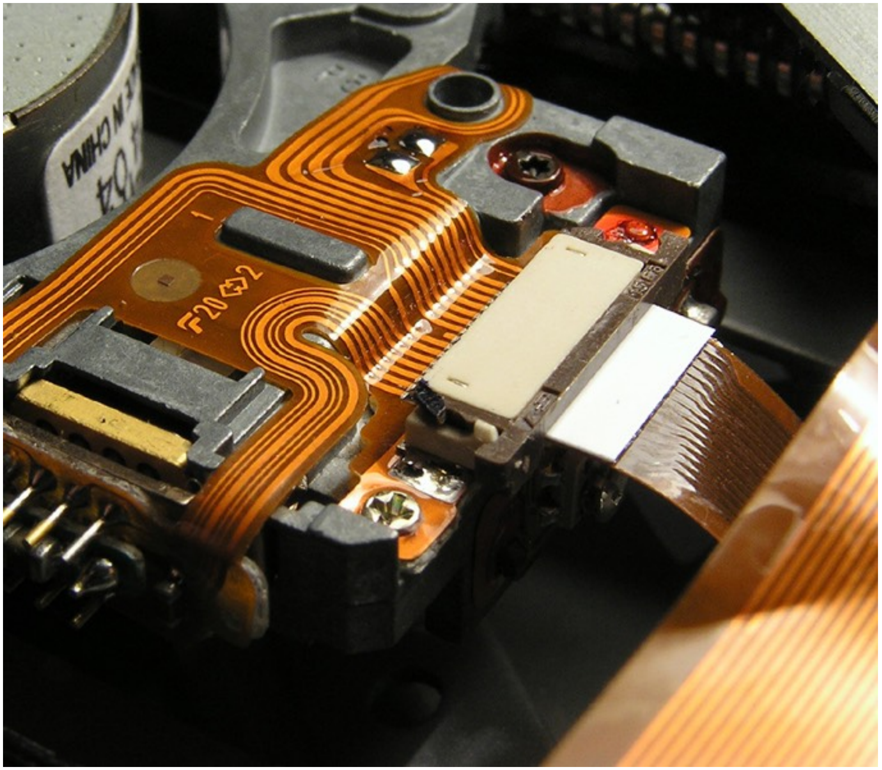
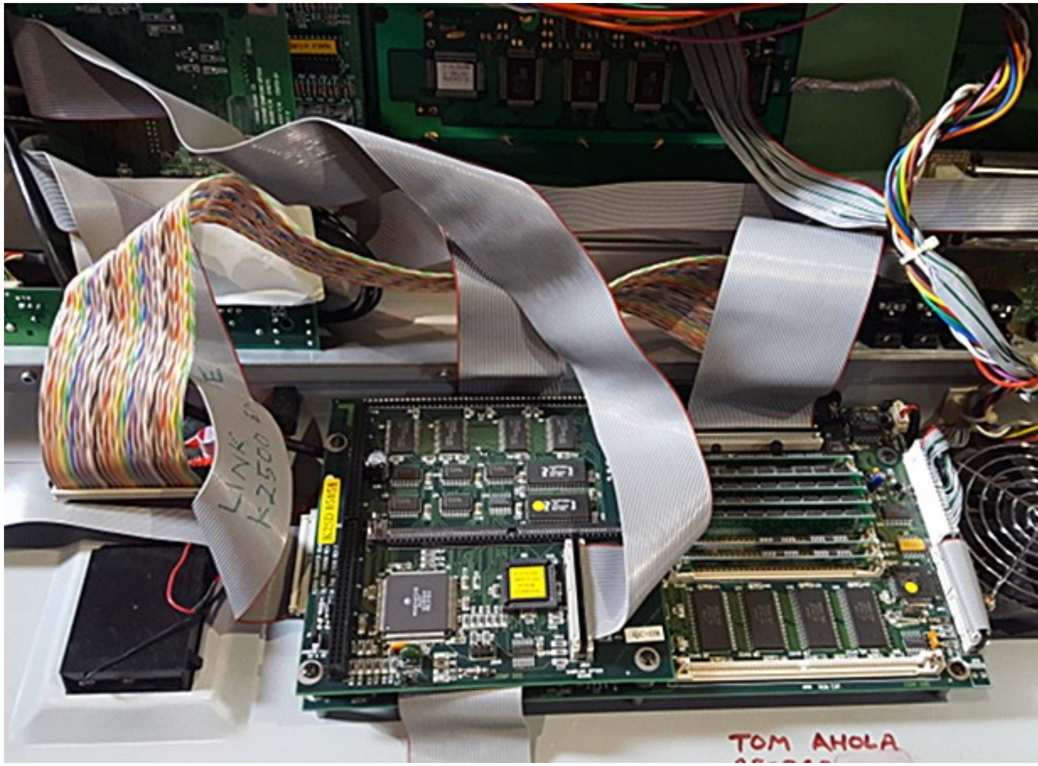
# PHYS127AL Lecture 8

David Stuart, UC Santa Barbara, October 19, 2021

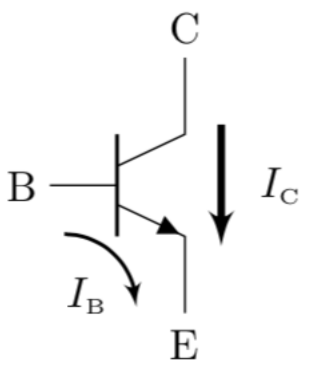
More transistor circuits: Ebers-Moll, current mirror, differential amplifier, FETs





# Review: Transistor rules of operation

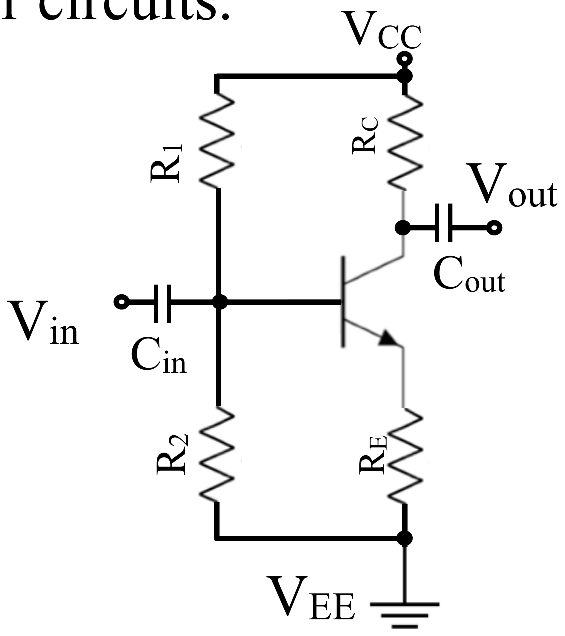
1). $V_{BE} = 0.6$ V or the transistor is off
I.e., $V_B = V_E + 0.6$ V
Once the transistor is on, $\Delta V_B = \Delta V_E$.



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

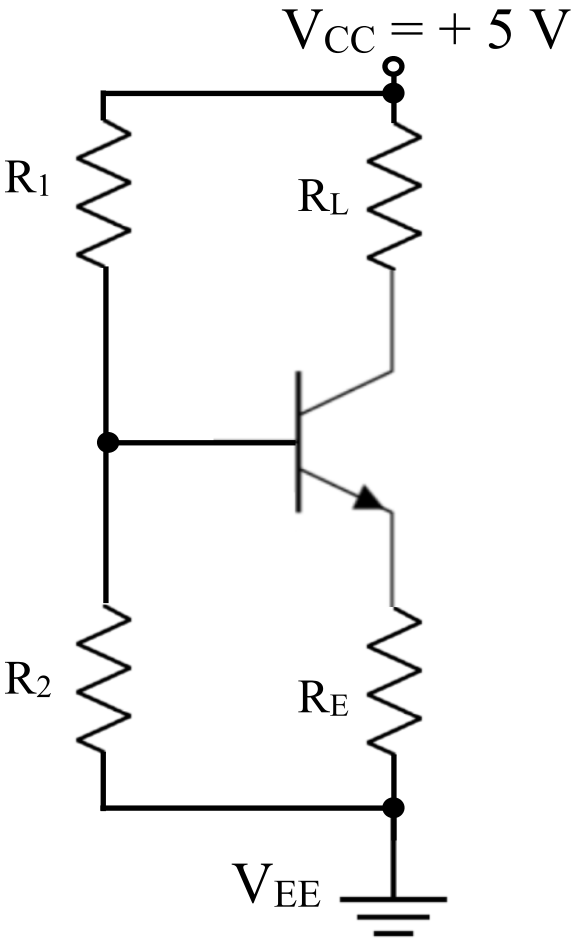
3). $V_{CE} > 0.2$ V

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



# Review: Constant current source

We can use a transistor to pull a *constant* specified current through a load.



To get a constant 1mA flow through $R_L$, even as $R_L$ changes, we can set $R_E$ to 1k and $V_E$ to 1 V.

That sets the value of $I_E$, which is equal to $I_C$, regardless of $R_L$.

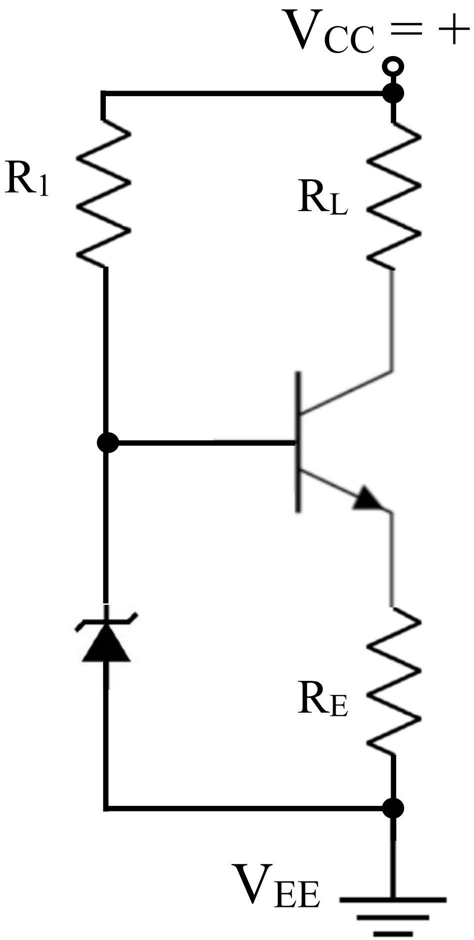
Choose $R_1$ and $R_2$ to make $V_B = 1.6$ V.
Then $V_E = 1.0$ V.
$I_E = 1$ mA.
$I_C = 1$ mA, regardless of $R_L$.

This works until $V_C<V_E+0.2$

*Note that there is no input signal here.*

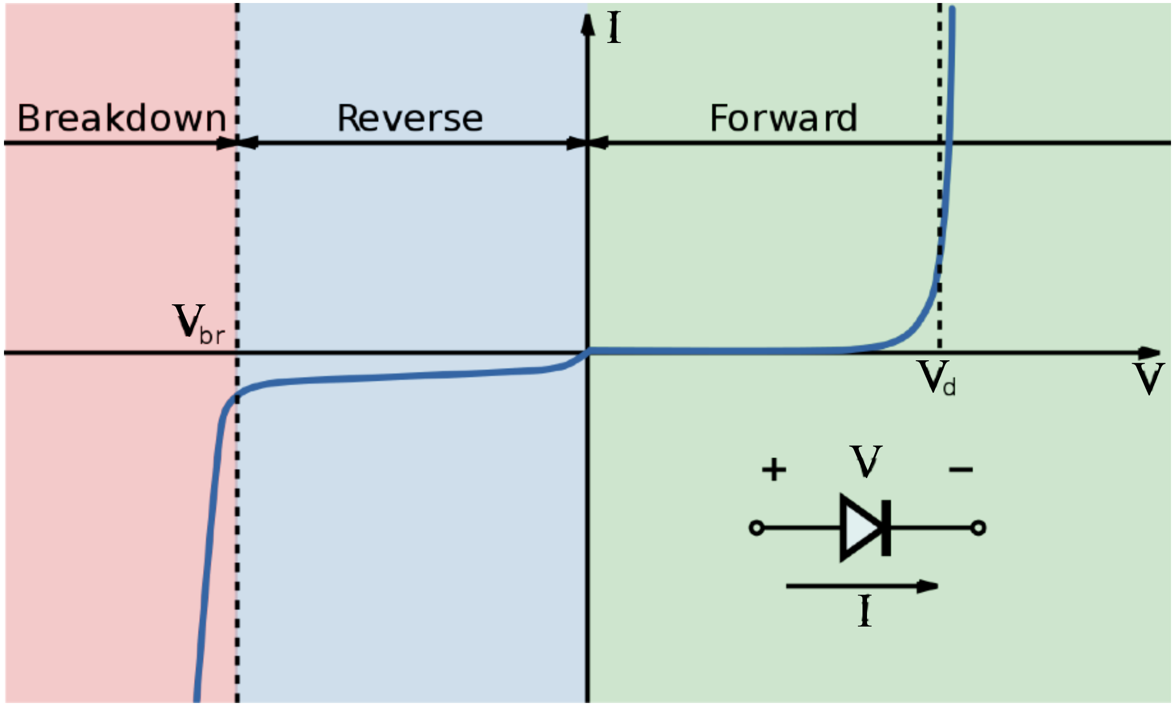
# Review: Constant current source

We can use this to pull a specified current through a load.



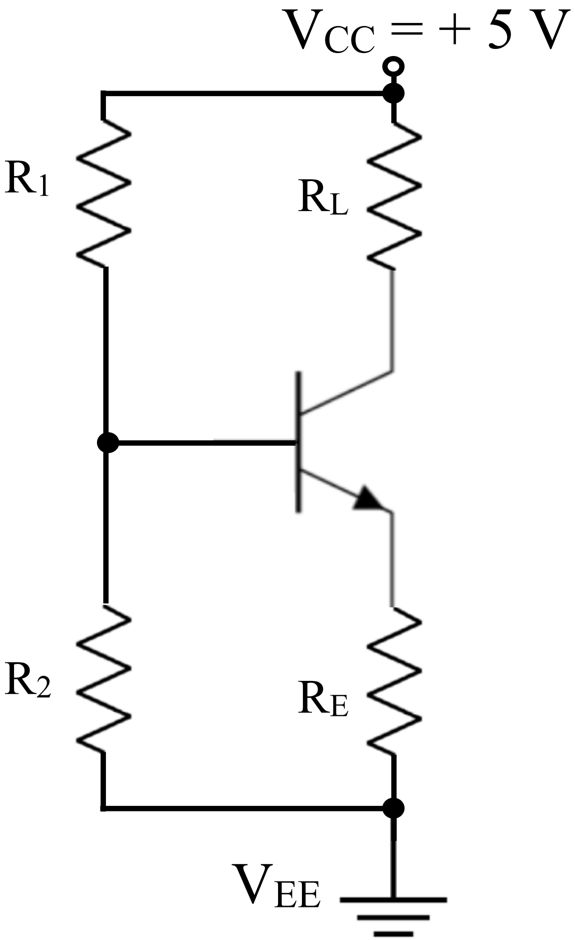
To get a constant 1mA flow through $R_L$, even as $R_L$ changes, we can set $R_E$ to 1k and $V_E$ to 1 V.
That sets $I_E$ which is equal to $I_C$, regardless of $R_L$.

Choose the zener diode to make $V_B$ = 1.6 V.
The zener reduces sensitivity to $V_{CC}$ variations.

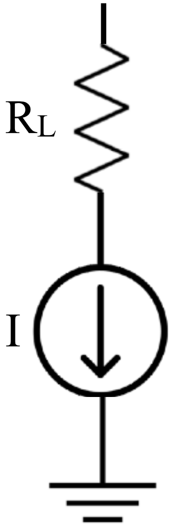


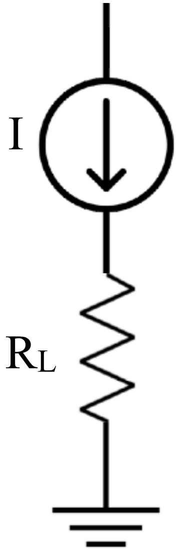
# Constant current source

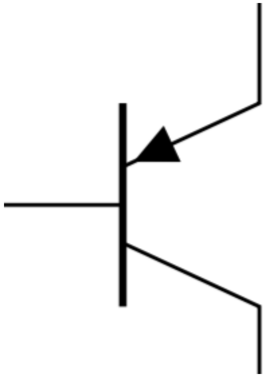
We can use a transistor to *pull* a *constant* specified current through a load. This is actually called a *current sink* since it pulls current from $R_L$.



If we wanted to push current through $R_L$ with the bottom of $R_L$ connected to ground, then we need a different polarity transistor. PNP vs NPN.



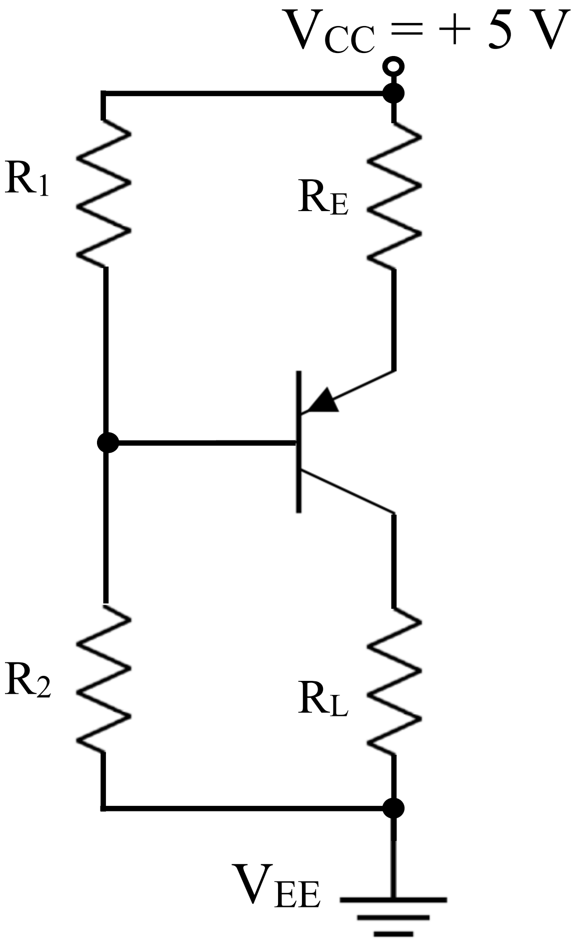




Turns on when
$V_E = V_B + 0.6$

# Constant current source

We can use a PNP transistor to *push* a *constant* specified current into a load.



