CSE 251

Electronic Devices and Circuits

Lecture 18

Course instructor:
Ankan Ghosh Dastider (AGD)
Lecturer, Department of Computer Science and Engineering,
School of Data and Sciences, Brac University
Email: ankan.ghosh@bracu.ac.bd

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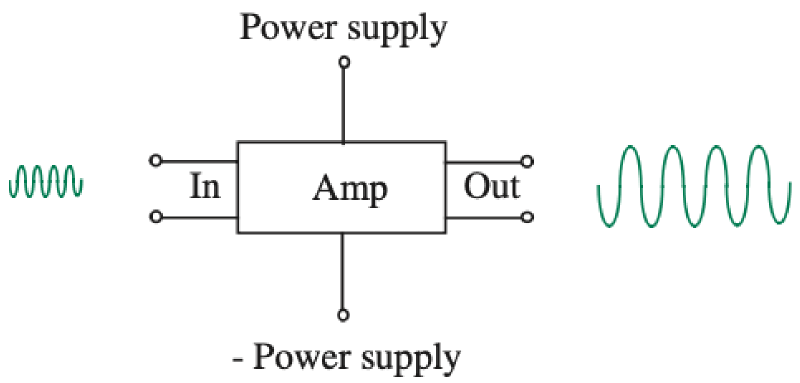
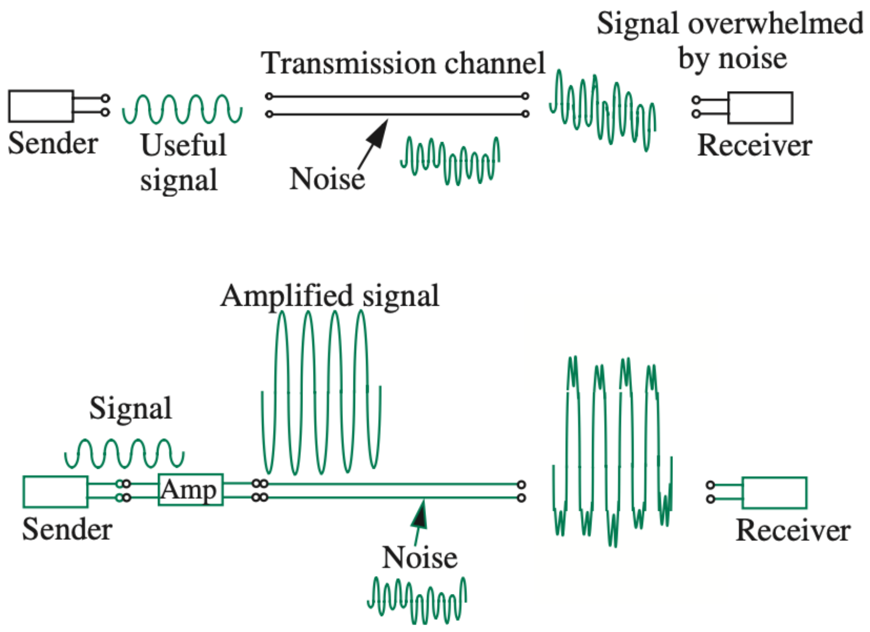
Lecture 13: Amplifiers Using Transistors

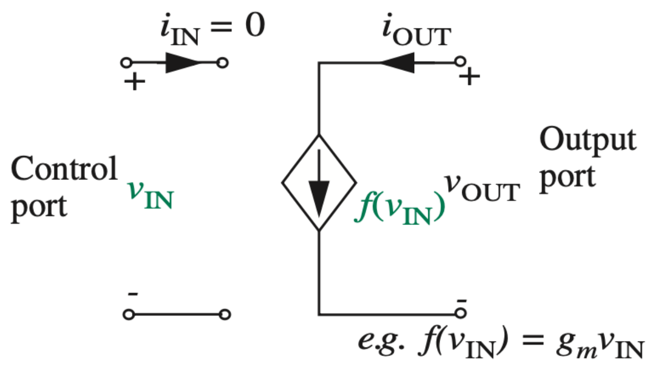
- Linear amplifier ⇒ $OUT = k \times IN$
- OUT/IN can be voltage or current
- Amplifier must provide power gain $(P_{OUT} > P_{IN})$, hence need power supply
- Usage: during communication





Types of Amplifier and Circuit Realization

- Depending on input (voltage or current) and output (V or I) – 4 types
  1. Voltage amplifier (In = V, Out = V)
  2. Current amplifier (In = I, Out = I)
  3. Transconductance amplifier (In = V, Out = I)
  4. Transresistance amplifier (In = I, Out = V)
- How to realize (make) amplifiers using circuits? Dependent Source!
- E.g, for transconductance amplifier $I_{out} = g_M \times V_{in} \Rightarrow$ VCCS (voltage controlloded current source)



