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 $> 0.6 \text{ V}$ it becomes forward biased. Negative charge carriers 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 larger current into the collector.

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

\[ I_B \text{ controls } I_C \]
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 \( I_E \approx I_C \)

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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You also have others we will discuss later.
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The 2N3904 is an NPN transistor.
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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 $V_{EE}$. 
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.

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

\[ V_{out} = 3.4 + 2 \sin \omega t \]
Emitter follower

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

\[ V_{\text{in}} = 2.2 + 2 \sin \omega t \]

\[ V_{\text{out}} = 1.6 + 2 \sin \omega t \] \quad \text{but output clips at 0 V}
Emitter follower

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\[ V_{\text{in}} = 2.2 + 2 \sin \omega t \]

\[ V_{\text{out}} = 1.6 + 2 \sin \omega t \]

but output clips at 0 V

We will soon find work-arounds to avoid clipping.
Emitter follower

The benefit here is **increased input impedance**. 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 \( \Delta V \)

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

\[
R_{in} = \frac{\Delta V_{in}}{\Delta I_{in}} = \frac{\Delta V_B}{\Delta I_B}
\]

The base current is \( 1/\beta \) of the emitter current, since \( I_E \approx I_C = \beta I_B \). So,

\[
R_{in} = \frac{\Delta V_{in}}{\Delta I_{in}} = \frac{\Delta V_B}{(\Delta I_E/\beta)} = \beta \frac{\Delta V_B}{\Delta I_E}
\]

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

\[
R_{in} = \beta \frac{\Delta V_B}{\Delta I_E} = \beta \frac{\Delta V_E}{\Delta I_E} = \beta R_E
\]

The input impedance is \( \beta \) times larger than \( R_E \). The transistor amplifies the impedance by \( \beta \approx 100 \).
Emitter follower

The benefit here is increased input impedance. Recall that impedance is \( R = \frac{\Delta V}{\Delta I} \)

The transistor amplifies the impedance by \( \beta \approx 100 \).

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 \( V_{\text{in}} \) is the signal.

The additional power needed is supplied by \( V_{\text{CC}} \).
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The additional power needed is supplied by \( V_{cc} \).

Can get a factor of \( \beta^2 \) 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.

$V_{CC} = +5 \text{ V}$

$V_{EE} = -5 \text{ V}$

$V_{out} = 1.6 + 2 \sin \omega t$

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

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.

$$V_{CC} = +5 \text{ V}$$

$$V_{EE} = -5 \text{ V}$$

The input and output are with respect to ground, but we don’t really need to show ground here. The transistor only cares about relative voltage differences.
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Common-emitter amplifier

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

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

**Diagram:**

- $V_{CC} = +5 \text{ V}$
- $V_{EE} = -5 \text{ V}$
- $R_C$
- $R_E$
- $V_{out}$
- $V_{in}$
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First we’ll do the DC part, \( V_{in} \), then the AC part, \( \Delta V_{in} \).

\[ V_E = V_B - 0.6 \text{ V} = V_{in} - 0.6 \text{ V} \quad \text{and} \quad \Delta V_E = \Delta V_B = \Delta V_{in} \]
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\[ V_E = V_B - 0.6 \text{ V} = V_{in} - 0.6 \text{ V} \] and \( \Delta V_E = \Delta V_B = \Delta V_{in} \)

\[ V_{out} = V_{CC} - I_C R_C \approx V_{CC} - I_E R_C. \] Because \( I_E = I_B + I_C \) & \( I_E \approx I_C \)
\[ I_E = ? \]
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$V_E = V_B - 0.6 \text{ V} = V_{in} - 0.6 \text{ V}$ and $\Delta V_E = \Delta V_B = \Delta V_{in}$
$V_{out} = V_{CC} - I_C R_C \approx V_{CC} - I_E R_C$. Because $I_E = I_B + I_C$ & $I_E \approx I_C$
$I_E$ can be found from $V_E - I_E R_E = V_{EE}$. So $I_E = (V_E - V_{EE})/R_E$.

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

$\Delta V_{out} = ?$
Common-emitter amplifier

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

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

$V_E = V_B - 0.6\,V = V_{in} - 0.6\,V$ and $\Delta V_E = \Delta V_B = \Delta V_{in}$

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

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

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

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

Negative gain OK for music.

