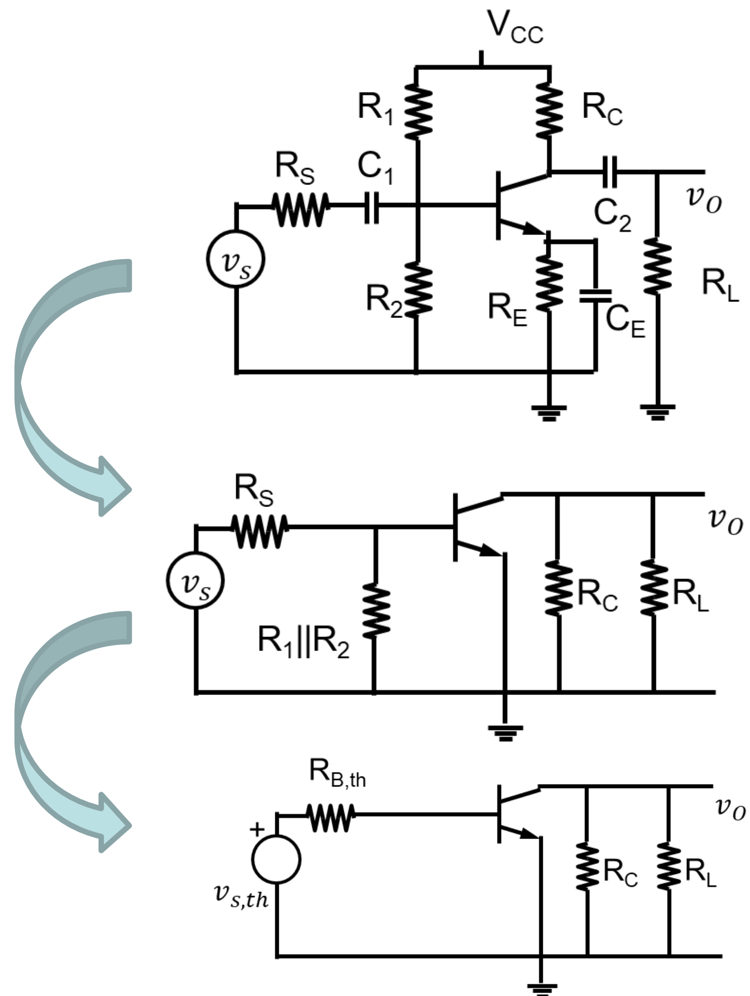

$$A_v = -(g_m r_\pi)\left(\frac{r_o \parallel R_C}{r_\pi + R_B}\right)$$

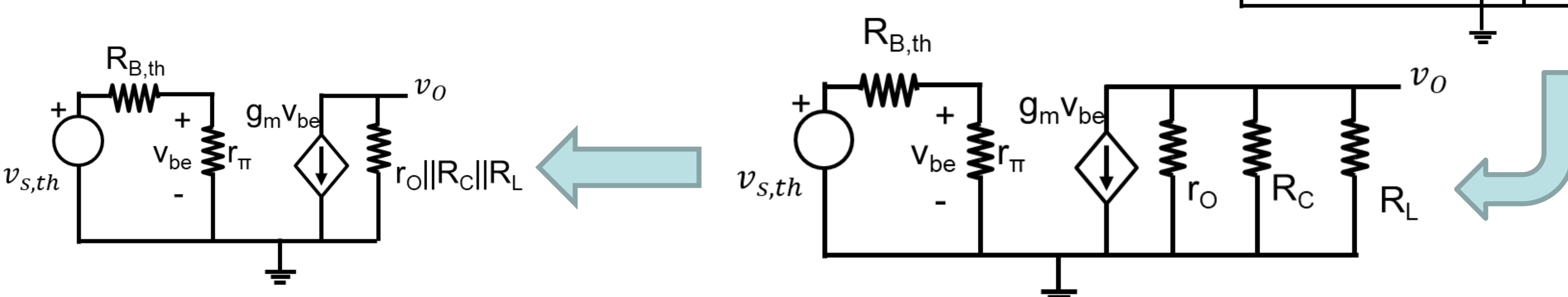
# Single transistor amplifier analysis: procedure

