VICTORIA UNIVERSITY OF WELLINGTON
TE HERENGA WAKA
NEW ZEALAND

XMUT204 Electronic Design

Lecture 3d - BJT DC Analysis

Chapter Topics

1. BJT as Current and Voltage Amplifiers.
2. Amplification.
3. Design Procedure.
4. Load Lines for BJT Transistor.
5. Q-Point and Transistor Bias.
6. Operation of Various Amplifier Configurations.
7. A Graphical Representation of the Transistor Curve.

1. BJT as Current and Voltage Amplifiers

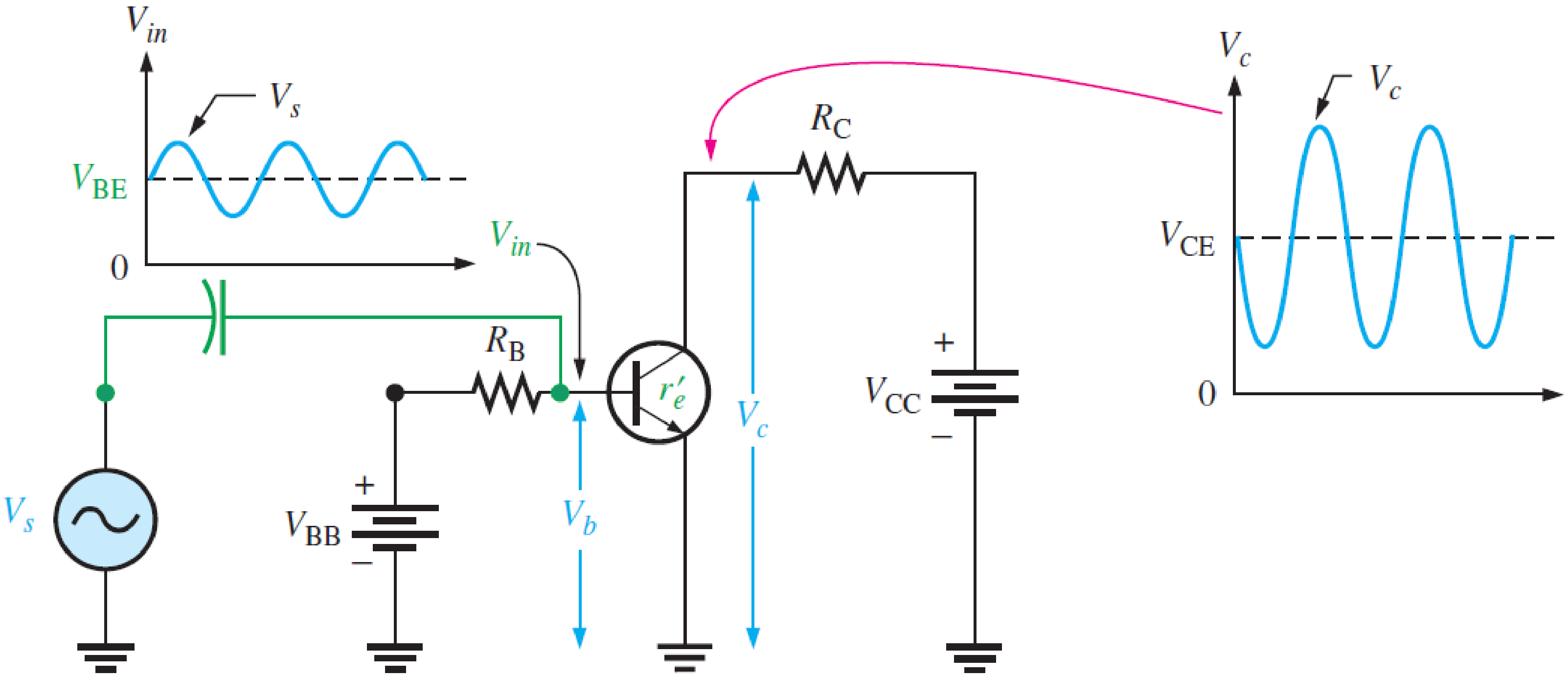
- Transistor has been viewed as a current amplifier as the collector current is much larger than the base current:

$$I_C = \beta_{DC} I_B$$

- In the active region of operation, this value of β will be a constant and any increase or decrease in I_B will lead to a proportional increase or decrease in I_C.
- We will now look at the transistor as a voltage amplifier where the signals are small AC voltages compared to the DC bias voltages.
- Need to distinguish between DC and AC quantities in our analysis.

2. Amplification

- The process of (linear) increase in the amplitude of a signal. This can be achieved when BJT is operating in active mode.



- We now have to deal with both DC voltage and currents (the bias) and AC voltages and currents (the signal) and have to distinguish between them.

- We will normally use capital letters (I and V) for both AC and DC currents and voltages.
- For *DC quantities*, we will use a capital subscript:

  V_{BE} : base – emitter DC voltage.

  I_C : DC Collector current.

  V_B : The DC voltage between base and ground.
- For *AC quantities*, we use a lowercase italic subscript:

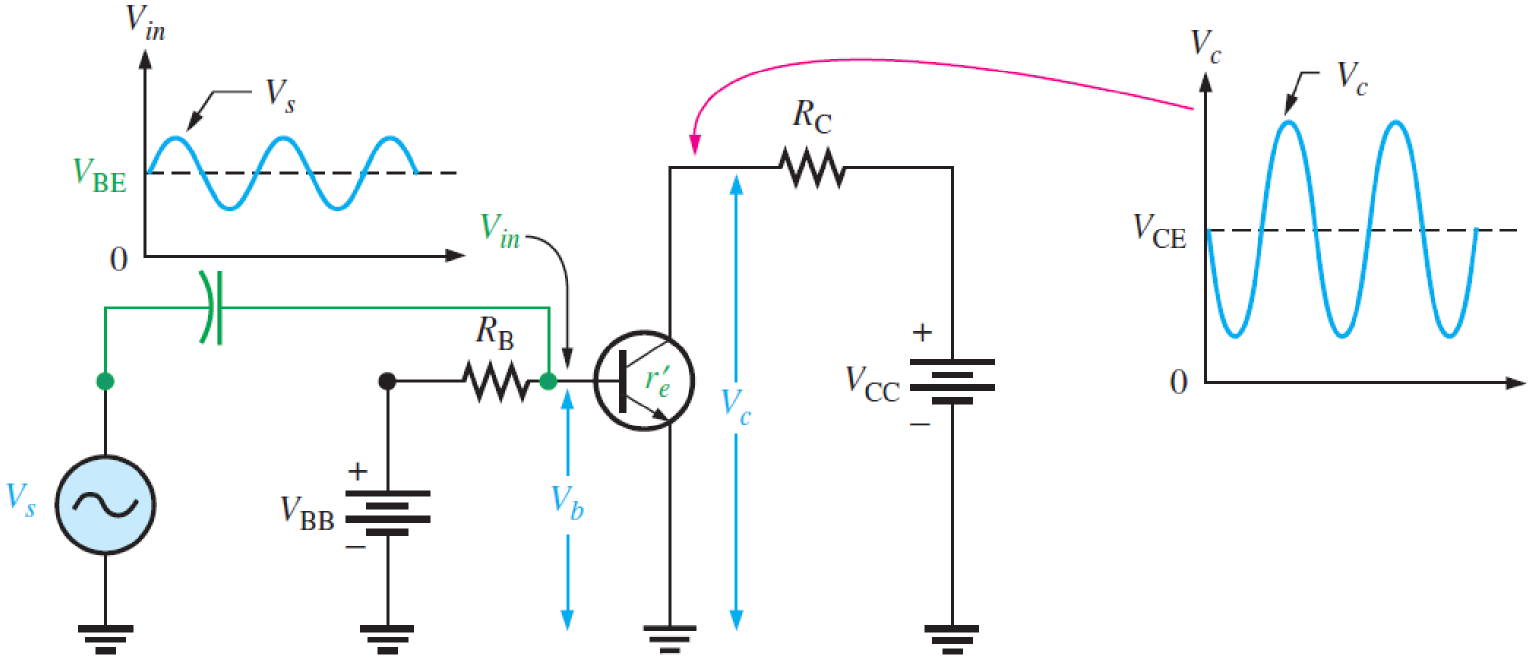
  V_{be} : AC voltage over the base – emitter.

  I_c : AC collector current.

  V_b : AC voltage from transistor base terminal to ground.

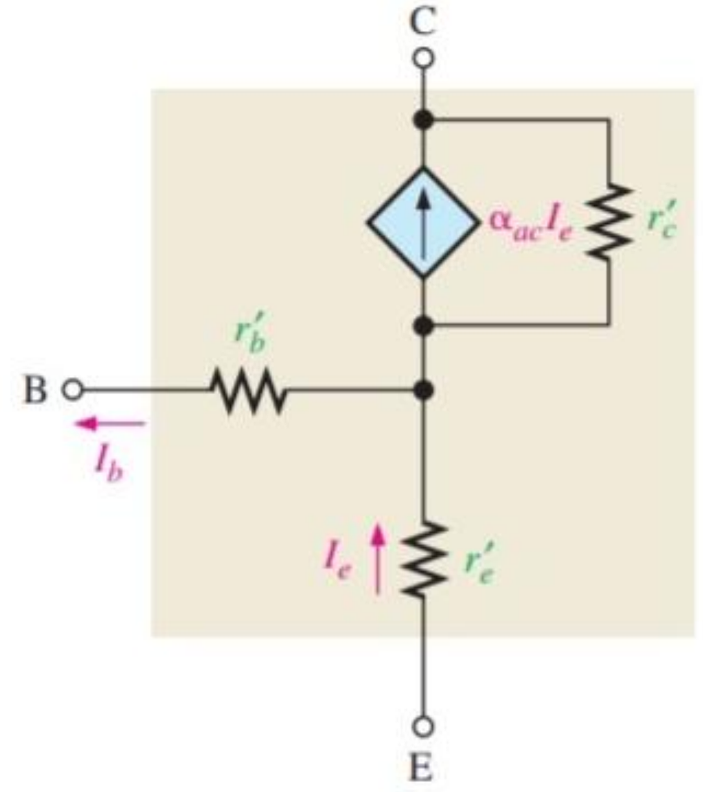
- We also have to distinguish between internal transistor resistances and external resistances in the circuit.
- *Internal transistor resistances* are indicated by a lowercase r' with a subscript e.g. r_e' is the internal emitter AC resistance.
- *External circuit resistances* are indicated by capital R with appropriate subscript e.g. R_E is the external DC emitter resistance.
- Compared this external DC emitter resistance with R_e which is the external AC emitter resistance.

- Now, superimpose a small AC on top of the DC bias voltage V_{BB}.

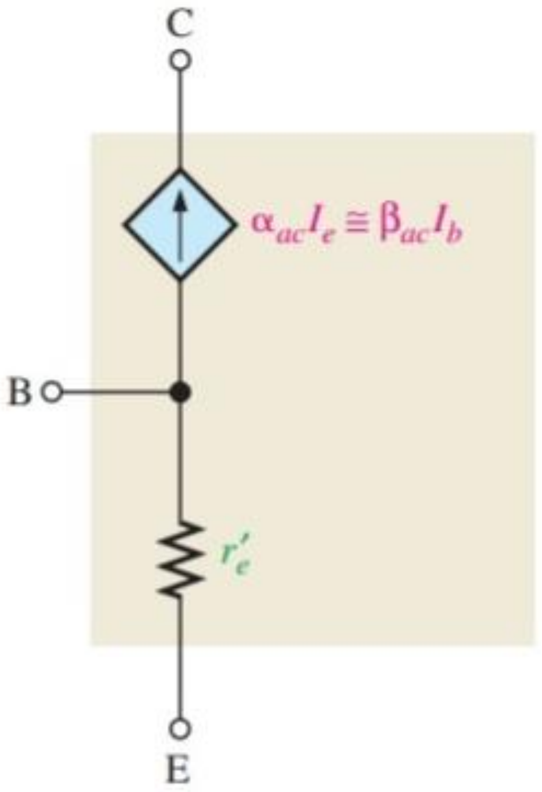


- We will thus have a variation in the base current, which will lead to a much larger variation in the collector current.
- This AC collector current will then also produce an AC voltage over R_C so that V_c will be amplified but inverted from V_s.

- The forward biased base-emitter junction has a very low resistance to the AC signal.
- This resistance is indicated by r'_e.
- The other internal resistances e.g. r'_c and r'_b are zero.



(a) Generalized *r*-parameter model for a BJT



(b) Simplified *r*-parameter model for a BJT

- The AC voltage at the base is then given by:

$$V_b = I_e r_e'$$

- The AC collector voltage V_c equals the AC voltage drop over R_C:

$$V_c = I_c R_C$$

- But since $I_c \approx I_e$, we can write: $V_c \approx I_e R_C$
- V_b can be considered the transistor input voltage with:

$$V_b = V_s - I_b R_B$$

- The voltage gain can then be defined as the ratio of output voltage to the input voltage. So that for AC voltages, we can write:

$$A_v = \frac{V_c}{V_b}$$

- Insert values for V_c and V_b:

$$A_v = \frac{I_c R_c}{I_c r_e'}$$

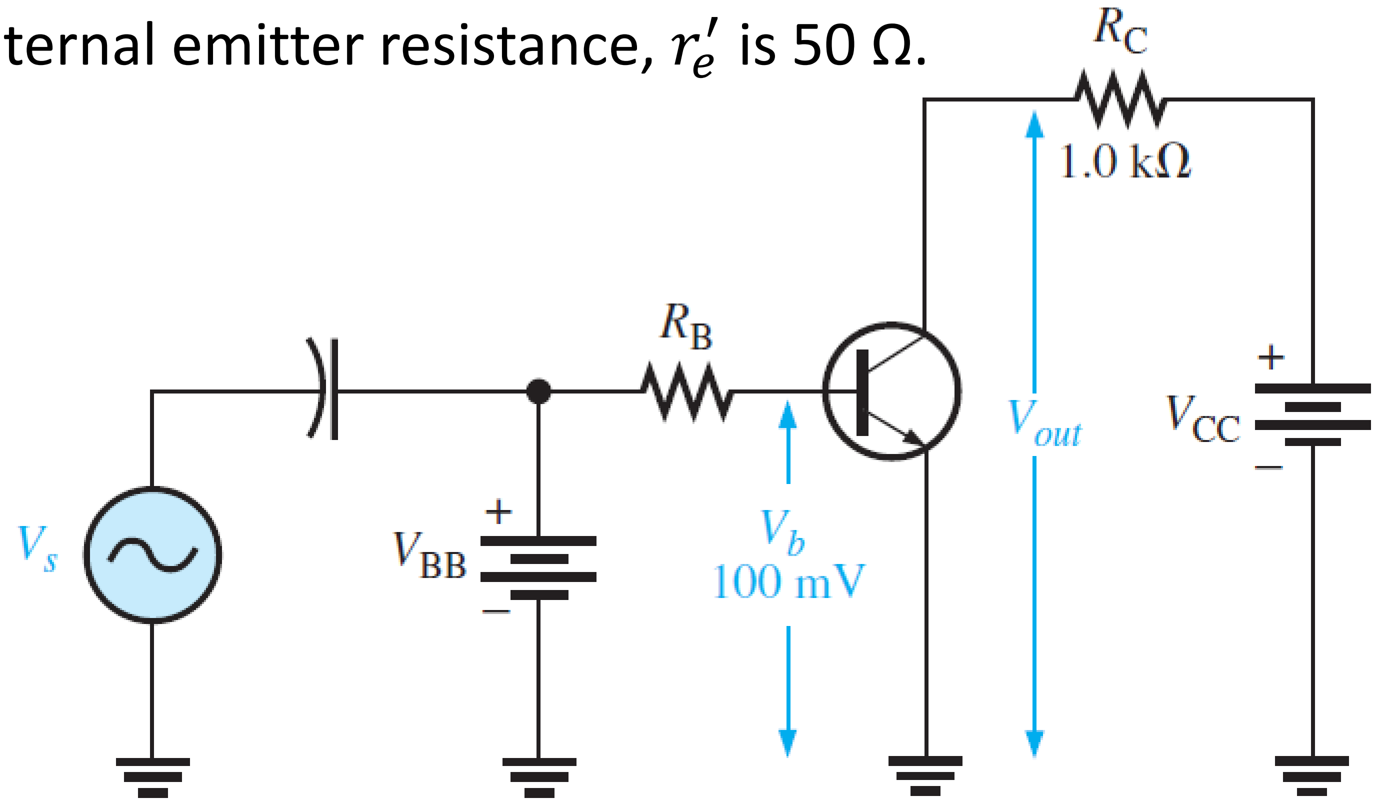
- So that the voltage gain can be written as:

$$A_v \cong \frac{R_c}{r_e'}$$

- The transistor thus provides voltage gain which depends on the values of R_c and r_e'.

Example for Tutorial 1 – Parameters in BJT Amplifier

For the circuit below, voltage at the base, V_b is 100 mV and output voltage, V_{out} is taken at the collector of the BJT. Calculate the voltage gain of the amplifier circuit and the AC output voltage if internal emitter resistance, r_e' is 50 Ω.



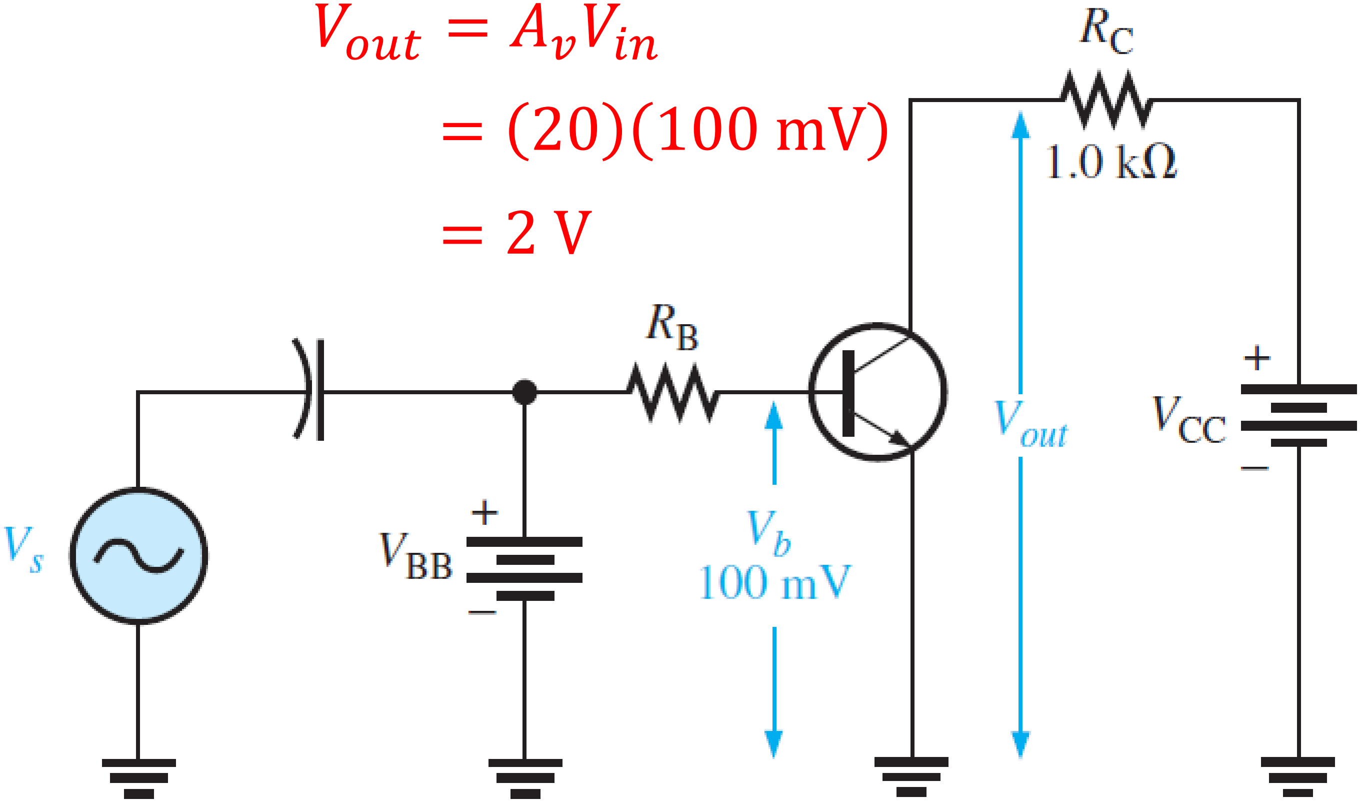
Answer

- The voltage gain of the amplifier circuit is:

$$A_v \approx \frac{R_c}{r_e'} = \frac{1\ \text{k}\Omega}{50\ \Omega} = 20$$

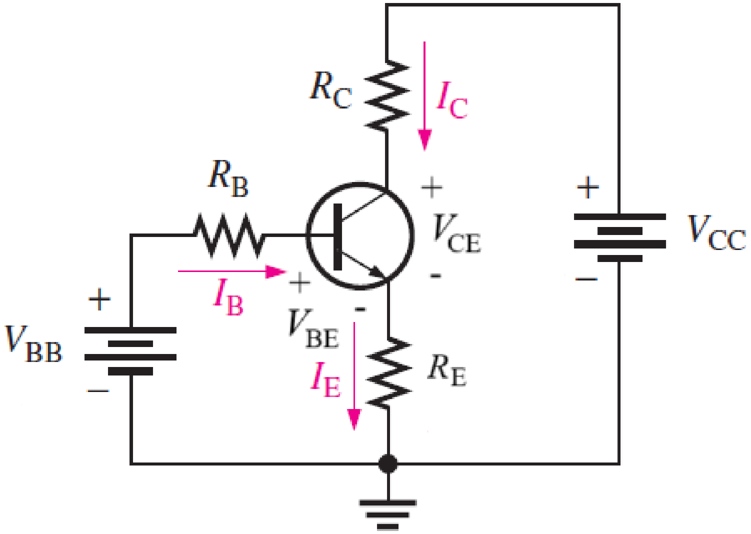
- The output voltage is:

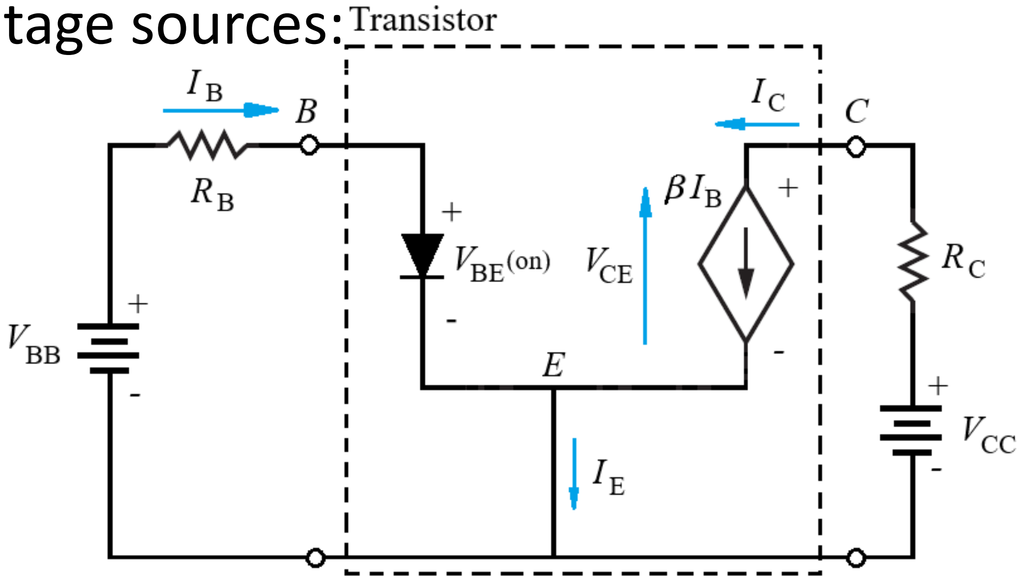
$$\begin{aligned} V_{out} &= A_v V_{in} \\ &= (20)(100\ \text{mV}) \\ &= 2\ \text{V} \end{aligned}$$



3. Design Procedure

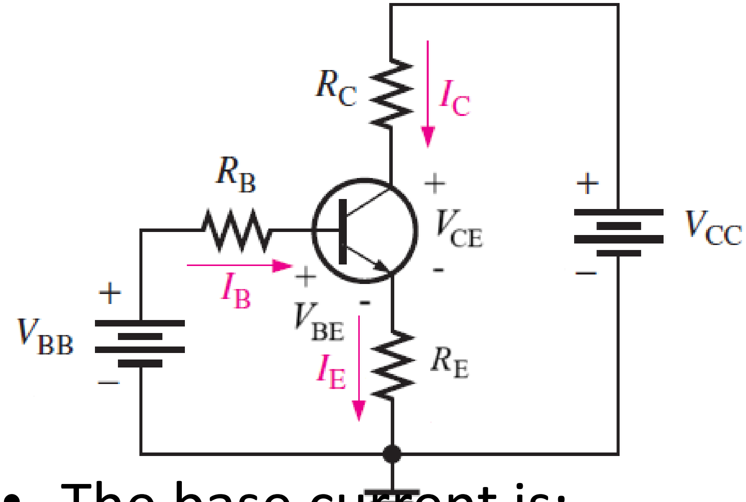
- We will first analyse and design the DC bias of BJTs to ensure that they operate efficiently as amplifiers. Look at a common-emitter circuit with two voltage sources:

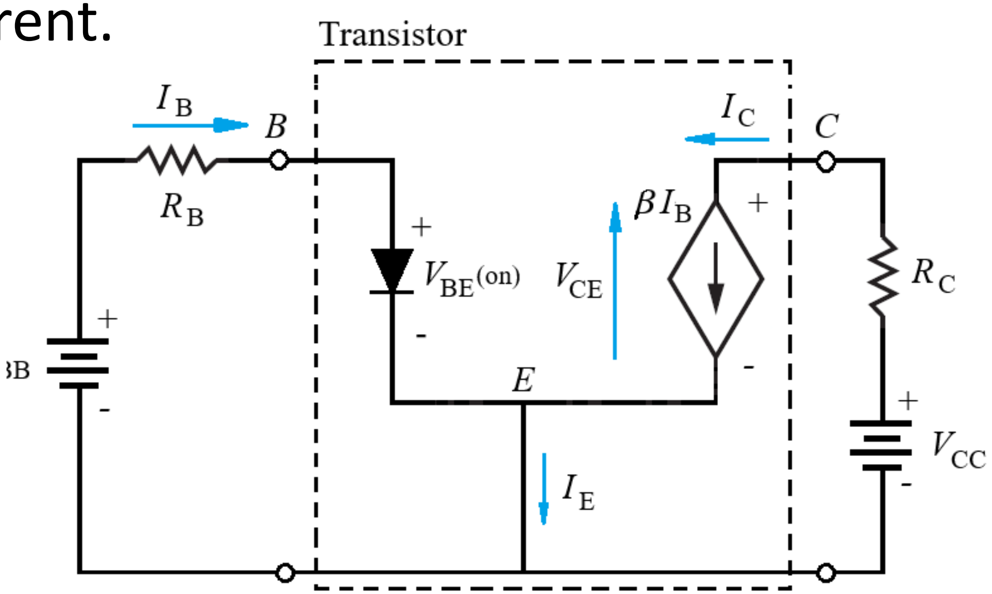




- We can model the transistor in the active region by:
  - A forward biased diode the represents the BE junction.
  - A constant current source with current βI_B that represents the collector current.

- Assuming forward bias for BE junction, the turn-on voltage needed is $V_{BE}(\text{on})$.
- The collector current is now a dependent current source – controlled by the base current.