Choose amplification by choosing resistance values.
Common-emitter amplifier

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

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

\[ V_E = V_B - 0.6 \, V = V_{in} - 0.6 \, V \quad \text{and} \quad \Delta V_E = \Delta V_B = \Delta V_{in} \]
\[ V_{out} = V_{CC} - I_C R_C \equiv V_{CC} - I_E R_C. \quad \text{Because} \quad I_E = I_B + I_C \quad \text{&} \quad I_E \equiv I_C \]

$I_E$ can be found from $V_E - I_E R_E = V_{EE}$. So $I_E = (V_E - V_{EE})/R_E$.

\[ V_{out} = V_{CC} - I_E R_C = V_{CC} - (V_E - V_{EE})R_C/R_E \]
\[ V_{out} = V_{CC} - V_E(R_C/R_E) + V_{EE}(R_C/R_E) \]

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

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

\[
V_{\text{out}} = V_{\text{CC}} - V_E \left( \frac{R_C}{R_E} \right) + V_{\text{EE}} \left( \frac{R_C}{R_E} \right) \quad \& \quad \Delta V_{\text{out}} = - \Delta V_{\text{in}} \left( \frac{R_C}{R_E} \right)
\]

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

Transistor requires: \( V_{\text{out}} < V_{\text{CC}} \) and \( V_{\text{out}} > V_E + 0.2 \)

Can’t have \( V_{\text{in}} \) and \( V_{\text{out}} \) both oscillating around zero.

Gain = -2, with \( R_C = 2k \) and \( R_E = 1k \).
Common-emitter amplifier

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

\[ V_{\text{out}} = V_{\text{CC}} - V_{\text{E}} \left( \frac{R_C}{R_E} \right) + V_{\text{EE}} \left( \frac{R_C}{R_E} \right) \]

& \[ \Delta V_{\text{out}} = - \Delta V_{\text{in}} \left( \frac{R_C}{R_E} \right) \]

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Can’t have \( V_{\text{in}} \) and \( V_{\text{out}} \) both oscillating around zero.

Gain = -2, with \( R_C = 2k \) and \( R_E = 1k \).

This works without any clipping.
Common-emitter amplifier

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

\[ V_{\text{out}} = V_{\text{CC}} - V_E \left( \frac{R_C}{R_E} \right) + V_{\text{EE}} \left( \frac{R_C}{R_E} \right) \quad \& \quad \Delta V_{\text{out}} = -\Delta V_{\text{in}} \left( \frac{R_C}{R_E} \right) \]

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

Transistor requires: \( V_{\text{out}} < V_{\text{CC}} \) and \( V_{\text{out}} > V_E + 0.2 \)

Can’t have \( V_{\text{in}} \) and \( V_{\text{out}} \) both oscillating around zero.

Gain = -3, with \( R_C = 3k \) and \( R_E = 1k \).

This works without any clipping.
We can use the current amplification of the transistor to get voltage amplification.

\[ V_{\text{out}} = V_{CC} - V_{E}(R_{C}/R_{E}) + V_{EE}(R_{C}/R_{E}) \] & \[ \Delta V_{\text{out}} = -\Delta V_{\text{in}}(R_{C}/R_{E}) \]

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

Transistor requires: \( V_{\text{out}} < V_{CC} \) and \( V_{\text{out}} > V_{E} + 0.2 \)

Can’t have \( V_{\text{in}} \) and \( V_{\text{out}} \) both oscillating around zero.

Gain = -5, with \( R_{C} = 5k \) and \( R_{E} = 1k \). \(|V_{\text{in}}| = 2 \text{ V}\)
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.

\[ V_{CC} = +5 \text{ V} \]

Apply an “input bias” that puts the emitter close to \( V_{EE} \), within a \( \Delta V \) that defines the max input swing.

\[ V_{EE} = -5 \text{ V} \]
Apply an input bias that puts the emitter close to $V_{EE}$, within a $\Delta V$ that defines the max input swing.

