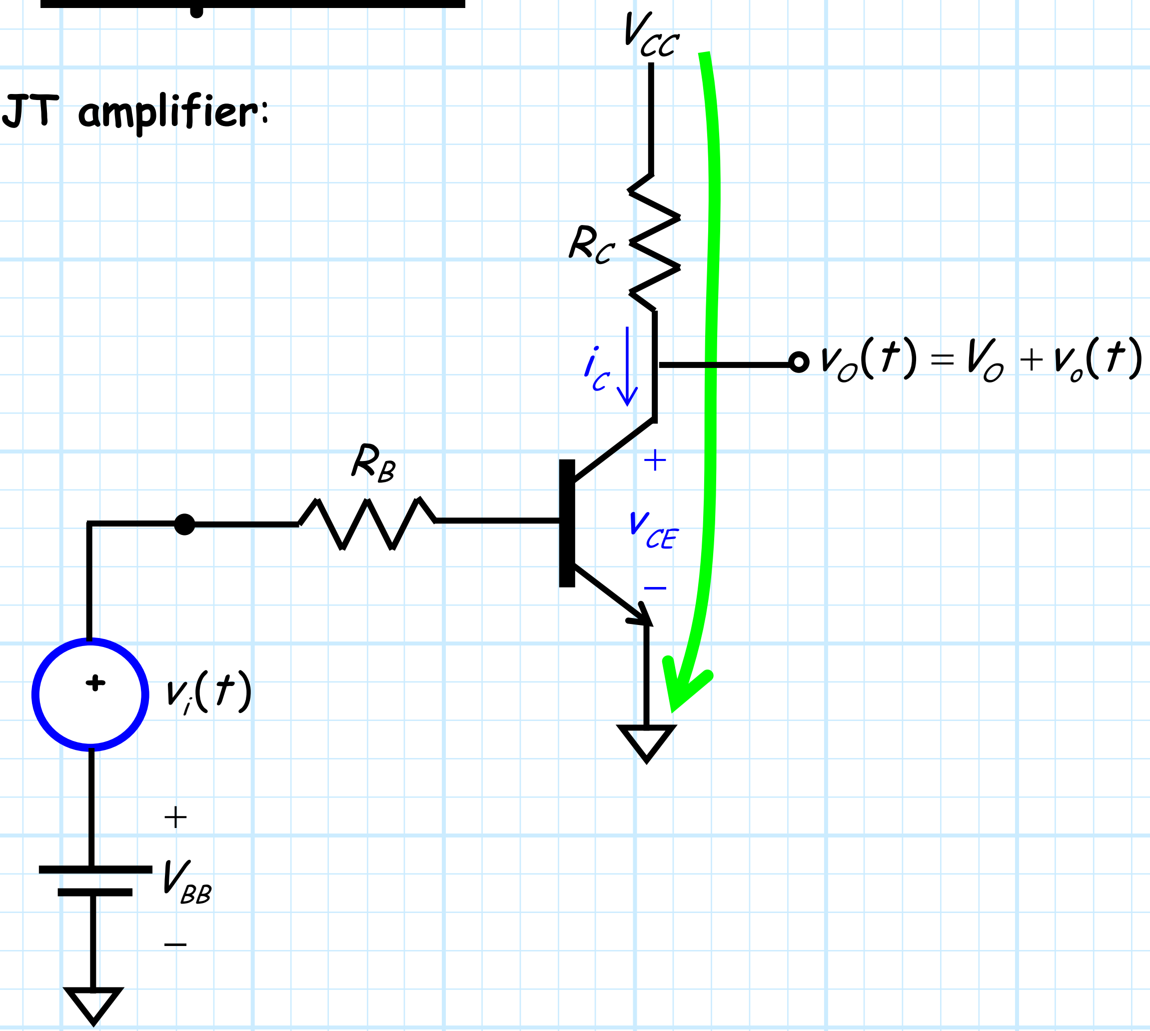
Graphical Analysis of a BJT Amplifier

Consider again this simple **BJT amplifier**:



We note that for this amplifier, the **output** voltage is equal to the **collector-to-emitter** voltage ($v_O(t) = v_{CE}(t)$).

y = m x + b

If we apply **KVL** to the collector-emitter leg, we find:

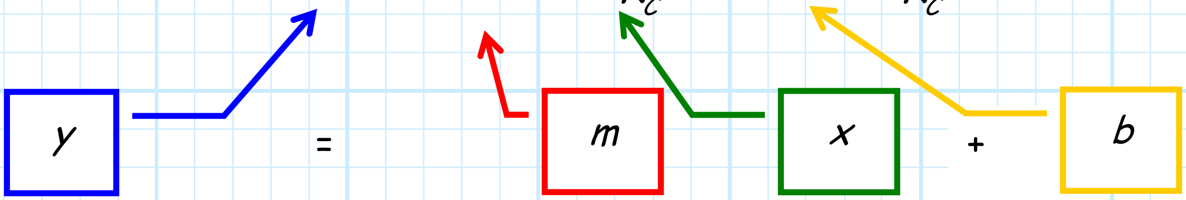
$$V_{CC} - i_C R_C - v_{CE} = 0$$

We can rearrange this to get an expression for the **collector current** i_C in terms of voltage v_{CE} (i.e., $i_C = f\left(v_{CE}\right)$):

$$i_C = \frac{1}{R_C} v_{CE} + \frac{V_{CC}}{R_C}$$

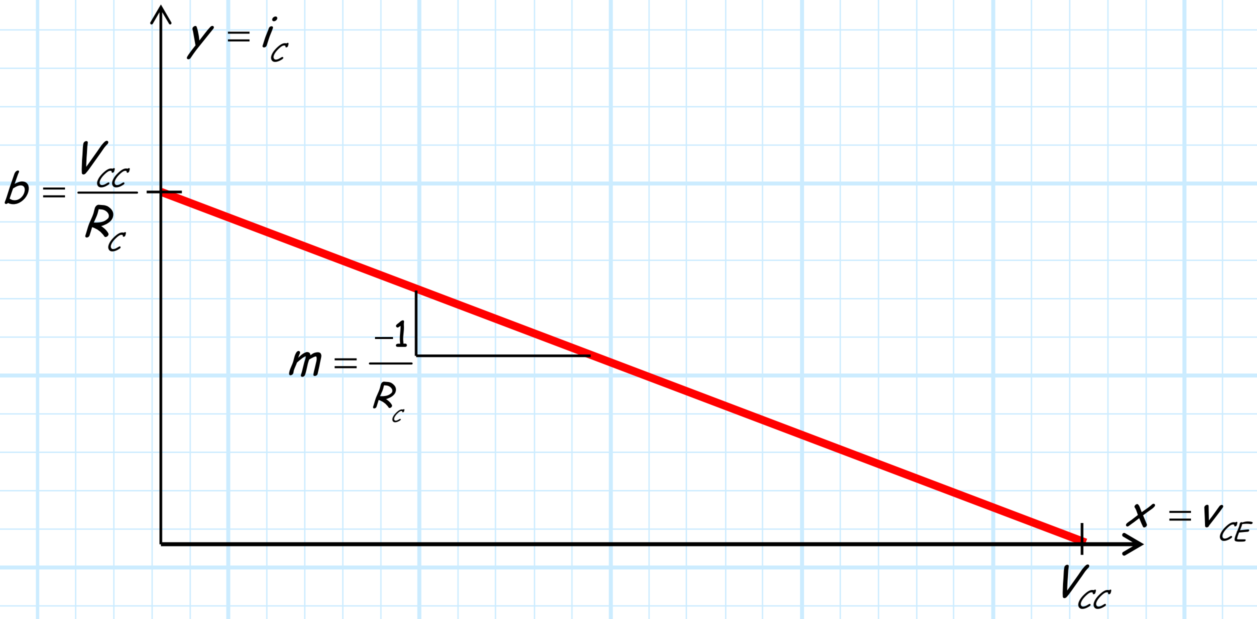
Note this is an equation of a **line**!

$$i_C = \frac{-1}{R_C} \quad v_{CE} \quad + \quad \frac{V_{CC}}{R_C}$$



The load line

This equation is referred to as the amplifier's **load line**, which we can graphically represent as:



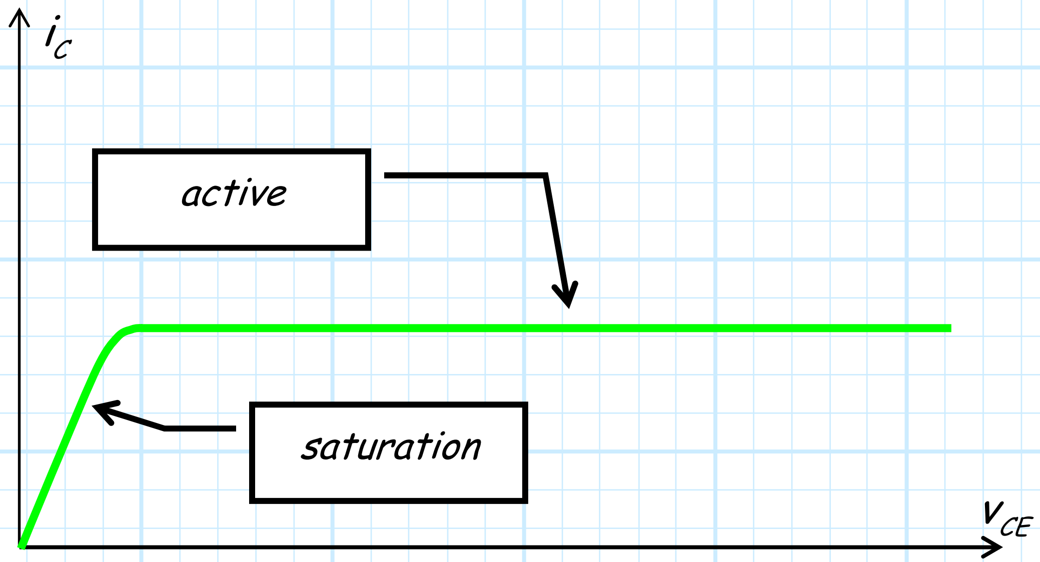
The load line provides the **circuit** relationship (via KVL) between i_C and v_{CE}.