1. Determine DC operating point (Q-points) and calculate small signal parameters

$$r_\pi = \frac{V_T}{I_{BQ}},\ g_m = \frac{I_{CQ}}{V_T},\ r_O = \frac{V_A}{I_{CQ}}$$

2. Convert to the AC only model
   a) DC voltage sources are shorts to ground
   b) DC current sources are open circuits
   c) Large capacitors are short circuits
   d) Large inductors are open circuits
3. Use Thevenin's theorem (if necessary) to have a single resistor and a single voltage source connected to the base terminal.
4. Replace transistor with small signal model.
5. Simplify the circuit as much as possible
6. Calculate the gain etc.



# Amplifier parameters

- Amplifier voltage gain
- Amplifier current gain
- Amplifier power gain
- Input resistance
- Output resistance
- 3dB frequency bandwidth

**In an amplifier we want:**

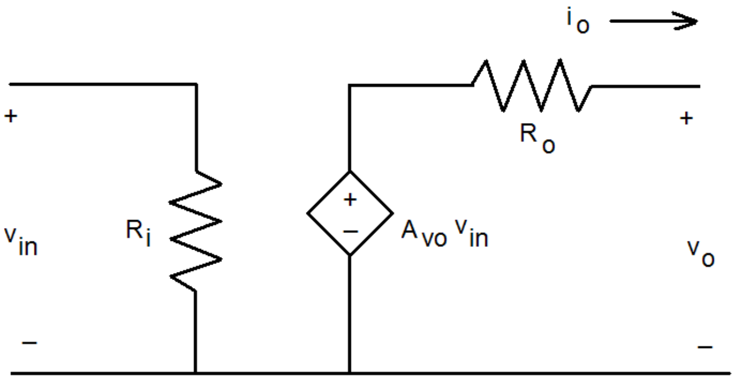
- High power gain
- High input resistance
- Low output resistance

# difference between CB,CE,CC transistor configurations

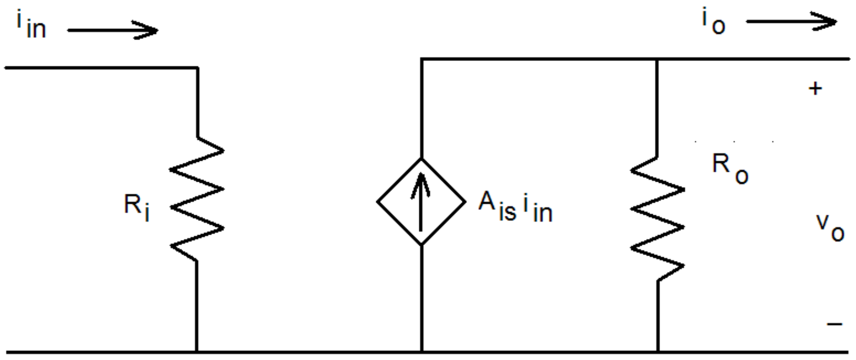
| Parameter | Common Base | Common Emitter | Common Collector |
|---|---|---|---|
| Voltage Gain | **High** | **High** | Less than Unity |
| Current Gain | Less than Unity | **High** | **High** |
| Power Gain | Moderate | **High** | Moderate |
| Phase inversion | No | **Yes** | No |
| Input Impedance | Low (50Ω) | Moderate (1KΩ) | **High** (300KΩ) |
| Output Impedance | High (1MΩ) | Moderate (50KΩ) | **Low** (300Ω) |

