5.7 Single Stage BJT Amplifiers

Reading **Assignment**: 460-485

Small signal BJT amplifiers typically can be classified as one of three types.

Each type has its own specific characteristics, and thus each type has its own specific uses!

First, we consider the common-emitter amplifier:

HO: THE EMITTER CAPACITOR: WHAT'S UP WITH THAT?

Next, the common collector amplifier—otherwise known as the emitter follower.

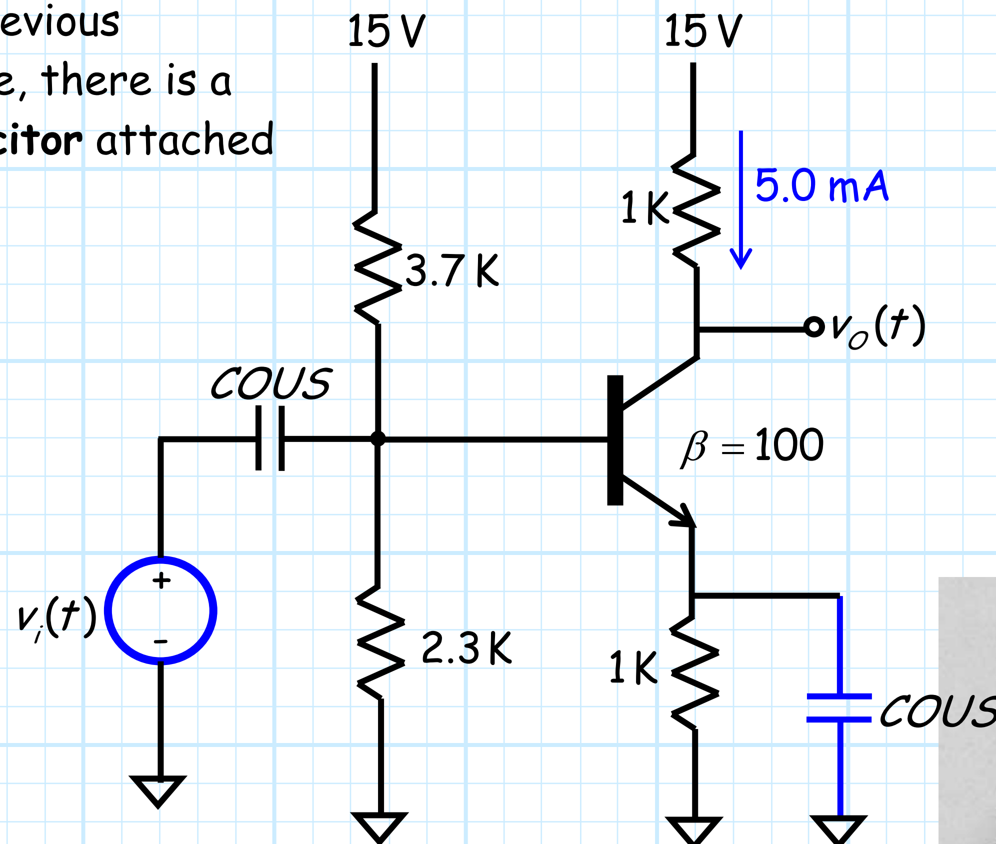
HO: THE COMMON-COLLECTOR AMPLIFIER

Finally, the common-base amplifier:

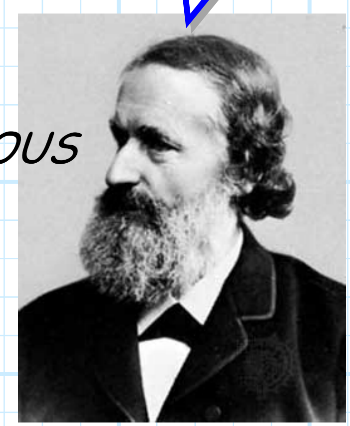
HO: THE COMMON-BASE AMPLIFIER

The Emitter Capacitor: What's up with that?

Note that in a previous amplifier example, there is a **mysterious capacitor** attached to the emitter:



Q: ***Why*** *is this big capacitor here? Is it really required?*



A: Let's do a **small-signal** analysis and see **why** we place this large capacitor at the emitter.

Let's analyze this amplifier!

Step 1 - *DC Analysis*

This is **already** completed! Recall that we **designed** the single supply DC bias circuit such that:

$$I_C = 5 \text{ mA}$$

and

$$V_{CE} = 5.0 > 0.7 \checkmark$$

Step 2 - *Calculate the BJT small-signal parameters*

If we apply the **hybrid-π** model, we will require the small signal parameters:

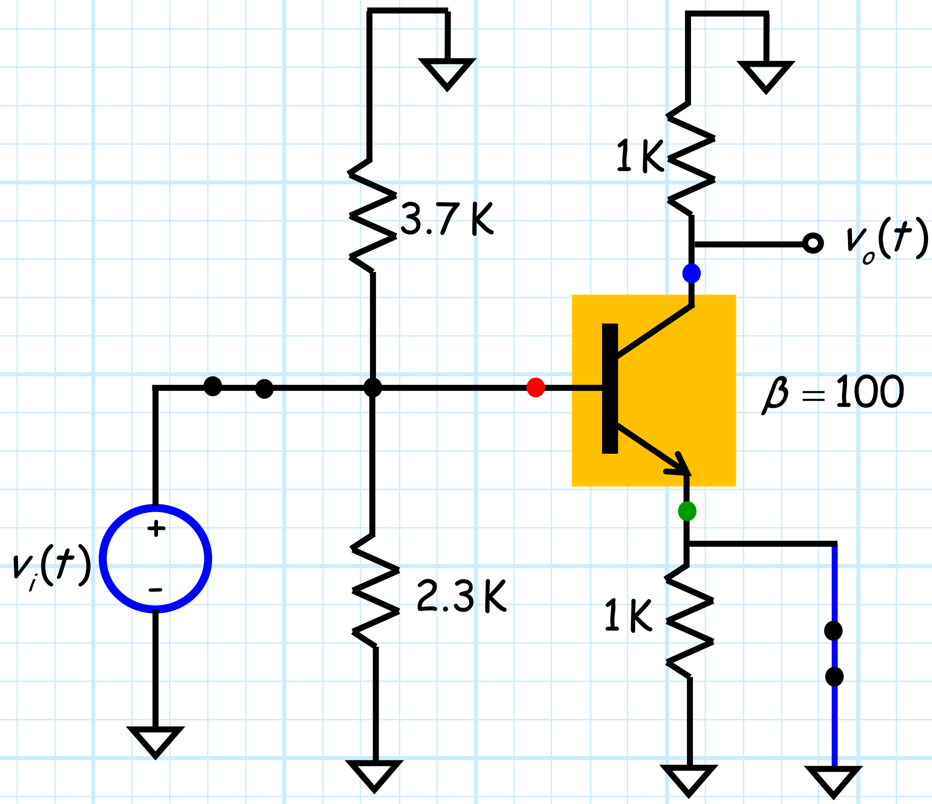
$$g_m = \frac{I_C}{V_T} = \frac{5 \text{ mA}}{0.025\text{V}} = 200 \text{ mA/V}$$

$$r_\pi = \frac{V_T}{I_B} = \frac{\beta V_T}{I_C} = \frac{100(0.025)}{5.0} = 0.5 \text{ K}$$