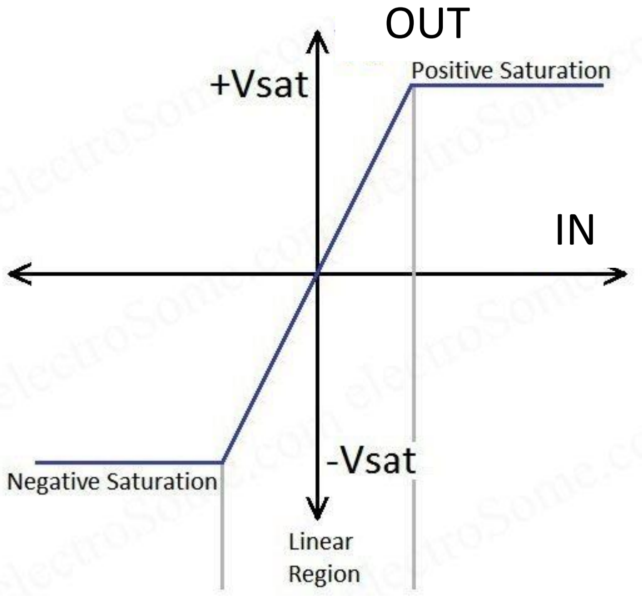
Amplifier TC

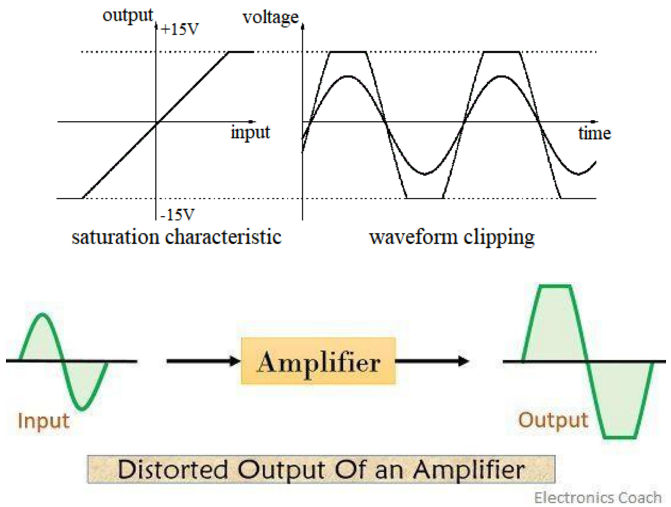
Translation: Your money will be doubled within 25 days

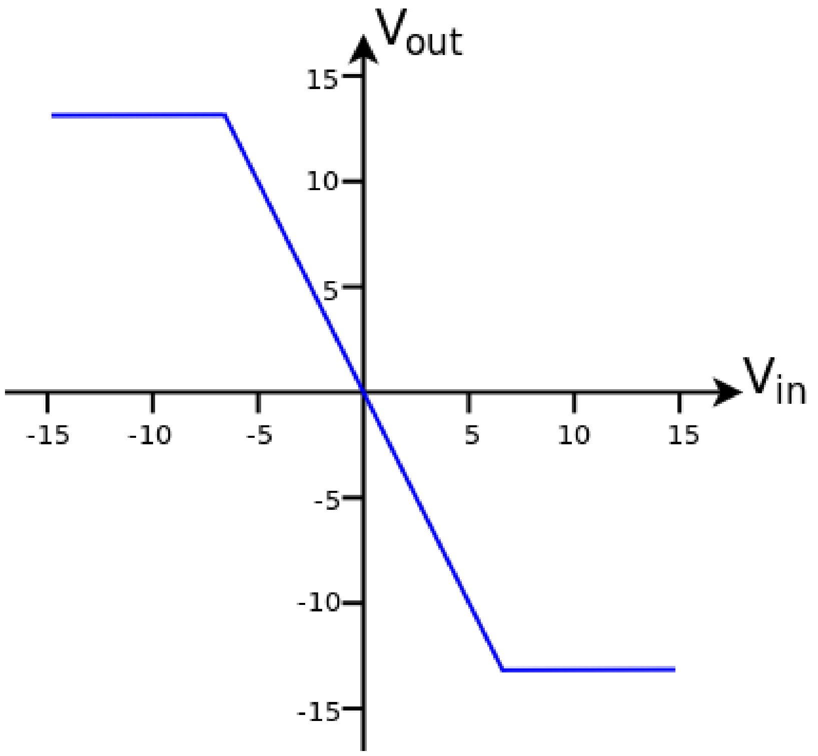
Screenshot from Phir Hera Pheri, produced by Base Industries Group. Used for educational purposes only.

Amplifier TC

- Saturation due to limited power supply (leftmost Figure)
- Input must be within a **valid input range**, otherwise output will be distorted
- Inverting amplifier, gain = -ve (rightmost Figure)

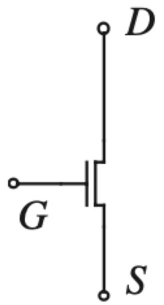


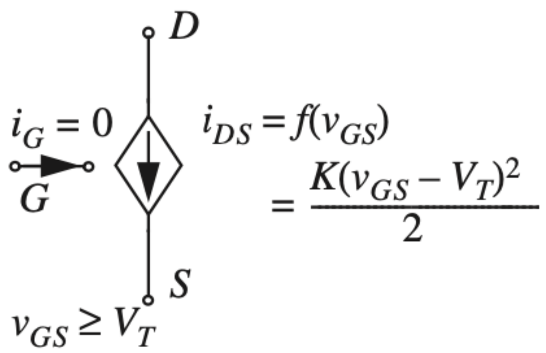




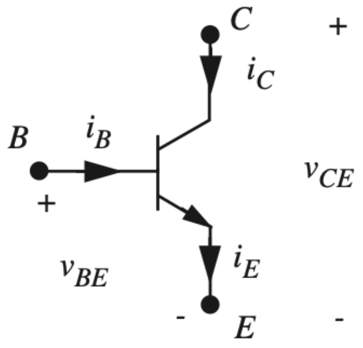
Making Dependent Sources

- BJT in Active mode acts like a current controlled current source
- MOSFET in Saturation mode acts like a voltage controlled current source
- So, we can use them to make amplifiers!
- BJT in Active is preferable since the relation is linear

