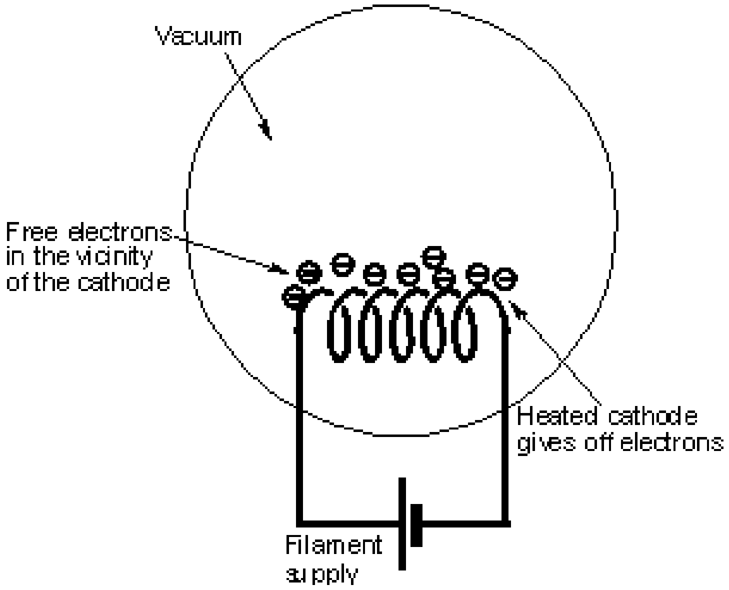
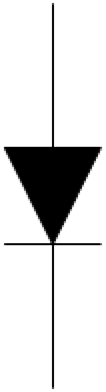
Semiconductors

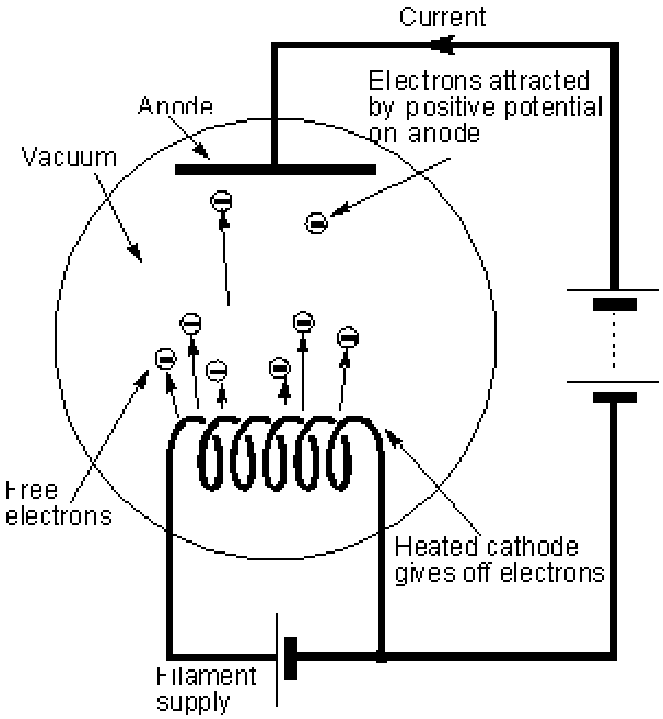
Vacuum Tubes



Semiconductors

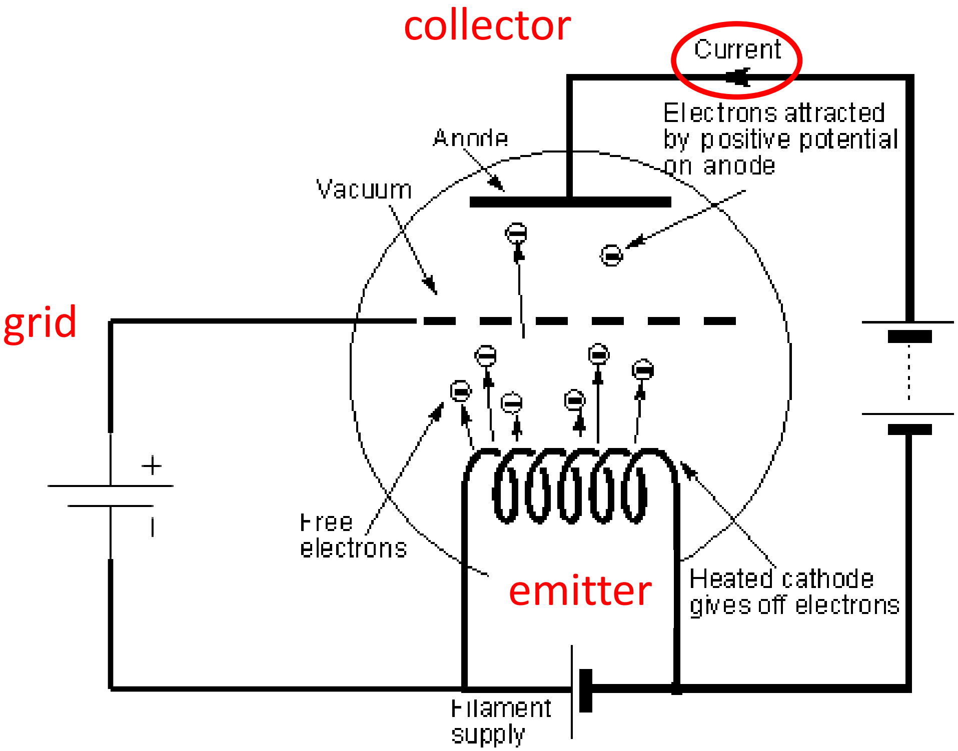
Vacuum Tubes





Semiconductors

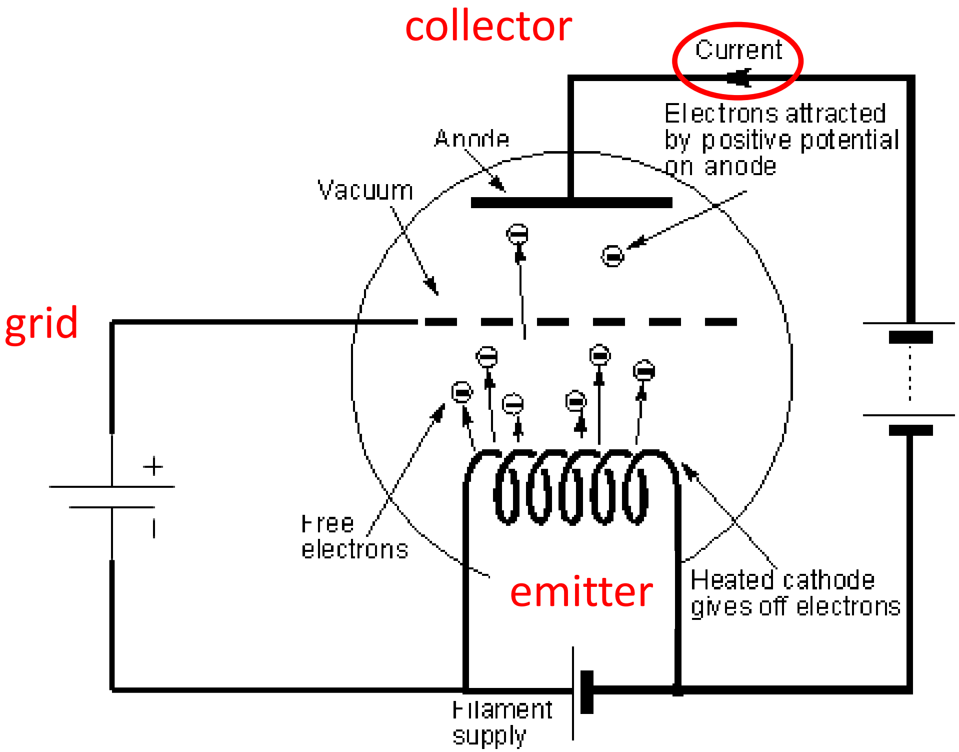
Vacuum Tubes



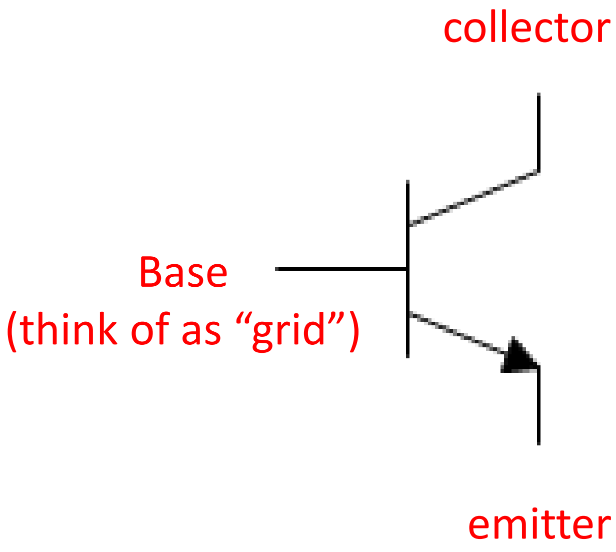
Small voltage on grid can block large current between emitter & collector.

Semiconductors

Vacuum Tubes



Transistors

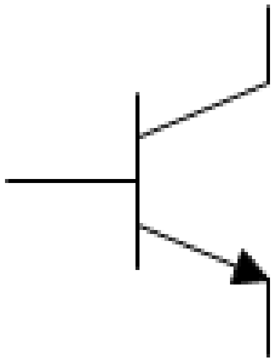


Small voltage on grid can block large current between emitter & collector.

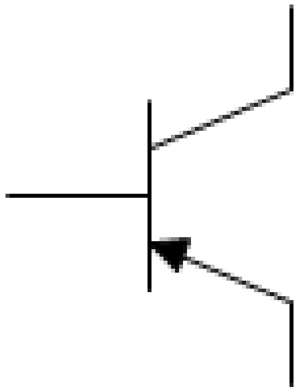
Semiconductors

Transistors (bi-polar)
Transistors come in two flavors, “npn” & “pnp”.