This is step 3…

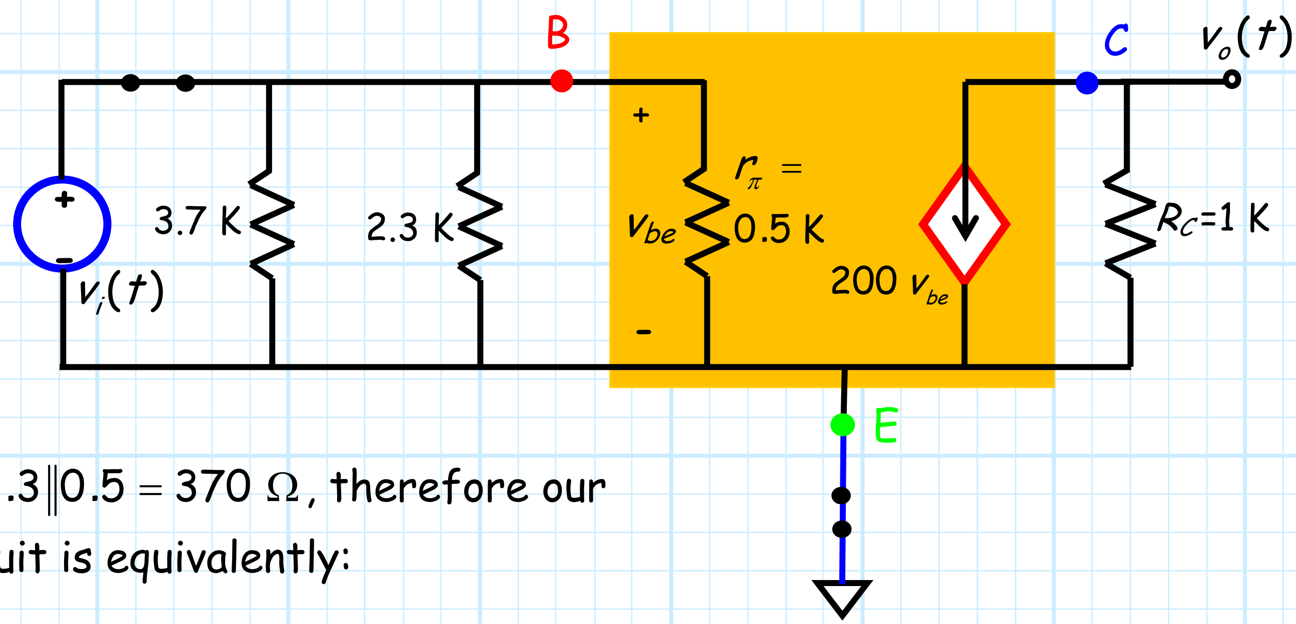
Steps 3 and 4 – *Replace the BJT with its small-signal equivalent circuit , and turn off all DC sources.*

Tuning off the DC sources, and replacing the **C**apacitors **O**f **U**nusual **S**ize with **short** circuits, we find that the circuit becomes:

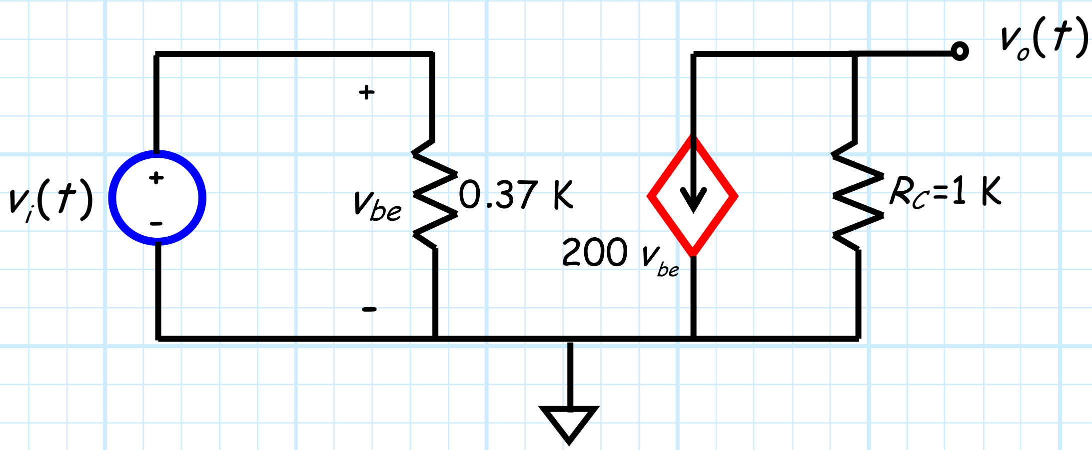


...and this is step 4

Now carefully replace the BJT with its small-signal model:



Note that $3.7 \| 2.3 \| 0.5 = 370\ \Omega$, therefore our small-signal circuit is equivalently:



A hefty gain

Step 5 - *Analyze the small-signal circuit.*

Since for **this** circuit $v_{be} = v_i$ and $v_o = -(1)200 v_{be}$, the open-circuit, small-signal **voltage gain** of this amplifier is:

$$A_{vo} = \frac{v_o}{v_i} = \frac{-200 v_{be}}{v_{be}} = -200$$

Likewise, we can find that the small-signal **input** and **output resistances** are:

$$R_{in} = 370\Omega$$

and

$$R_{out} = 1.0 \text{ K}$$

Note that the gain in this case is fairly **large**—46 dB.

Still, what's up with the capacitor?

Q: *I still don't understand why the* ***emitter capacitor*** *is required.*

Sure, our amplifier has large voltage ***gain****, but I don't see how a* ***capacitor*** *could be responsible for* ***that****.*

A: To see why the emitter capacitor is important, we need to compare these results to those obtained if the **emitter capacitor is removed**.

Note that if we **remove** the emitter capacitor, the first **two** steps of the small-signal analysis remains the **same**—the DC **operating point** is the same, and thus the small-signal **parameters** remain unchanged.

However, this does **not** mean that our resulting small signal **circuit** is left unchanged!

The emitter resistor is not "shorted out"!

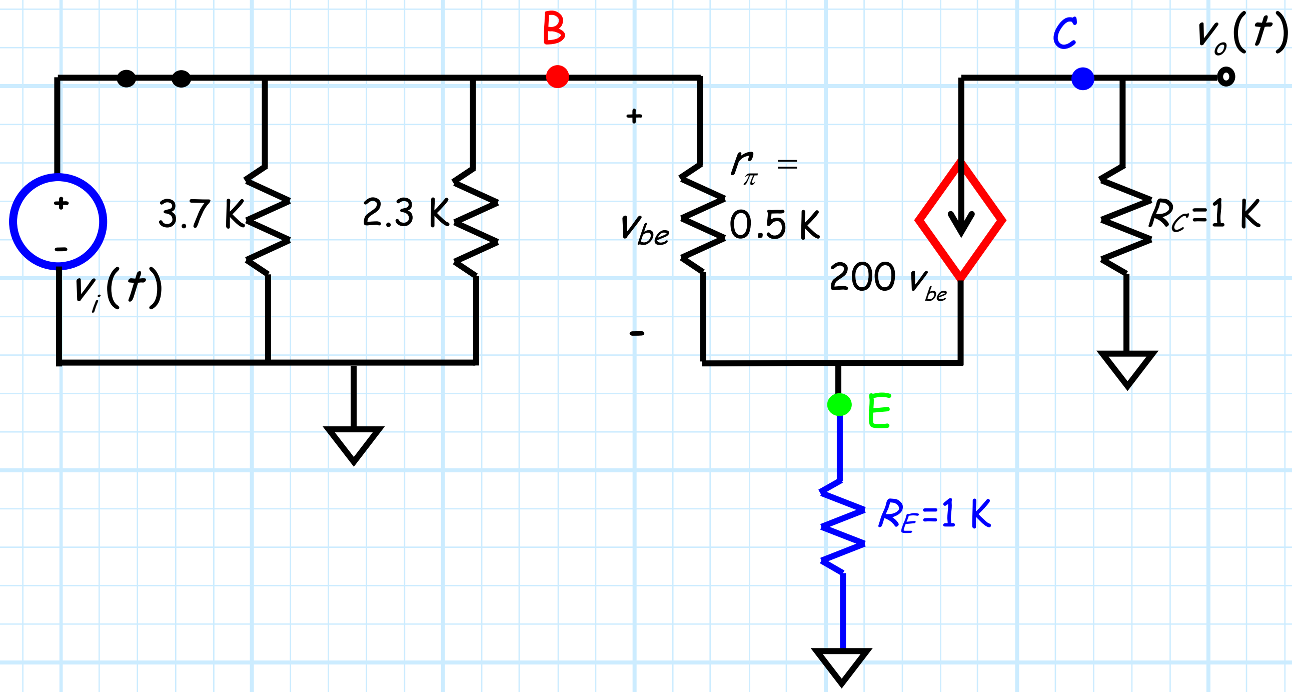
* Recall that **large** capacitors (COUS) are approximated as *AC* **shorts** in the small-signal circuit.

* The emitter capacitor thus "shorts out" the emitter resistor in the small-signal circuit—the BJT **emitter** is connected to small-signal **ground**.

* If we remove the emitter capacitor, the emitter resistor is **no longer** shorted, and thus the BJT emitter is **no longer** connected to ground!

