Physics 310
Lecture 5 – Transistors

Fri. 2/10	**Ch 8.1-.3:** Transistors	**Lab 4 Notebook**
Mon. 2/13 Wed. 2/15 Thurs. 2/16 Fri. 2/17	**Ch 8.3-.9:** Transistors **Quiz** Ch 8, **Lab 5:** Transistors More of the same **Ch 9.1-.5, .9, App B-3:** Operational Amplifiers	**HW5**: * ; **Lab 5 Notebook**

Equipment

ppt

Handout (in lecture):

- Vacuum Tube hand out from Brophy
- Take-home quiz
- biasing example
- FET diagram (corrected from Holton)?

Study List for Quiz #5

1. Rules for the NPN bipolar junction transistors.
2. Simple transistor devices.

Equation List:

$I_B = I_E - I_C$ $\qquad$ $I_C = \beta I_B$ $\qquad$ $V_E = V_B - 0.6\text{ V}$

Bipolar Junction Transistor – concentrate on NPN type

- Use H&H model of transistor as valve – a current controls a current
- Basic rules
- Darlington Configuration – boosts current amplification
- Example devices:
  - Current Source
  - Transistor Switch
  - Emitter Follower
  - Common-Emitter Amplifier – just a little about biasing

Field Effect Transistors (FET)

- A voltage controls a current

Ch 8 Transistors

8.1 Intro

A diode is generally used in a not-so-subtle way: it's on or it's off. It's like an open switch and virtually no current flows, or it's like a closed switch and all the current you want flows.

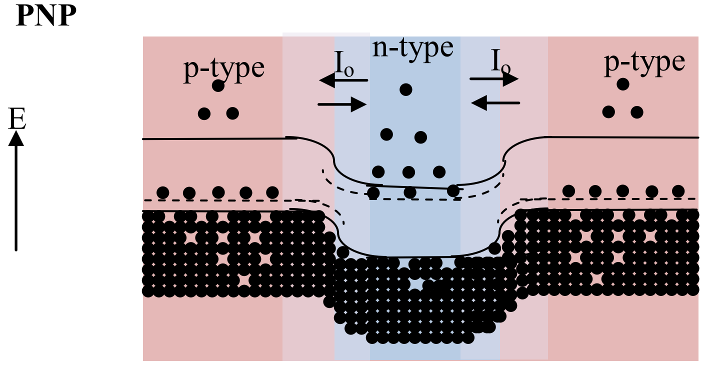
A common transistor is essentially two of these devices back to back. As we'll see, this configuration allows for much subtler uses. Primarily amplifying – a small change in current at one terminal can result in a large change at another. The transistor is one of the essential components of Integrated Circuits. Integrated Circuits can be designed to do a wide range of things, from simply amplifying a signal to converting 2-chanel stereo into Doubly 5.1.

It's worth noting that, in the days of yore, when giants roamed the land, there were vacuum tubes that performed a very similar function to that of transistors. They were indeed comparatively giant – one would be the size of a light bulb rather than thousands together on one chip the size of a dime (as for transistors.) Since vacuum tubes have been completely displaced, except for a few niche applications, standard texts/courses don't discuss them; however, if you're interested, older texts do still discuss them, for example (living on my shelf), James J. Brophy's "Basic Electronics for Scientists", 3rd Ed. published by McGraw/Hill (1977.)

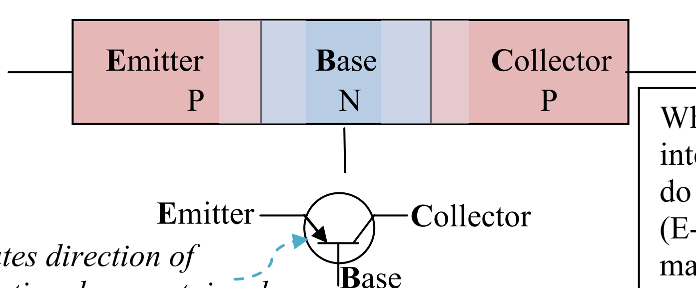
8.2 The Bipolar Junction Transistor

To understand the Transistor, we'll return to an energy-band cartoon. As a diode has two different ends – one that's P-doped (has more positively charged mobile holes than electrons) and one that's N-doped (has more negatively charged mobile electrons than holes), there are two simple kinds of transistors: P-N-P, and N-P-N. In either kind, the material sandwiched in the middle is usually *narrow* and *lightly doped* so that when a current flows across the device, the mid section doesn't draw/contribute many charge carriers to the net flow from end to end. Here are a few different ways of visualizing these devices

PNP



Unbiased



Indicates direction of conventional current, i.e., base – emitter diode's orientation

Why aren't Emitter & Collector interchangeable? Probably has something to do with doping being heavier at one interface (E-B or B-C) than at the other and this making one barier more flexible than the other.