# Amplifier classification

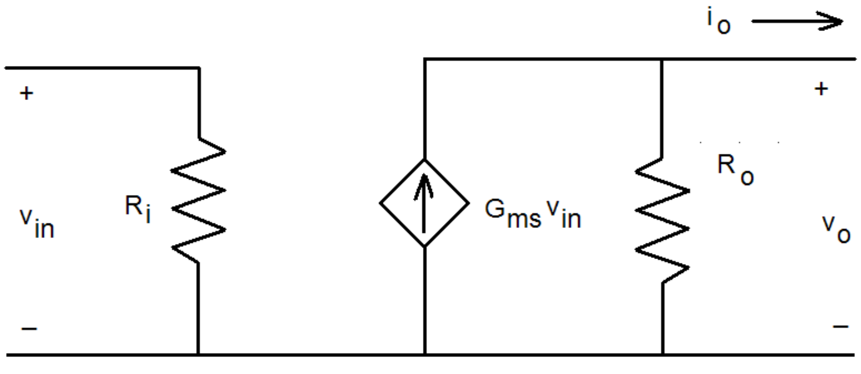
## Voltage Amplifier



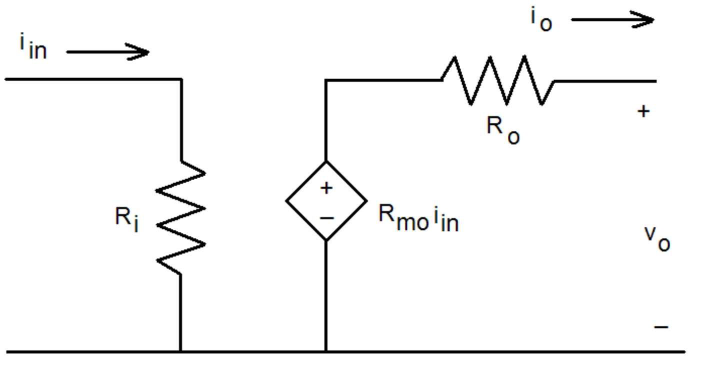

## Current Amplifier




## Transconductance Amplifier

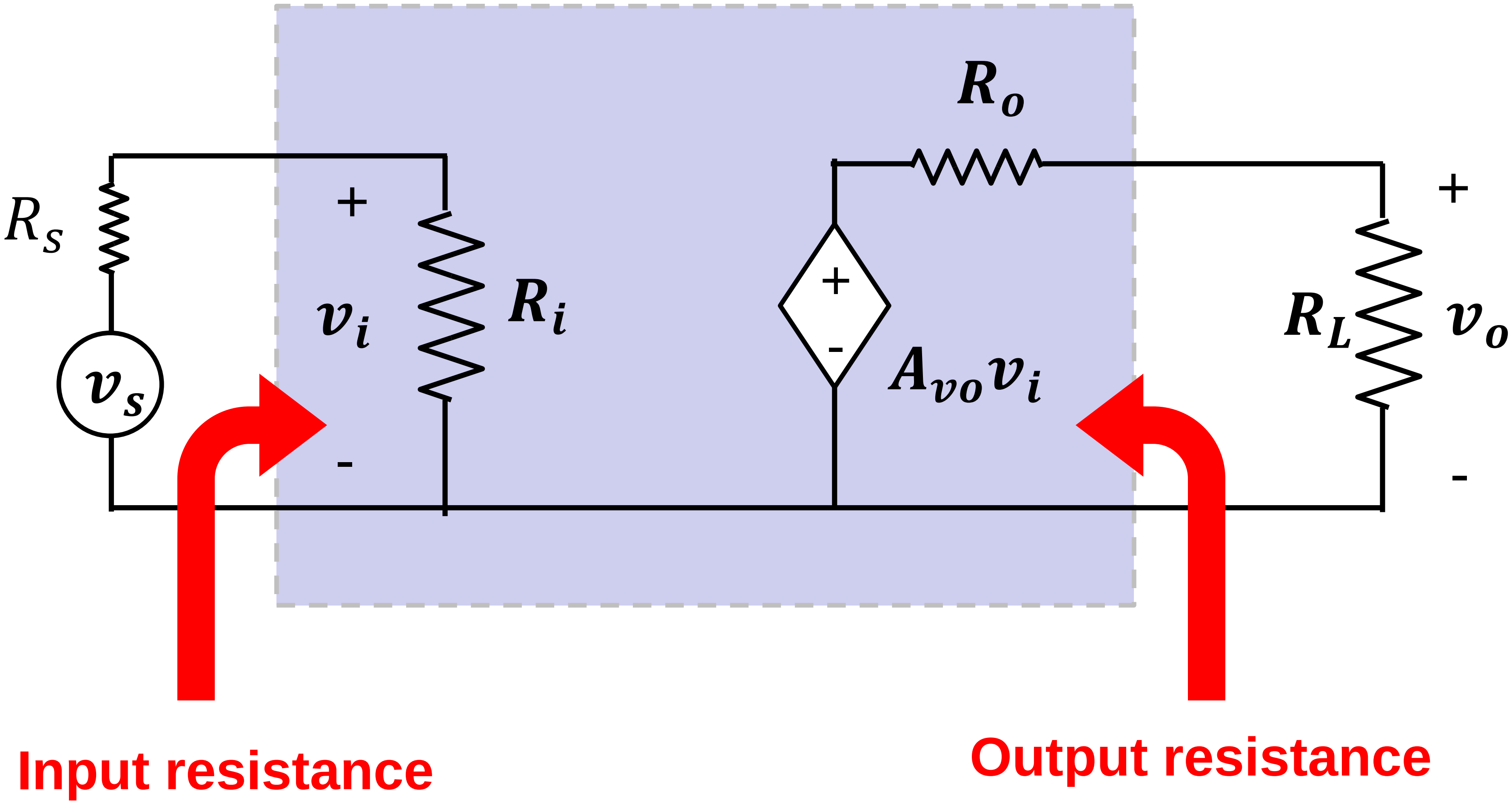