A horse of an entirely different color

The small-signal circuit in this case is:

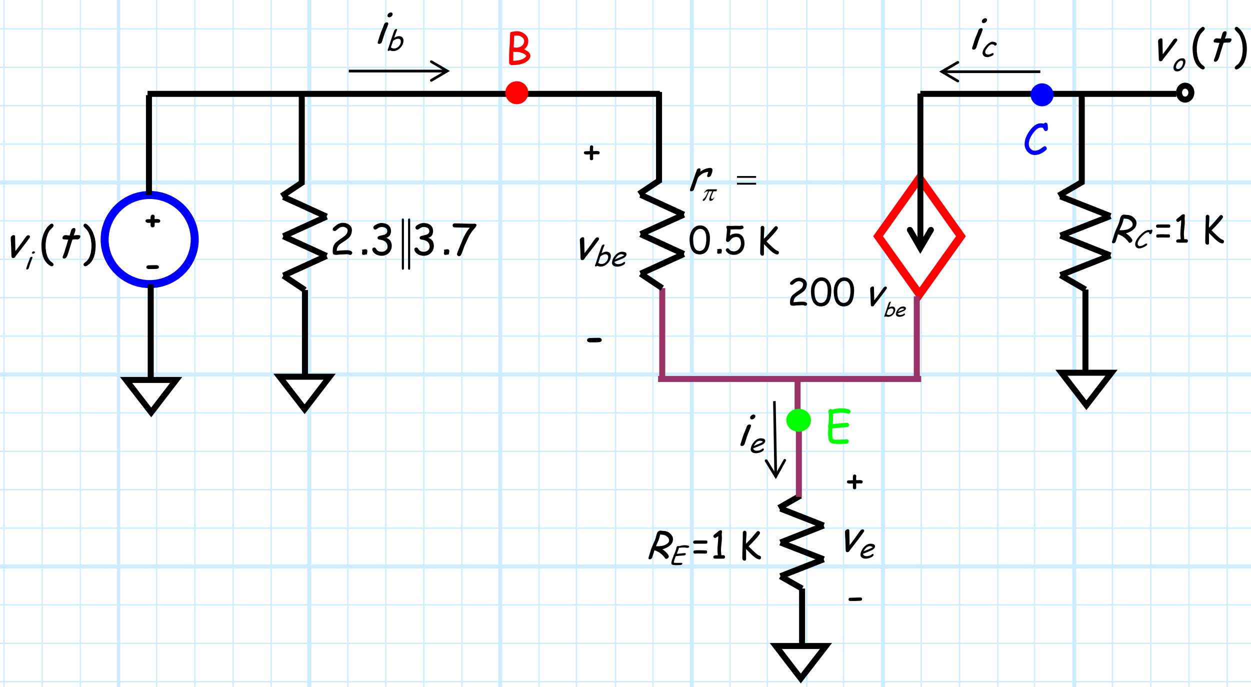


Note that the resistors $R_1 = 3.7$ K and $R_2 = 2.3$ K are **no longer** in parallel with base resistance $r_\pi = 0.5$ K!

As are result, we find that small signal voltage v_{be} is **not** equal to small signal input voltage v_i.

This circuit—it's harder

Note also that the collector resistor is **not** connected in parallel with the dependent current source!



Analyzing **this** small-signal circuit is not so easy!

We first need to determine the small signal **base-emitter** voltage v_{be} in terms of **input** voltage v_i.

Start with KCL

From **KCL**, we know that:

$$i_e = i_b + i_c$$

Where:

$$i_e = \frac{v_e}{R_E} = \frac{v_e}{1} = v_e$$

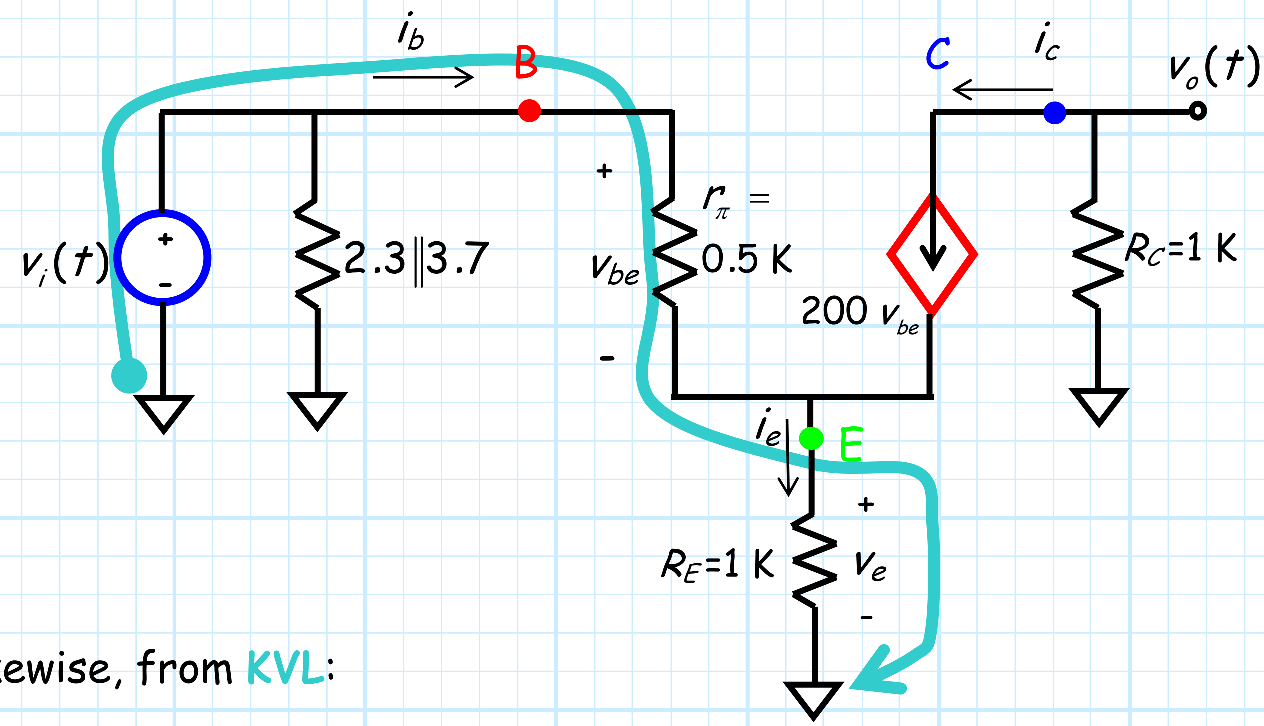
$$i_b = \frac{v_{be}}{r_\pi} = \frac{v_{be}}{0.5} = 2.0\, v_{be}$$

$$i_c = 200\, v_{be}$$

Therefore:

$$v_e = 2.0\, v_{be} + 200\, v_{be} = 202\, v_{be}$$

And now for KVL



Likewise, from KVL:

$$0 + v_i - v_{be} - v_e = 0$$

$$\Rightarrow \quad v_{be} = v_i - v_e$$

This is NOT voltage division!

Inserting this into the first **KCL** result:

$$\begin{aligned} v_e &= 202\, v_{be} \\ &= 202\, v_i - 202\, v_e \end{aligned}$$

And now solving for small-signal emitter voltage:

$$v_e = \frac{202}{203} v_i$$

Note that the small-signal base voltage is **not** related to the small signal input voltage by **voltage division**, i.e.:

$$v_e \neq \frac{R_E}{r_\pi + R_E} v_i = \frac{1}{1.5} v_i \quad !!!$$

v_{be} is really small!

Therefore, we can **finally** determine v_{be} in terms of input voltage v_i:

$$v_{be} = v_i - v_e = v_i - \frac{202}{203} v_i = \left(1 - \frac{202}{203}\right) v_i = \frac{v_i}{203}$$

Note then that not only is $v_{BE} \neq v_i$, the small-signal base-emitter voltage is **much smaller** than input voltage v_i!