- The base current is:

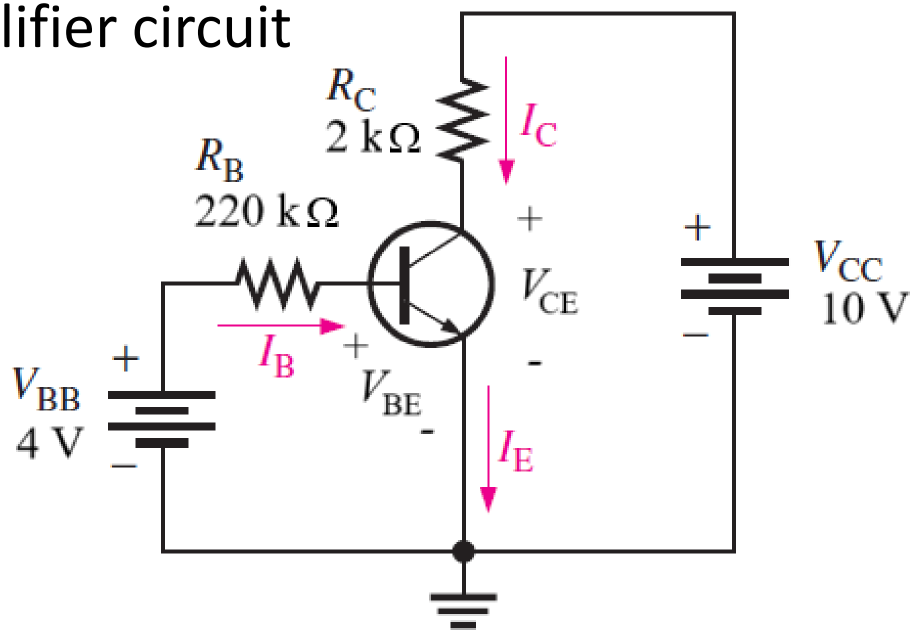
$$I_B = \frac{V_{BB} - V_{BE}(\text{on})}{R_B} \qquad \text{and} \qquad I_C = \beta I_B$$

- For the CE portion of the circuit, we have:

$$V_{CC} = I_C R_C + V_{CE} \qquad \text{or} \qquad V_{CE} = V_{CC} - I_C R_C$$

Example for Tutorial 2 – BJT Amplifier Design

For the common emitter amplifier circuit shown below, given that:



V_{BE} = 4 V, R_B = 220 kΩ,
R_C = 2 kΩ, V_{CC} = 10 V,
$V_{BE}(\text{on})$ = 0.7 V,
and β_{DC} = 200.

a. Calculate the base, emitter, and collector currents, and the voltage across the collector and emitter. [6 marks]

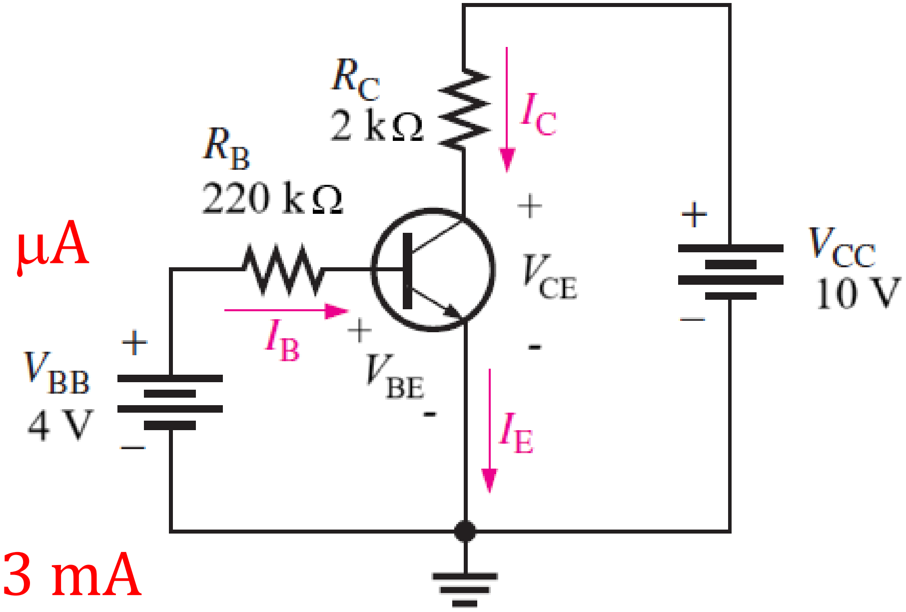
b. Show that the BJT is biased in the forward-active mode if $V_{CE(\text{sat})}$ = 0.2 V. [4 marks]

Answer

a. The base current in the transistor circuit is:

$$I_B = \frac{V_{BB} - V_{BE(\text{on})}}{R_B}$$

$$= \frac{4\text{ V} - 0.7\text{ V}}{220\text{ k}\Omega} = 15\ \mu\text{A}$$



The collector current is:

$$I_C = \beta_{DC} I_B$$

$$= (200)(15\ \mu\text{A}) = 3\text{ mA}$$

The emitter current is:

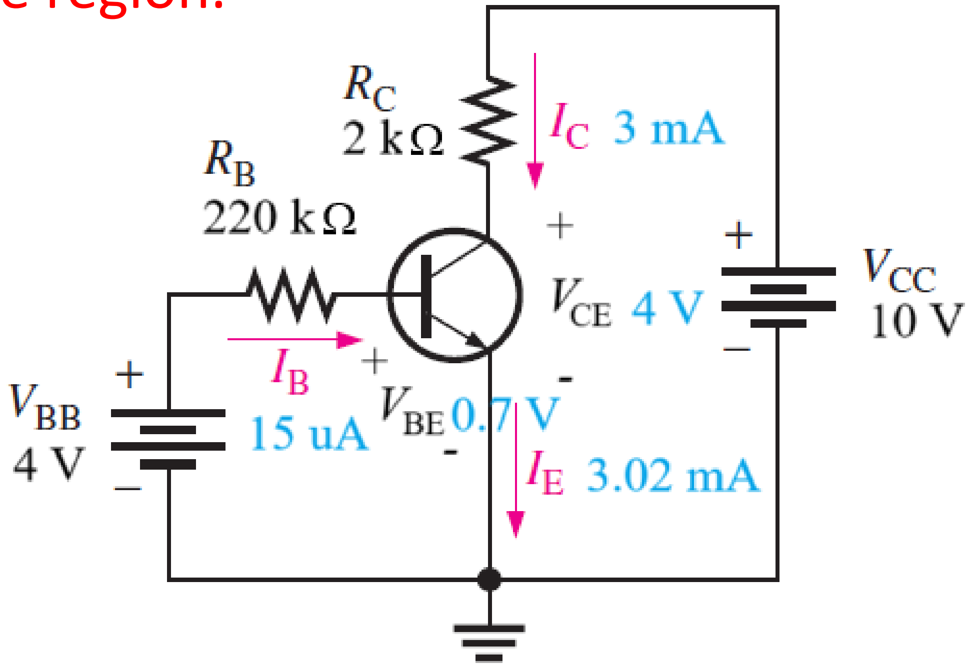
$$I_E = (\beta_{DC} + 1) I_B$$

$$= (200 + 1)(15\ \mu\text{A}) = 3.02\text{ mA}$$

The voltage across the collector and emitter is:

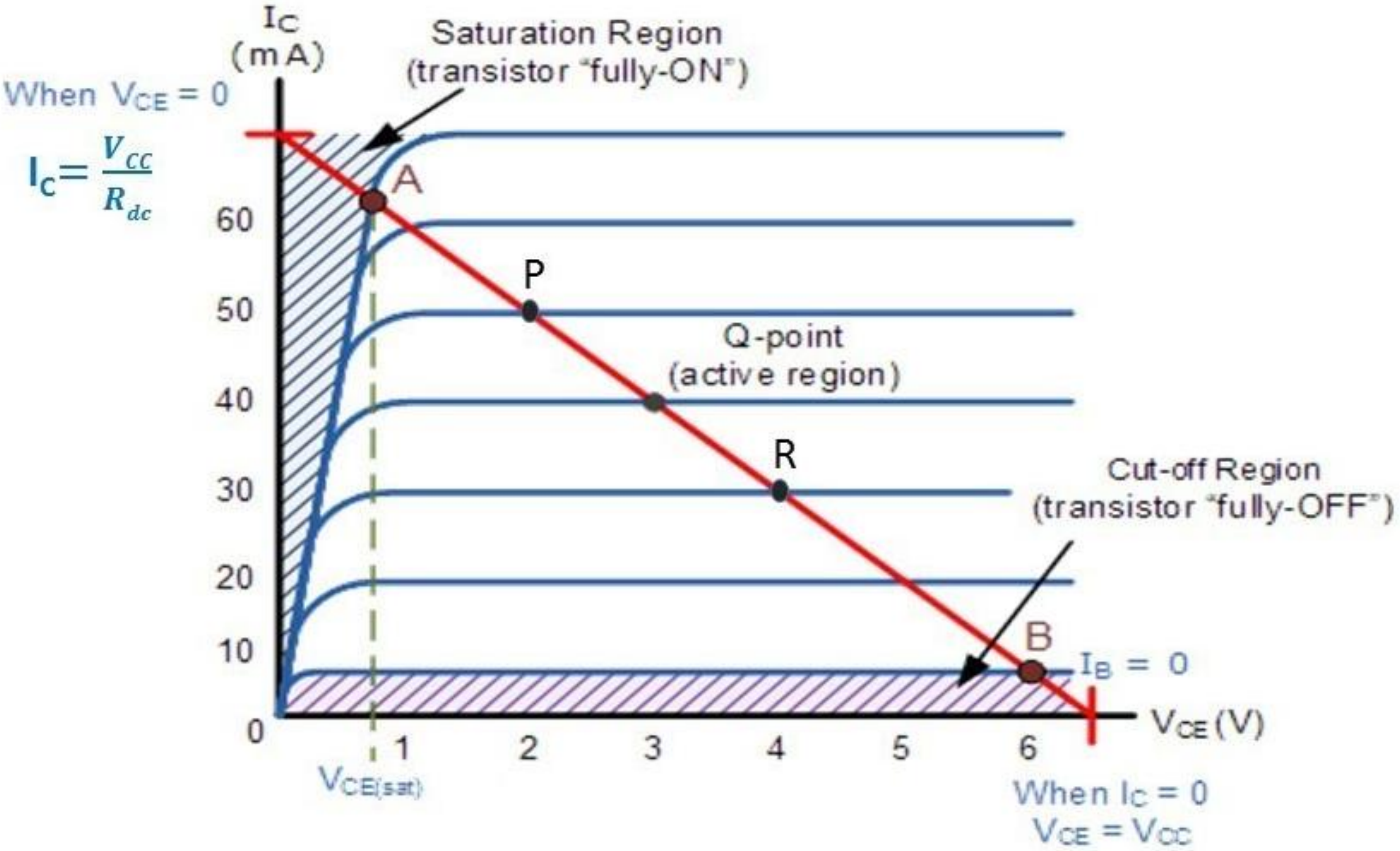
$$V_{CE} = V_{CC} - I_C R_C$$
$$= 10\text{ V} - (3\text{ mA})(2\text{ k}\Omega) = 4\text{ V}$$

b. So, based on results in part (a), since $V_{CE} > 0.2$ V, transistor is in active region.



4. Load Lines for BJT Transistors

- Load lines can again help us visualise transistor characteristics.



- The input load line is obtained from Kirchhoff's voltage law around the base-emitter loop:

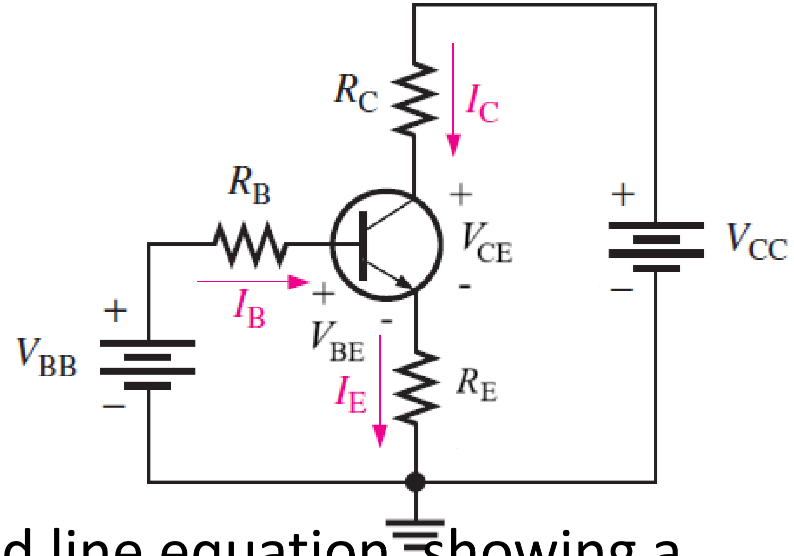
$$I_B = \frac{V_{BB} - V_{BE}}{R_B}$$

- This is essentially same as for diode. The output load line around the CE loop:

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

- This can be written as:

$$I_C = \frac{V_{CC} - V_{CE}}{R_C}$$



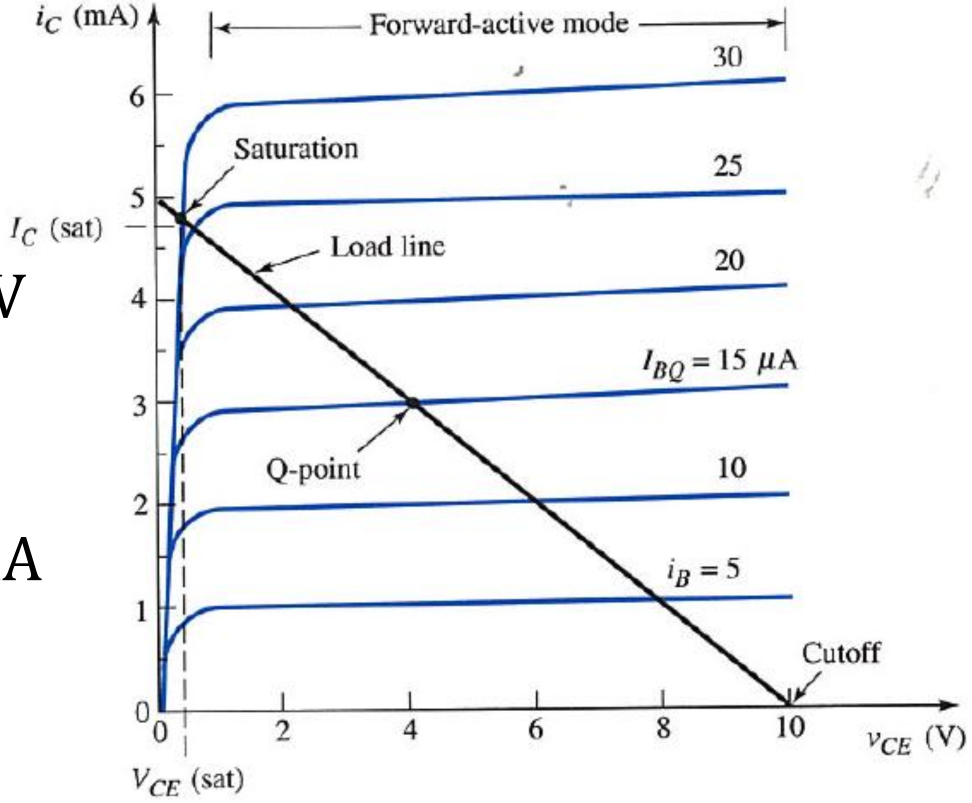
- This last equation is the load line equation, showing a linear relationship between I_C and V_{CE}.