➡ The value of i_C and v_{CE} **must** lie somewhere along the load line!

i_C vs v_{CE} for a BJT

Exactly where on the load line depends on the **device** (BJT) relationship between i_C and v_{CE} .

Recall that this relationship is:

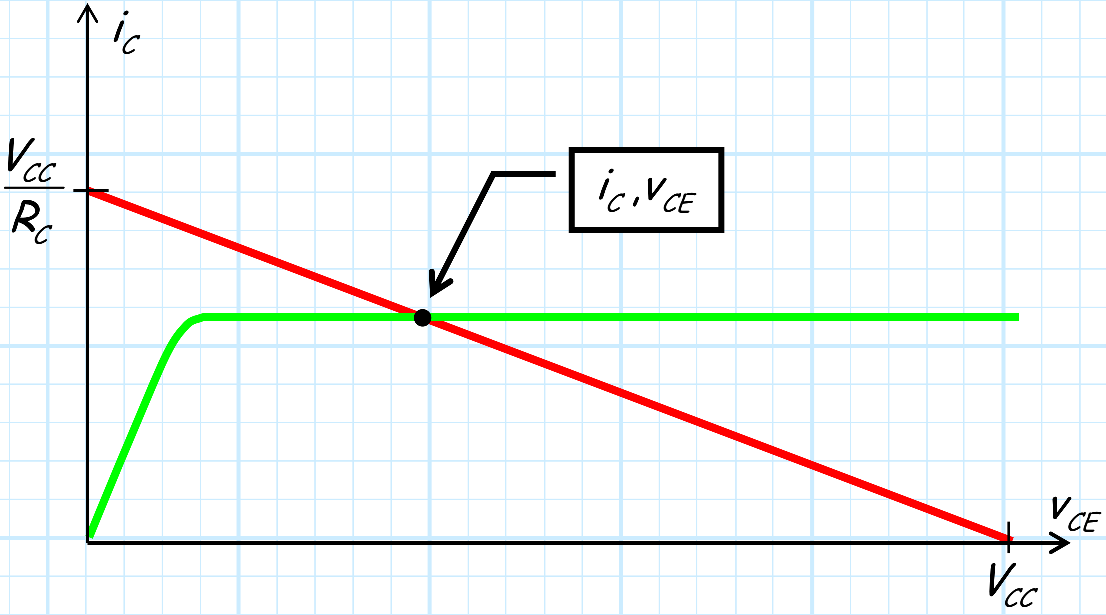


➡ The value of i_C and v_{CE} **must** also lie somewhere along this device curve!

Sort of like the Grandview triangle

Q: *How can the values for i_C and v_{CE}* ***simultaneously*** *be a point on the load line, and a point on the device (BJT) curve?*

A: Easy! the values for i_C and v_{CE} lie at the point where the two curves **intersect**!



But it all depends on the input!

Of course, the values of i_C and v_{CE} depend on the **input** to the amplifier:

$$v_I(t) = V_{BB} + v_i(t)$$

As the voltage $v_I(t)$ changes, so will the values i_C and v_{CE}.

Note, however, that the load line will **not** change—the slope $-1/R_C$ and y-intercept V_{CC}/R_C are **independent** of voltage $v_I(t)$.

What **does** change is the **BJT** relationship between i_C and v_{CE}.