Symbol:



npn

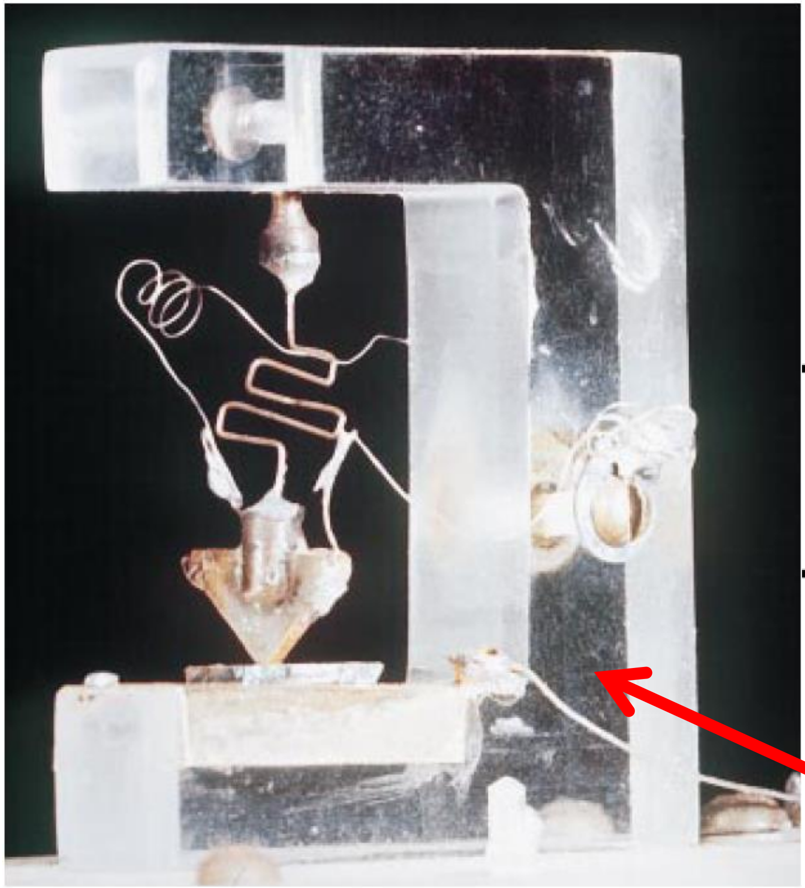


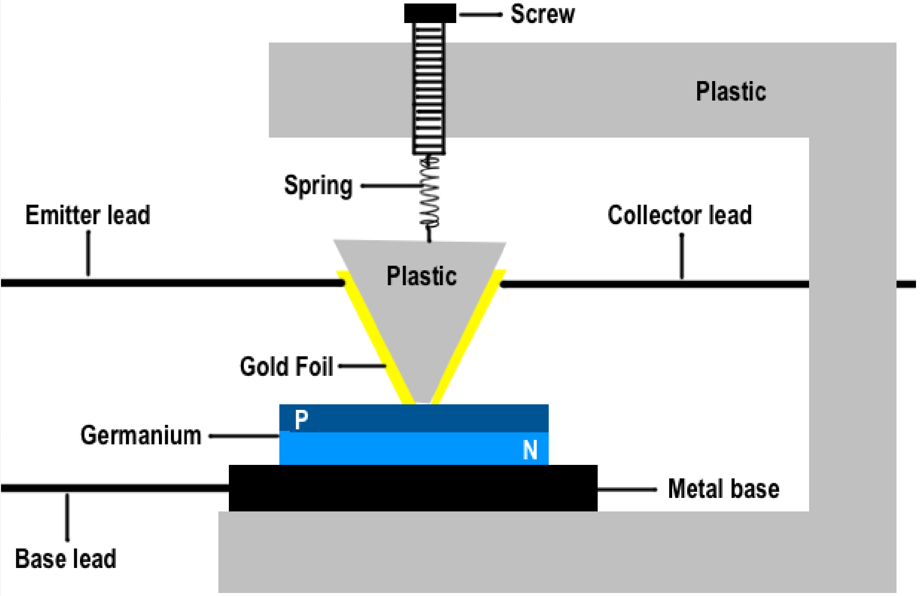
pnp

Handy mnemonic: “Not Pointed iN”

Semiconductors

First Transistor

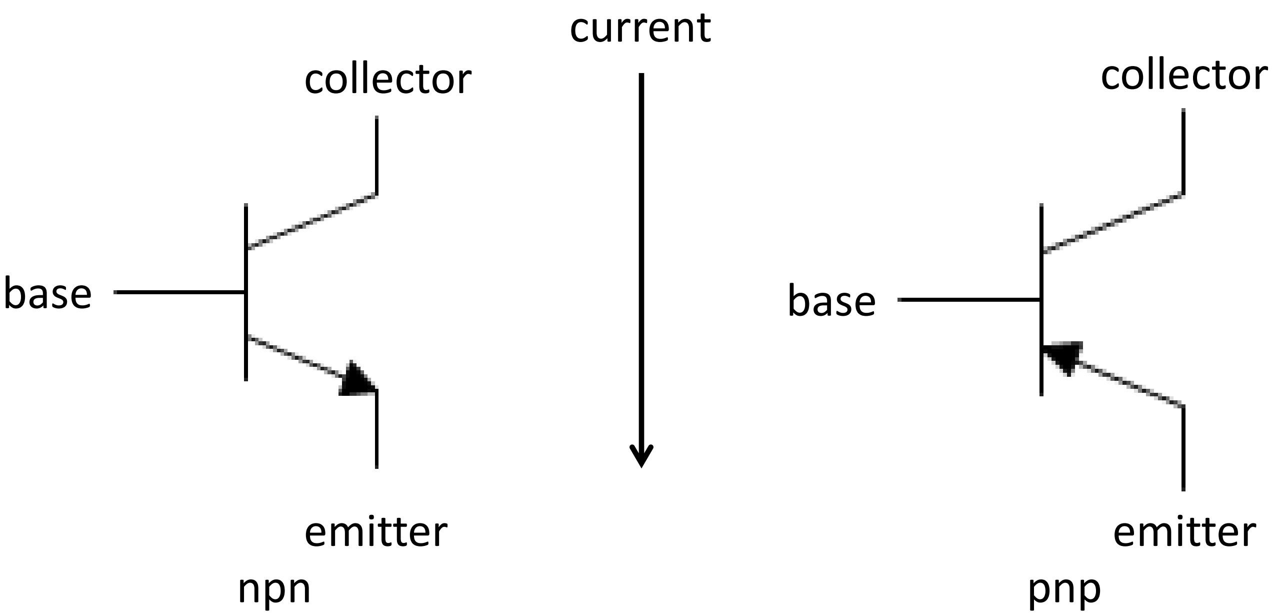




Yes, that is what a Physics Nobel Prize winning experiment looks like.

Semiconductors

Transistors (bi-polar)



current

collector

base

emitter

npn

collector

base

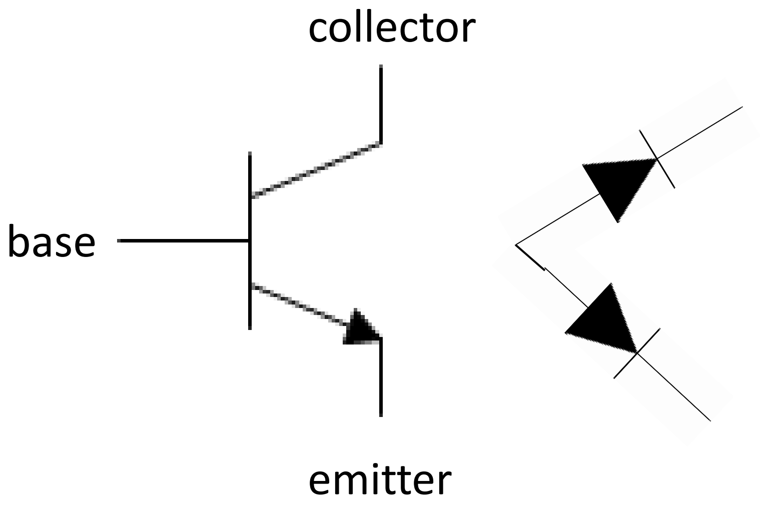
emitter

pnp

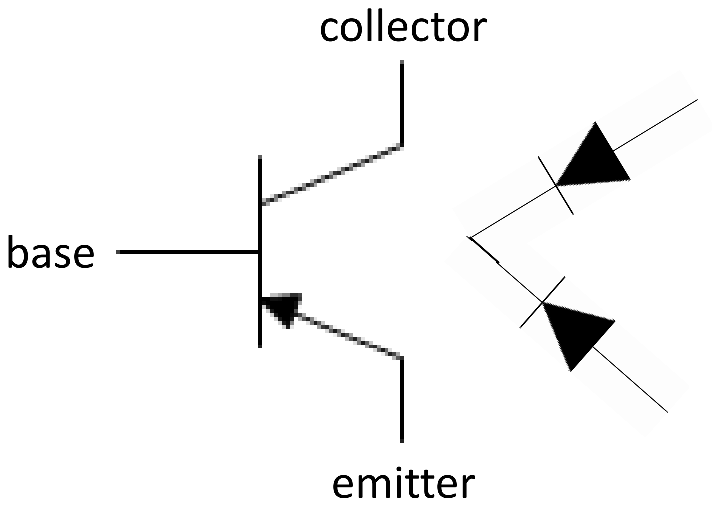
Convention is to always draw transistors with the current flowing down.

Semiconductors

Transistors (bi-polar)



npn

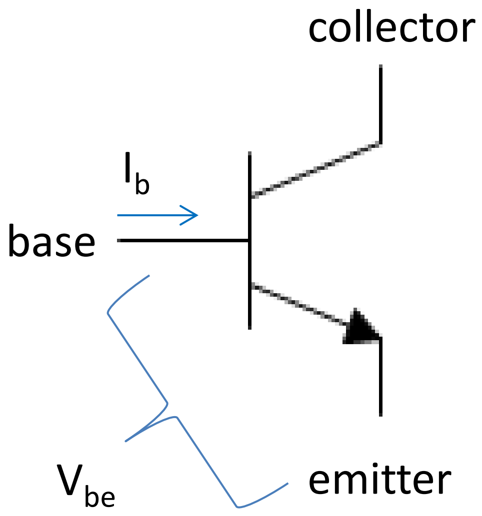


pnp

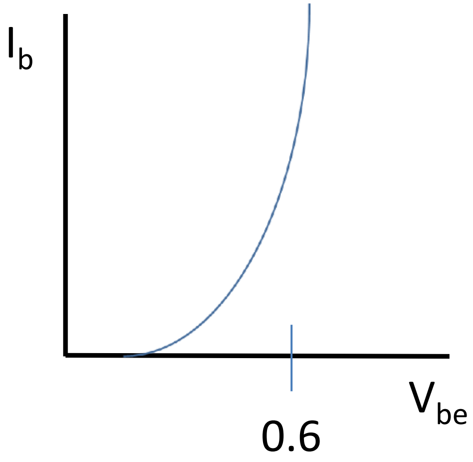
For certain intuitive purposes, one can think about these as weird diode pairs.

Semiconductors

Transistors (bi-polar)

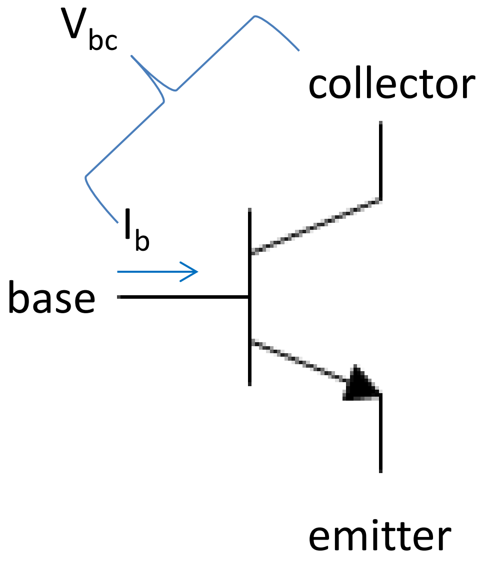


a) Base-emitter “diode” is forward biased. Therefore V_{be} clamped at ~0.6V for a silicon transistor.



