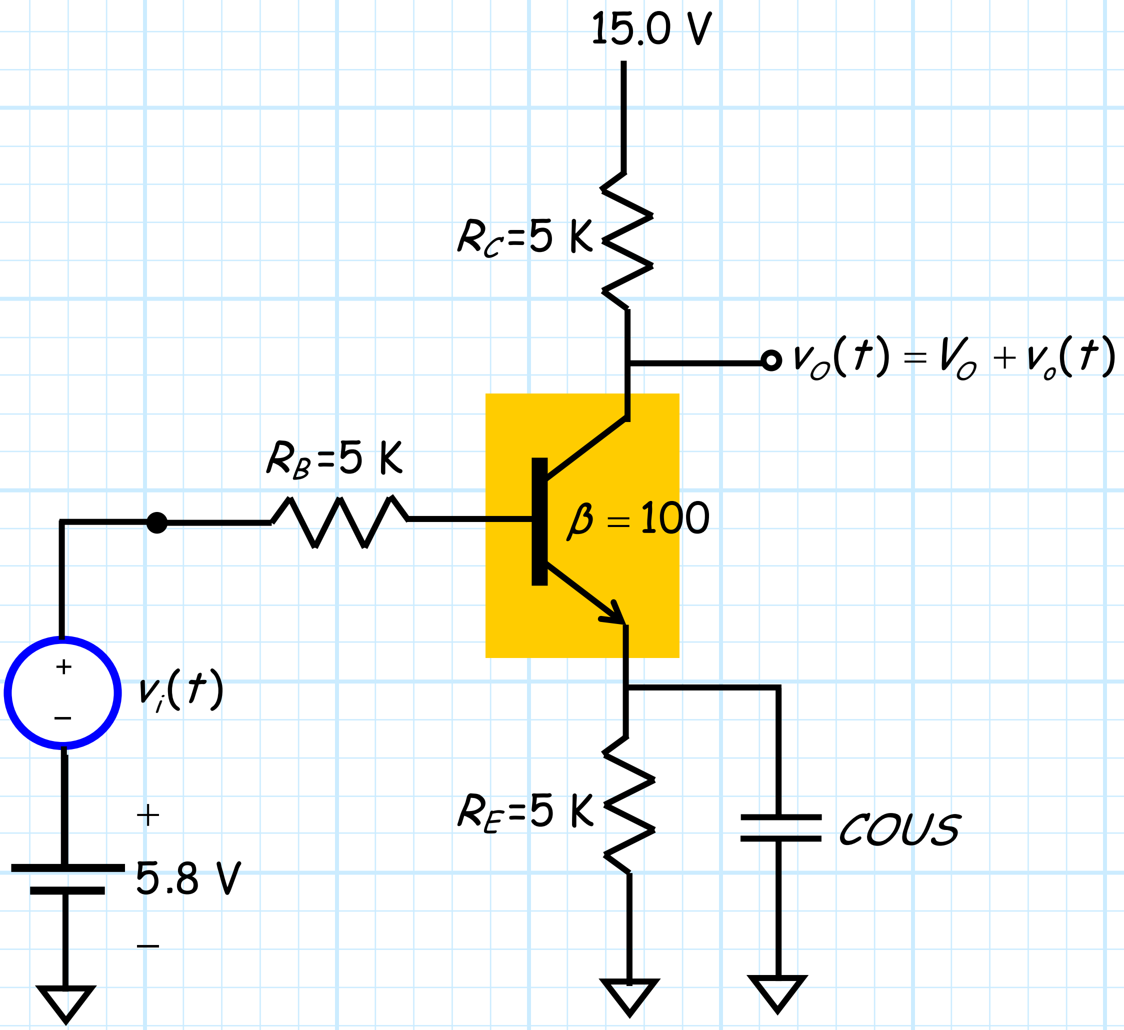
Example: Amplifier Distortion

Recall this circuit from a previous handout:



We found that the small-signal **voltage gain** is:

$$A_{vo} = \frac{v_o(t)}{v_i(t)} = -66.7$$

Say the **input** voltage to this amplifier is:

$$v_i(t) = V_s \cos\omega t$$

Q: *What is the* ***largest*** *value that V_s can take without producing a* ***distorted*** *output?*

A: Well, we know that the **small-signal output** is:

$$\begin{aligned} v_o(t) &= A_{vo}\, v_i(t) \\ &= -66.7 V_s \cos\omega t \end{aligned}$$

BUT, this is **not** the output voltage!