## Transresistance Amplifier



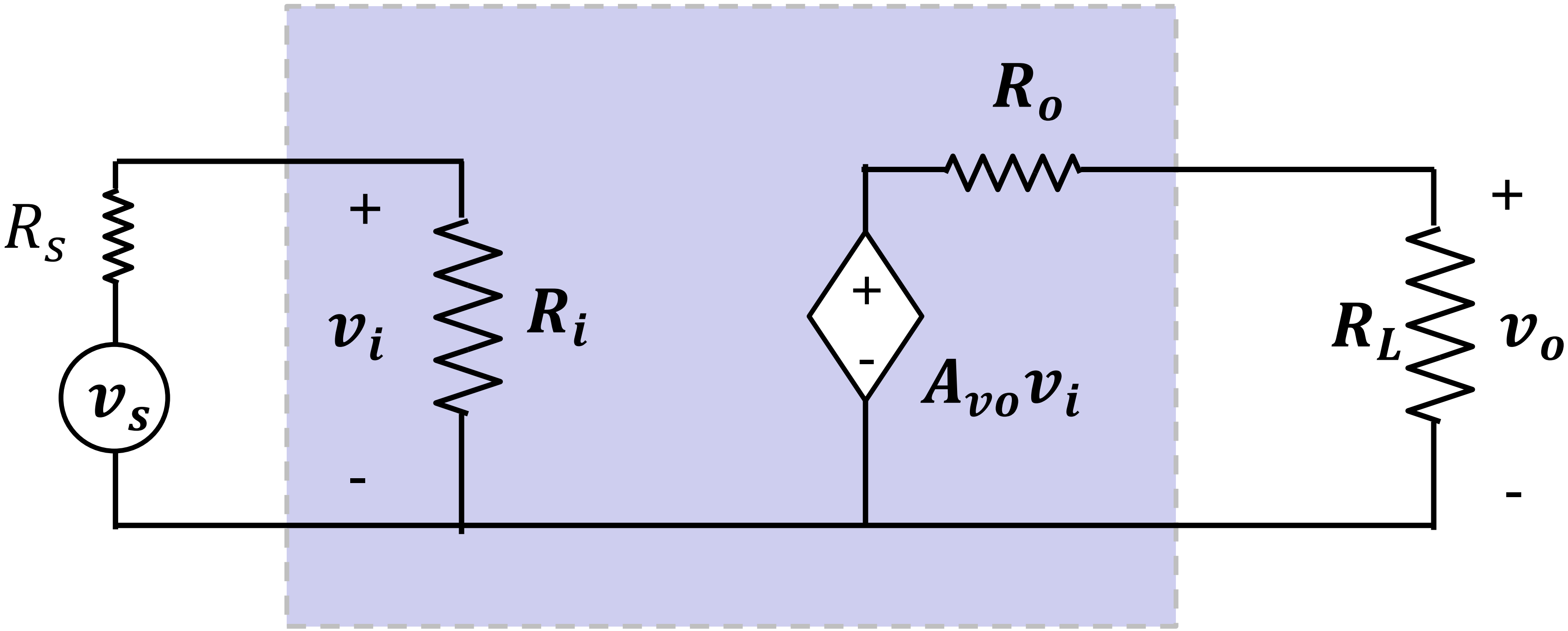
# Amplifier parameters

**Voltage amplifier**



# Amplifier parameters

## Voltage amplifier




$$A_v = \frac{R_L}{R_L + R_o}\frac{R_i}{R_i + R_s}A_{vo}$$