This of course is evident from the relationship:

$$v_e = \frac{202}{203} v_b = \frac{202}{203} v_i$$

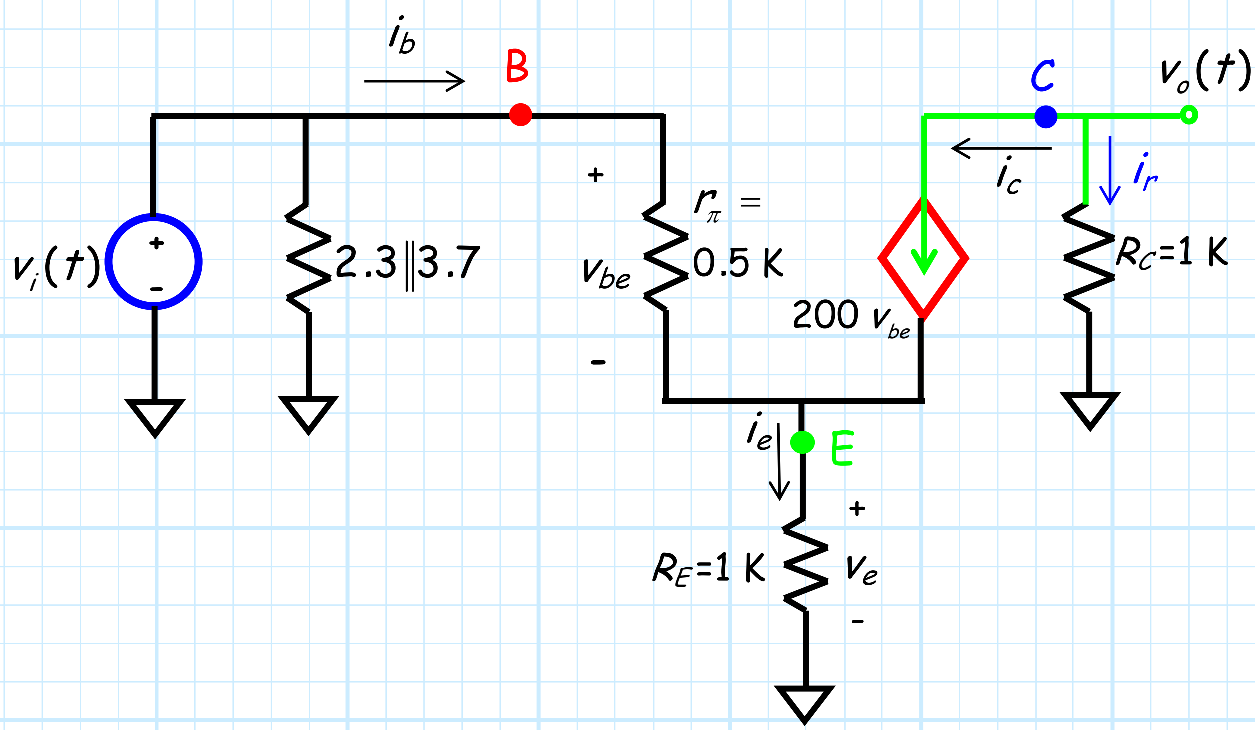
which states that the emitter voltage is **approximately equal** to the base (input) voltage v_b (v_i).

Now for the output voltage

This result will have a **profound** impact on amplifier performance!

To determine the output voltage, we begin with **KCL**:

$$i_r = -i_c = -200\, v_{be}$$



What a wimpy gain

Now applying Ohm's Law to R_C:

$$\frac{v_o - 0}{R_C} = \frac{v_o}{1} = i_r = -200\, v_{be} \qquad \Rightarrow \qquad v_o = -200\, v_{be}$$

But recall that:

$$v_{be} = \frac{v_i}{203}$$

so we find that the small-signal **output voltage** is:

$$v_o = -200\ v_{be} = -\frac{200}{203}\, v_i$$

And thus the open-circuit **voltage gain** of this amplifier is:

$$A_{vo} = \frac{v_o}{v_i} = -\frac{200}{203} \approx -1.0$$

See, the emitter capacitor is important

Yikes! Removing the emitter capacitor cause the voltage gain to change from –200 (i.e., 46 dB) to approximately –1.0 (i.e., 0dB)—a ***46 dB reduction****!*

That emitter capacitor makes a **big** difference!

We can likewise finish the analysis and find that the small-signal input and output **resistances** are:

$$R_{in} \approx R_1 \| R_2 = 3.7 \| 2.3 = 1.42 \text{ K}$$

$$R_{out} = 1.0 \text{K}$$

Note that **input** resistance actually **improved** in this case, increasing in value from 370 Ω to 1.42 KΩ.

However, the decrease in voltage gain makes this amplifier (without a emitter capacitor) almost completely **useless**.

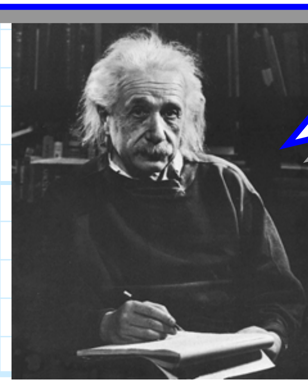
He only knows this because your TA explained it to him

*The amplifier in this case (with the emitter capacitor) is an example of a design known as a **common-emitter** amplifier.*

*There are an infinite number of common-emitter designs, but they all share one thing in common—the **emitter** of the BJT is **always** connected directly to **small-signal ground**.*

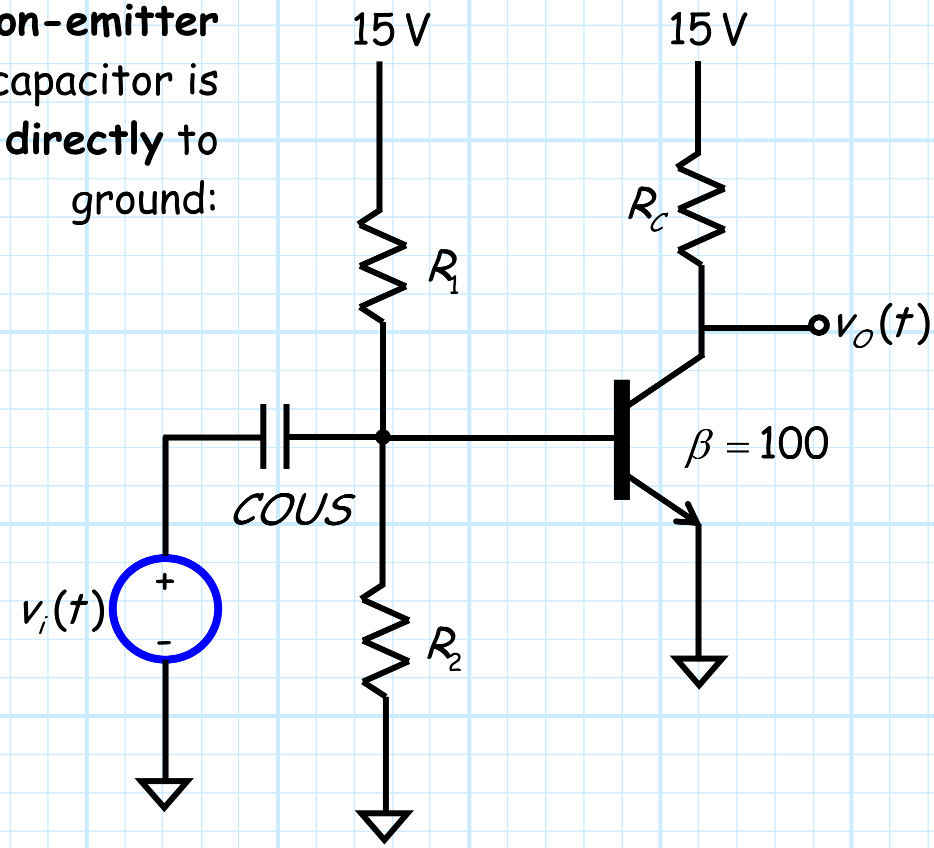
*Common-emitter amplifier, such as the one examined here, typically result in **large** small-signal **voltage gain** (this is **good**!).*

*However, **another** characteristic of common emitter amplifiers is a typically **low** small-signal **input** resistance and high small-signal output resistance(this is **bad**!).*



Make sure you can answer this question

One way to construct a **common-emitter** amplifier **without** using an emitter capacitor is simply to connect the BJT emitter **directly** to ground:



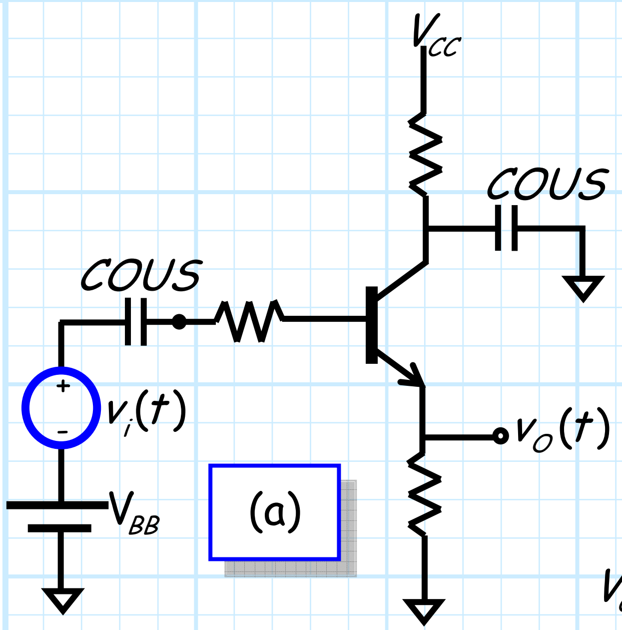
In this case, the emitter is at **both** AC (small-signal) ground and DC ground!