Suppose I want a max input swing of $\pm0.1$ 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.

\[
V_{in} = V_{EE} + (V_{CC} - V_{EE}) \frac{R_2}{(R_1 + R_2)}
\]

-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 $\Delta V$ 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 $\Delta V$ that defines the max input swing.

$$V_{CC} = +5 \, \text{V}$$

$$V_{EE} = -5 \, \text{V}$$

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
$$20 = \frac{1}{2\pi} (10k)C$$
$$C \cong \frac{1}{6*120*10k} \cong \frac{1}{1/1k*10k} = 0.1 \, \mu\text{F}$$
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 $V_{out}$ swings by $\pm 1$ V.
Then quiescent point for $V_{out}$ to be at least 1 V away from $V_{CC}$ and $V_E$.
But,

$$V_{out} = V_{CC} - V_E \left(\frac{R_C}{R_E}\right) + V_{EE} \left(\frac{R_C}{R_E}\right)$$
only depends on the gain ratio.

$$V_{out} = 5 - (-4.9 \times 10) - 5 \times 10$$
$$= 4$$
That works, but just barely.
Common-emitter amplifier input biasing

Now we need to pick $R_E$ and $R_C$

$V_{CC} = +5\,\text{V}$

$R_1$

$R_C$

$V_{out}$

$V_{in}$

$C_{in}$

$R_2$

$R_E$

$V_{EE} = -5\,\text{V}$

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

Choose gain = 10.

That means $V_{out}$ swings by $\pm 1\,\text{V}$.

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

But,

$$V_{out} = V_{CC} - V_{EE} \left( \frac{R_C}{R_E} \right) + V_{EE} \left( \frac{R_C}{R_E} \right)$$

only depends on the gain ratio.

$$V_{out} = 5 - (-4.9\times10)-5\times10$$

$$= 4$$

That works, but just barely.
Common-emitter amplifier input biasing

Now we need to pick $R_E$ and $R_C$

$V_{CC} = +5 \text{ V}$

$V_{EE} = -5 \text{ V}$

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.
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 DC quiescent voltages and a small $R_E$ for setting AC gain.
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 $V_{out}$.

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.

Gain = -10, with $R_C = 100k$, $R_E = 10k$, $R_G = \infty$

$|V_{in}| = 0.1$ V

$V_{CC} = +5$ V

$V_{EE} = -5$ V

$V_{out}$

$V_{in}$

$C_{in}$

$R_1$

$R_C$

$B$

$C$

$E$

$R_E$

$R_G$

$C_g$
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Gain = -10, with $R_C = 100k$, $R_E = 10k$, $R_G = \infty$

$|V_{in}| = 0.3$ 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 $V_{out}$.

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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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.

Gain = -10, with $R_C = 100k$, $R_E = 10k$, $R_G = \infty$

$|V_{in}| = 0.1$ V

Gain = 10

Go back to base gain of 10 then reduce $R_G$.\vspace{1cm}
Common-emitter amplifier input biasing

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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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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.

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.
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.

$V_{CC} = +5 \text{ V}$

$V_{EE} = -5 \text{ V}$

Gain = -10, with $R_C = 100k$, $R_E = 10k$, $R_G = 200$

$|V_{in}| = 0.005 \text{ V}$

Gain = 500

$C_{out}$

$V_{in}$

$C_{in}$

$R_1$

$R_C$

$R_E$

$R_G$

$V_{out}$

$V_{EE}$

Gain = -10, with $R_C = 100k$, $R_E = 10k$, $R_G = 200$

$|V_{in}| = 0.005 \text{ V}$

Gain = 500

$C_{out}$

$V_{in}$

$C_{in}$

$R_1$

$R_C$

$R_E$

$R_G$

$V_{out}$

$V_{EE}$

Gain = -10, with $R_C = 100k$, $R_E = 10k$, $R_G = 200$

$|V_{in}| = 0.005 \text{ V}$

Gain = 500
Common-emitter amplifier input biasing

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

\[ V_{CC} = +5 \text{ V} \]

Gain = -10, with $R_C = 100k$, $R_E = 10k$, $R_G = 250$

$|V_{in}| = 0.005 \text{ V}$

Gain = 400
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 $V_{EE} = \text{Gnd}$, 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.

\[ V_{CC} = +5 \text{ V} \]

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.