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Holes – Majority Carrier. You'll notice that there are generally more holes in the valance band than free electrons in the conduction band, so when current flows, it's the holes' motion that accounts for most of it. We'd say that the holes are the "majority carrier."

Base – Barrier. Not wired-up, there's about an 0.6 eV step down from emitter to Base and an 0.6 eV step back up from Base to Collector (*energy* steps for negatively charged electrons go in the opposite direction from voltage steps.) Looked at the from the holes' (majority carriers') perspective, the base forms something of a barrier to free flow between the emitter and collector – only the 'deeper' or more energetic holes can get past that barrier.

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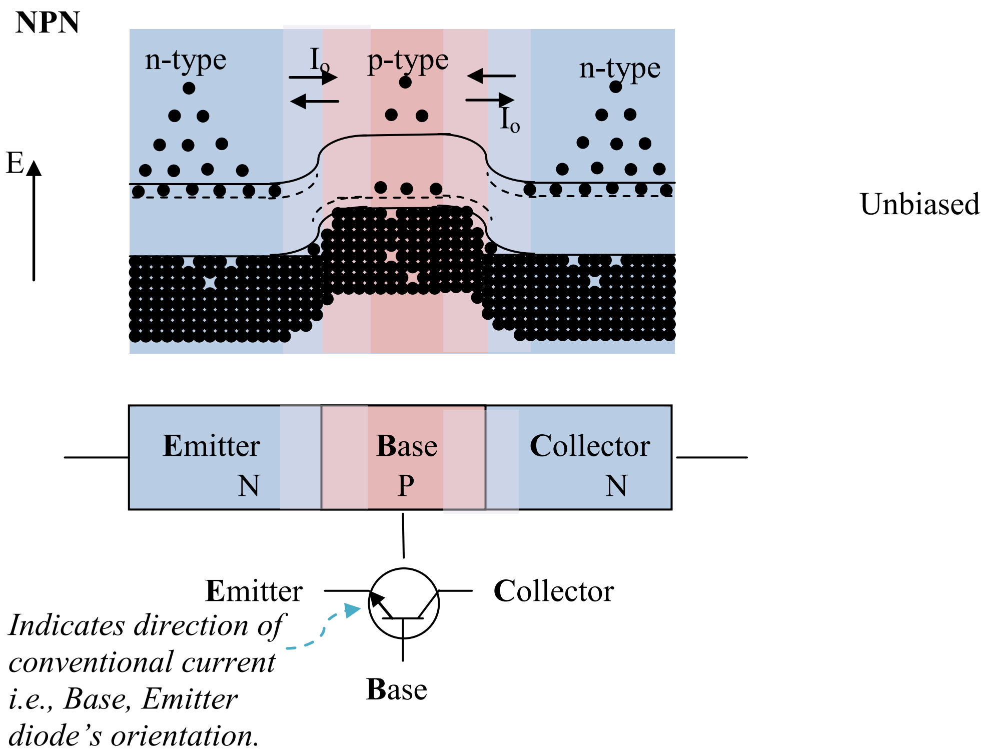

Electrons – Majority Carrier. In the NPN transistor, you'll observe that there are far more mobile *electrons* in the conduction band than there are holes in the valance band. Not wired-up to anything, there'd be about an 0.6eV step up from Emitter to Base and an 0.6eV step back down from Base to Collector (again, *energy* steps are reverse for *negatively* charged electrons from voltage steps).