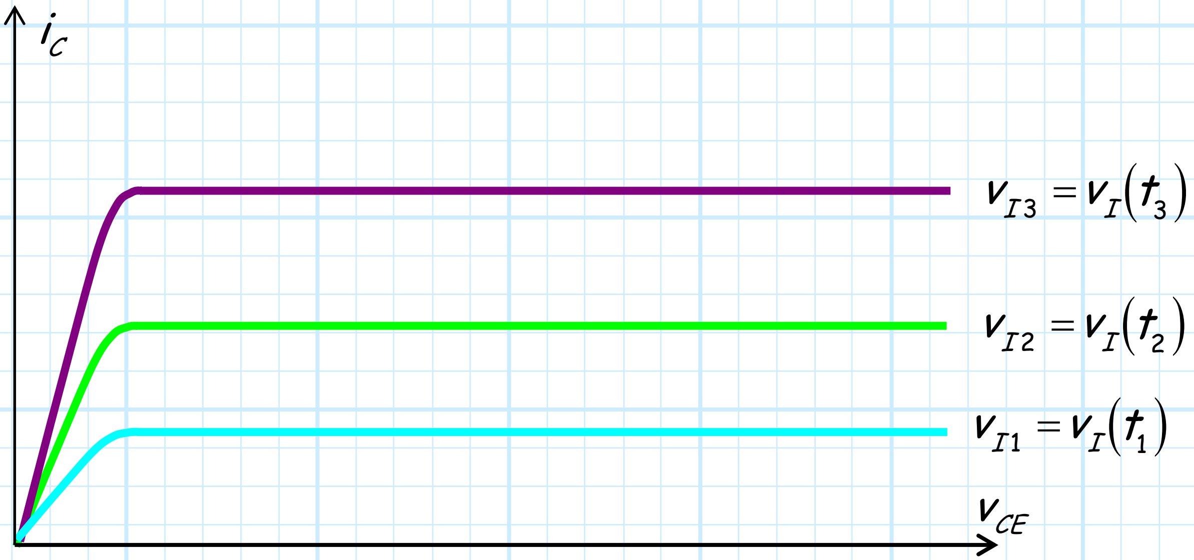
For example, in active mode, the collector current i_C is **independent** of v_{CE} (we're ignoring the Early effect)!

However, the collector current i_C of a BJT **is** dependent on the voltage base-to-emitter v_{BE}.

Thus, as $v_I(t)$ changes, so does v_{BE}, resulting in a **new** BJT relationship (curve) between i_C and v_{CE}.

i_c changes as the input changes

Graphically, we can represent this as:



where V_{I1}, V_{I2}, V_{I3} are three different **input** voltages such that $V_{I1} < V_{I2} < V_{I3}$.

Thus, as the **input** voltage $v_I(t)$ changes with time, the BJT i_C versus v_{CE} **curve** will change, and its **intersection** with the amplifier load line will change—i_C and v_{CE} will likewise be a function of **time**!

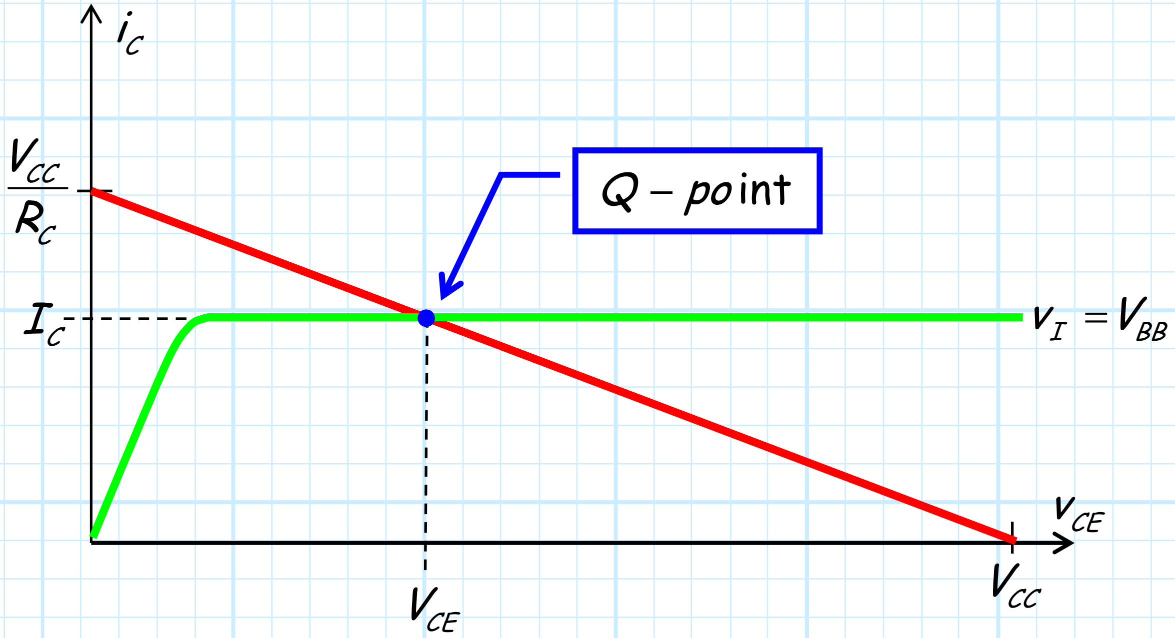
The operating point

Say that the **small-signal** input voltage is **zero** ($v_o(t) = 0$).

