# PHYSICS 364, 2010-10-12

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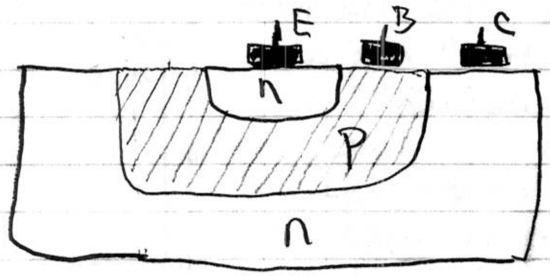
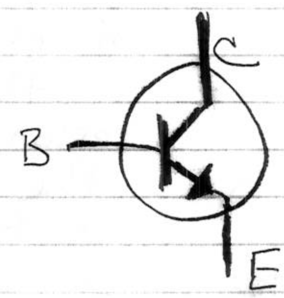
## TRANSISTORS I

The transistor is the basis of nearly all modern electronics. A transistor enables a low-power signal to control a much higher-power signal (higher current, higher voltage, or both). Thus, transistors can form switches, amplifiers, digital logic gates, and much more.

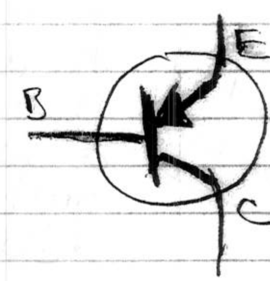
There are two widely used varieties of transistor — the Bipolar Junction Transistor and the Field Effect Transistor. We will study BJTs this week and look at FETs next week.




NPN transistor

BJTs come in two flavors: NPN and PNP. An NPN (PNP) transistor is a 3-terminal device consisting of two layers of n-type (p-type) material separated by a layer of p-type (n-type) material.




PNP transistor

We'll mostly discuss NPN transistors. For PNP, reverse all of the polarities.

The simplest way to see a BJT is:

1. The base→emitter junction is a diode
2. The current from collector to emitter ($I_C$) is proportional to the base→emitter current ($I_B$) by a factor $\beta \sim 100$. (In practice, $50 \lesssim \beta \lesssim 300$.)

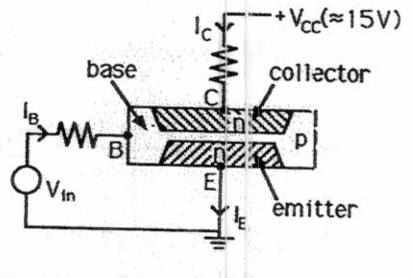
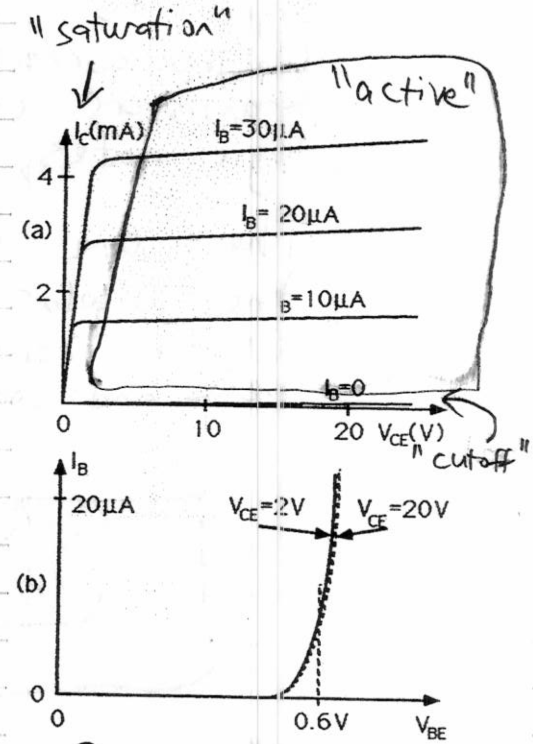



Fig. 9.29. The npn bipolar transistor.

③ To keep the transistor in the "active" region (where $I_C = \beta I_B$), the collector must be at least a few tenths of a volt above the emitter! $V_{CE} \gtrsim 1V$, more at higher currents, as shown at right.