Now we can switch the location of $R_L$ and $R_E$. The base's bias voltage sets $R_E$ which sets $I_E$ and hence $I_C$.

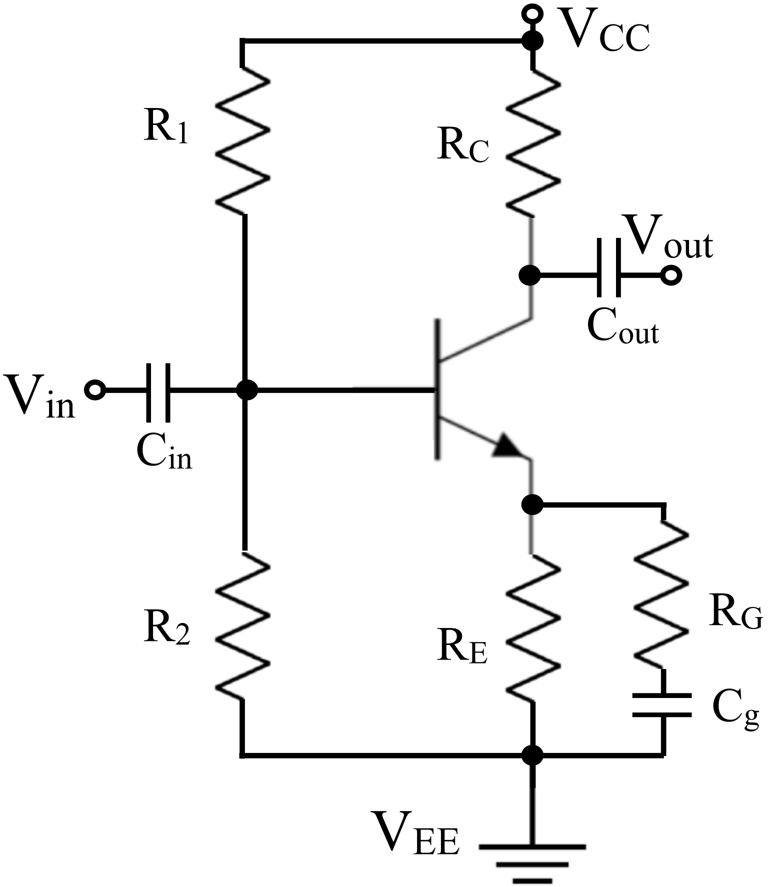
For 1 mA we could set $R_E$ = 1k and $V_E$ = 4 V. That requires $V_B$ = 3.4 V which we get from $R_1$ & $R_2$ choice.

$3.4 = 5\,R_2/(R_1+R_2)$

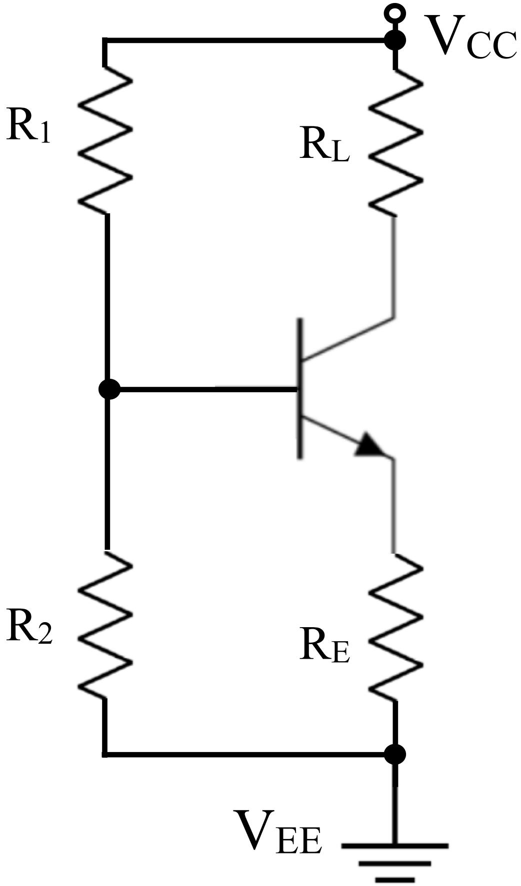
# Ebers-Moll model

The simple transistor rules we have been using aren't the full picture. Two examples of features it misses.

Gain limit with $R_G$=0.

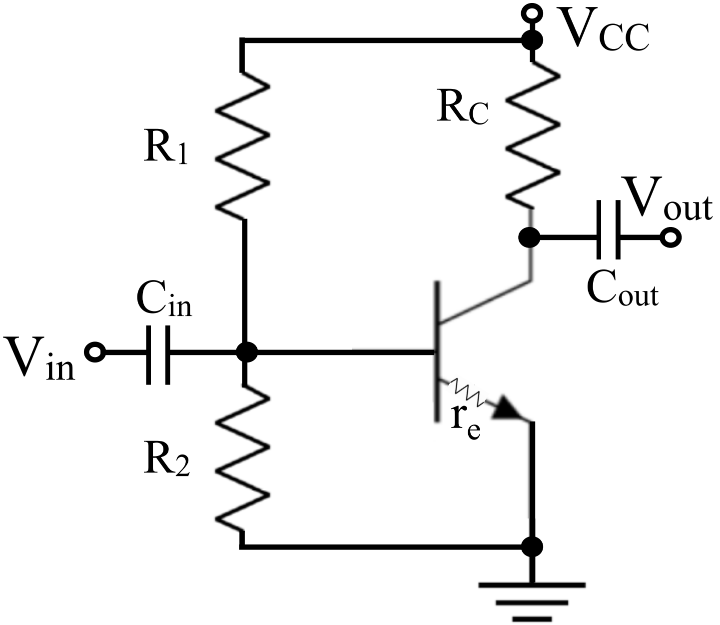


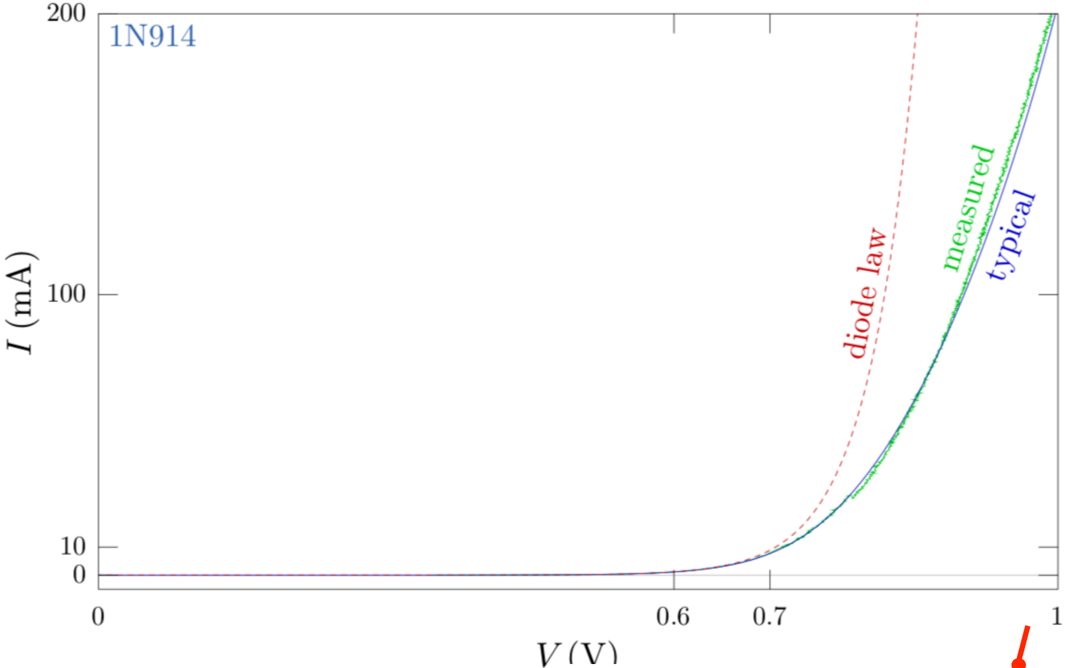
$I_L$ is temperature dependent.

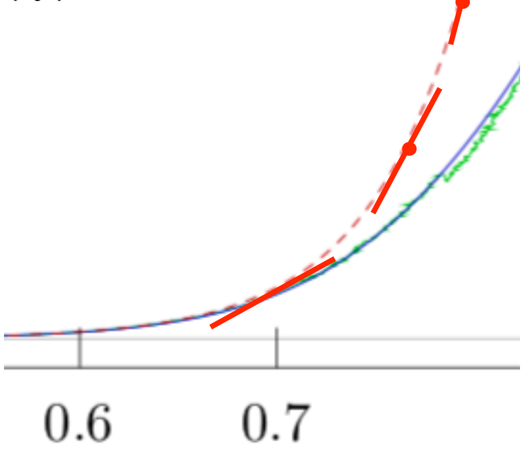


# Ebers-Moll model

Gain limit comes from intrinsic resistance in the transistor.







There is a small current-dependent resistance present even when $R_E=0$. Call it $r_e$.   $r_e \cong 25\Omega$ / I[mA]

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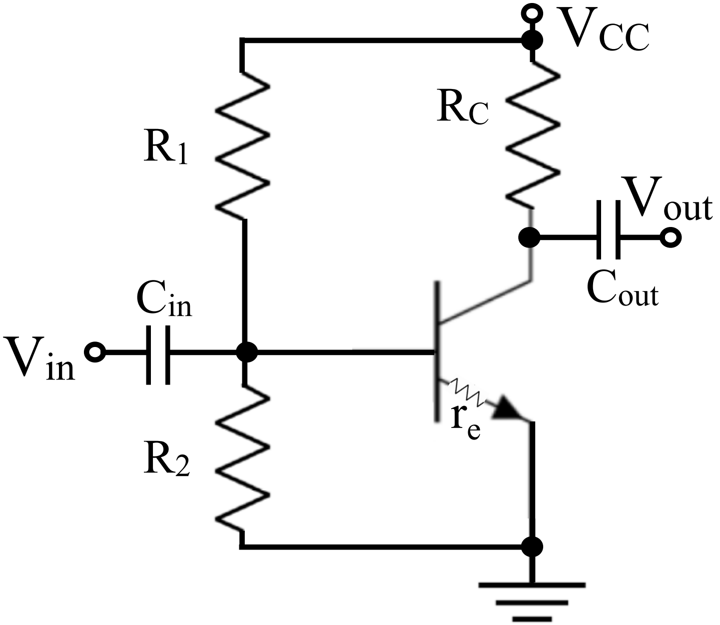
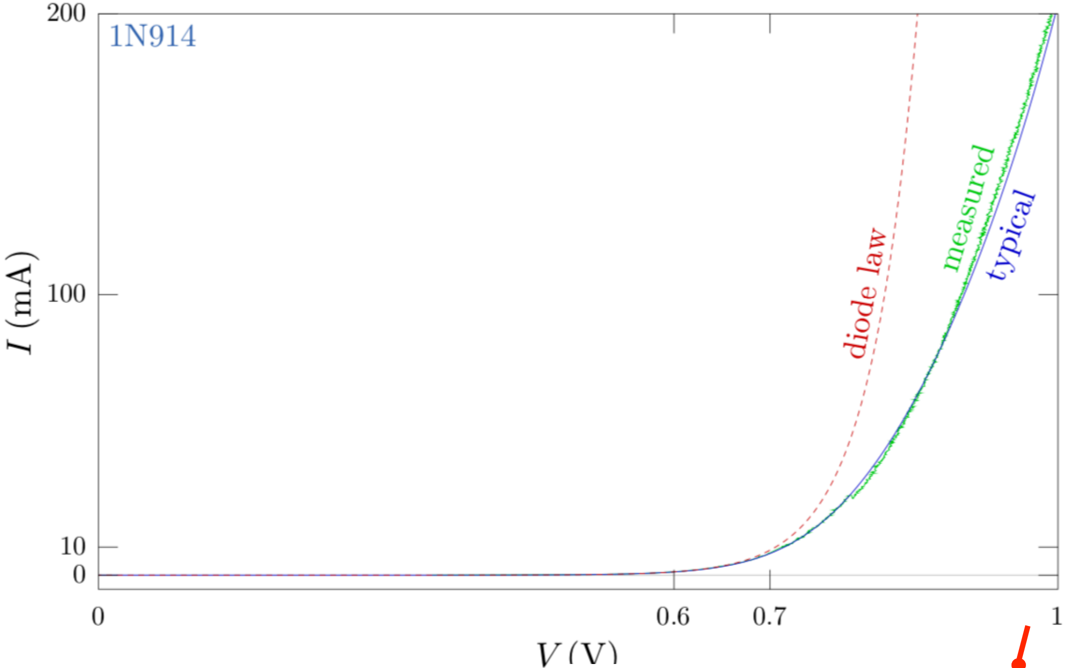




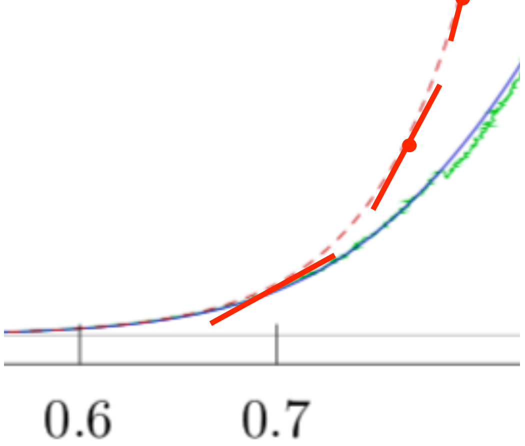
There is a small current-dependent resistance present even when $R_E$=0. Call it $r_e$. $r_e \cong 25\Omega$ / I[mA]

And it is temperature dependent.

$$I_C = I_s\left(e^{V_{BE}/nV_T} - 1\right) \quad \text{where} \quad V_T = \frac{k_B T}{e}$$

$V_T \cong$ 25 mV at room temperature.

$I_s$ is also temperature dependent.



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# More complete transistor model

We used simplified (0th and 1st order) models:

1). $V_{BE} = 0.6$ V or the transistor is off
   I.e., $V_B = V_E + 0.6$ V
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$$I_C = I_s\left(e^{V_{BE}/nV_T} - 1\right)$$

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A 2nd order correction incorporates effects from collector voltage differences

$$I_{\mathrm{C}} = I_{\mathrm{S}}\left(e^{V_{\mathrm{BE}}/nV_{\mathrm{T}}} - 1\right)\left(1 + \frac{V_{\mathrm{CE}}}{V_{\mathrm{AF}}}\right) - I_{\mathrm{S}}\left(e^{V_{\mathrm{BC}}/nV_{\mathrm{T}}} - 1\right)\left(1 + \frac{V_{\mathrm{CE}}}{V_{\mathrm{AR}}}\right) - \frac{I_{\mathrm{S}}}{\beta_{\mathrm{R}}}\left(e^{V_{\mathrm{BC}}/nV_{\mathrm{T}}} - 1\right)$$

$$I_{\mathrm{B}} = \frac{I_{\mathrm{S}}}{\beta_{\mathrm{F}}}\left(e^{V_{\mathrm{BE}}/nV_{\mathrm{T}}} - 1\right) - \frac{I_{\mathrm{S}}}{\beta_{\mathrm{R}}}\left(e^{V_{\mathrm{BC}}/nV_{\mathrm{T}}} - 1\right).$$

(Ebers–Moll equations with Early correction)

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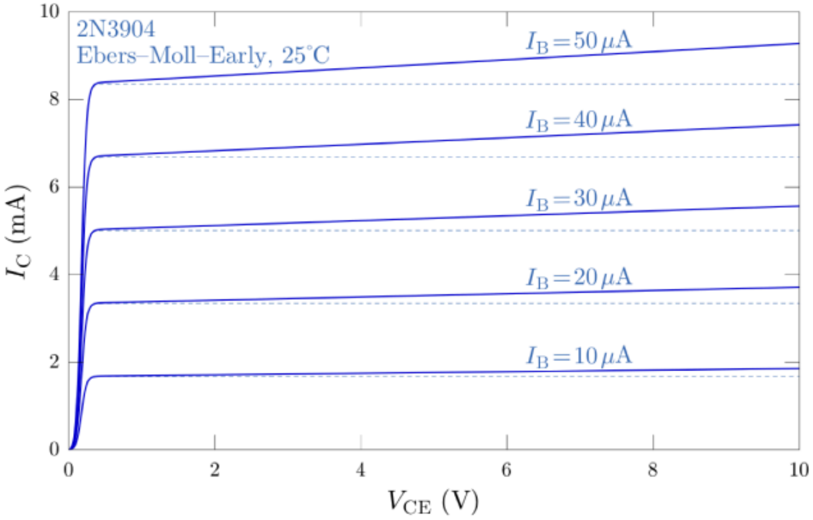

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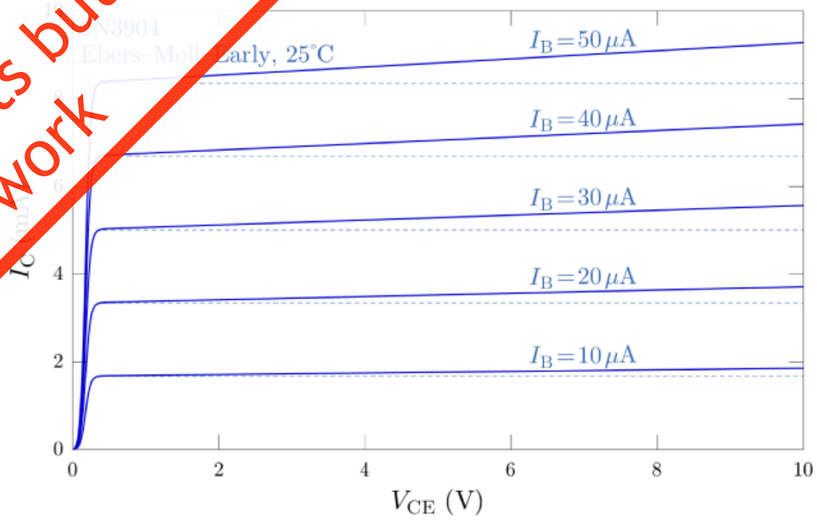
$I_E = I_B + I_C$ so $I_E \cong I_C$