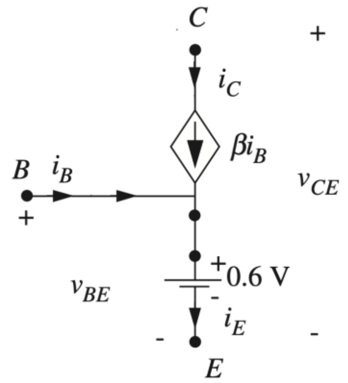




Valid when $v_{DS} \geq v_{GS} - V_T$



(a)

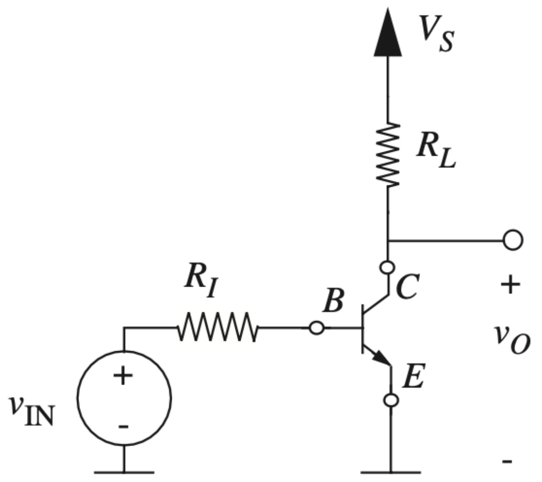


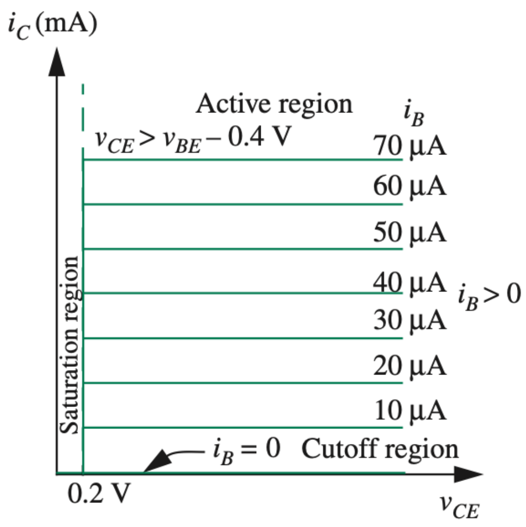
(b) Active region

$i_B > 0$ $v_{CE} > 0.2$

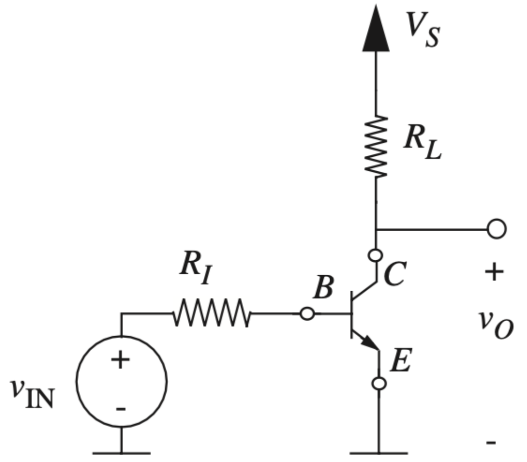
BJT Common Emitter Amplifier

- When BJT is in active mode, $I_{out} = \beta I_{in}$ here $I_{in} = I_B$ and $I_{out} = I_C$
- R_I converts input voltage (v_{IN}) to input current
- R_L converts output current to output voltage (v_o)
- But how does it work? Need to know relation between v_O and v_{IN}





Finding VTC of CE Amplifier



KVL: $v_O = v_{CE} = V_S - I_C \times R_L$ (True for any mode)

Cutoff: $I_B = 0 \Rightarrow v_{BE} \leq 0.7V \Rightarrow v_{IN} \leq 0.7V$

$$v_o = V_S - 0 \times R_L = V_S$$

(since in cutoff $I_B = 0$)

Active: $v_{CE} = v_o > 0.2V$

$$V_S - I_C R_L > 0.2V \Rightarrow I_C < (V_S - 0.2)/R_L$$

Since $I_C = \beta I_B \Rightarrow I_B < (V_S - 0.2)/\beta R_L$

Since $v_{in} = I_B R_I + 0.7 \Rightarrow v_{in} < 0.7 + \left(\frac{V_S - 0.2}{\beta R_L}\right) R_I$

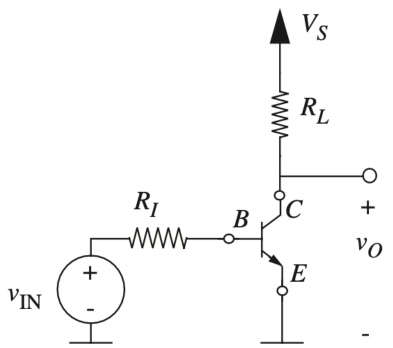
So as long as $0.7 < v_{IN} < 0.7 + \left(\frac{V_S - 0.2}{\beta R_L}\right) R_I$ BJT will be in Active and

$$v_o = V_S - I_C \times R_L$$

$$\Rightarrow v_o = V_S - \frac{\beta(v_{IN} - 0.7)}{R_I} R_L \Rightarrow v_o = \left(V_S + \frac{0.7\beta R_L}{R_I}\right) - \frac{\beta R_L}{R_I} v_{IN}$$

Saturation: $v_{in} > 0.7 + \left(\frac{V_S - 0.2}{\beta R_L}\right) R_I \Rightarrow v_o = v_{CE} = 0.2V$