- End points of load line:
  - At I_C = 0:

$$V_{CE} = V_{CC} = 10\text{ V}$$

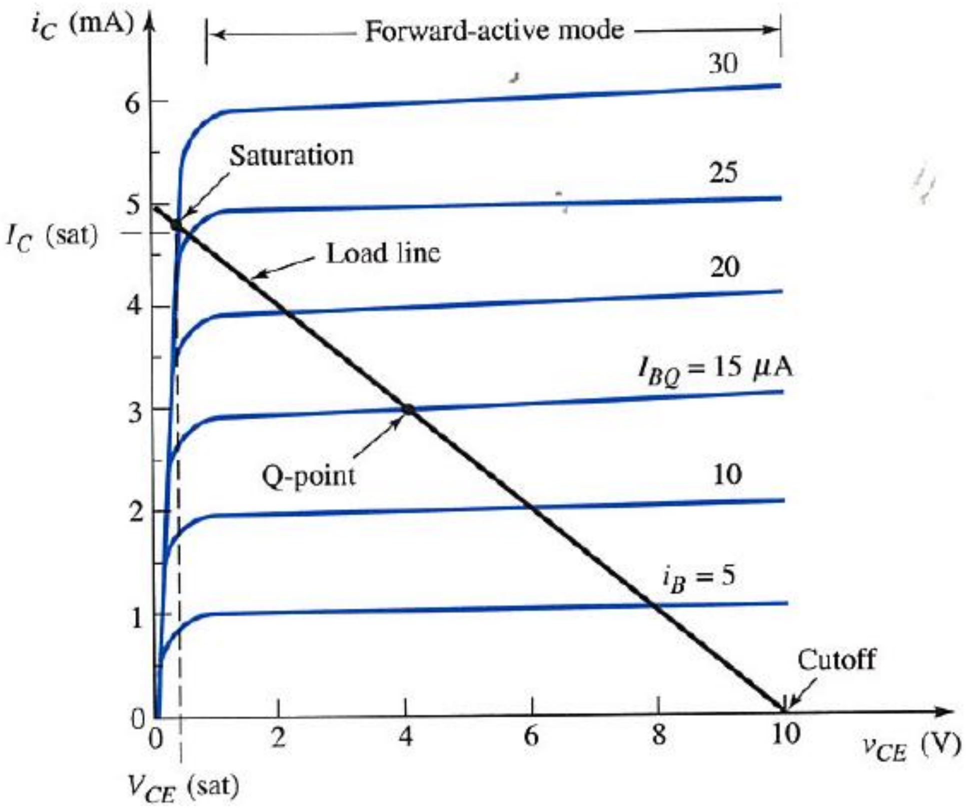
  - At V_{CE} = 0:

$$I_C = \frac{10\text{ V}}{2\text{ k}\Omega} = 5\text{ mA}$$



Note:

- If $V_{BB} < V_{BE(\text{on})}$ then $I_B = I_C = 0$ and transistor in cut-off mode. At this point $V_{CE} = V_{CC} = 10$ V.
- As V_{BB} increases to $V_{BB} > V_{BE(\text{on})}$, the base current increases and the Q-point moves up the load line.

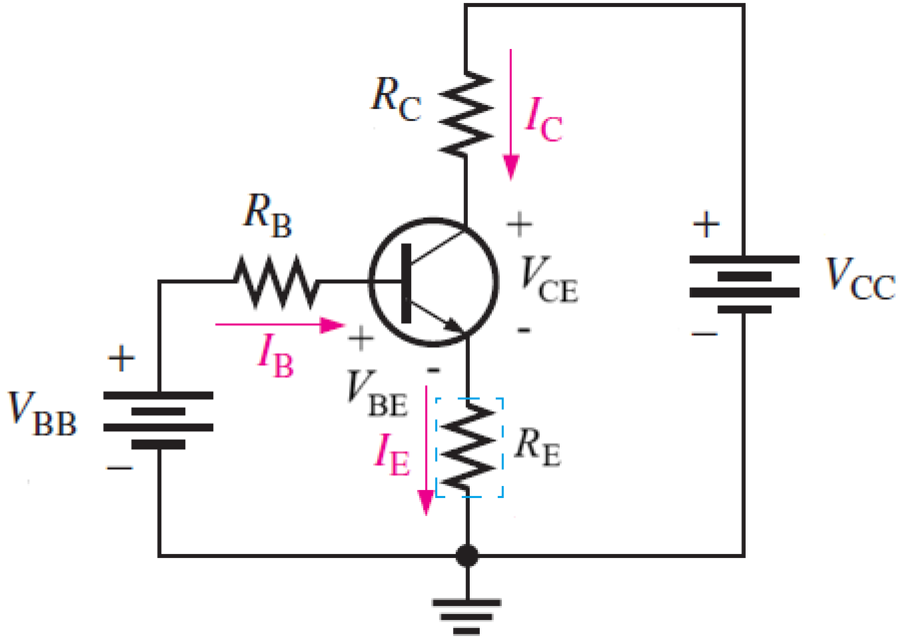


Note (cont.):

- A point will be reached where I_C can no longer increase – the transistor is now in saturation (i.e. both junctions of the transistor acting as short circuits).
- The BC junction is now forward biased and I_B and I_C are no longer linear.

DC Operating Point Improvement with Feedback Resistor (R_E)

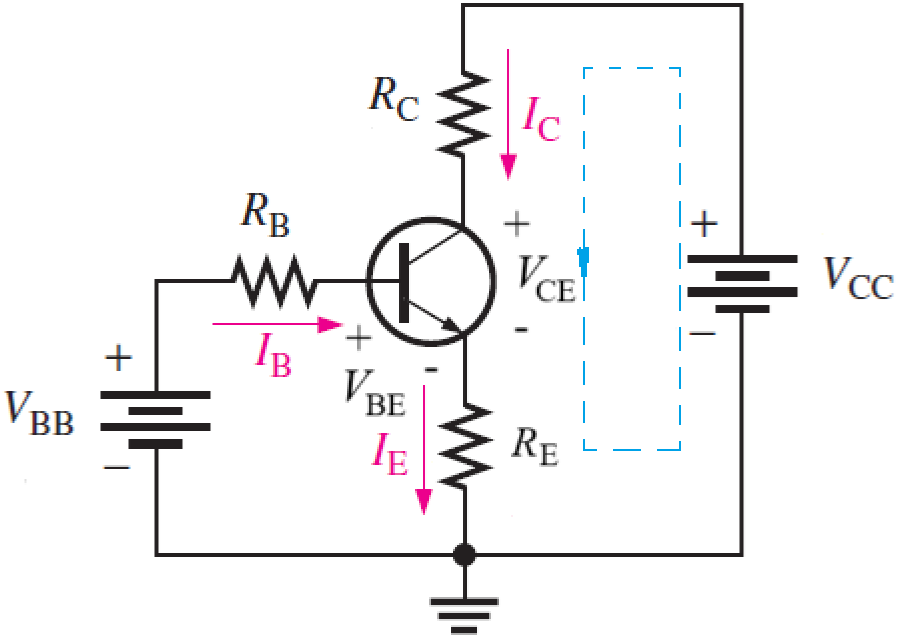
- Feedback resistor at the emitter improves stability at the output of the amplifier.



- Any increase of voltage or current at the collector will be compensated by any increase of voltage or current at the emitter. For fixed V_{CC}, this increase will be minimised.

Determining $I_{C(\text{max})}$ and $V_{CE(\text{cutoff})}$ in the Load Line

- First, calculate $I_{C(\text{max})}$ first and then $V_{CE(\text{cutoff})}$.



- Take KVL around collector-emitter loop of the BJT:

$$V_{CC} - I_C R_C - V_{CE} - I_E R_E = 0 \qquad (Eq. 1)$$

- The BJT is saturated when V_{CE} = 0, so the current in the collector I_{CQ} is calculated from:

$$I_{C(\max)} = \frac{V_{CC} - I_E R_E}{R_C} \qquad (Eq. 2)$$

- From previous relevant topics in the BJT, we can show that:

$$I_C = \left(\frac{\beta_{DC}}{\beta_{DC} + 1}\right) I_E \qquad \text{so} \qquad I_E = \frac{I_C(\beta_{DC} + 1)}{\beta_{DC}} \qquad (Eq. 3)$$

- Substitute I_E in equation (2) with (3) at saturation condition, the saturation collector current is calculated from.

$$I_{C(\max)} = \frac{V_{CC} - \left[\frac{I_{C(\max)}(\beta_{DC} + 1)}{\beta_{DC}}\right] R_E}{R_C}$$

- Rearrange the equation given above, the saturation current that flow in the collector is:

$$I_{C(\mathrm{max})} = \frac{V_{CC}}{R_C + \left(\frac{\beta_{DC} + 1}{\beta_{DC}}\right) R_E}$$

- For calculating the cut-off voltage across the collector emitter V_{CE}, at cut-off condition, collector current $I_C = 0$.
- By considering the equation (3), when $I_C = 0$, the current in the emitter I_E is also zero. Thus, the equation (1) becomes:

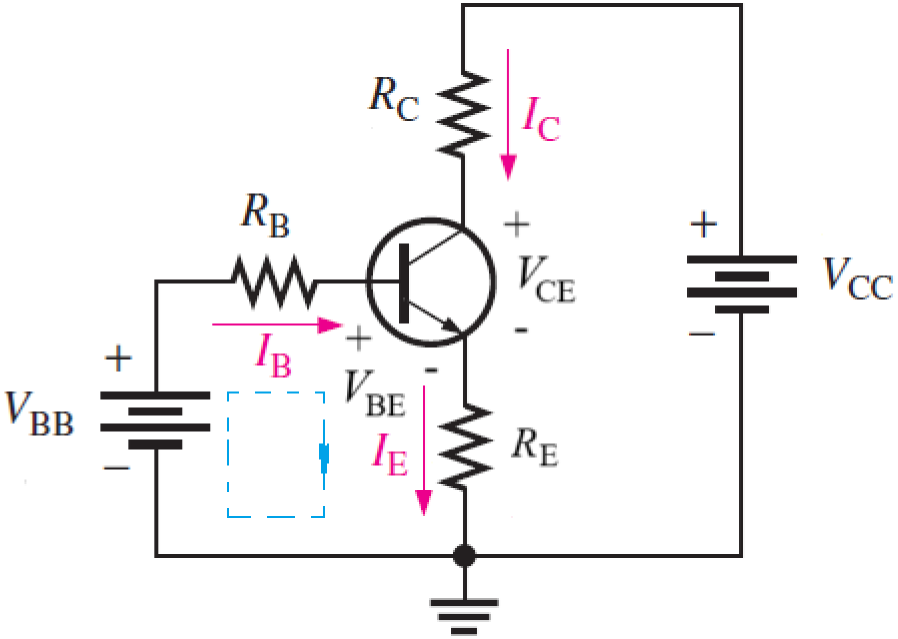
$$V_{CC} - 0 - V_{CE(\mathrm{cutoff})} - 0 = 0$$

- The cut-off voltage drop across the collector emitter junction is:

$$V_{CE(\mathrm{cutoff})} = V_{CC} = 12\ \mathrm{V}$$

Determining Q Points in the Load Line

- To calculate the operating (Q) point of the amplifier circuit, first find the quiescent base current. Then, calculate the quiescent collector current and collector-emitter voltage.



- Applying KVL around the base-emitter loop of the BJT:

$$V_{BB} - I_B R_B - V_{BE(\text{on})} - I_E R_E = 0 \qquad (Eq. 4)$$

- Assuming the BE junction is on for active mode, from previous relevant topics in the BJT, the current in the emitter is found from:

$$I_E = (\beta_{DC} + 1)I_B \qquad (Eq. 5)$$

- Substitute I_E in equation (4) with equation (5), it becomes:

$$V_{BB} - I_B R_B - V_{BE(\mathrm{on})} - [(\beta_{DC} + 1)I_B]R_E = 0$$

- Rearrange the equation above and solve for the current in the base of BJT, it is now:

$$I_B = \frac{V_{BB} - V_{BE(\mathrm{on})}}{R_B + (\beta_{DC} + 1)R_E}$$

- Thus, entering values into equation below, the quiescent collector current is:

$$I_{CQ} = \beta_{DC} I_{BQ}$$

- The quiescent current in the emitter is calculated from:

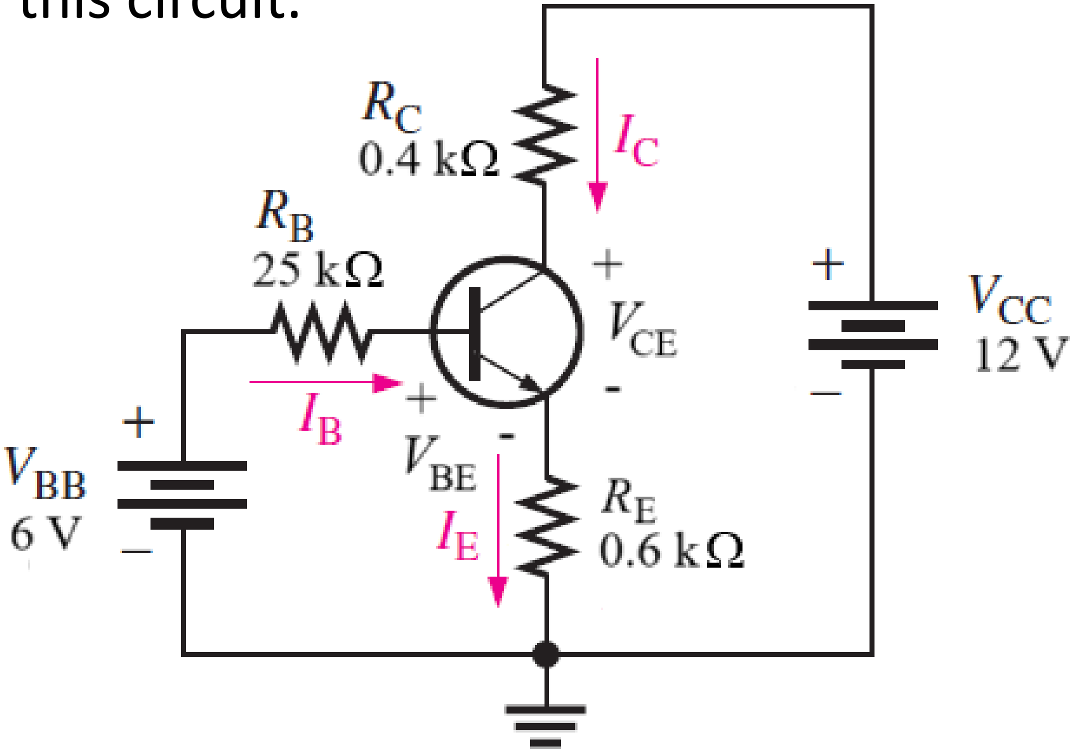
$$I_{EQ} = (\beta_{DC} + 1) I_{BQ}$$

- Rearranging the equation (1), the quiescent collector to emitter voltage of the BJT is found from:

$$V_{CEQ} = V_{CC} - I_{CQ} R_C - I_{EQ} R_E$$

Example for Tutorial 3 – BJT Amplifier with Emitter Feedback

For analysing the characteristics of the circuit below, use $V_{BE(\mathrm{on})}$ = 0.6 V and β_{DC} = 75. Note the use of an emitter resistor in this circuit.