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

These are typically not important for electronics use by physicists but are important for EE design work

$$I_C = I_S\left(e^{V_{BE}/nV_T} - 1\right)$$



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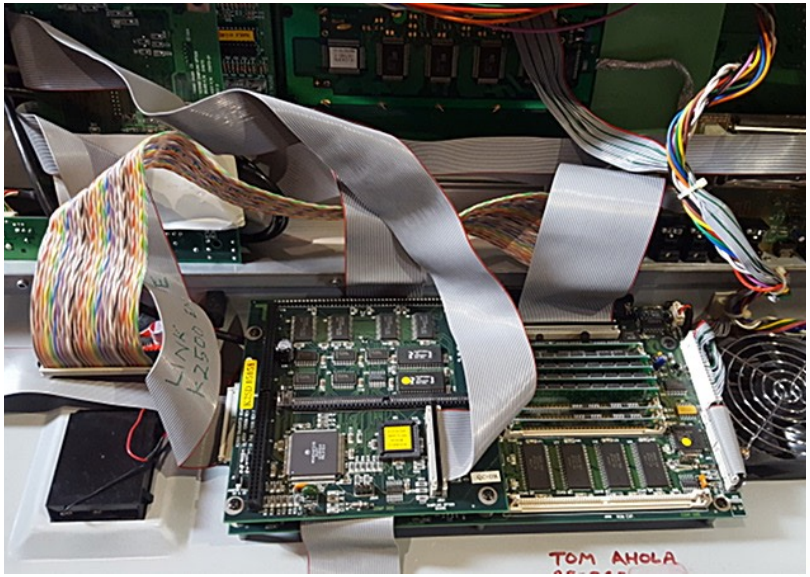
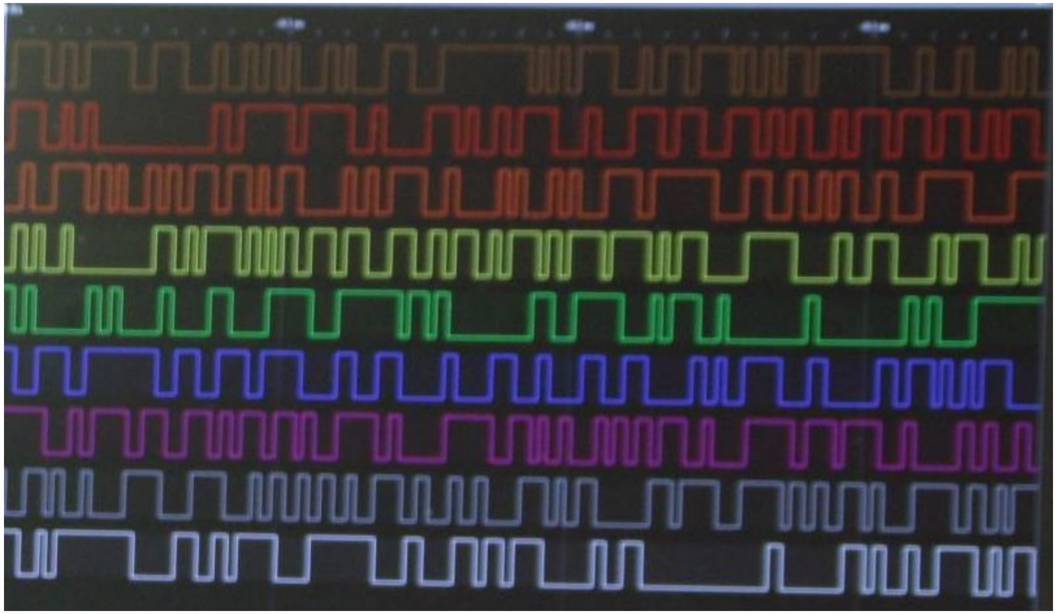
# Differential amplifier

If we try to transmit a signal a long distance, we need to worry about RF pickup because the wires act as an antenna (or capacitively couple).

We could amplify the signal before transmitting to make it large compared to any pickup. But then it becomes a powerful transmitter causing pickup on other wires nearby.





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Best to transmit signals with small signals that are immune to pickup; use low-voltage differential signals (LVDS) on twisted pairs of wires.

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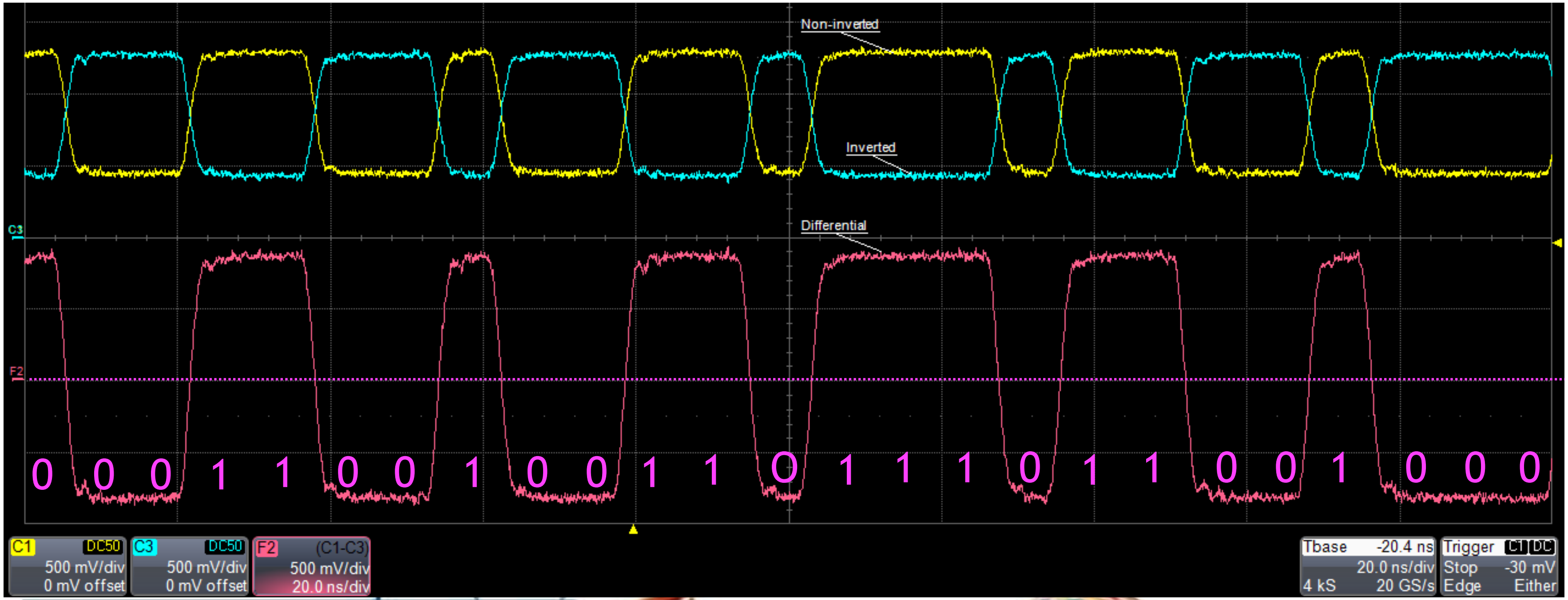
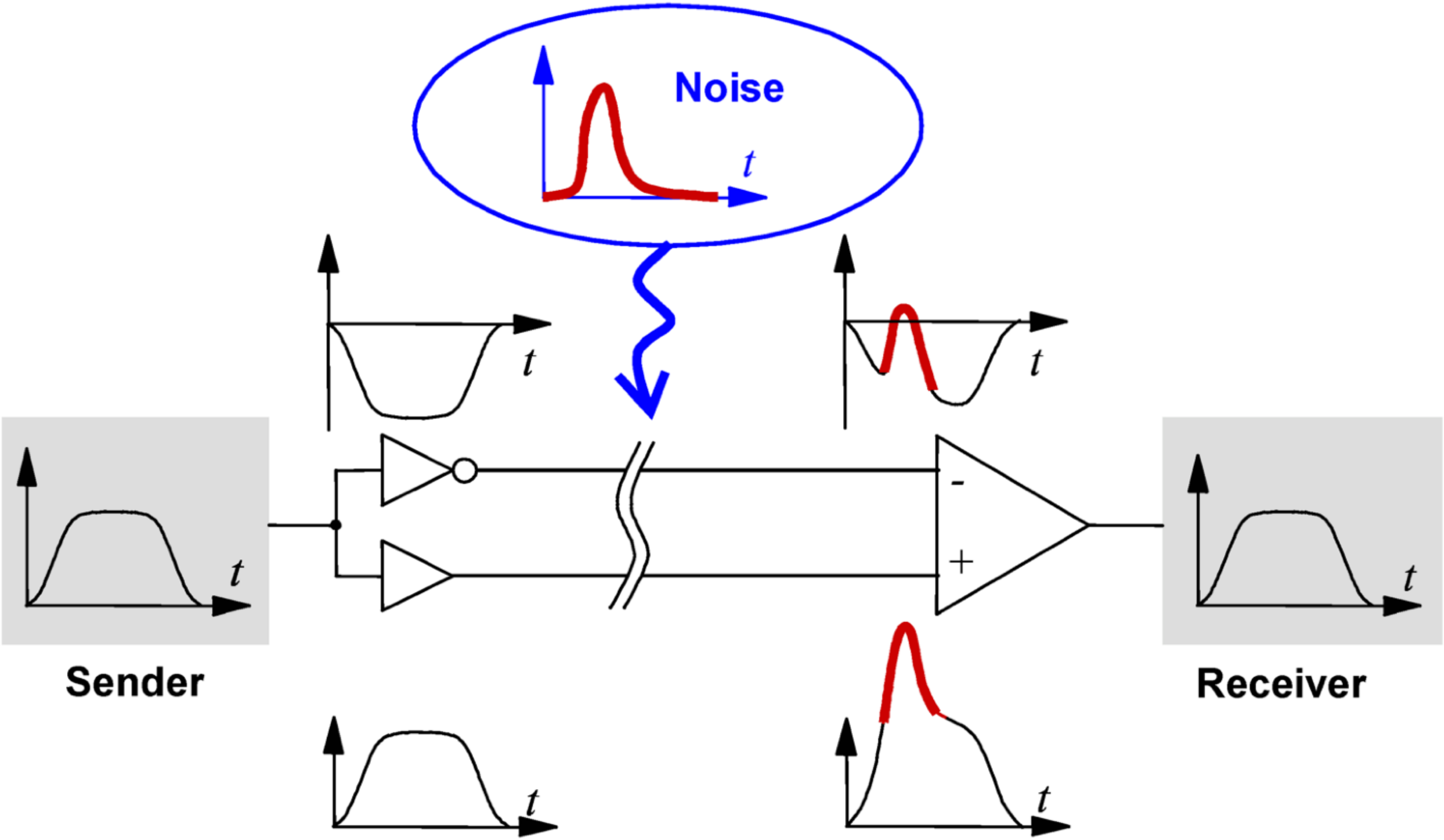
# Differential amplifier



Signal+ = +ΔV/2

Signal- = -ΔV/2

# Differential amplifier



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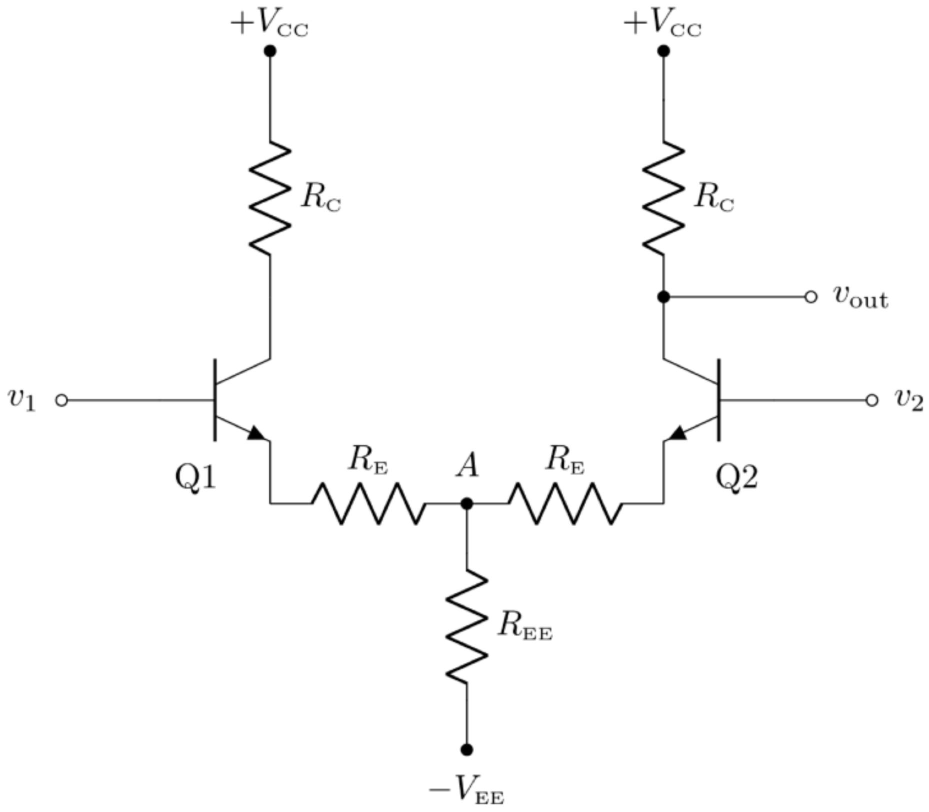


Analyze this by 1st calculating $V_A$.

$$V_A = V_{EE} + I_{EE}R_{EE}$$

$$I_{EE} = I_{E1} + I_{E2}$$

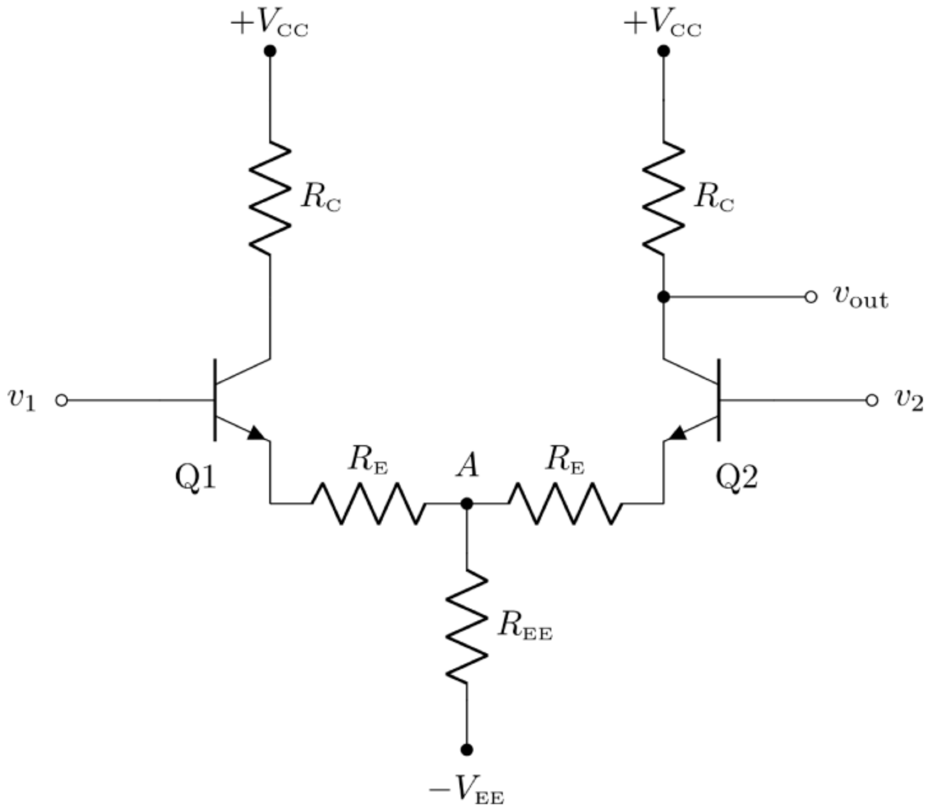
$$= (V_{E1}-V_A)/R_E + (V_{E2}-V_A)/R_E$$

$$= (V_{E1}+V_{E2})/R_E - 2V_A/R_E$$

$$V_A = V_{EE} + R_{EE}/R_E\,(V_{E1}+V_{E2})/R_E - 2R_{EE}V_A/R_E$$

$$V_A = \frac{R_EV_{EE} + R_{EE}\,(V_{E1}+V_{E2})}{R_E + 2R_{EE}}$$

# Differential amplifier



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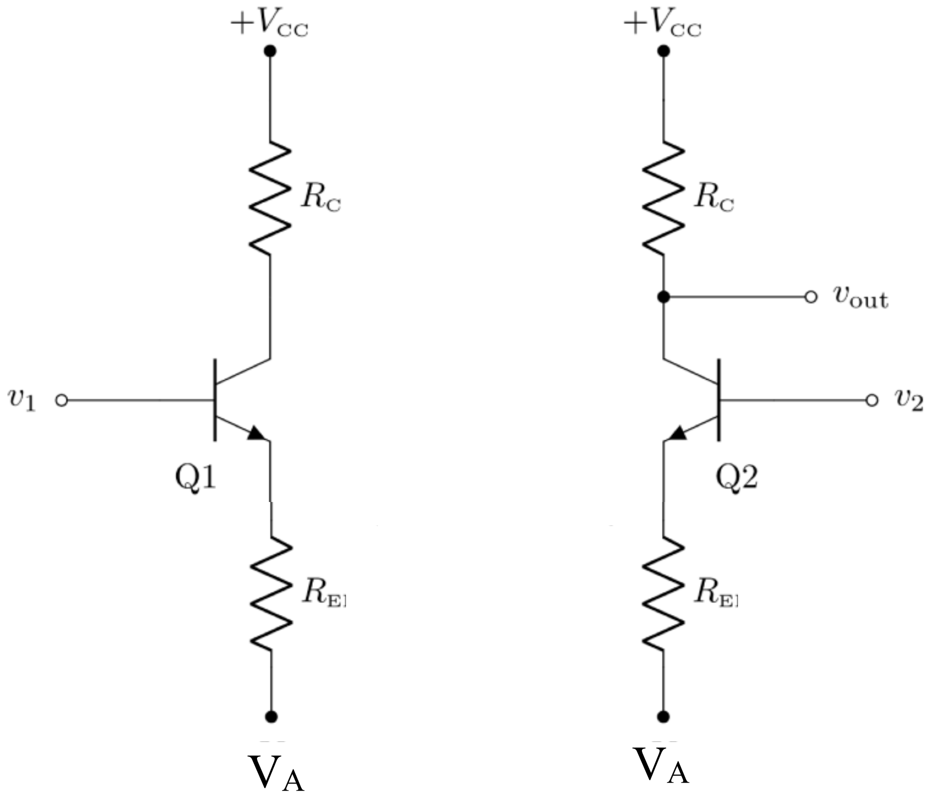
$$V_A = \frac{R_E V_{EE} + R_{EE}\,(V_{E1}+V_{E2})}{R_E + 2R_{EE}}$$