VTC of CE Amplifier

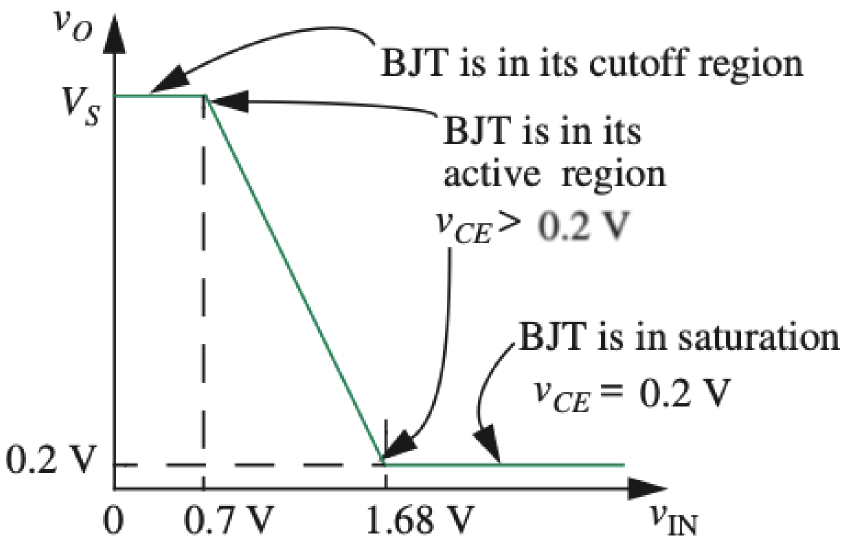


Assume that $R_I = 100\ \text{k}\Omega$, $R_L = 10\ \text{k}\Omega$, $\beta = 100$, and $V_S = 10$ V.

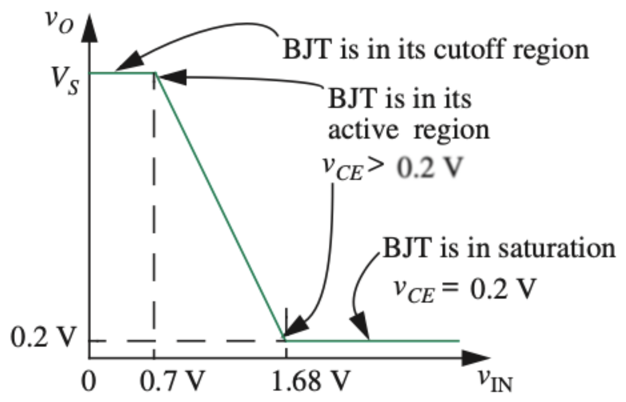
$$\Rightarrow 0.7 + \left(\frac{V_S - 0.2}{\beta R_L}\right) R_I = 0.7 + \left(\frac{10 - 0.2}{100 \times 10k\Omega}\right) 100k\Omega = 1.68V$$

And $v_o = \left(V_S + \frac{0.7\beta R_L}{R_I}\right) - \frac{\beta R_L}{R_I} v_{IN} \Rightarrow v_o = 17 - 10v_{IN}$

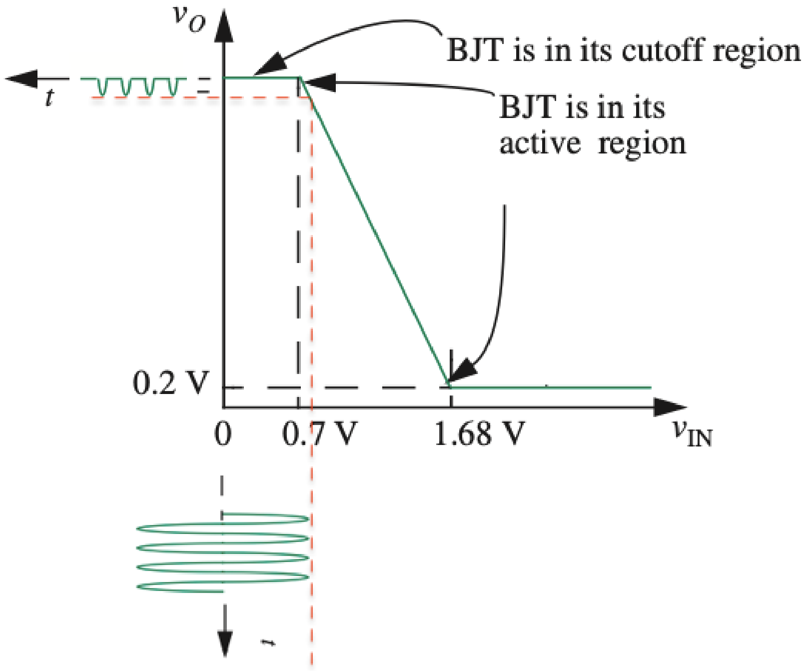
$v_{IN} \leq 0.7$	$v_O = 10$	Cutoff mode
$0.7 < v_{IN} < 1.68$	$v_o = 17 - 10v_{IN}$	Active mode
$v_{IN} \geq 1.68$	$v_o = 0.2$	Saturation mode



VTC of CE Amplifier



But the TC does not look like that of an amplifier!