# Amplifier parameters

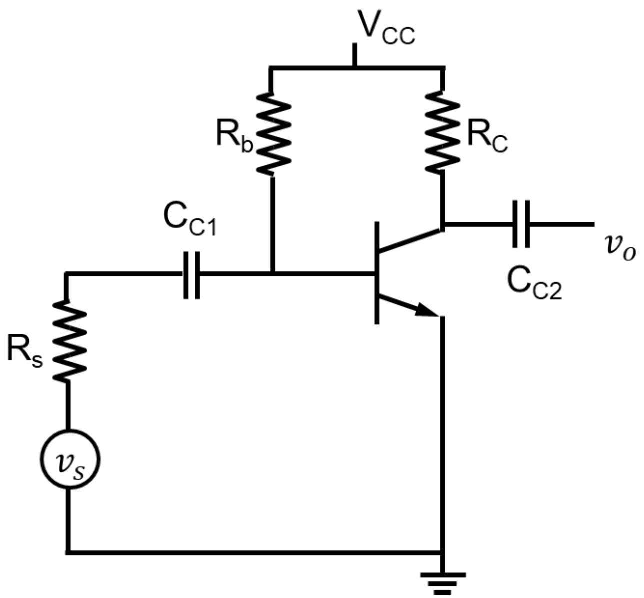
## Effect of input & output resistance

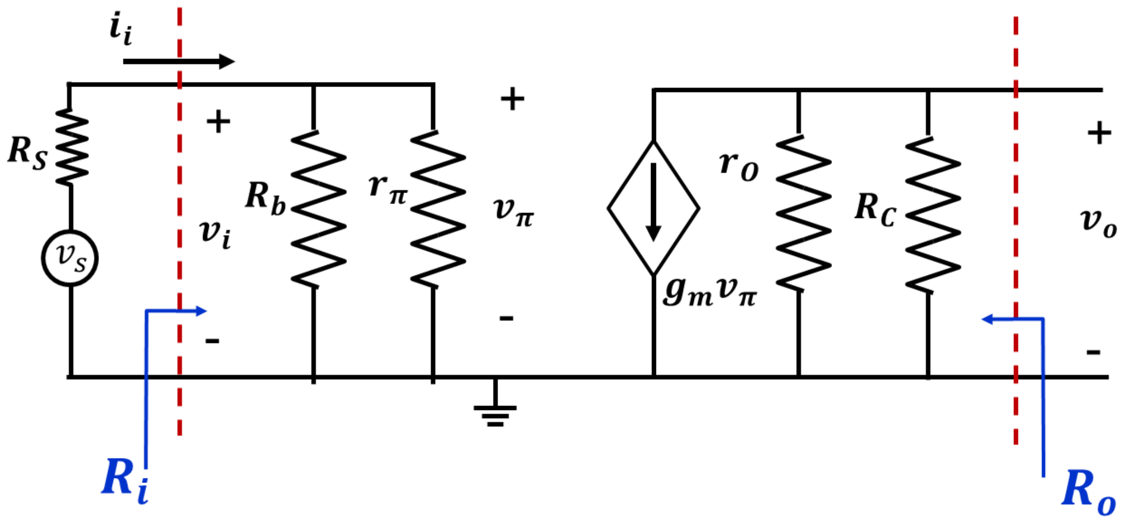
$$A_v = \frac{R_L}{R_L + R_o} \frac{R_i}{R_i + R_s} A_{vo}$$