Bugg.

Fig. 9.30. Characteristics of the bipolar transistor.

(Below the "active" region is the "cutoff" region, where the collector passes no current; and to the left of the "active" region is the "saturation" region, which is like the "ON" state when a transistor is used as a switch rather than as a linear amplifier. The usefulness of saturation is that you can switch a large current with quite small power $I_C \cdot V_{CE}$ dissipated in the transistor.)

WARNING! reversing $V_{BE}$ beyond $\simeq$ a few volts will cook the transistor

We will mostly consider "active" mode, where $I_C = \beta I_B$, $I_E = I_B + I_C = (\beta+1) I_B$


$I_C = \beta I_B$, $\beta \sim 10^2$

$I_B \sim e^{V_{BE}/25mV}$

where $kT/e \simeq 25mV$ at room temperature

Small $V_{BE}$ (hence $I_B$) controls large $I_C$

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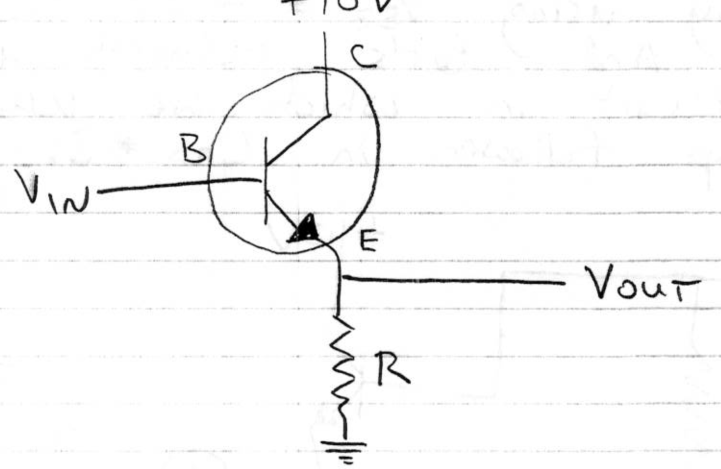
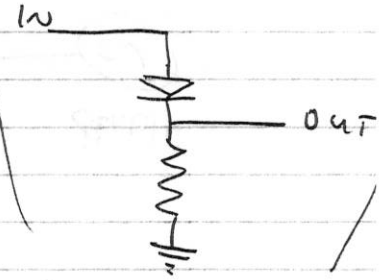
First circuit example: emitter follower.

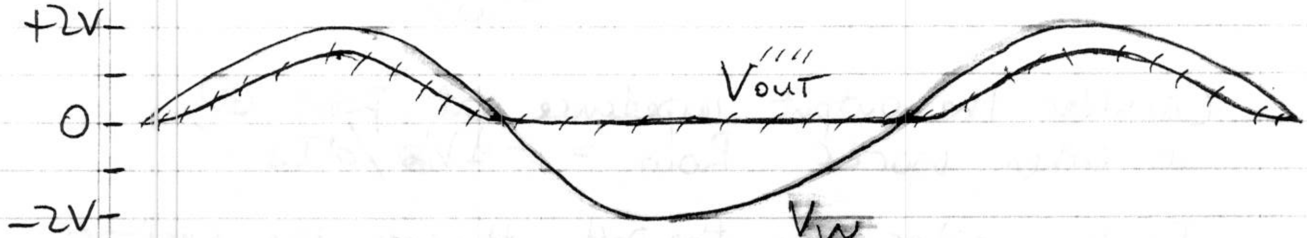



Recall this circuit from Lab 1:




Treating base → emitter junction as a diode,
$V_{OUT} \simeq V_{IN} - 0.7\,V$

Consider sine wave input, 2V amplitude:

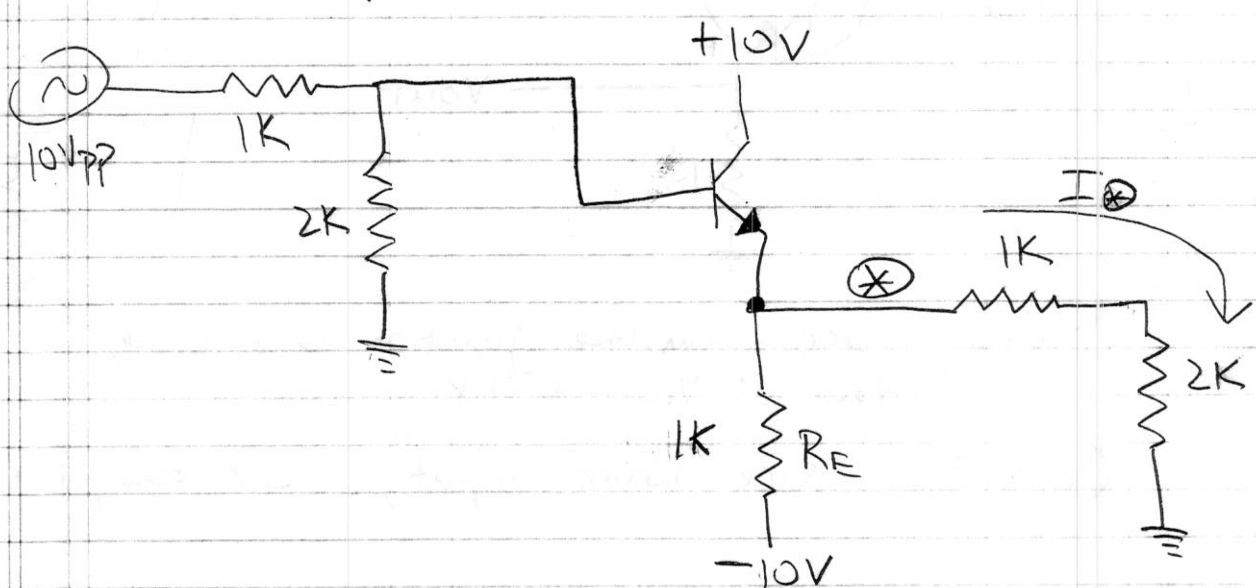



Consider input impedance: change $V_{IN}$ by $\Delta V$.
$V_{OUT}$ changes by same $\Delta V$ (as long as $V_{BE}$ is not reverse-biased), so $\Delta I_E = \Delta V / R$.
Thus $\Delta I_B = \Delta I_E / (\beta+1) = \Delta V / ((\beta+1)R)$.

So $R_{IN} = \dfrac{dV_{IN}}{dI_{IN}} = (\beta+1)R$.

The follower makes the load appear (to the source) to be a factor $(\beta+1) \sim 10^2$ larger (and for a voltage source, larger $R_{IN}$ is easier to drive).

Let's prevent the follower from clipping at zero volts by using $V_{EE} = -10V$ instead of ground. And let's actually use it in the circuit in which we used our opamp follower in Lab #3.




Consider the output impedance at point $\circledast$, in other words $R_{OUT} = -dV_{\circledast}/dI_{\circledast}$.

First consider only the path through the emitter (e.g. let $R_E \to \infty$). Then $\Delta I_B = \Delta I_{\circledast}/(\beta+1)$.
And $\Delta V_{\circledast} = \Delta V_B = \Delta I_B \cdot R_{SOURCE}$
$= \Delta I_B \cdot (1K \parallel 2K)$

So $R_{OUT} = \dfrac{R_{SOURCE}}{\beta+1} = \dfrac{1K \parallel 2K}{\beta+1} \sim 670\Omega \cdot 10^{-2} \sim \mathcal{O}(10\Omega)$

Now include the parallel resistance of $R_E$, which makes $\cong$ no difference:

$$R_{OUT} = \frac{R_{SOURCE}}{\beta+1} \parallel R_E$$

$$\sim \mathcal{O}(10\Omega) \parallel 1K \sim \mathcal{O}(10\Omega)$$

[Recall that $R_{OUT}$ wants to be small for a voltage source.]

So you can see that the emitter follower makes the source think it is driving a load that is $\mathcal{O}(10^2)$ times larger, and it makes the load think that it is being driven by a source that is $\mathcal{O}(10^2)$ times stiffer (lower $R_{THEVENIN}$).