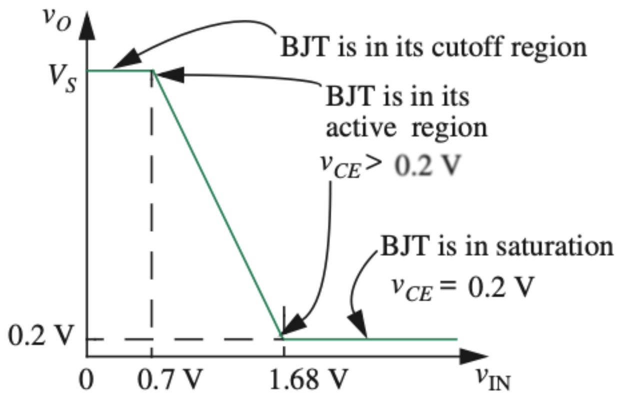


In fact, if $v_{IN} = 1\sin\omega t$, output will be distorted since for $v_{IN} \leq 0.7$ in cutoff, and $0.7 < v_{IN} < 1$ in active. Hence, does not amplify “Large” Signals

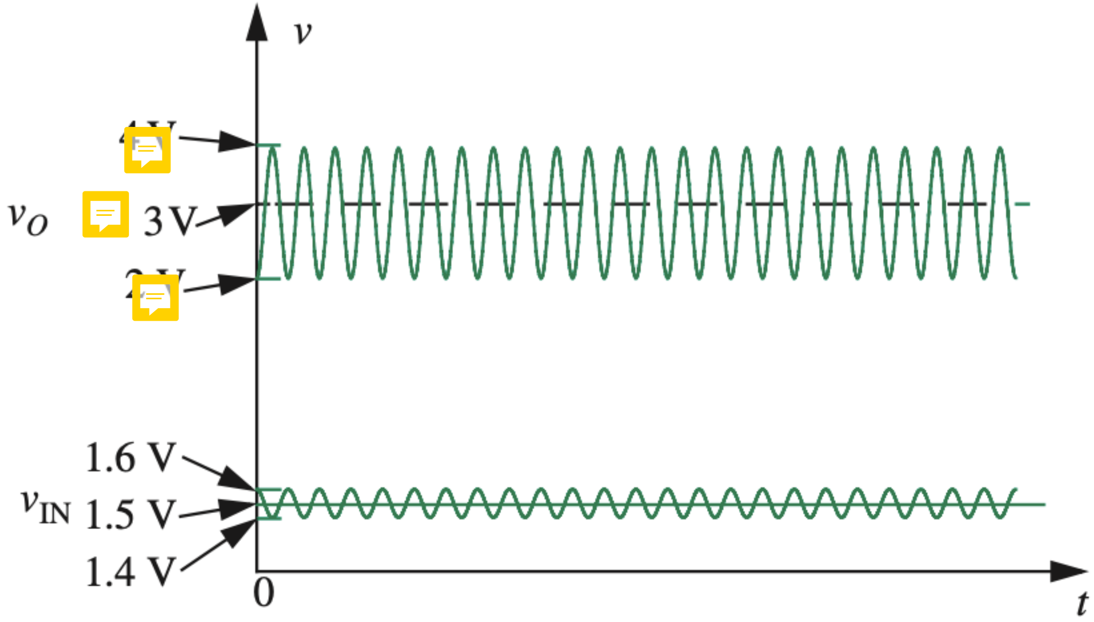
Small Signal Amplification

$v_{IN} \leq 0.7$	$v_O = 10$	Cutoff mode
$0.7 < v_{IN} < 1.68$	$v_o = 17 - 10v_{IN}$	Active mode
$v_{IN} \geq 1.68$	$v_o = 0.2$	Saturation mode

- Say $v_{IN} = 1.5 \pm 0.1V$, then $v_O = 2 \mp 1V$
- This means a "small" signal of $0.1V$ amplitude with **input offset** $1.5V$ will have a $1V$ amplitude for the small signal output with an **output offset** $2V$, and gain $k = -10$
- This is called **small signal amplification**



v_{IN}	v_O
0.5	10
0.7	10
1	7
1.3	4
1.4	3
1.5	2
1.6	1
1.7	0.2
1.8	0.2



- Overall gain, 1.3V Δ in inp, 9.8V Δ in out
- But non-linear overall
- Red: Linear (Active) Region
- 0.1V change in inp ⇒ 1V change in out
- 10-fold change! ⇒ Amplification!

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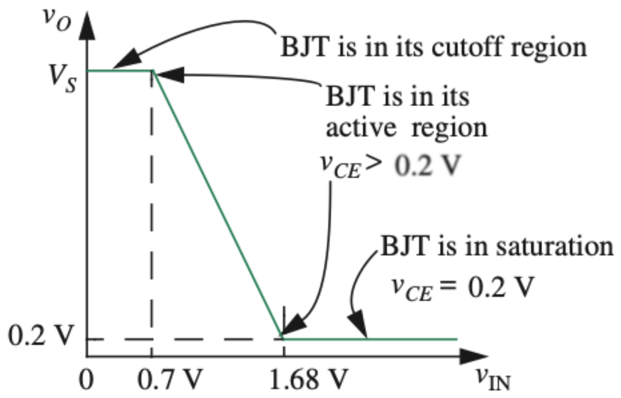