Semiconductors

Transistors (bi-polar)



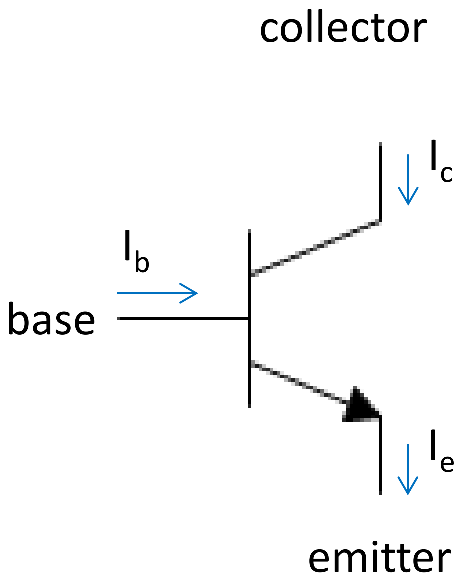
b) Base-collector "diode" is reverse biased.

Therefore $I_{bc} \cong 0$ (all base current flows through emitter).

Therefore V_{bc} can vary.

Semiconductors

Transistors (bi-polar)



c) When I_b flows into a base-emitter circuit.

$I_c = \beta I_b$ or $I_c = h_{FE} I_b$ (There's two symbols in use.)

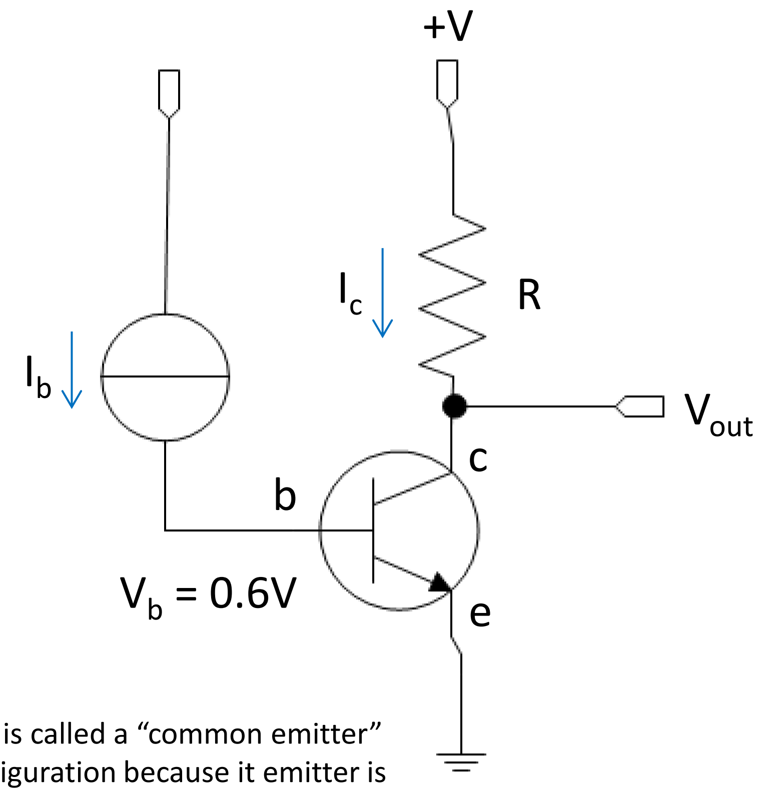
Where $\beta \gg 1$ current gain just like in a vacuum tube.

Typical $\beta \sim 100$

$$I_e = I_c + I_b = I_c + I_c/\beta \cong I_c + I_c/100 \cong 1.01\, I_c \cong I_c$$

Semiconductors

Transistors (bi-polar)



This is called a "common emitter" configuration because it emitter is "common" to both input & output voltages.

$V_{out} = V - Ri_c$

$V_{out} > 0.6$

Why? There is a forward biased "diode" between c & ground. (Through the b-e "forward biased diode".)

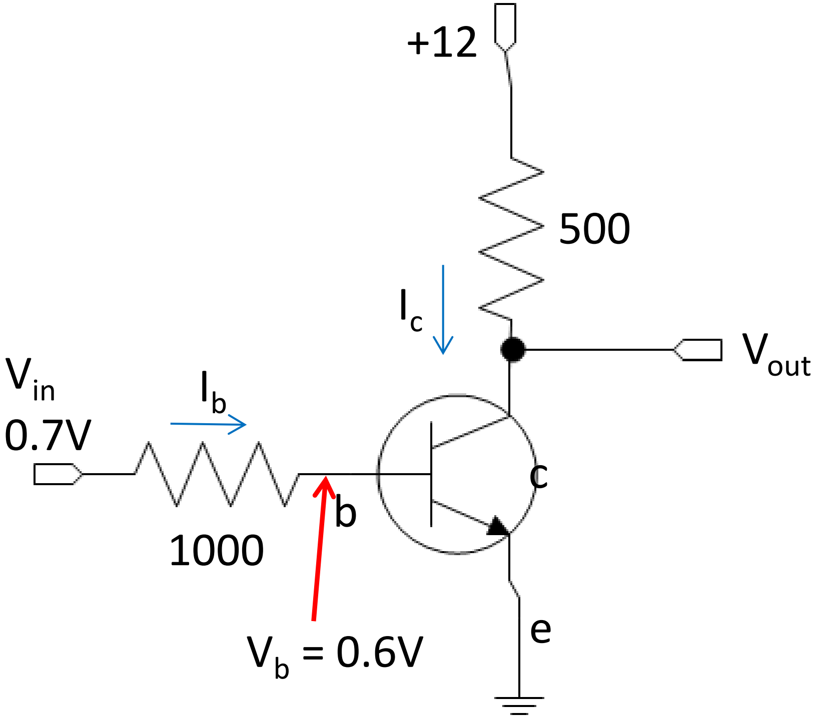
$I_c = \beta I_b$

$V_{out} = V - RI_c$

$\therefore\ V_{out} = V - R\beta I_b$

Semiconductors

Transistors (bi-polar)



$V_{out} = V - Ri_c$

$V_{out} > 0.6$

Why? There is a forward biased "diode" between c & ground. (Through the b-e "forward biased diode".)

$I_c = \beta I_b$

$\therefore\ V_{out} = V - R\beta I_b$

$I_b = 0.1/1000 = 10^{-4}$A, V = 12volts, R=500

Typical β ~100

$V_{out} = 12\text{-}500\ 10^2 10^{-4} = 12\text{-}5 = 7$ volts

Semiconductors

Transistors (bi-polar)

More things to remember about transistors:

Current gain β typically ~ 100, but can vary for the same transistor part number by factors of 2.

β Depends of temperature, current, voltage & frequency.

Transistors want certain voltage (biases) on the terminals. We use voltage dividers to do this.

Semiconductors

Transistors (bi-polar)

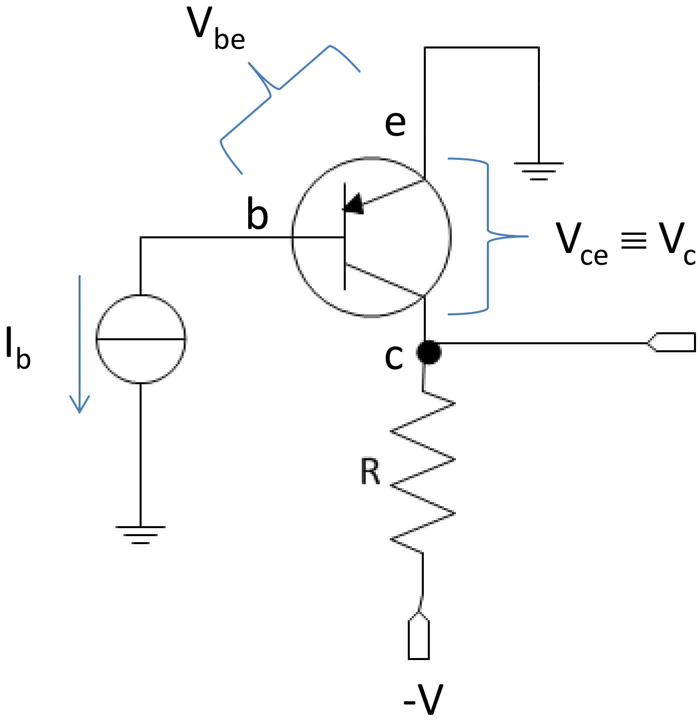
Nomenclature:

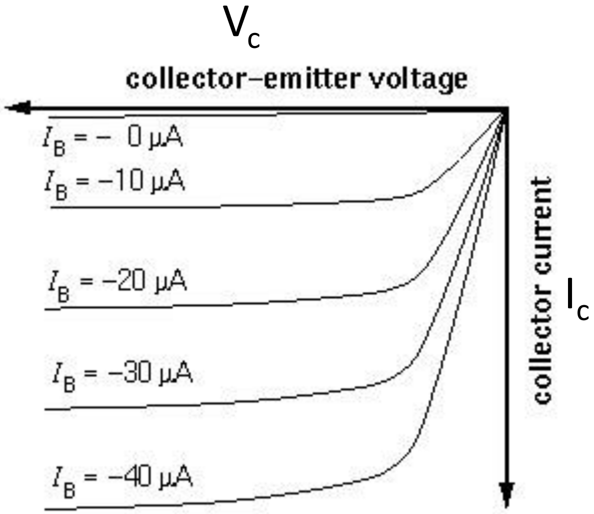
Absolute current & voltages are I & V (capital letters).

Signals are small changes in current & voltage are denoted as i & v, or *di* & *dv* that may sit on top of a steady voltage or current.

Semiconductors

Transistors (bi-polar)





Looks like a diode curve translated along I_c in a controlled manner by I_b.

