Electronics - 03

: Transistors

Transistors - dynamic description

RC circuit

Transistor

The transistor is the fundamental building block of the circuitry that governs the operation of computers, cellular phones, and all other modern electronics. It is a three terminal device.

There are largely two different types of transistors : BJT and MOSFET

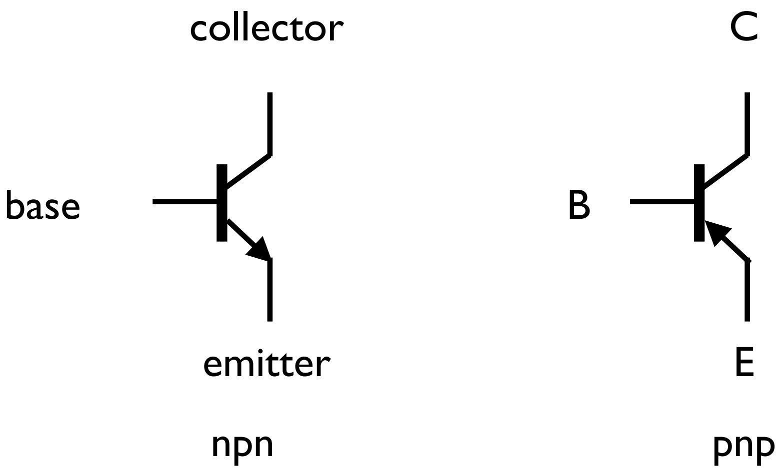
We quickly go over two types and focus on BJT only in later classes

"**A picture of the first transistor ever assembled, invented in Bell Labs in 1947**. It was called a point contact transistor because amplification or transistor action occurred when two pointed metal contacts were pressed onto the surface of the semiconductor material. The contacts, which are supported by a wedge shaped piece of insulating material, are placed extremely close together so that they are separated by only a few thousandths of an inch. The contacts are made of gold and the semiconductor is germanium. The semiconductor rests on a metal base.

BJT

BJT: Bipolar Junction Transistor

A bipolar transistor is a 3-terminal device available in two flavors (npn and pnp)



Emitter: the emitter is the source of majority carriers that result in the gain mechanism of the BJT. These carriers which are "emitted" into the base are electrons for the npn transistor and holes for the pnp transistor

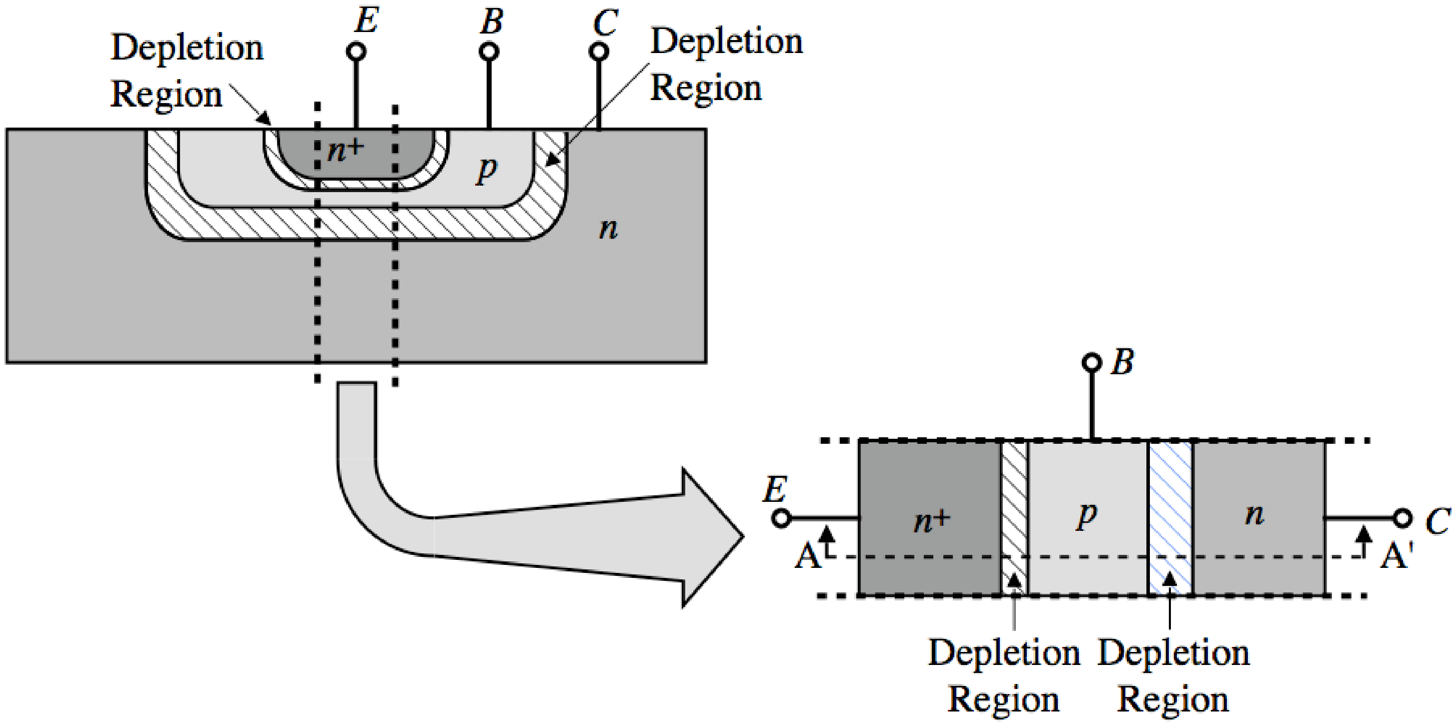
Base: the base is a region which physically separates the emitter and collector and has an opposite doping (holes for the npn and electrons for the pnp BJTs). The word "base" comes from the way that the first transistors were constructed. The base supported the whole structure

Collector: the collect serves to "collect" those carries injected from the emitter into the base and which reach the collector without recombination

BJT

Physical Aspects of an npn BJT

A cross-section of an npn BJT is shown below:



Things to note:

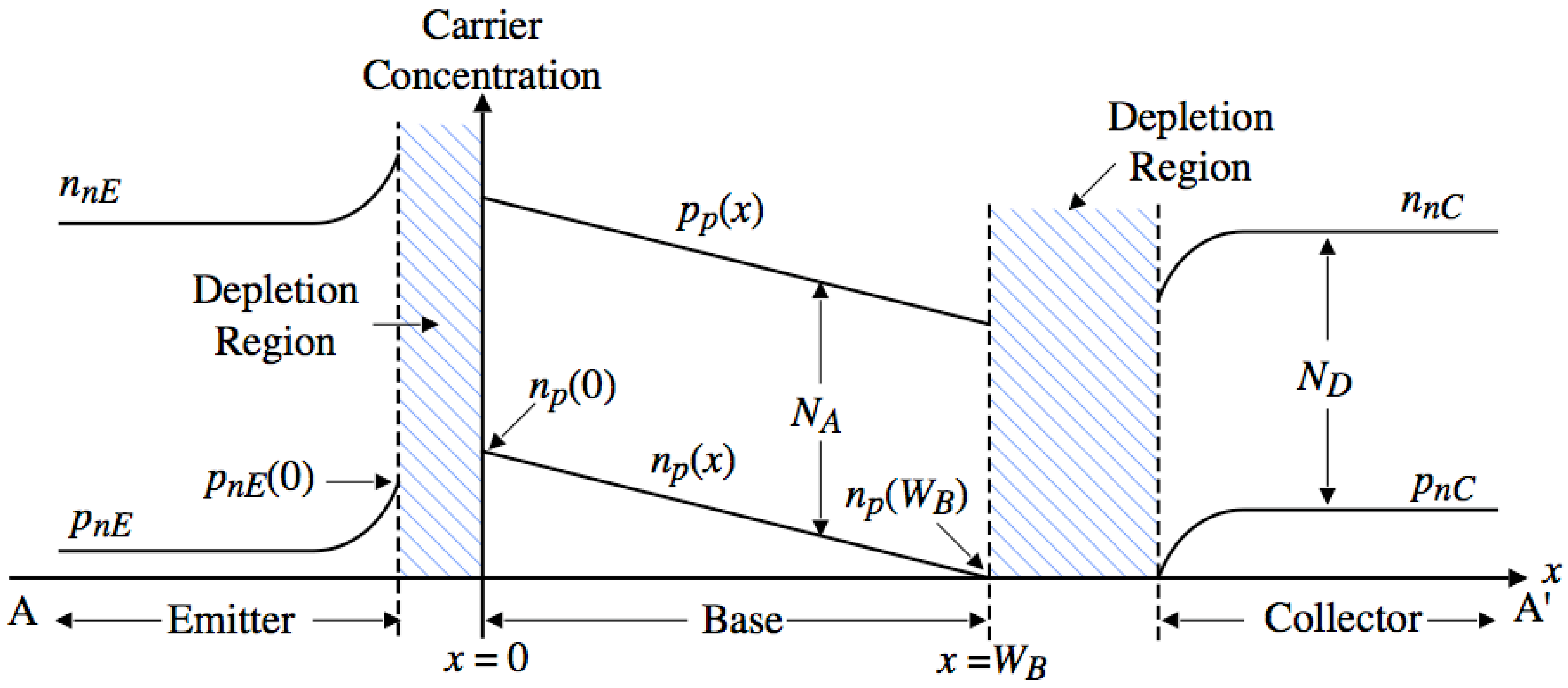
The emitter-base depletion region is generally smaller in width because the doping level is higher and base-emitter junction is generally forward-biased

We will examine the carrier concentrations along the cross sectional area defined by A-A’

BJT

Carrier Concentration of the npn BJT

The carrier concentration (not to scale) for the npn BJT are shown below



Things to note:

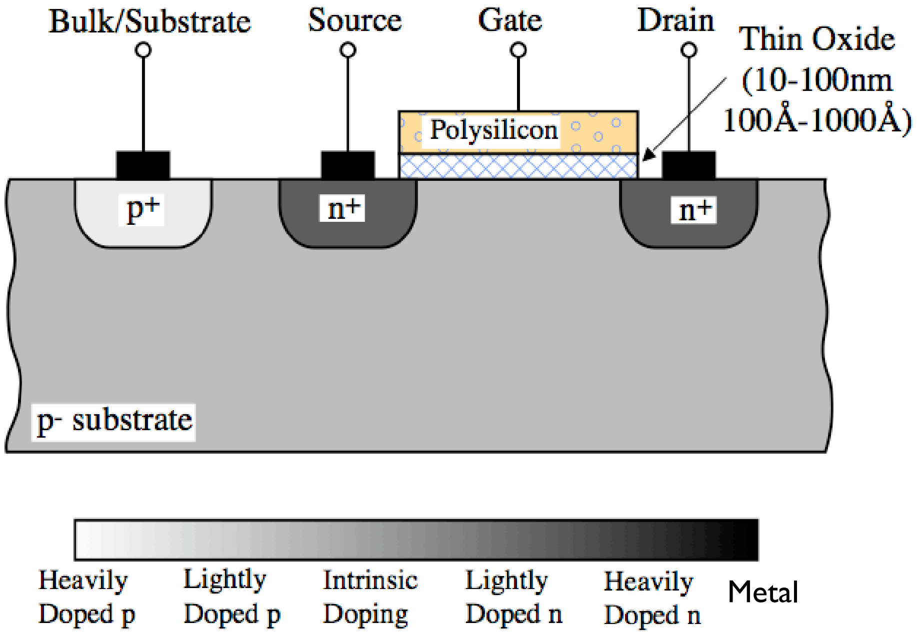
The above carrier concentrations assume that the base-emitter junction is forward biased and base-collector junction is reverse biased