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- But non-linear overall
- Red: Linear (Active) Region
- 0.1V change in inp ⇒ 1V change in out
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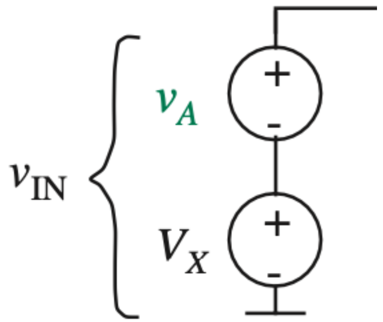
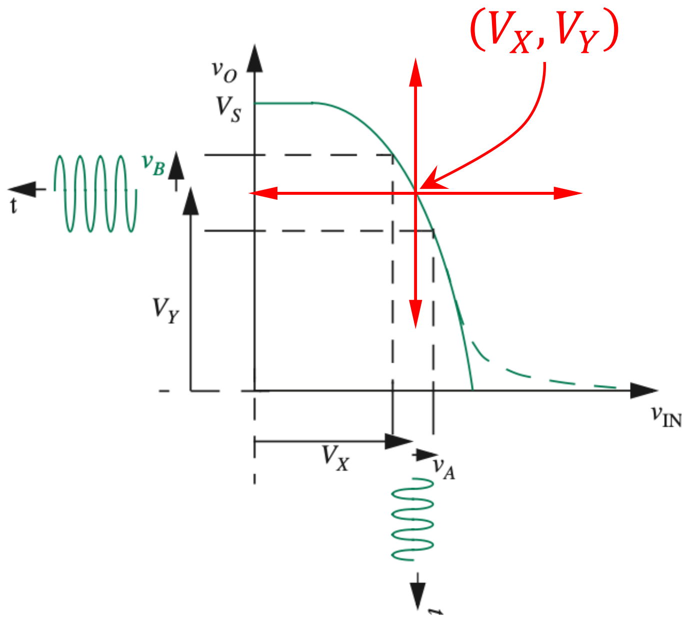
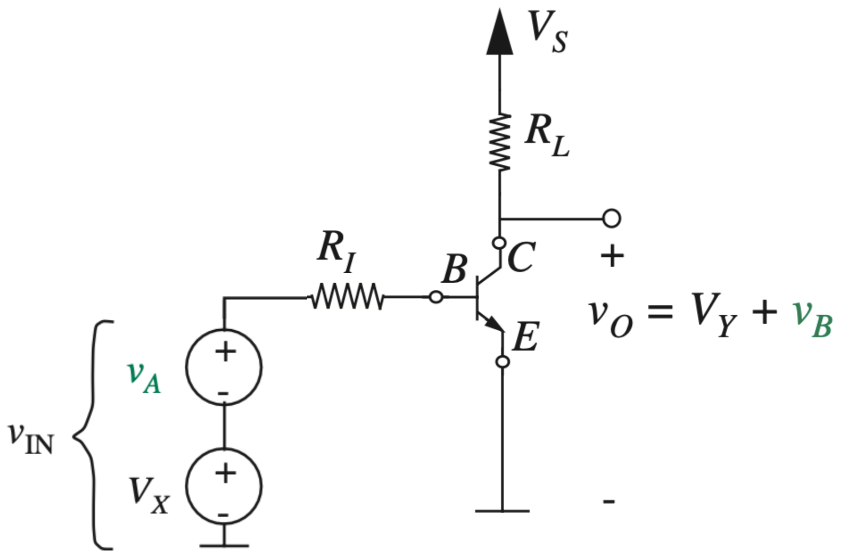
- In general, $v_{IN} = V_X + v_A \Rightarrow v_O = V_Y + v_B$
- Here, v_A and v_B are input/output small signals of interest and $v_B = k \times v_A$, where gain $k = -\frac{\beta R_L}{R_I}$
- V_X and V_Y are input/output biases, (V_X, V_Y) is called the **Operating point** or **Bias point** or **Q-point**
- **Biasing** is used to ensure BJT stays in Active





Summary

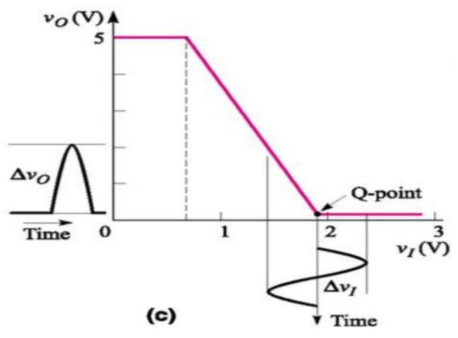


BJT Common Emitter Amplifier

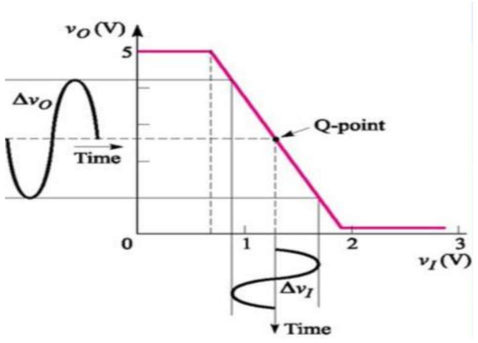
- Input small signal v_A, output small singnal v_B. Both are AC signals
- $v_B = k \times v_A$, where the gain $k = -\frac{\beta R_L}{R_I}$
- (V_X, V_Y) is called the **Operating point** or **Bias point** or **Q-point**. Both DC Offset
- $V_Y = \left(V_S + \frac{0.7\beta R_L}{R_I}\right) - \frac{\beta R_L}{R_I} V_X$

Valid voltage range The range of input for which the BJT in the circuit operate in the Active region.

If not maintained, output might be distorted



Biased, but ***Valid voltage range*** not maintained



Biased, and ***Valid voltage range*** maintained

- Need to select Q-point or Bias point in such a way that input is within ***Valid voltage range***
- In this case, ***Valid voltage range:*** $0.7 < v_{IN} < 0.7 + \left(\frac{V_S - 0.2}{\beta R_L}\right) R_I$
- How to select Q-point? Best option: middle of active region, which will give maximum swing (peak-to-peak) for v_A

Example 1

Consider the BJT common emitter circuit with $\beta = 100, R_I = 100k\Omega, \mathrm{R_L} = 10k\Omega, \text{and } V_S = 10V$

We want to set bias the point in such a way that the DC portion of the input, i.e., $V_X = 1.2V$.