- If $R_i$ increases, $A_v$ increases
- If $R_o$ decreases, $A_v$ increases

# Equivalent Circuits for various amplifier configuration

## Common emitter with fixed base resistor circuit



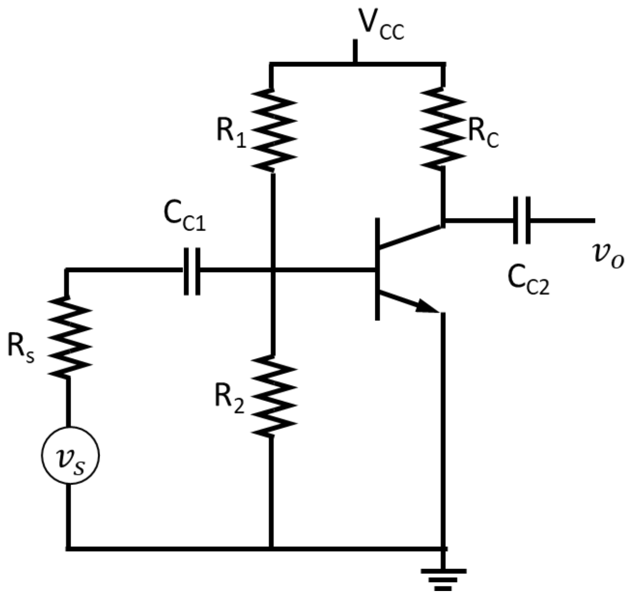

$$A_v = \frac{v_o}{v_s} = g_m \frac{r_\pi || R_b}{r_\pi || R_b + R_s} (r_o || R_C)$$

$$R_i = \frac{v_i}{i_i} = r_\pi || R_b$$

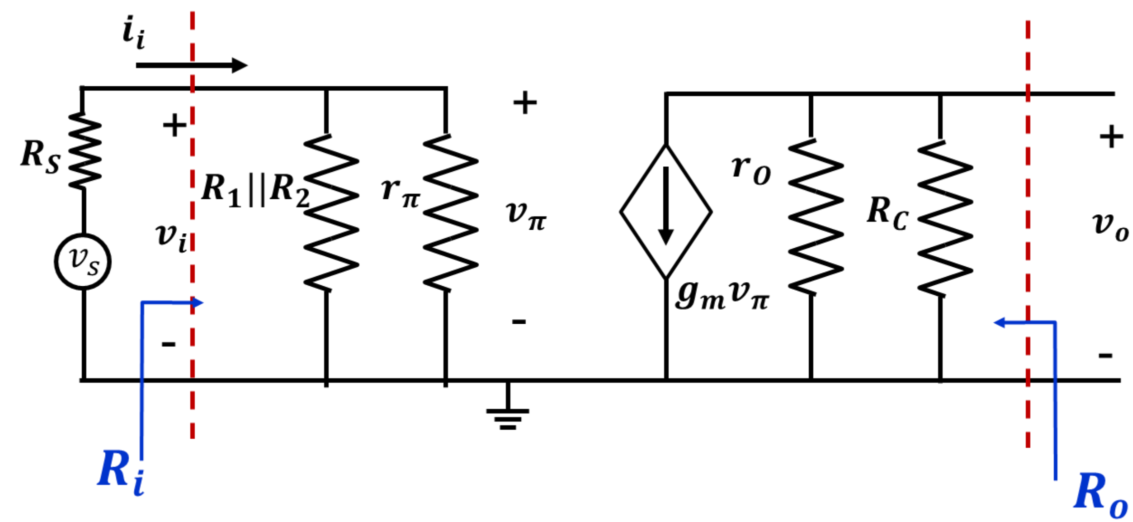
$$R_o = r_o || R_C$$ (found by setting the input signal to zero)

