PHYS127AL Lecture 6

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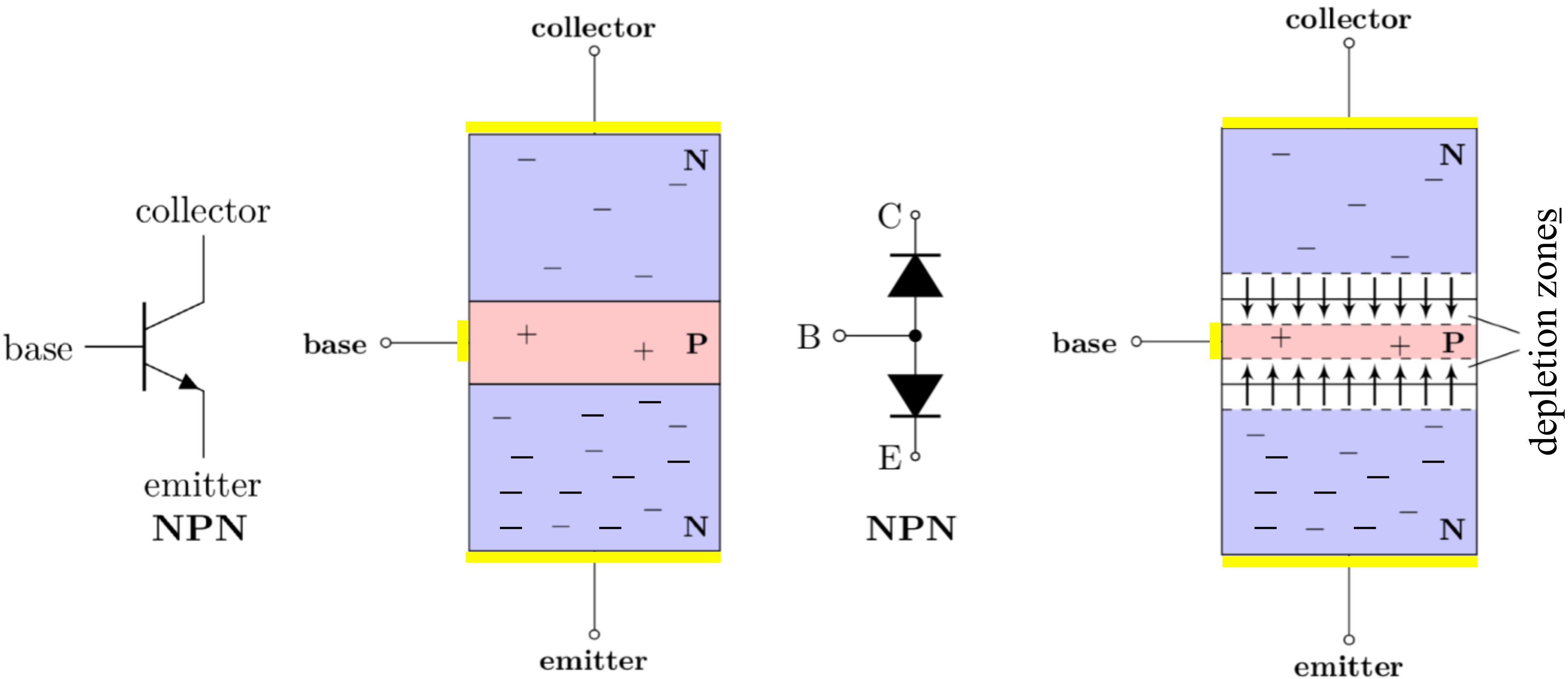
Transistors and amplifiers

Transistors

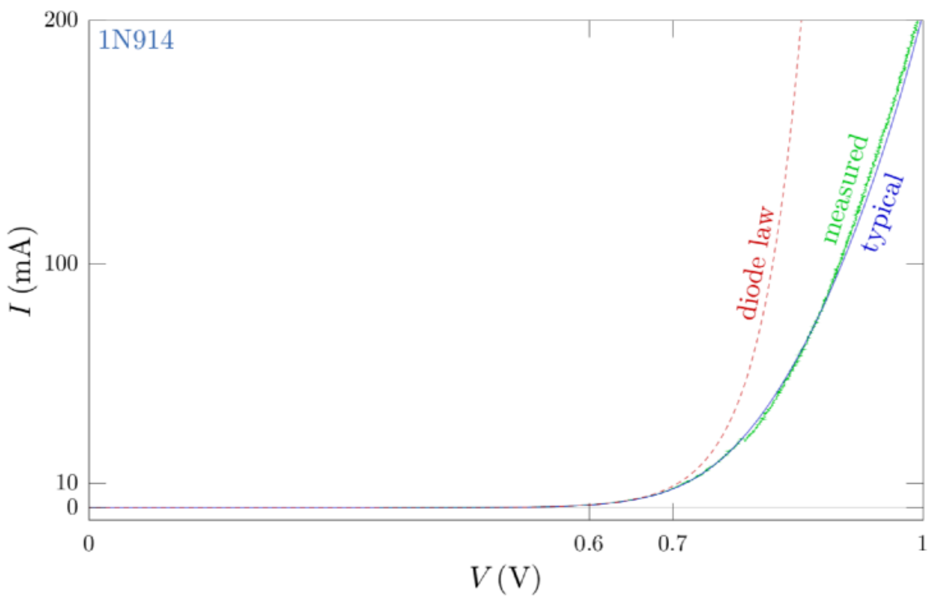
A transistor operates by amplifying current.
It is *active*, meaning more power out than in.
Previous components were *passive*.

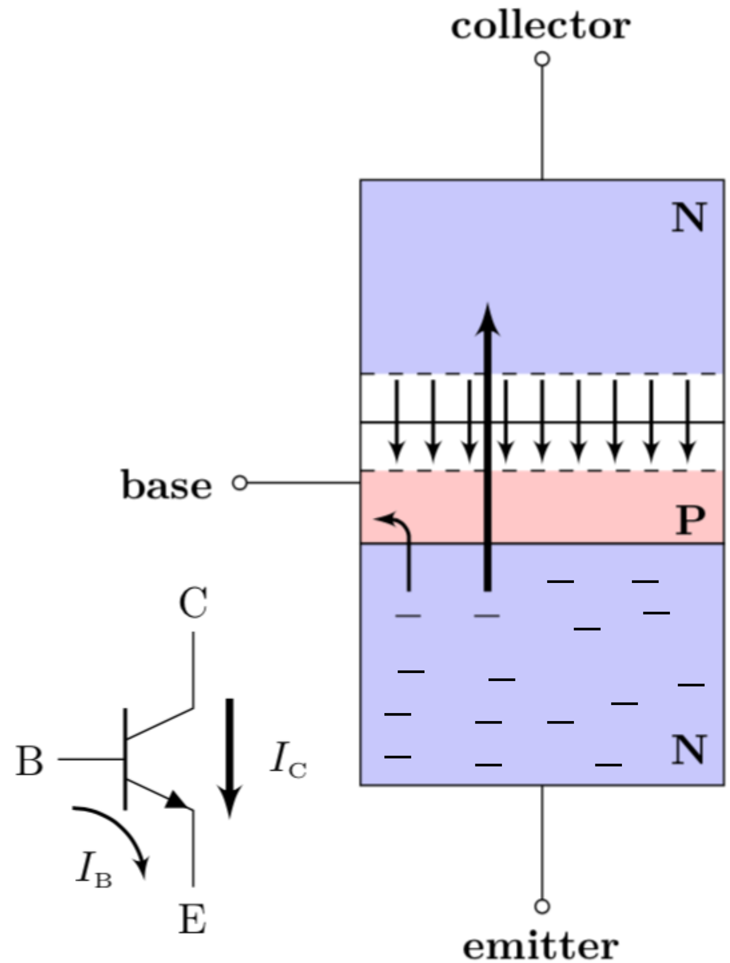
Made by sandwiching a thin, lightly-doped p-type layer between n-type regions.



Transistors

If we have a voltage across the base-emitter junction > 0.6 V it becomes forward biased.
Negative charge carries move from the emitter to the base, but they can also move across the field region to the collector.

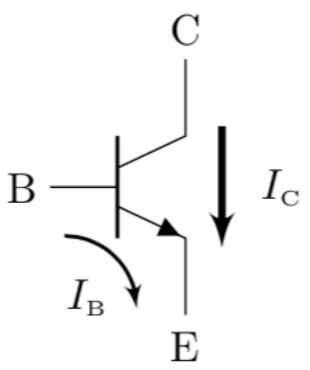




This corresponds to a small current into the base and a <u>larger</u> current into the collector.

I_B controls I_C and amplifies it by a factor $\beta \cong 100$.

Transistor rules of operation



1). $V_{BE} = 0.6$ V or the transistor is off
I.e., $V_B = V_E + 0.6$ V
Once the transistor is on, $\Delta V_B = \Delta V_E$.

2). $I_C = \beta\, I_B$.
And by charge conservation $I_E = I_B + I_C$ so $I_E \cong I_C$

3). $V_{CE} > 0.2$ V

With these simple rules we can analyze most transistor circuits.
We'll add some nuance later.

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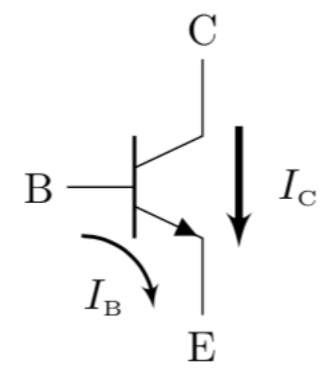

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2N3904

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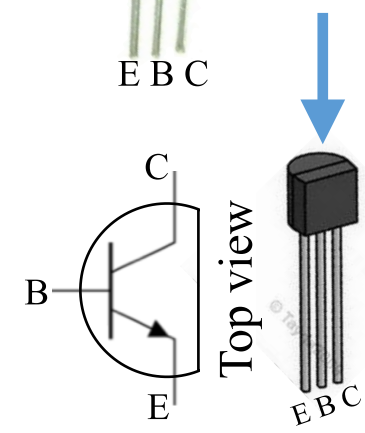
The 2N3904 is an NPN transistor.
You also have others we will discuss later.



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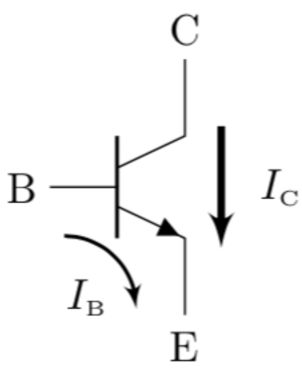

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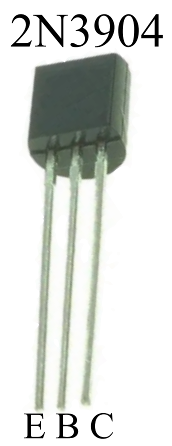

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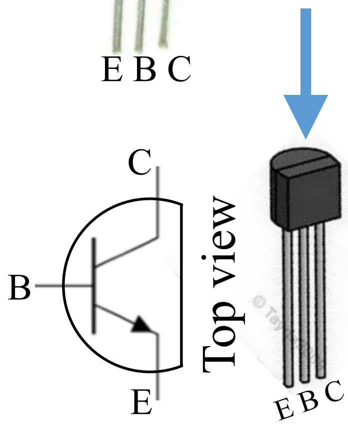
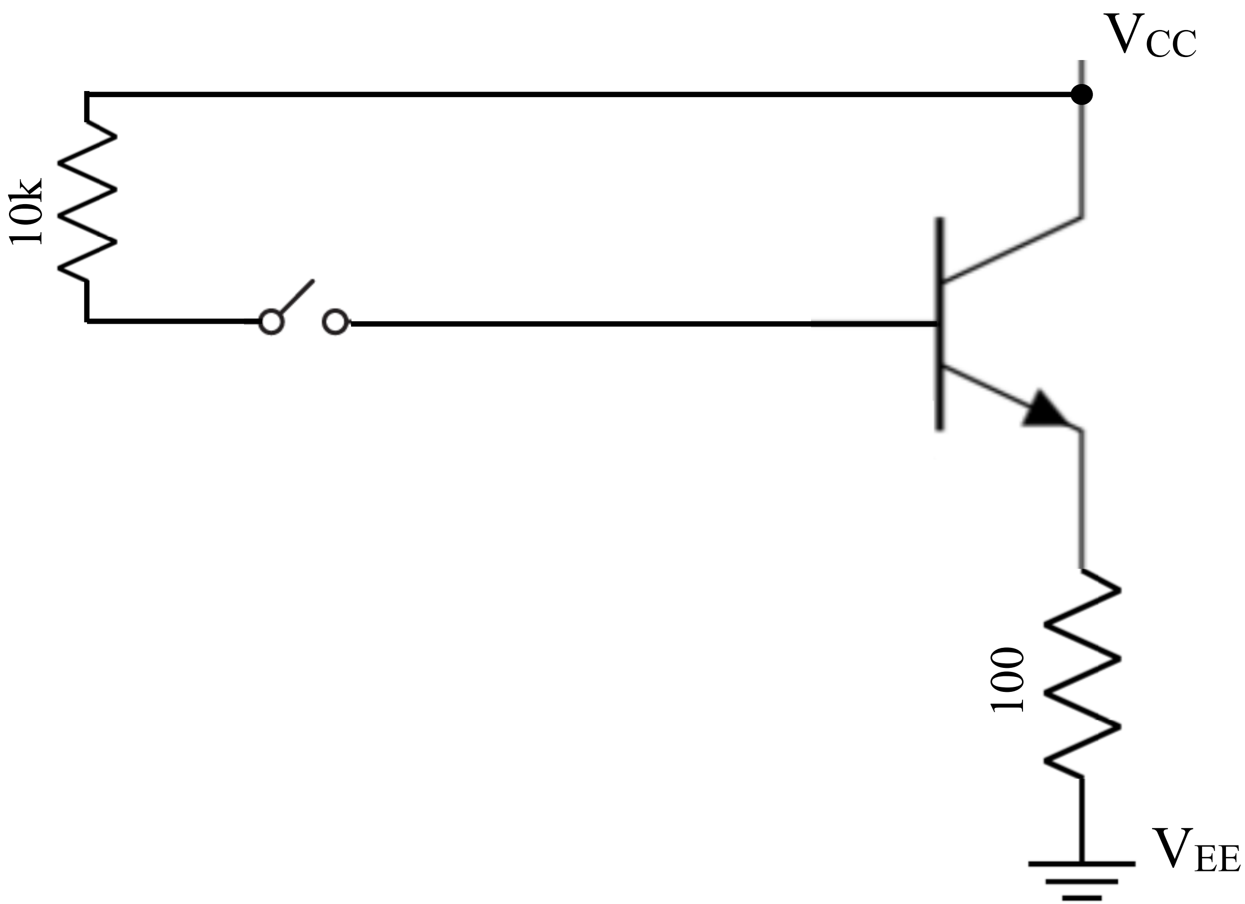
Some terminology:
    The power supply connected to the collector is called V_{CC}.
    The power supply connected to the emitter is called V_{EE}.



Simplest transistor circuit

A transistor allows us to switch a large current with a small current.



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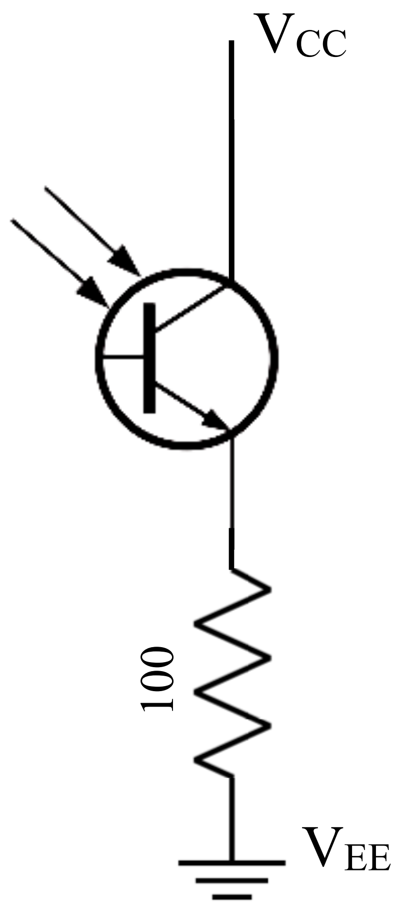
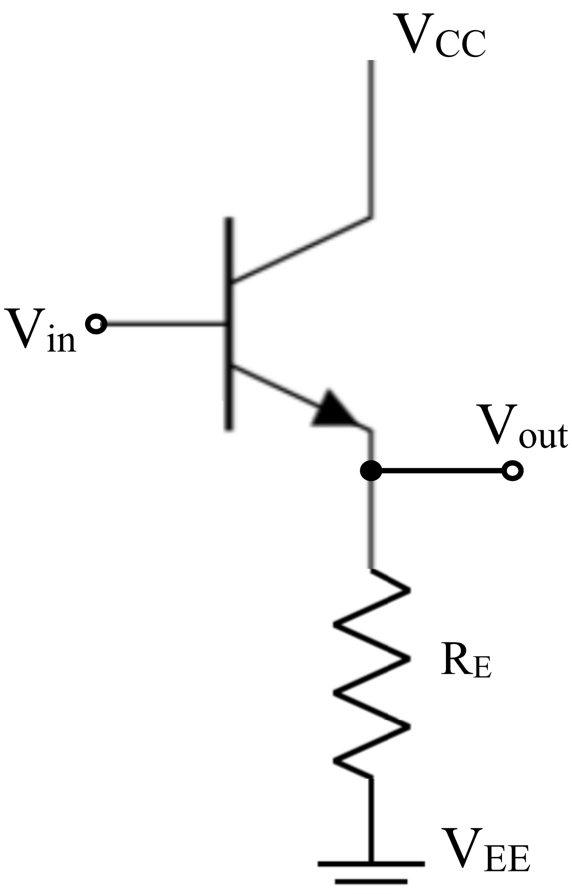


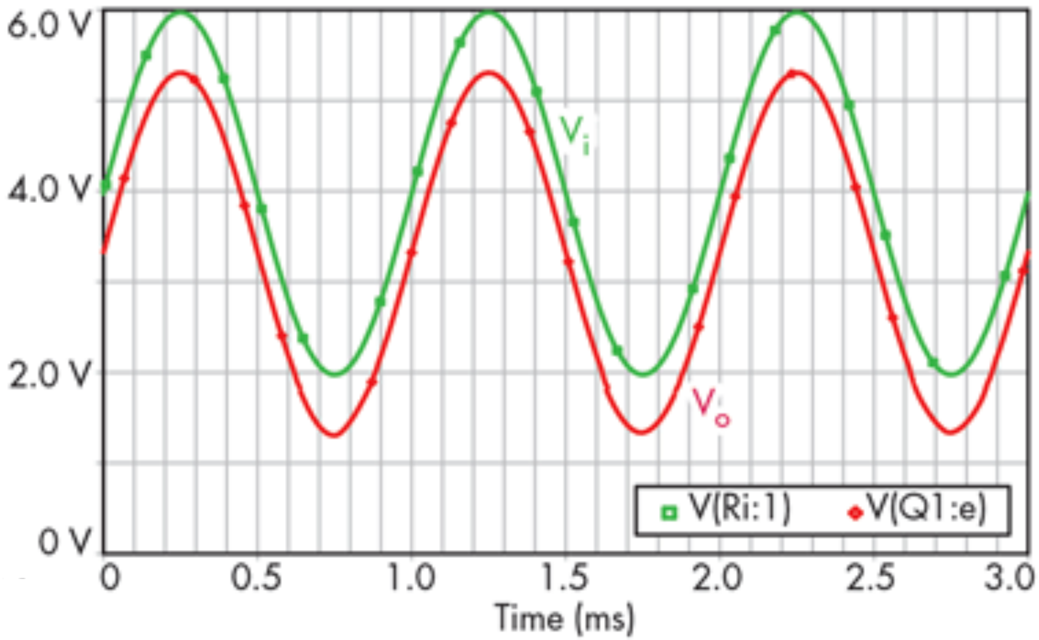
Emitter follower

This transistor circuit has the output "follow" the input, with a 0.6 V drop.