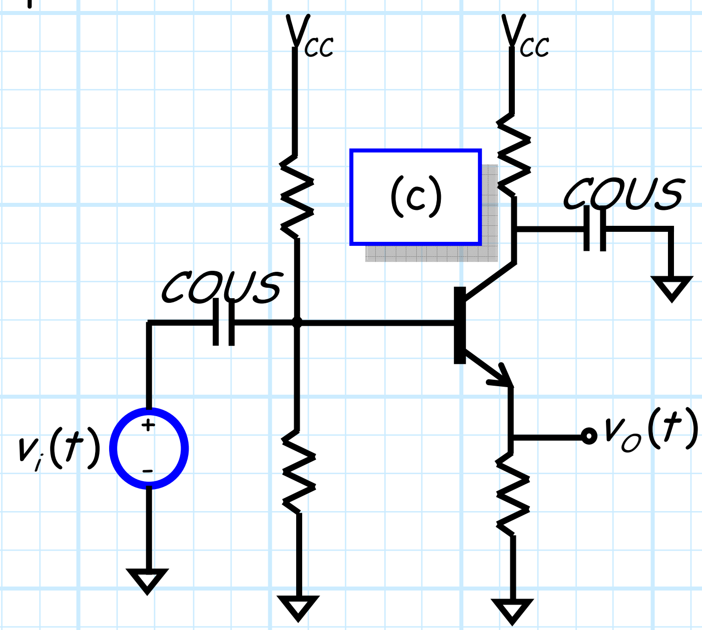
Q: *Why is this common-emitter design **seldom** used??*

A:

The Common-Collector Amplifier

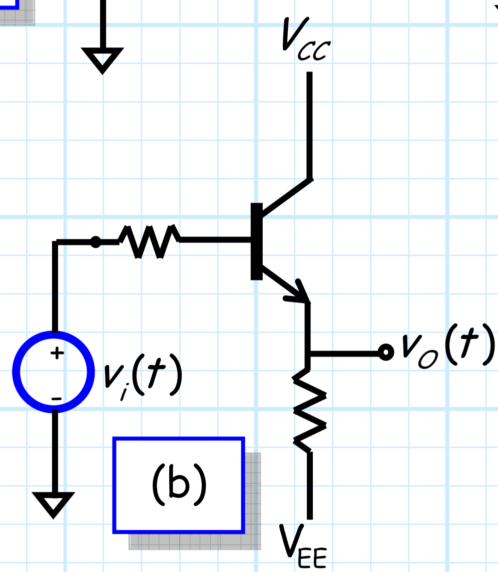
The **common-collector** amplifier: the BJT **collector** is at small-signal **ground**! Examples of this type of amplifier include:

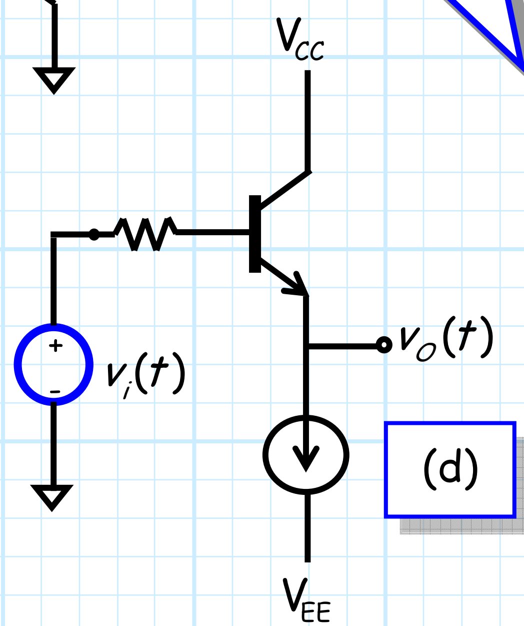




*Do **you** see **why** each of these four circuits is a gul-durn **common-collector** amplifier?*

*Make **dang** sure that you do!*



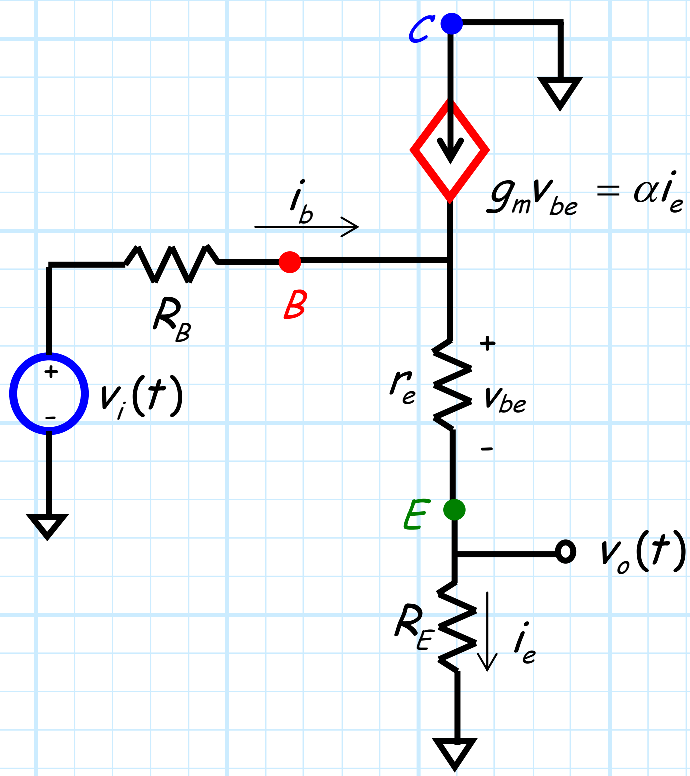


We'll use the T-model

Let's consider **circuit (a)**.

It turns out that for **common-collector** amplifiers, the **T-model** (as opposed to the hybrid-π) typically provides the **easiest** small-signal analysis.

Using the **T-model**, we find that the **small-signal circuit** for amplifier (a) is:



Let's analyze this amplifier!

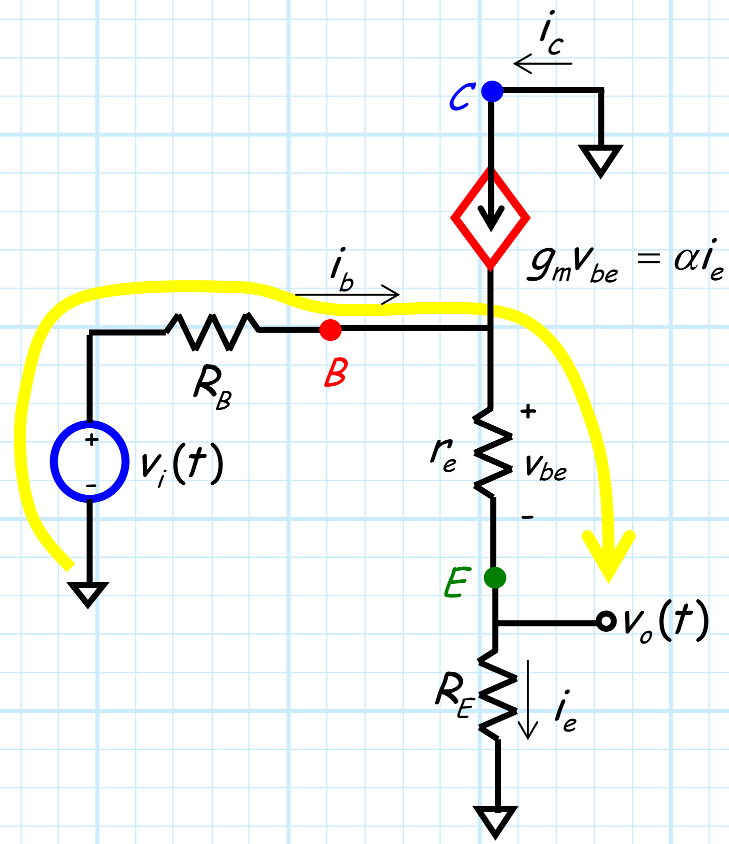
Let's determine the open-circuit voltage gain of this small-signal amplifier:

$$A_{vo} = \frac{v_o^{oc}}{v_i}$$

We therefore must determine the output voltage v_o in terms of input voltage v_i

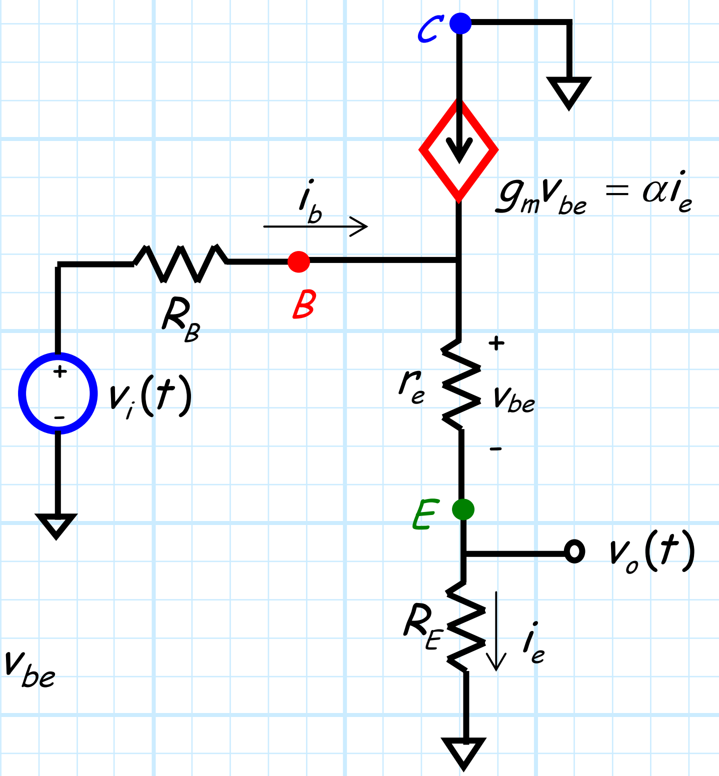
From **KVL**, we find that:

$$0 + v_i - R_B\, i_b - v_{be} = v_o$$



Let's apply KCL!

And from **KCL**, we find:



$$\begin{aligned} i_b &= i_e - i_c \\ &= i_e - g_m v_{be} \end{aligned}$$

Where from Ohm's Law:

$$i_e = \frac{v_o - 0}{R_E} = \frac{v_o}{R_E}$$

So:

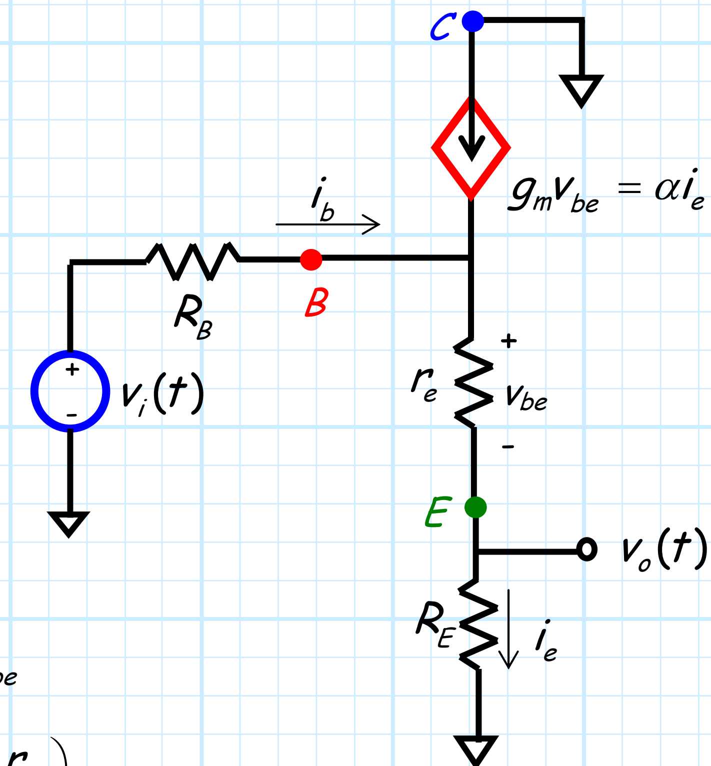
$$i_b = i_e - g_m v_{be} = \frac{v_o}{R_E} - g_m v_{be}$$

Inserting this into the **KVL** equation above:

$$\begin{aligned} v_o &= v_i - R_B\, i_b - v_{be} \\ &= v_i - R_B\left(\frac{v_o}{R_E} - g_m v_{be}\right) - v_{be} \\ &= v_i - \frac{R_B}{R_E} v_o + g_m R_B\, v_{be} \end{aligned}$$

Let's apply Ohm's Law!

Likewise using KCL and Ohm's Law:



$$i_e = \frac{v_{be}}{r_e} = \frac{v_o}{R_E}$$

Or rearranging:

$$v_{be} = \frac{r_e}{R_E} v_o$$

Inserting this result in the solution above:

$$\begin{aligned} v_o &= v_i - \left(\frac{R_B}{R_E}\right) v_o + g_m R_B \, v_{be} \\ &= v_i - \left(\frac{R_B}{R_E}\right) v_o + g_m R_B \left(\frac{r_e}{R_E}\right) v_o \\ &= v_i - \left(\frac{R_B}{R_E}\right) v_o + g_m r_e \left(\frac{R_B}{R_E}\right) v_o \\ &= v_i + \left(g_m r_e - 1\right)\left(\frac{R_B}{R_E}\right) v_o \end{aligned}$$

It's the gain—but look closer!

From this result we can determine the small-signal output voltage:

$$v_o = \left(1 + (1 - g_m r_e)\frac{R_B}{R_E}\right)^{-1} v_i$$

And so the open-circuit voltage gain is:

$$A_{vo} = \frac{v_o}{v_i} = \left(1 + (1 - g_m r_e)\frac{R_B}{R_E}\right)^{-1}$$

We now note that:

$$g_m\, r_e = \frac{V_T}{I_E}\frac{I_C}{V_T} = \frac{I_C}{I_E} = \alpha$$

Therefore:

$$1 - g_m\, r_e = 1 - \alpha = 1 - \frac{\beta}{\beta + 1} = \frac{1}{\beta + 1}$$

The output is no bigger than the input!

And so the gain becomes:

$$A_{vo} = \frac{v_o}{v_i} = \left(1 + \frac{1}{\beta+1}\frac{R_B}{R_E}\right)^{-1}$$

We note here that:

$$\frac{1}{\beta+1} \ll 1$$

We find therefore, that the **small-signal gain** of this common-collector amplifier is approximately:

$$\begin{aligned} A_{vo} &= \left(1 + \frac{1}{\beta+1}\frac{R_B}{R_E}\right)^{-1} \\ &\cong (1+0)^{-1} \\ &= 1.0 \end{aligned}$$

The gain is approximately **one**!

This doesn't seem to be useful

Q: *What!? The gain is equal to one? That's just **dog-gone** silly!*

*What good is an amplifier with a gain of **one**?*

A: Remember, the open-circuit voltage gain is just **one** of **three** fundamental amplifier parameters.

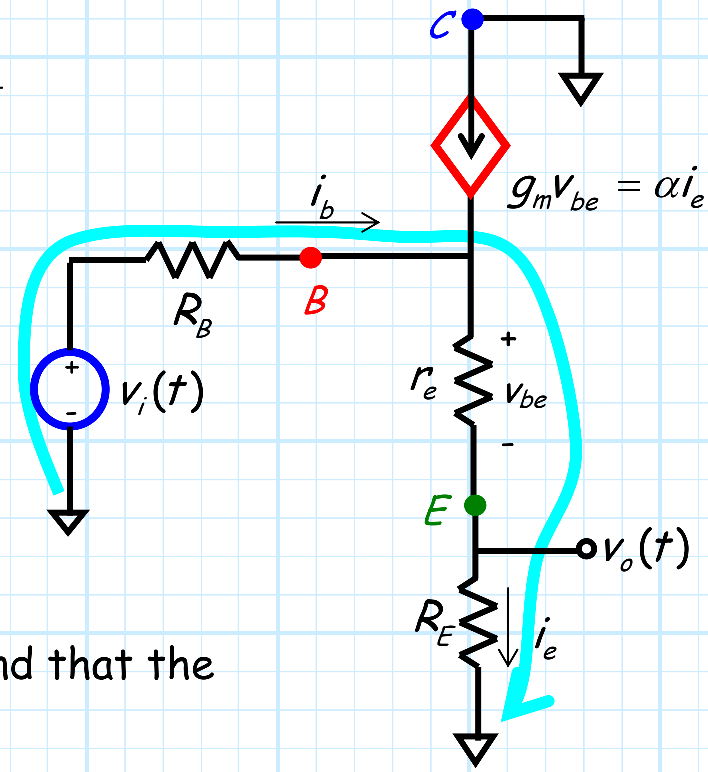
The other two are **input resistance** R_{in} and **output resistance** R_{out}.