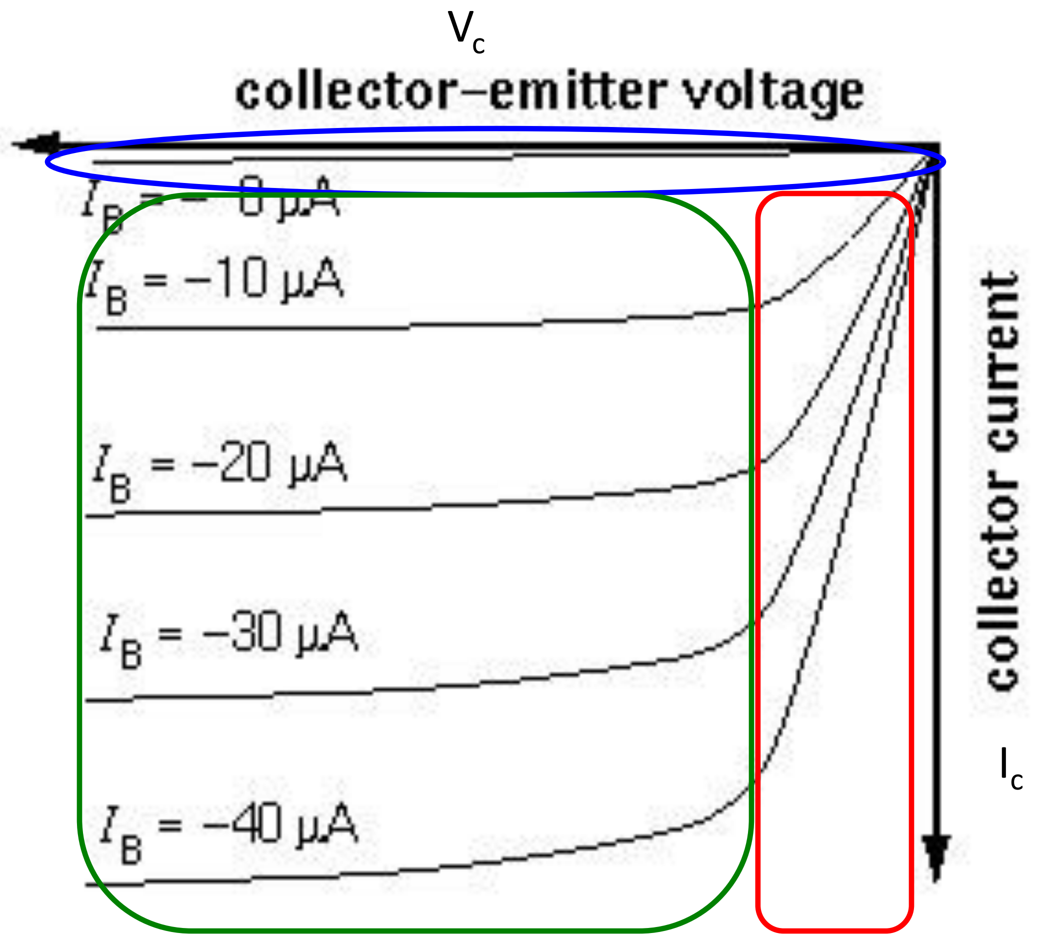
Semiconductors

Transistors (bi-polar)

Region where $I_b = 0$ (or negative) is called the cutoff region. The transistor resistance between c & e is very high.

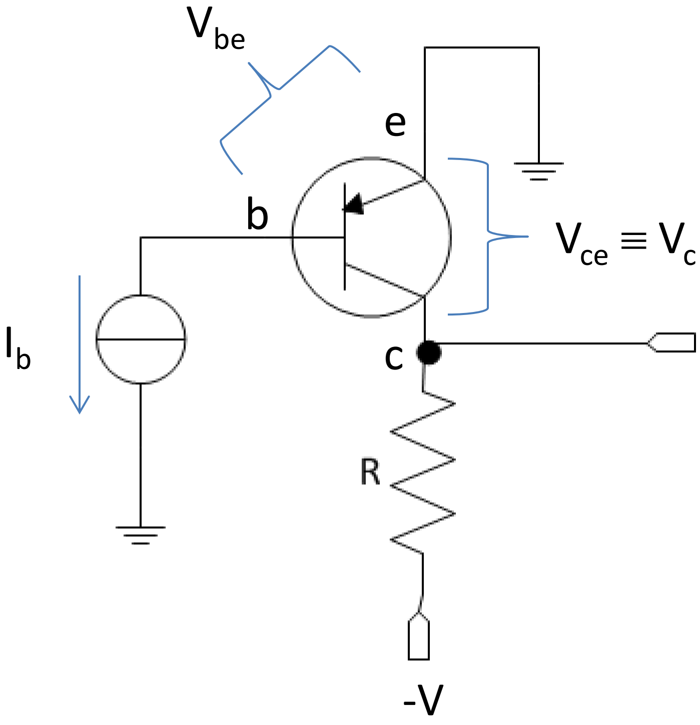
Region where $I_c \cong$ constant & roughly linear in I_b is called the “active region”

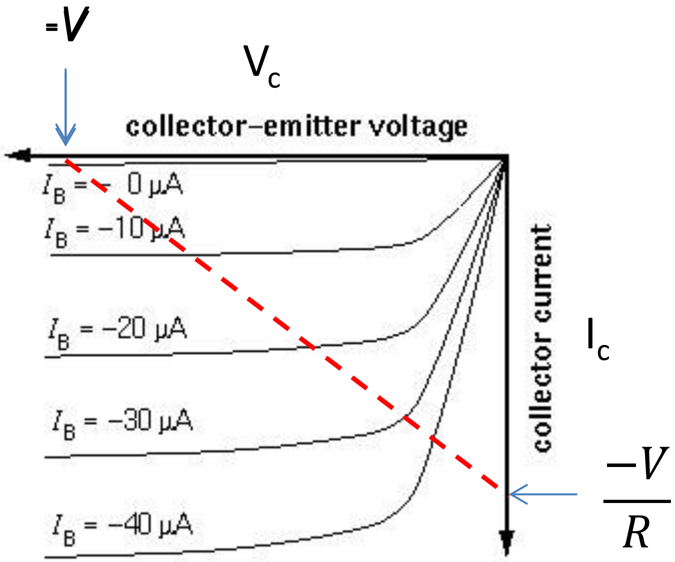
Region where the transistor is fully “on” is the saturation region & collector-emitter voltage looks “ohmic” (linear in current).



Semiconductors

Transistors (bi-polar)





Dashed line is called a "load line". As I_b is changed, I_c varies. V_c follows along this line.

$V_{c\,max}$ = -V (when I_b=0)

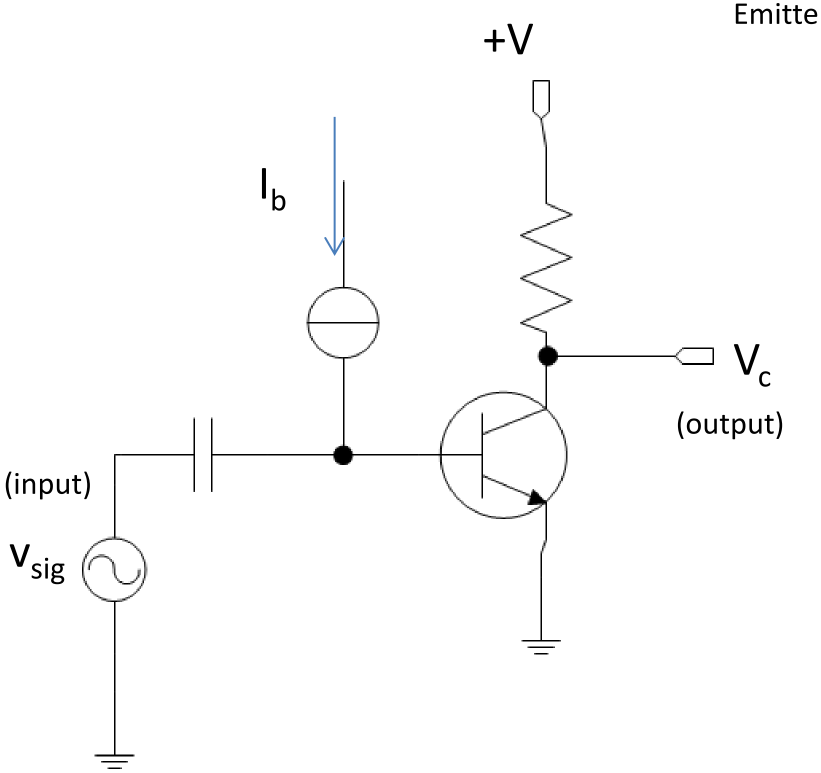
$I_{c\,max} = -\frac{V}{R}$ (when transistor fully on)

Semiconductors

Transistors (bi-polar) Common configurations

Common emitter (npn)

Emitter is common (ground) for both the input signal & output signal



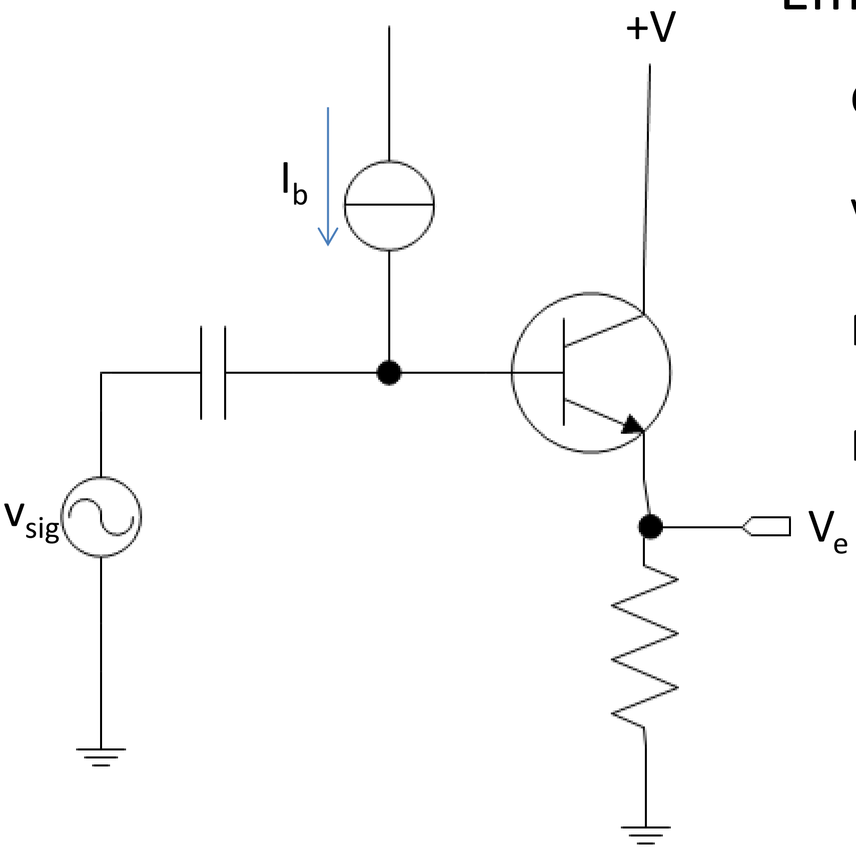
Voltage, current gain

Inverting (v_c 180° phase shift from v_{sig})

Midrange input & output impedances

Semiconductors

Transistors (bi-polar) Common configurations



Emitter follower

Current gain

Voltage gain ~1 (V_e always 1 diode drop from V_b)

Non-Inverting (v_e 0° phase shift from v_{sig})