$V_{in} = 4 + 2 \sin \omega t$

$V_{out} = 3.4 + 2 \sin \omega t$



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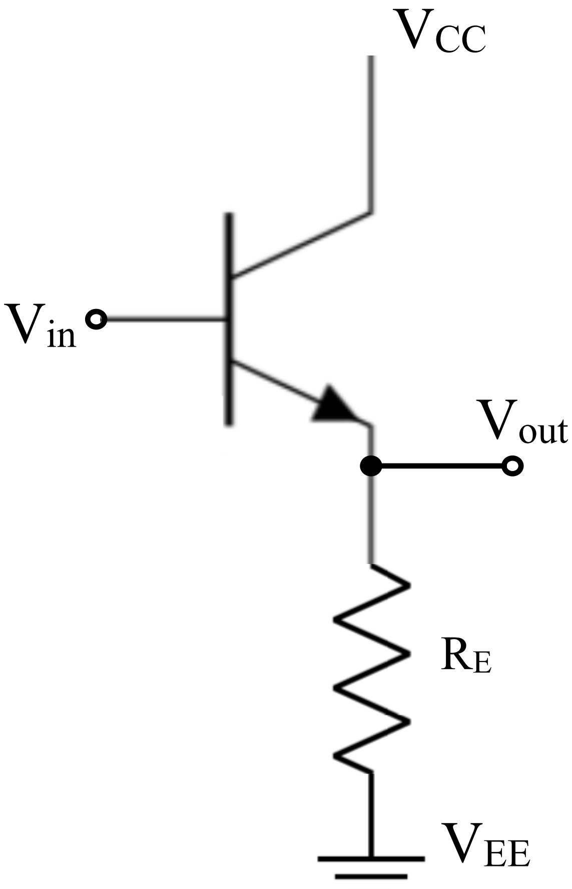
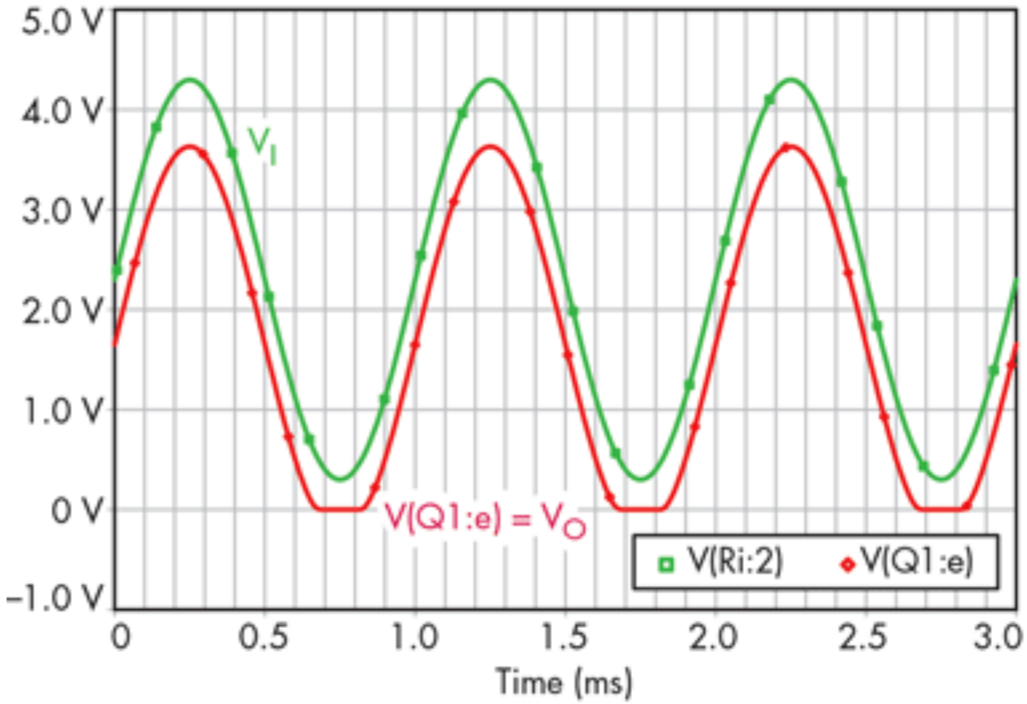


$V_{in} = 2.2 + 2 \sin \omega t$

$V_{out} = 1.6 + 2 \sin \omega t$ but output clips at 0 V



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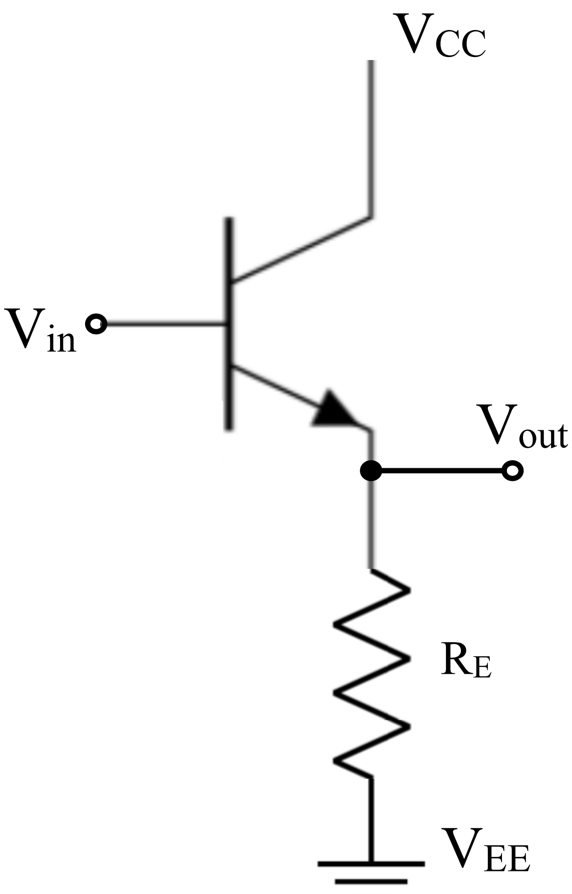

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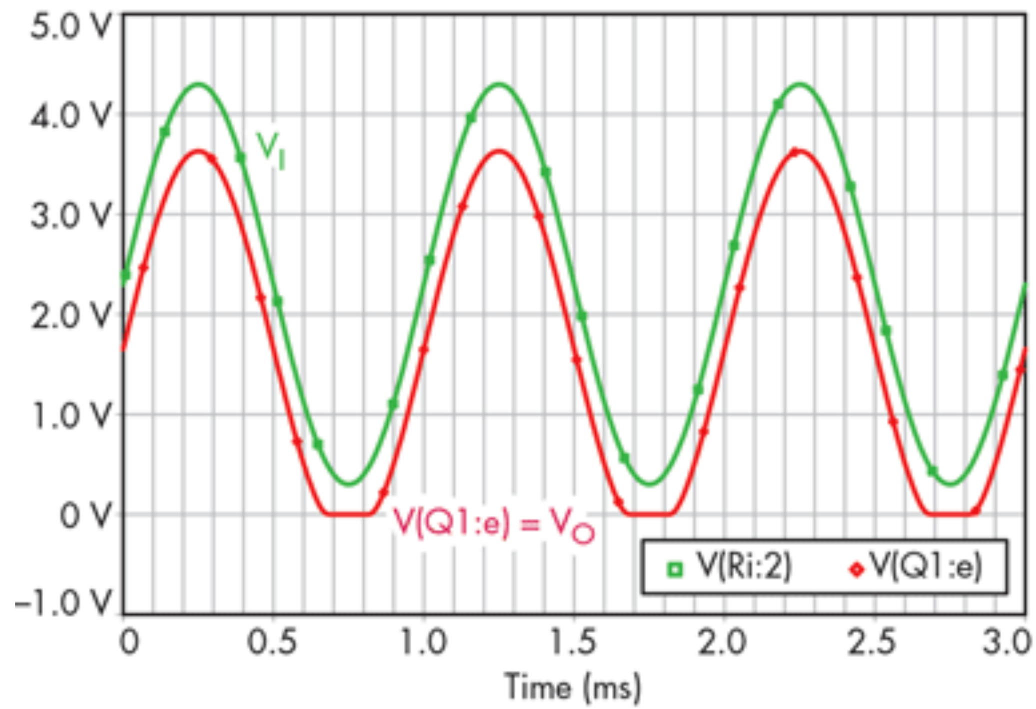
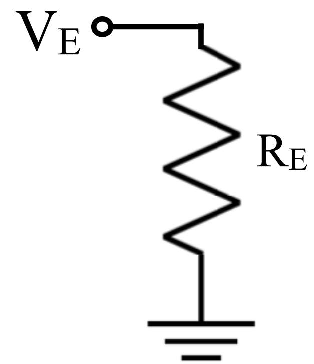
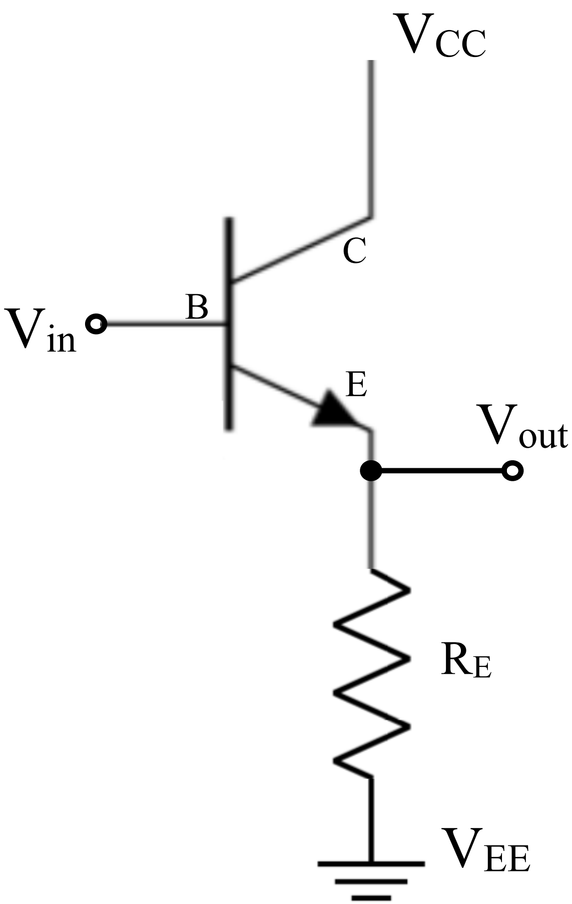
We will soon find work-arounds to avoid clipping.



Emitter follower

The benefit here is <u>increased input impedance</u>. Recall that impedance is $R = \Delta V / \Delta I$





Without the transistor we need to flow $\Delta I = \Delta V / R_E$ to change V_{in} by ΔV

With the transistor, we can calculate R_{in} from

$$R_{in} = \Delta V_{in} / \Delta I_{in} = \Delta V_B / \Delta I_B$$

The base current is $1/\beta$ of the emitter current, since $I_E \cong I_C = \beta\, I_B$. So,

$$R_{in} = \Delta V_{in} / \Delta I_{in} = \Delta V_B / (\Delta I_E/\beta) = \beta \Delta V_B / \Delta I_E$$

We also had from the transistor rules that $V_B = V_E + 0.6$, so $\Delta V_B = \Delta V_E$, so

$$R_{in} = \beta \Delta V_B / \Delta I_E = \beta \Delta V_E / \Delta I_E = \beta R_E$$

The input impedance is β times larger than R_E.
<u>The transistor amplifies the impedance by $\beta \cong 100$.</u>

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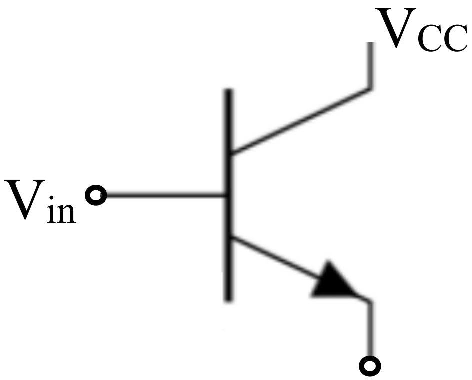

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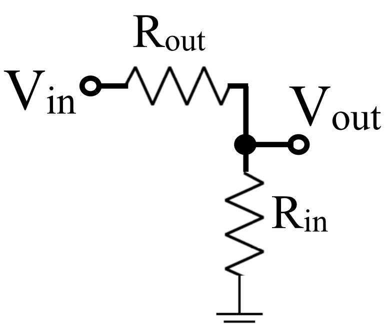
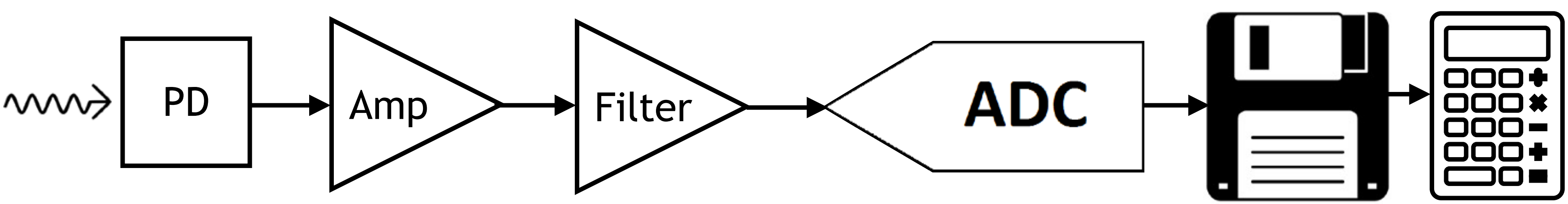
This is the way to make each stage have large input impedance; put a transistor at its input.

The emitter will follow the *variations* in the input.
The DC shift of 0.6 V is not a problem because
the variation of V_{in} is the signal.

The additional power needed is supplied by V_{CC}.