Base-Barrier. So, again the base acts as a barrier to the majority charge carriers. Only the relatively small population with high enough energies will be able to migrate between the emitter and base.
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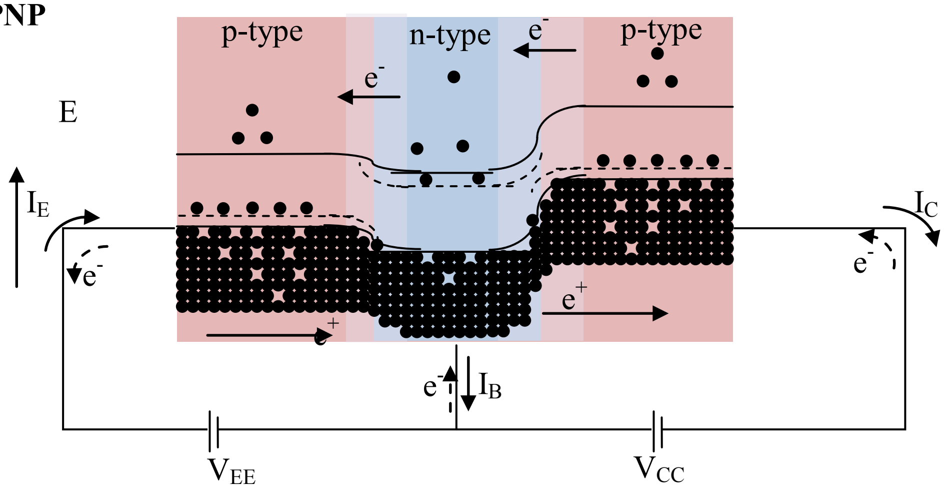
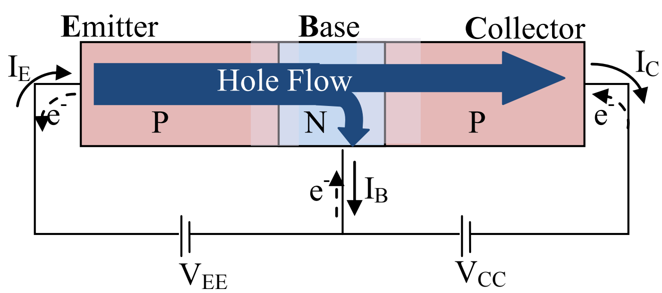
8.2.1 Transistor Operation

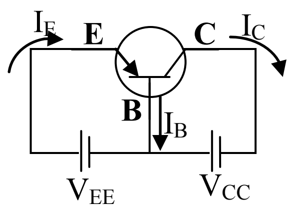
Just like a resistor with no voltage applied across it, the unbiased transistor doesn't do anything terribly interesting. So let's consider one of these things in action.

PNP





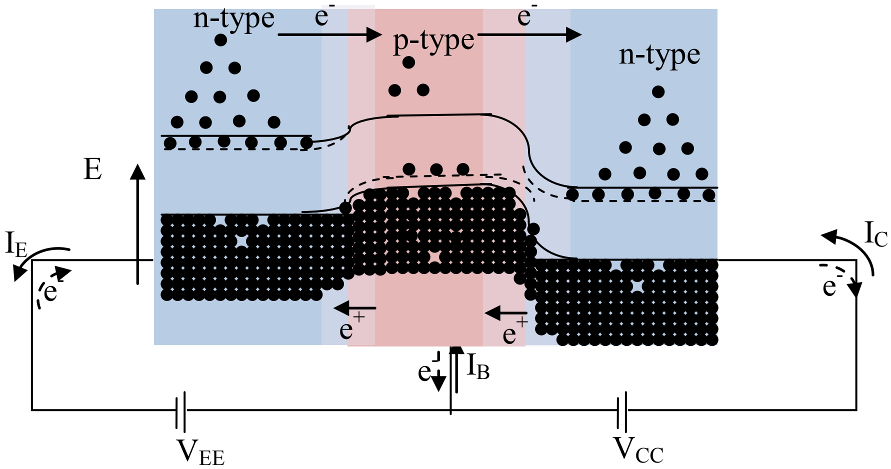
Note: had I drawn the free hole and free electron populations appropriately, it would be obvious that there are far more mobile holes than electrons, so the holes are the majority carriers.

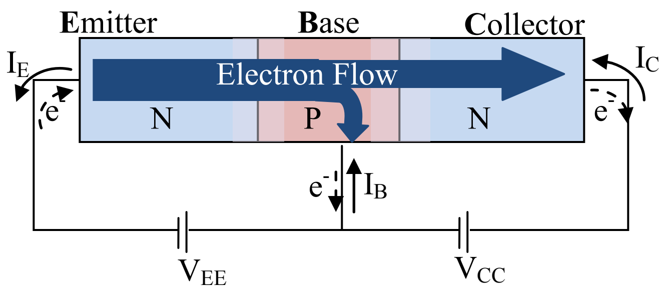


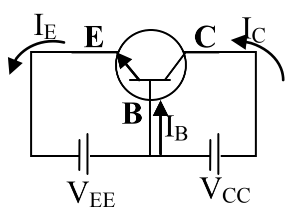
Notice that, by wiring the three leads directly to voltage supplies, we're *forcing* bigger/smaller voltage steps between emitter and base and base and collector. Recall that the current passed across either junction goes *exponentially* with the voltage step across the junctions – so small voltage supplies could enable large currents to flow.