The above carrier concentration can be used to derive the large signal model (DC behavior) : we skip for now

MOSFET

Metal-Oxide Semiconductor Field Effect Transistor : commonly called MOS transistor

MOSFET structure (NMOS is shown here)



Terminals:

Bulk: used to make ohmic contact to the substrate

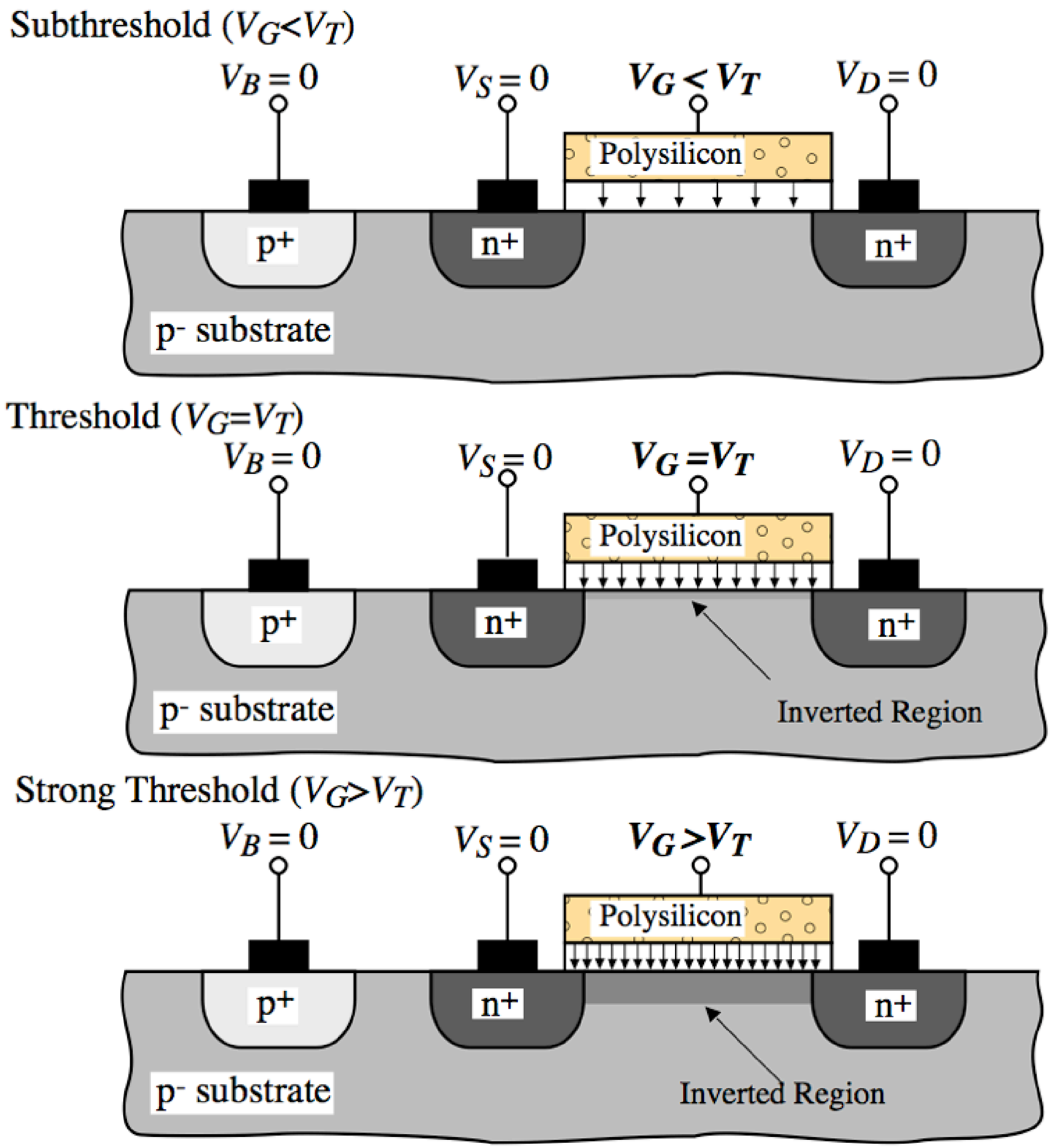
Gate: the gate voltage is applied in such a manner as to invert the doping of the material directly beneath the gate to form a channel between the source and drain

Source: source of the carriers flowing in the channel

Drain: collects the carriers flowing in the channel

MOSFET

Formation of the channel for a MOS transistor



Channel refers a stream path of charge carriers between the source and the drain

As the gate voltage is increases, electrons from n+ are collected under the gate

(called inverted as such region is no longer p-type anymore)

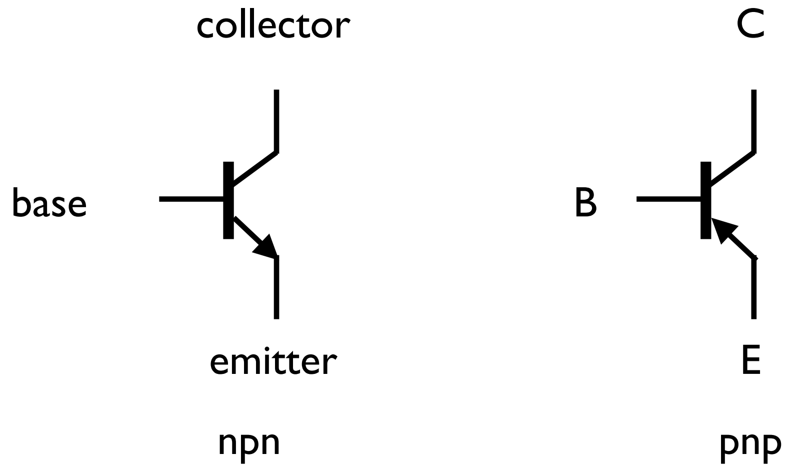
Inverted region is now large enough to form a channel

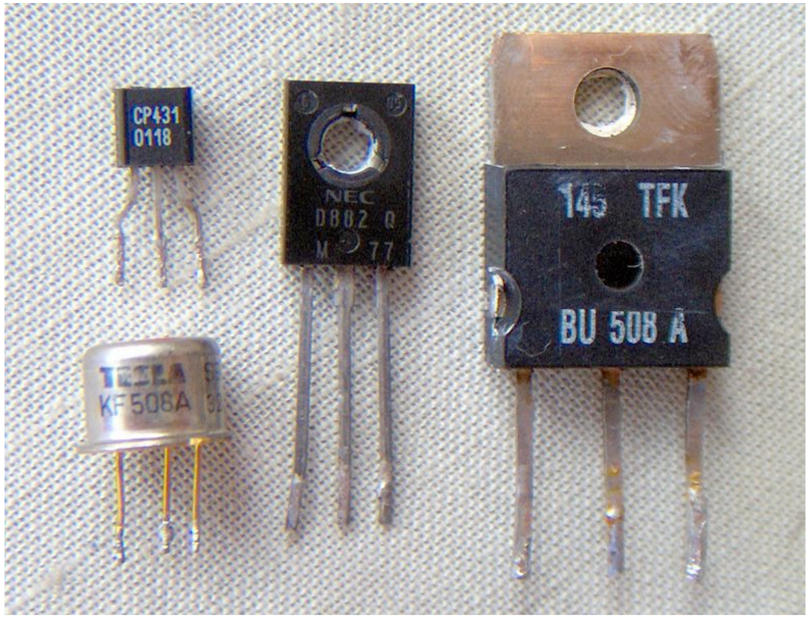
(BJT) Transistor

From now on, we focus on qualitative behavior of BJT for our discussion

We will build up a very simple introductory transistor model and immediately work out some circuits with it

A bipolar transistor is a 3-terminal device available in two flavors (npn and pnp)

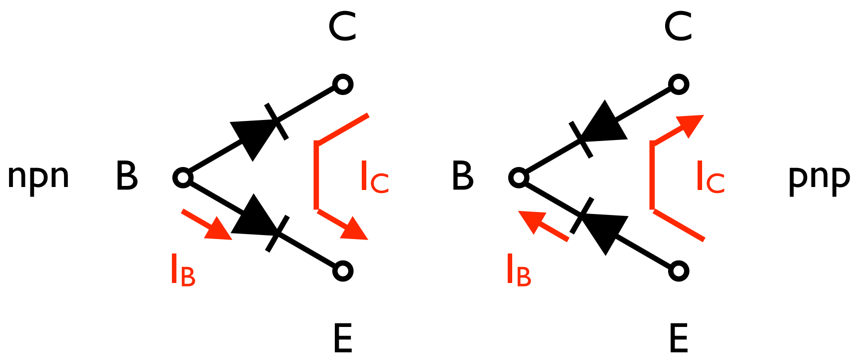




Transistor - 1st model

Rules for npn transistors (for pnp, reverse all polarities)

1. The collector must be more positive than the emitter
2. The base-emitter and base-collector circuits behave like diodes
3. Any given transistor has maximum values of I_C, I_B, and V_{CE}



If 1-3 are obeyed

$$V_B \approx V_E + 0.6\ \mathrm{V}$$

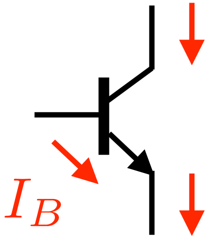
$$V_B = V_E + V_{BE}$$

4. $$I_C = h_{FE} I_B = \beta I_B$$

h_{FE} (or beta) : the current gain is about 100

A small current flowing into the base controls a much larger current flowing into the collector