It's not nearly as large an improvement as you get from an opamp, and there is the annoying diode drop, but it's not bad.

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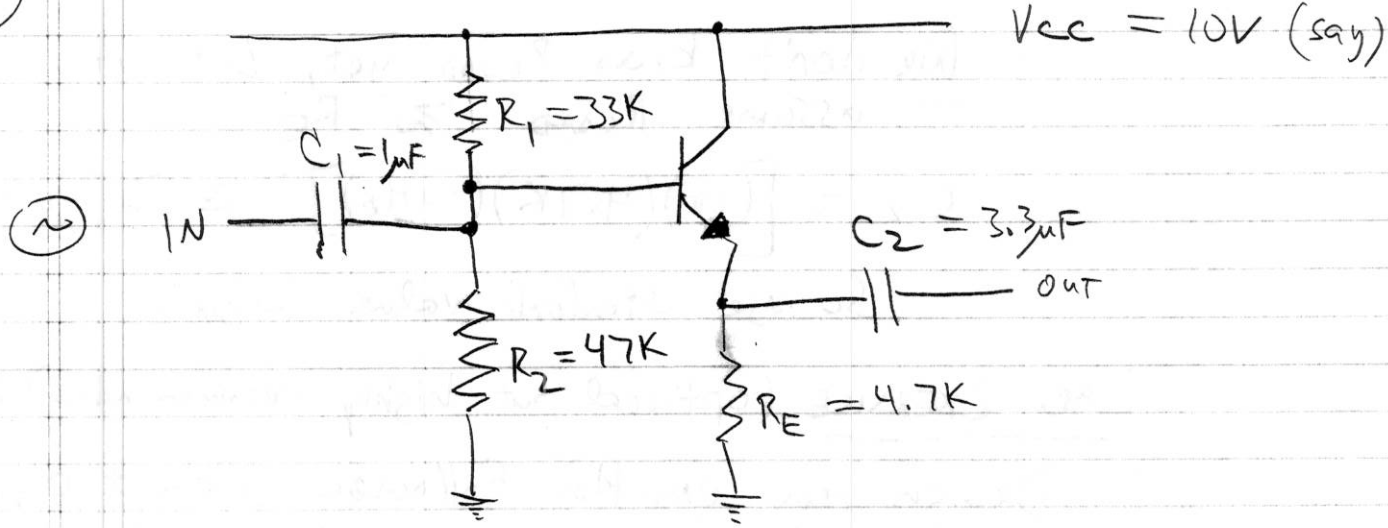
Now let's bias the follower (and AC-couple the input & output) so that we can operate it from a single (positive) power supply.




(Design steps from HH §2.05.)

① Choose $V_E$ for largest symmetric swing: $V_E = \frac{1}{2} V_{CC}$

② Choose $R_E$ for a reasonable "quiescent" (steady state) current. In this case, $4.7K \Rightarrow I_E \simeq 1mA$.

③ Choose $R_1$ & $R_2$ for $V_B = V_E + 0.7$ volt $\Rightarrow R_2/R_1 = 5.7/4.3$

Want $(R_1 /\!/ R_2) \ll \beta \cdot R_E \sim 500K$. E.g. $R_1 /\!/ R_2 \approx 25K$, 50K and 38K would be ideal, but 47K and 33K are available in RCA lab and are pretty close.

$$10V \cdot \frac{47}{47+33} \approx 5.9V.$$

④ choose $C_1$ such that $f_{3dB} \lesssim 10\,Hz$
(for their example of passing audio frequencies $20\,Hz \sim 20\,kHz$)

$$10\,Hz = f_{3dB} = \frac{1}{2\pi RC}$$

$$R \simeq R_1 \parallel R_2 \parallel (\beta \cdot (R_E + R_{LOAD}))$$
$$\simeq 33K \parallel 47K \simeq 20K$$

$$C_1 = \frac{1}{2\pi R f_{3dB}} = \left[(2\pi)(20\,k\Omega)(10\,Hz)\right]^{-1} \simeq 0.8\,\mu F$$

Using $\boxed{1\,\mu F} \Rightarrow f_{3dB} \simeq 8\,Hz$

⑤ choose $C_2$ for $f_{3dB} \lesssim 10\,Hz$

We don't know $R_{LOAD}$ yet, but it's safe to assume $R_{LOAD} \gtrsim R_E$

$$C_2 = \left[(2\pi)(4.7K)(10\,Hz)\right]^{-1} \simeq 3.2\,\mu F$$

So use standard value $3.3\,\mu F$.