Notice that the arrow within the transistor symbol points in the direction of the conventional current, and that the majority carriers (*holes* in this case) flow from the **e**mitter toward the **c**ollector: "emitted" by the emitter and "collected" by the collector.

NPN







Again, notice that the arrow within the transistor symbol points in the direction of the conventional current, and that the majority carriers (*electrons* in this case) flow from the **e**mitter toward the **c**ollector: "emitted by the emitter and "collected" by the collector.

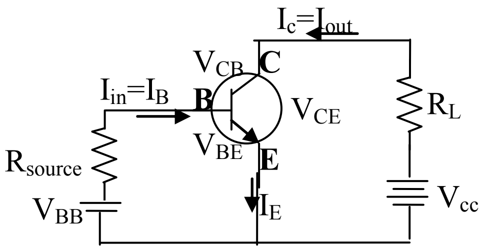
8.2.2 External Circuit Configurations

Let's plug one of these things into a circuit and think about how it behaves. The book shows three common configurations and some different uses for them: the "Common" Emitter, Base, or Collector. Here, since we're inputting a signal to one terminal, and taking the output from another, the remaining terminal is called the "common." It is often wired (more or less) directly to a voltage supply line, be that +, -, or ground.

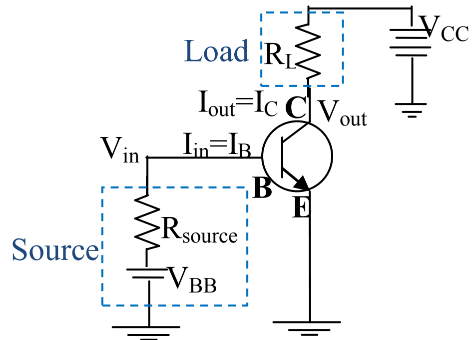
We'll start with the Common Emitter configuration and consider it thoroughly before moving on to the other two.

Common Emitter (emitter wired to common / ground)

The book shows it as

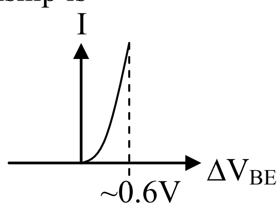


if it helps, we can unwrap it as



As we'll see, by varying the input voltage / current, you affect the much-larger output current.

Look at the connection between the Base and Emitter first. It's forward biased, and, if you recall, the current-voltage relationship is



Unlike the very simple circuit that I'd previously shown (one transistor and two batteries), this one has a *resistor* between the battery that joins the Base and the Emitter (I'm taking it as our reference or as 'ground' for simplicity.) The significance of that resistor is that it restricts the current, most likely keeping it in the 'reasonable' range, for which the Base-Emitter junction has roughly an 0.6V drop across it.

So, $V_E = V_B - 0.6\ \text{V}$.

Most transistor applications are going to allow this to be true.

Characterizing a Transistor / Convenient definitions

With different electrical components, there are parameters that largely sum up their key behaviors in circuits; with a resistor, it's the resistance, R; with the capacitor, it's the capacitance, C. With a diode, it's the forward voltage drop and backward break-down voltage. With the Transistor, there are three relevant relations.

$\boxed{V_E = V_B - 0.6\ \text{V}}$ as just noted.

$\boxed{I_C = I_E - I_B}$ (as is obvious when you look at the flow diagram on pages 4 and 5).

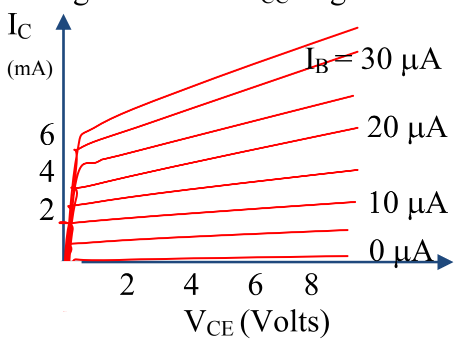
And finally, $\alpha \equiv \frac{I_C}{I_E}$, or, more commonly $\boxed{\beta \equiv \frac{I_C}{I_B}} = \frac{\alpha}{1-\alpha} = h_{FE}$ is called the "current gain." Often a transistor's "current gain" is a specified parameter.