$$\Delta V_A = (\Delta V_{E1} + \Delta V_{E2})\,\frac{R_{EE}}{R_E + 2R_{EE}}$$

If $\Delta V_{E1} = -\,\Delta V_{E2}$ then $\Delta V_A = 0$

# Differential amplifier



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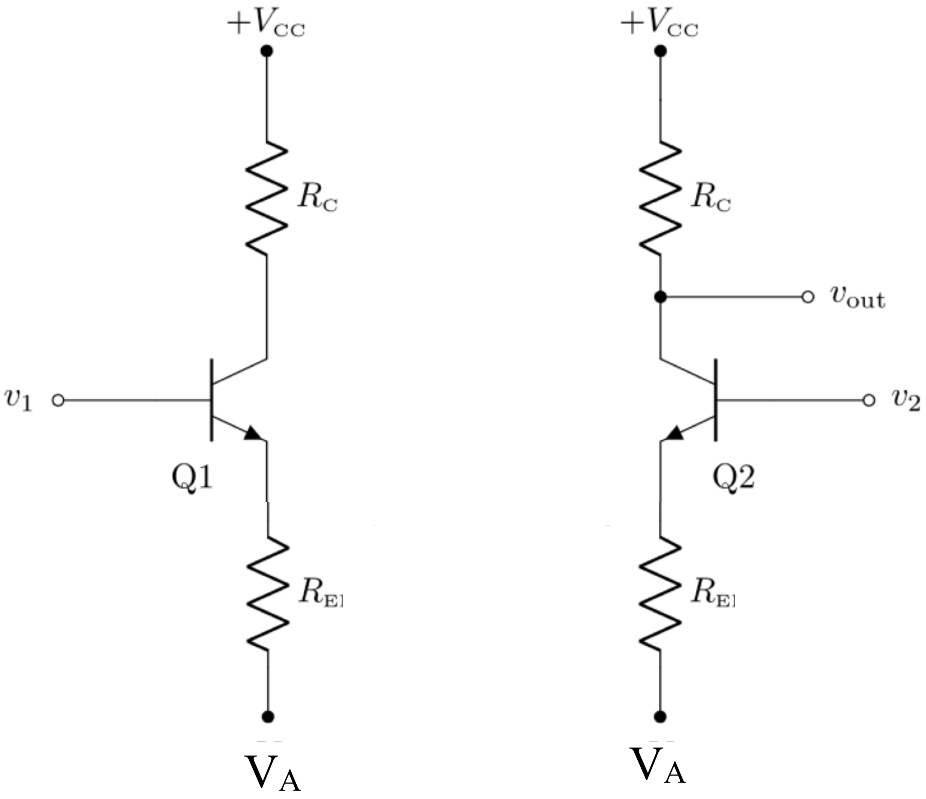
If $\Delta V_{E1} = -\Delta V_{E2}$ then $\Delta V_A = 0$

This makes the right side just a common-emitter amp with $v_{out} = (-R_C/R_E)\,v_2$

If $v2 = -\Delta V_{in}/2 = -v_{in}/2$ then $v_{out} = (R_C/R_E)v_{in}/2$.

# Differential amplifier



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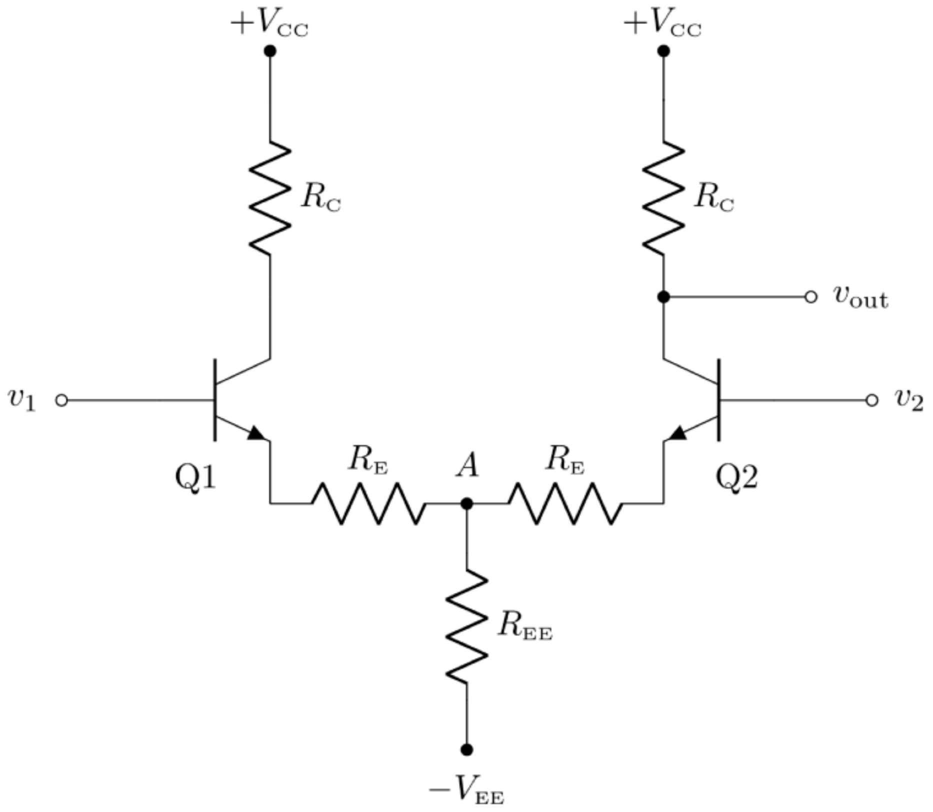
Differential gain = $R_C/2R_E$

# Differential amplifier



Common mode gain = $-R_C/(R_E+2R_{EE})$

Differential gain = $R_C/2R_E$

Now consider the *common mode* signal, where $v_1 = v_2 = \overline{v} = v_{CM}$

That makes $\Delta I_{E1} = \Delta I_{E2}$ & $\Delta I_{EE} = 2\Delta I_{E1}$

Written with "variation notation" its

$i_{E1} = i_{E2}$ and $i_{EE} = 2i_{E1}$

So, $\Delta V_A = v_A = i_{EE}R_{EE} = 2i_{E1}R_{EE}$

Now use Ohm's law to find $i_{E1}$ as

$i_{E1} = (v_E - v_A) / R_E$

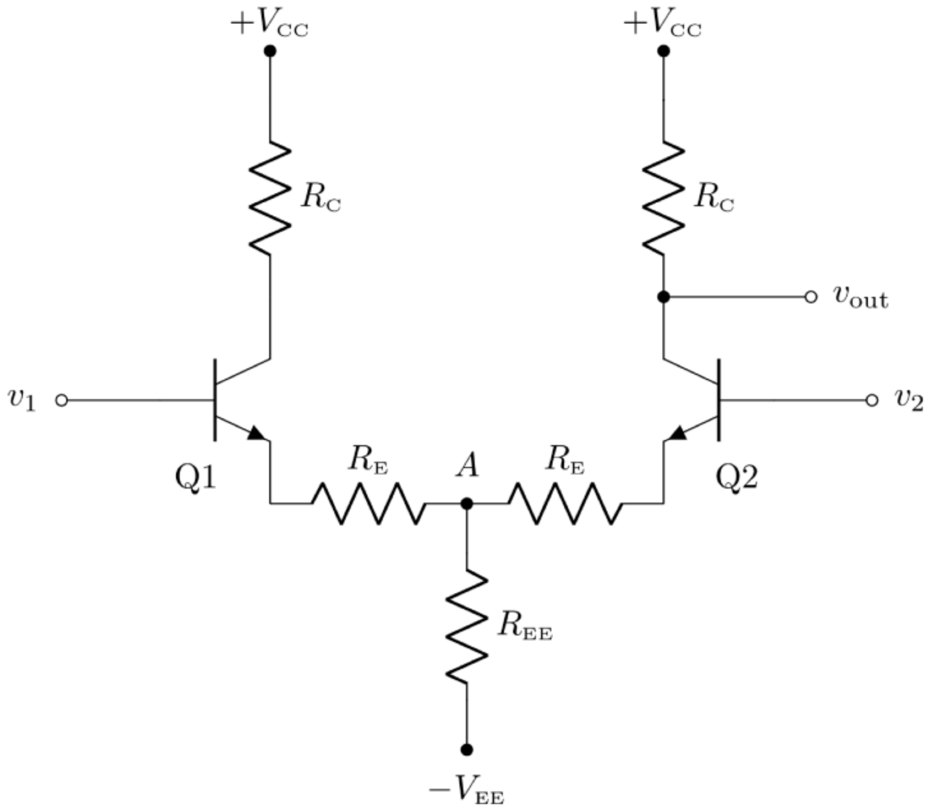
$= (v_{CM} - 2i_{E1}R_{EE}) / R_E$

So,

$i_{E1} = v_{CM} / (R_E+2R_{EE})$

$v_{out} = -i_{E1} R_C = - v_{CM} R_C / (R_E+2R_{EE})$

# Differential amplifier



Get positive gain by selecting output from $v_2 = -v/2$

Don't need output from other side, but we do need the other side to get the common mode suppression.

Comment on "CM" jargon.

To maximize the CMRR = $G_{Diff}/G_{CM}$ make $R_{EE}$ large.

A current source has infinite impedance.

Common mode gain = $-R_C/(R_E+2R_{EE})$
Differential gain = $R_C/2R_E$

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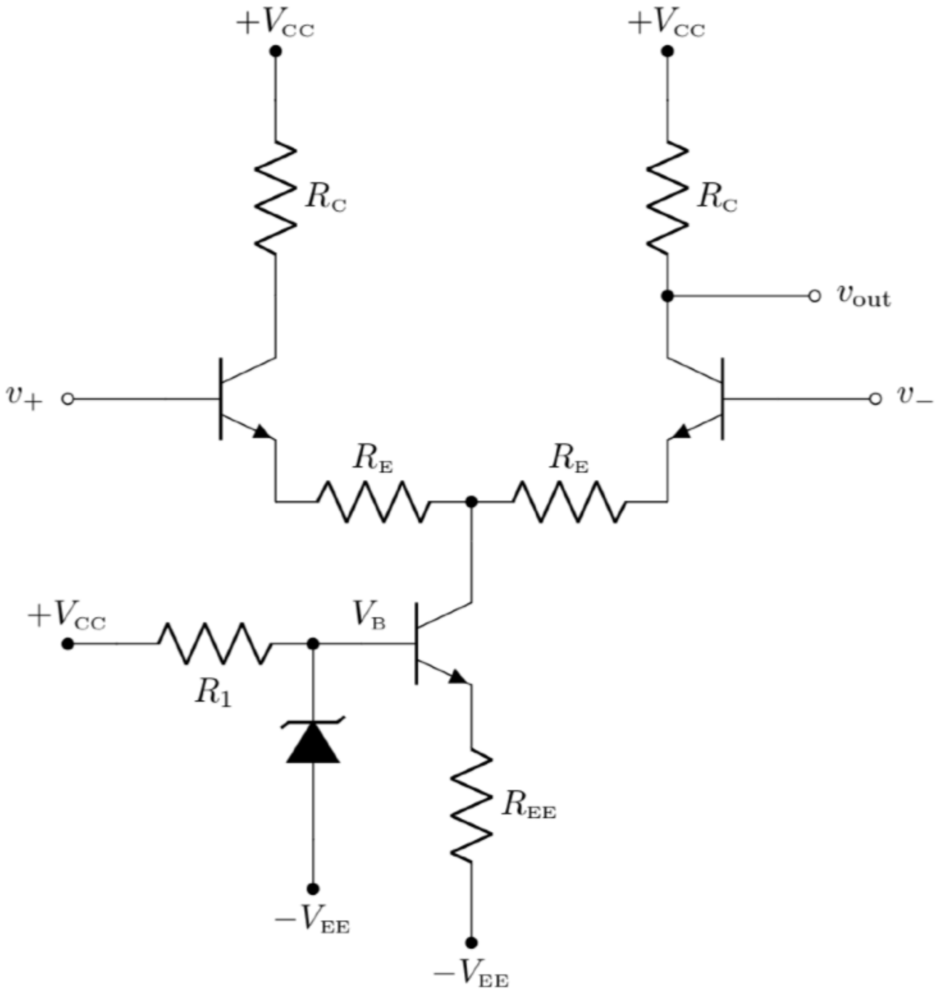
# Differential amplifier



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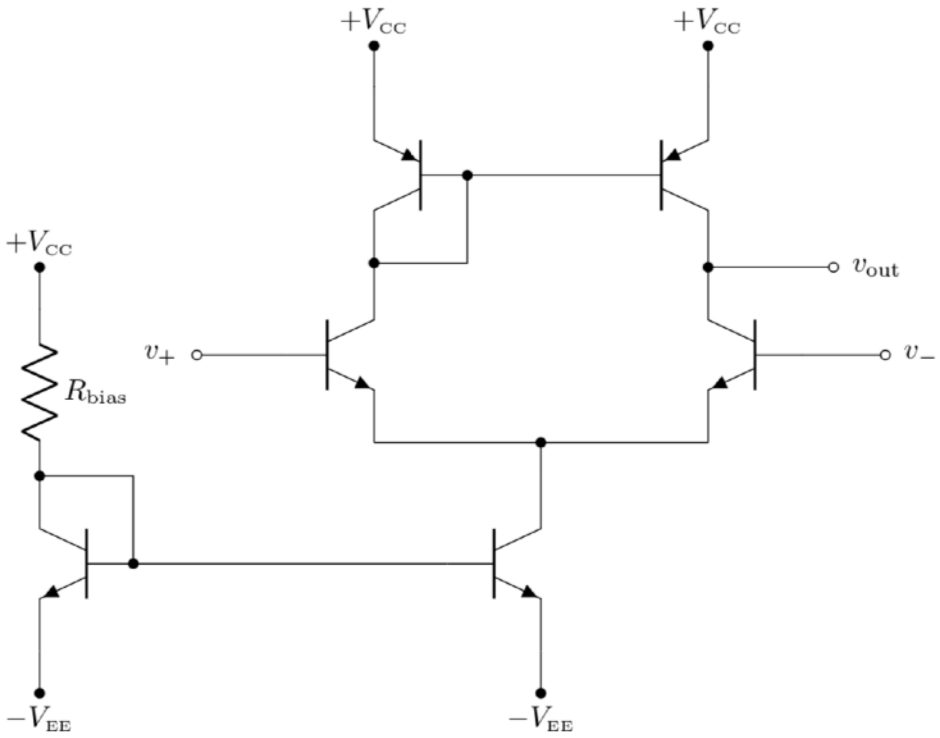

To maximize the CMRR = $G_{Diff}/G_{CM}$ make $R_{EE}$ large.

A current source has infinite impedance.

A current mirror makes $R_C$ large for differential signals and small for common mode.

So this circuit gives very maximal $G_{Diff}$ and a large common mode rejection ratio. But we no longer control the gain; we'll see how to do that separately later.

Common mode gain = $-R_C/(R_E+2R_{EE})$
Differential gain = $R_C/2R_E$

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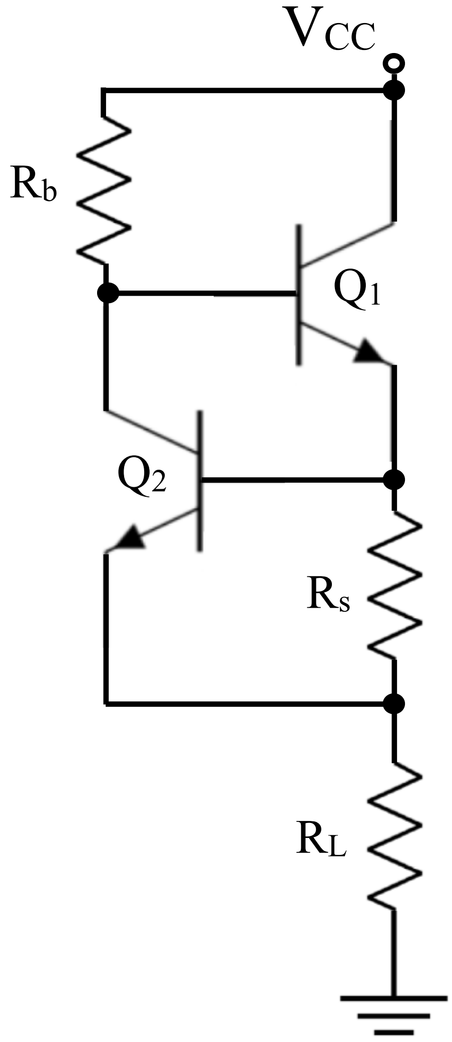
# Current limiter

Separate from having a constant current, we often want to limit $I<I_{max}$.



If $Q_2$'s $V_{BE}<0.6$ V it turns off, so no current flows through $R_b$ and $Q_1$ has a high $V_b$ and $Q_1$ is on.