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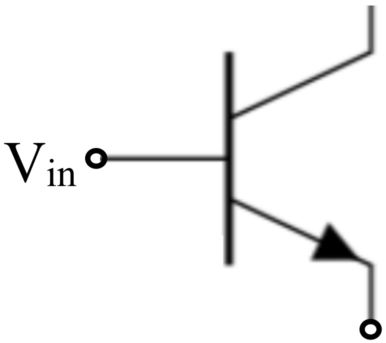

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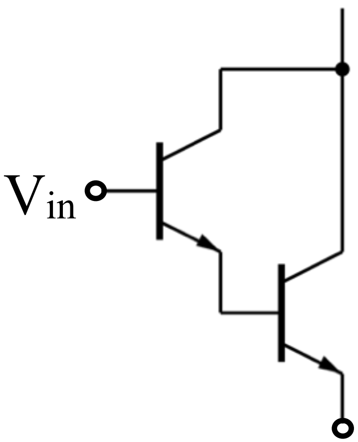
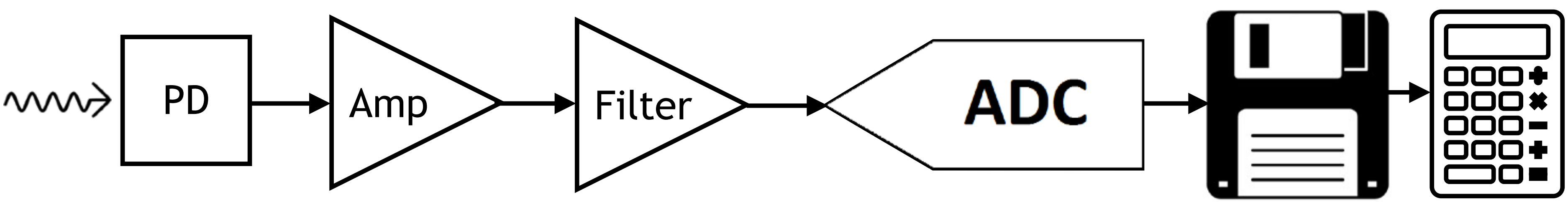
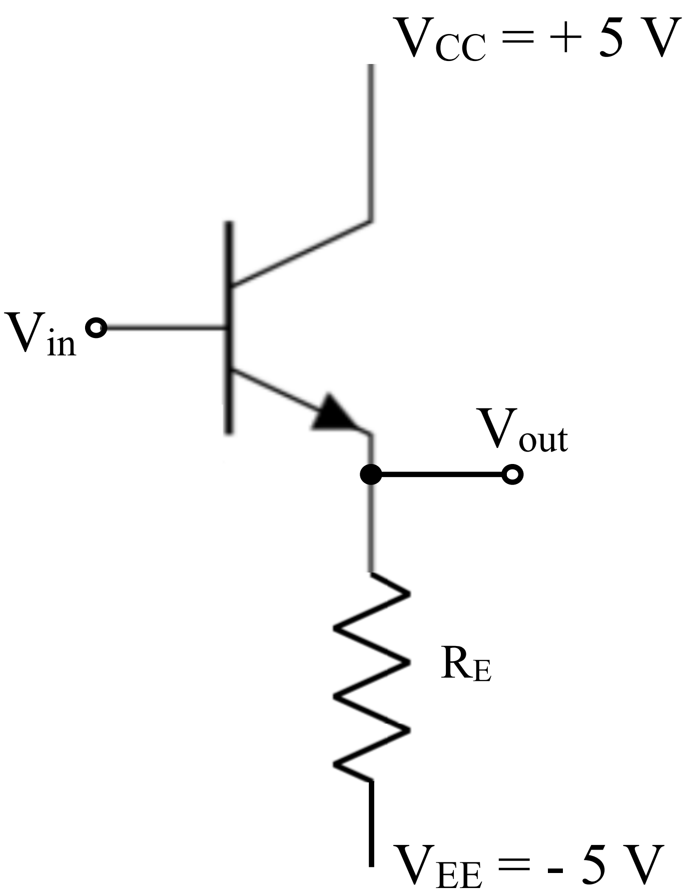


Can get a factor of β^2 with two followers. (Darlington configuration.)
However, that costs two diode drops.



Emitter follower

We can remove the clipping at 0 V by setting V_{EE} to a negative supply.



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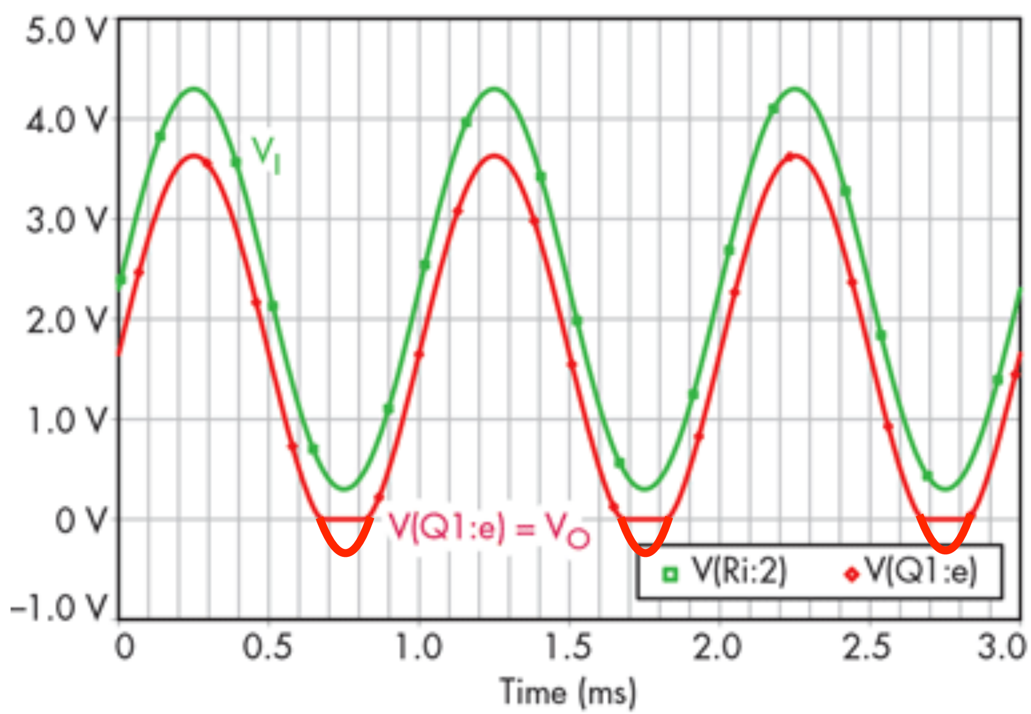
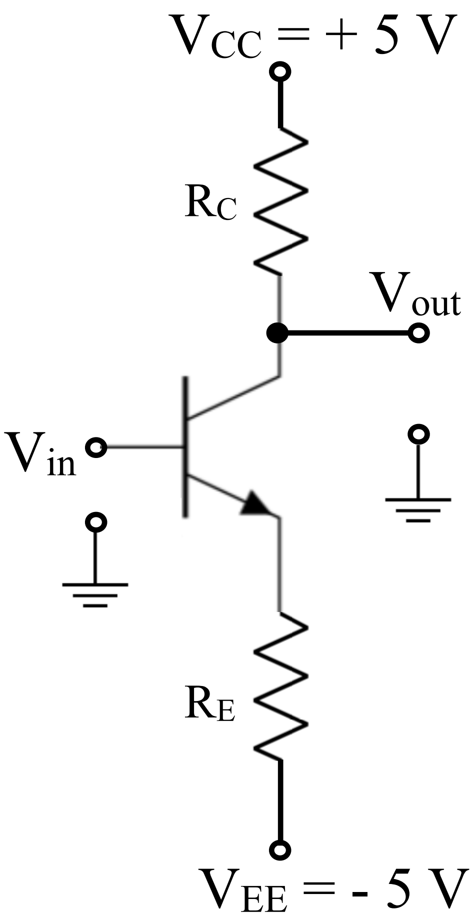


Output clips at V_{CC} and 0.6 V above V_{EE}.

Common-emitter amplifier

We can use the current amplification of the transistor to get voltage amplification.



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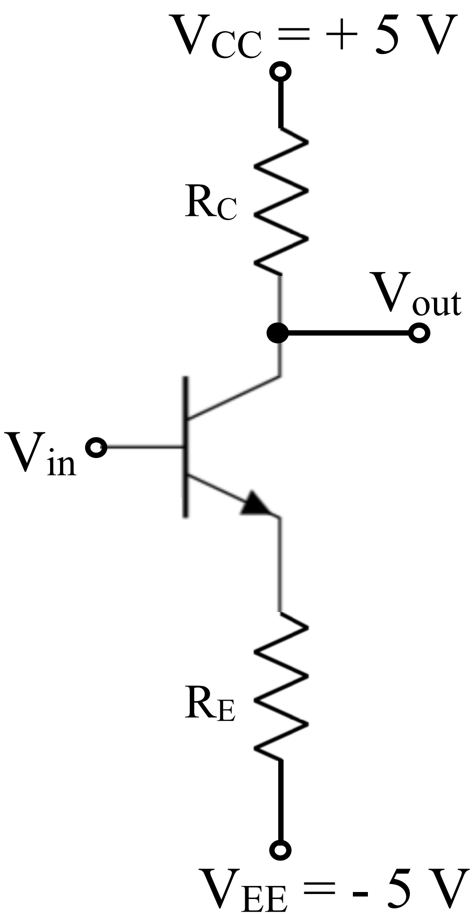

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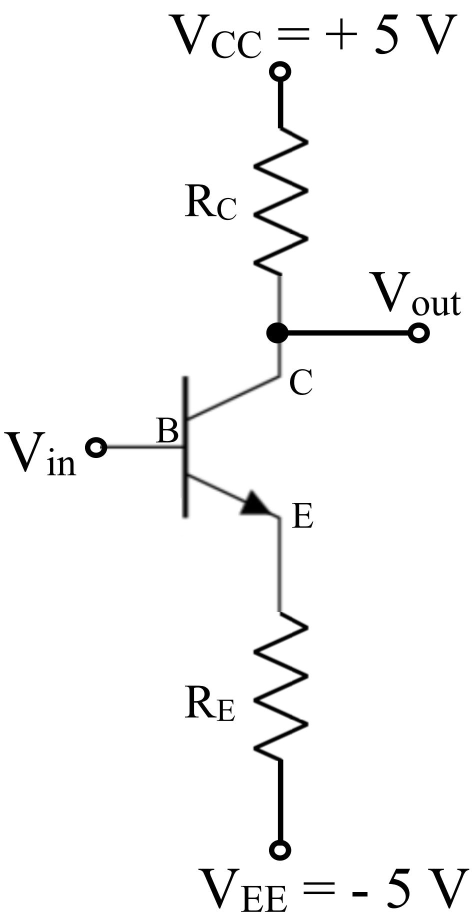

The signal is ΔV_{in} not just the value of V_{in}.
So we want to calculate both V_{out} and ΔV_{out}.
First we'll do the DC part, V_{in}, then the AC part, ΔV_{in}.

$V_E = ?$ and $\Delta V_E = ?$

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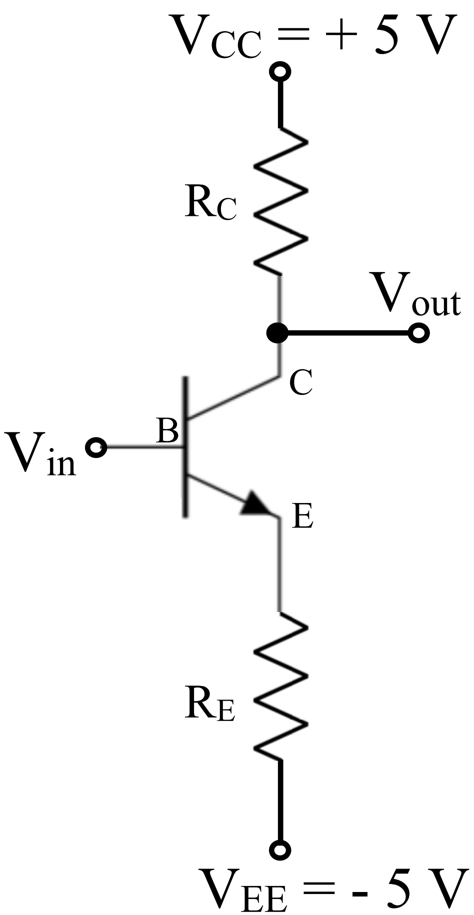

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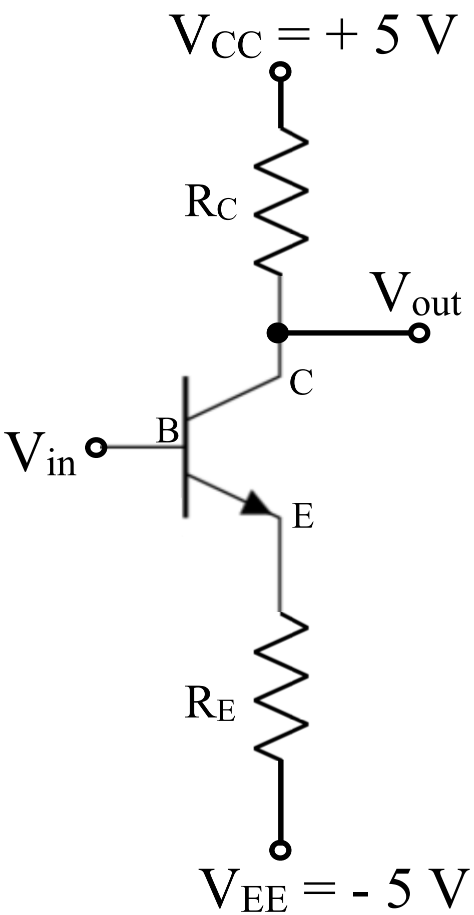

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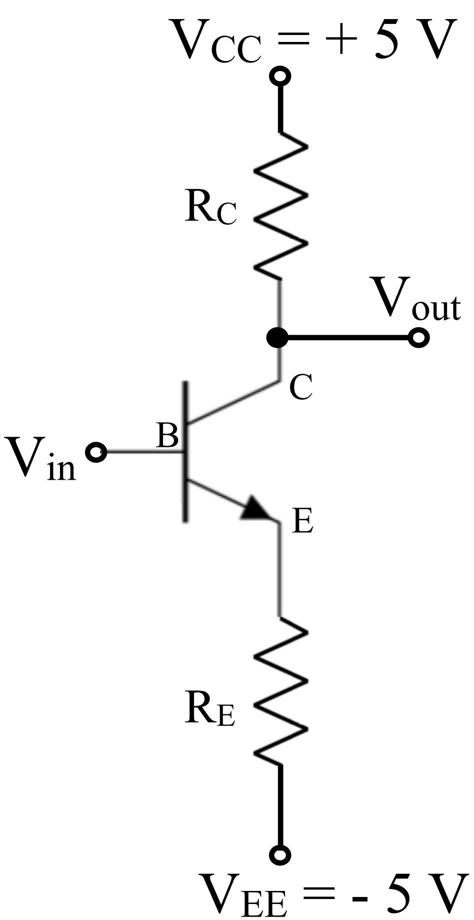

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$V_{out} = V_{CC} - I_C R_C \cong V_{CC} - I_E R_C$. Because $I_E = I_B + I_C$ & $I_E \cong I_C$

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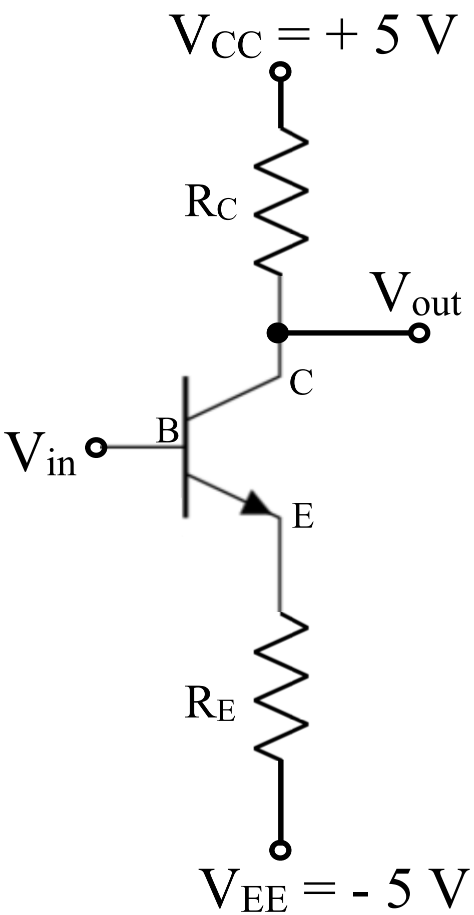

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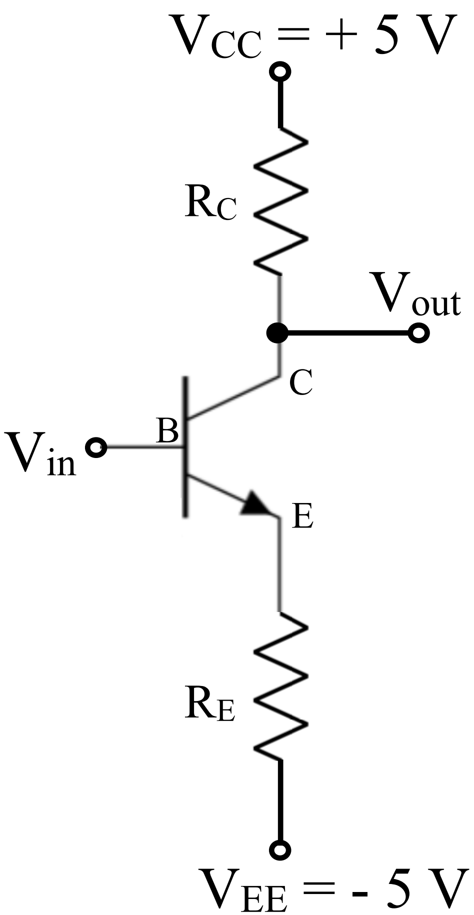

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$\Delta V_{out} = -\Delta V_E(R_C/R_E) = -\Delta V_B(R_C/R_E) = -\Delta V_{in}(R_C/R_E)$

Gain $= \Delta V_{out} / \Delta V_{in} = -R_C/R_E$

Negative gain OK for music.
Choose amplification by choosing resistance values.