Note that, since transistors are often manufactured (with very small base regions?) so as to make $I_B << I_E$, α is quite close to 1, or β>>1. That will often allow for simplifying approximations when analyzing the behavior of transistor circuits.

8.2.3 Characteristic Curves

Now that we're armed with the basic relations for a transistor, let's get a little familiar with its behavior.

Characteristic Curve. A rather revealing characterization of the circuit is the family of "characteristic curves", that is, the current that passes through the load (collector current) as a function of the collector's voltage above ground (V_{CE}) for different base currents (imagine the two batteries in the schematic being variable, so you select a V_{BB}, and thus the current that goes in the base, I_B, then you sweep through values of V_{CC} to generate one curve.)



Apparently, the first few tenths of a volt go to 'turning on' the forward-biased diode formed by the Base and the Emitter. With that comes a tremendous gain in electrons that are free to travel the length of the transistor. Beyond that, most of the increased voltage further reverse biases the Base-Collector diode which returns more modest, linear increases in current that can flow down the transistor.

If the source is wired to the Base and the load is wired to the Collector, then there is a significant current (and corresponding power) gain – micro-amp input currents lead to milli-amp output currents.

As these curves suggest, the ratio of I_B to I_C (β) is *not* really constant; however, we'll often be able to approximate it as such over any given range of currents we're dealing with.

Find Input Resistance. Here's how one might analyze such a thing. Say V_{BB}, V_{CC}, R_s and R_L are known, and so is β. Then let's find the "input resistance", that is, what single resistor could we plug into the "supply" and get the same amount of current drawn out of it?

$$R_{input} \equiv \frac{-V_{in}}{I_{source}} = \frac{-V_{in}}{-\Delta V_{R_{source}} / R_{source}} = \frac{V_{in}}{\Delta V_{R_{source}}} R_{source} = \frac{\Delta V_{E\to B}}{\Delta V_{E\to B} - \Delta V_{BB}} R_{source} = \frac{1}{1 - \frac{\Delta V_{BB}}{\Delta V_{E\to B}}} R_{source}$$

$$R_{input} \approx \frac{1}{1 - \frac{\Delta V_{BB}}{0.6V}} R_{source}$$

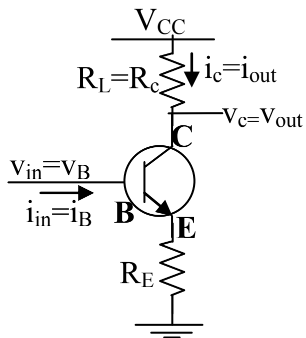
So,

If, say, V_{BB} = 10 V, and R_{source} = 500Ω, then R_{input} = 32Ω.

8.3 The Common-Emitter Amplifier

Common Emitter Amplifier

Variation on a theme: Input & Output Resistance. Let's find the input resistance of *this* transistor circuit. It's another Common-Emitter circuit, but with a resistor between the emitter and ground.



The characteristic relations we have on hand are

$$I_B = I_E - I_C \qquad I_C = \beta I_B \qquad V_E = V_B - 0.6\ \text{V}$$

From the perspective of a supply that's maintaining voltage V_{in} and pumping out current I_{in}, the whole circuit illustrated might as well be a single resistor to ground with value

$$R_{input} = -\frac{(0 - V_{in})}{I_{in}} = \frac{V_B}{I_B}$$

We can rephrase the numerator via $V_B = V_E + 0.6\,\text{V}$ and the denominator via $I_B = I_E - I_C = I_E - \beta I_B \Rightarrow I_B = I_E/(1+\beta)$

$$R_{input} = \frac{V_B}{I_B} = \frac{V_E + 0.6V}{I_E/(1+\beta)} = \left(\frac{V_E}{I_E} + \frac{0.6V}{I_E}\right)(1+\beta) = R_E\left(1+\frac{0.6V}{V_E}\right)(1+\beta)$$

Now, as long as V_E>>0.6V and β>>1, this is approximately

$$R_{input} \approx R_E\beta\ .$$

Which is what the book quotes.