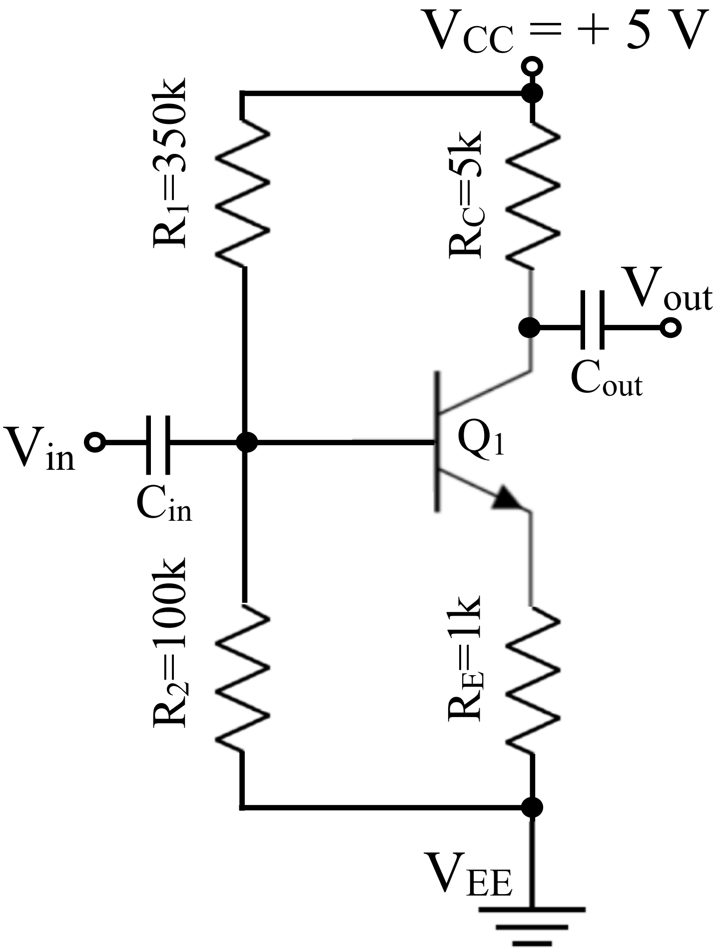
If enough current flows to cause the voltage drop across $R_s$ to go above 0.6 V, $Q_2$ turns on and current flows through $R_b$. That reduces the base voltage of $Q_1$, lowering the current through $Q_1$ and hence the current through $R_s$ to turn off $Q_2$. This rapid on/off leads to an equilibrium at the max current of $0.6/R_s$.

I.e., attempts to increase the load current beyond $I_L = 0.6/R_s$ (either by higher $V_{CC}$ or lower $R_L$) will lead to a max current of $0.6/R_s$.

E.g., $R_S = 0.6\Omega$ limits load current to 1 A.

# Intuition on transistor operation

It may help your intuition to think about the changing voltage drops



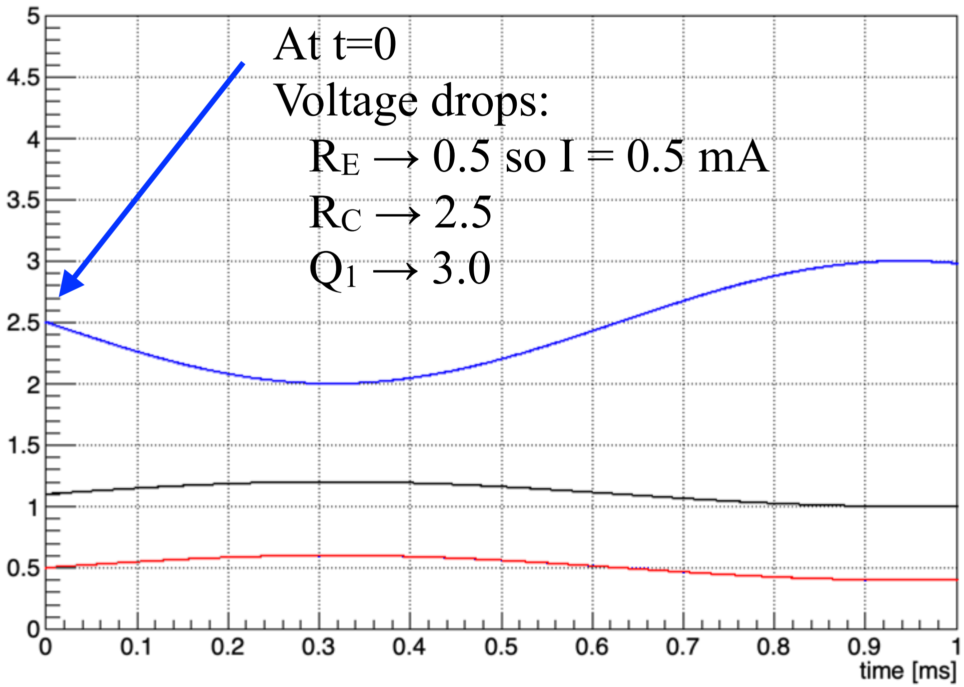
Set gain = 5 and choose quiescent point of

$V_E$=0.5 and $V_C$=2.5

Requires $V_B$ = 1.1, so pick $R_2$=100k and calculate $R_1$ with

$$V_B = V_{CC}\ 100\text{k} / (R_1+100\text{k})$$

$$R_1 = 100\text{k}\ V_{CC} / V_B - 100\text{k} = 350\text{ k}$$



At t=0

Voltage drops:

$R_E \rightarrow 0.5$ so I = 0.5 mA

$R_C \rightarrow 2.5$

$Q_1 \rightarrow 3.0$

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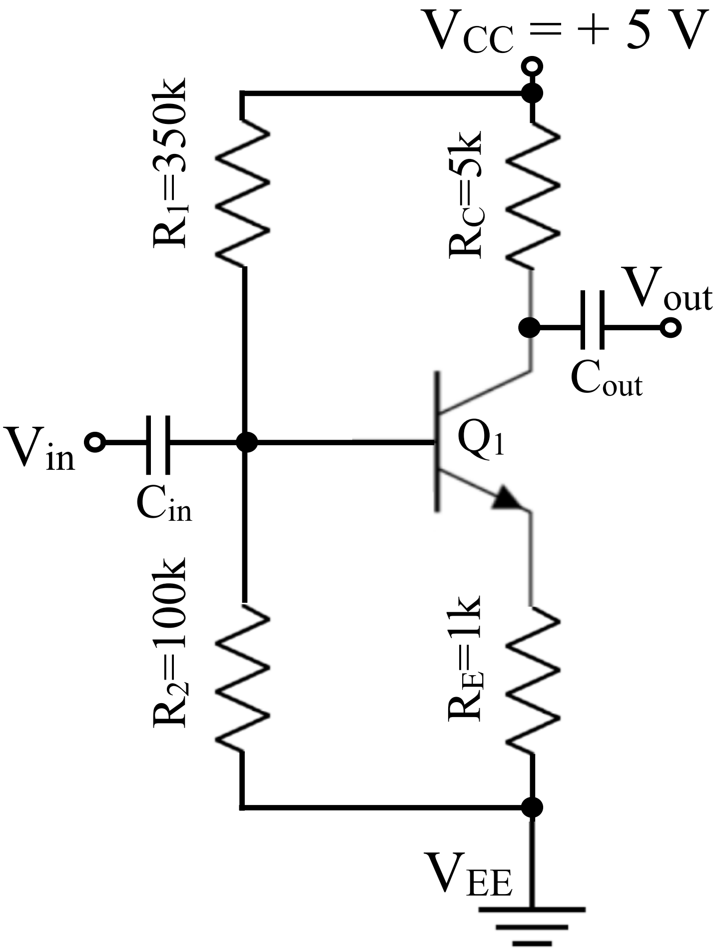

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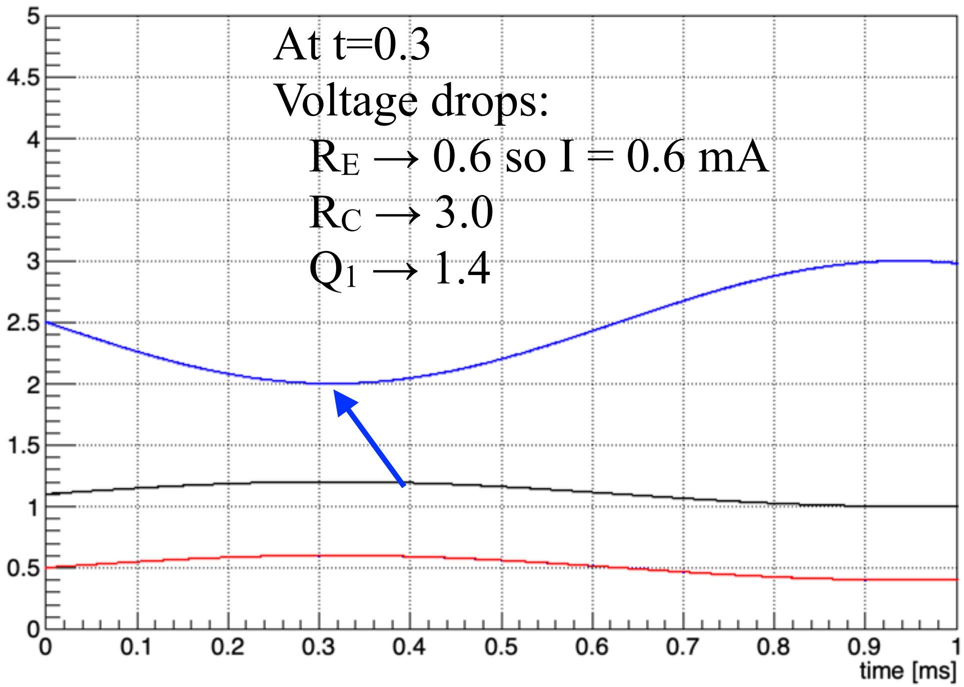

At t=0.3

Voltage drops:

$R_E \rightarrow 0.6$ so I = 0.6 mA

$R_C \rightarrow 3.0$

$Q_1 \rightarrow 1.4$

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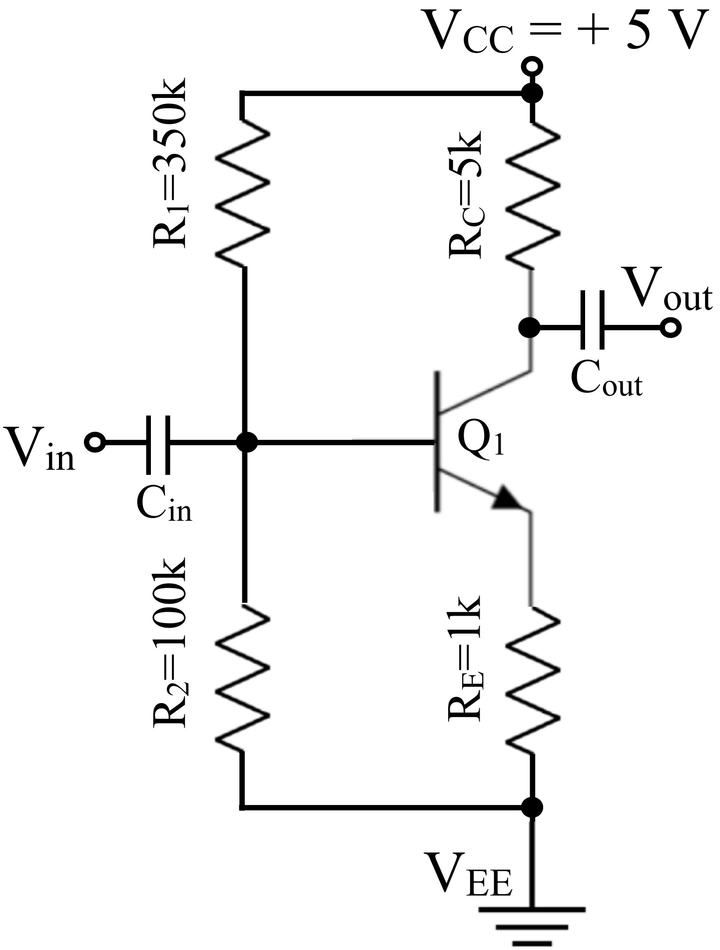
# Intuition on transistor operation

It may help your intuition to think about the changing voltage drops



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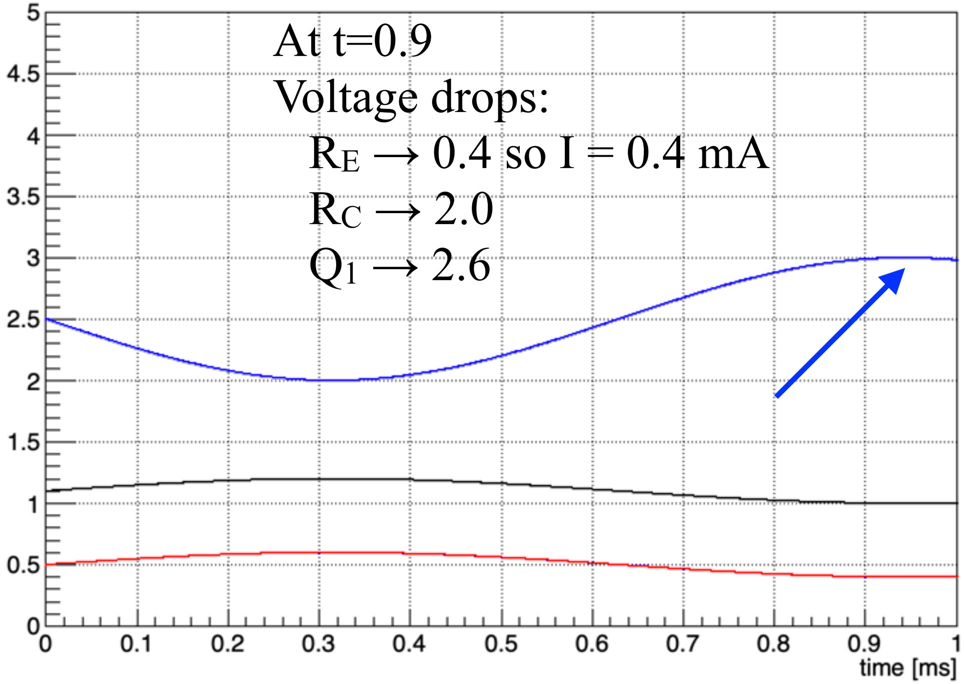

At t=0.9

Voltage drops:

$R_E \rightarrow 0.4$ so I = 0.4 mA

$R_C \rightarrow 2.0$

$Q_1 \rightarrow 2.6$

# Intuition on transistor operation

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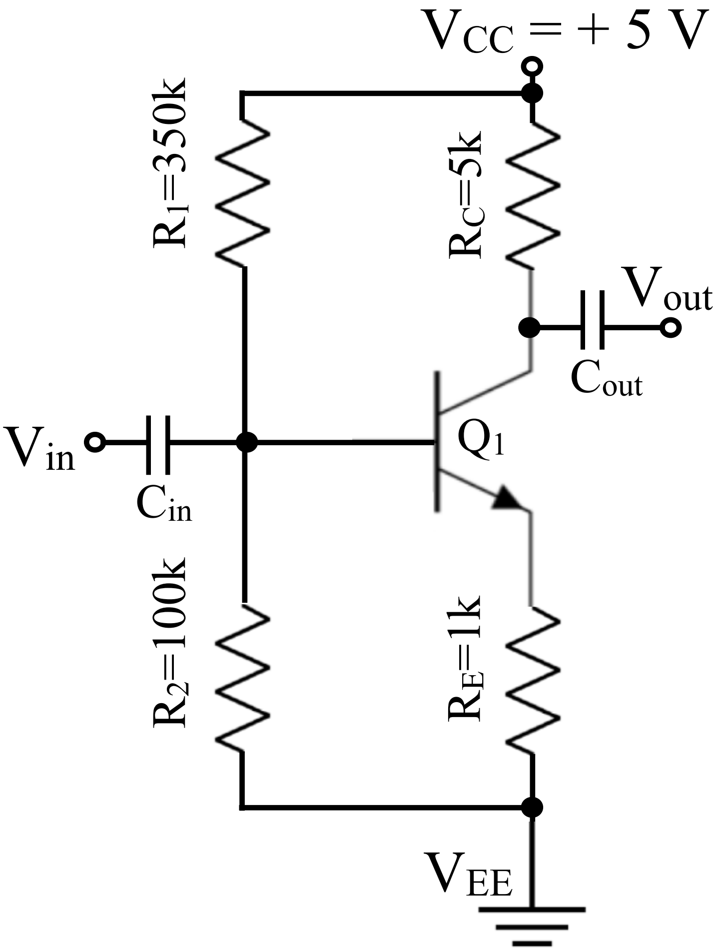

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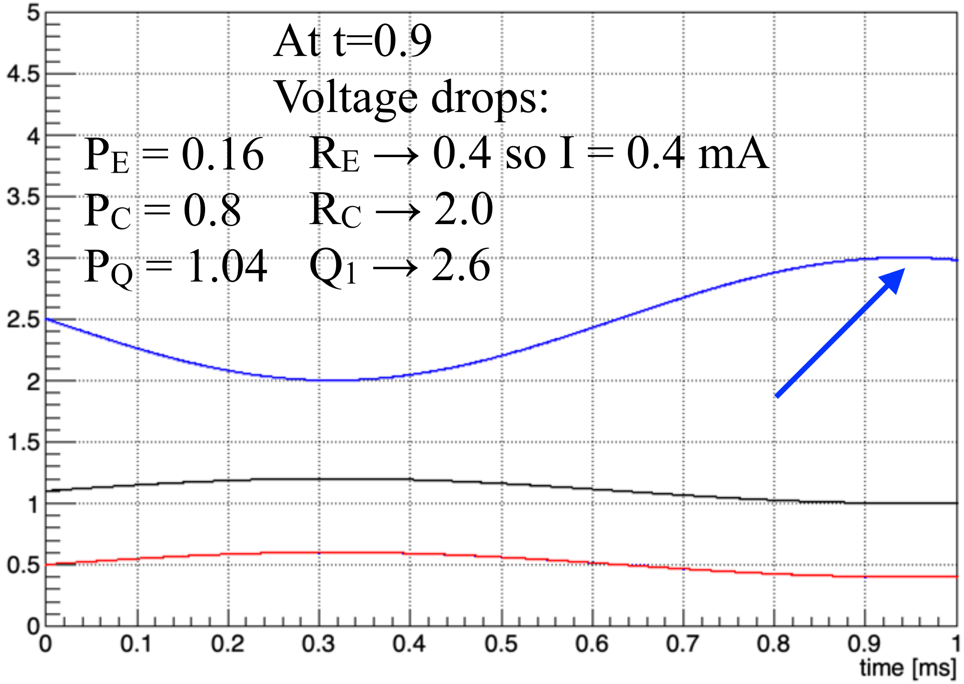