First, let's examine the **input** resistance.

Let's determine the input resistance

Using the **small-signal circuit**, we find that:

$$R_{in} = \frac{v_i}{i_i} = \frac{v_i}{i_b}$$



Using **KVL**,

$$0 + v_i - R_B\, i_b - (r_e + R_E)\, i_e = 0$$

and adding the fact that $i_e = (\beta + 1) i_b$, we find that the small-signal **base** current is:

$$i_b = \frac{v_i}{R_B + (\beta + 1)(r_e + R_E)}$$

A large input resistance; it's a very good thing

Combining these equations, we find that the input resistance for **this** common-collector amplifier is:

$$R_{in} = \frac{v_i}{i_b} = R_B + (\beta + 1)(r_e + R_E)$$

Since beta is large, the input resistance is **typically large**—this is **good**!

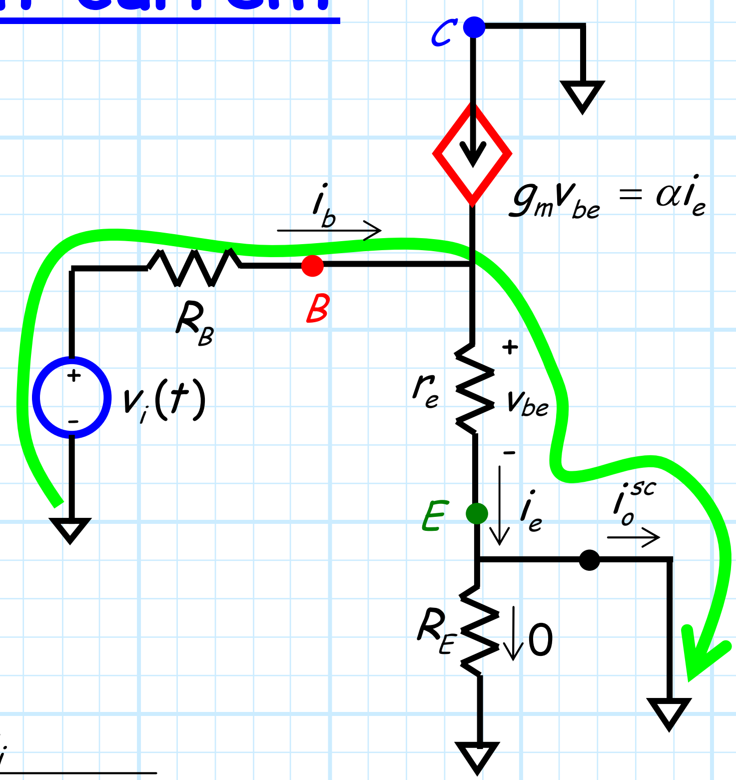
Now, let's consider the **output** resistance R_{out} of this particular common-collector amplifier.

Recall that the output resistance is defined as:

$$R_{out} = \frac{v_o^{oc}}{i_o^{sc}}$$

where v_o^{oc} is the **open-circuit output voltage** and i_o^{sc} is the **short-circuit output current**.

We must find the short circuit output current



Using **KVL**,

$$0 + v_i - R_B\, i_b - r_e\, i_e = 0$$

and adding the fact that $i_b = (\beta+1)^{-1} i_e$, we find that the small-signal **emitter** current is:

$$i_e = \frac{v_i}{R_B(\beta+1)^{-1} + r_e}$$

And from KCL, this emitter current is likewise the short circuit output current:

$$i_o^{sc} = i_e = \frac{v_i}{R_B(\beta+1)^{-1} + r_e}$$

A small output resistance; it's a very good thing as well

Of course, we already have determined that the open-circuit **output** voltage is approximately **equal** to the **input** voltage:

$$v_o^{oc} = v_i \qquad (\text{i.e., } A_{vo} \cong 1)$$

Therefore, we find that the **output** resistance will be:

$$R_{out} = \frac{v_o^{oc}}{i_o^{sc}} = R_B\left(\beta+1\right)^{-1} + r_e$$

Since the emitter resistance r_e is typically **small** (e.g., $r_e = 2.5\Omega$ if $I_E = 10.0mA$), and β is typically large, we find that the **output** resistance of this common-collector amplifier will typically be **small**!

The emitter follower is like a voltage follower—it's a buffer!

Let's **summarize** what we have learned about this **common-collector amplifier**:

1. The small-signal voltage **gain** is approximately equal to **one**.

2. The **input** resistance is typically very **large**.

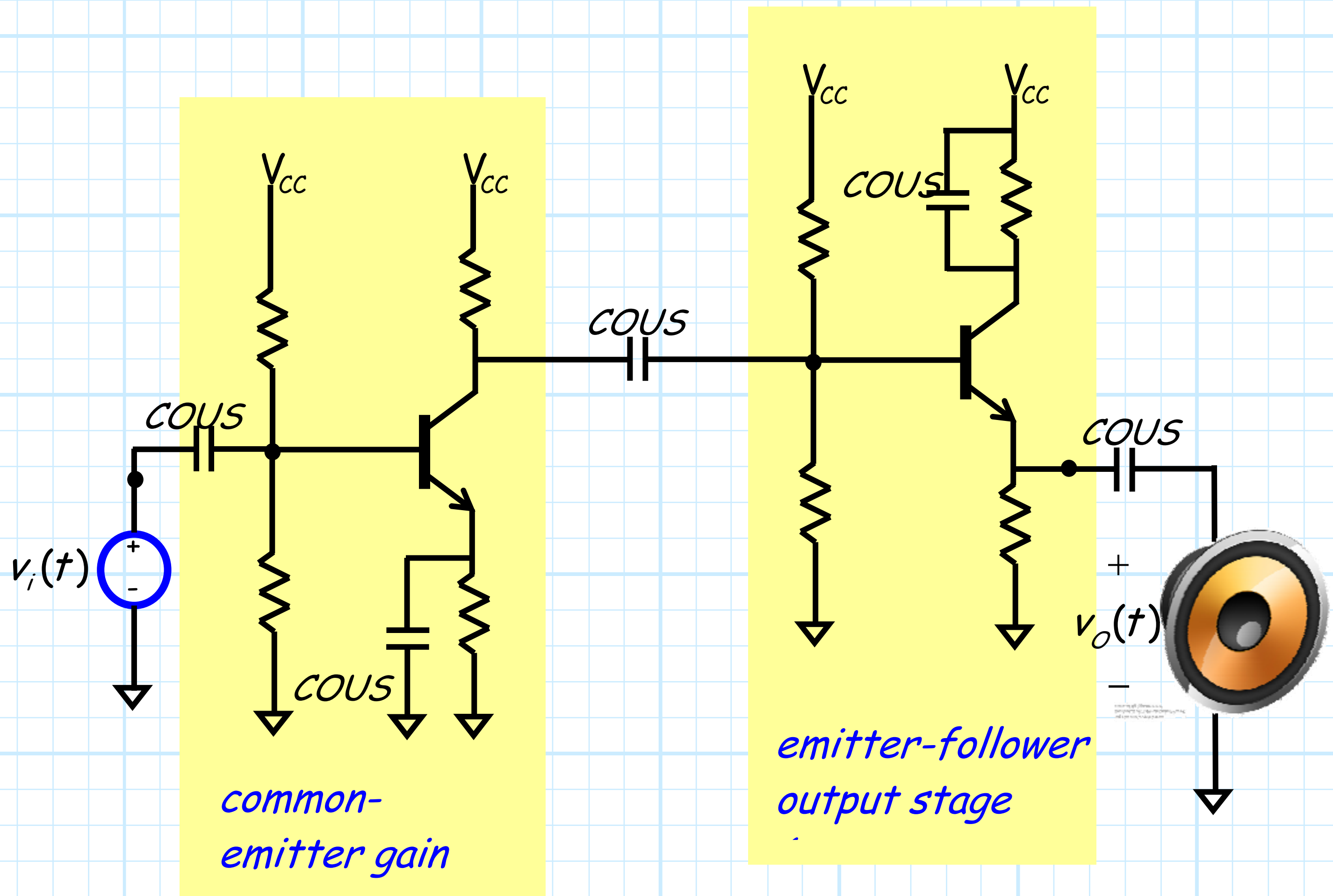
3. The **output** resistance is typically very **small**.