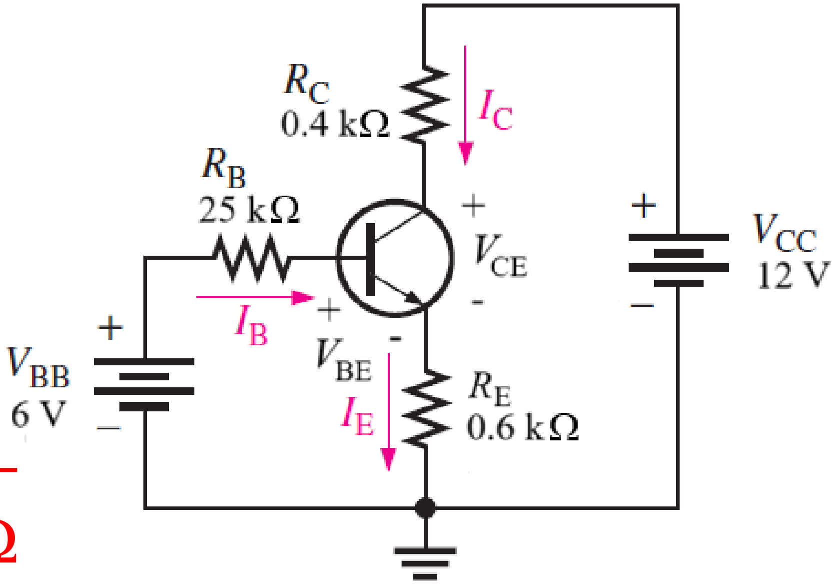
a. Determine the cut-off voltage $V_{CE(\mathrm{cutoff})}$ and saturation current $I_{C(\mathrm{max})}$ in the load line. [8 marks]

b. Determine the quiescent collector current I_{CQ} and quiescent collector-emitter voltage V_{CEQ} at the operating (Q) point of the BJT and calculate the quiescent base current at this point. [8 marks]

c. Sketch the load line of the amplifier circuit. [4 marks]

Answer

a. Entering values into the equation below, the saturation collector current I_C is:



$$I_{C(\text{max})} = \frac{V_{CC}}{R_C + \left(\frac{\beta_{DC} \ + 1}{\beta_{DC}}\right) R_E}$$

$$= \frac{12}{0.4 + \left(\frac{75+1}{75}\right) 0.6 \text{ k}\Omega}$$

$$= 11.9 \text{ mA}$$

The cut-off voltage drop across the collector emitter junction is:

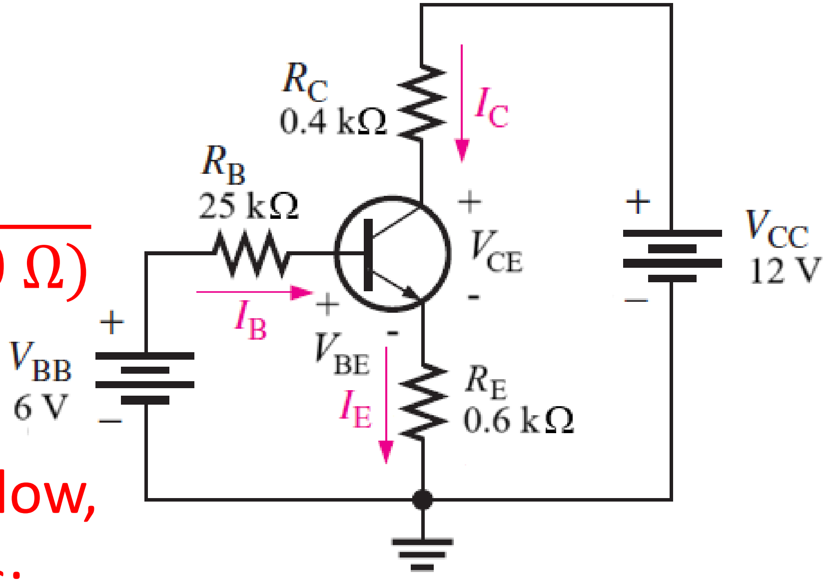
$$V_{CE(\text{cutoff})} = V_{CC} = 12 \text{ V}$$

b. Entering the values into the equation below, the quiescent current that flows in the base of the BJT at operating points is:

$$I_{BQ} = \frac{V_{BB} - V_{BE(\text{on})}}{R_B + (\beta_{DC} + 1)R_E}$$

$$= \frac{6\text{ V} - 0.6\text{ V}}{25{,}000\ \Omega + (75 + 1)(600\ \Omega)}$$

$$= 75.1\ \mu\text{A}$$



Entering values into equation below, the quiescent collector current is:

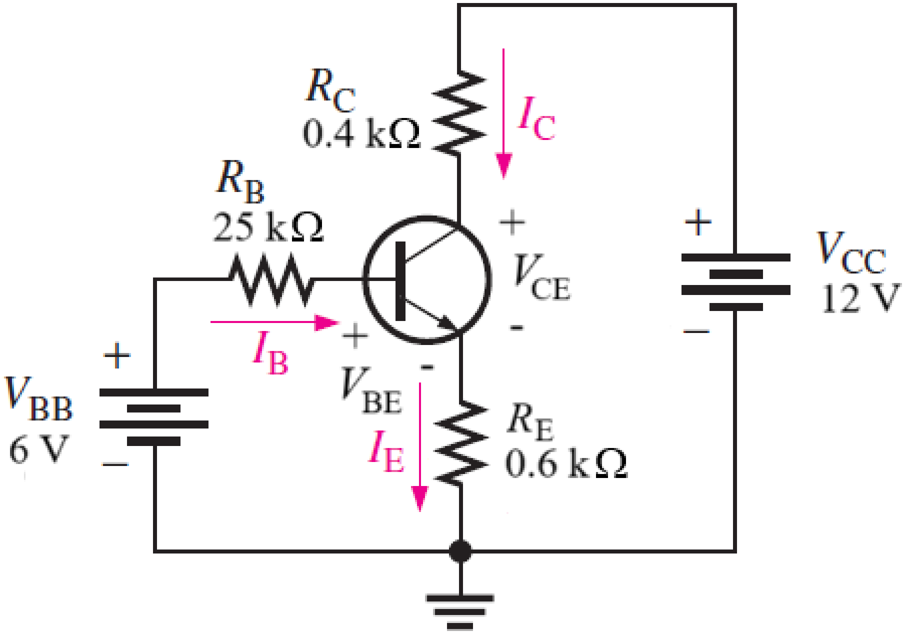
$$I_{CQ} = \beta_{DC} I_{BQ} = (75)(75.1\ \mu\text{A}) = 5.63\text{ mA}$$

The quiescent current in the emitter is calculated from:

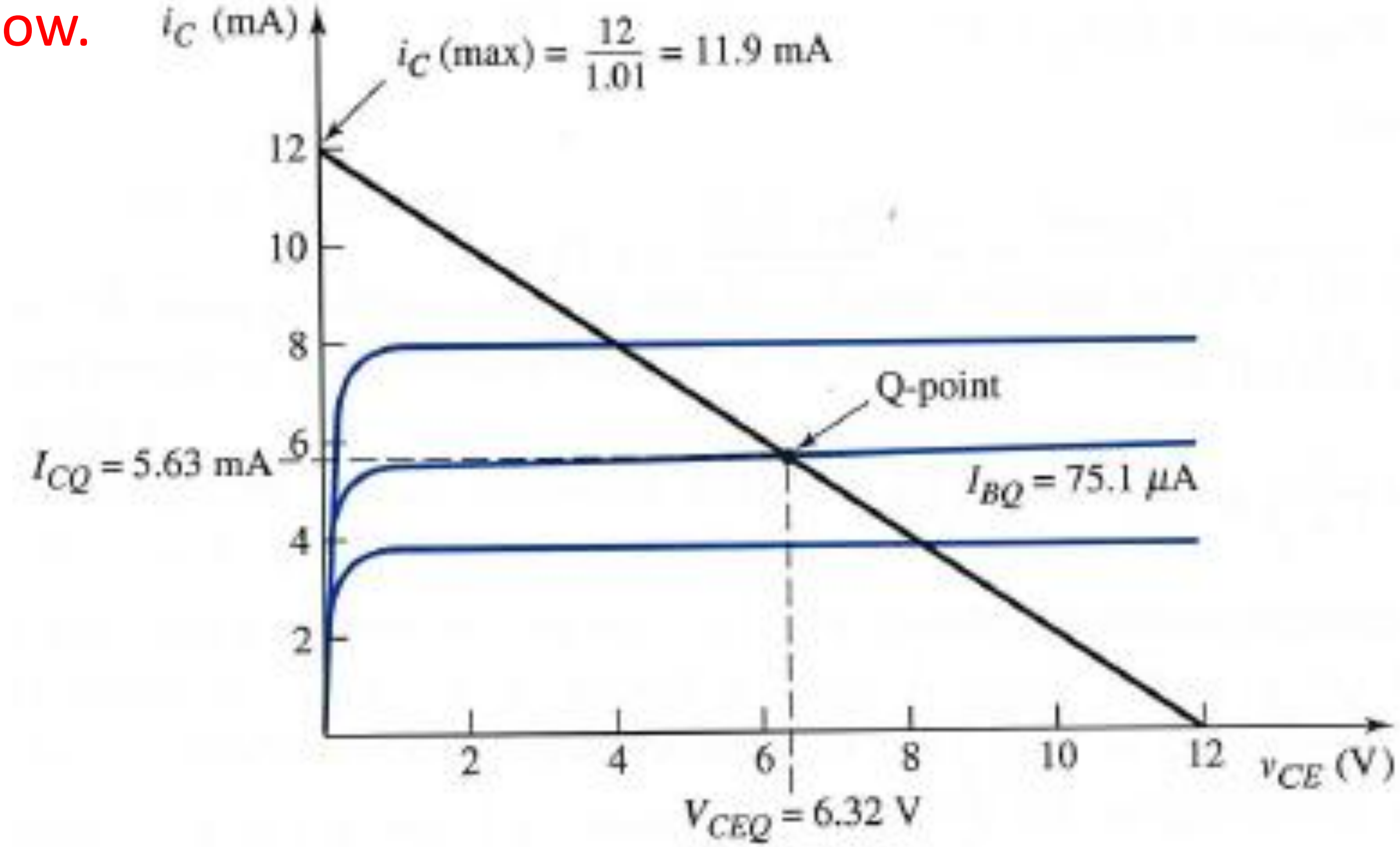
$$I_{EQ} = (\beta_{DC} + 1)I_{BQ} = (75 + 1)(75.1\ \mu\text{A}) = 5.71\text{ mA}$$

As a result, the quiescent collector to emitter voltage of BJT is:

$$
\begin{aligned}
V_{CEQ} &= V_{CC} - I_{CQ}R_C - I_{EQ}R_E \\
&= 12\ \mathrm{V} - (5.63\ \mathrm{mA})0(.4\ \mathrm{k\Omega}) - (5.71\ \mathrm{mA})(0.6\ \mathrm{k\Omega}) \\
&= \ 6.32\ \mathrm{V}
\end{aligned}
$$



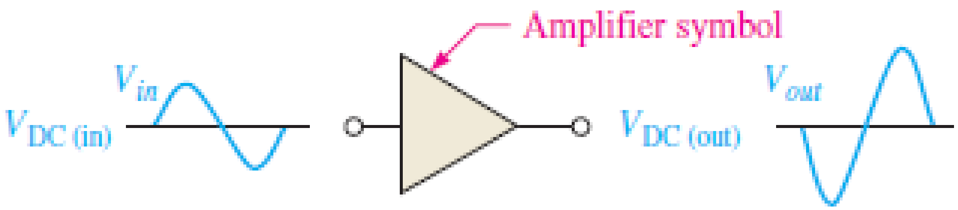
c. The Q point (6.32 V, 5.63 mA) on the load line is sketched as below.



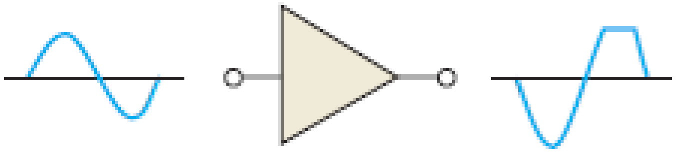
Thus, this operating (Q) point is also the intersection of the load line with the line representing a quiescent base current I_{BQ} = 75.1 µA.

5. The Q-point and Transistor Bias

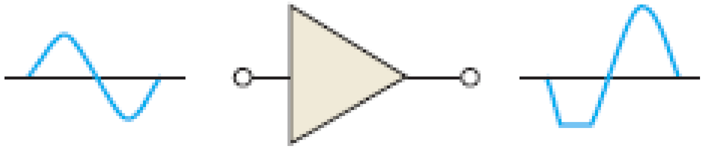
- It is then essential that we establish the correct operating point or Q-point for the transistor to operate efficiently as a linear amplifier without distortion.