In this case, the input voltage is simply a **constant** bias voltage ($v_I(t) = V_{BB}$).

The collector current and voltage collector-to-emitter are likewise **DC bias** values (I_C and V_{CE}).

The intersection of the two curves in this case define the **operating point** (bias point, Q point) of the amplifier.

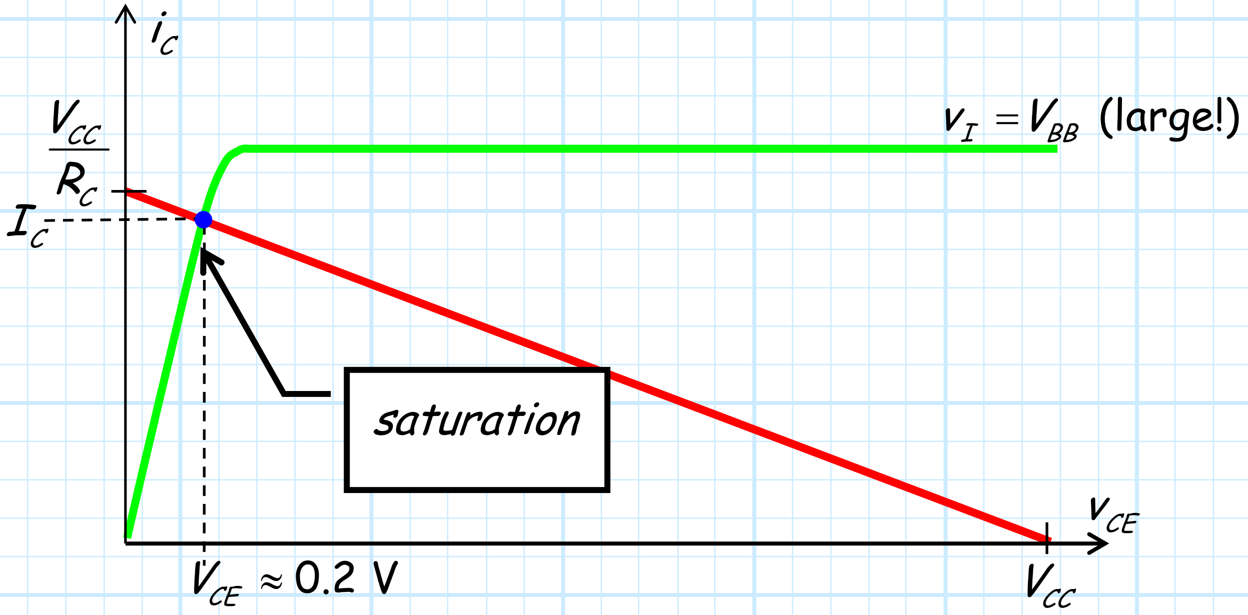


What happens if you make I_B too large

Q: *I see! We know that a **large** DC collector current results in a **large** transconductance g_m—a result that is typically required for **large voltage gain**. It appears that we should make V_{BB} (and thus I_C) as large as possible, **right?***

A: **NO!** There is a **big problem** with making the bias voltage V_{BB} too large—BJT **saturation** will result !

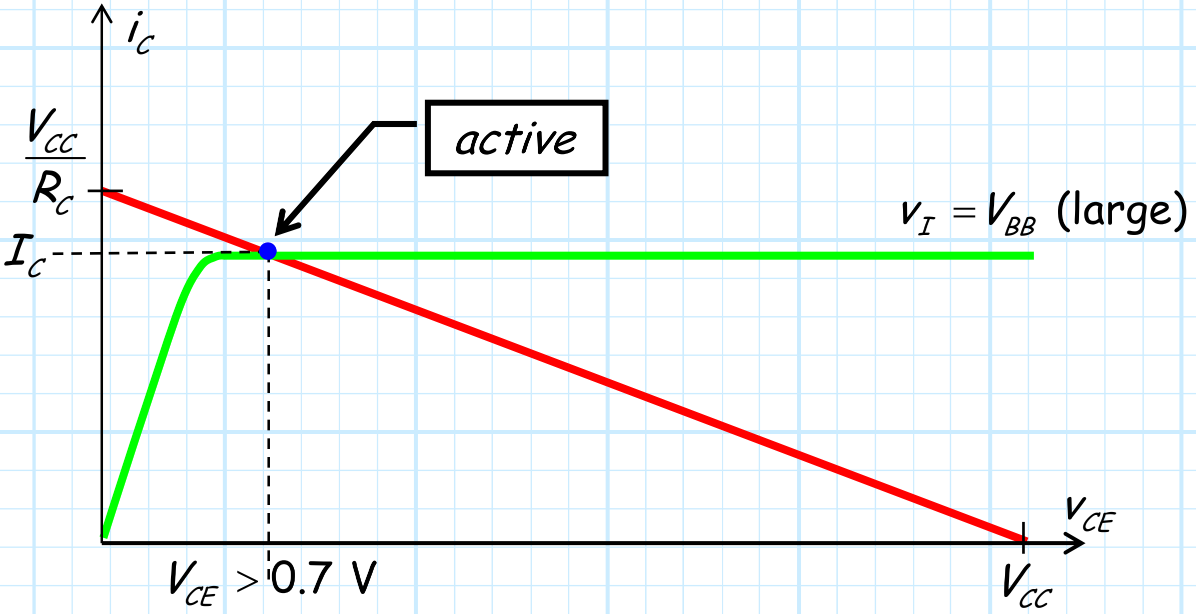
We can **graphically** show this unfortunate occurrence:



There's still a problem

A BJT in **saturation** makes a **poor** amplifier!

Q: *Oh I see! We need to set bias voltage V_{BB} to be large, but* ***not*** *so large that we push the BJT into saturation, right?*



A: **NO!!** There is a **big problem** with this strategy as well!

Remember, it is the **total** input voltage that will determine the BJT curve. If we DC bias the amplifier so that it is **nearly** in saturation, then even a small voltage v_i can "push" the BJT into saturation mode.

A little more than bias; then a little less than bias

For **example**, recall that the small signal input $v_i(t)$ is an **AC** signal. In other words its time averaged (i.e., DC) value is **zero**, meaning that the value of $v_i(t)$ will effectively be **negative** half of the time and positive the other half.

Say then that the **magnitude** of the small signal input is limited to a value Δv_i:

$$|v_i(t)| \leq \Delta v_i$$

So that:

$$-\Delta v_i \leq v_i(t) \leq \Delta v_i \quad \text{for all time } t$$

and thus:

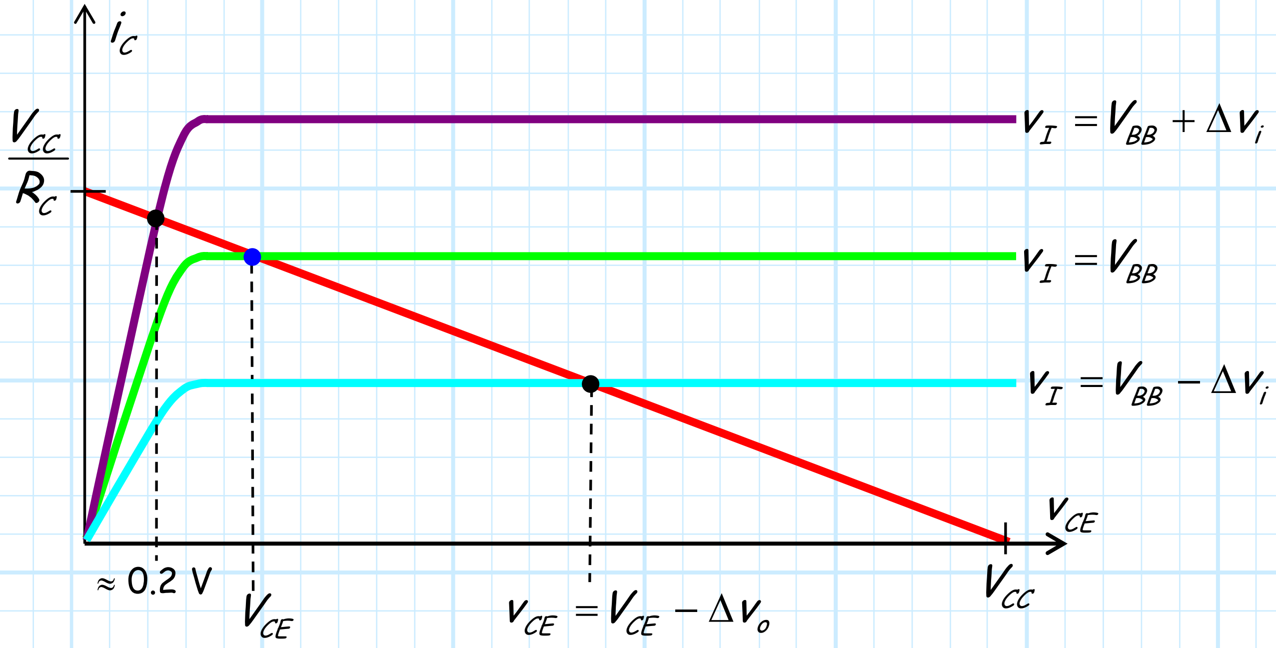
$$V_{BB} - \Delta v_i \leq v_I(t) \leq V_{BB} + \Delta v_i \quad \text{for all time } t$$

Let's now look at **three** scenarios for the small-signal input voltage v_i:

1) $v_i = -\Delta v_i$ **2)** $v_i = 0$ **3)** $v_i = +\Delta v_i$

We're hitting the floor

The resulting **output voltage** will of course be different for each case:



Look what happened here!