This is just like the op-amp ***voltage follower*** *!*

The common-collector amplifier is alternatively referred to as an **emitter follower** (i.e., the output voltage follows the input voltage).

The emitter follower is a great output stage

The common-collector amplifier is typically used as an **output stage**, where it **isolates** a high gain **amplifier** with large output resistance (e.g. a **common emitter**) from an output **load** of small resistance (e.g. an audio speaker).

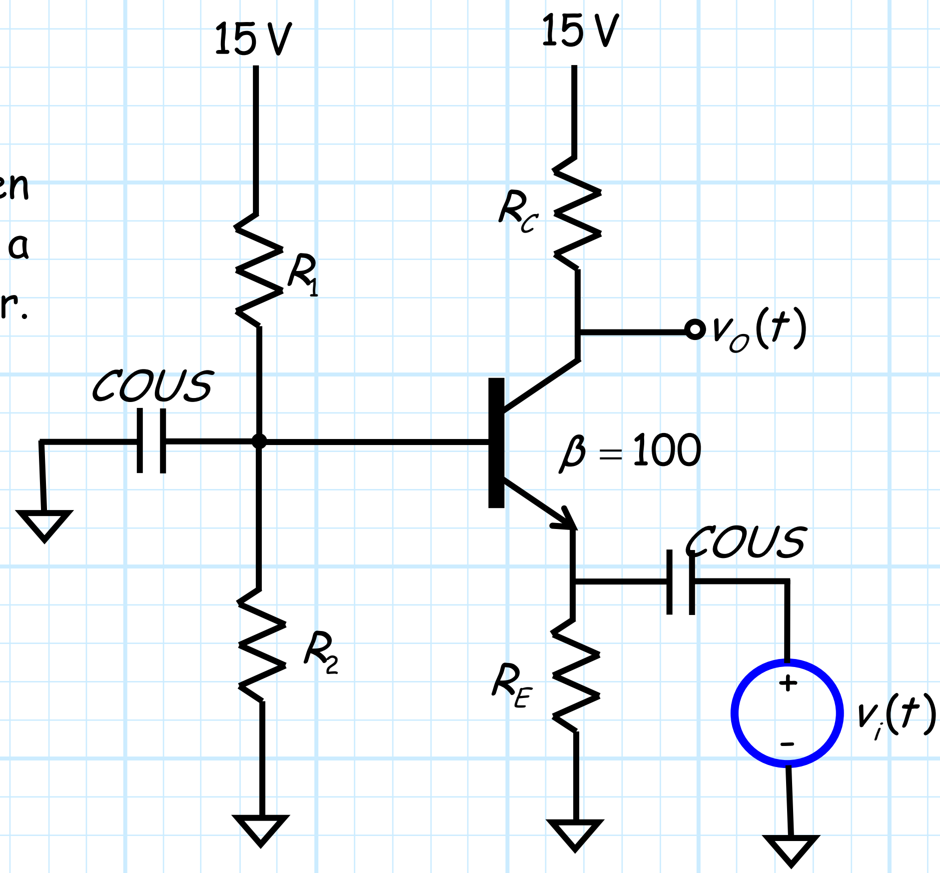


The Common-Base Amplifier

The final amplifier type is the **common-base** amplifier.

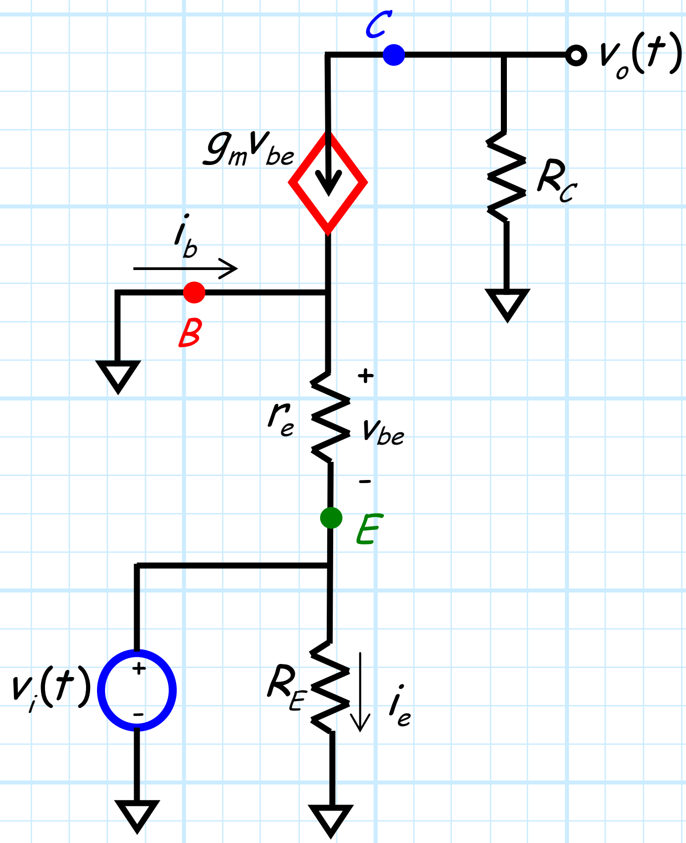
As with the other amplifier types, the name indicates that the **base** terminal is **at small-signal ground**.

For example, a COUS between base and ground make **this** a **common-base** amplifier.



Look at the base terminal

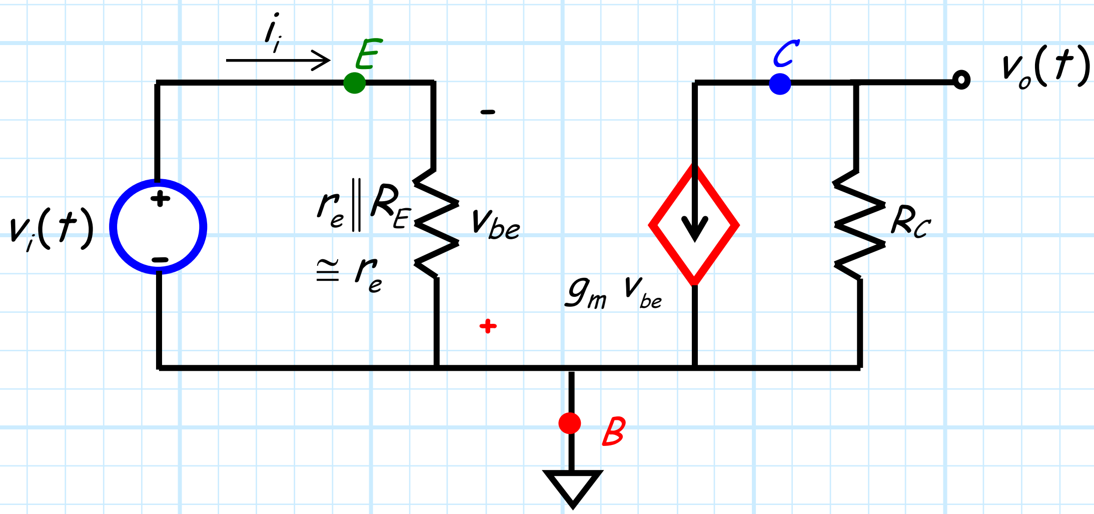
The **small-signal circuit** of this common-base amplifier is most easily analyzed using the **T-model**.



Clearly, the **base** is connected to **small-signal ground**!

The input resistance: very interesting

Rearranging this circuit:



The interesting feature of this amplifier is its **input** and **output** resistances.

It is apparent from the small-signal circuit that the **input resistance** is:

$$R_{in} = r_e \| R_E \cong r_e$$

And the output resistance is:

$$R_{out} = R_C$$

It's so darn small!

Recall that the **small-signal emitter resistance**:

$$r_e = \frac{V_T}{I_e}$$

is typically **very small**.

For **example**, if $I_e = 10\ mA$, then $r_e = 2.5\Omega$!

Therefore, since the input resistance R_{in} of this common-base amplifier is equal to the small-signal emitter resistance r_e, the **input resistance** of this **common-base** amplifier is likewise **very small**!

Recall the ideal current amplifier

Q: *A **small** input resistance!? I thought a **large** input resistance is **ideal**.*

A: Are **large** input resistance **is** desirable for an ideal **voltage** amplifier.

However, recall that a **small** input resistance is desirable for the ideal **current** amplifier!

Thus, common-base amplifiers are very useful as an **input stage** in a **current amplifier**.