(a) Linear operation: larger output has same shape as input except that it is inverted

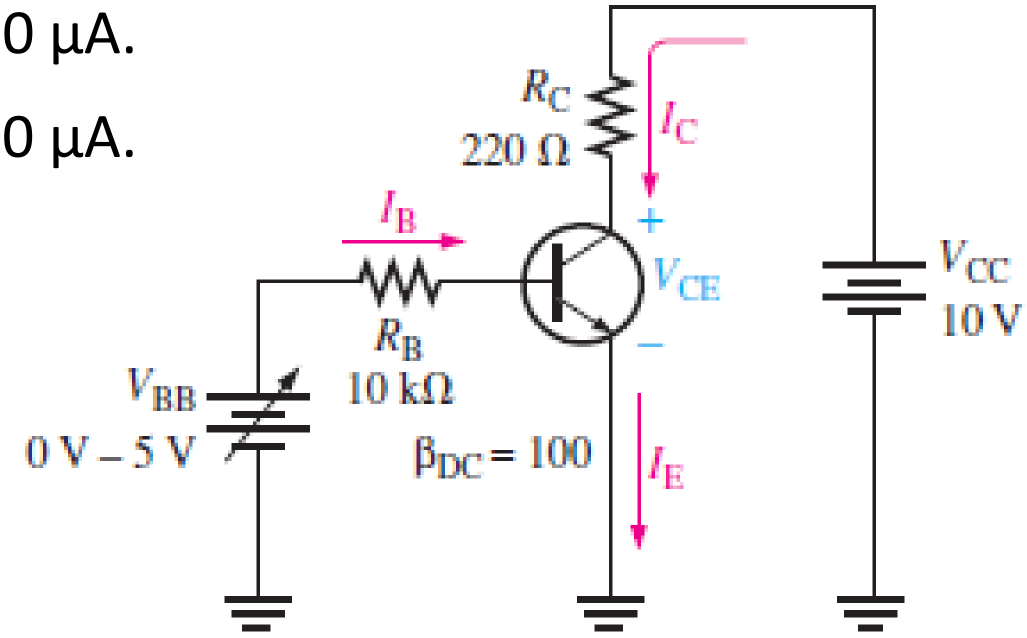


(b) Nonlinear operation: output voltage limited (clipped) by cutoff

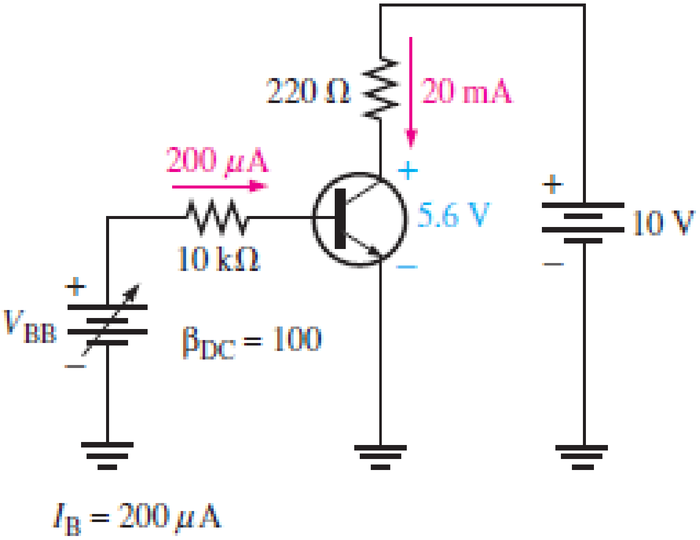


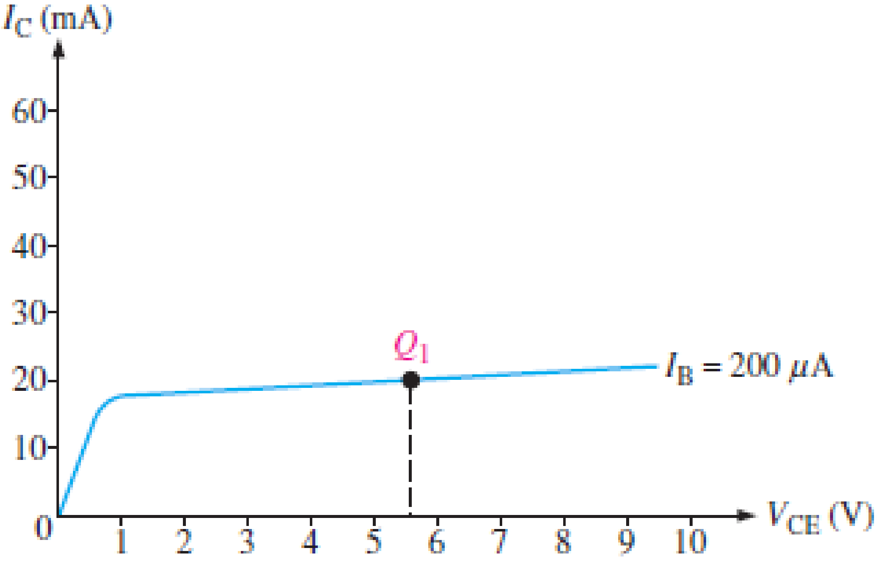
(c) Nonlinear operation: output voltage limited (clipped) by saturation

- The DC bias of a transistor circuit is established by the values set for V_{BB} and V_{CC} as well as the resistor values R_B and R_C.
- Take circuit below and set different values of V_{BB} in order to achieve different values of I_B:
  a. Current I_B = 200 µA.
  b. Current I_B = 300 µA.
  c. Current I_B = 400 µA.

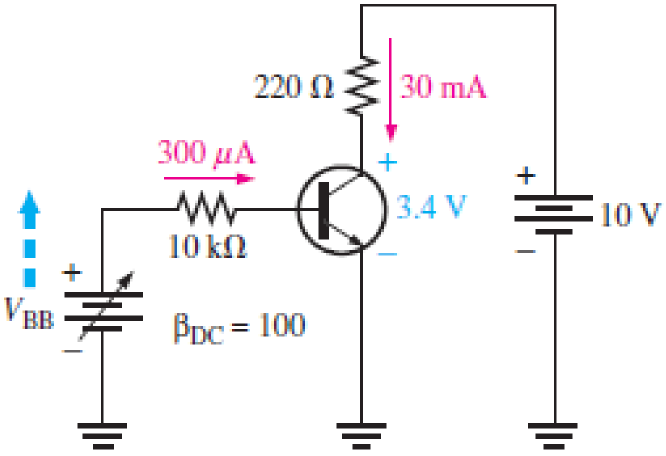


- From the standard calculation, we find that $I_C = \beta_{DC} I_B$ = 20 mA for I_B = 200 μA, so that V_{CE} = 10 V – (20 mA)(220 Ω) = 5.6 V.
- This provides us with point Q_1 on curve, i.e. the operating point for the transistor when I_B = 200 μA.

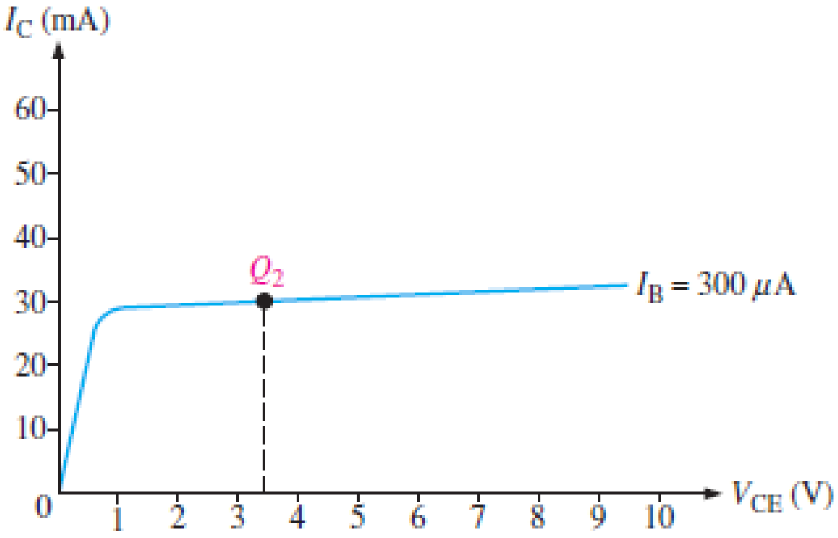




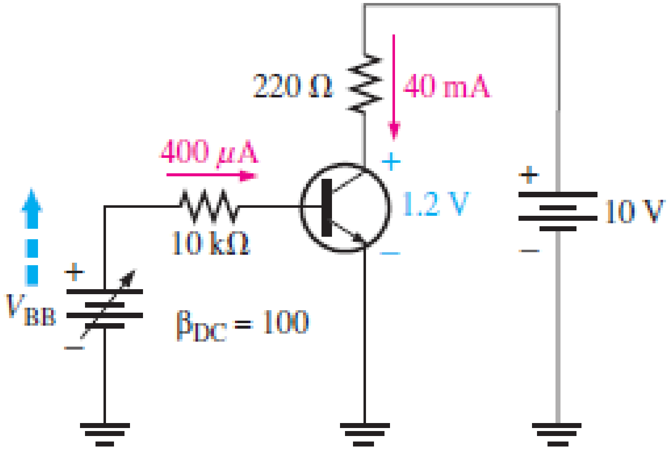
- Similarly, we find a value of V_{CE} = 10 V – (30 mA)(220) = 3.4 V when I_B = 300 µA which provides point Q_2 on the curve.



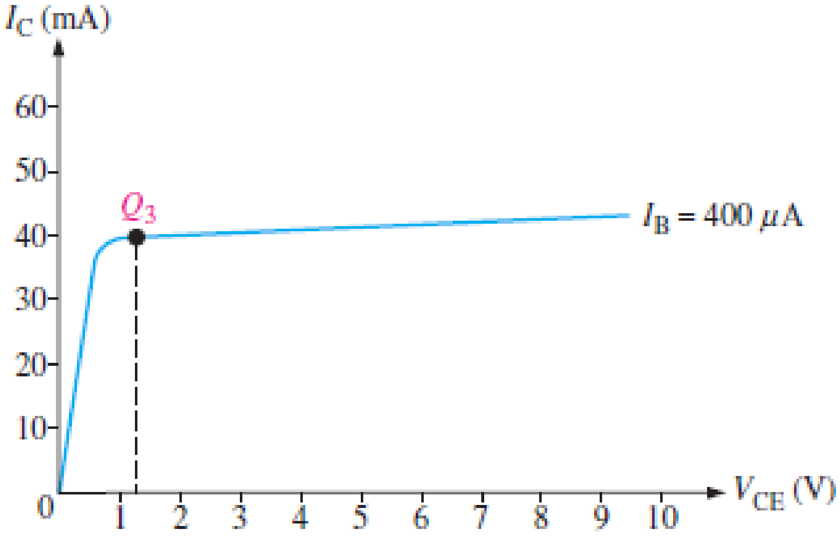
Increase I_B to 300 µA by increasing V_{BB}



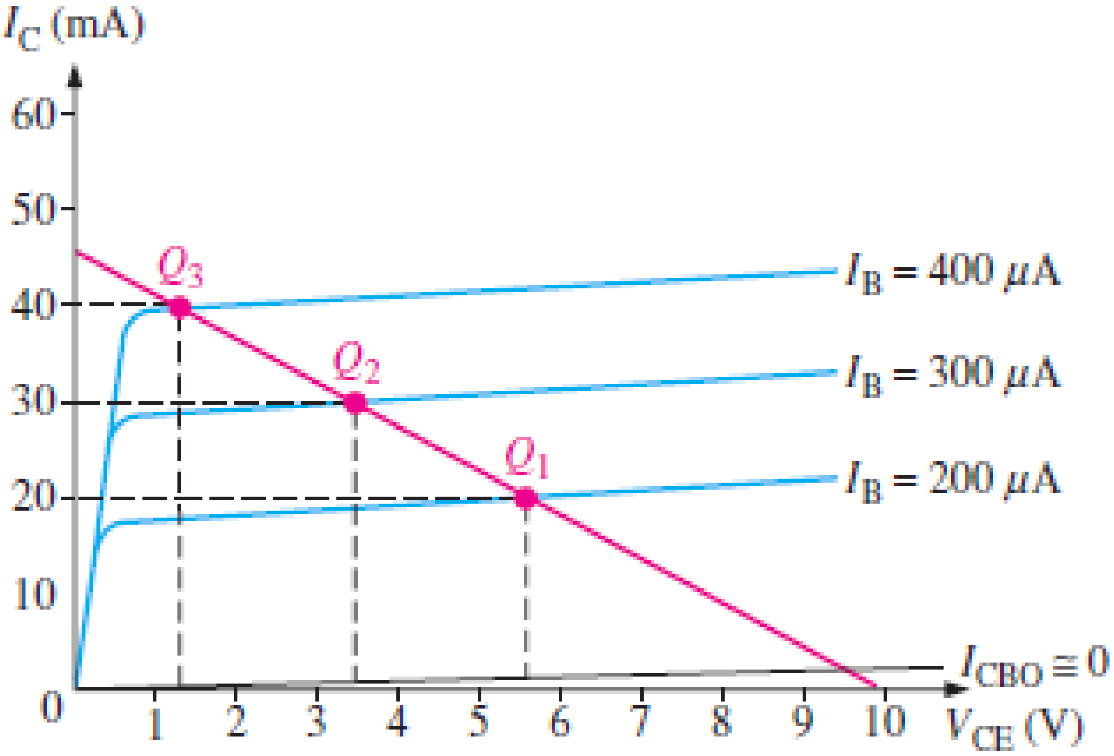
- Similarly, we find a value of V_{CE} = 10 – (40 mA)(220) = 1.2 V when I_B = 400 μA which provides point Q_3 on the curve.



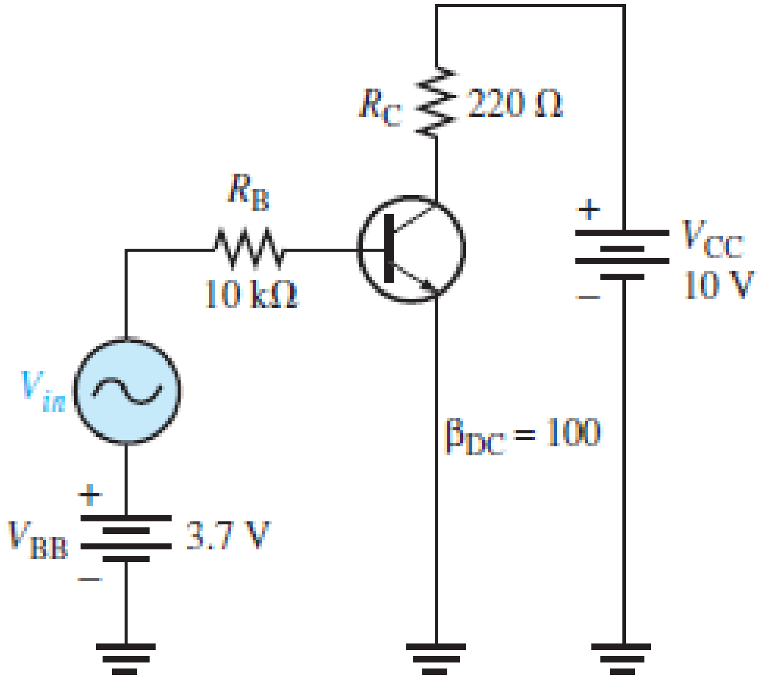
Increase I_B to 400 μA by increasing V_{BB}



- Combining the individual graph, we can also draw up a DC load line for this circuit as shown by the line below.



- The Q point calculations as below.
- Set I_B for 300 µA. Start with V_{in} = 0 initially.
- Now, increase V_{in} so that I_B varies sinusoidally by 100 µA above and below the initial value.