At t=0.9

Voltage drops:

$P_E = 0.16$ $R_E \rightarrow 0.4$ so I = 0.4 mA

$P_C = 0.8$ $R_C \rightarrow 2.0$

$P_Q = 1.04$ $Q_1 \rightarrow 2.6$

# Intuition on transistor operation

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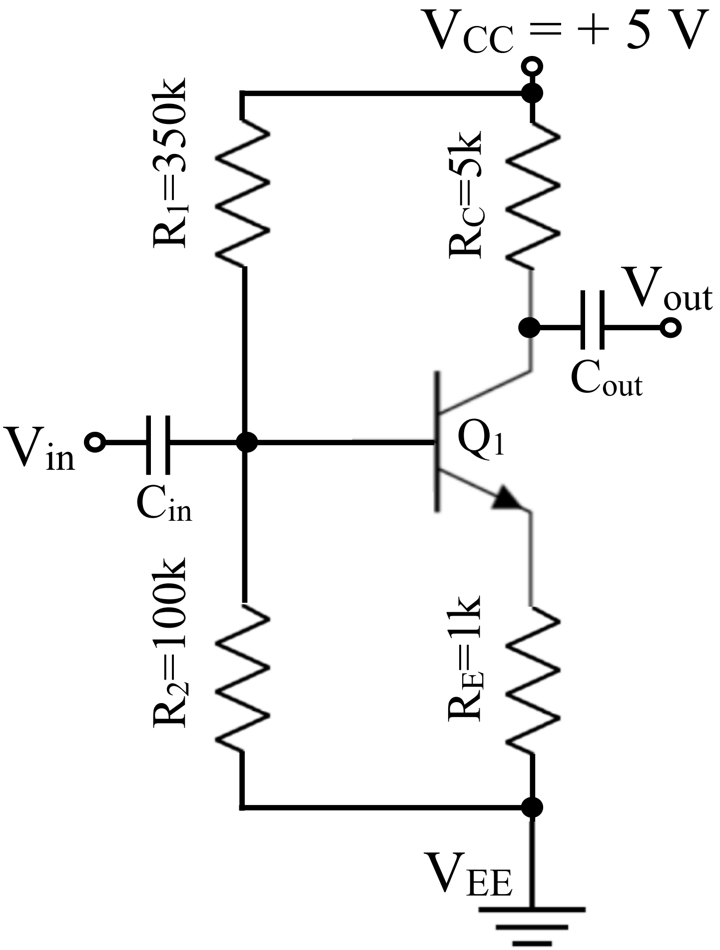

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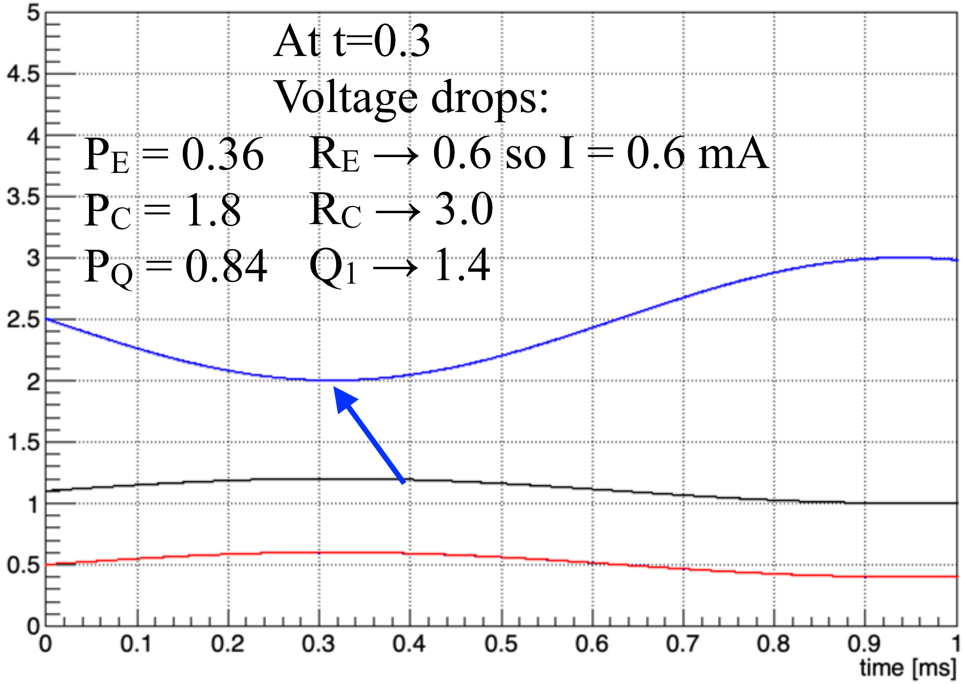
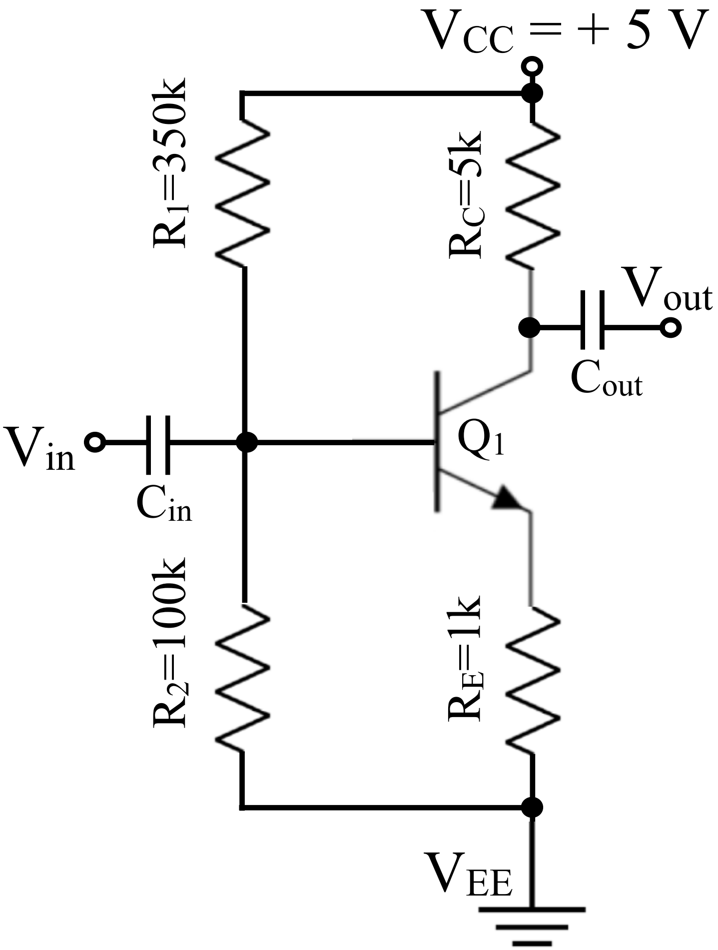


At t=0.3
Voltage drops:

$P_E$ = 0.36   $R_E$ → 0.6 so I = 0.6 mA
$P_C$ = 1.8   $R_C$ → 3.0
$P_Q$ = 0.84   $Q_1$ → 1.4

# Intuition on transistor operation

It may help your intuition to think about the changing voltage drops



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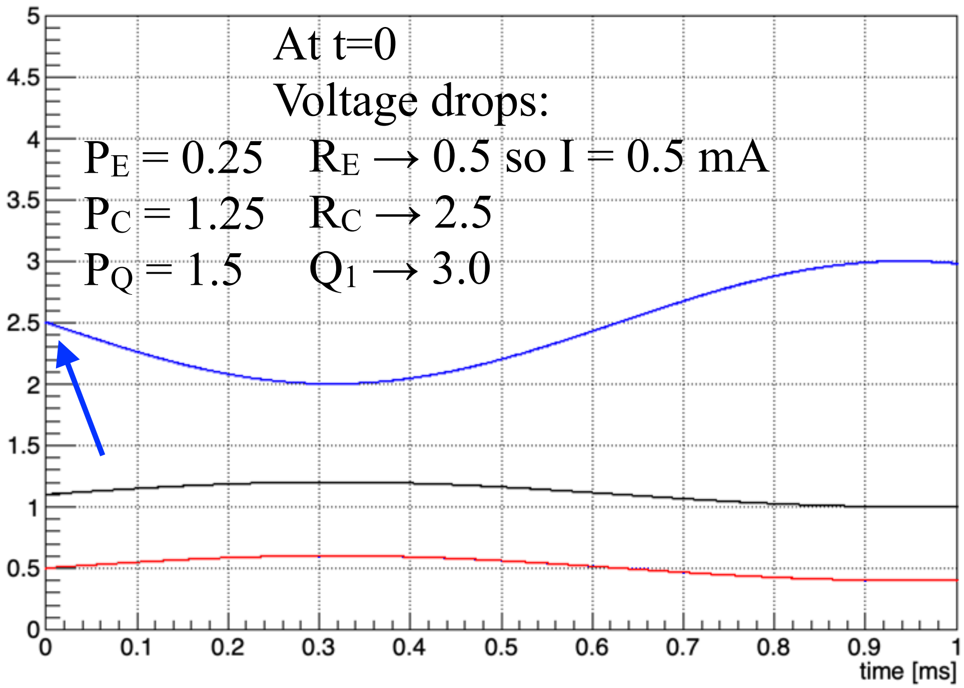

At t=0

Voltage drops:

$P_E$ = 0.25 $R_E$ → 0.5 so I = 0.5 mA

$P_C$ = 1.25 $R_C$ → 2.5

$P_Q$ = 1.5 $Q_1$ → 3.0

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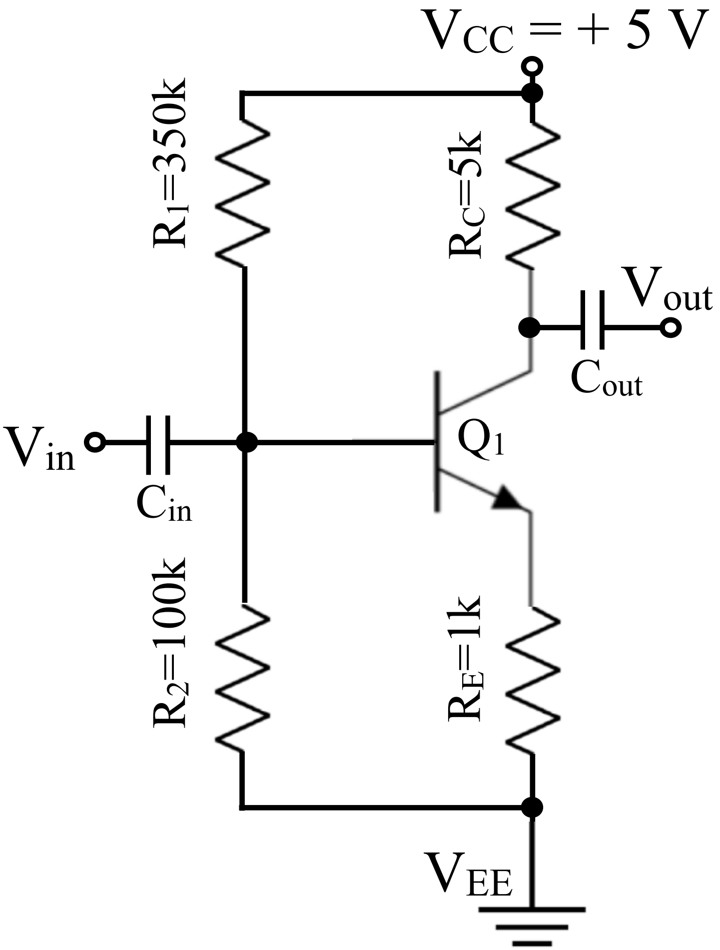
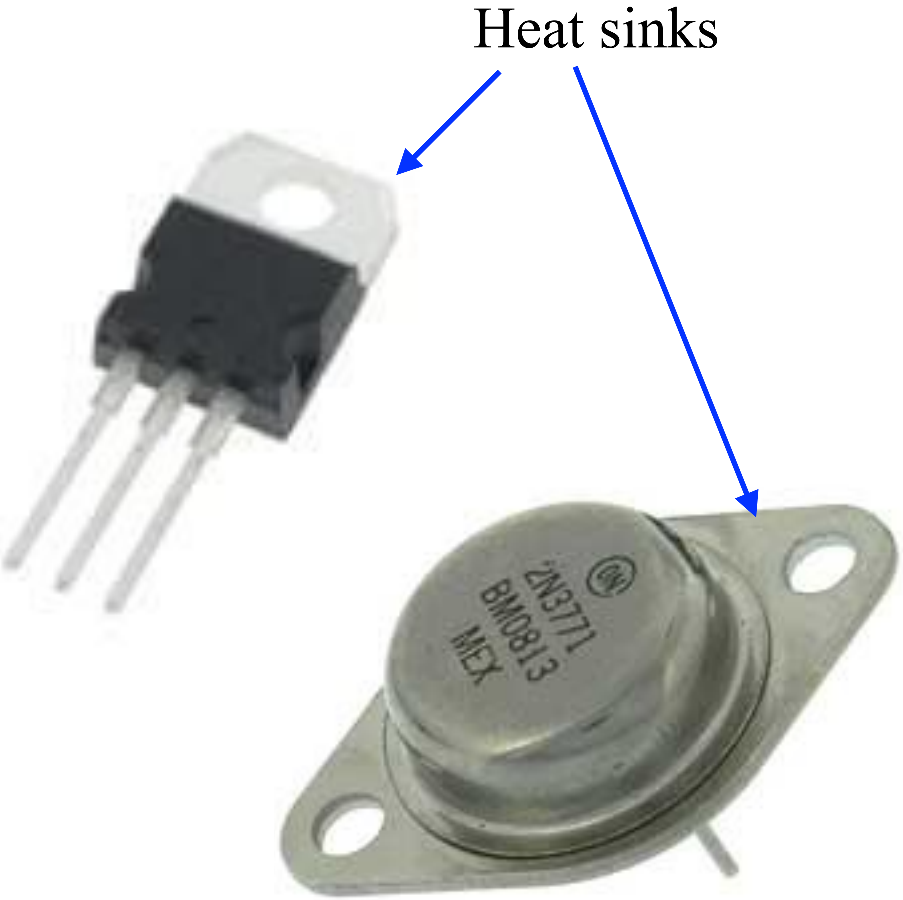
# Power transistors

If we wanted to drive a high current load, like a speaker, we need a low $R_C$ ($X_{out}$), and a low $R_E$. So transistor dissipates a lot of power.





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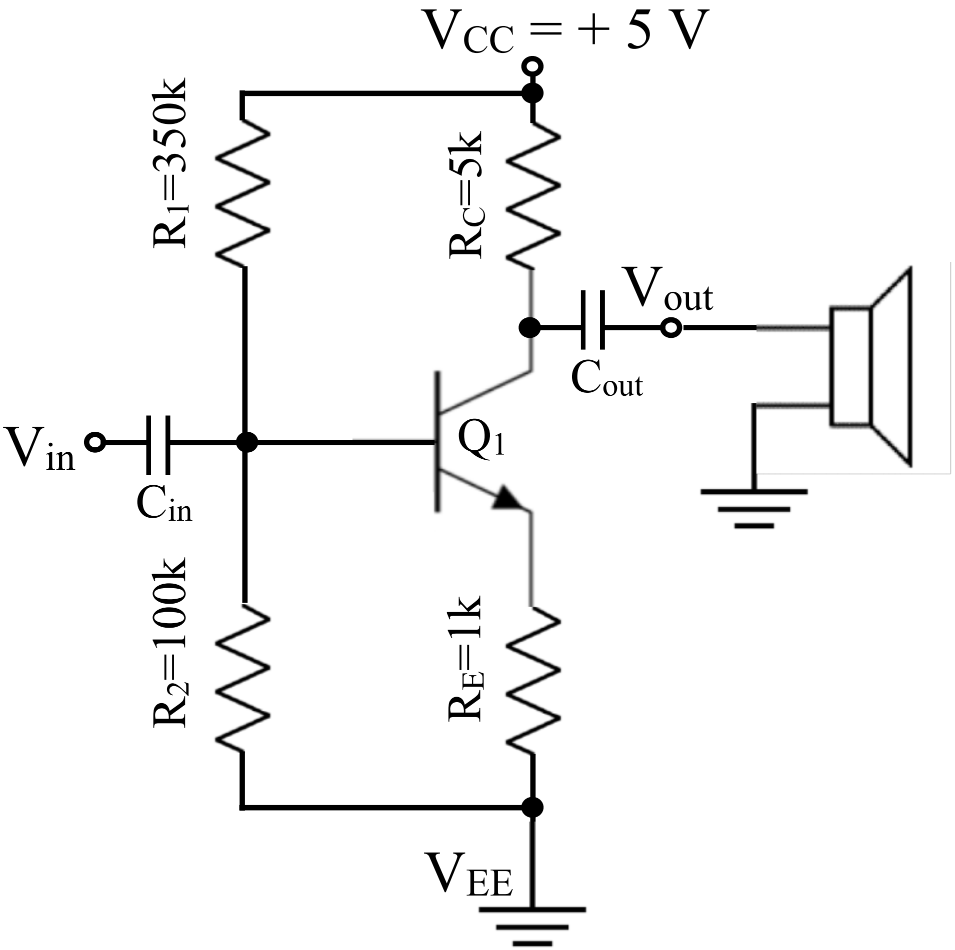

Speakers are usually 8Ω, so we need a very small $R_C$ to match.

And a very large $C_{out}$ for audio frequency: 20 Hz = 1/RC = 1/8*C
C = 1/160 = 6mF!