Transistor - 1st model



$I_C = \beta I_B$

I_B

$I_E = I_C + I_B = (1+\beta) I_B$

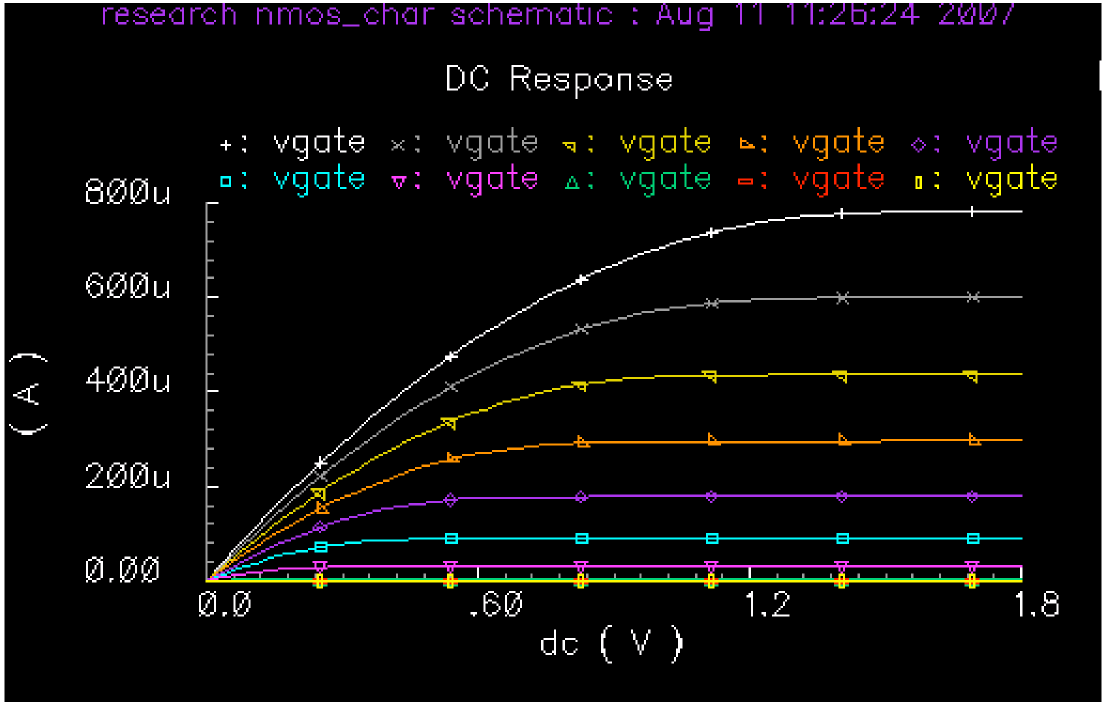
Transistor as current-controlled valve or amplifier

Simple rules (approximation)

- V_{BE} is constant at about 0.6 V
- $I_C = I_E$

Real story:

I_C

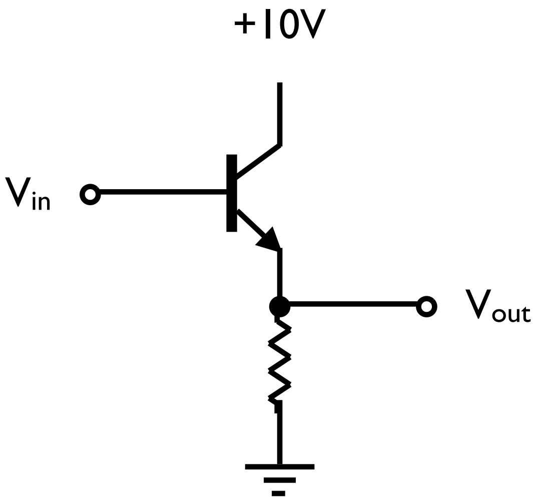


V_C

Each curve is for different value of V_B

Transistor turns on when V_B > threshold voltage

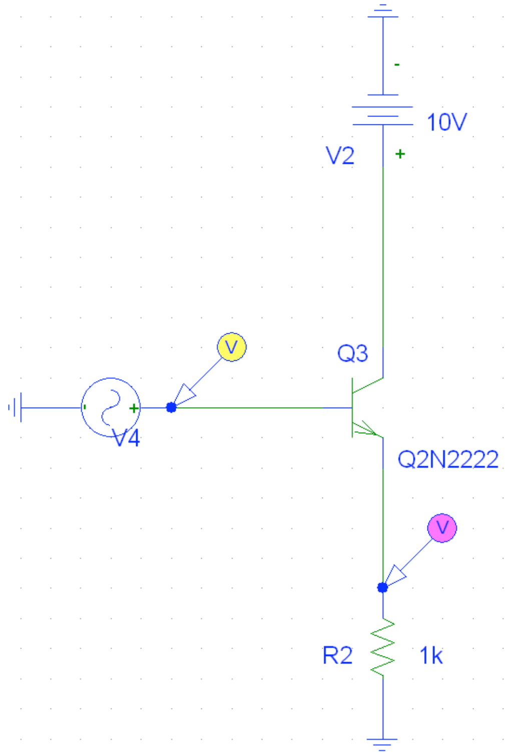
Emitter Follower

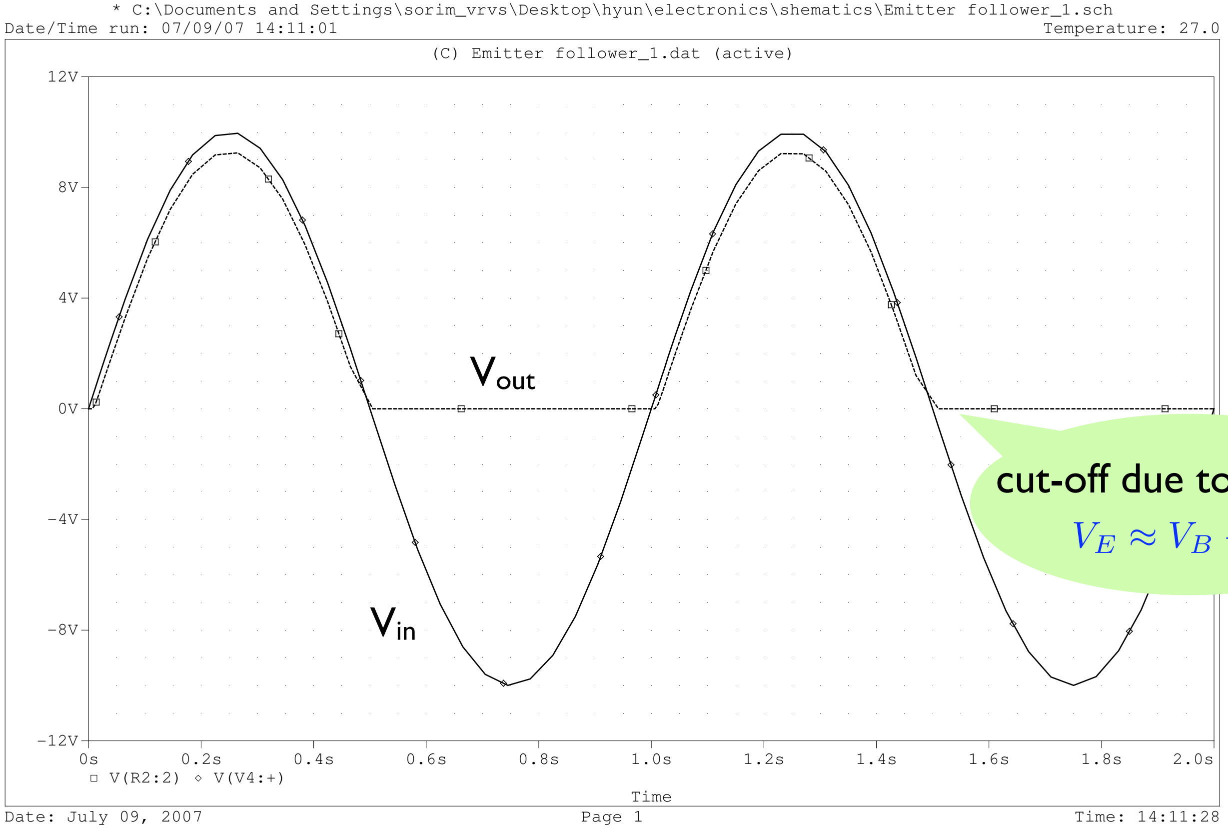


emitter follower: the output terminal is the emitter, which follows the input (the base)

$$V_E \approx V_B - 0.6\text{V}$$

The output is a replica of the input, but 0.6 V to 0.7 V less positive

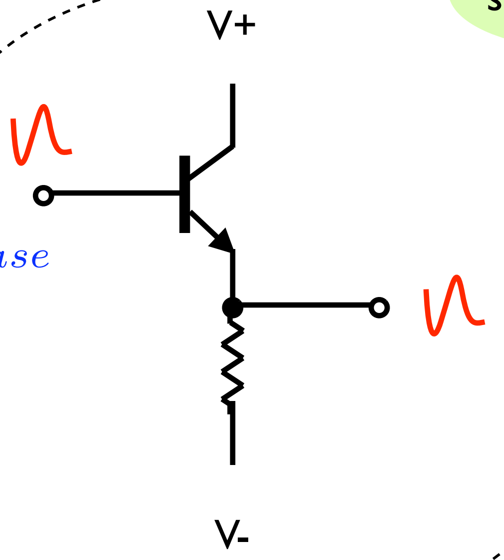




cut-off due to the rule $V_E \approx V_B - 0.6\text{V}$

Emitter Follower

Simple view



same ΔV

small ΔI_B

$\Delta V_{in} = \Delta V_{base}$

$$Z = \frac{\Delta V}{\Delta I} >> 1$$

large ΔI_E

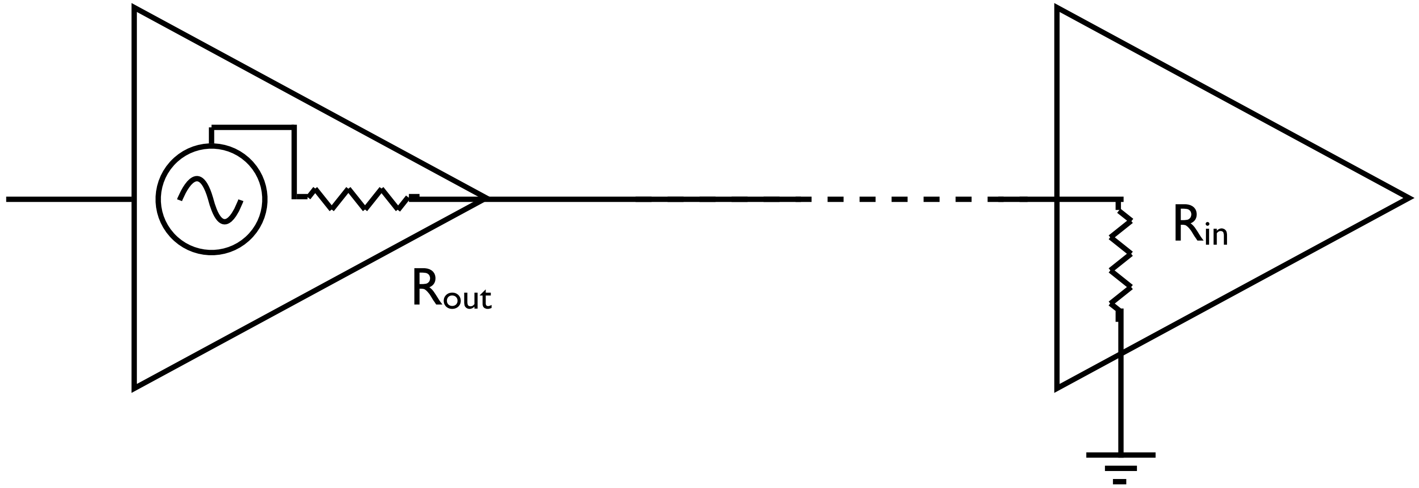
$\Delta V_{out} = \Delta V_{emitter}$

$$Z = \frac{\Delta V}{\Delta I} << 1$$

... but very different ΔI

Impedances of sources and loads

You are always hooking the output to input of the other



: take this circuit as "loading" as a voltage divider

to minimize the reduction, $R_{out} << R_{in}$ (or in general $Z_{out} << Z_{in}$ for impedance)

rule of thumb:
$10Z_{out} = Z_{in}$

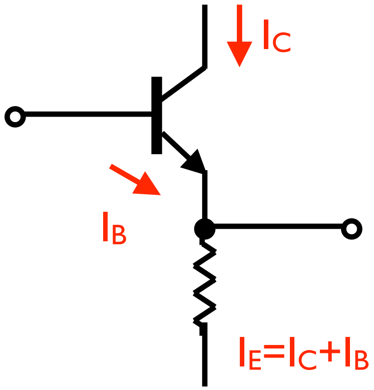
two exceptions

1) radio-frequency circuit: $Z_{out} = Z_{in}$

2) signal being coupled is a current : $Z_{out} >> Z_{in}$

(ex current source: Z_{out} = infinity)