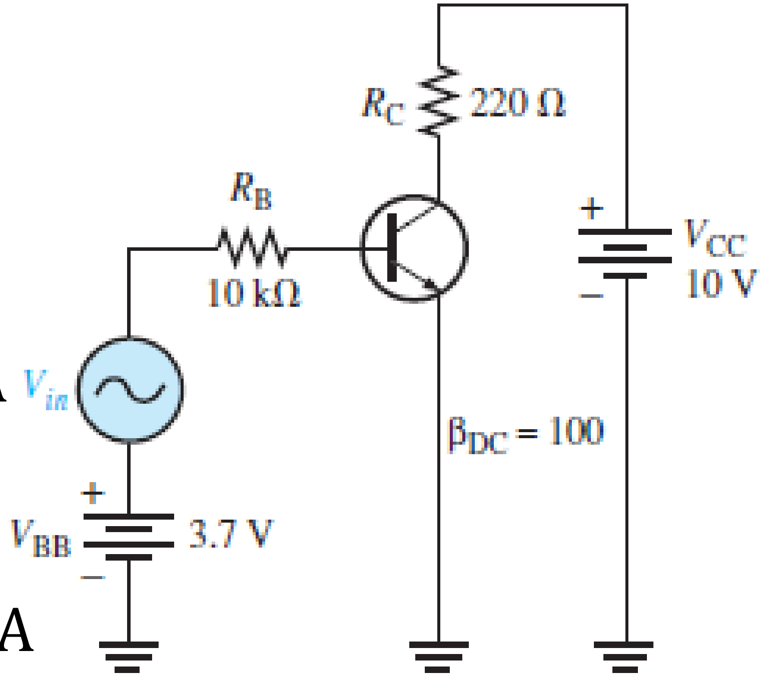
- Collector current is determined from:

$$I_{BQ} = \frac{V_{BB} - V_{BE}}{R_B}$$

$$= \frac{3.7\ \text{V} - 0.7\ \text{V}}{10\ \text{k}\Omega} = 300\ \mu\text{A}$$

$$I_{CQ} = \beta_{DC} I_{BQ}$$

$$= (100)(300\ \mu\text{A}) = 30\ \text{mA}$$



- Voltage across collector-emitter is calculated from:

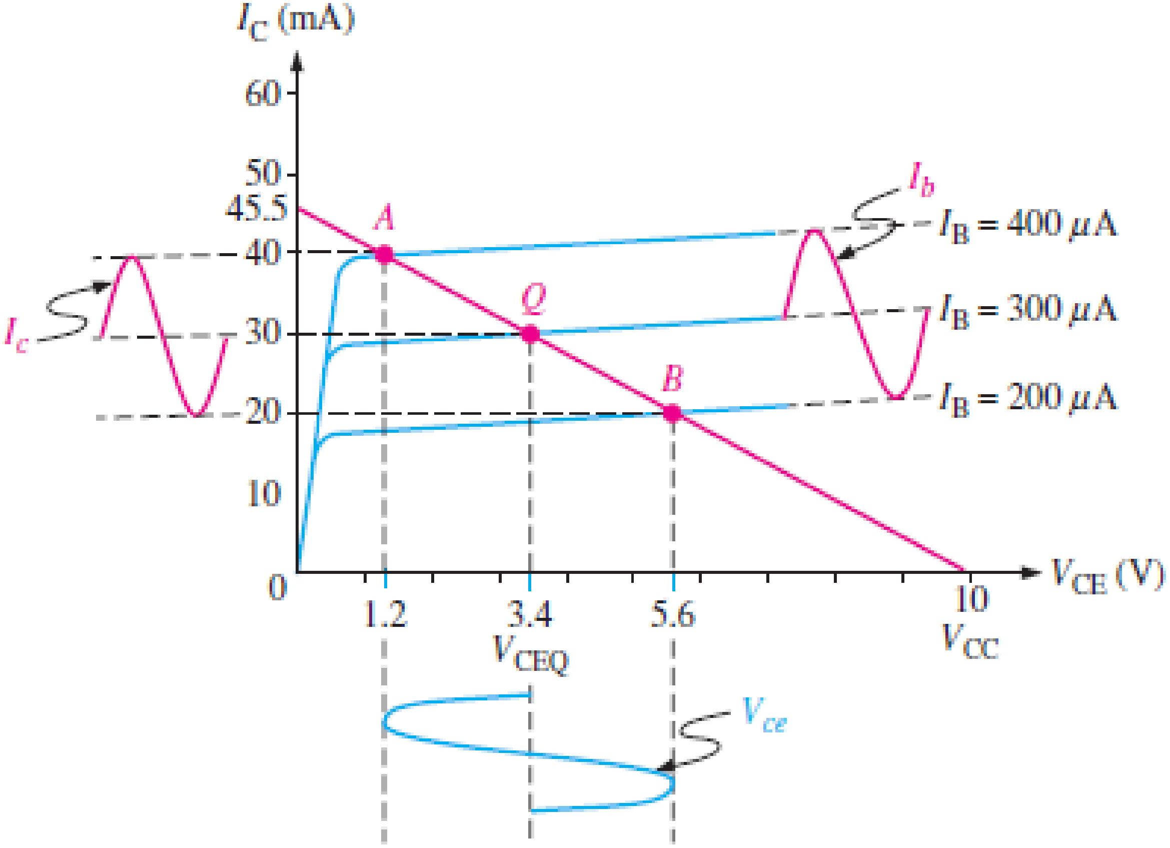
$$V_{CEQ} = V_{CC} - I_{CQ} R_C$$

$$= 10\ \text{V} - (30\ \text{mA})(220\ \Omega) = 3.4\ \text{V}$$

6. Operation of Various Amplifier Configurations

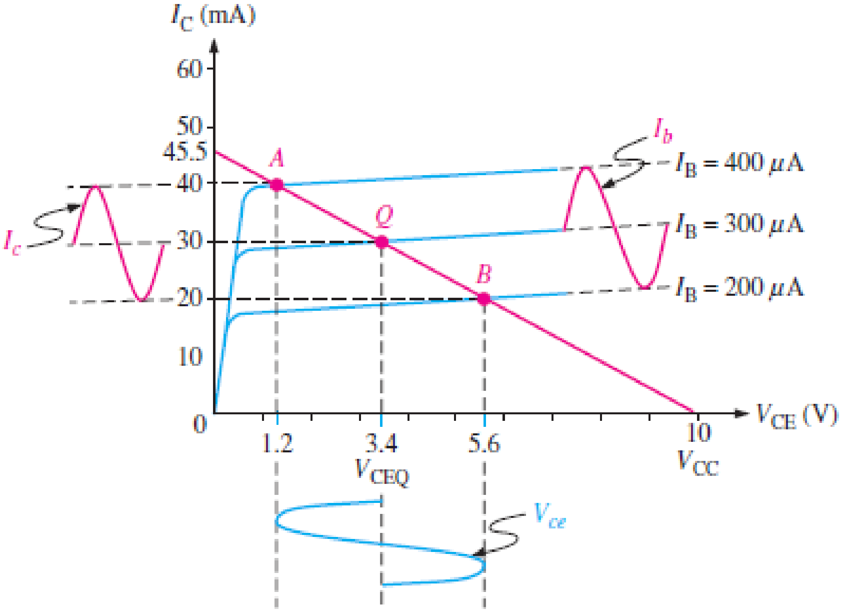
Normal optimum operation:

- Peak swings of the base current equally spaced along the load line i.e. marked as points “B” and “A” on the line.



- This gives a theoretical maximum input signal to the base terminal of 200 µA peak-to-peak, (or 100 µA peak) without producing any distortion to the output signal.

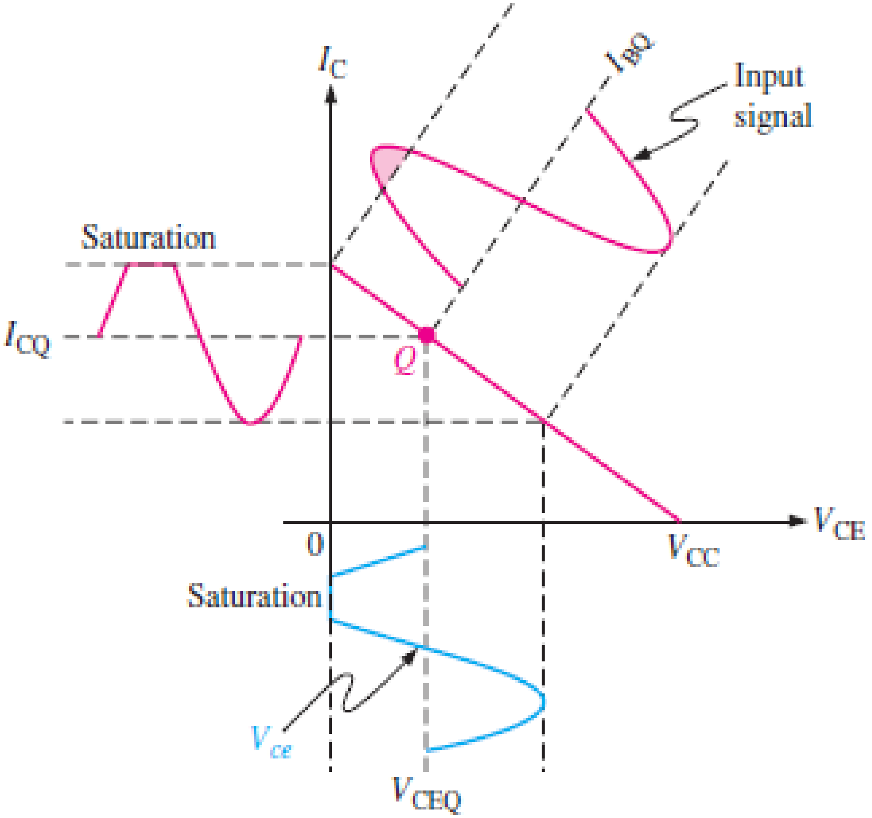
- Any input signal giving a base current greater than this value drive the transistor to go beyond point “B” and into its “cut-off” region or beyond point “A” and into its saturation region.



- This results in distortion to the output signal in the form of “clipping”.

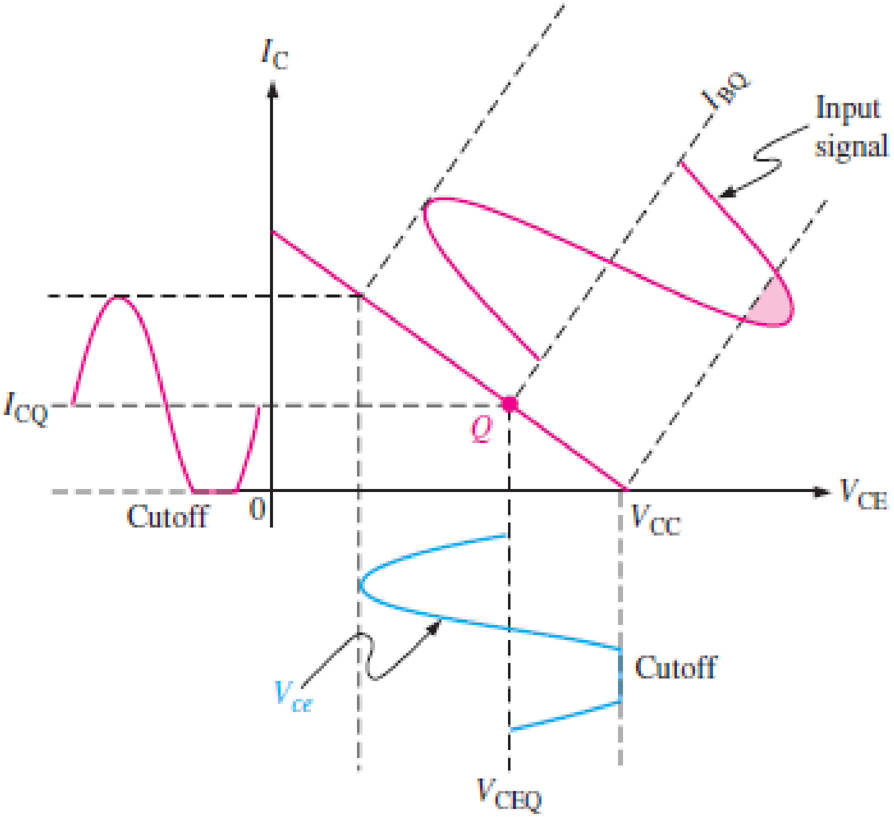
Saturation condition:

- Clipping at maximum values of the I_{CQ} and V_{CEQ}.
- Transistor is saturated and it could not go further for its signal excursion.



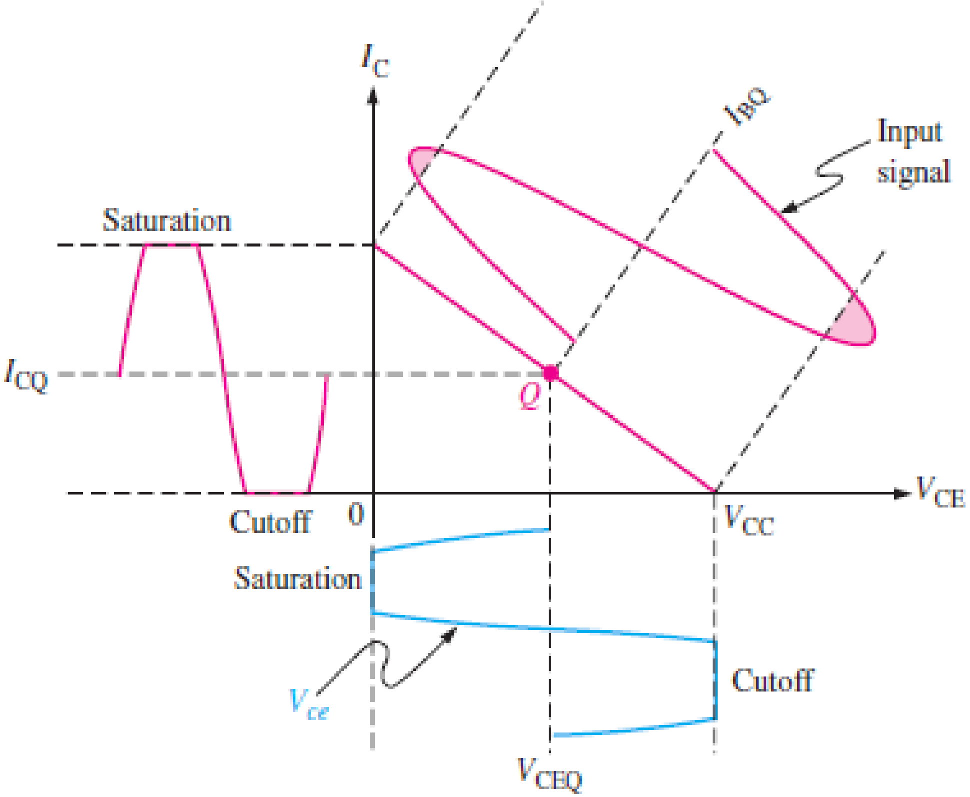
Cut-off condition:

- Clipping at minimum values of the I_{CQ} and V_{CEQ}.
- Transistor could not go further for its signal excursion as the transistor is already turned off.