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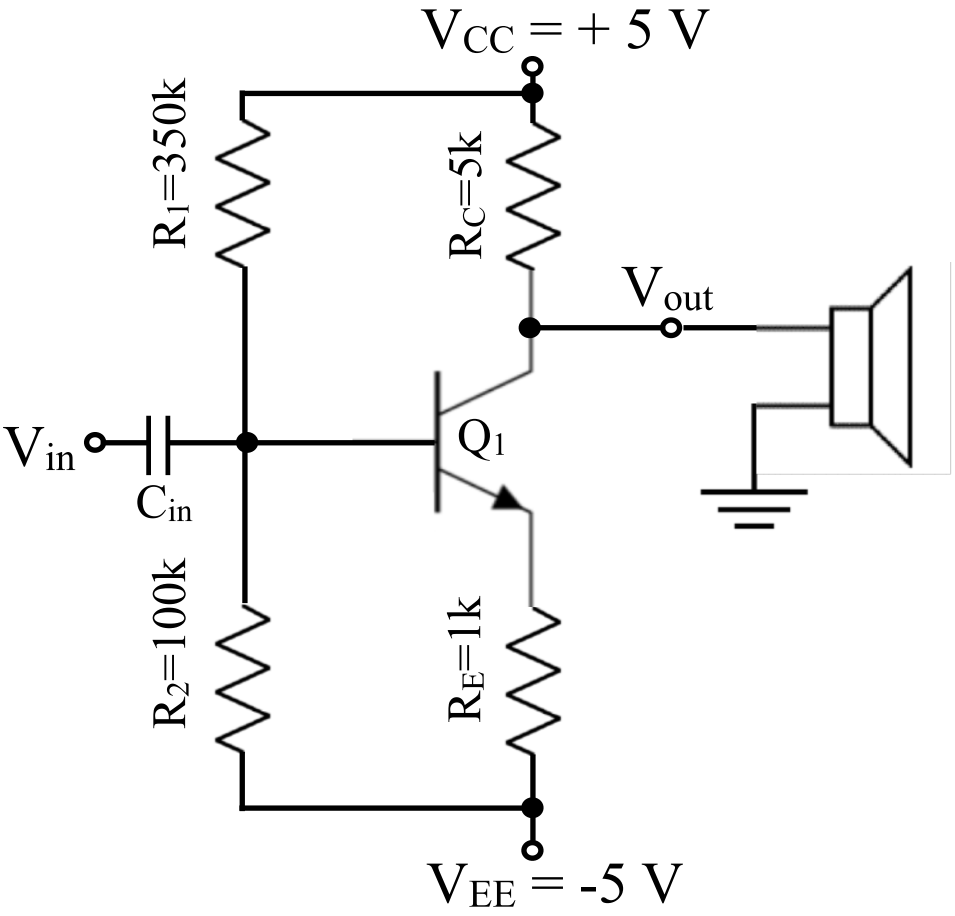

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C = 1/160 = 6mF!

Better to set the $V_{out}$ quiescent point at ground, with a dual power supply, and DC couple the output.

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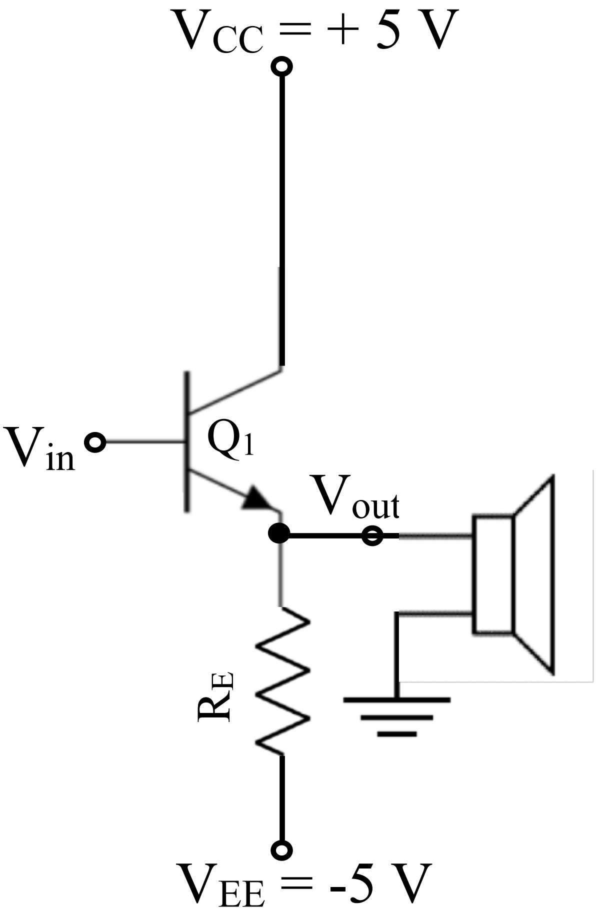

Even better to use an emitter follower as the output stage.

Amplification done in a previous stage. This just drives the speaker.

$R_E$ still needs to be small, with high power to $V_{EE}$.

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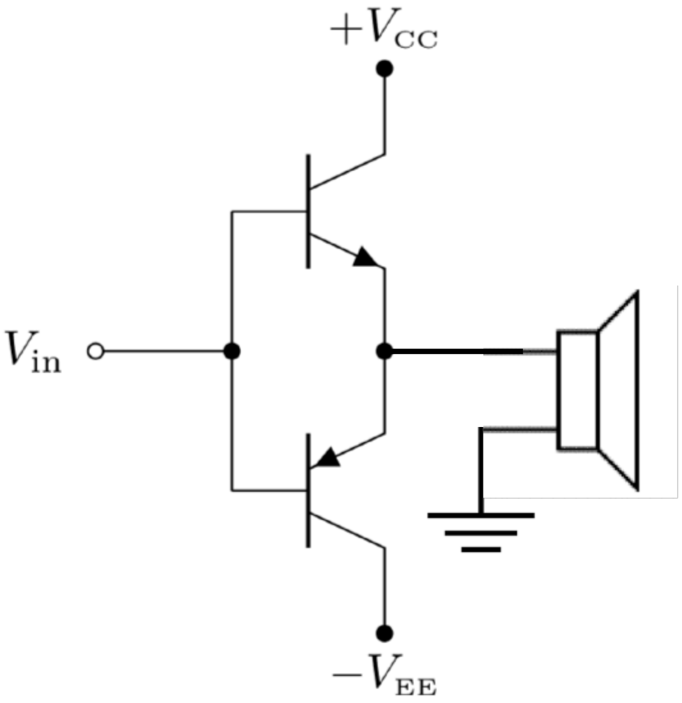

Fix that by making the speaker be $R_E$
Connect it only to ground
But need two transistors to drive it;
They push and pull current.

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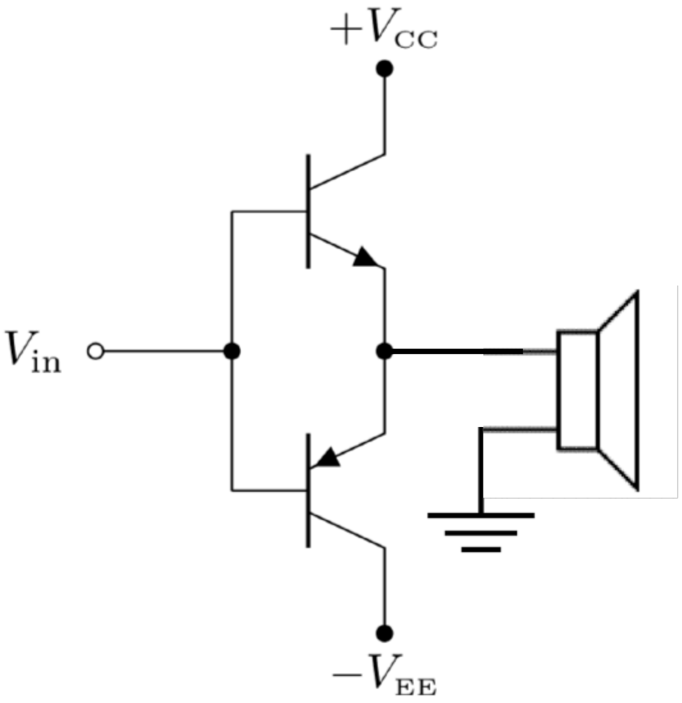

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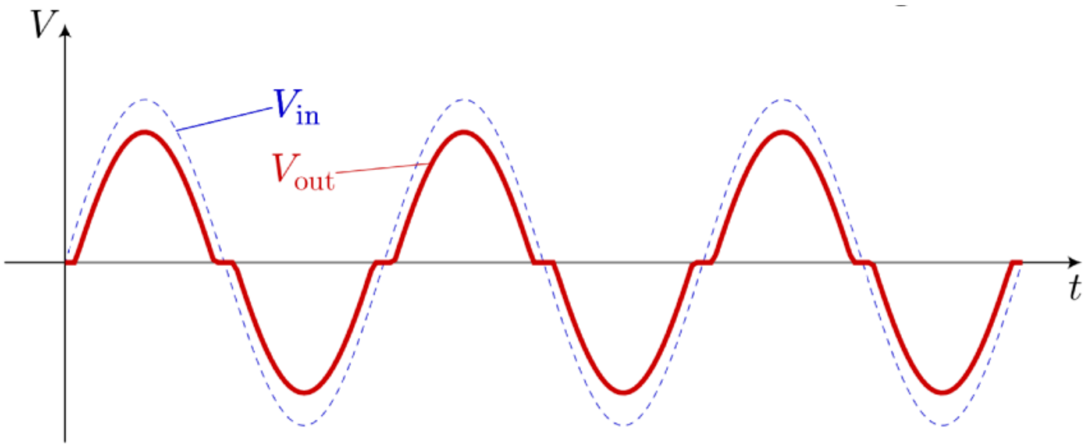

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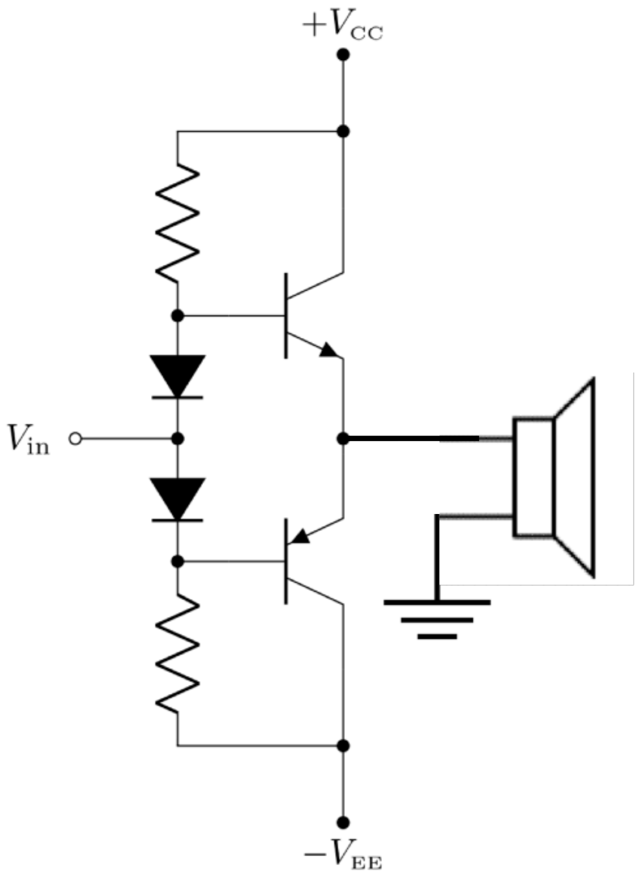

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A diode does that, but temperature sensitive.

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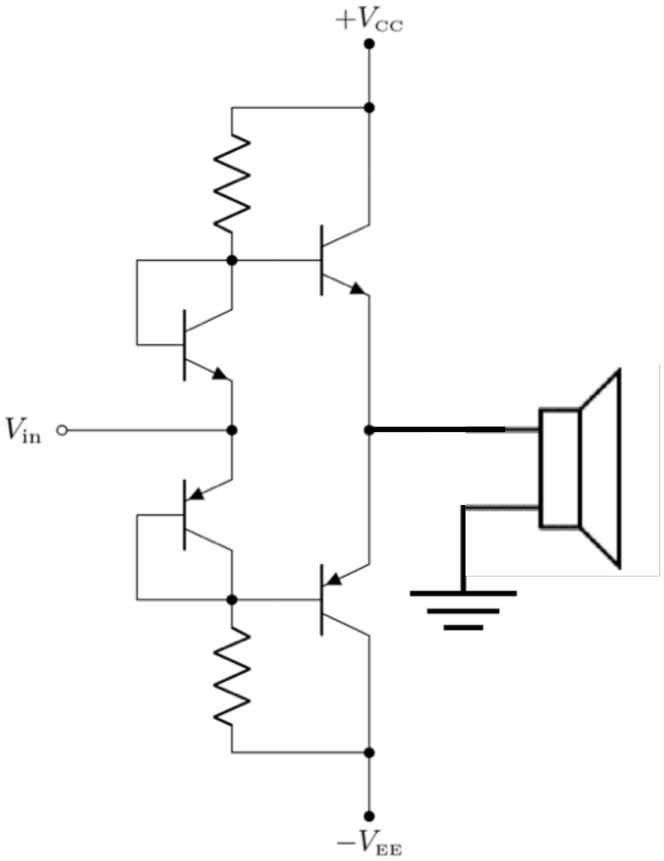

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A diode does that, but temperature sensitive. So use identical copies of the push-pull transistors. (Ebers-Moll)

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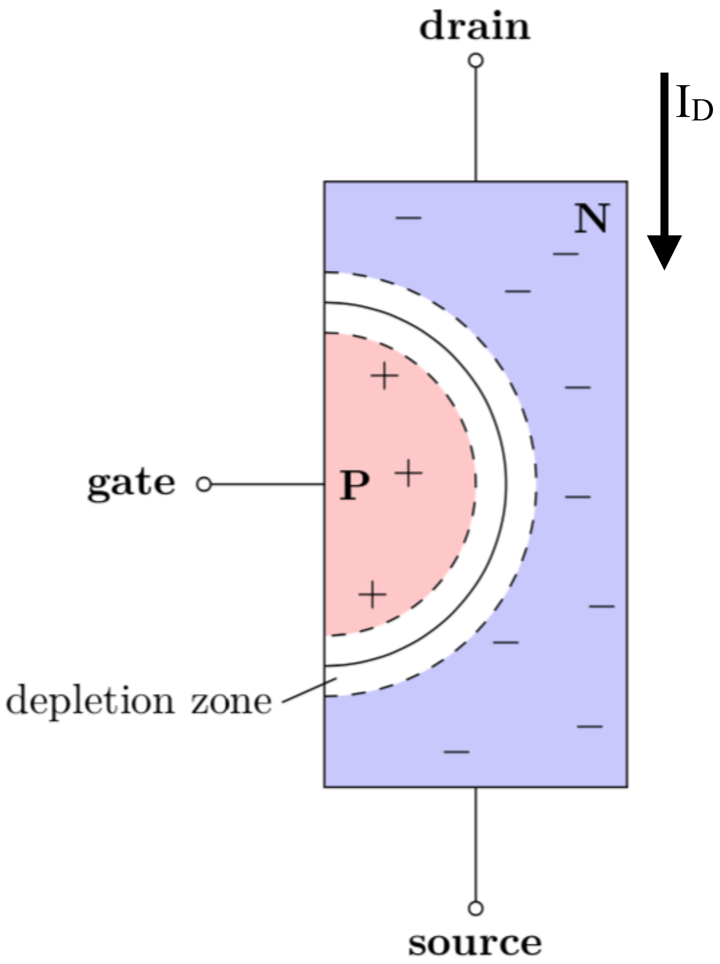
# Field effect transistors (FETs)

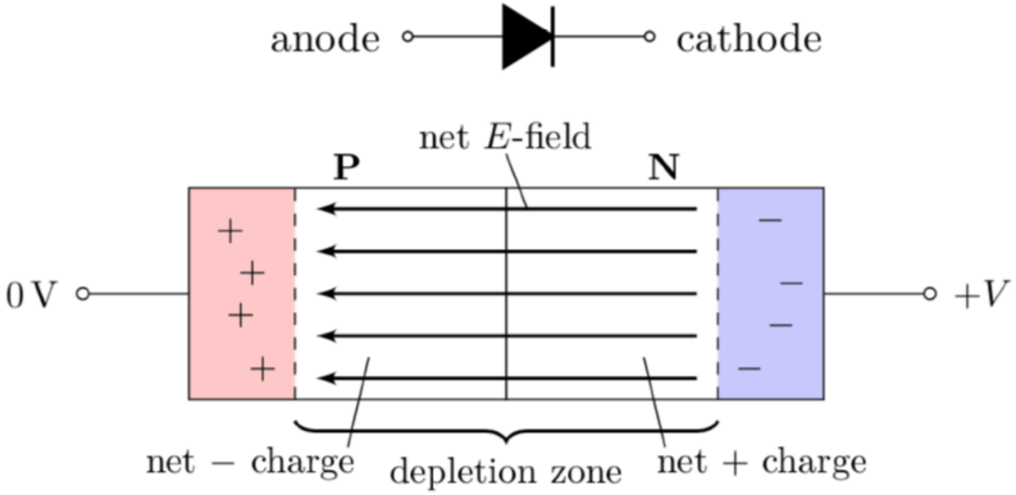
The NPN and PNP transistors we've discussed so far are called bi-polar junction transistors (BJT). FETs operate under a different mechanism.



This is a junction FET (jFET) where a p-type region is implanted within an n-type bulk. The depletion region can be controlled by the gate. Lower $V_g$ increases the depletion.

$$I = n\,A\,q\,v$$

So changing the gate voltage controls n and I. Like pinching off a hose.