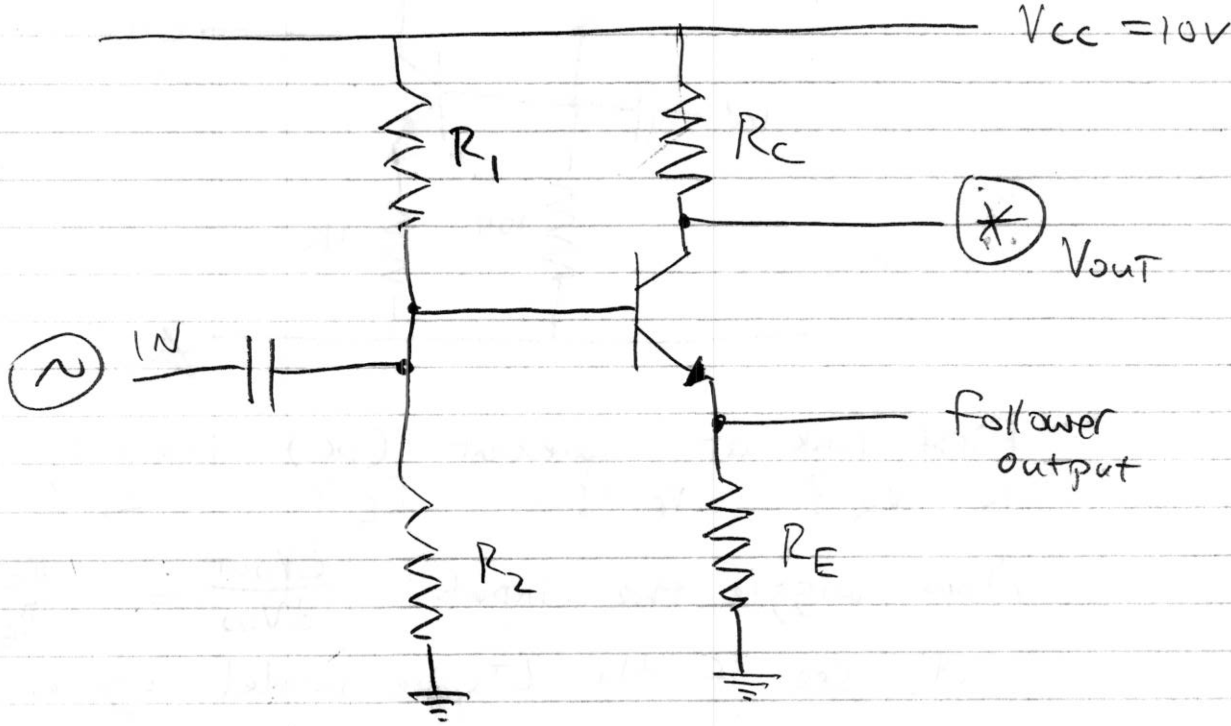
LAB EXERCISE (optional but highly recommended):

Design an emitter follower with ±10 volt supplies to operate over the audio range (20 Hz – 20 kHz). Use 3 mA quiescent current.

First assume that input source provides a DC path to ground. Then modify your design to use capacitively coupled input. Remember that there must be a DC path from base to ground.