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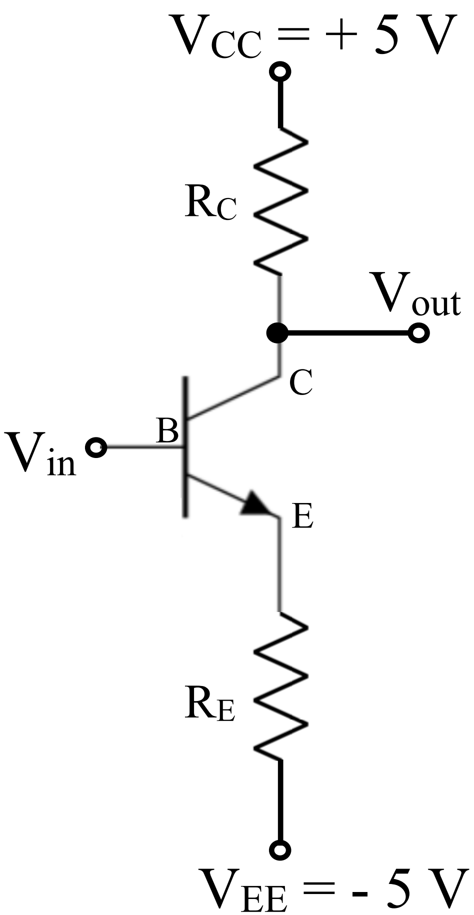

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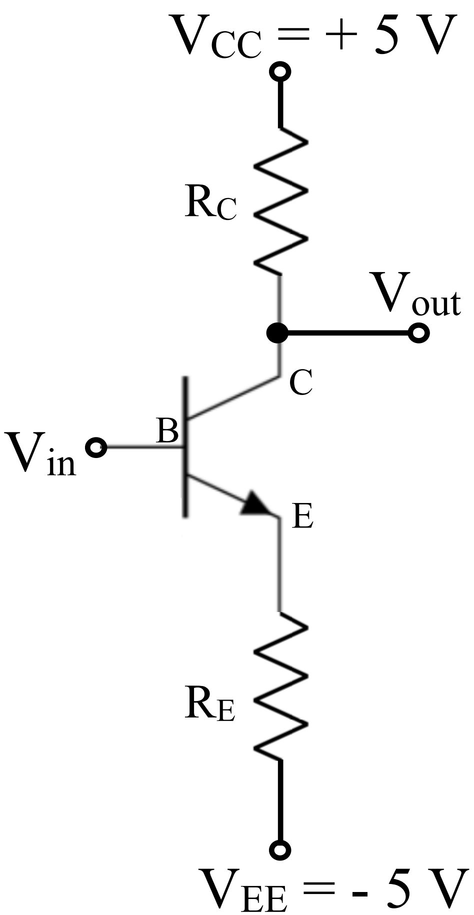
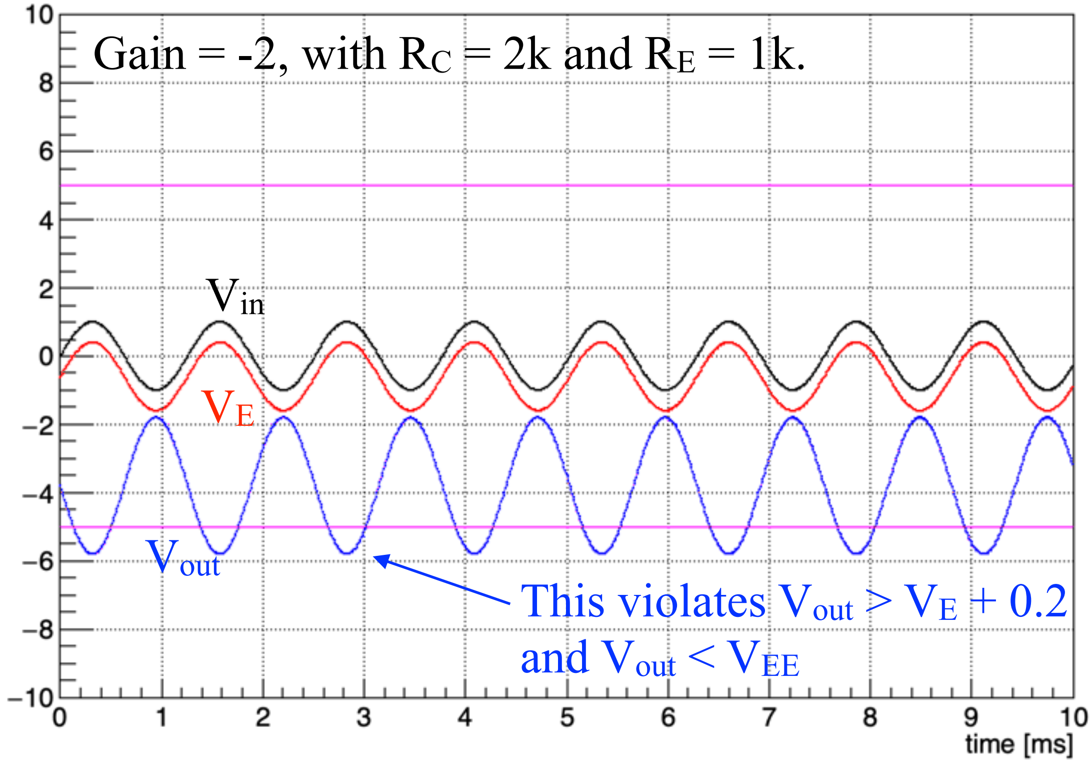
The AC response matters for the signal amplification, but the DC offset matters for clipping.

Transistor requires: $V_{out} < V_{CC}$ and $V_{out} > V_E + 0.2$

Can't have V_{in} and V_{out} both oscillating around zero.





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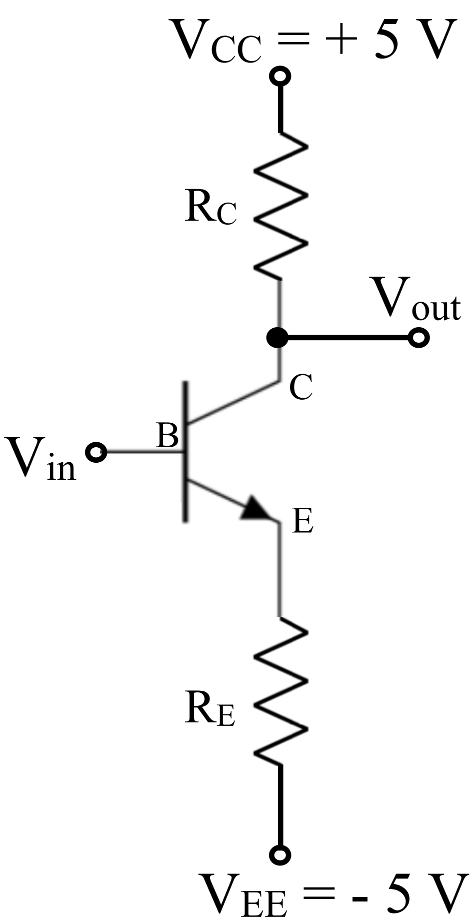

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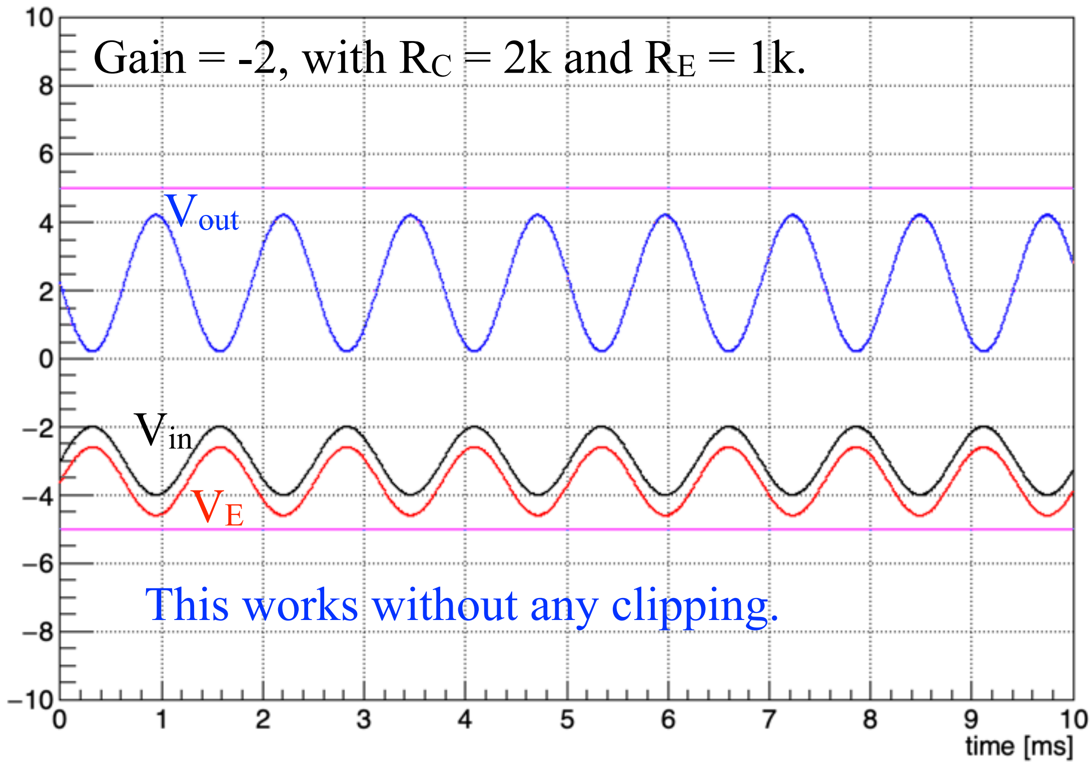

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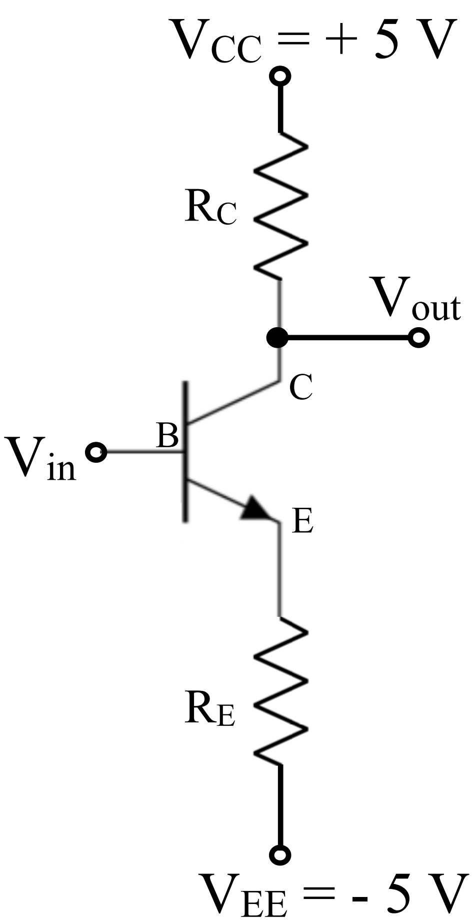

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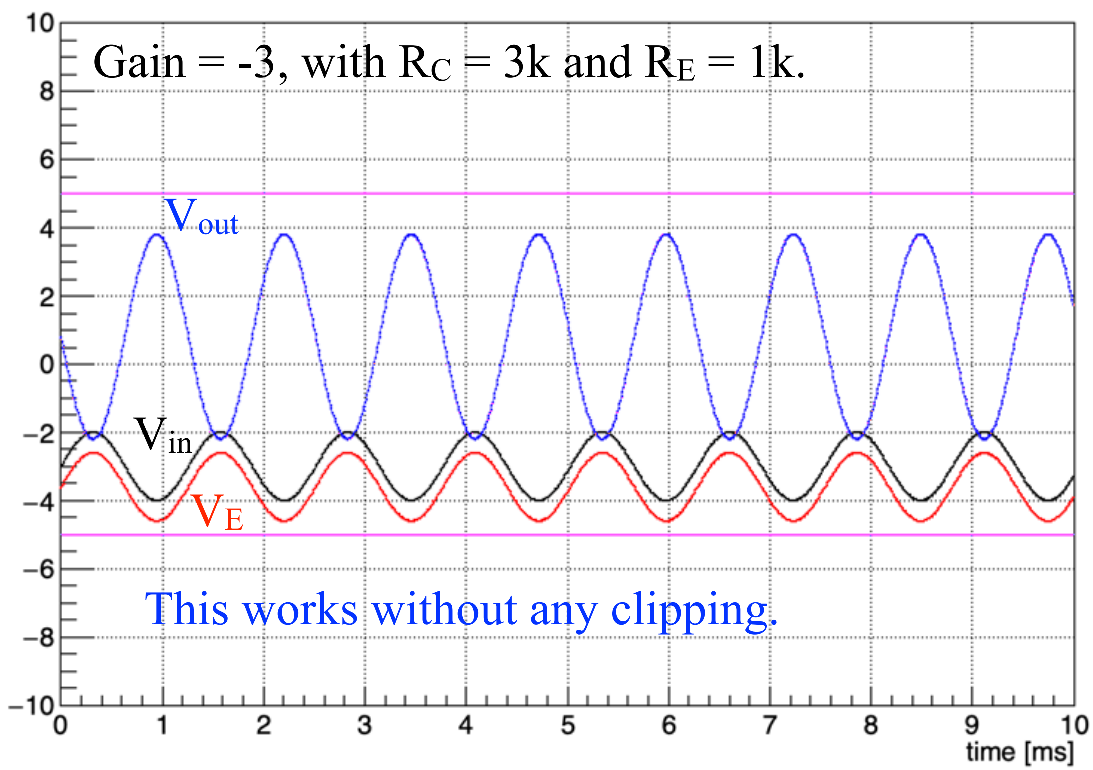
The AC response matters for the signal amplification, but the DC offset matters for clipping.

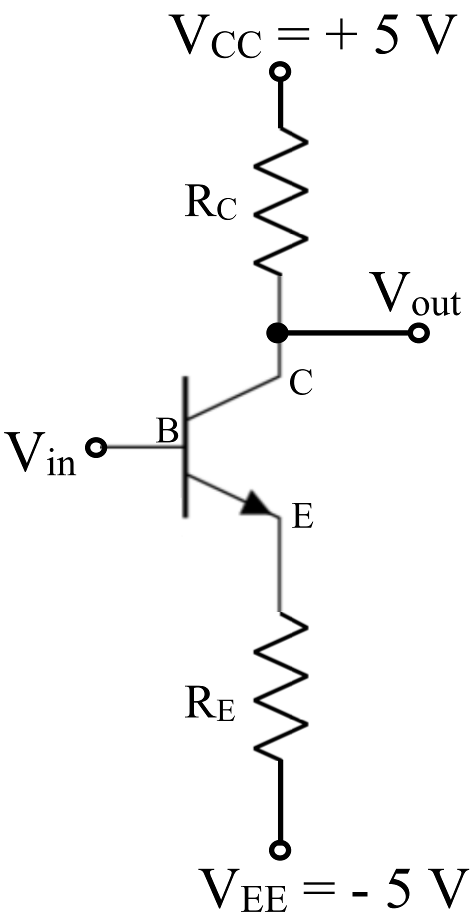
Transistor requires: $V_{out} < V_{CC}$ and $V_{out} > V_E + 0.2$

Can't have V_{in} and V_{out} both oscillating around zero.



Common-emitter amplifier

We can use the current amplification of the transistor to get voltage amplification.



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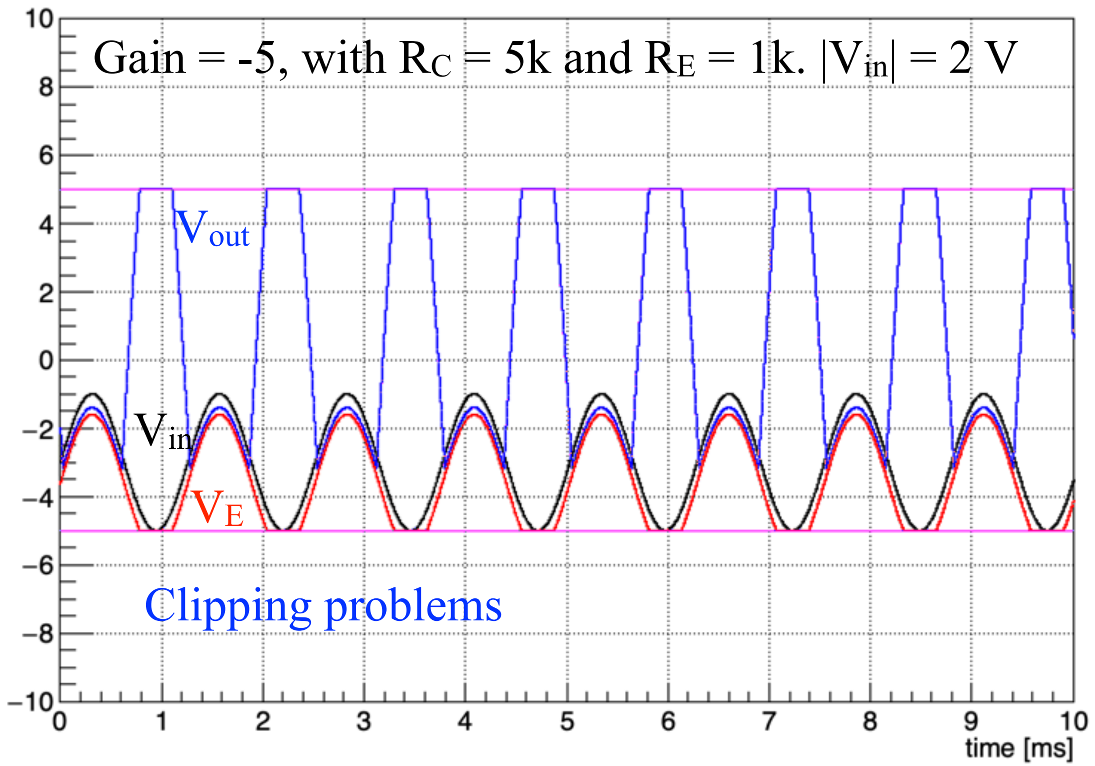
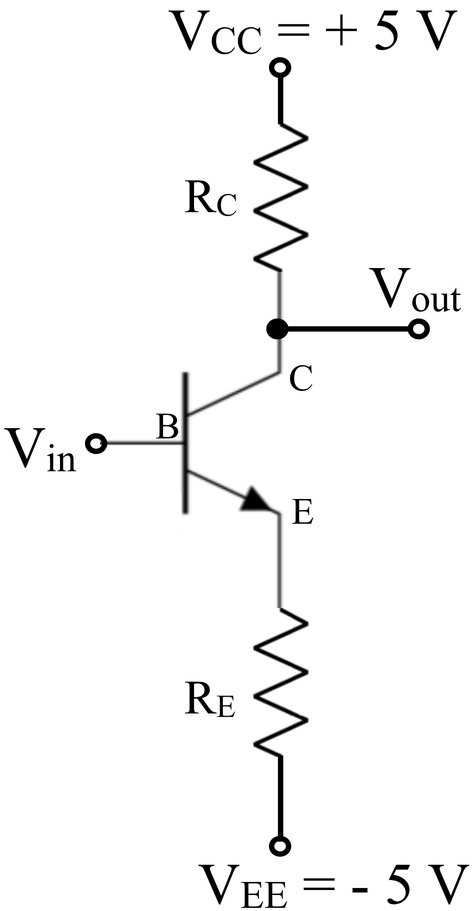


Common-emitter amplifier input biasing

We want an amplifier stage that doesn't need the previous stage to carefully adjust the offset voltage to avoid clipping. So build it in.