Under small signal approximation, if the input $v_{IN} = V_X + v_i(t)$, the output will be $v_O = V_Y + kv_i(t)$. This means the output will be some DC value V_Y plus the amplified version of the small signal $v_i(t)$.

Here assume that $v_i = 0.1 \cos \omega t$.

- What is the value of DC part of the output, i.e., V_Y?
- What will be the value of gain k under small signal approximation?
- What is amplitude (peak-to-peak) of the input small signal waveform $v_i(t)$?
- What is amplitude (peak-to-peak) of the output small signal waveform?

Example 1

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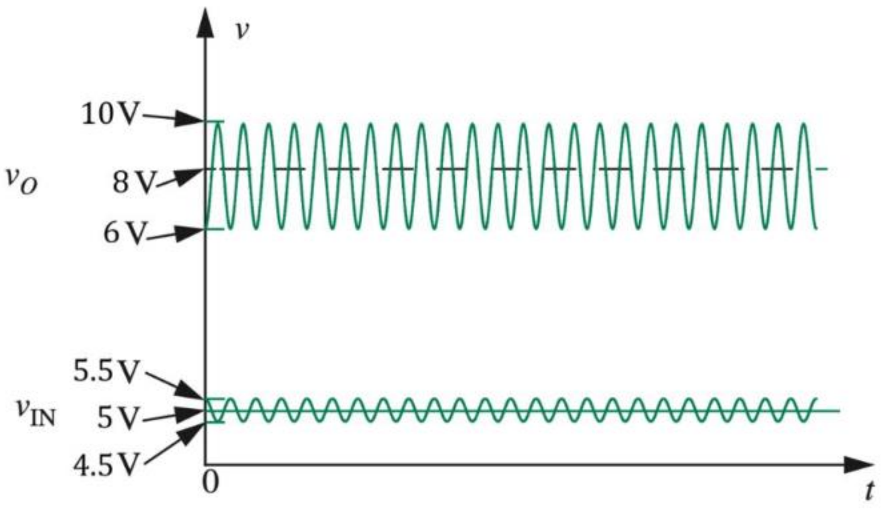
Here assume that $v_i = 0.1\cos\omega t$.

- What is the value of DC part of the output, i.e., V_Y?
  $V_X = 1.2$, therefore $V_Y = \left(V_S + \frac{0.7\beta R_L}{R_I}\right) - \frac{\beta R_L}{R_I} V_X = 5$
- What will be the value of gain k under small signal approximation?
  $$k = -\frac{\beta R_L}{R_I} = -10$$
- What is amplitude (peak-to-peak) of the input small signal waveform $v_i(t)$?
  max = 0.1V, min = -0.1V. Therefore, peak-to-peak amplitude = 0.2V
- What is amplitude (peak-to-peak) of the output small signal waveform?
  Amplitude of output = $|k|$ ×Amplitude of input $\Rightarrow 10 \times 0.2 = 2V$

Example 2

The input voltage of a common source amplifier is given as $v_{IN} = V_X + v_i(t)$ and the output voltage is given $v_O = V_Y + kv_i(t)$. Here, $v_i(t)$ is a sinusoidal voltage with amplitude a, V_X is the input DC offset voltage, V_Y is the output DC offset voltage. The input and output waveforms are given below. Notice the output small signal is inverted compared to input small signal. Hence, the small signal gain, k, will be negative.



- What is the amplitude of the input small signal $vi(t)$?
- What is the amplitude of the output small signal?
- Hence, what is the small signal gain k?
- From the above graph, what is the value of input DC voltage V_X and the output DC voltage V_Y?
- Design the circuit, i.e., find the value of V_S, R_I, and R_L to achieve given input-output voltage relation. Given $\beta = 100$

Example 2

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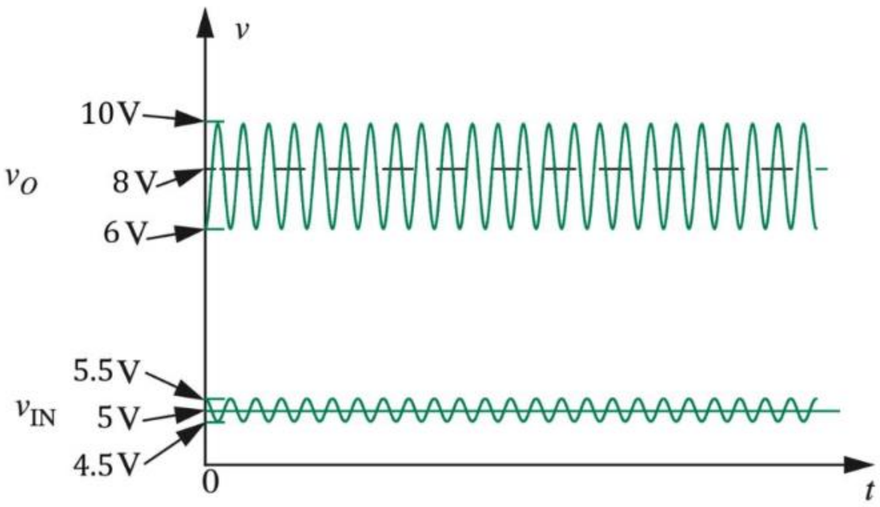
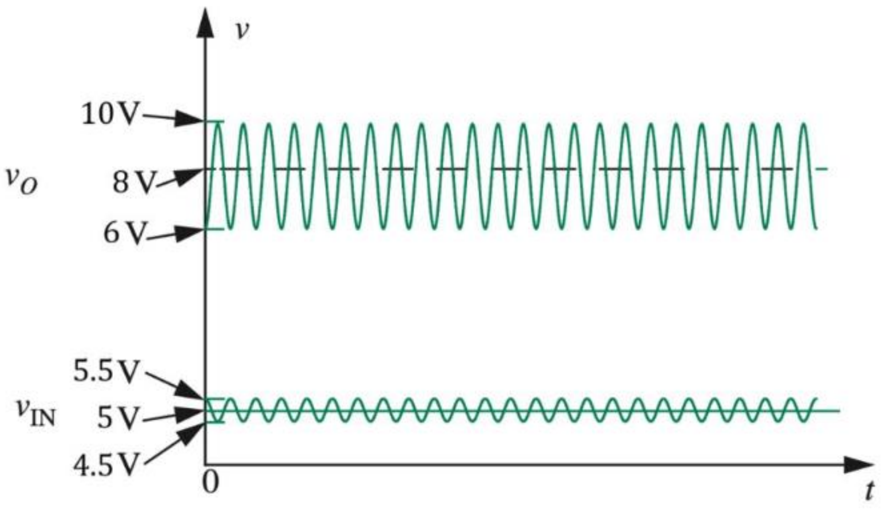