If the input small-signal is "large" and **positive**, the **total** input voltage (and thus total v_{BE}) will be **too large**, and thus push the BJT into **saturation**.

Distortion!!!!!!!!

The **output** voltage in this case (when $v_I = V_{BB} + \Delta v_i$) will simply be equal to:

$$v_O(t) \approx 0.2 \quad \text{(BJT saturated)}$$

as opposed to the **ideal** value:

$$v_O(t) = V_{CE} + \Delta v_o \quad \text{(BJT active)}$$

where $\Delta v_o = A_{vo} \, \Delta v_i$. Note for this amplifier, the small-signal voltage gain A_{vo} is **negative**, so that the value Δv_o is **also** negative:

$$\Delta v_o = A_{vo} \, \Delta v_i < 0$$

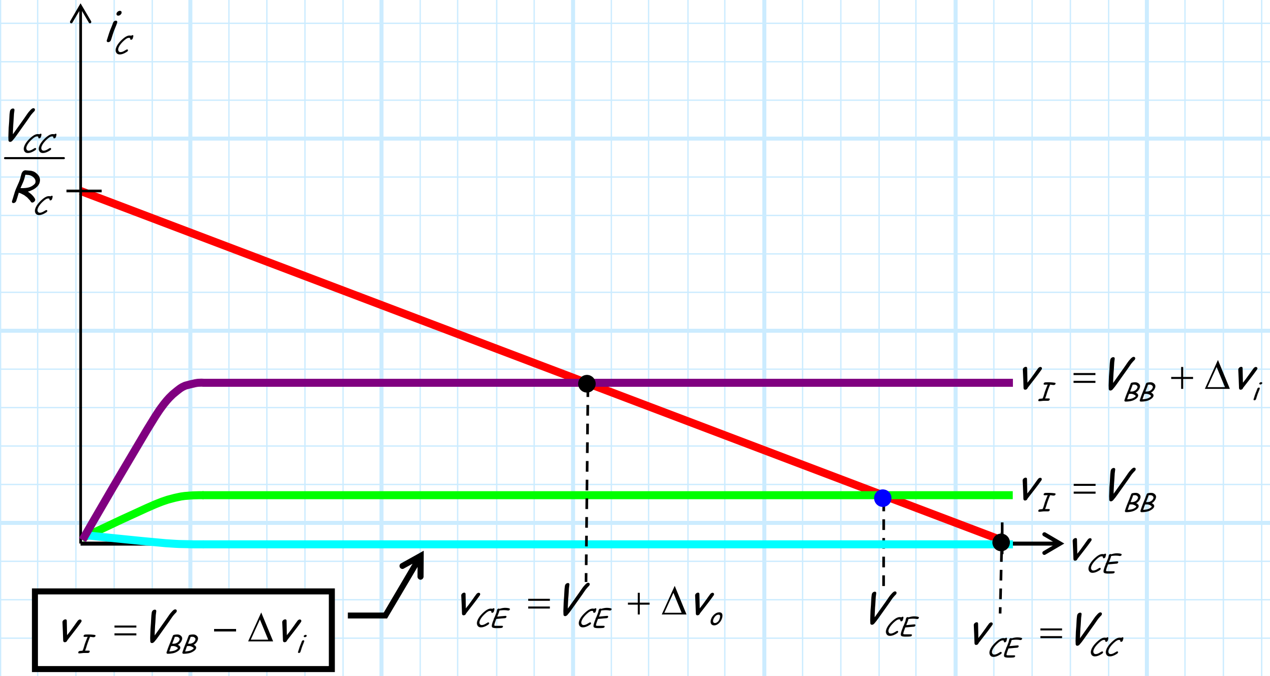
Since the BJT is in saturation during some portion of $v_i(t)$, the amplifier output signal will **not** look like the input signal—**distortion** will result!

I never said this was easy

Q: *Now I get it! We need to make V_{BB}* ***small****, so that the BJT does* ***not*** *enter saturation, and the output signal is* ***not*** *distorted!*

A: **NO!!** There is a **problem** with this too!

We can again **graphically** examine what happens if we make the bias voltage V_{BB} too **small**.



Look what happened here!

Now we're hitting the ceiling

If the **input** small-signal is "large" and **negative**, the **total** input voltage (and thus total v_{BE}) will be too **small**, and thus push the BJT into **cutoff**.

Note the collector current will be **zero** ($i_C = 0$) when the BJT is in cutoff!