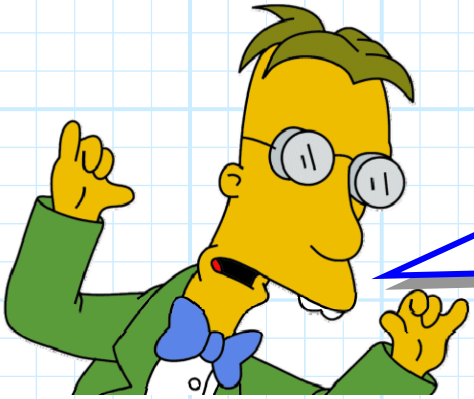
The **total** output voltage is the **sum** of the **small-signal** output voltage and the **DC** output voltage!

Note for this example, the **DC output** voltage is the **DC collector** voltage, and we recall we determined in an earlier handout that its value is:

$$V_O = V_C = 10 \text{ V}$$

Thus, the **total output voltage** is :

$$\begin{aligned} v_O(t) &= V_O + v_o(t) \\ &= 10.0 - 66.7\, V_s \cos\omega t \end{aligned}$$



*It is very important that you realize there is a **limit** on both how high and how low the **total** output voltage $v_O(t)$ can go!*

*That's right! If the **total** output voltage $v_O(t)$ tries to exceed these limits—even for a moment—the BJT will leave the **active** mode.*

*And leaving the active mode results in **signal distortion**!*

Let's break the problem down into **two** separate problems:

1) If **total** output voltage $v_O(t)$ becomes too **small**, the BJT will enter saturation.

2) If **total** output voltage $v_O(t)$ becomes too **large**, the BJT will enter cutoff.

We'll first consider **problem 1**.

For the BJT to remain in active mode, $v_{CE}(t)$ must remain **greater than 0.7** V for all time t (or equivalently $v_{CB}(t) > 0.0$).

From an earlier handout, we know that $V_E = 5.05$ V. The large **capacitor** on the emitter keeps this voltage **constant** with respect to time.

Therefore, the voltage $v_{CE}(t)$ will remain greater than 0.7 V **only** if the collector voltage $v_C(t)$ remains **greater** than $5.05 + 0.7 = 5.75$ V. Note 5.75 is the **base voltage** V_B.

Of course, the collector voltage is also the output voltage ($v_O(t) = v_C(t)$), so that we can conclude that the **output** voltage must remain **larger** than V_B=5.75 V to remain in **active** mode:

$$5.75 < v_O(t) = 10 - 66.7 V_s \cos\omega t$$

In other words, the **lower** limit on the **total** output voltage is:

$$L_- = 5.75\, V$$

Note that we can solve this equation to determine the **maximum** value of small-signal **input** magnitude V_s:

$$\begin{aligned} 5.75 &< 10 - 66.7 V_s \cos\omega t \\ 66.7 V_s \cos\omega t &< 4.25 \\ V_s \cos\omega t &< 0.064 \end{aligned}$$

Since $\cos\omega t$ can be as large as 1.0, we find that the magnitude of the **input** voltage can be **no larger** than 64 mV, i.e.,

$$V_s < 0.064 \text{ V}$$

If the **input** magnitude exceeds this value, the BJT will (momentarily) leave the active region and enter the **saturation** mode!

Now let's consider **problem 2**

For the BJT to remain in **active** mode, the **collector** current must be **greater** than zero (i.e., $i_C > 0$). Otherwise, the BJT will enter **cutoff** mode.

Applying **Ohm's Law** to the collector resistor, we find the **collector current** is:

$$i_C = \frac{V_{CC} - v_O}{R_C} = \frac{15 - v_O}{5}$$

it is evident that collector current is **positive** only if $v_O < 15$ V.

In other words, the **upper** limit on the **total** output voltage is:

$$L_+ = 15.0\,V$$

Since:

$$v_O(t) = 10 - 66.7V_s \cos\omega t$$

we can conclude that in order for the BJT to remain in **active** mode:

$$10 - 66.7V_s \cos\omega t > 15.0$$

Therefore, we find:

$$V_s\cos\omega t > \frac{-5.0}{66.7} = -0.0075$$

Since $\cos\omega t \geq -1$, the above equation means that the **input** signal magnitude V_s can be **no larger** than:

$$V_s < 75 \text{ mV}$$

If the input magnitude **exceeds** 75 mV, the BJT will (momentarily) leave the active region and enter the **cutoff** region!