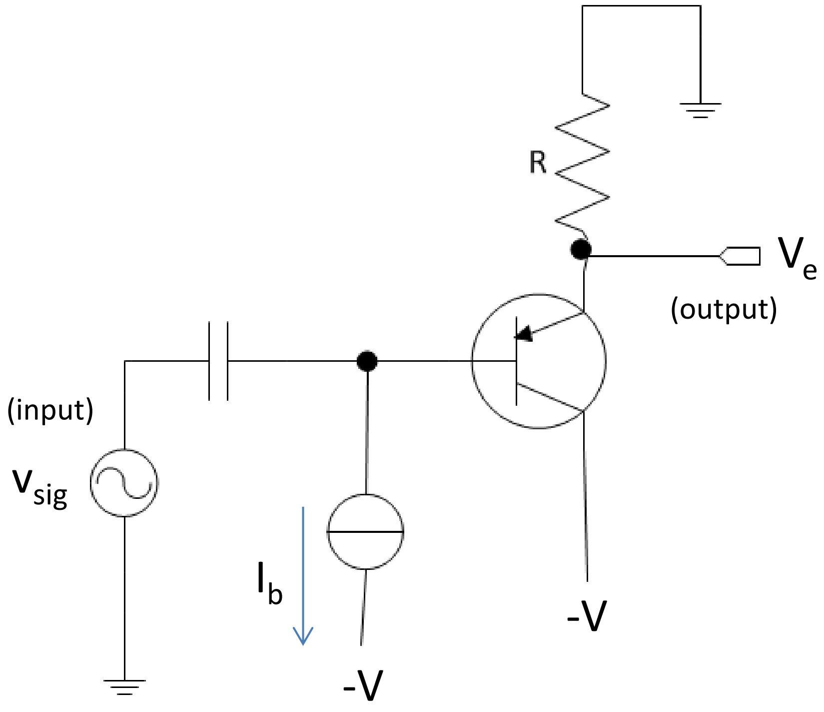
Midrange input & output impedances

Semiconductors

Transistors (bi-polar) Common configurations

Common collector (pnp)

Is the pnp transistor version of the emitter follower.



Current gain

Voltage gain ~1 (V_e always 1 diode drop from V_b)

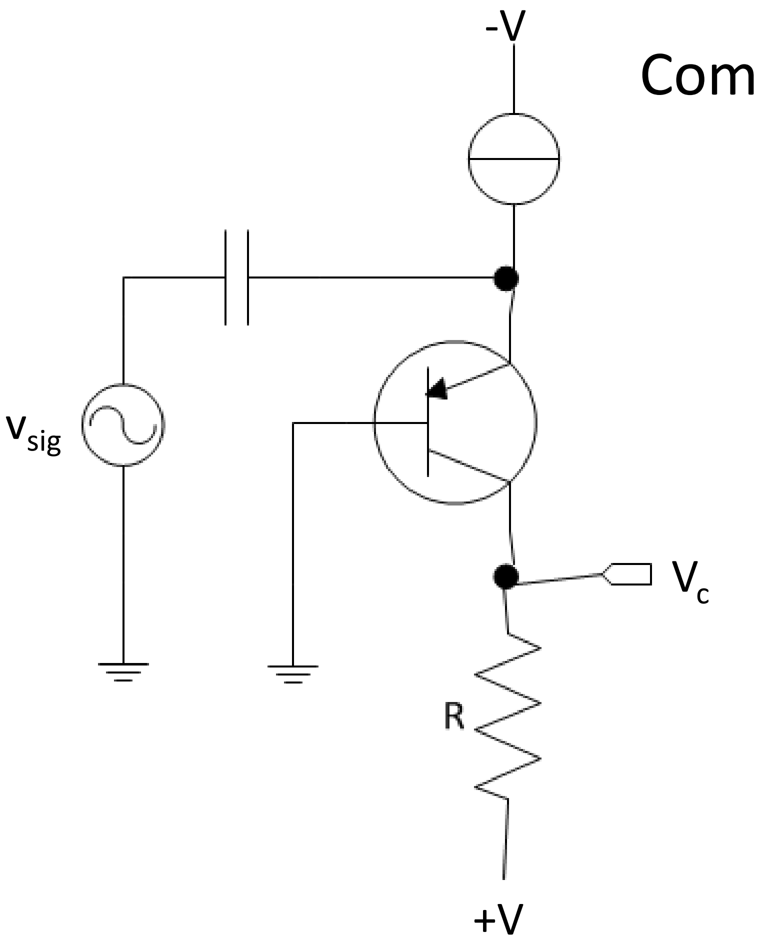
Non-Inverting (v_e 0° phase shift from v_{sig})

Midrange input & output impedances

Semiconductors

Transistors (bi-polar) Common configurations

Common base (pnp)



Voltage gain

Current gain ~1

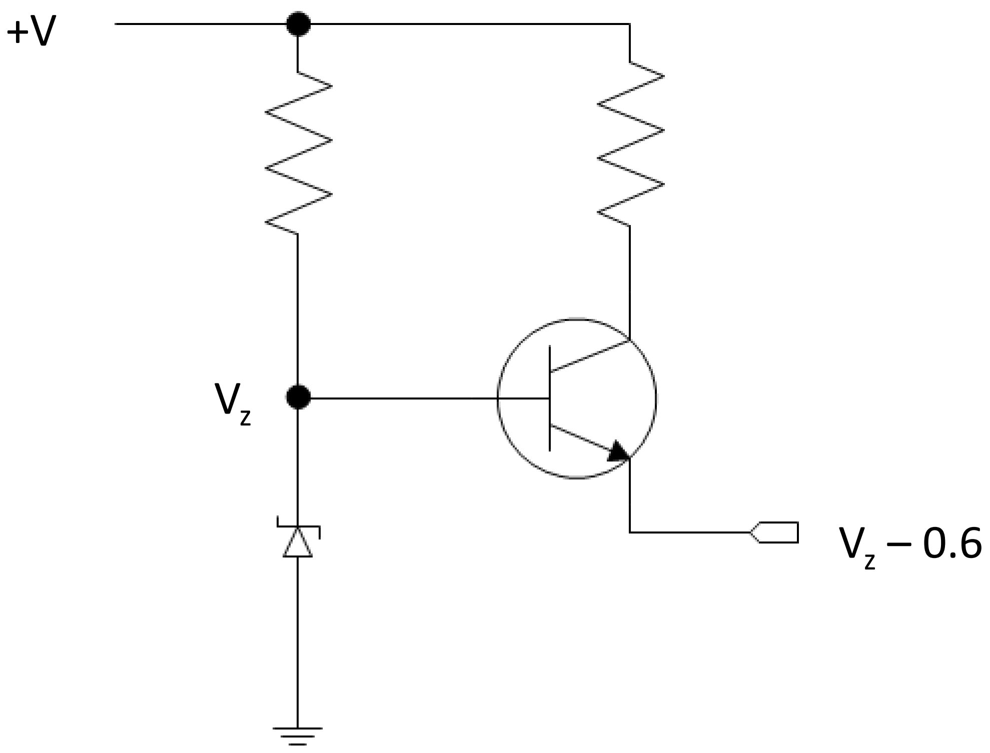
Non-Inverting (v_c 0° phase shift from v_{sig})

Midrange input & output impedances

Semiconductors

Transistors (bi-polar) Real Example

Emitter follower voltage reference with higher current capability

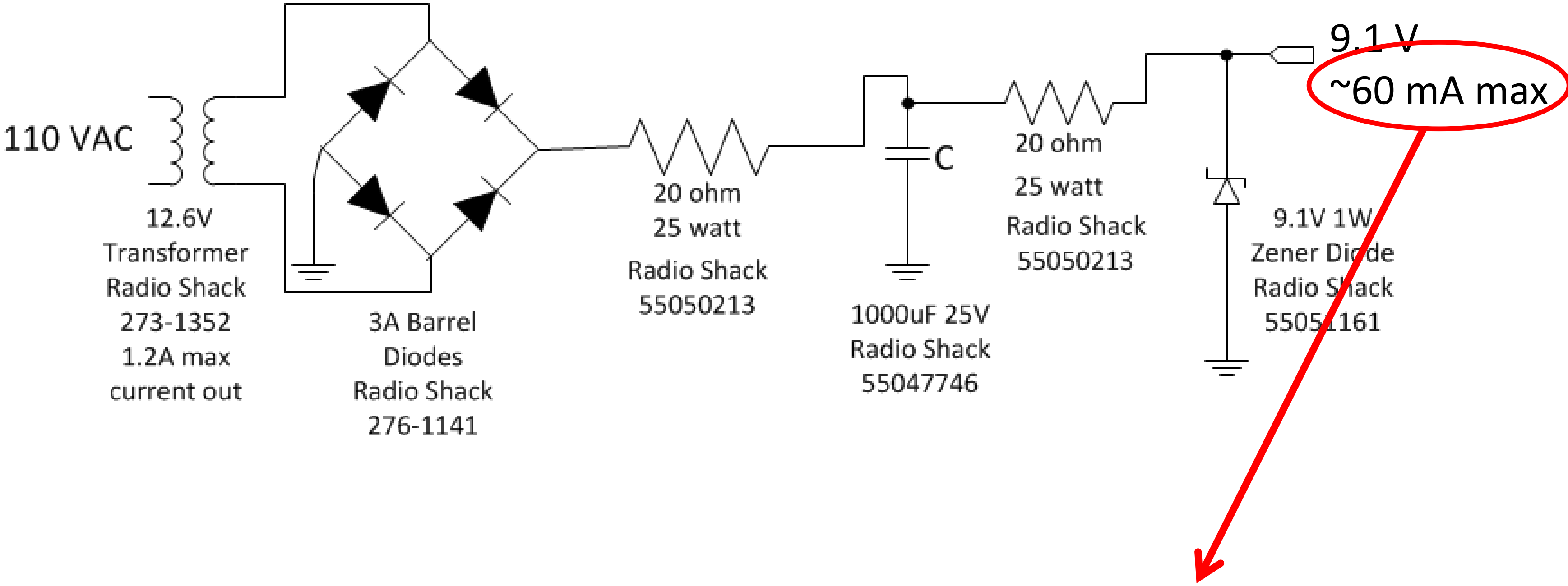


Semiconductors

Diode Circuits

Regulated Full Wave Rectifier Power Supply

Example using real parts



9.1 V

~60 mA max

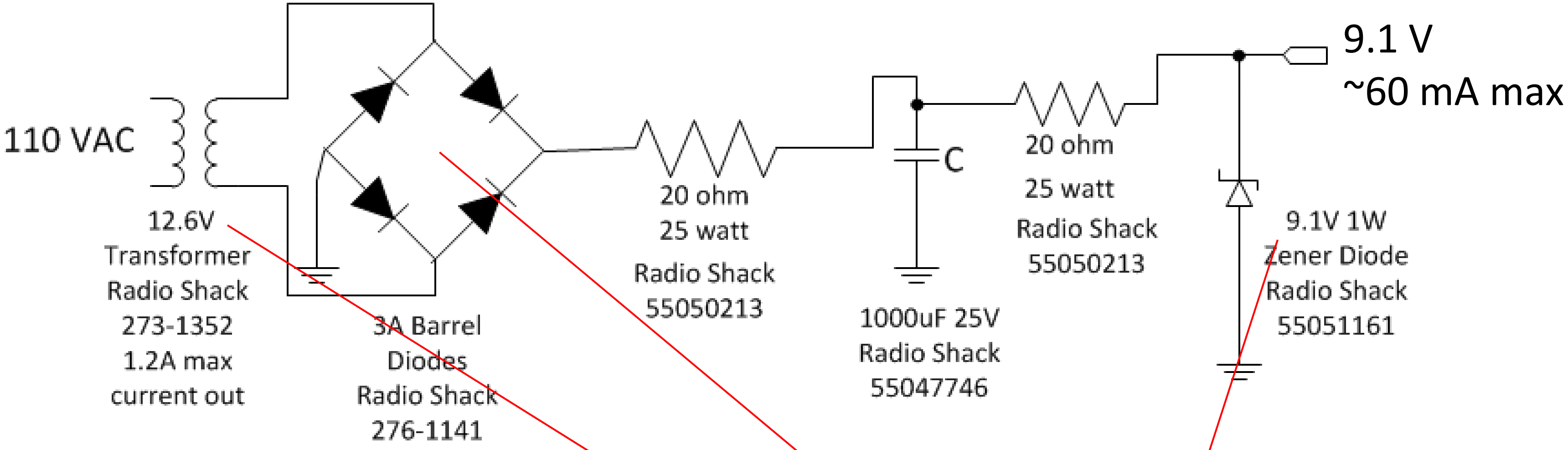
How do I know this?