Next circuit example: <u>common emitter amplifier</u>

start from emitter follower, and add a resistor at the collector




Now what happens when we wiggle $V_{IN}$?

$$V_E \simeq V_B - 0.7V$$

$$I_E = V_E/R_E \simeq \frac{V_B - 0.7V}{R_E}$$

$$I_C = I_E - I_B = I_E - \frac{I_E}{\beta+1} \simeq I_E$$

$$\Rightarrow V_{\circledast} = V_{cc} - I_C R_C \simeq V_{cc} - I_E R_C$$

$$= V_{cc} - \frac{R_C}{R_E} \cdot (V_B - 0.7\,\text{volt})$$

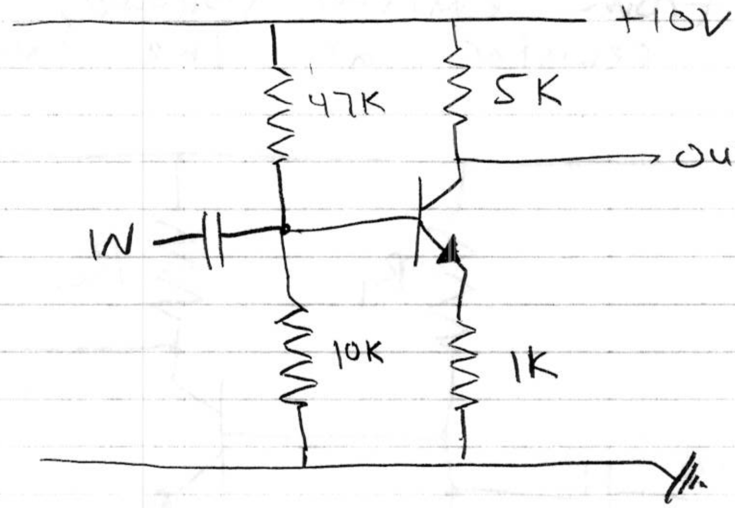
So $$\frac{dV_{\circledast}}{dV_{in}} = -\frac{R_C}{R_E}$$

Inverting amplifier!

Voltage gain can be arranged by suitable component choic

Common emitter amplifier, continued:

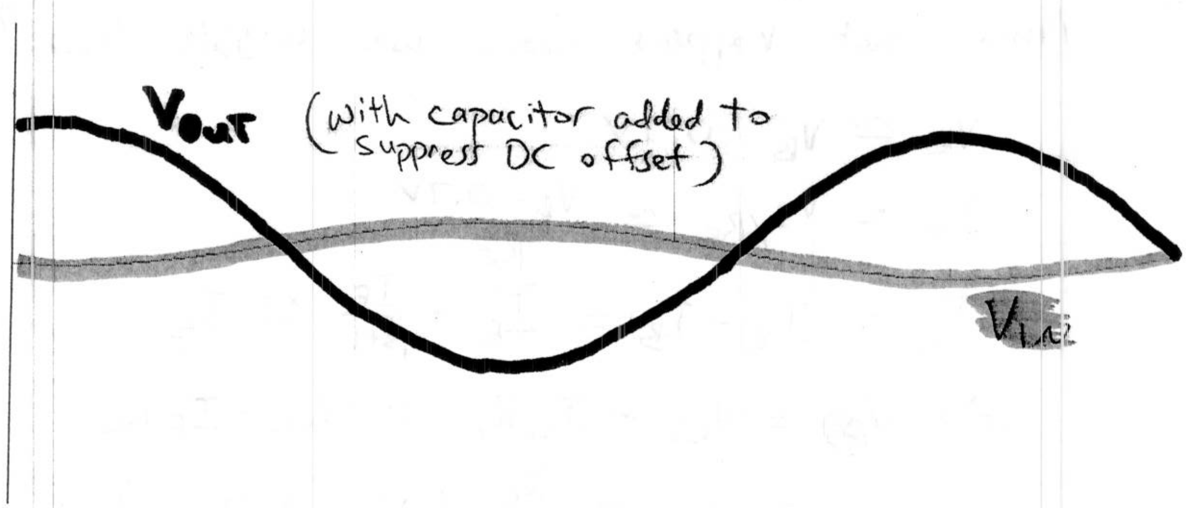
Let's fill in some component values:




First look at quiescent (DC) state: What is $V_B$? $V_E$? $I_E$? $I_C$? $V_{OUT}$?

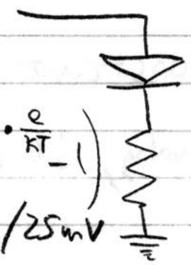
Now wiggle the input. $\frac{dV_{OUT}}{dV_{IN}} = -\frac{R_C}{R_E} = -5.$

Let's see if the LTspice model agrees.