Input and Output impedance of emitter followers



:as you have seen, the emitter follower is useful for changing impedances of signals or loads

Let's calculate the input and output impedance

assume ΔV_B : voltage change at the base

$$\Delta V_B = \Delta V_E \quad (\because V_B \approx V_E + 0.6 \text{ V})$$

$$\begin{aligned} I_E &= I_C + I_B \\ &= (h_{fe}+1)I_B \\ & (\because I_C = h_{fe} I_B) \end{aligned}$$

$$\Delta I_E = \frac{\Delta V_E}{R} = \frac{\Delta V_B}{R}$$

Now, $(h_{fe}+1)\Delta I_B = \Delta I_E$ → $\Delta I_B = \frac{1}{(h_{fe}+1)}\Delta I_E = \frac{1}{(h_{fe}+1)}\frac{\Delta V_B}{R}$

the input resistance is $\frac{\Delta V_B}{\Delta I_B} = R(h_{fe}+1)$

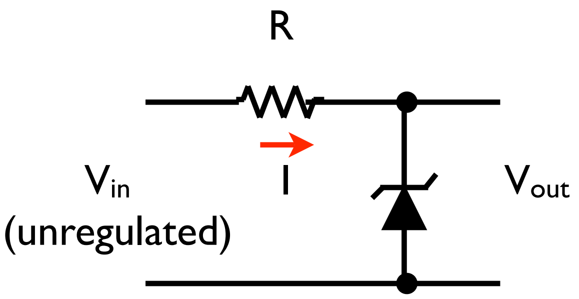
$$\therefore r_{in} = (h_{fe}+1)R$$

: low-impedance load looks much higher impedance at the base

~ 100

Emitter followers as voltage regulators

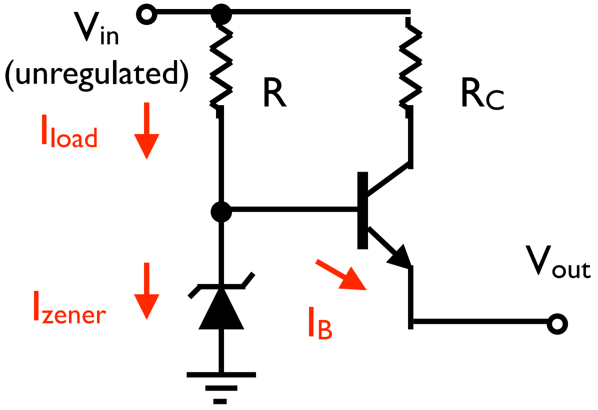
For the simple zenor regulator, there are limitations:



1. V_{out} is not adjustable
2. Regulation against changes of input or load

(load changes → current changes → Vout changes)

Emitter follower gives an improved circuit:



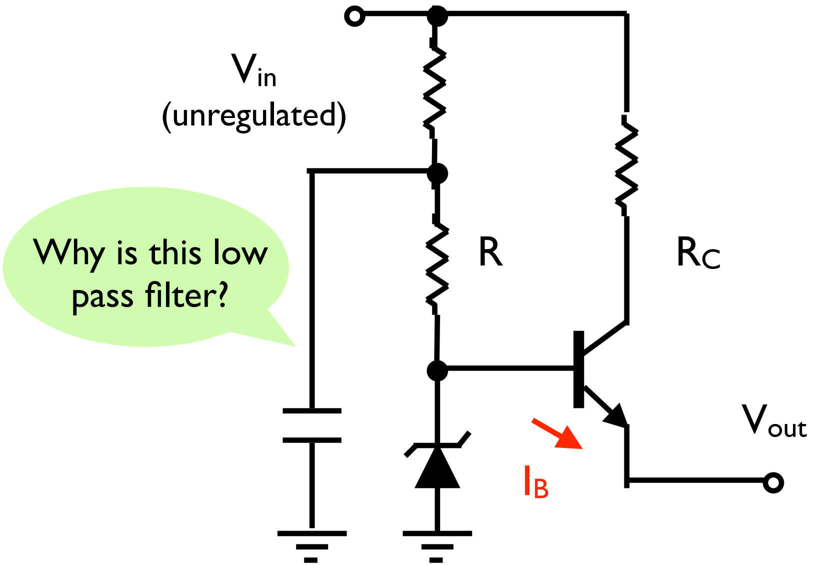
I_B is small (by $1/h_{fe}$)

Changing R does not change I_{Zenor} too much

→ zener current can be made relatively independent of load current

Reducing the effect of ripple current:

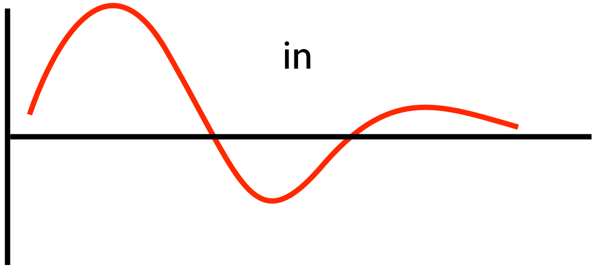
low pass filter ini the zener regulator

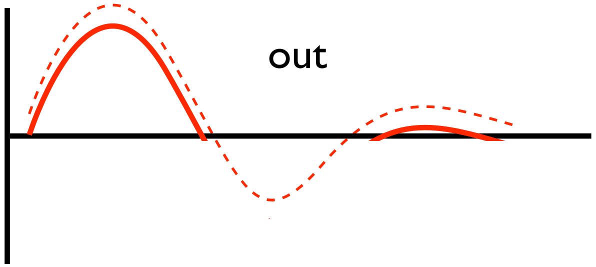


Why is this low pass filter?

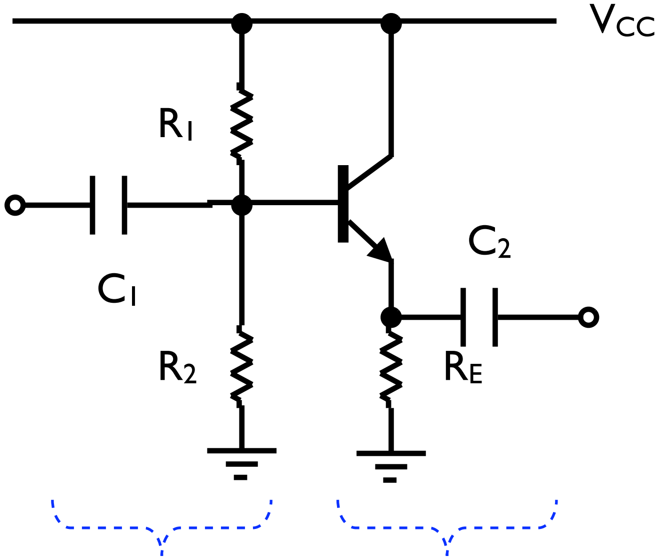
Emitter followers biasing

In the case the signal's average voltage is zero, direct coupling to an emitter follower will give





it is necessary to bias the follower (in fact, any transistor amplifier) : voltage divider is the simplest way

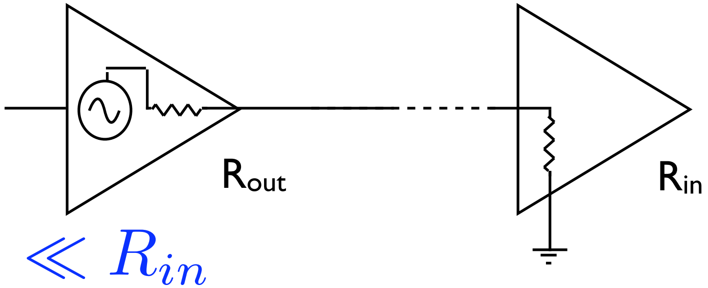


base biased voltage divider

ac-coupled emitter follower

process of choosing V_{CC} in the absence of signal is called setting the quiescent point : quiescent point is chosen to allow max. signal swing of the output

R_1 and R_2 are chosen to put base halfway between ground and V_{CC} ($R_1 \sim R_2$)



: think about this!

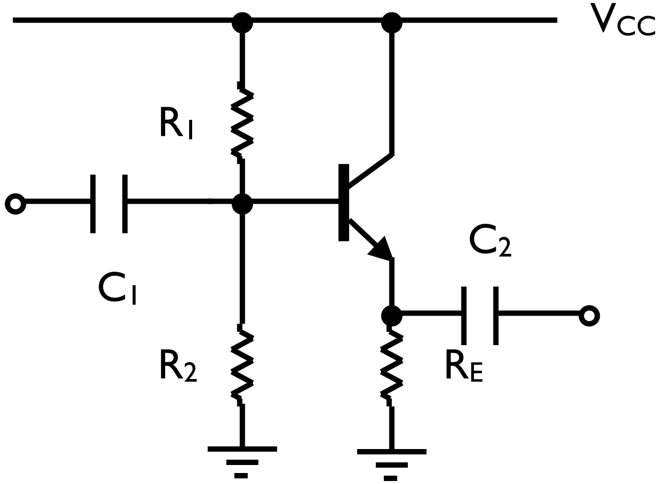
we had $R_{out} \ll R_{in}$

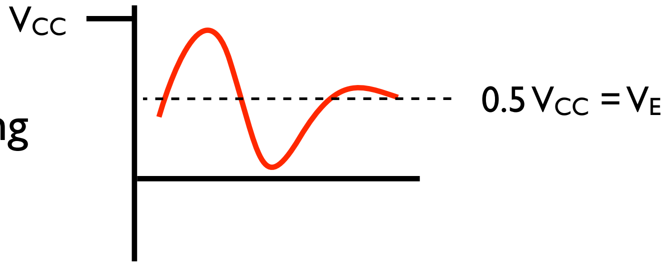
so, we require $R_1||R_2 \ll h_{FE}R_E$

(current following in the voltage divider should be large compared with the current drawn by the base)