Apply an "input bias" that puts the emitter close to V_{EE}, within a ΔV that defines the max input swing.

Common-emitter amplifier input biasing

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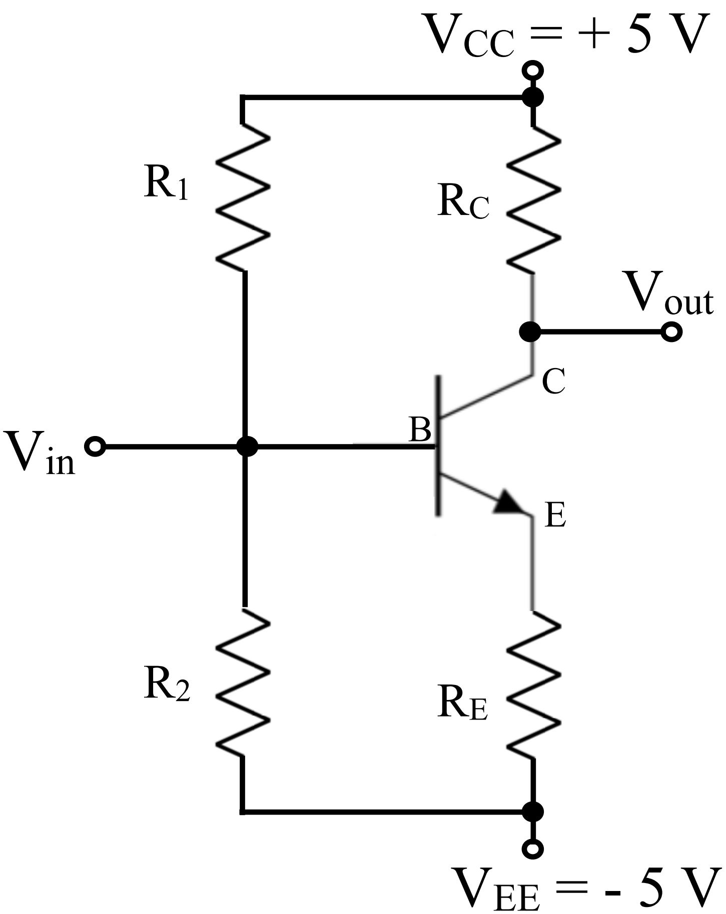


Suppose I want a max input swing of ±0.1 V

Set V_E to vary from -4.8 to -5.0, i.e.,

DC set point for V_E is -4.9 V.

DC set point for V_{in} is -4.3 V.

These are called the *quiescent* values, meaning "when quiet, ie without signal".

Choose R_1 and R_2 to be a voltage divider setting V_{in} at -4.3 V.

$V_{in} = V_{EE}+(V_{CC}-V_{EE})*R_2/(R_1+R_2)$

$-4.3 = -5 + 10*1k/(1k+R_2)$

$R_1 = 13k$ and $R_2 = 1k$

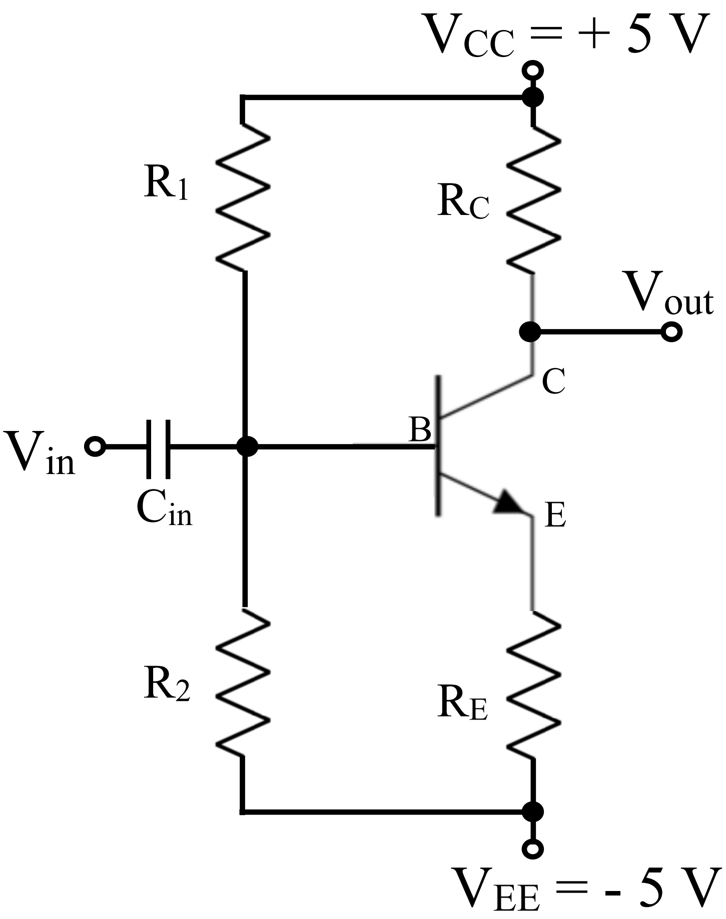
Or I could use

$R_1 = 130k$ and $R_2 = 10k$

Which choice is better?

Common-emitter amplifier input biasing

Apply an input bias that puts the emitter close to V_{EE}, within a ΔV that defines the max input swing.



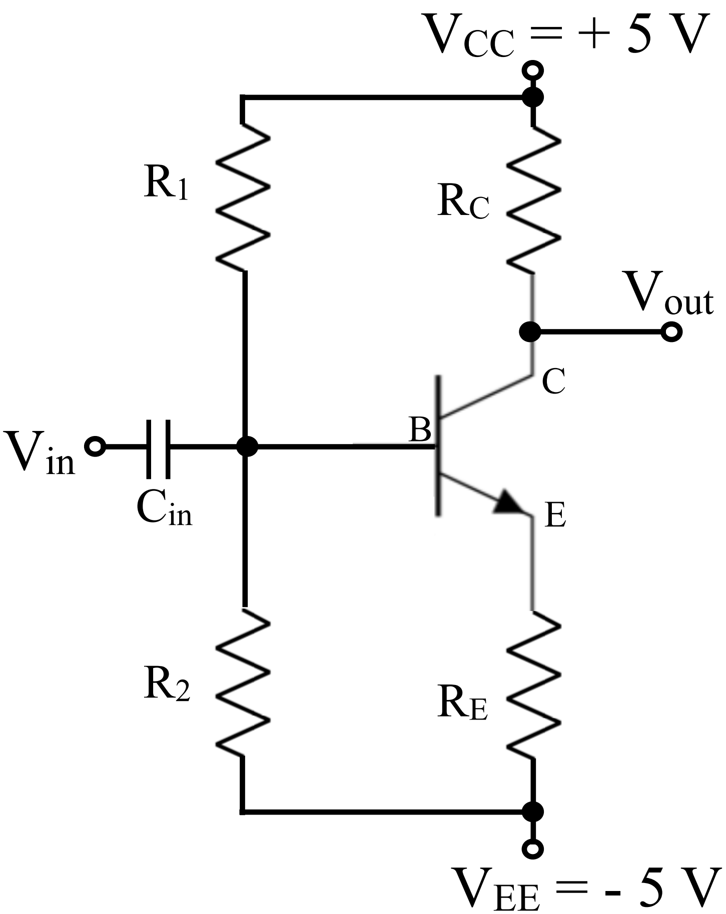
Suppose I want a max input swing of ±0.1 V
Set quiescent points: V_E=-4.9 V & V_{in}=-4.3 V.
R_1 = 130k and R_2 = 10k

But now this stage yanks the output of the previous stage to a different voltage.
Fix that by *decoupling* the input from this "DC bias voltage" with a "decoupling capacitor".

$R_{in}C_{in}$ make a high-pass filter letting the signal through and blocking the DC offsets.
What is R_{in}?

Common-emitter amplifier input biasing

Apply an input bias that puts the emitter close to V_{EE}, within a ΔV that defines the max input swing.



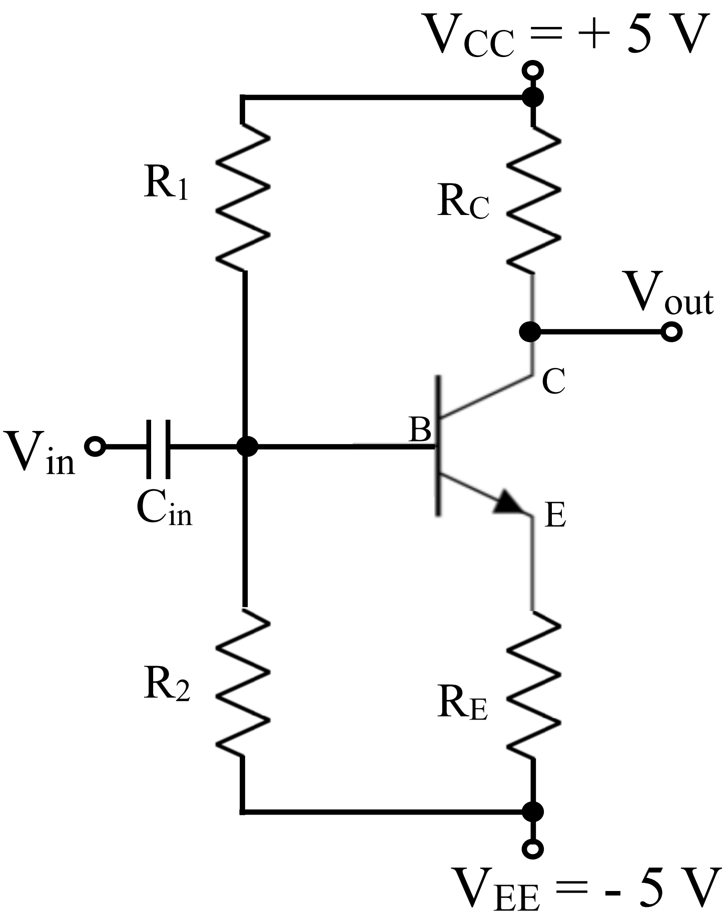
Input impedance is all paths from input to a fixed voltage (V_{CC}, V_{EE}, or Gnd).

$R_{in} = R_1 \parallel R_2 \parallel \beta R_E \cong 130k \parallel 10k \parallel \beta R_E \cong R_2.$

High-pass filter should have f_{3dB}<signal frequency range.
For audio signals, that is 20 Hz, so
$20 = 1/2\pi(10k)C$
$C \cong 1/6*120*10k \cong 1/1k*10k = 0.1\ \mu F$

Common-emitter amplifier input biasing

Now we need to pick R_E and R_C



The ratio of R_E and R_C is set by the desired gain, and avoiding output clipping.

Choose gain = 10.

That means Vout swings by ±1 V.

Then quiescent point for V_{out} to be at least 1 V away from V_{CC} and V_E.

But,

$$V_{out} = V_{CC} - V_E(R_C/R_E)+V_{EE}(R_C/R_E)$$

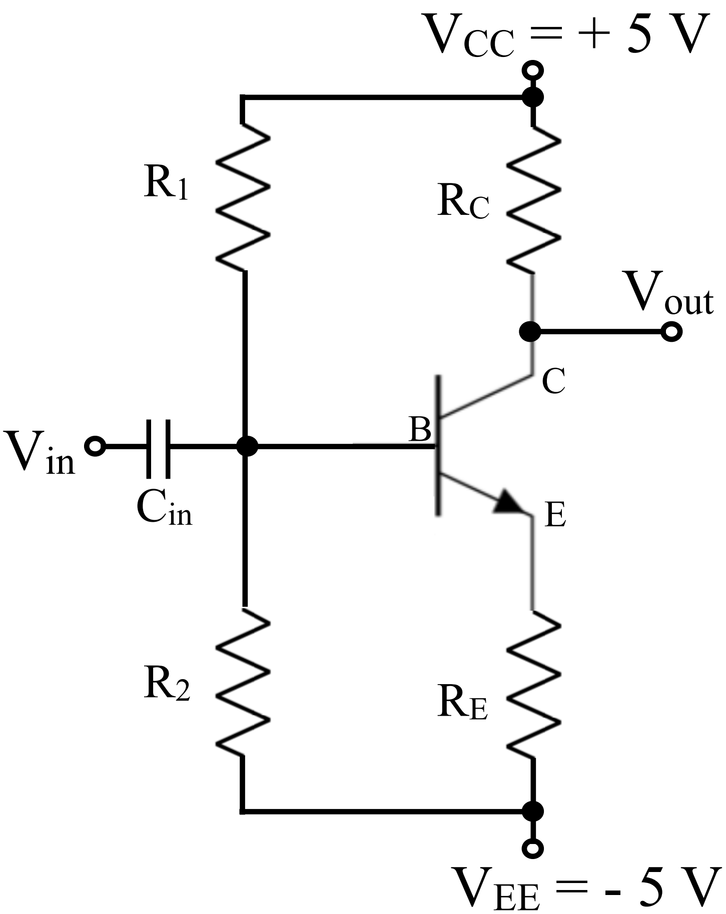
only depends on the gain ratio.

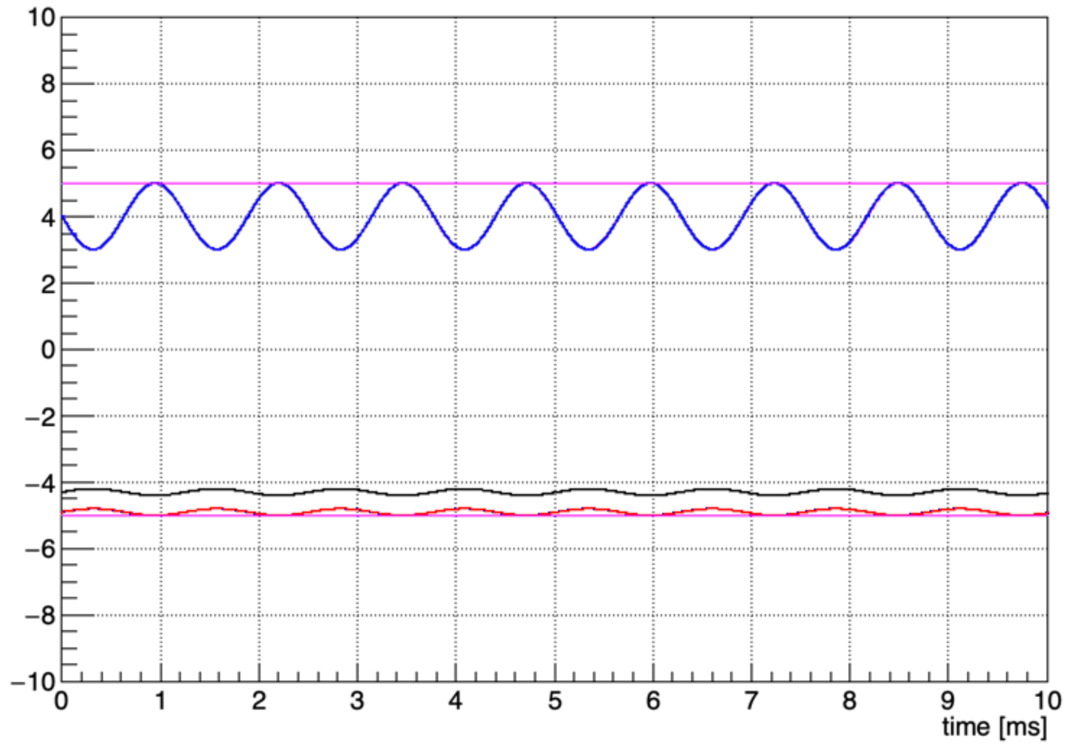
$$V_{out} = 5 - (-4.9*10)-5*10$$
$$= 4$$

That works, but just barely.