- What is the amplitude of the input small signal $vi(t)$? 0.5 V
- What is the amplitude of the output small signal? 2 V
- Hence, what is the small signal gain k? $k = -\frac{2}{0.5} = -4$
- From the above graph, what is the value of input DC voltage V_X and the output DC voltage V_Y? $V_X = 5, V_Y = 8$
- Design the circuit, i.e., find the value of V_S, R_I, and R_L to achieve given input-output voltage relation. Given $\beta = 100$.

Example 2

The input voltage of a common source amplifier is given as $v_{IN} = V_X + v_i(t)$ and the output voltage is given $v_O = V_Y + kv_i(t)$. Here, $v_i(t)$ is a sinusoidal voltage with amplitude a, V_X is the input DC offset voltage, V_Y is the output DC offset voltage. The input and output waveforms are given below. Notice the output small signal is inverted compared to input small signal. Hence, the small signal gain, k, will be negative.



- Design the circuit, i.e., find the value of V_S, R_I, and R_L to achieve given input-output voltage relation. Given $\beta = 100$.

$$k = -4 = -\frac{\beta R_L}{R_I} \Rightarrow \frac{\beta R_L}{R_I} = 4 \Rightarrow R_L = 0.04R_I$$

Let $R_I = 100k\Omega \Rightarrow R_L = 4k\Omega$

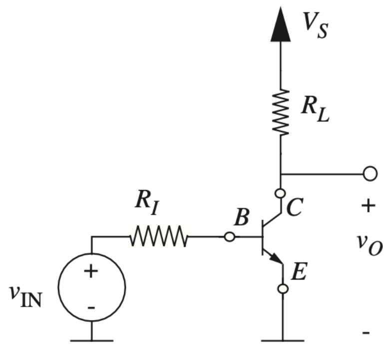
$$V_Y = \left(V_S + \frac{0.7\beta R_L}{R_I}\right) - \frac{\beta R_L}{R_I}V_X \Rightarrow 8 = (V_S + 0.7 \times 4) - 4 \times 5$$

$$\Rightarrow V_S = 8 + 20 - 2.8 = 25.2\ V$$

Example 3

Choose an operating point for the amplifier below to maximize the input voltage swing.

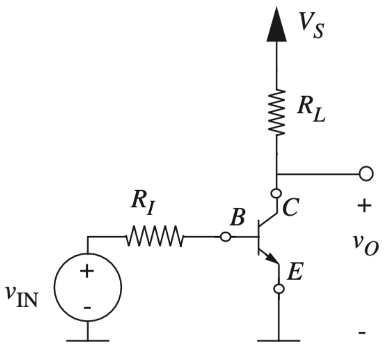
Here $R_I = 100\ k\Omega, R_L = 10\ k\Omega, \beta = 100, V_S = 10\ V$



Example 3

Choose an operating point for the amplifier below to maximize the input voltage swing.

Here $R_I = 100\ k\Omega, R_L = 10\ k\Omega, \beta = 100, V_S = 10\ V$



Solution: BJT will be active for the ***valid input range:*** $0.7 < v_{IN} < 0.7 + \left(\frac{V_S - 0.2}{\beta R_L}\right) R_I$

Here, $0.7 + \left(\frac{V_S - 0.2}{\beta R_L}\right) R_I = 0.7 + \left(\frac{10-0.2}{100\times 10}\right) = 0.7 + 0.98 = 1.68\ \mathrm{V}$

Therefore, ***valid input range:*** $0.7V < v_{IN} < 1.68\ V$

For maximum input swing, V_X should be midway between the ***valid input range***

Hence, $V_X = \frac{0.7+1.68}{2} = 1.19\ V$

Therefore, $V_Y = \left(V_S + \frac{0.7\beta R_L}{R_I}\right) - \frac{\beta R_L}{R_I} V_X = \left(10 + \frac{0.7\times 100\times 10}{100}\right) - \frac{100\times 10}{100} \times 1.19 = 5.1$

Therefore, maximum peak-to-peak input swing $= (1.19 - 0.7) = (1.68 - 1.19) = \mathbf{0.58\ V}$

Note: $V_Y = 5.1$ is midway between the ***valid output range:*** $0.2 \le v_o < 10$