Emitter follower design example

Let us make an emitter follower for audio signals: 20 Hz to 20 kHz, V_{CC} = +15 V, quiescent current: 1mA





Step 1 : set V_E as half of V_{CC} (for largest possible symmetrical swing without clipping)

Step 2 : Choose R_E

quiescent current= 1mA, V_E = 7.5 V, $R_E = V_E$ / 1 mA = 7.5 k

Step 3 : Choose R_1 and R_2

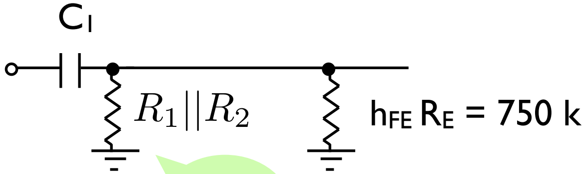
$V_B = V_E$ + 0.6 V = 8.1 V so, R1 : R2 = 6.9 : 8.1 = 1: 1.17

$$R_1||R_2 \ll h_{FE}R_E \rightarrow R_1||R_2 = \frac{1}{10}h_{FE}R_E \rightarrow \frac{R_1R_2}{R_1+R_2} = \frac{1}{10} \times 100 \times 7.5 \text{ k}$$

If we put R_1 = r, R_2 = 1.17r $\quad \frac{1.17r^2}{2.17r} = 75 \text{ k} \quad r = \frac{2.17}{1.17} \times 75 \text{ k} = 140 \text{ k}$ → R_1 = 140 k, R_2 = 160 k (two significant digits only)

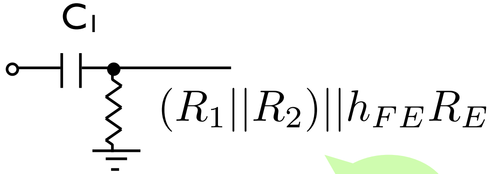
Step 4 : Choose C_1 : C_1 and $R_{1,2}$ form a high pass filter

Treating the above circuit as



75 k

→



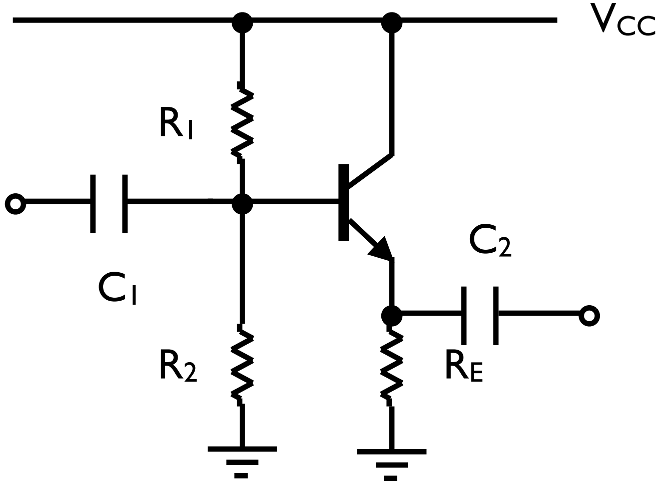
68 k

Now for the 3 dB point

$$f = \frac{1}{2\pi RC}$$ with f = 20 Hz

$$C_1 = \frac{1}{2\pi \times 68 \ k\Omega \times 20 \ s^{-1}} \sim 0.12 \ \mu\text{F}$$

Emitter follower design example



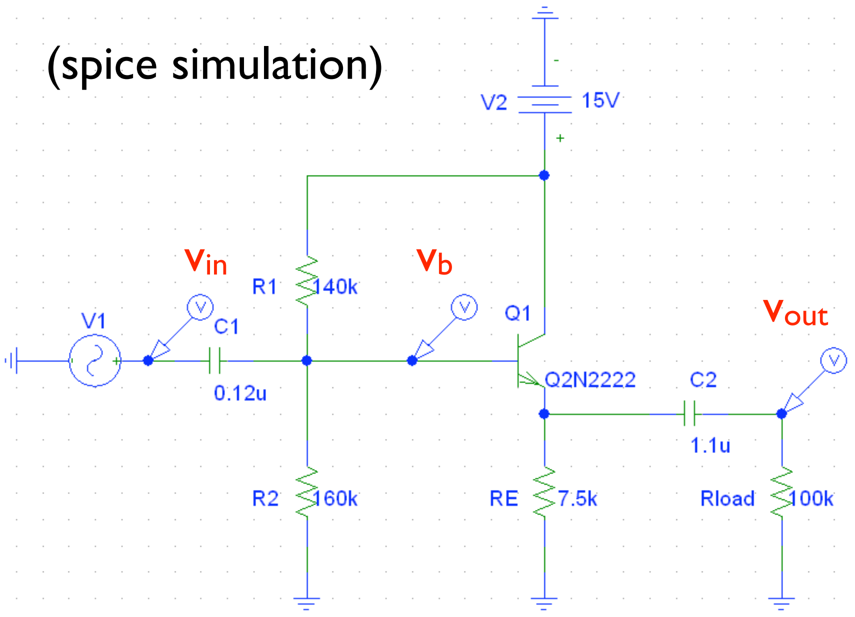
Step 5 : Choose C_2

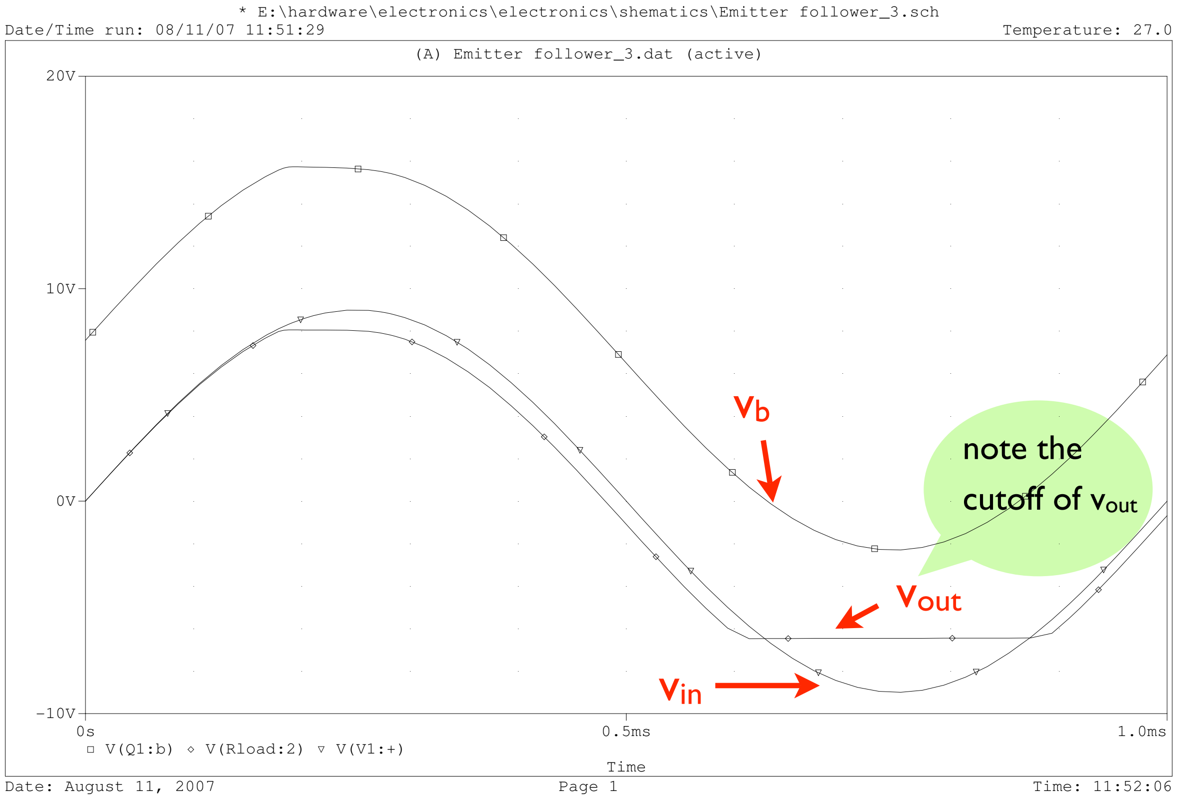
C_2 forms a high pass filter with the load impedance to be attached (so impedance unknown)

It is safe to assume that the load impedance won't be smaller than R_E (7.5 k)

For R_E (7.5 k), 3 dB point is $C_2 = \frac{1}{2\pi \times 7.5\ k\Omega \times 20\ s^{-1}} \sim 1.1\ \mu\text{F}$

(spice simulation)

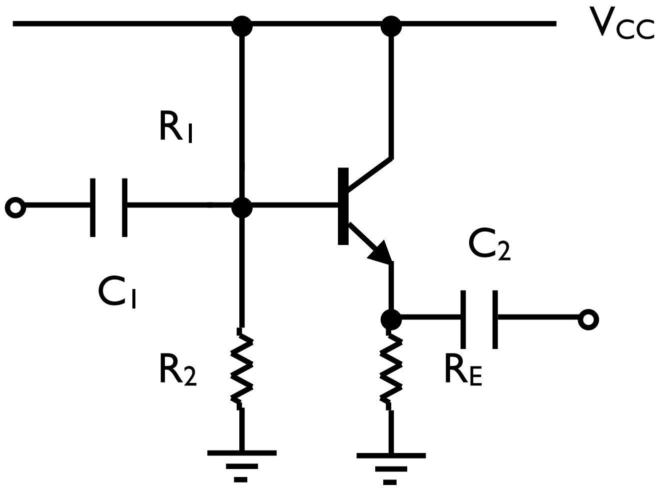




note the cutoff of v_{out}

(wrong) Emitter follower design example

What if we remove R_1 ? Will it work?