Common-emitter amplifier input biasing

Now we need to pick R_E and R_C





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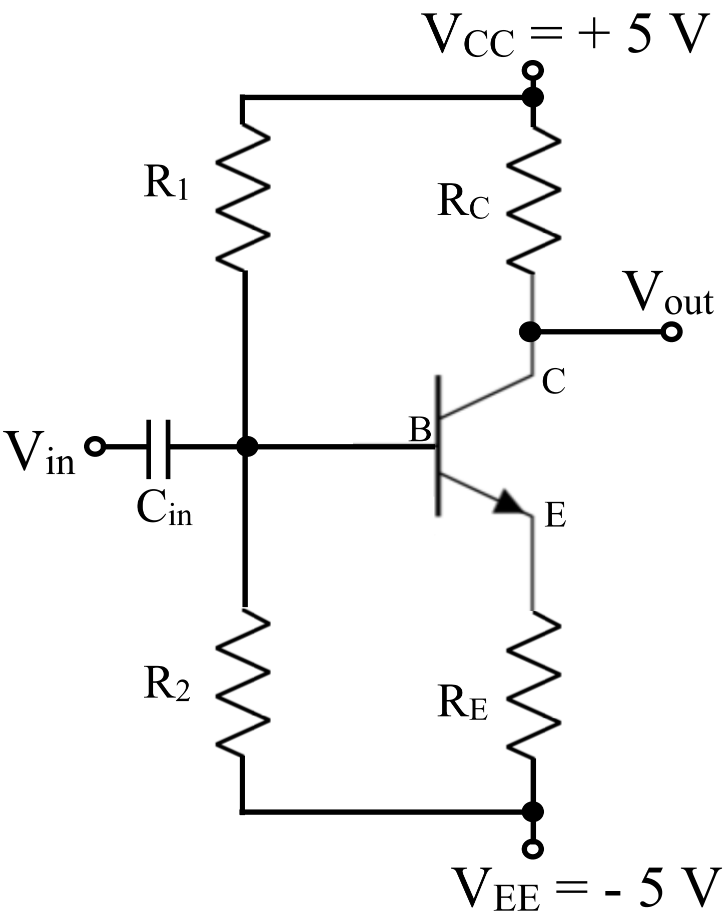
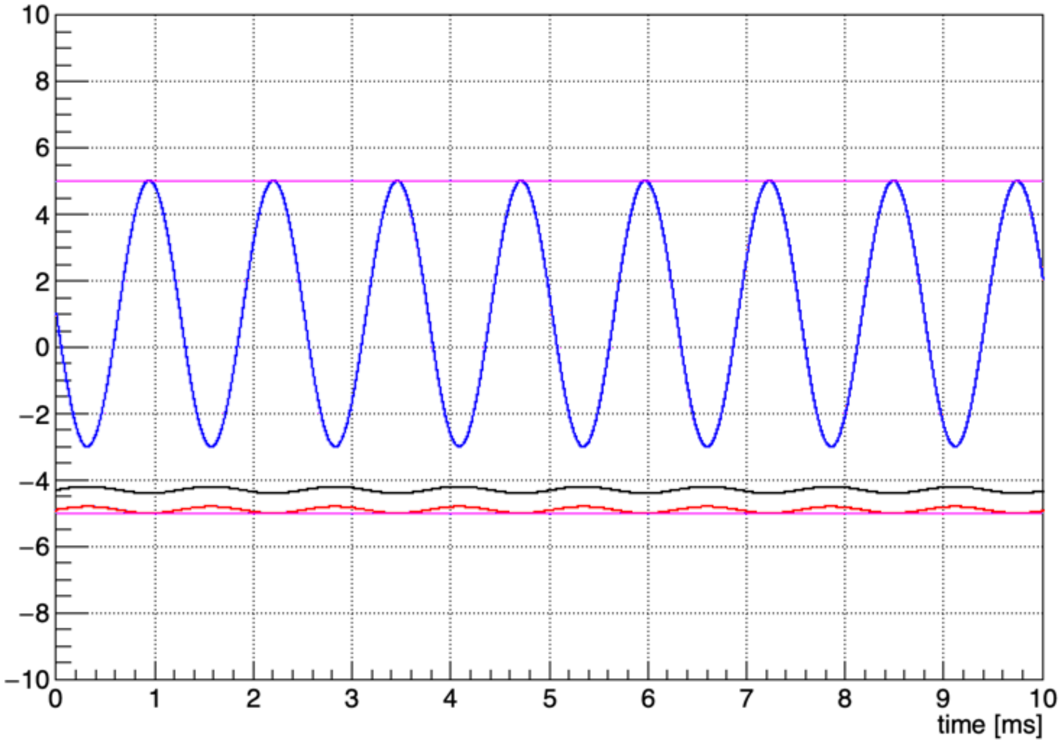
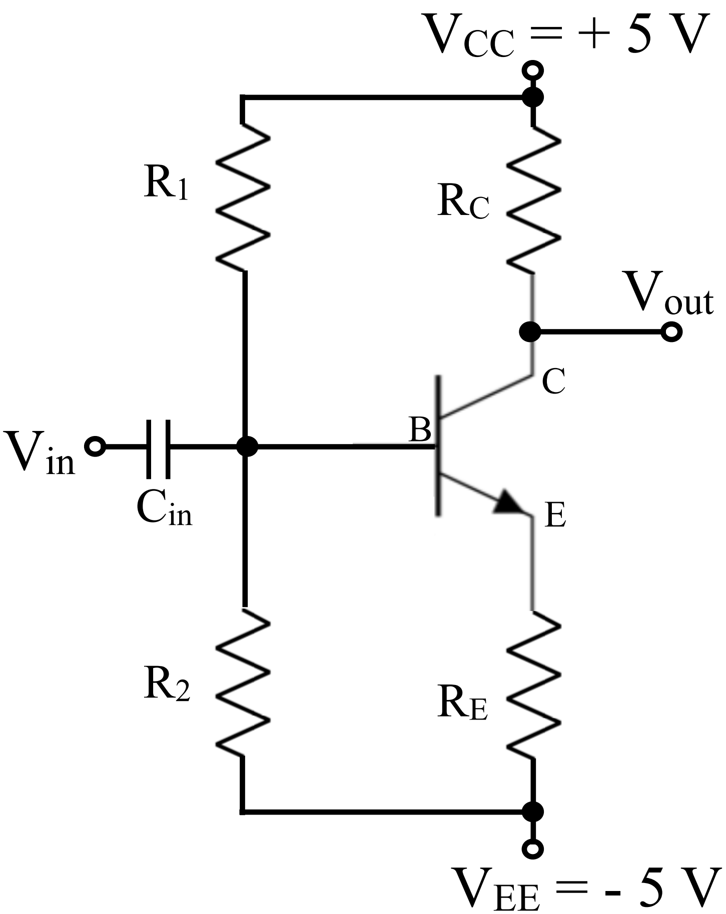




Gain of 40 also works, with V_{out} DC at 1 V.

Common-emitter amplifier input biasing

The challenge here is that R_E affects both the gain and the quiescent V_{out}.
A small R_E gives big gain but large I_E which affects quiescent V_{out}.



We want a large R_E for setting quiescent voltages and a small R_E for setting gain.

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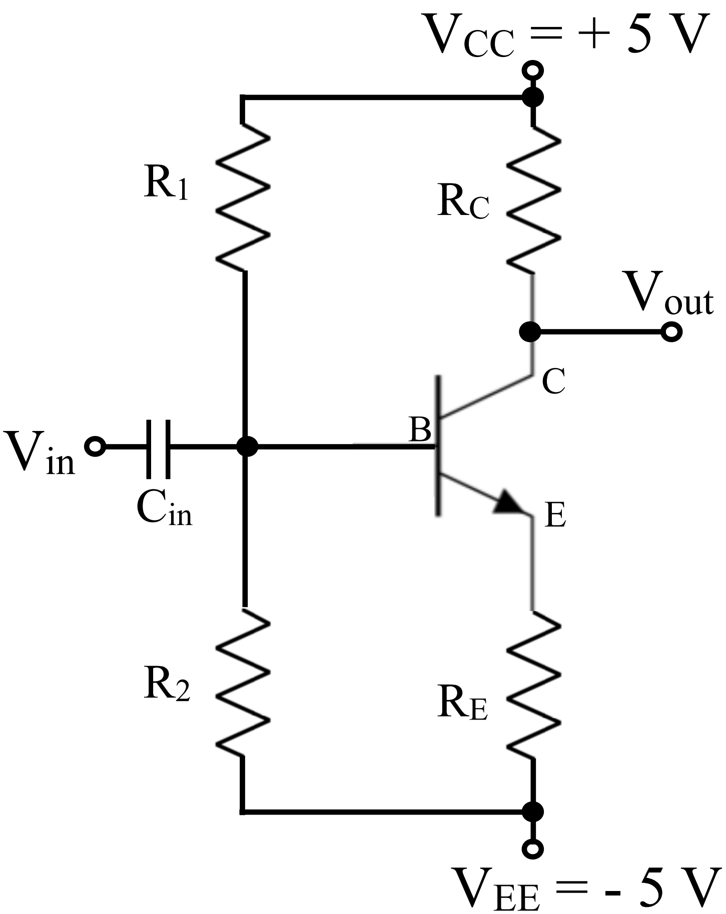

We want a large R_E for setting DC quiescent voltages and a small R_E for setting AC gain.

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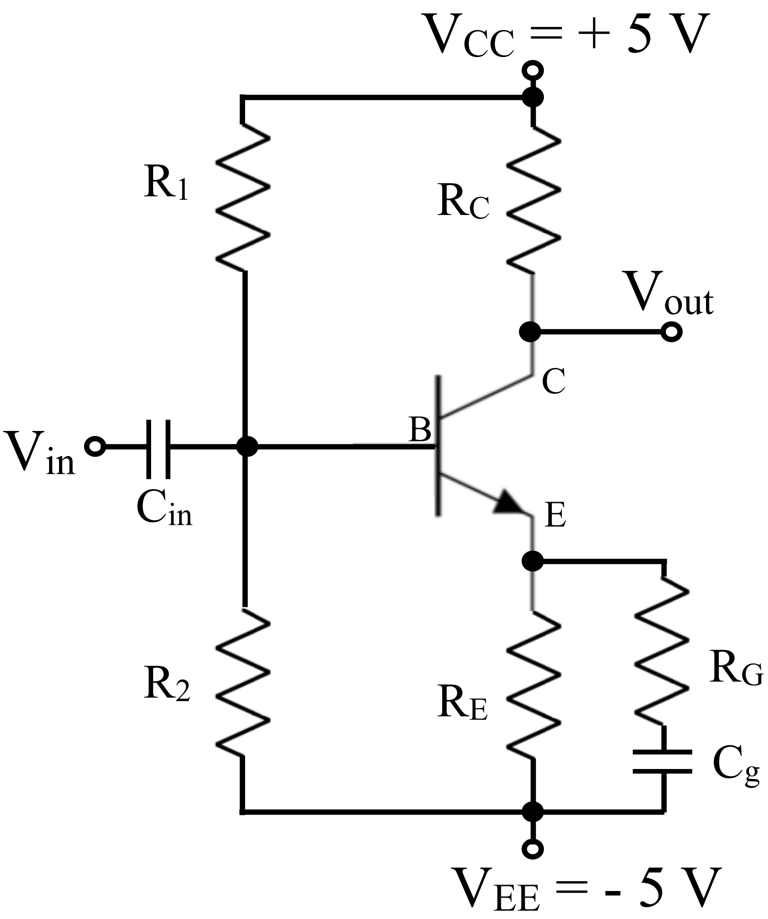
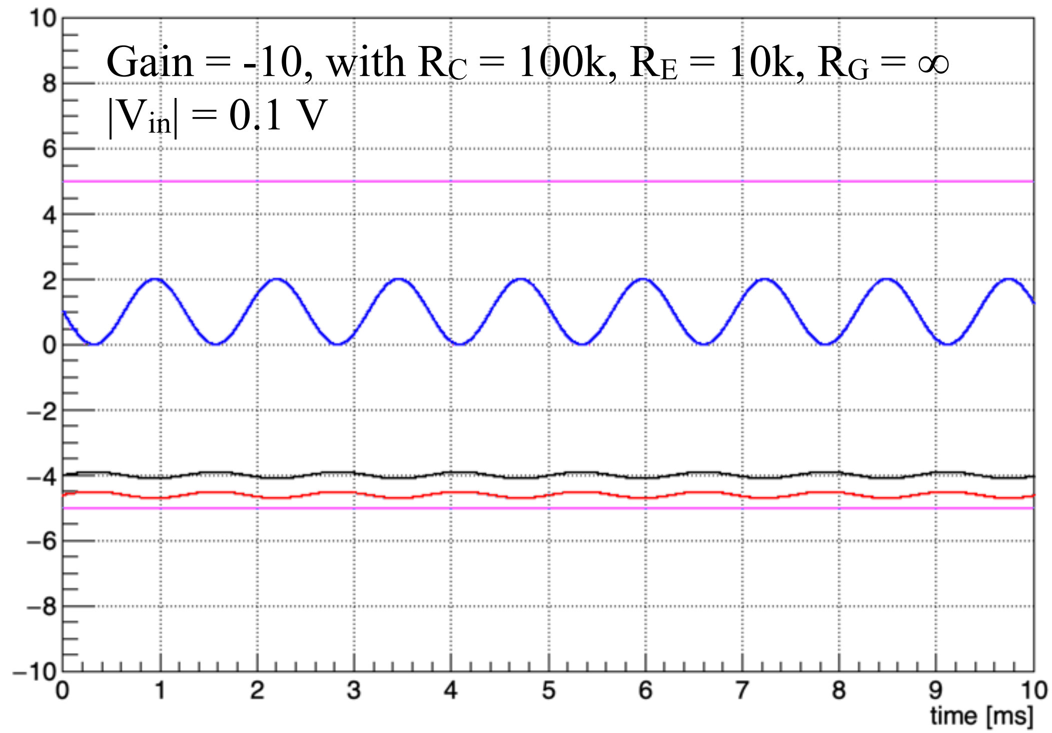


Choose R_1 and R_2 for quiescent V_E = -4 V.
Choose R_E =10k and R_C =100k for quiescent V_{out} = 1 V and base gain of 10.



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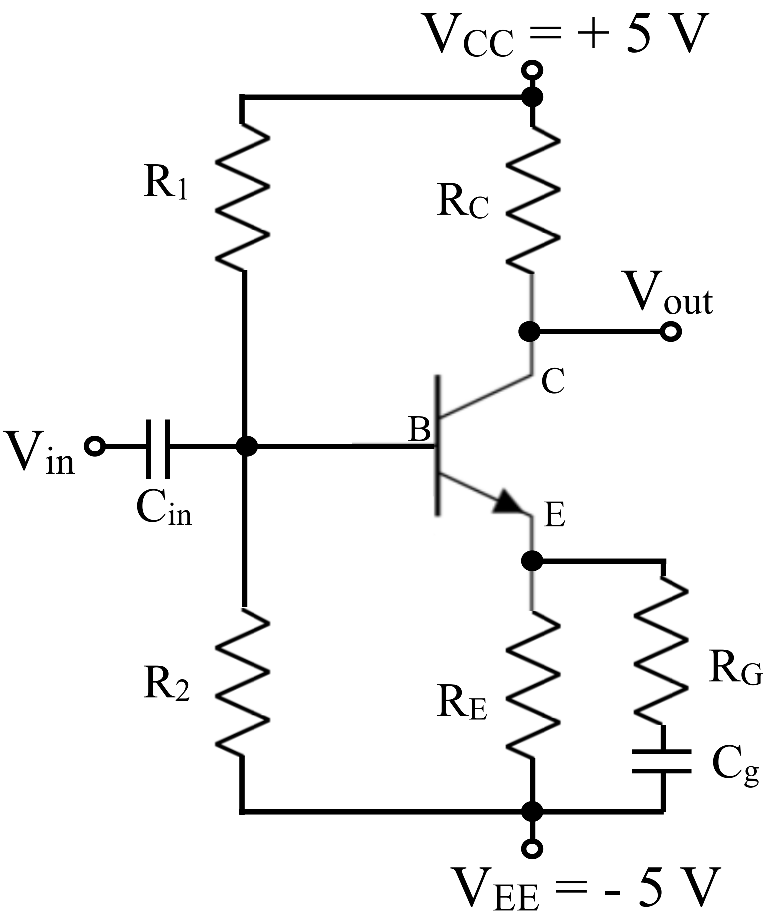

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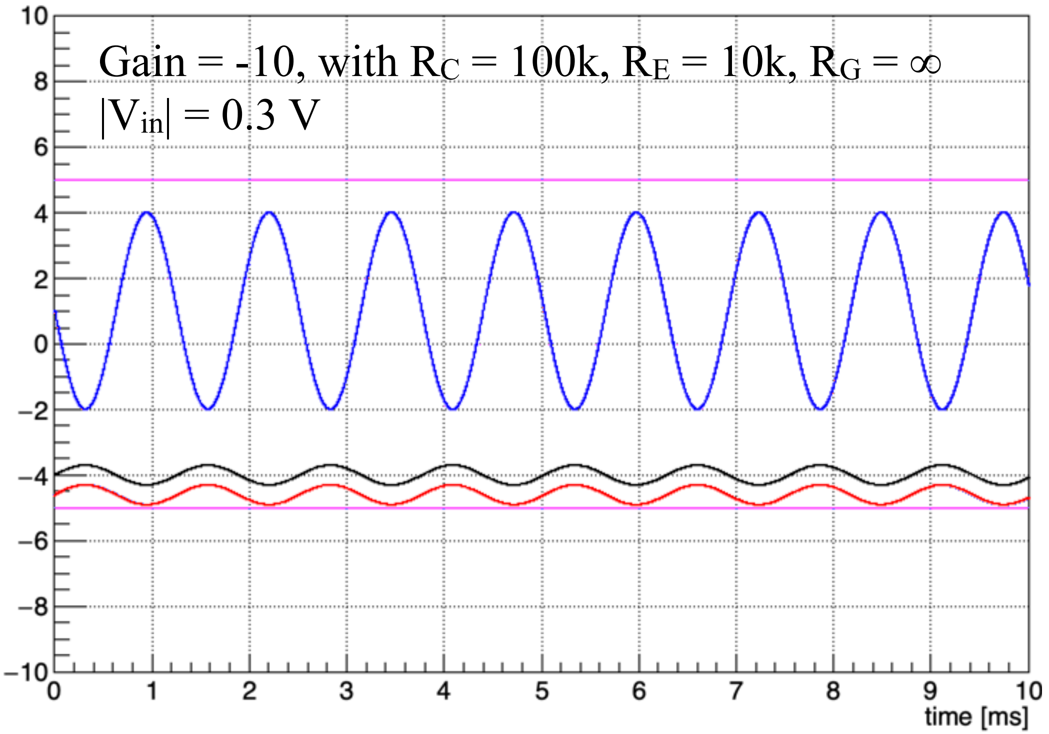