Semiconductors

Diode Circuits

Regulated Full Wave Rectifier Power Supply

Example using real parts



9.1 V
~60 mA max

How do I know this?

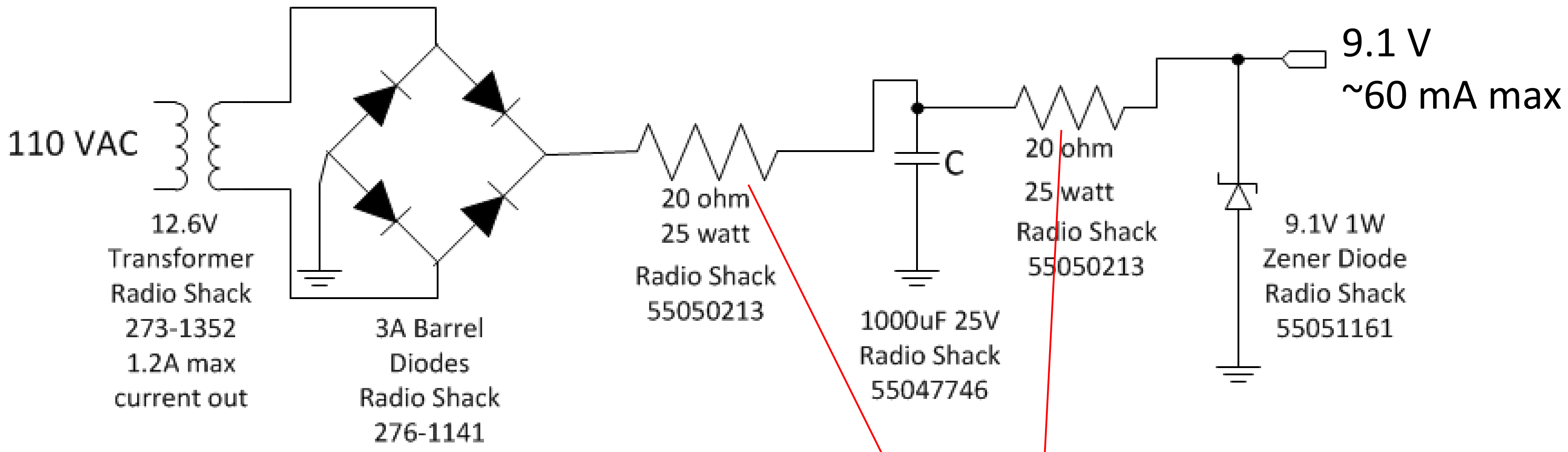
12.6V – 1.2V– 9.1V = 2.3V

Semiconductors

Diode Circuits

Regulated Full Wave Rectifier Power Supply

Example using real parts



How do I know this?

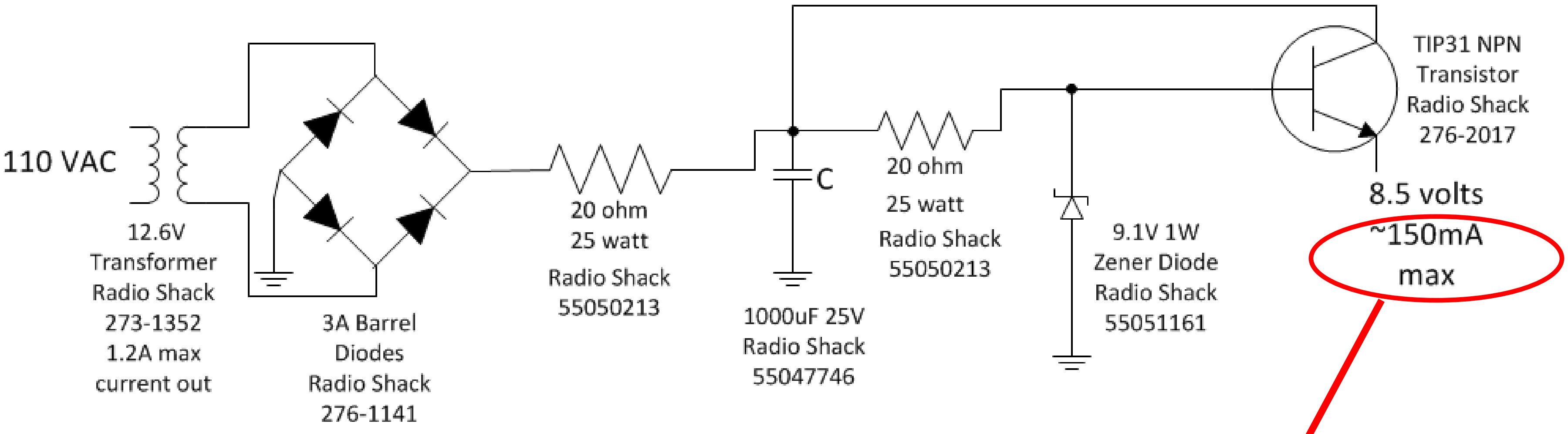
12.6V – 1.2V– 9.1V = 2.3V

2.3V/40 ohms = 57.5mA

Semiconductors

Transistors (bi-polar) Real Example

Emitter follower voltage reference with higher current capability

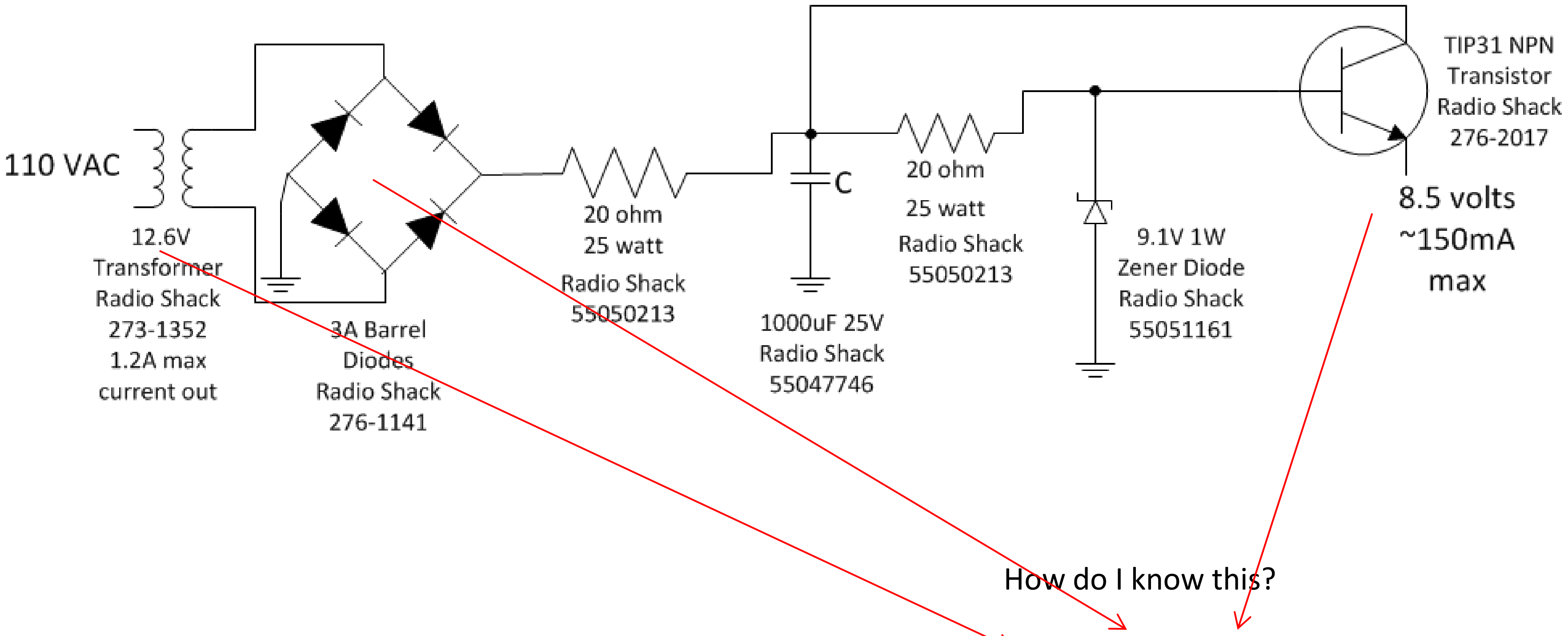


How do I know this?