Alternatively, sometimes what's of interest isn't the actual resistance, but how the voltage *varies as a function of the current,* that is,

$$\frac{dV_B}{dI_B} = \frac{d}{dI_B}(V_E + 0.6V) = \frac{d}{dI_B}(I_E R_E + 0.6V) = \frac{d}{dI_B}(I_B(1+\beta)R_E + 0.6V) = (1+\beta)R_E \approx \beta R_E$$

Which is what he book quotes.

Output Impedance.

On the previous page I arrived at the book's expression for Input Impedance but without invoking approximations right up front (so you can better see the limitations of those approximations). As for the "output impedance", the answer we get depends upon what we consider to be the "load" – that defines the perspective form which we're looking at the circuit.

If the resistor connected to the collector is *not* the load, but another component of the 'circuit', and the load will be connected between v_{out} and ground, then the question is essentially what the Thevenin Equivilant resistor is for the circuit. That's the ratio of the 'short' current and the 'open' voltage.

$$R_{th} = \frac{v_c}{i_{short}} = \frac{v_c}{\frac{v_{cc}}{R_C}} = \frac{v_c}{v_{cc}} R_C = \frac{v_{cc} - i_c R_c}{v_{cc}} R_C = \frac{v_{cc} - \left(i_E \left(\frac{1}{1+\frac{1}{\beta}} \right) \right) R_c}{v_{cc}} R_C = \frac{v_{cc} - \left(\left(\frac{V_E}{R_E} \right) \left(\frac{1}{1+\frac{1}{\beta}} \right) \right) R_c}{v_{cc}} R_C$$

$$\frac{v_{cc} - \left(\left(\frac{v_B - 0.6V}{R_E} \right) \left(\frac{1}{1+\frac{1}{\beta}} \right) \right) R_c}{v_{cc}} R_C = R_C \left(1 - \left(\frac{v_B - 0.6V}{v_{cc}} \right) \left(\frac{1}{1+\frac{1}{\beta}} \right) \frac{R_c}{R_E} \right) \approx R_C \left(1 - \left(\frac{v_B - 0.6V}{v_{cc}} \right) \frac{R_c}{R_E} \right)$$

If the resistor connected to the collector, R_C is the load resistor, then the question is what single resistor to ground could be inserted in place of the transistor & R_E.

$$R_{eq} = \frac{v_c}{I_c} \text{ , now } V_{CC} - v_c = R_C I_c \Rightarrow v_c = V_{CC} + R_C I_c ,$$

so this can be replaced with

$$R_{eq} = \frac{V_{CC} + R_C I_c}{I_c} = \frac{V_{CC}}{I_c} + R_C \text{, for that matter, } I_c = I_E / \left(1 + \tfrac{1}{\beta}\right)$$

So,

$$R_{eq} = \frac{V_{CC}}{I_E} \left(1 + \tfrac{1}{\beta}\right) + R_C \text{, but we also have } I_E = v_E / R_E = \left(v_B - 0.6V\right) / R_E$$

So,

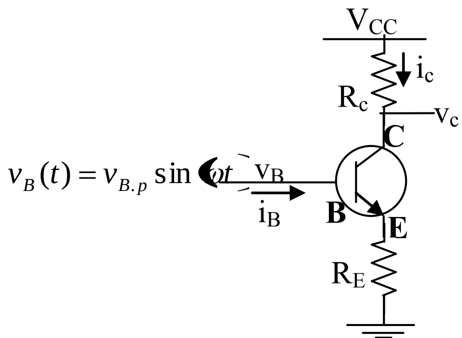
$$R_{eq} = \frac{V_{CC}}{v_B - 0.6V} \left(1 + \tfrac{1}{\beta}\right) R_E + R_C \approx \frac{V_{CC}}{v_B - 0.6V} R_E + R_C$$

To get a qualitative feel for this, consider that v_{source} will be on order of, but less than v_{cc} (the transistor won't work of $v_{source} > v_{cc}$) and R_C and R_E are probably on order of each other. So the whole second term is on order of 1, so the output impedance is something on order of R_c.

Interestingly, neither of these yields the result that the book quotes on page 162 (but does not support) : R_c. What *does* yield this result is not the resistance but the derivative

$$\frac{dv_{out}}{di_c} = \frac{d}{di_c}\left(V_{cc} - i_c R_c\right) = -R_c$$

AC Gain. This kind of circuit is usually used to amplify a signal, that is, if there's a small voltage applied at the base, a corresponding large voltage is generated at the collector. The ratio of the two would be the circuit's "voltage gain."