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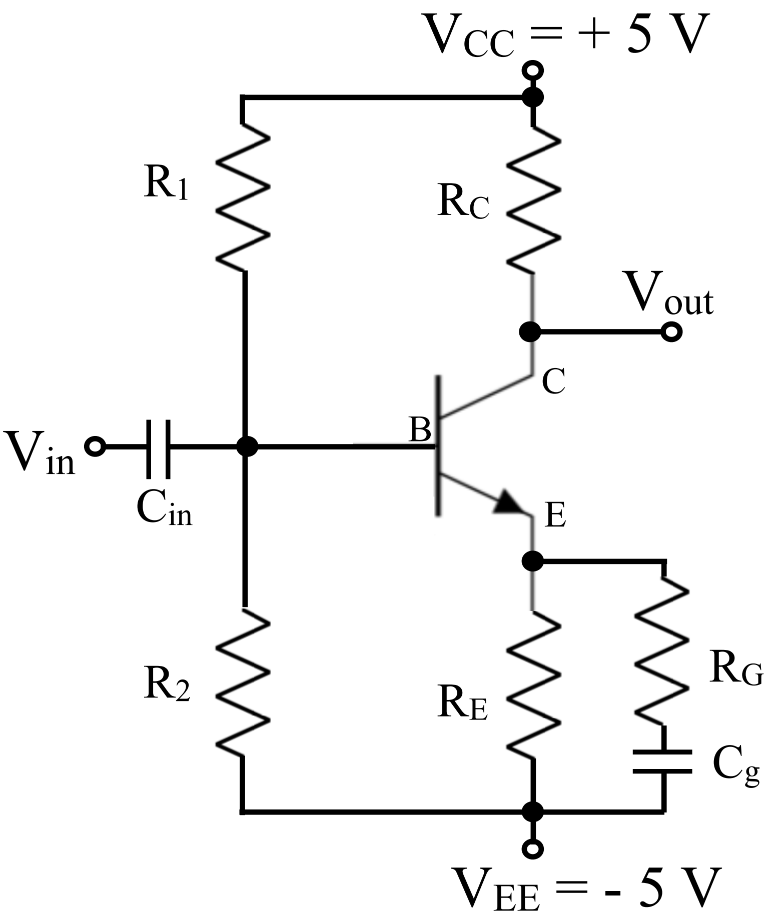

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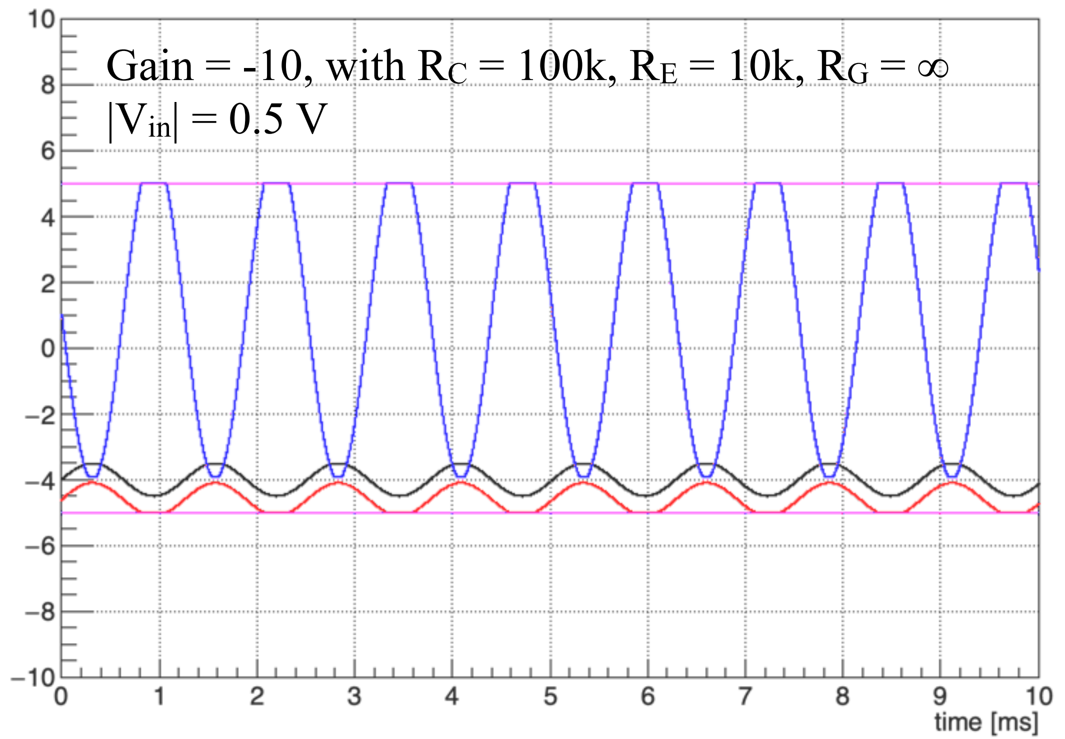

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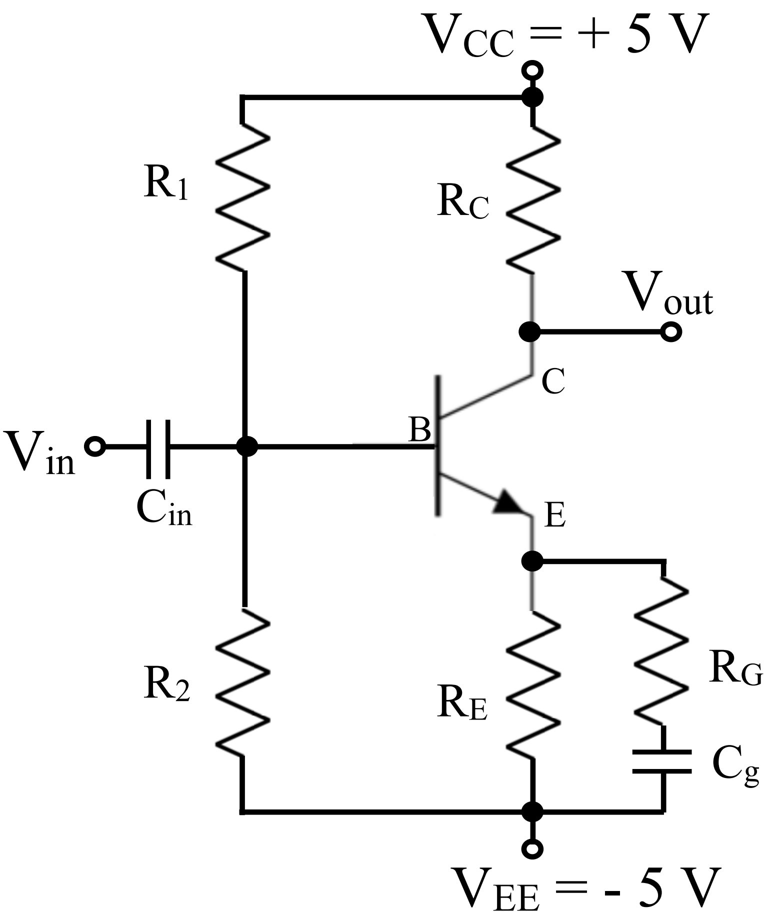

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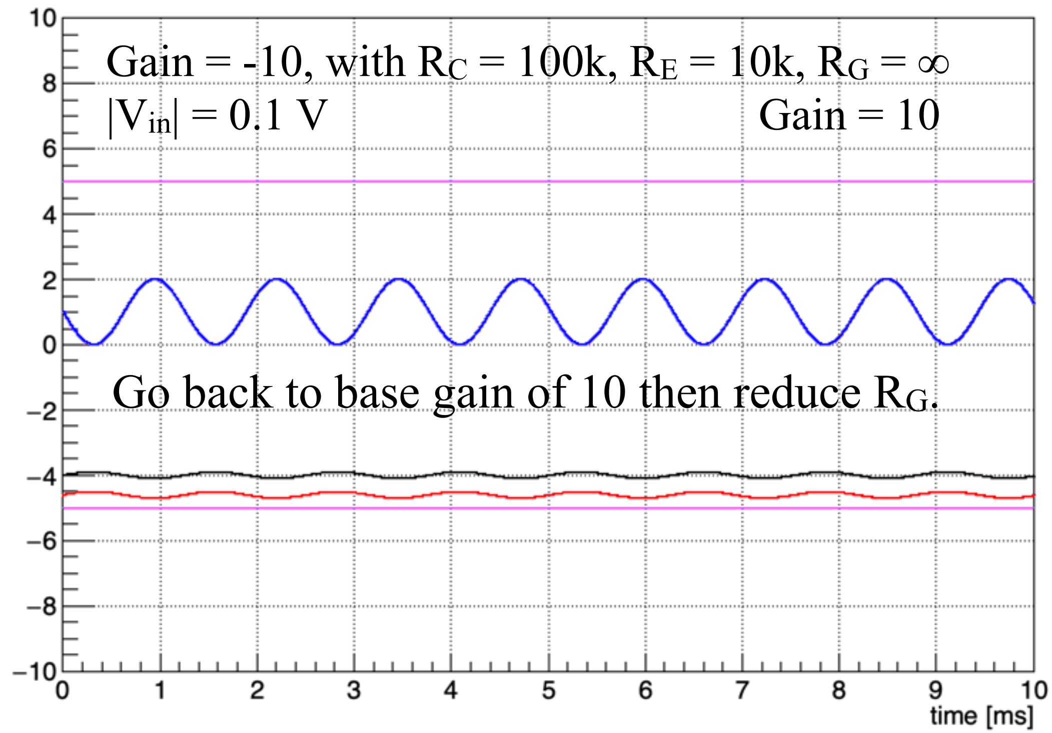

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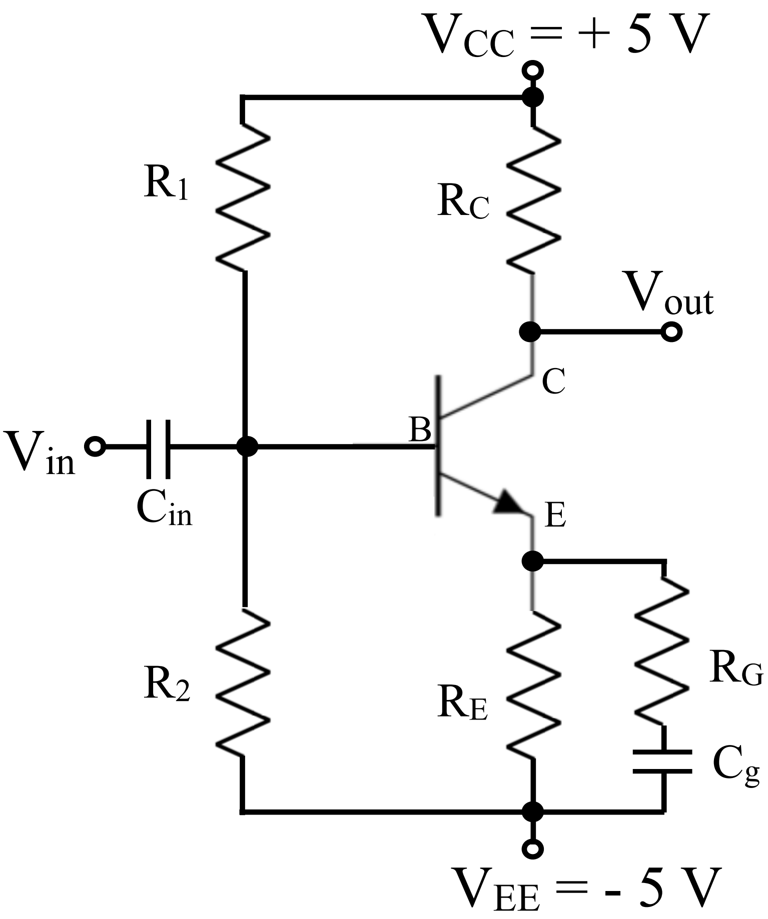

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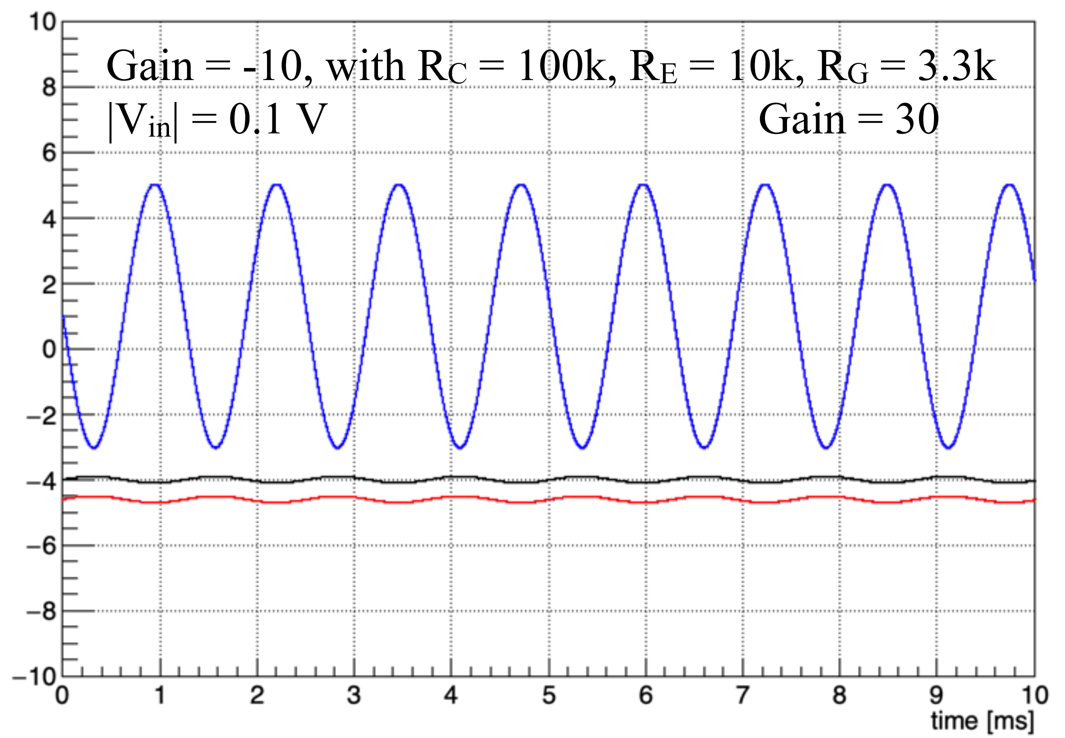

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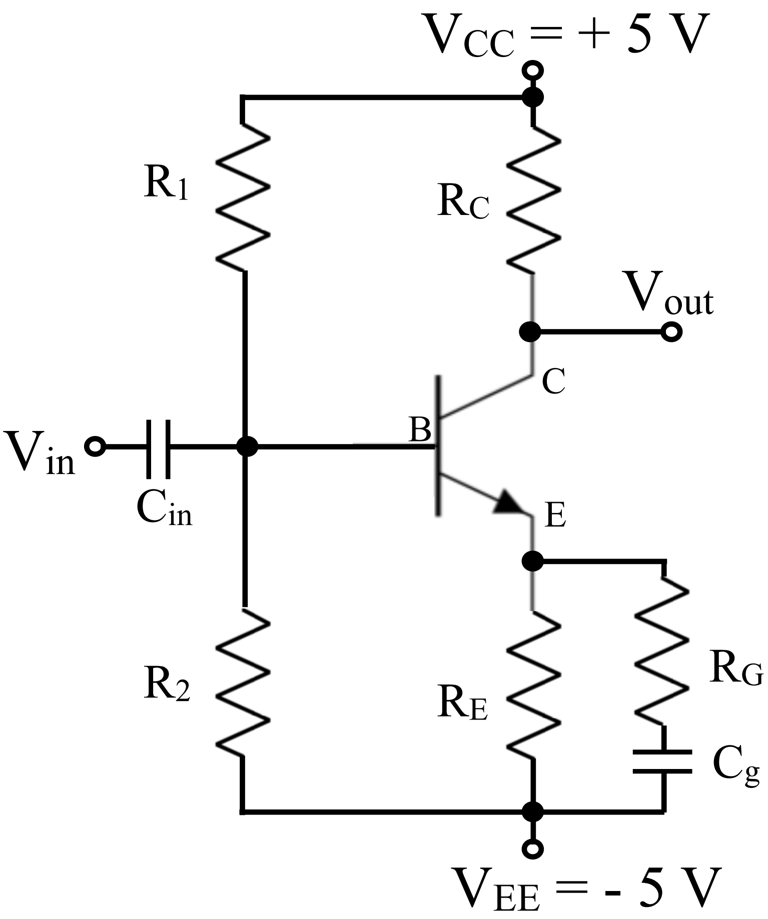