In **summary**:

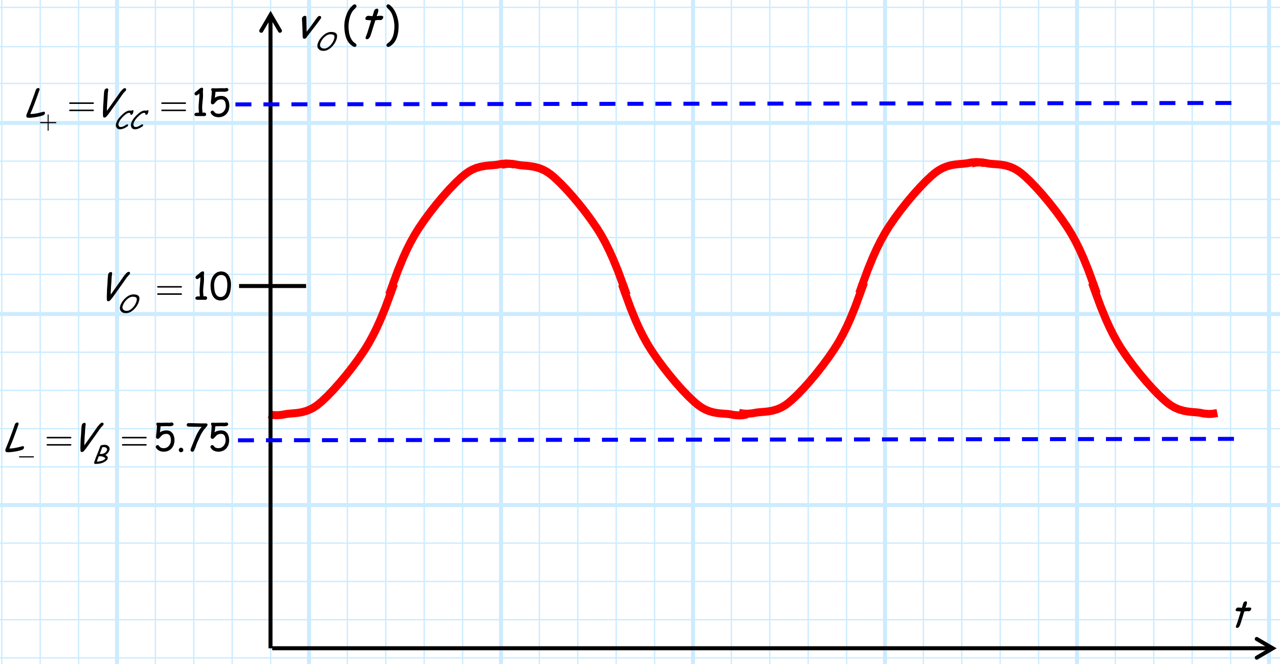
1) If $V_s > 64$ mV, the BJT will at times enter **saturation**, and **distortion** will occur!

2) If $V_s > 75$ mV, the BJT will at times enter **cutoff**, and **even more** distortion will occur!

To demonstrate this, let's consider **three** examples:

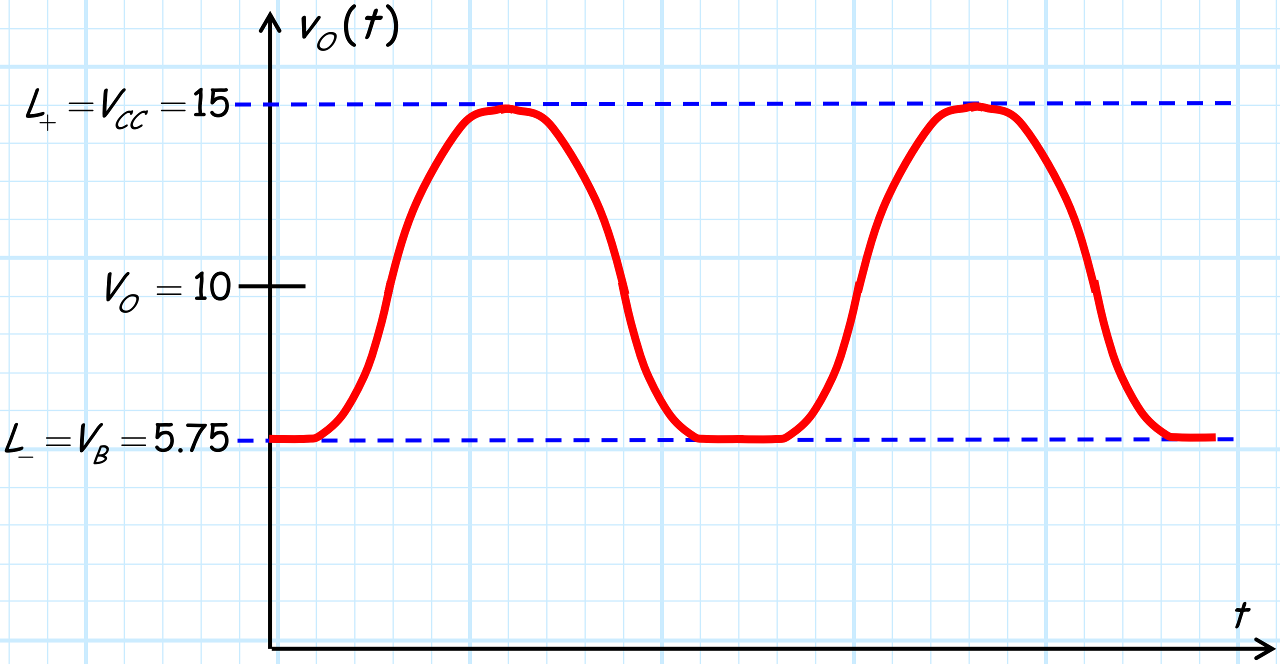
1. $V_s < 64$ mV

The output signal in this case remains between V_{CC}=15.0 V and V_B=5.75 V for **all** time t. Therefore, the output signal is **not distorted**.



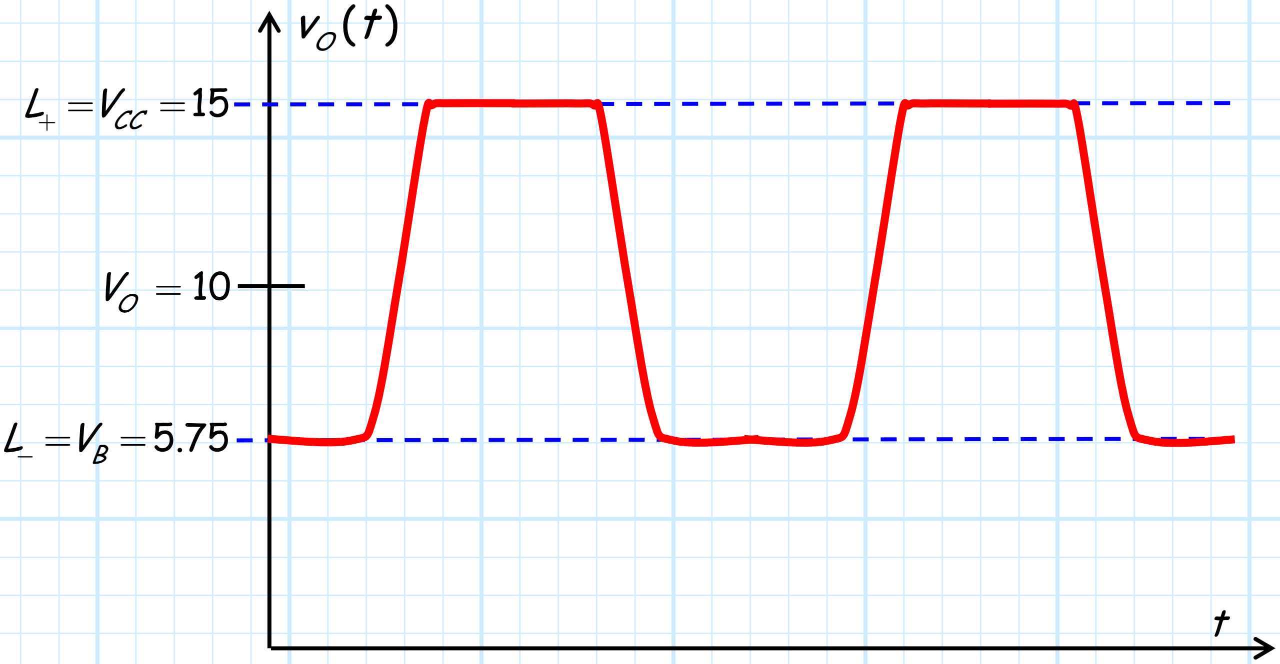
2. 64 mV $< V_s <$ 75 mV

The output signal in this case remains less than V_{CC}=15.0 V for all time t. However, the small-signal output is now large enough so that the total output voltage at times tries to drop **below** $V_B = 5.75\,\text{V}$ (i.e., V_{CE} drops below 0.7 V). For these times, the BJT will enter **saturation**, and the output signal will be **distorted**.



3. $V_s > 75$ mV

In this case, the small-signal input signal is sufficiently **large** so that the total output will attempt to exceed **both** limits (i.e., $V_{CC} = 15.0\,\text{V}$ and $V_B = 5.75\ \text{V}$). Therefore, there are periods of time when the BJT will be in **cutoff**, and periods when the BJT will be in **saturation**.



For a given amplifier voltage gain, you must determine the ***largest possible*** *input $v_i(t)$ that will produce a* ***distortion-free*** *output signal.*

To do this, you must determine the ***limits*** *of the* ***total*** *output voltage. There will be* ***two*** *limits—one for* ***saturation*** *(L_-) and one for* ***cutoff*** *(L_+).*