Semiconductors

Transistors (bi-polar) Real Example

Emitter follower voltage reference with higher current capability



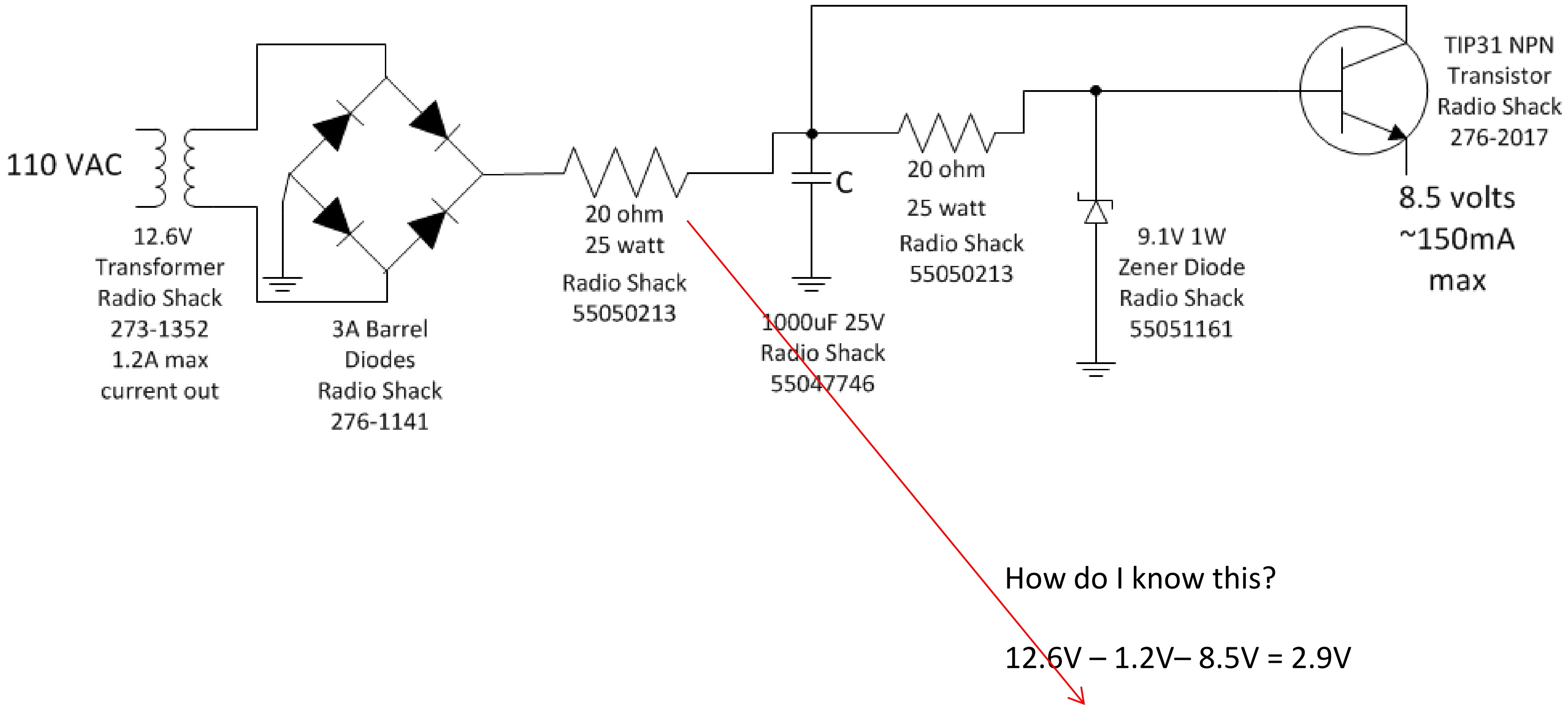
How do I know this?

12.6V – 1.2V– 8.5V = 2.9V

Semiconductors

Transistors (bi-polar) Real Example

Emitter follower voltage reference with higher current capability



How do I know this?

12.6V – 1.2V– 8.5V = 2.9V

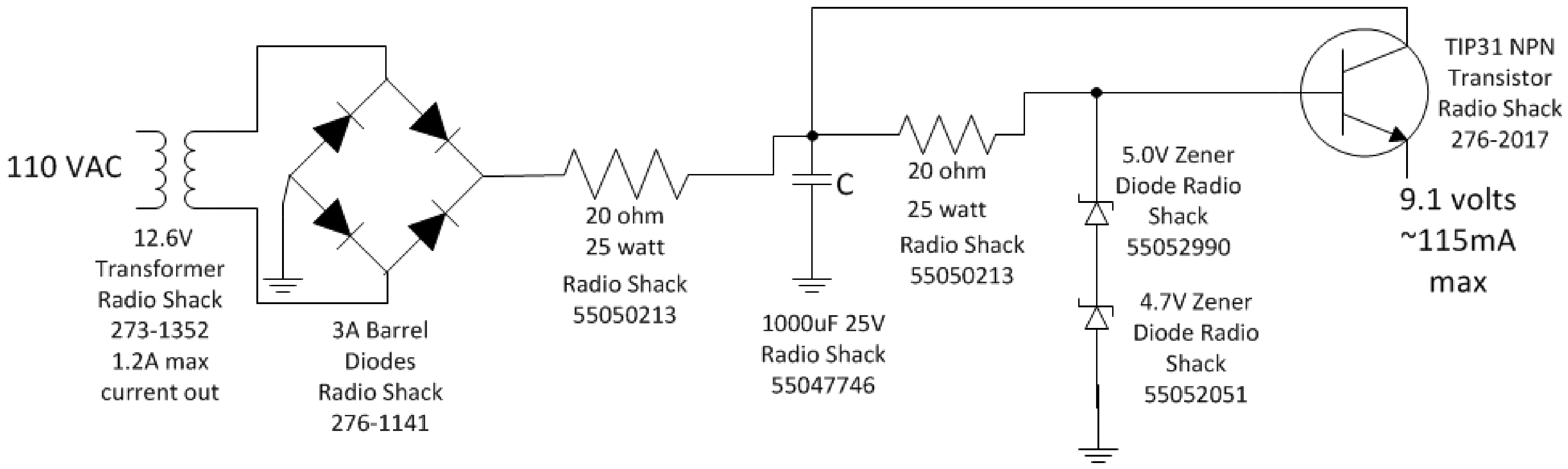
2.9V/20 ohms = 145mA

Semiconductors

Transistors (bi-polar) Real Example

Common collector (npn)

Emitter follower voltage reference with higher current capability



Semiconductors

Transistors (bi-polar) Biasing

How/why bias the base?

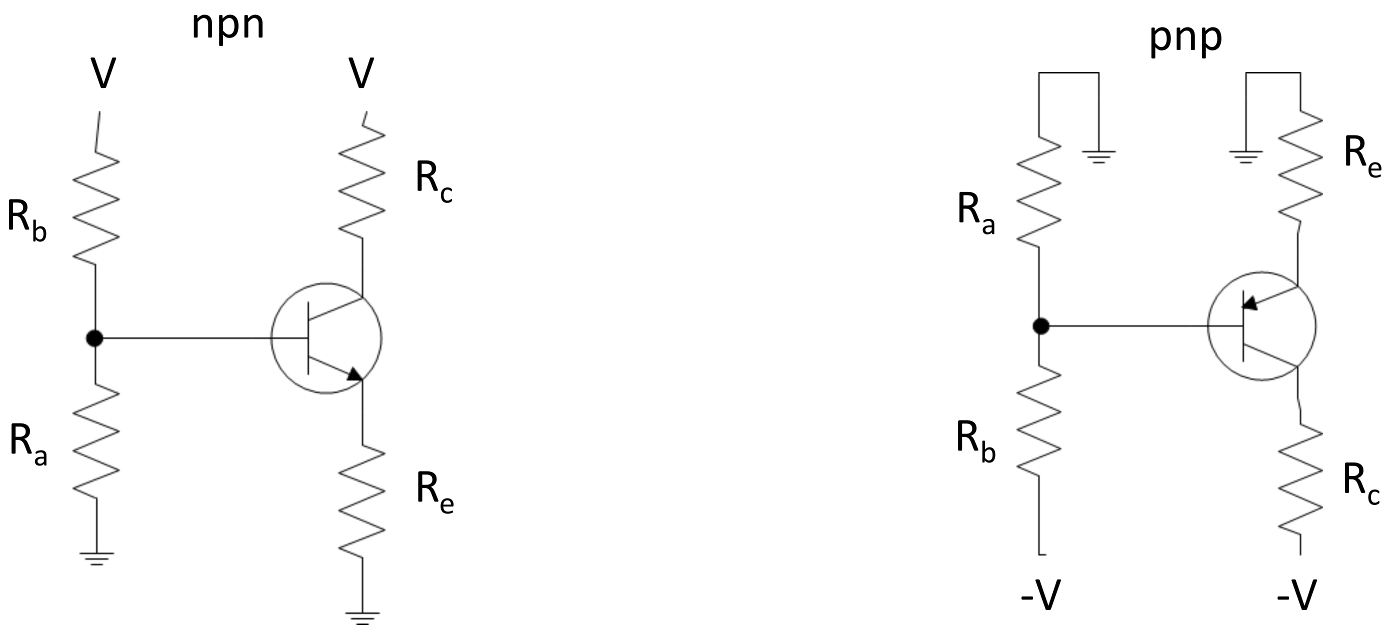
We usually want to sit in the middle of the active region.

We want to control the transistor in a manner which will be insensitive to perturbations such as:

- **Variations in β with respect to temperature or part substitution.**
- **Variations in V_{be}. Although V_{be} ~ 0.6V = 600mV, it changes by -2.5mV/°K.**

Semiconductors

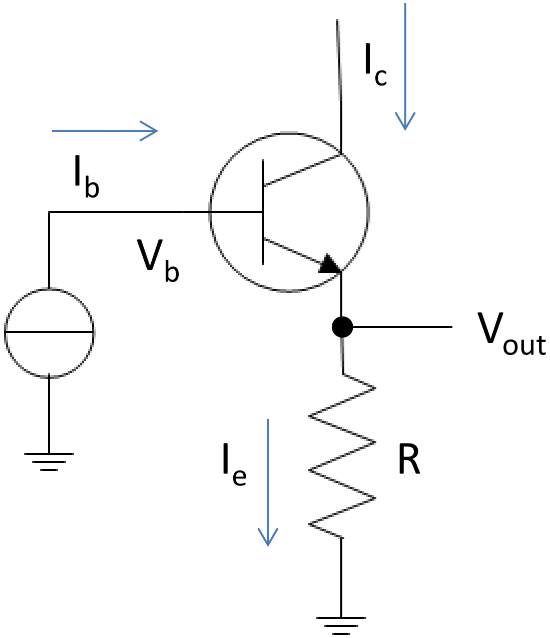
Transistors (bi-polar) Bias



Bias the base-emitter junction by an external voltage divider. We can choose R_a & R_b such that any signal is a small perturbation and we stay in the active region.

Semiconductors

Transistors (bi-polar) Input & Output Impedance



$V_b = 0.6 + V_{out}$

$\Delta V_b = \Delta\, V_{out}$

$I_e = I_b + I_c\,, \quad I_c = \beta\, I_b \;\rightarrow\; I_e = I_b\,(1+\beta)$

$\Delta I_e = (1+\beta)\,\Delta I_b$ (current amplification)

Input resistance:

$$r_{in} \equiv \frac{\Delta\, V_b}{\Delta Ib} = \frac{\Delta\, V_{out}}{\Delta Ib} = \underbrace{\frac{\Delta\, V_{out}}{\Delta Ie}}_{R}\,(1+\beta)$$

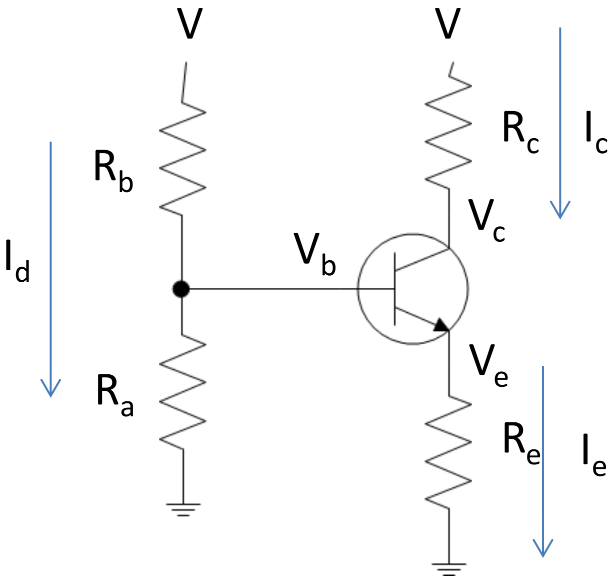
$r_{in} = R\,(1+\beta)$

$\beta \cong 100$ More generally, $Z_{in} \cong (1+\beta)\, Z_{load}$

Semiconductors

Transistors (bi-polar) Bias

How does this work?