In the particular case that you're dealing with just an AC signal, or at least that's the only aspect that you're interested in, the AC Gain is how the output voltage varies with the input voltage.

Target: $G_{ACv} \equiv \frac{dv_{out}}{dv_{in}} = \frac{dv_C}{dv_B}$ (this essentially gives the AC voltage gain – neglects any offsets).

Tools: In addition to being able to apply Ohm's law across individual resistors, our basic tools for characterizing the transistor are

$I_B = I_E - I_C$ $\qquad I_C = \beta I_B$ $\qquad V_E = V_B - 0.6\ \text{V}$

So, let's try to use these relations to phrase the collector voltage as a function of the base voltage and then take the derivative.

$$\left(v_c - V_{cc}\right) = -i_c R_c \Rightarrow v_c = V_{cc} - i_c R_c = V_{cc} - \left(i_E\left(\frac{1}{1+\frac{1}{\beta}}\right)\right)R_c = V_{cc} - \left(-\frac{0 - v_E}{R_E}\left(\frac{1}{1+\frac{1}{\beta}}\right)\right)R_c$$

$$v_c = V_{cc} + \left(-\frac{v_B - 0.6V}{R_E}\left(\frac{1}{1+\frac{1}{\beta}}\right)\right)R_c$$

Okay, now we can take the derivative,

$$G_{ACv} = \frac{dv_{out}}{dv_{in}} = \frac{dv_C}{dv_B} = -\left(\frac{1}{1+\frac{1}{\beta}}\right)\frac{R_C}{R_B} \approx \frac{R_C}{R_E} \approx \frac{R_C}{R_{input}}\beta$$

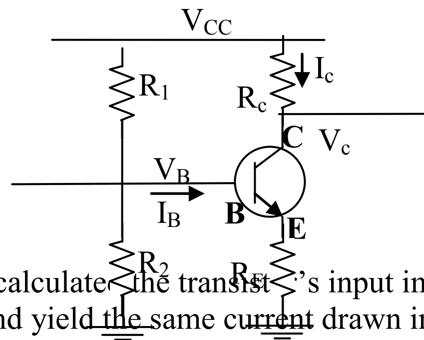
The last step uses $R_{input} \approx R_E \beta$ from page 8 of these notes.

8.3.1 Biasing the Base

Input Bias. The astute reader might have noticed a problem with this gain. While this may be the voltage gain *while the transistor is functioning properly,* the transistor can't possibly produce an output voltage any lower then ground or higher than V_{CC} the way it's wired up.

A related complication is that, as can be seen in the "characteristic curves," β is by no means a constant over the full range; for very small bias currents, the circuit 'turns on' rather dramatically before settling into nice linear behavior.

For both these reasons, it's nice to ensure that V_B is always high enough so that the transistor is "on", even while the input signal itself may oscillate around zero. Thus we modify the circuit just a little to offset the signal presented to the base. The first step in doing this is adding a voltage divider at the input.

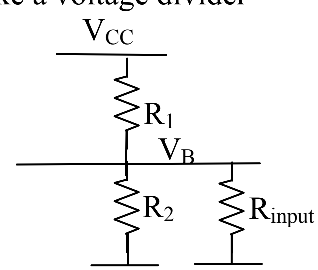


We've already calculated the transistor's input impedance, i.e., what single resistor could replace the transistor and yield the same current drawn in the base for the same base voltage, that was

$$R_{input} \approx R_E \beta$$

(not quite right for a *DC* signal, but, gets the right ballpark for an argument we'll make.)

So, from the perspective of the base, the circuit looks like a voltage divider



$$V_B = \frac{R_{2-input}}{R_{2-input} + R_1} V_{CC} = \frac{1}{1 + R_1 \frac{1}{R_{2-input}}} V_{CC}$$

Then $$\frac{1}{1 + R_1 (1/R_2 + 1/R_{input})} V_{CC}$$

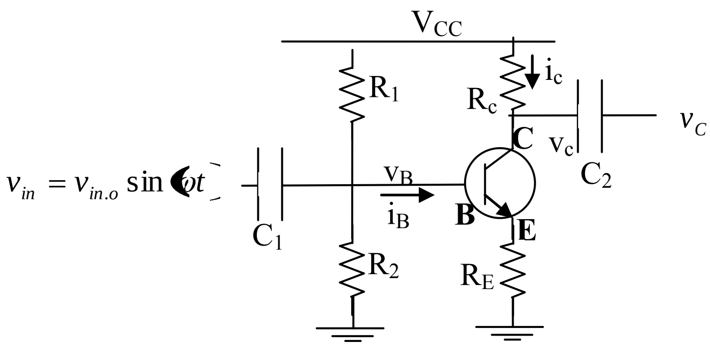
$$\frac{1}{1 + R_1 (1/R_2 + 1/(\beta R_E))} V_{CC}$$