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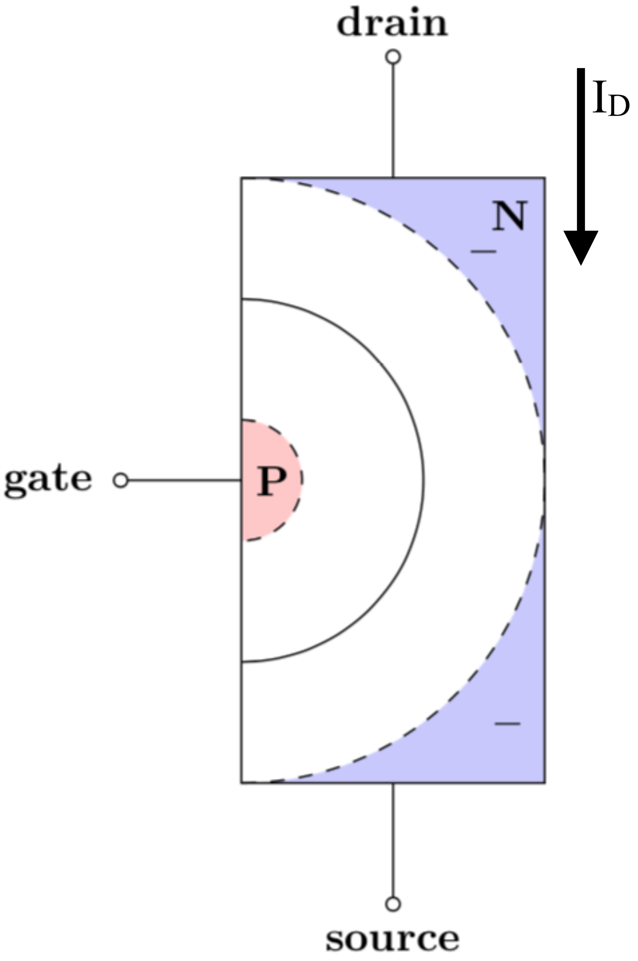

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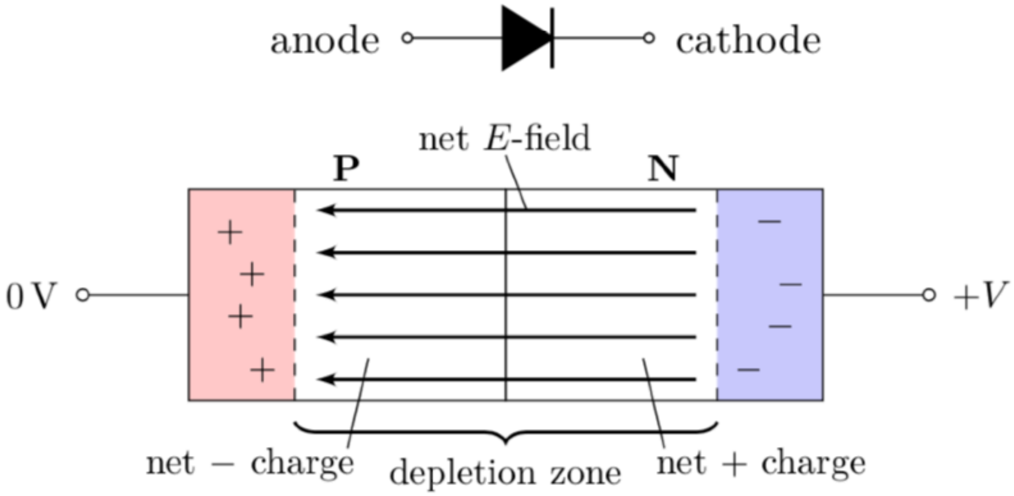

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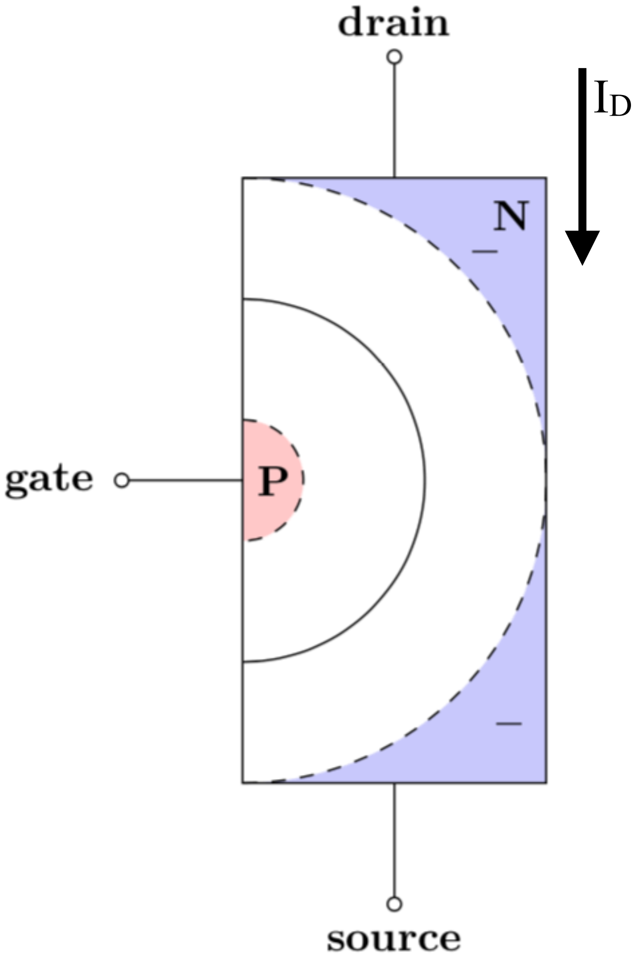

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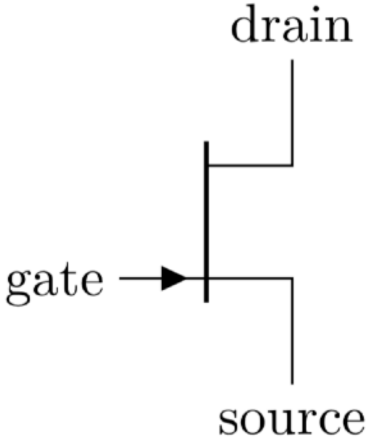

**n-channel**

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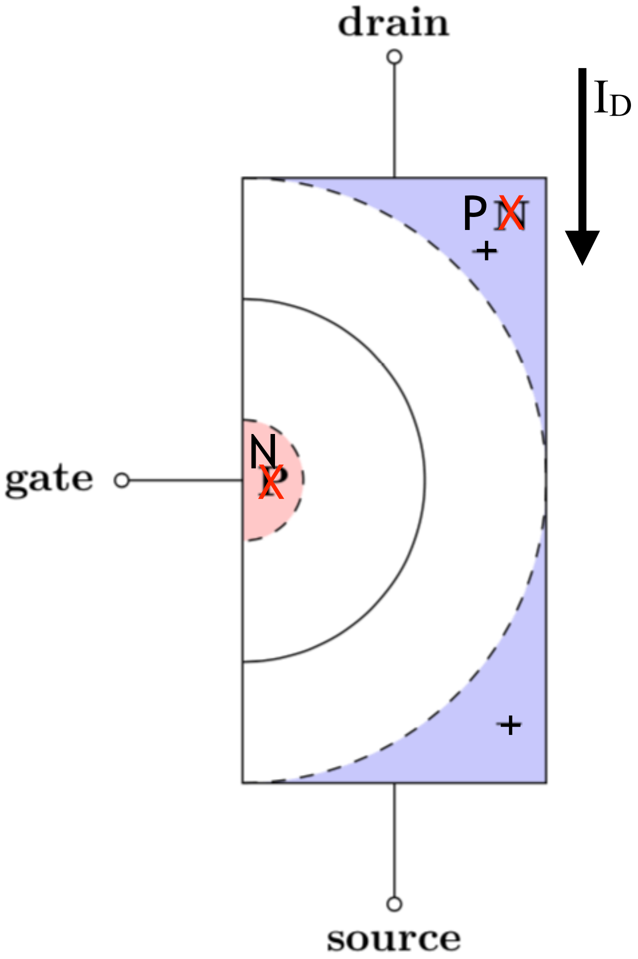

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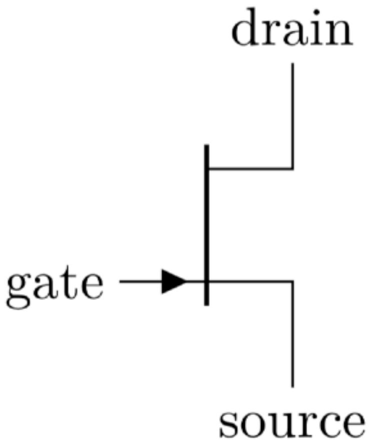

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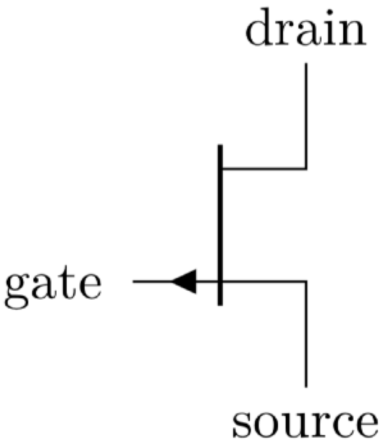

**p-channel**

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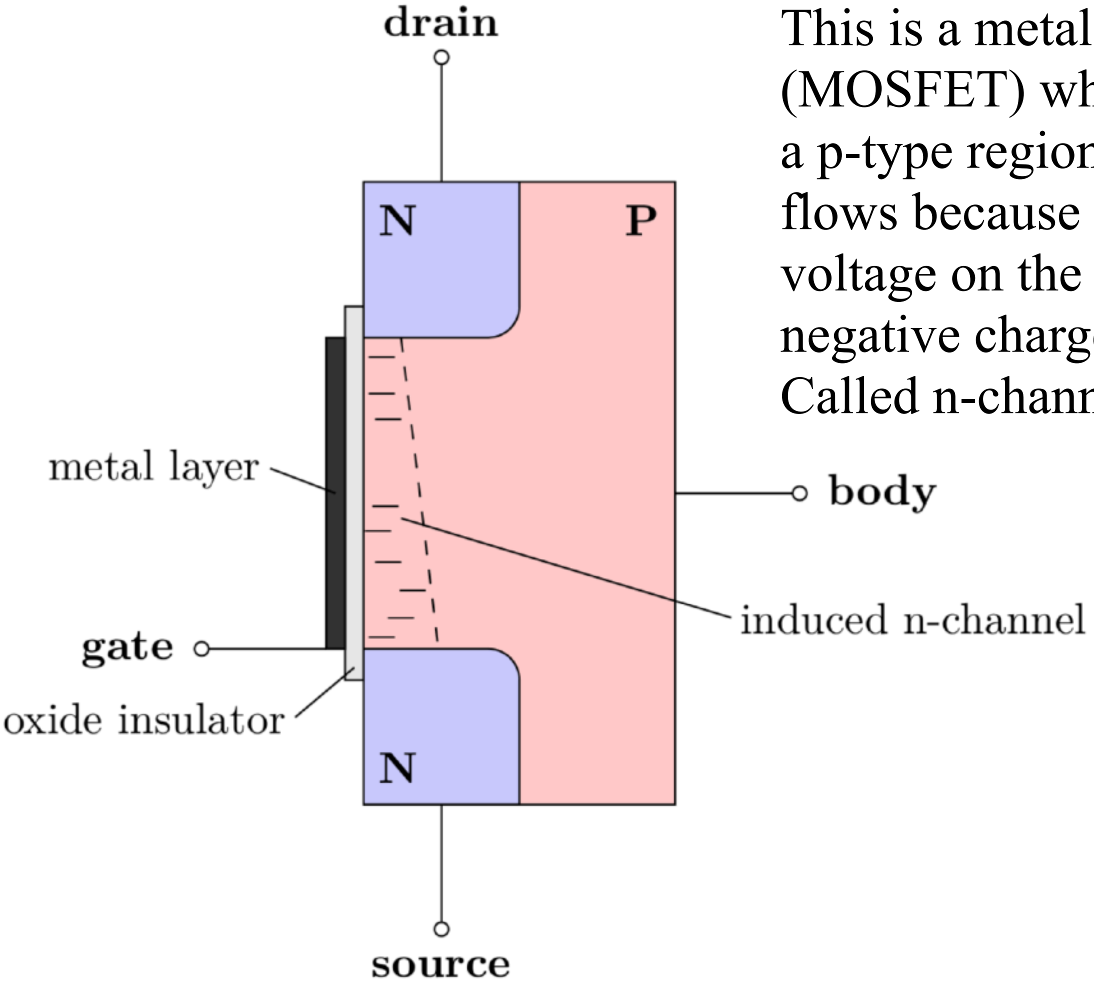
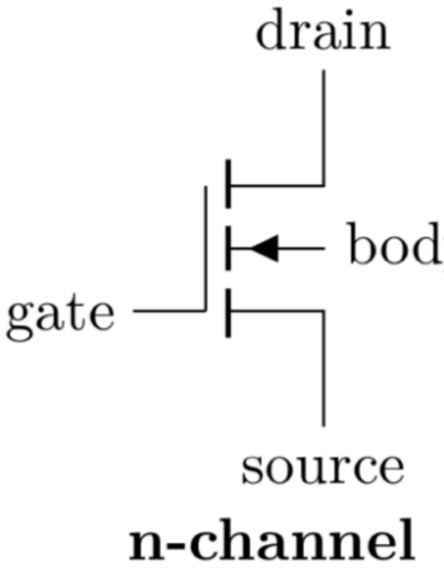
# Field effect transistors (FETs)

The NPN and PNP transistors we've discussed so far are called bi-polar junction transistors (BJT). FETs operate under a different mechanism.

This is a metal-oxide-semiconductor FET (MOSFET) where a thin capacitor is placed over a p-type region between two n-types. No current flows because of depletion regions. But a positive voltage on the gate (wrt the body) induces negative charge carriers in the p-type region. Called n-channel since n-type carriers move.





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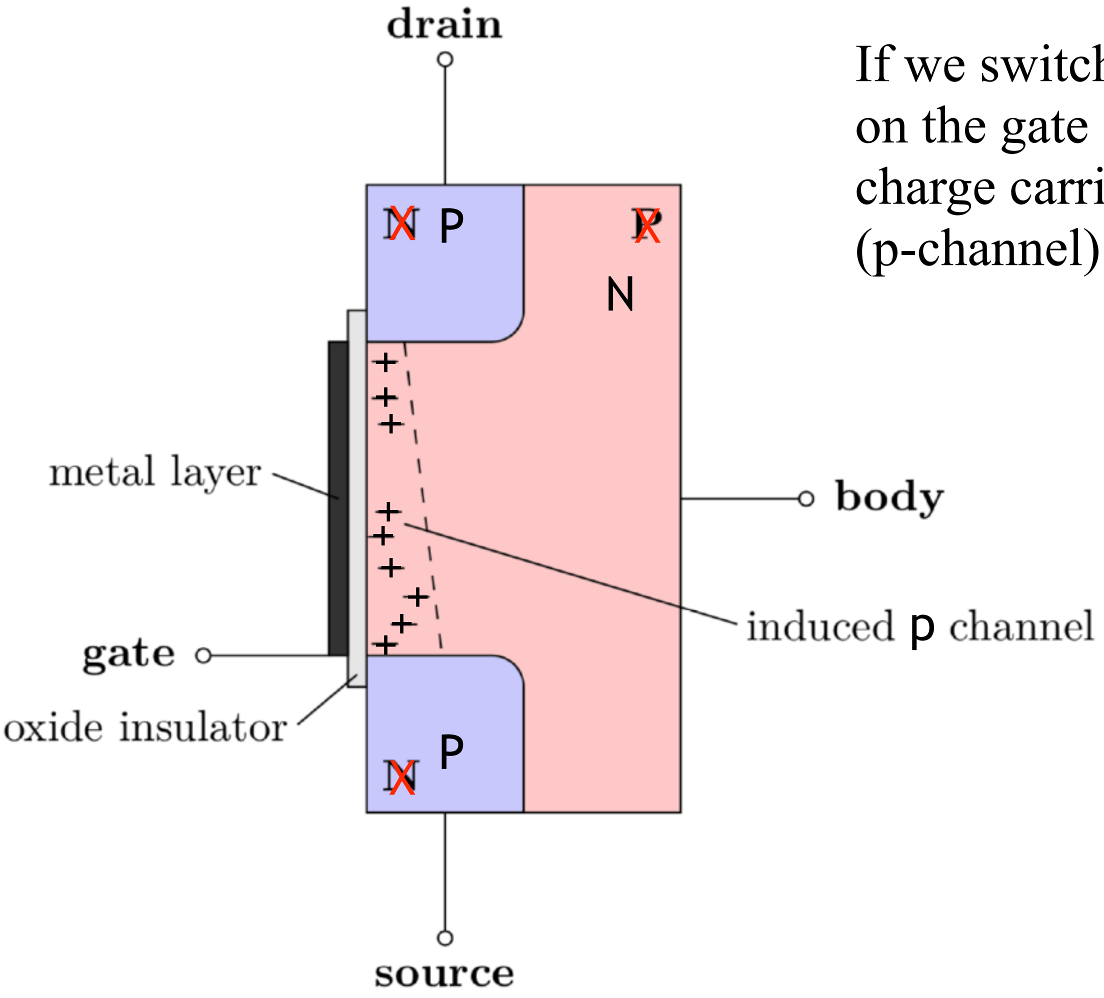
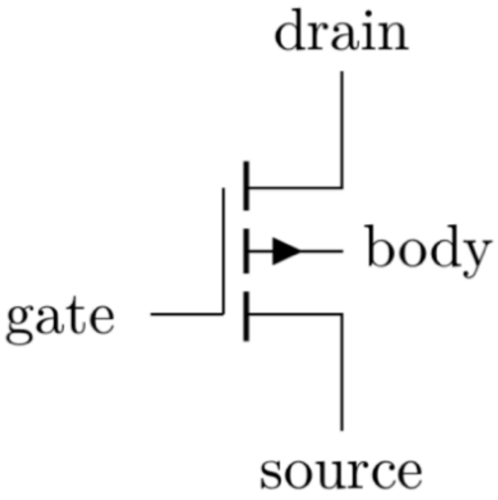
# Field effect transistors (FETs)

The NPN and PNP transistors we've discussed so far are called bi-polar junction transistors (BJT). FETs operate under a different mechanism.

If we switch to n-bulk then a negative voltage on the gate (wrt the body) induces positive charge carriers in the p-type region. (p-channel).





**p-channel**

# Field effect transistors (FETs)

Electro-static discharge (ESD) is a risk for MOSFETs due to thin oxide.