All voltages with respect to ground.

$I_e = V_e/R_e$

$V_b = V_e + 0.6$

$V_c = V - I_cR_c$

Suppose I_b is small compared to the divider current, $I_d \gg I_b$. (We can use small values for R_a & R_b.)

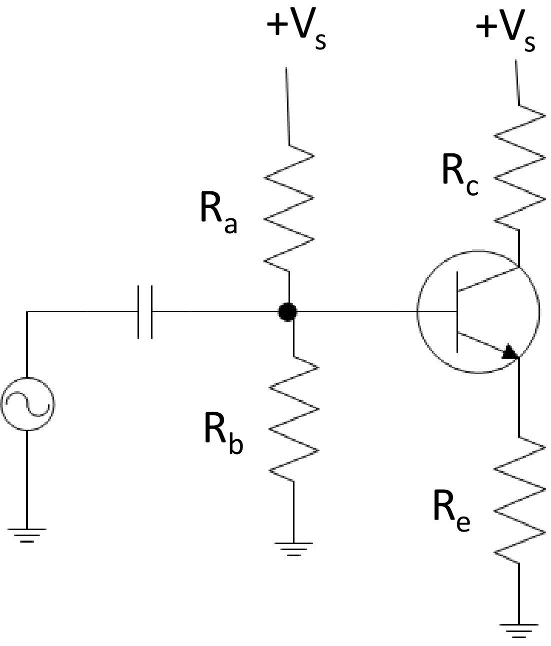
$I_d = \frac{V}{R_a+R_b}$ We also know from our resistor voltage divider equation, that $V_b = V\frac{R_a}{R_a+R_b}$.

So $V_e = V\frac{R_a}{R_a+R_b} - 0.6$ & $I_e = V_e/R_e = \frac{\left\{V\frac{R_a}{R_a+R_b} - 0.6\right\}}{R_e}$. Also, I_b is I_c/β & $\beta \sim 100$, so $I_c \cong I_e$

Semiconductors

Transistors (bi-polar) How do we go about designing something?

Choose some things – calculate the rest



1) Choose Transistors
   - Availability
   - Current carrying capacity (I_{CMAX})
   - npn or pnp
2) Power Supply Voltage
   - $V_s = V_{supply} < V_{ce\ MAX}$ for chosen transistors
3) Operating Point (Bias circuit)

   Want to operate in the active region.

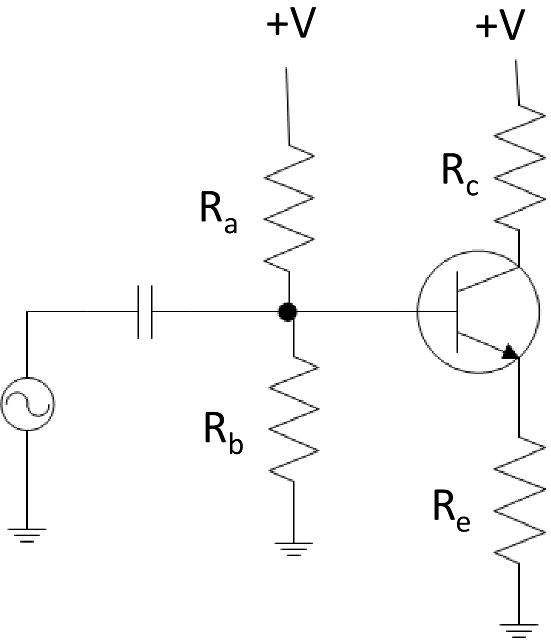
   $I_c \leq ½\, I_{CMAX}$

   $V_c \approx ½\, V_s$

4) V_e on the order of 1 volt, typically ~1/20 V_s

Semiconductors

Transistors (bi-polar) How do we go about designing something?



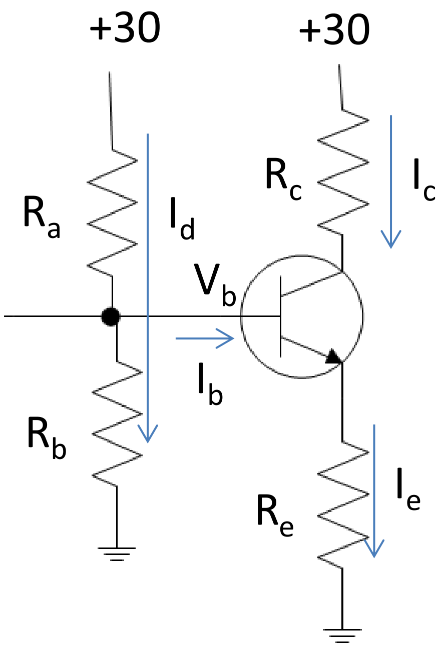
Suppose our Box ‘O Transistors from Radio Shack says:

β Or h_{FE} = 100 @ I_c = 10ma

And we have a 30 volt power supply.

Semiconductors

Transistors (bi-polar) Quick & Dirty



Choose V_e = 1 volt. So $V_b = V_e + 0.6 = 1.6$ volts

Want $I_d \gg I_b$, so the voltage divider isn’t perturbed by I_b

I_b is on the order of μamps, so lets set I_d = 1ma

$(R_a + R_b)I_d$ = 30 volts → $\boxed{(R_a + R_b) = 30\text{k}\Omega}$

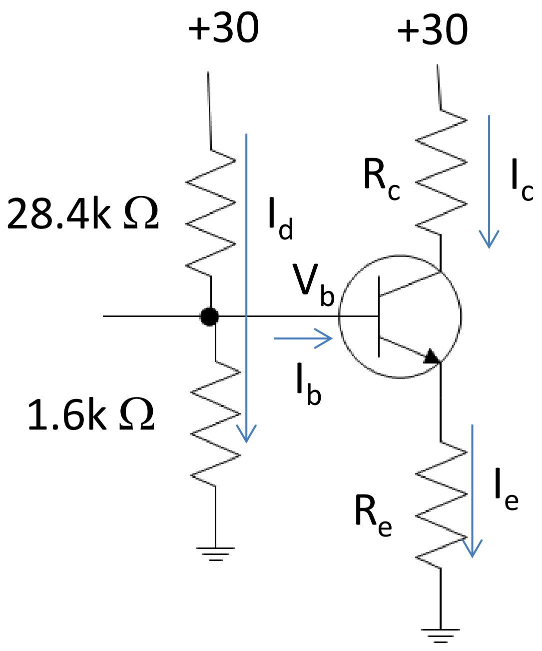
$$V_b = V_{divider} = V_s \frac{R_a}{R_a + Rb} \rightarrow \boxed{\frac{R_a}{R_a + Rb} = \frac{1.6}{30}}$$

So $R_a = 28.4\text{k}\ \Omega$, $R_b = 1.6\text{k}\ \Omega$

Semiconductors

Transistors (bi-polar) Quick & Dirty

So $R_a = 28.4\text{k}\ \Omega$, $R_b = 1.6\text{k}\ \Omega$



Set $V_c \approx \frac{1}{2} V_s$ = 15 volts

We want to operate at I_c = 10ma & we know $\beta \approx 100$,
So we know

$$R_e = \frac{V_e}{I_e} \cong \frac{V_e}{I_c} = \frac{1\text{ volt}}{10\text{ ma}} = 100\Omega$$

$$R_c = \frac{V_c}{I_c} = \frac{15\text{ volts}}{10\text{ma}} = 1500\ \Omega$$

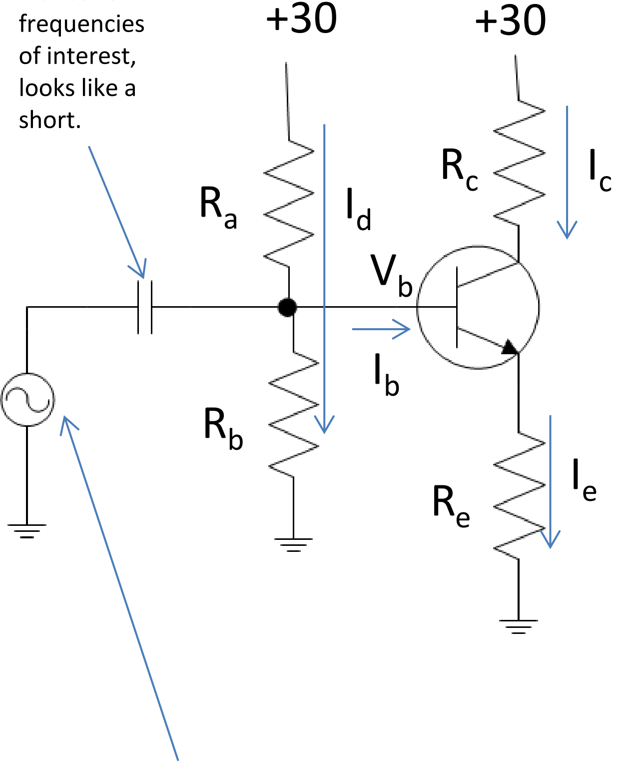
Given typical resistor manufacturing tolerances, this is good enough.

Semiconductors

Transistors (bi-polar) Quick & Dirty

$$\text{So } \boxed{R_a = 28.4\text{k}\ \Omega,\ R_b = 1.6\text{k}\ \Omega}$$

Set $V_c \approx \frac{1}{2} V_s = 15$ volts



Pick so for frequencies of interest, looks like a short.

We want to operate at I_c = 10ma so $\beta \approx 100$,
So we know

$$\boxed{R_e = \frac{V_e}{I_e} \cong \frac{V_e}{I_c} = \frac{1 \text{ volt}}{100 \text{ ma}} = 100\Omega}$$

$$\boxed{R_c = \frac{V_c}{I_c} = \frac{15 \text{ volts}}{100 \text{ ma}} = 1500\ \Omega}$$

Input impedance for signal is $R_a || R_b || R_e (1+ \beta) \cong 1317\ \Omega$.

Thursday, September 28 & Thursday, October 5

Lab 4 The Transistor Amplifier