# Equivalent Circuits for various amplifier configuration

## Common emitter with voltage divider circuit




**Small-Signal Equivalent Circuit**



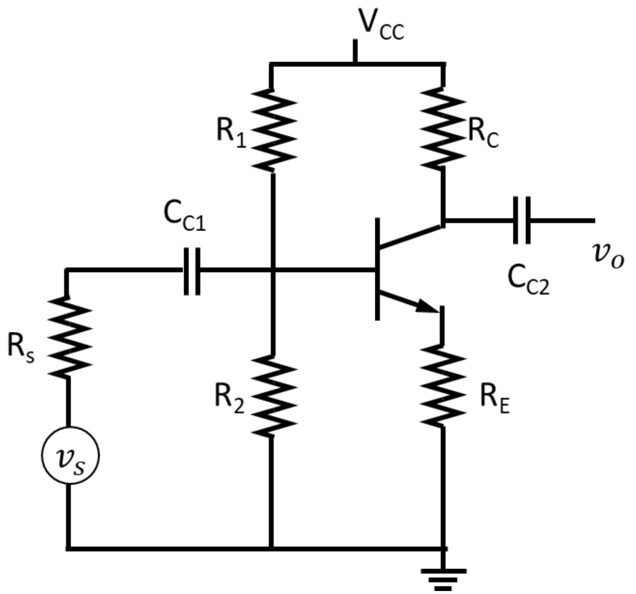

$$A_v = \frac{v_o}{v_s} = g_m \frac{r_\pi||R_1||R_2}{r_\pi||R_1||R_2 + R_s}(r_o||R_C)$$

$$R_i = \frac{v_i}{i_i} = r_\pi||R_1||R_2$$

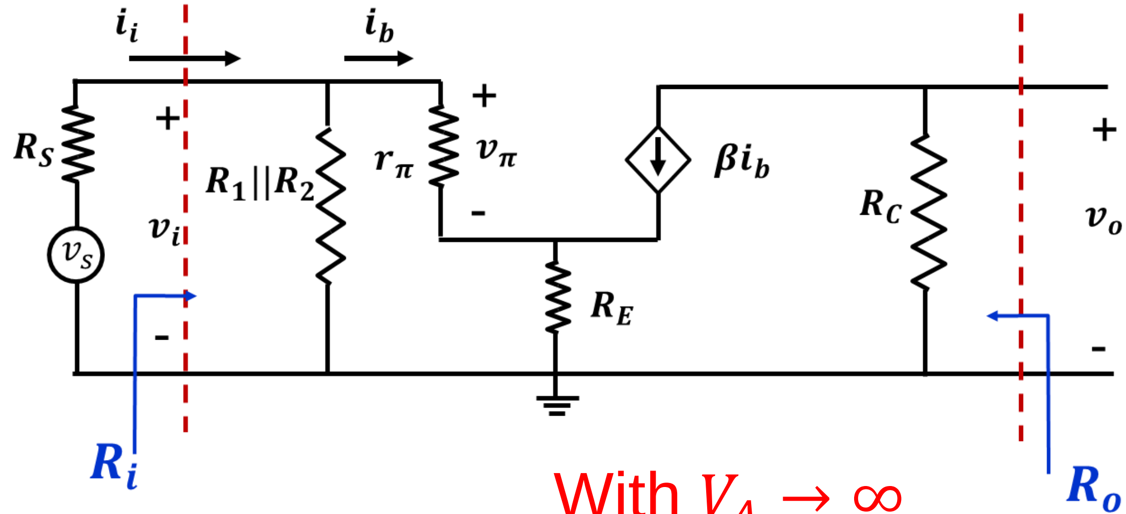
$R_o = r_o||R_C$ (found by setting the input signal to zero)

# Equivalent Circuits for various amplifier configuration

## Common emitter with voltage divider circuit and emitter resistance




**Small-Signal Equivalent Circuit**




With $V_A \to \infty$

$$A_v = \frac{v_o}{v_s} = \frac{-\beta R_c}{r_\pi + (1+\beta)R_E}\left(\frac{R_i}{R_i + R_s}\right)$$

$$R_i = \frac{v_i}{i_i} = R_1||R_2||(r_\pi + (1+\beta)R_E)$$

[resistance reflection rule]

$$R_o = R_c$$

If

$R_i \gg R_s$ and $(1+\beta)R_E \gg r_\pi$

$$A_v \approx \frac{-R_c}{R_E}$$

(gain stability)