The **output** voltage in this case (i.e., when $v_I = V_{CE} - \Delta v_i$) will simply be equal to:

$$v_O(t) = V_{CC} \quad \text{(BJT cutoff)}$$

as opposed to the **ideal** value:

$$v_O(t) = V_{CE} - \Delta v_o \quad \text{(BJT active)}$$

where $\Delta v_o = A_{vo}\, \Delta v_i$. Note for this amplifier, the small-signal voltage gain is **negative**, so that the value $-\Delta v_o$ is **positive**.

Since the BJT is in **cutoff** during some portion of $v_i(t)$, the amplifier output signal will **not** look like the input signal—**distortion** will result!

What do we do?

Q: *Yikes! Is there **nothing** we can do to avoid signal distortion?*

A: To get allow for the **largest** possible (distortion-free) output signal $v_o(t)$, we typically need to bias our BJT such that we are about **"half way"** between biasing the BJT in **saturation** and biasing the BJT in **cutoff**.

Note if the BJT is in **saturation**:

$$i_C \approx \frac{V_{CC}}{R_C}$$

$$v_{CE} \approx 0.2 \text{ V}$$

(BJT saturation)

Bias in the middle

Whereas, if it is in **cutoff**:

$$i_C = 0 \qquad \qquad v_{CE} = V_{CC} \qquad \text{(BJT cutoff)}$$

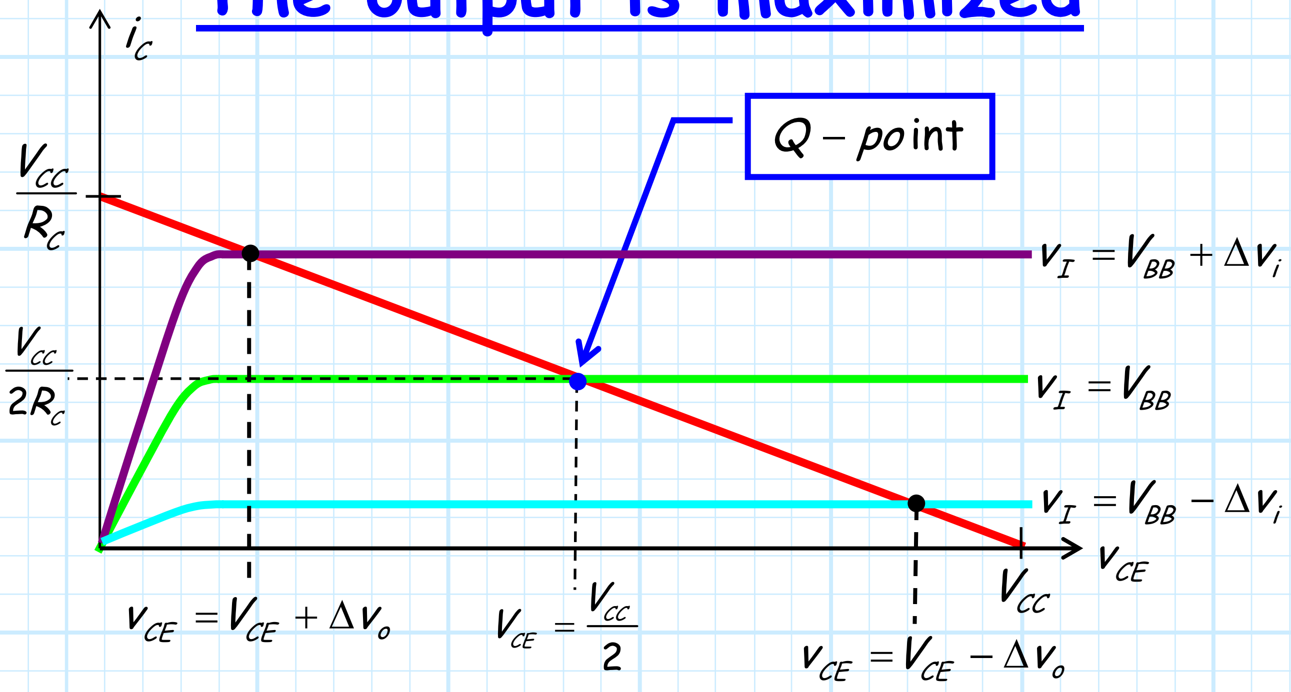
It is evident that for this particular amplifier, biasing **"half-way"** between saturation and cutoff means biasing such that:

$$V_{CE} \approx \frac{V_{CC}}{2}$$

or equivalently:

$$I_C \approx \frac{V_{CC}}{2R_C}$$

The output is maximized



The bias solution above is optimal for **this** particular amplifier design. **Other** amplifier designs will result in **other** optimal bias designs—it is up to **you** determine what they are.

Remember, the **total** voltage $v_{CE}(t)$ must be larger than 0.7 V for all time; otherwise **saturation** (and thus signal distortion will result).

Likewise, the **total** collector current $i_C(t)$ must be greater than zero for all time; other wise **cutoff** (and thus signal distortion) will result.