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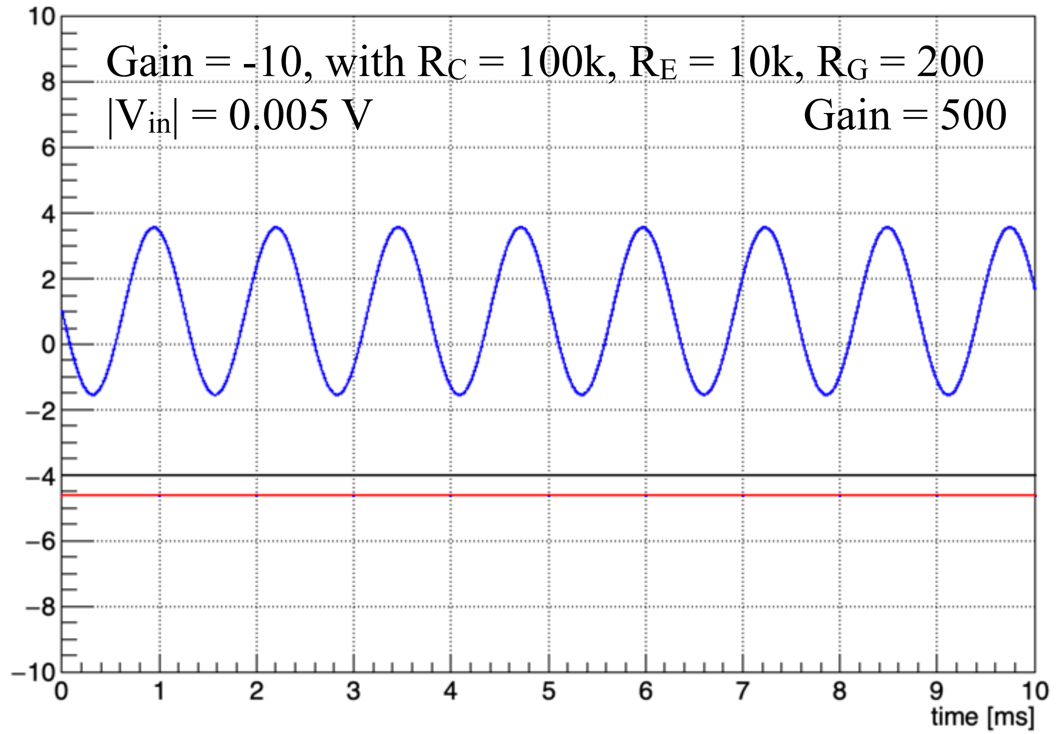
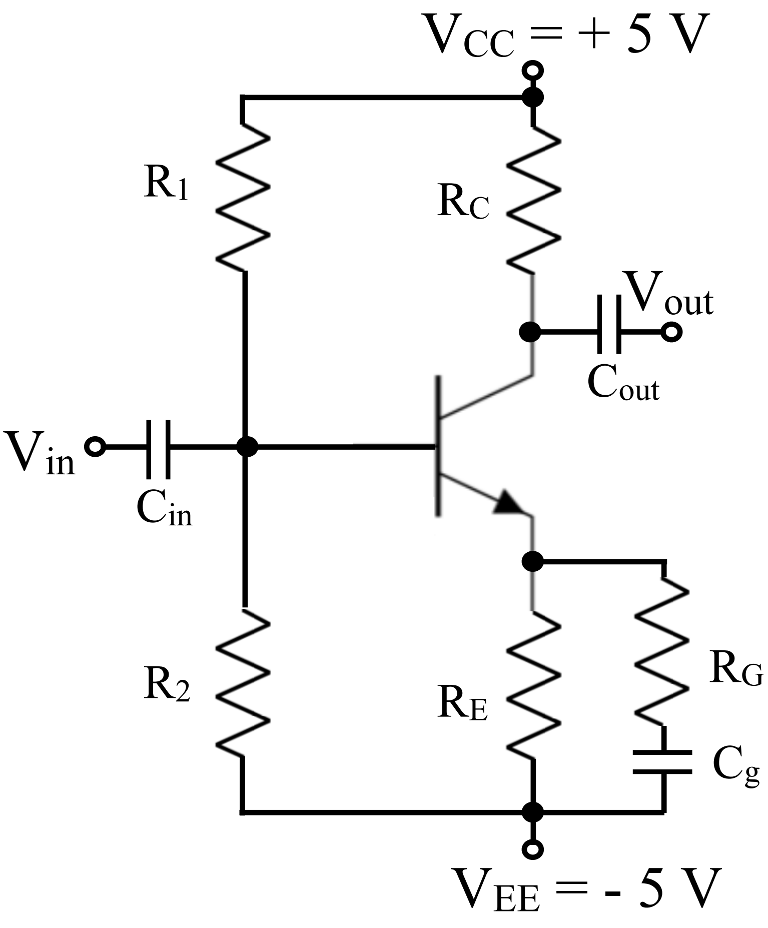
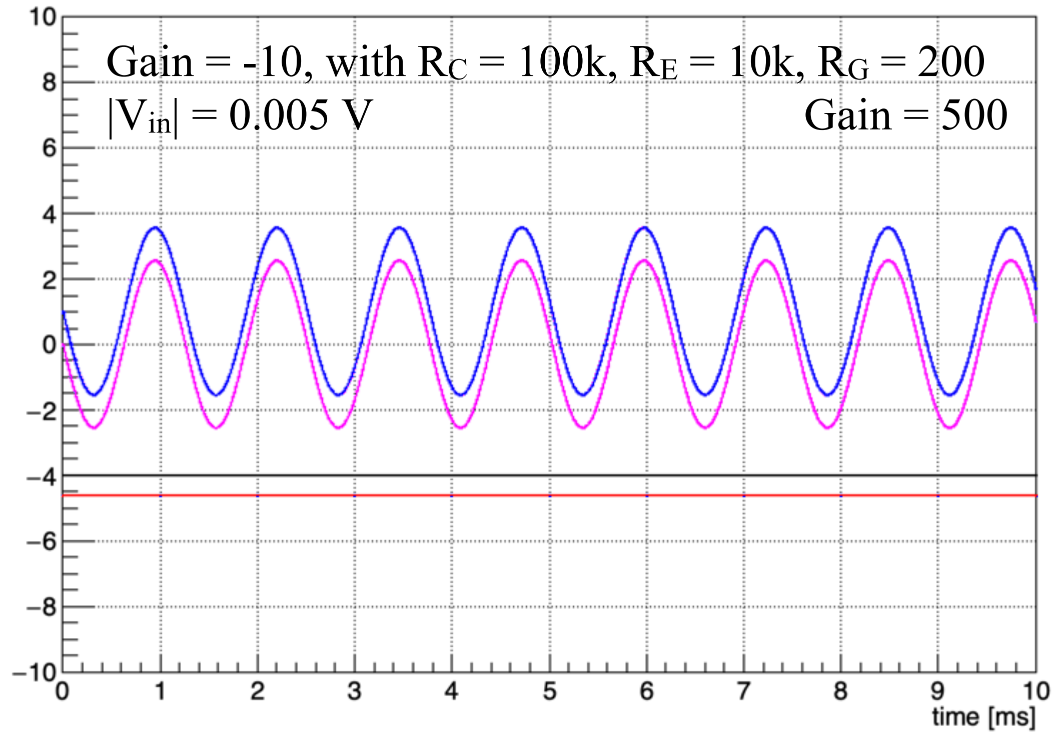


Common-emitter amplifier input biasing

Finally, what can we do about the 1 V quiescent offset on V_{out}?

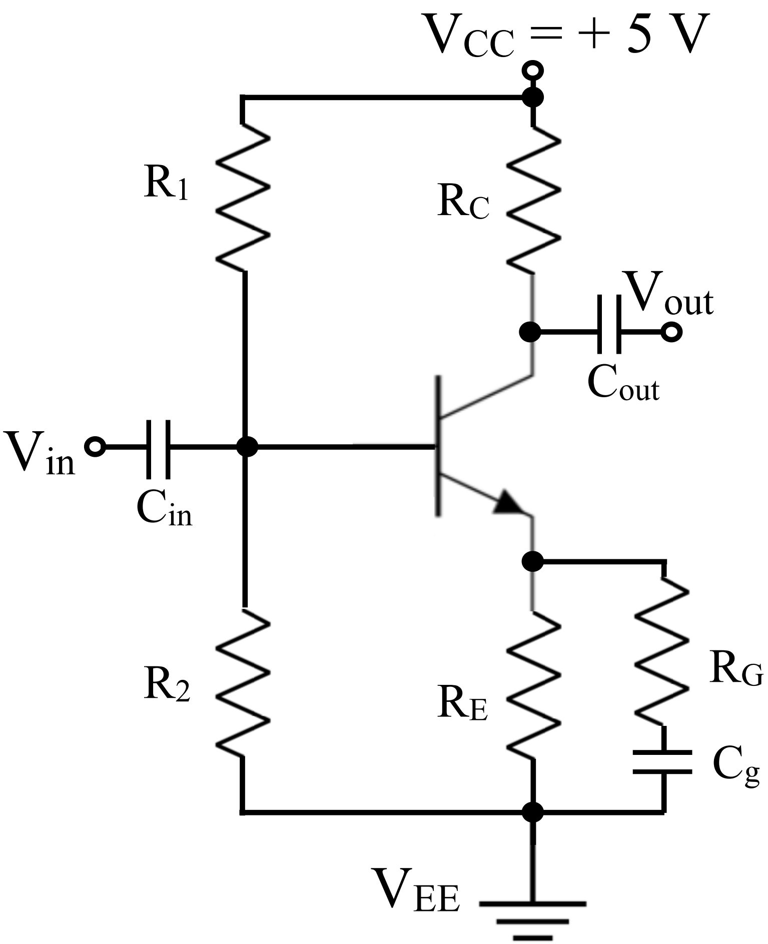


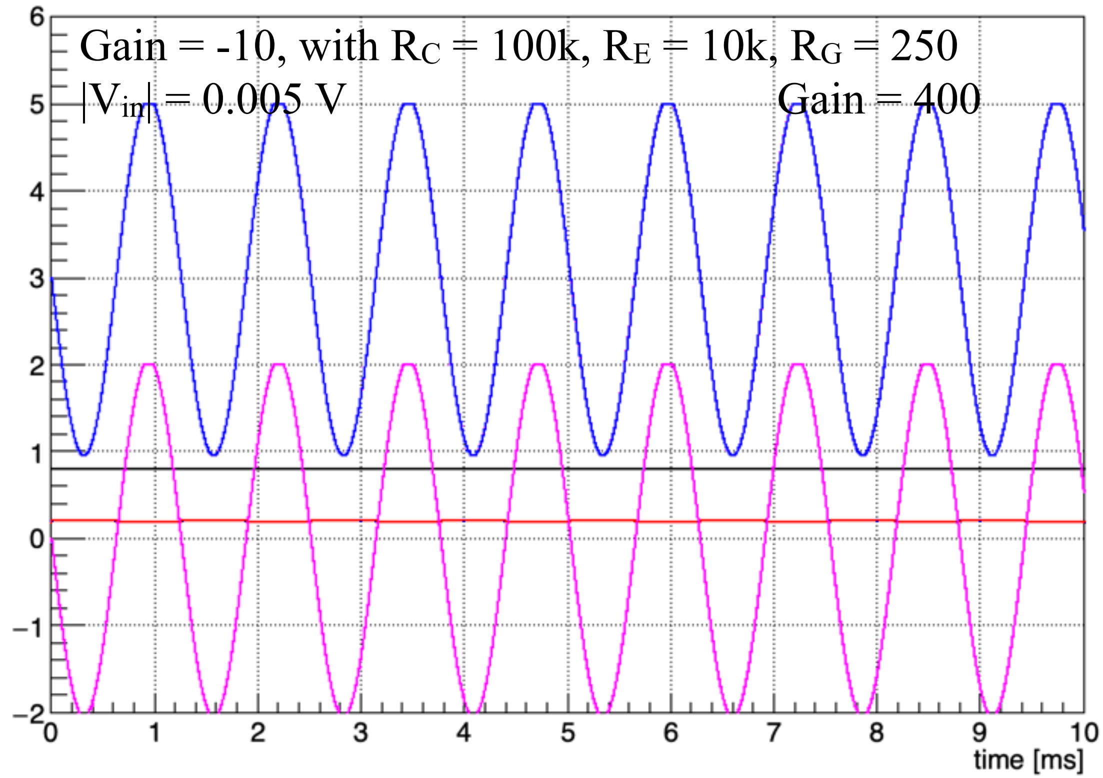
Remove it with a decoupling capacitor.



Common-emitter amplifier input biasing

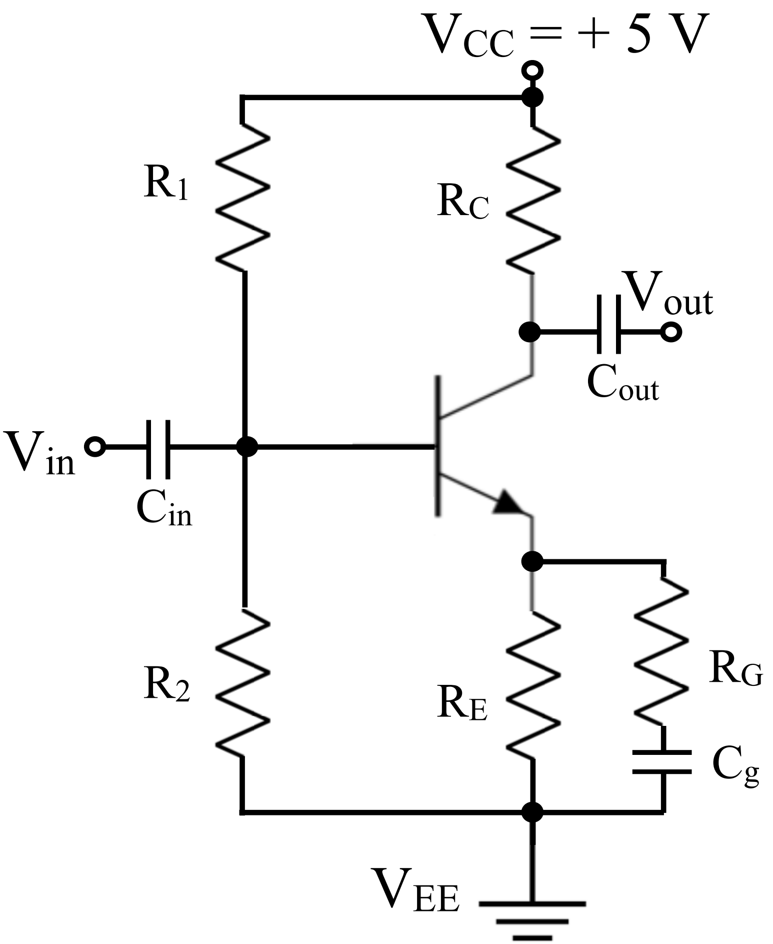
This all works if V_{EE} is ground. We just have to choose quiescent points.
In fact with V_{EE}=Gnd, we *must* have input biasing.





Common-emitter amplifier input biasing

Some checks of understanding.



Without DC biasing, what would limit the signal?

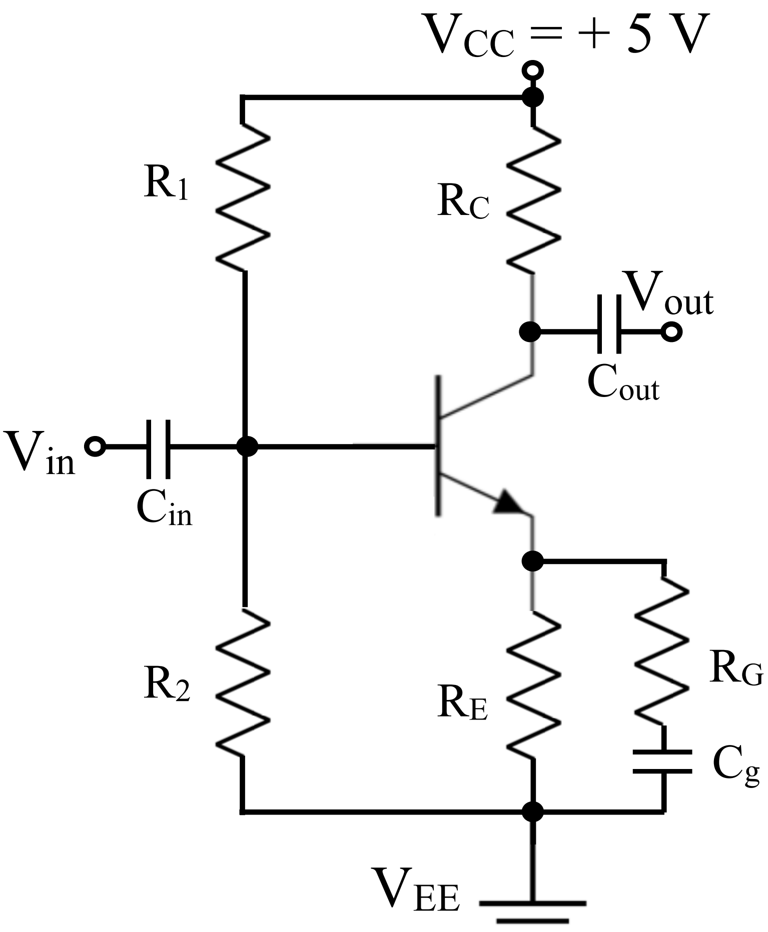
What is the output impedance of this circuit?

What would happen if you set $R_G = 0$?

With V_{EE} = Gnd, about where should you put the quiescent V_{out}? Where is the quiescent V_{in}?
In general, how do you maximize the *dynamic range*?

Common-emitter amplifier operation

The transistor is changing the voltage dropped across it to satisfy the rules of operation.



Increase in V_{in} causes increase in V_E
That causes an increase in I_E
That causes a decrease in V_C
The voltage across the transistor, V_{CE}, goes down to compensate.