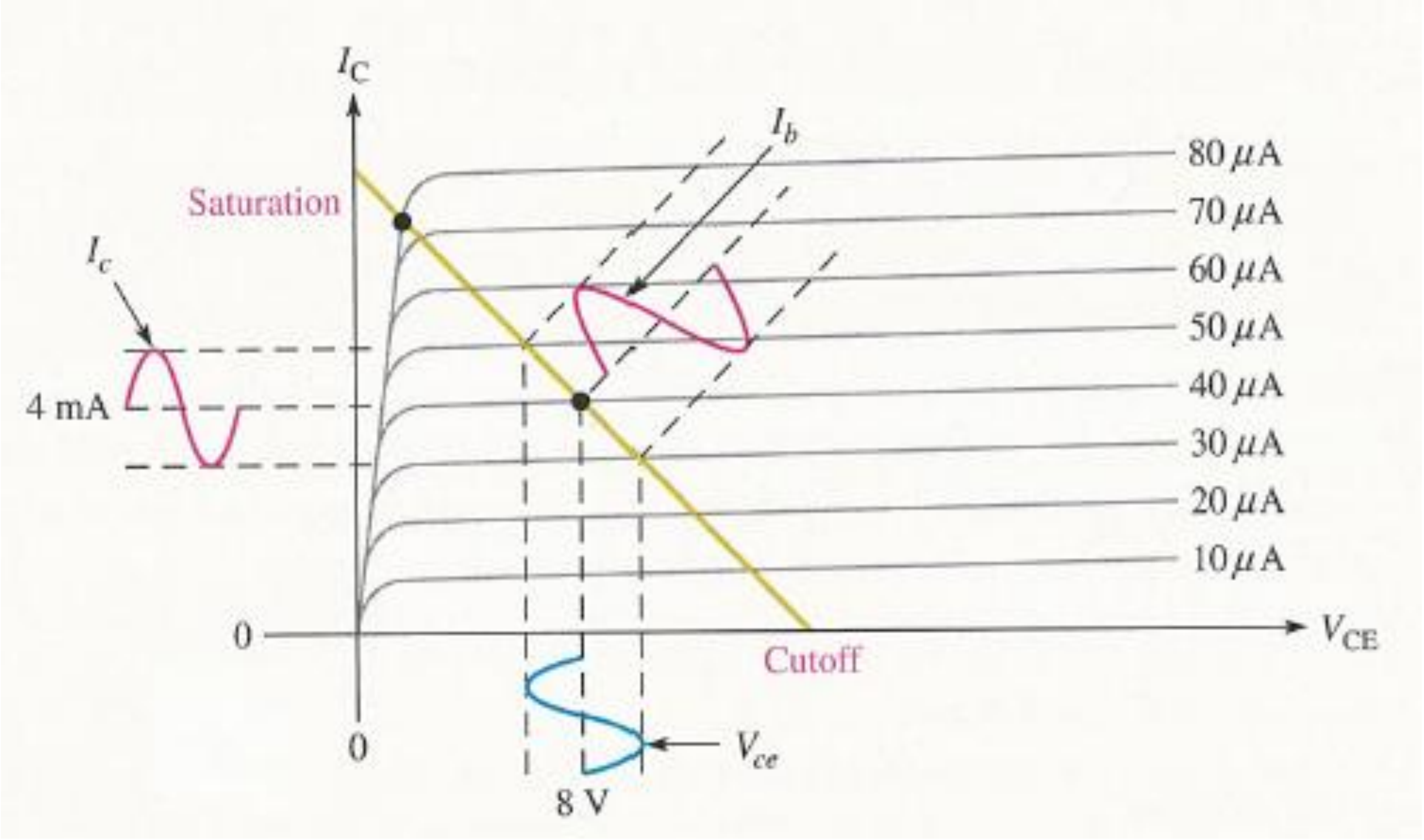
Saturation and cut-off conditions:

- Clipping at both maximum and minimum of I_{CQ} and V_{CEQ}.
- Transistor is either saturated at the maximum values or it is already turned off at minimum values.

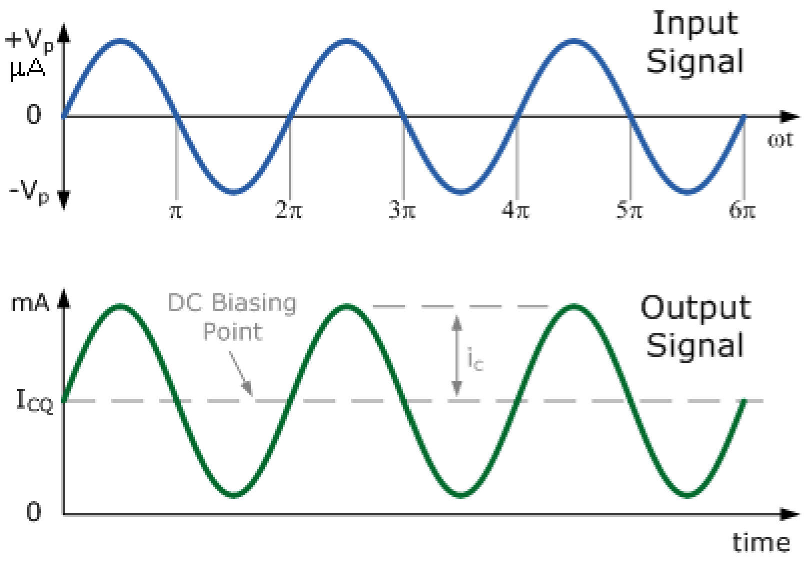


7. A Graphical Representation on the Transistor Curve

- The following graphic shows the transistor curve for a typical BJT transistor (β_{DC} = 100).



- Sinusoidal variation in I_B (µA) range leads to large variation in I_C (mA) range and a variation in V_{CE}.
- We will look at the amplification of small-time varying (sinusoidal) input voltages.
- Good example is an audio signal from a microphone that needs to be amplified to drive a speaker.



Points to Note for the Type of Amplifiers We Discuss:

1. Need to operate in forward active region of output.
2. The base current cannot go to zero or negative i.e. will go into cut-off. Thus, need to put a bias on the input voltage.
3. Base current cannot go too large i.e. will go into saturation and the output will not be linear anymore.
4. The amplification is a function of the input frequency i.e. amplifier will have a bandwidth.
5. Critical to get the correct bias point to ensure correct operation.

6. In the course, we will just consider Class A amplifier i.e. the transistor conducts for the full 360^o of input cycle. This type is typically used in low power (< 1 W) applications.
7. An increase in collector current means the voltage drop across R_C is increased; this means that V_o will decrease i.e. thus an increase in input voltage at the base has produced a decrease in output voltage i.e. an *inverting amplifier*

Choice of An Operating Point

Active operating region for amplification.

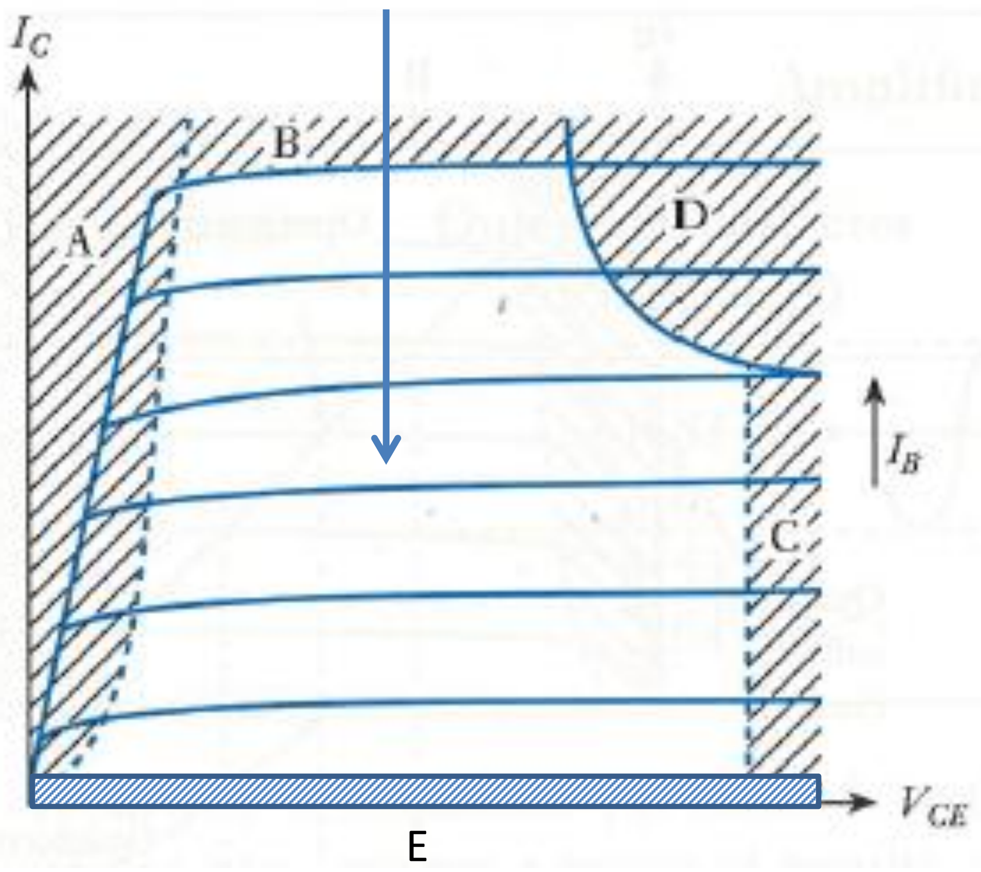
A: Saturation.

B: Exceeding the maximum value of I_C of the transistor.

C: Exceeding the maximum value of V_{BE} of the transistor.

D: Exceeding power dissipation of transistor.

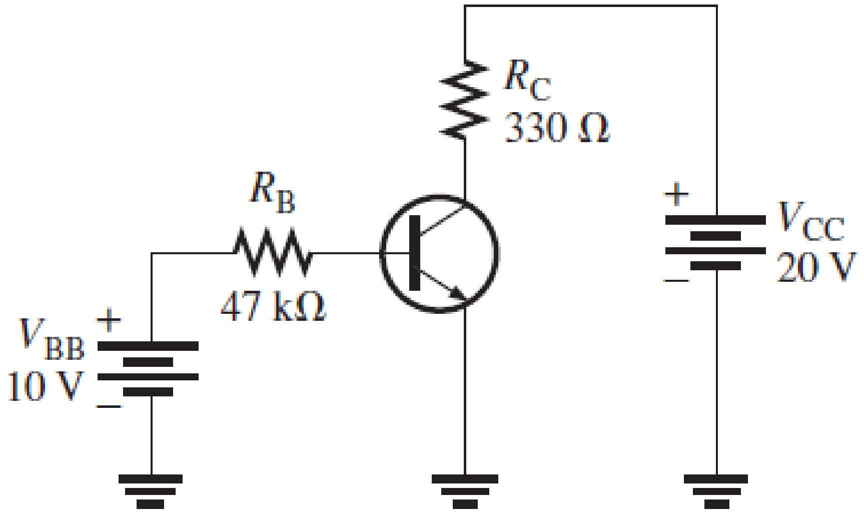
E: Cut-off.



Example 4 – BJT Circuit Operating Conditions

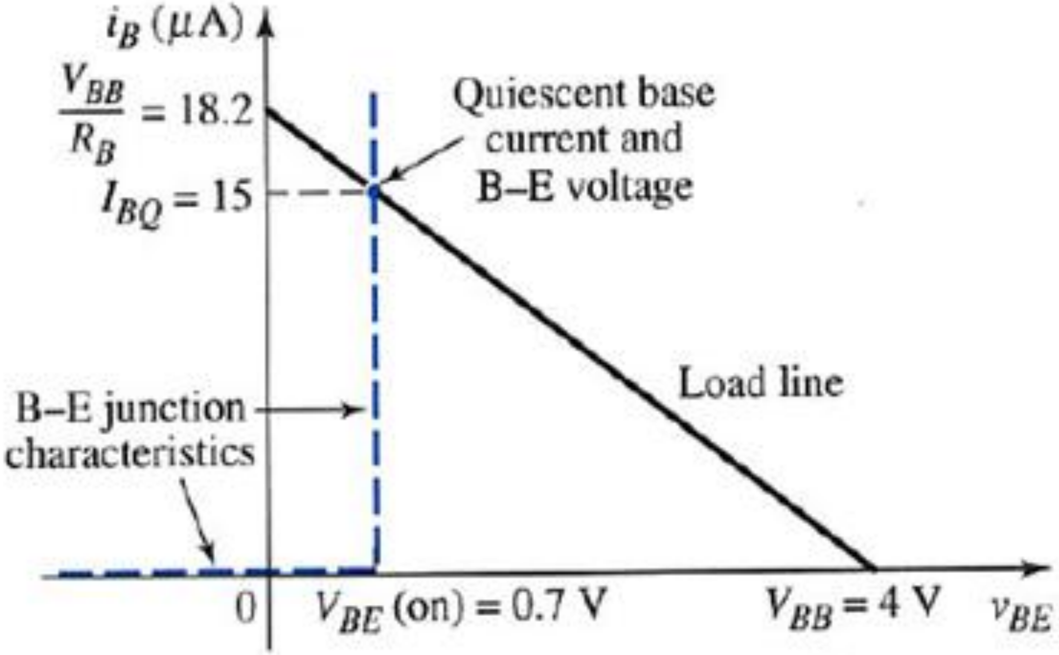
Determine the Q-point and draw the DC load line for the circuit above. Find the maximum peak value of base current for linear operation. Sketch the load line Assume β_{DC} = 200.

[12 marks]



Example 5 – Load Lines of BJT Circuit

For the load line graph of a common emitter BJT amplifier circuit given below, attempt the following tasks:



a. If the DC gain of the BJT transistor is 150, determine the Q point of the amplifier circuit that ensures maximum voltage swing at the output. [8 marks]

b. When the amplifier is to be powered by V_{CC} = 15 V voltage source, determine the value of collector resistor. [4 marks]