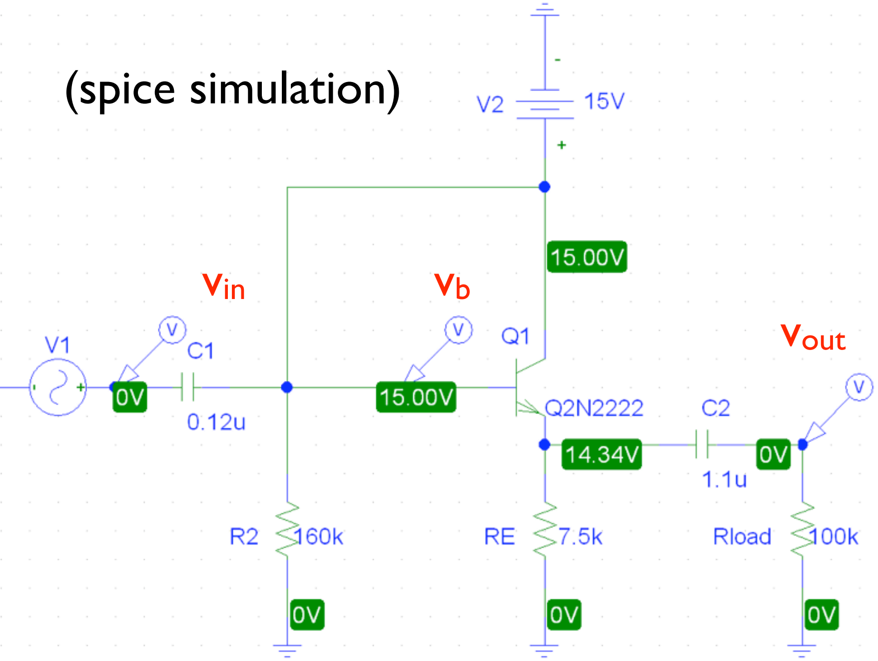


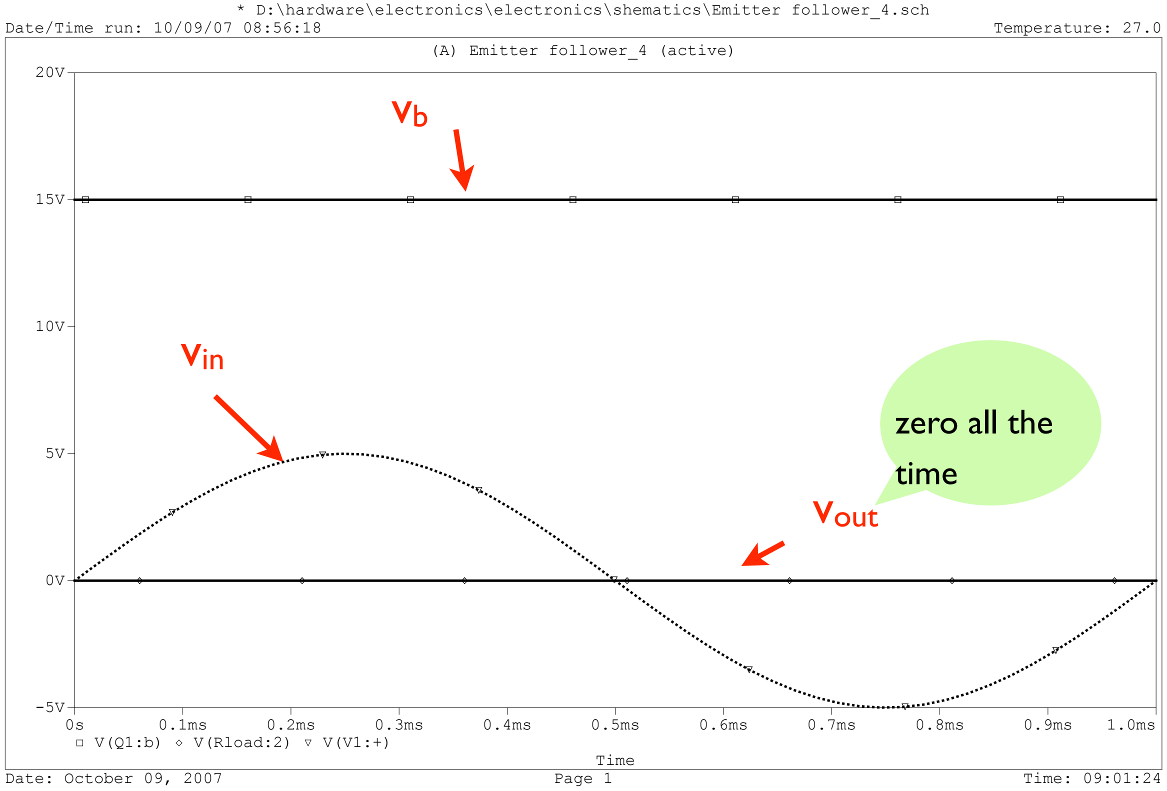
v_b is is forced to be 15 V all the time

No ac signal is passed through base

V_{out} is zero all the time

(spice simulation)

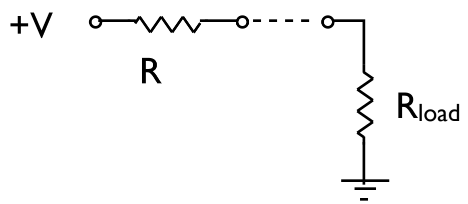




Transistor current source

: current source is a useful device to bias transistors. So, how can we make one?

- Resistor plus voltage source

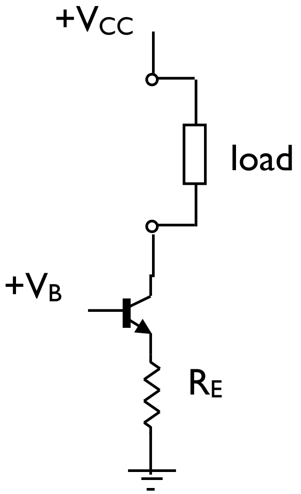


As long as $R_{load} << R$ (= $V_{load} << V$) the current is nearly constant and is approximately $I = \frac{V}{R}$

Drawbacks:
1) Power dissipation in the resistor
2) The current is not easily programmable

- Transistor current source

It is possible to make a very good current source with a transistor



Apply V_B to the base, with $V_B > 0.6$ V (ensuring the emitter is always conducting)

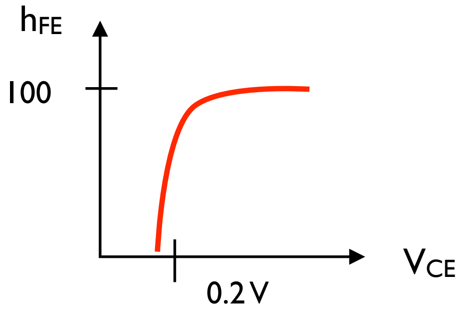
$$V_E = V_B - 0.6\ \text{V}$$

$$I_E = \frac{V_E}{R_E} = \frac{(V_B - 0.6\ \text{V})}{R_E}$$

, and for large h_{FE}, $I_E = I_C$

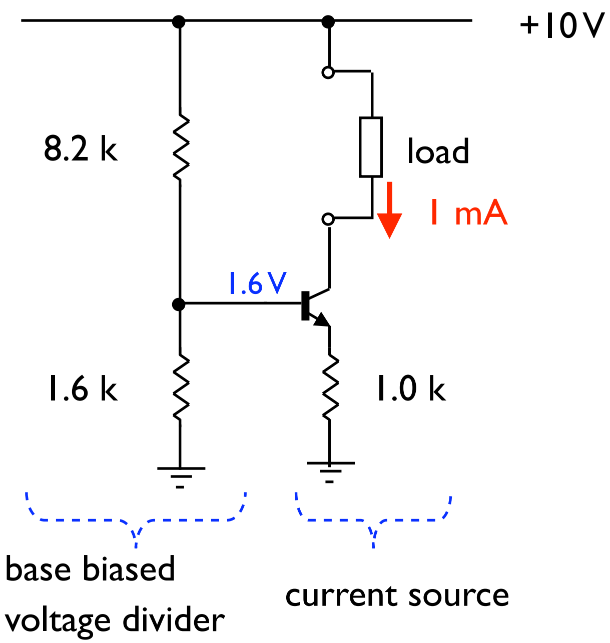
$$\rightarrow I_C \sim \frac{(V_B - 0.6\ \text{V})}{R_E}$$

, independent of V_C as long as the transistor satisfies ($V_C > V_E + 0.2$ V)



Transistor current source - biasing

- voltage divider



Note that V_B is 1.6 V (voltage drop due to 8.2 k resistor)

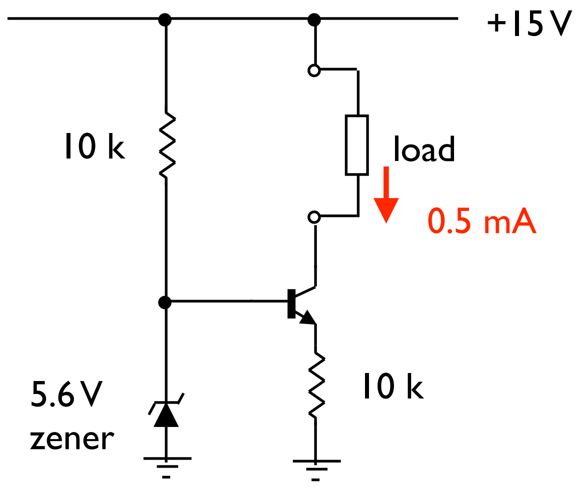
$$I_C = \frac{(V_B - 0.6\ \mathrm{V})}{R_E} = \frac{(1.6\ \mathrm{V} - 0.6\mathrm{V})}{1.0\ \mathrm{k}} = 1\mathrm{mA}$$

8.2 k || 1.6 k = 1.3 k

Impedance looking into the base ($h_{FE}R_E$) = 1.0 k x 100 = 100k

from the condition $R_{out} \ll R_{in}$,
we have 1.3 k << 100k

- zener diode biasing

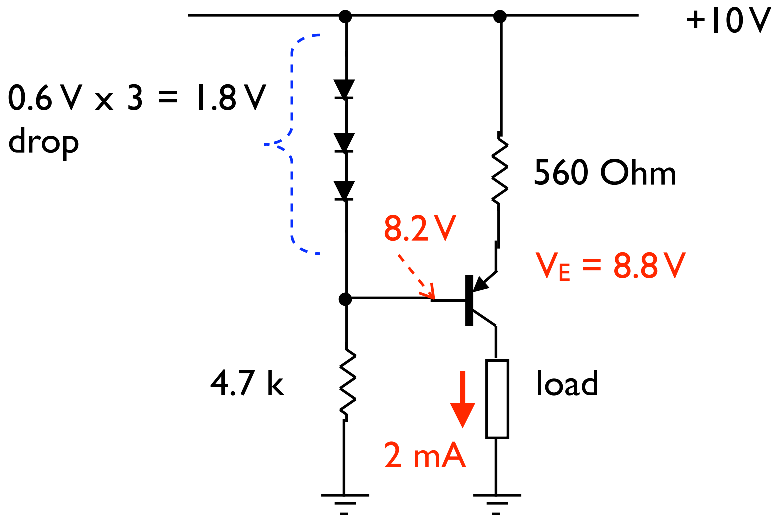


Note that V_B is 5.6 V (zener gives 5.6 V), so V_E = 5.6 V - 0.6 V = 5.0 V

$$I_C = \frac{(5.6\ \mathrm{V} - 0.6\mathrm{V})}{10\ \mathrm{k}} = 0.5\ \mathrm{mA}$$

Transistor current source - biasing

- pnp transistor source current



Note that V_B is 8.2 V (voltage drop due to three 1.8 V diodes)