Since the input impedance is quite large (thanks to β>>1), for reasonable R_1 and R_2, we have

$$V_{B.bias} \approx \frac{1}{1 + R_1 (1/R_2)} V_{CC} .$$

So, R_1 and R_2 would largely determine the base voltage in the absence of any other input signal. We'll call that $V_{B\ bias}$, and it's the base "bias" voltage.

Now, if we put a capacitor between this voltage divider and an input signal, the circuit looks like



The signal at the base is then

$$V_B = V_{B.bias} + v_{in}$$

$$V_B \approx \frac{1}{1 + R_1 (/ R_2)} V_{CC} + v_{in.o} \sin(\omega t)$$

So it mimics the input signal, but rather than oscillating around zero, it oscillates around the bias voltage (you'll notice that a capacitor has also been added to the output so whatever additional bit of circuitry receives this circuit's output can play a similar game and set the voltage bias that *it* wants.)

Keeping output in range. Recall that the transistor circuit can only produce outputs between V_{cc} and ground. So, we want to choose our input bias voltage (by choosing our R_1 and R_2) so the corresponding output bias is right in the middle of this range – that would maximize the range of input signals for which the circuit behaved well.

How do we choose the right resistors?

So, we have

$$V_{B.bias} = \frac{1}{R_1 / R_2 + 1} V_{CC} .$$

And we want

$$V_{C.bias} = \tfrac{1}{2} V_{CC}$$

If we say the transistor has a DC voltage gain of G (that is, $V_C / V_B = G$), then we want the base biased to only

$$V_{B.bias} = V_{C.bias} / G$$

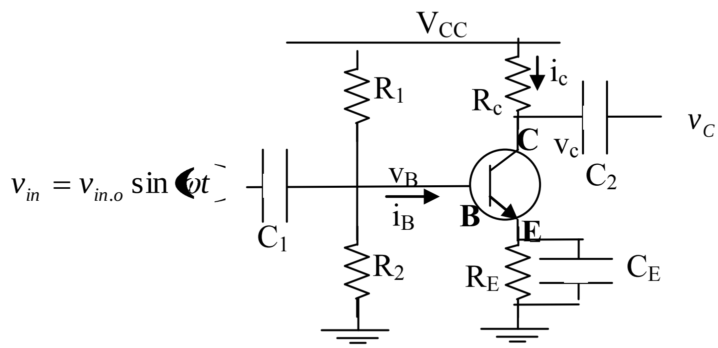
So, the resistors are chosen such that

$$\tfrac{1}{2}V_B / G = \frac{1}{R_1/R_2+1}V_{CC}$$

$$2G = R_1/R_2+1$$

Thermal Stability

A very high gain circuit operating on an AC signal oscillates between passing a lot of current, and not so much. While in the high-current fraction of its oscillation, the transistor can get it hot. Raising its temperature means increasing the carrier population in the transistor, and thus decreasing its effective resistance and increasing the current still more. Effectively, the circuit's *gain* oscillates – distorting the output signal. This is addressed by putting a capacitor in parallel with the emitter resistor.



This replaces R_E with $\vec{Z}_E = \dfrac{R_E}{1+j(R_E C_E 2\pi f)} = \dfrac{R_E}{\sqrt{1+(R_E C_E 2\pi f)^2}} e^{-j\tan^{-1}(R_E C_E 2\pi f)}$ as the reactance

and the gain is then $G_{ACv} \approx \dfrac{R_C}{\vec{Z}_E} = \dfrac{R_C}{R_E}\sqrt{1+(R_E C_E 2\pi f)^2}\, e^{j\tan^{-1}(R_E C_E 2\pi f)}$

Clearly, the gain increases with frequency; but so does the input impedance, $Z_{in} \approx \beta Z_E$. Now, if we're only planning on running relatively high frequency signals through this, then we can still have a large gain but not necessarily draw as large a current – keeping things cooler and stable.

All told, the common emitter configuration is pretty handy.