$V_E = V_B + 0.6\,V = 8.8\,V$

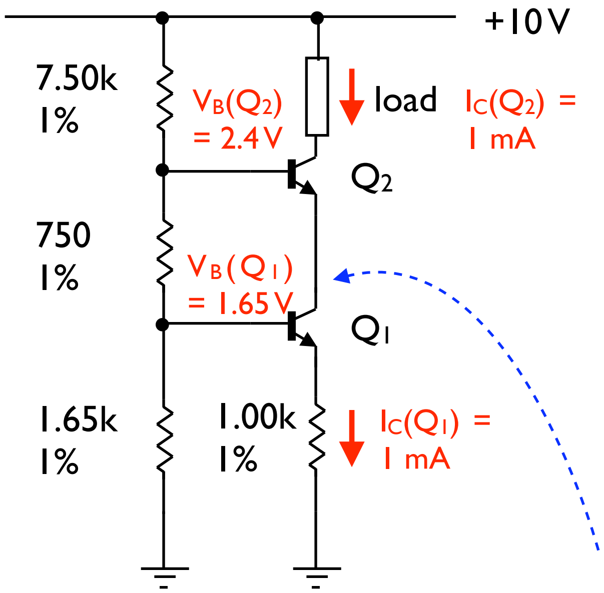
$I_C = V_E/R_E = (10-8.8)\,V/560\,Ohm = 2\,mA$

- deficiencies of current biasing (for npn)

1) V_{BE} and h_{FE} vary slightly with V_{CE}
   - Load changes and that gives V_{BE} to change
   - And therefore the emitter current changes

2) V_{BE} and h_{FE} depend on temperature, giving drift in output current

Improving current-source performance



Collector voltage of Q_1 is fixed by Q_2's emitter

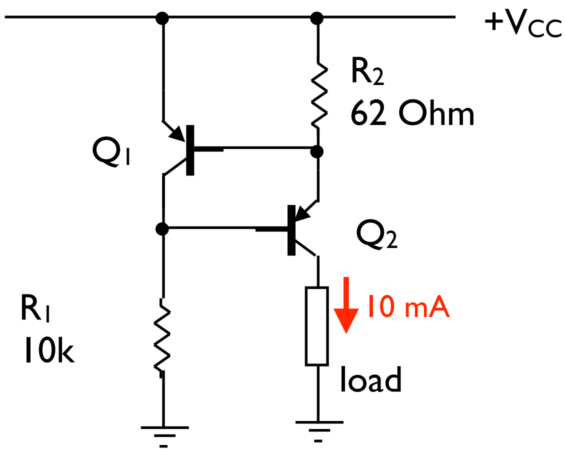
7.5k + 0.75k + 1.65k = 9.9k,   0.75k + 1.65k = 2.4k

$$V_B(Q_2) = \frac{2.4\ k}{9.9\ k} \times 10\ \text{V} \sim 2.4\text{V} \qquad V_B(Q_1) = \frac{1.65\ k}{9.9\ k} \times 10\ \text{V} \sim 1.65\ \text{V}$$

$$I_C(Q_1) = \frac{V_B(Q_1) - 0.6\ \text{V}}{R_E} = \frac{1.65\ \text{V} - 0.6\ \text{V}}{1.00\ \text{k}\Omega} \sim 1\ \text{mA} \quad I_C(Q_2) \sim I_C(Q_1)$$

collector voltage of Q_1 is fixed by Q_2's emitter
even if the load changes

(the geometry of Q_1 and Q_2 is called cascoding)



Transistor V_{BE}-referenced current source

Output current does not depend on supply voltage

$V_B(Q_1) = V_{CC} - 0.6$ V

so the voltage difference across R_2 is 0.6 V

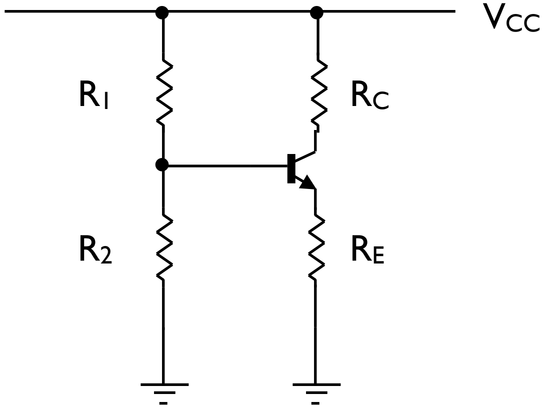
$$I(R_2) = \frac{0.6\ \text{V}}{62\ \Omega} \sim 10\ \text{mV} \rightarrow I_C(Q_2) = I_E(Q_2) = 10\ \text{mV}$$

Now, if V_{CC} changes, I_C does not change !

$$\because I_{out} = V_{BE}/R_2$$

Common-emitter amplifier

Consider a current source with a resistor as load



The collector voltage is: $V_C = V_{CC} - I_C R_C$

Now, let us consider again the below circuit with the capacitor in the input side:

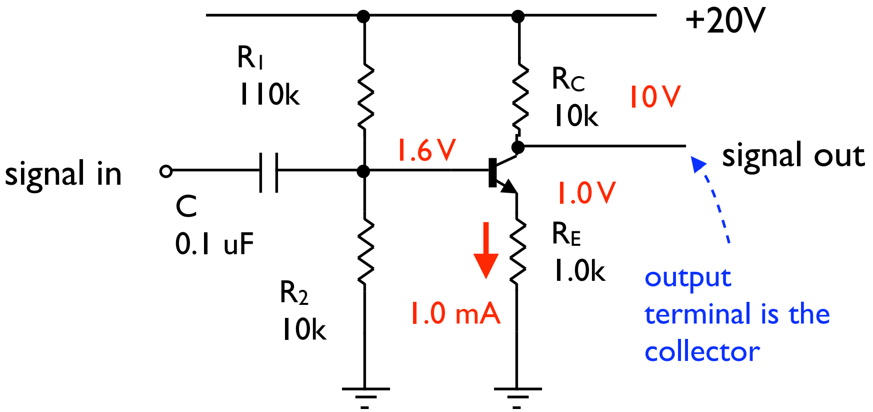
$$V_B = \frac{10}{110+10} \cdot 20\ \mathrm{V} \sim 1.6\ \mathrm{V}$$

$$V_E = V_B - 0.6\ \mathrm{V} = 1.0\ \mathrm{V}$$

$$I_E = \frac{1.0\ \mathrm{V}}{1.0\ \mathrm{k}} = 1.0\ \mathrm{mA}$$

$$I_E \sim I_C = 1.0\ \mathrm{mA}$$

$$V_C = V_{CC} - I_C R_C = 20\ \mathrm{V} - 1.0\ \mathrm{mA} \cdot 10\ \mathrm{k\Omega} = 10\ \mathrm{V}$$



output terminal is the collector

Now, imagine an wiggle in base voltage v_B

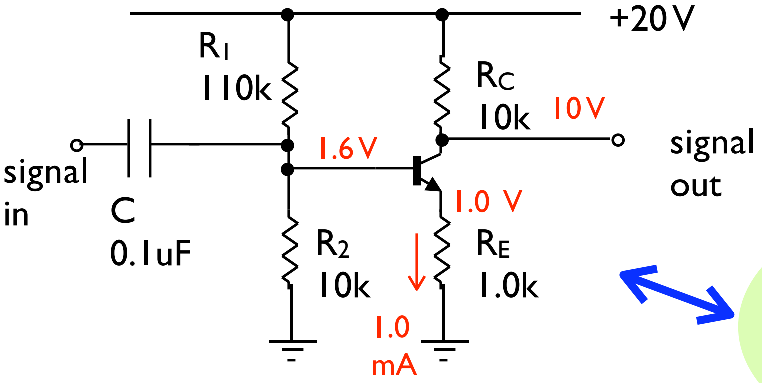
→ the emitter follows with $v_E = v_B$

→ a wiggle in the emitter current : $i_E = \frac{v_E}{R_E} = \frac{v_B}{R_E} (\sim i_C)$

So, the initial wiggle in base voltage causes a collector voltage wiggle $v_C = -i_C R_C = -v_B \left(\frac{R_C}{R_E} \right)$

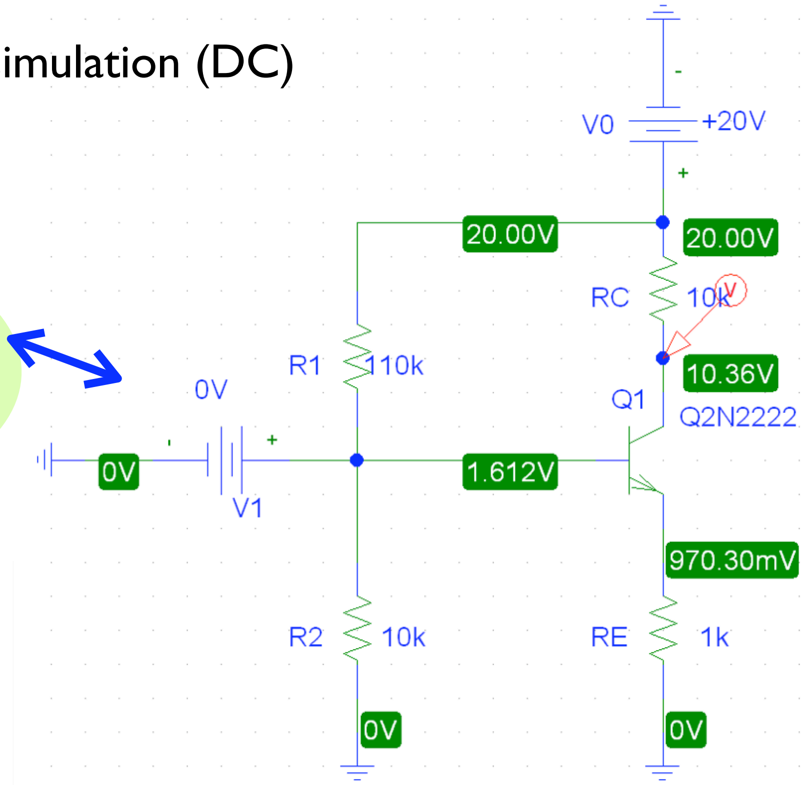
→ voltage amplifier with gain = $\frac{v_{out}}{v_{in}} = -\frac{R_C}{R_E}$ (= 10 k / 1.0 k = 10 in this example)

Common-emitter amplifier

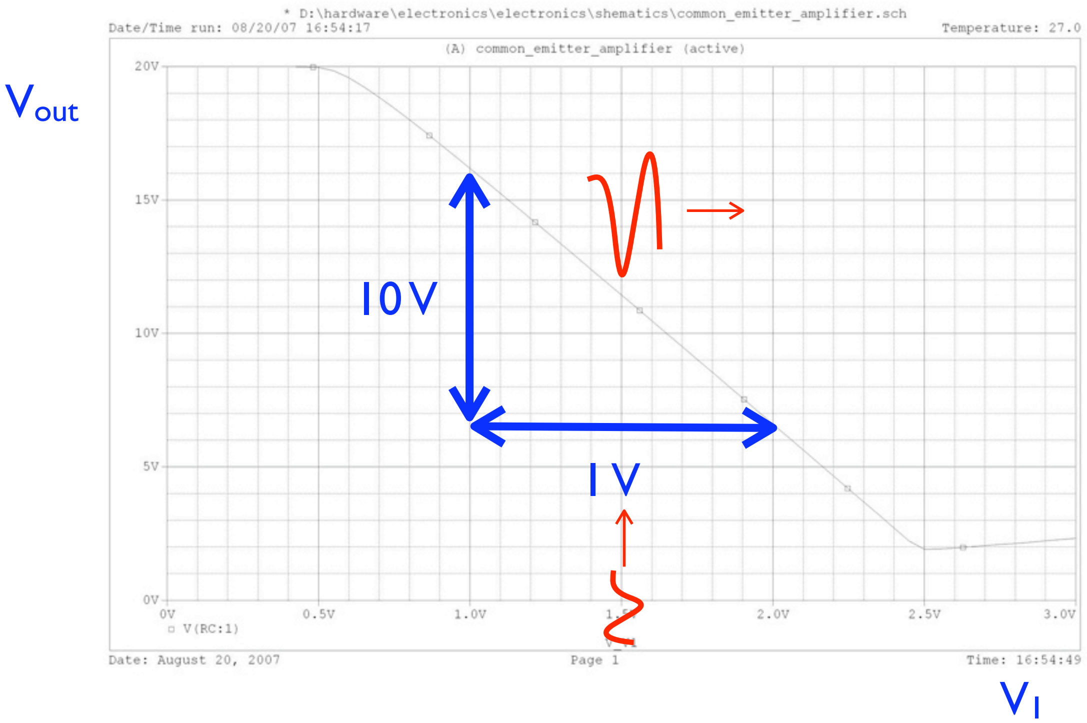


spice simulation (DC)

hand waving calculations and the spice simulations are in good agreements?



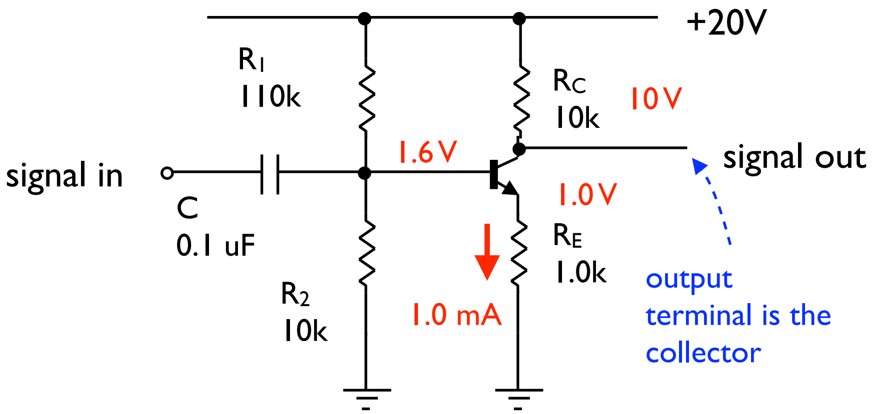
spice simulation (DC sweep)



spice simulation gives you the gain of 10 V/1 V = 10
and the slope is negative

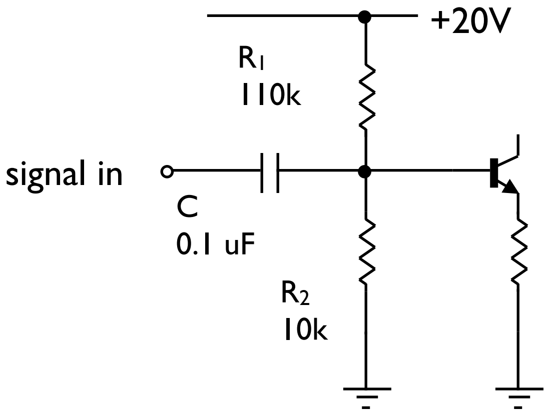
Input and Output impedance of the common-emitter amplifier

Let's come back to the previous example:



Input impedance

: in input signal sees, in parallel, 110k, 10k, and the impedance looking into the base



$$(110)||(10) = 9.2\ \text{k}\Omega$$

$$R_E \times h_{fe} = 1\ \text{k}\Omega \times 100 = 100\ \text{k}\Omega$$

R_E=1.0k x h_{fe}

Input impedance looking into base:

$$(9.2\ \text{k}\Omega||100\ \text{k}\Omega) = 8.4\ \text{k}\Omega$$

dominated by R2 (10k)

Input coupling capacitor

: Now, let us discuss the input coupling capacitor

→ It forms a high-pass filter (note that the signal sees the capacitor first)

Then, what is the 3 dB point? $f = \dfrac{1}{2\pi \cdot 8\ \text{k}\Omega \cdot 0.1\ \mu\text{F}} \approx 200\ \text{Hz}$

Output impedance

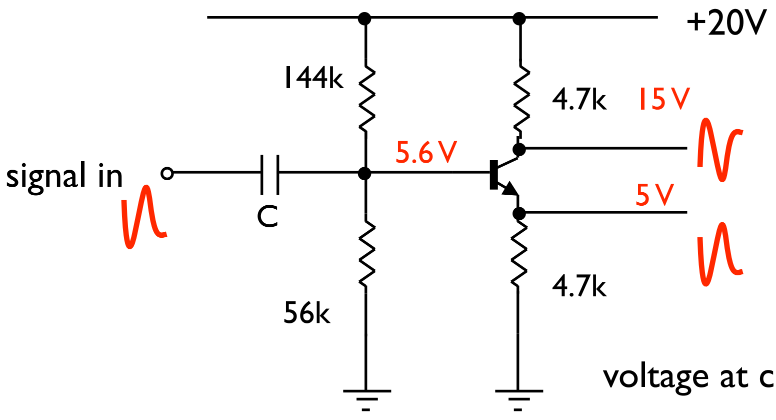
: output impedance is 10 k (R_C) in parallel with the impedance looking into the collector (very large: ~ MOhms)

$\dfrac{rR}{r+R} \sim \dfrac{rR}{R} \sim r \text{ if } r \ll R$ → so the output impedance is just the value of the collector resistor, 10 k

Note: impedance looking into a transistor's collector is high but emitter is low

Unity-gain Phase splitter

Sometimes it is useful to generate a signal and its inverse (two signals 180° out of phase)



voltage at base: $\dfrac{56\ \text{k}\Omega}{56\ \text{k}\Omega + 144\ \text{k}\Omega} \times 20\ \text{V} = 5.6\ \text{V}$

voltage at emitter: $V_E = V_B - 0.6\ \text{V} = 5.0\ \text{V}$

$$I_E = \frac{5\ \text{V}}{4.7\ \text{k}\Omega} = I_C$$

voltage at collector: $V_C = V_{CC} - I_C R_C = 20\ \text{V} - \dfrac{5\ \text{V}}{4.7\ \text{k}\Omega} \cdot 4.7\ \text{k}\Omega = 15\ \text{V}$

Voltage gain : $v_{OUT}/v_{IN} = - R_C/R_E = -1$

Note that the quiescent collector voltage is set to 0.75 V_{CC} (It was 0.5 V_{CC} for the common-emitter amplifier)

now if small signal comes in: emitter out follows input

collector out is amplified with the gain -1 (= 180° phase difference)

$V_C > V_E$ (rule 1)

$V_C > V_E$ (rule 1)

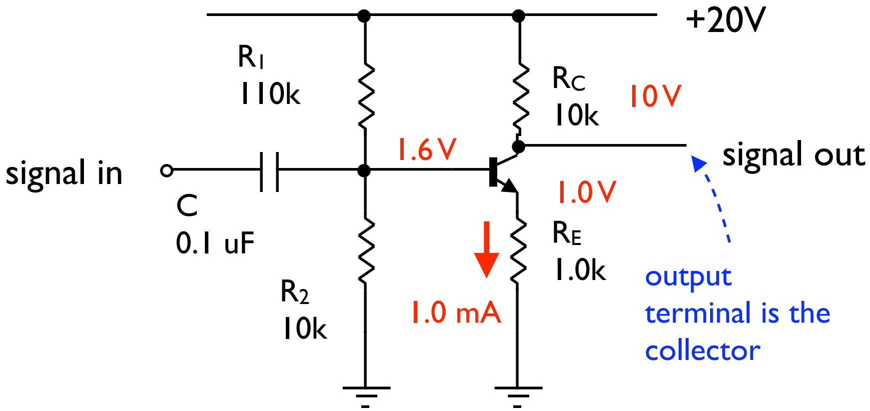
: therefore max. swing range for V_C : [20V, 10V] and for V_E : [0, 10V]

limited by V_{CC}

transistor will be off

Transconductance

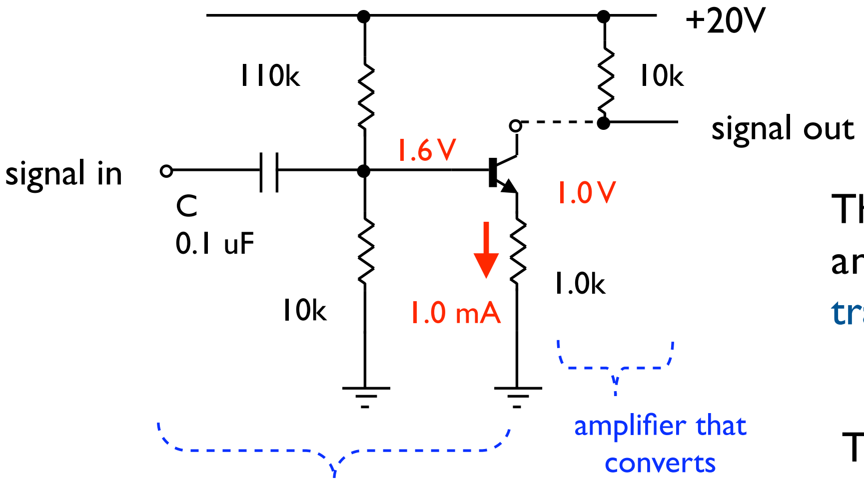
Our previous analysis of this had the following procedure



output terminal is the collector

a) imaging an applied base voltage swing and seeing that the emitter voltage had the same swing
b) calculating the emitter current swing; then ignoring the small base current contribution, we got the collector current swing and thus
c) the collector voltage swing is obtained
d) gain is now the ratio of collector (output) voltage to base (input) voltage swing

Another way to think about the amplifier : breaking it apart



voltage controlled current source

= transconductance amplifier

amplifier that converts current to voltage

The first part is a voltage-controlled current source with quiescent current of 1 mA and gain of -1mA/V

If V_E is increased by 1 V, the I_E is increased by - 1 mA

This new gain has dimension of 1/resistance and is called conductance: an amplifier whose gain has units of conductance is called transconductance amplifier (g_m = -1mA/V in this case)

transconductance $g_m \equiv \dfrac{I_{out}}{V_{in}}$

The 2nd part is an amplifier converts current to voltage: called a transresistance amplifier

transresistance $r_m \equiv \dfrac{V_{out}}{I_{in}}$

(r_m = 10kV/A in this case)

The overall voltage gain: $G_V \equiv g_m r_m = -\dfrac{1\ \mathrm{mA}}{\mathrm{V}} \cdot \dfrac{10\ \mathrm{kV}}{\mathrm{A}} = -10$