Now suppose we get greedy and try to increase the gain by reducing $R_E$.

Two problems:



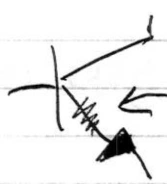
(1) recall $I_C = I_{sat}\left(e^{V_{BE}\cdot\frac{e}{kT}} - 1\right)$

$\simeq I_{sat}\, e^{V_{BE}/25\,mV}$

so $\dfrac{dV_{BE}}{dI_C} \simeq \dfrac{25\,mV}{I_C}$

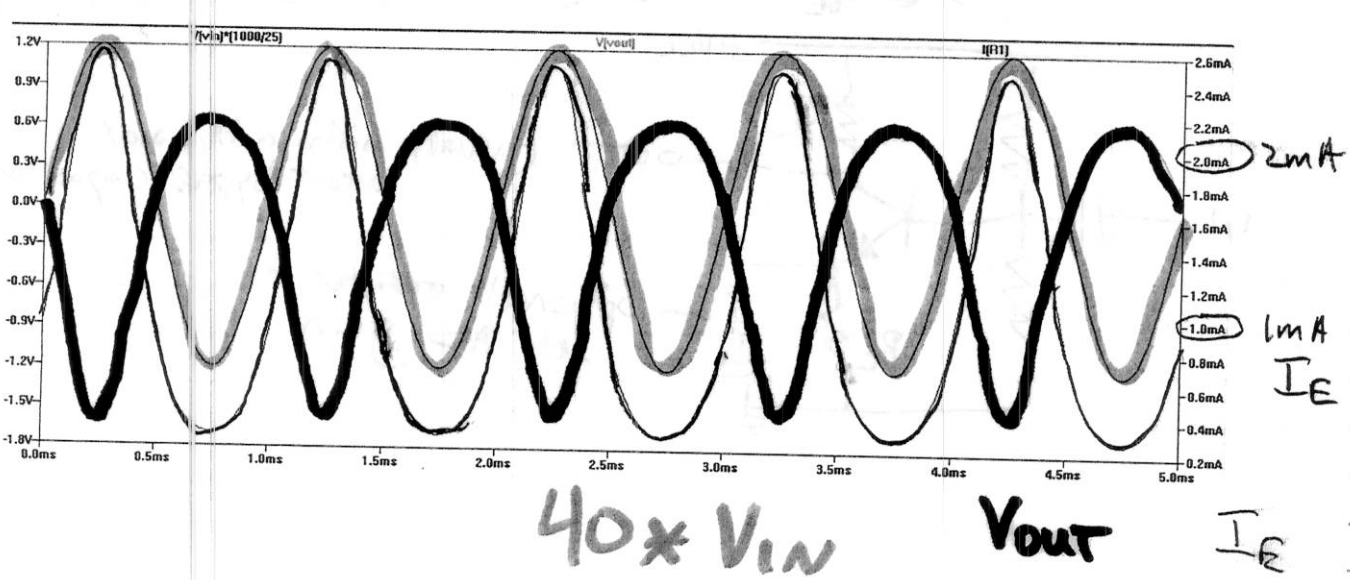
or since $I_E = \dfrac{\beta+1}{\beta} I_C \simeq I_C$,

$$\frac{dV_{BE}}{dI_E} \simeq \frac{25\,mV}{I_E} = \frac{25\,\Omega}{I_E\,[mA]}.$$



diode curve makes emitter look like a resistance $r_e = 25\Omega / I_E$, where $I_E$ is measured in milliamps.

If we don't keep $R_E \gg r_e$, we will see non linear response.



(2) second problem with omitting $R_E$ is thermal instability:

at constant $V_{BE}$, $I_C$ grows 9% per °C

(alternatively, at constant $I_C$, $V_{BE}$ falls $\simeq$ 2 mV per °C)

No $R_E$ ⇒ high gain (limited only by $r_e$)

⇒ transistor heats up

⇒ $I_C$ grows

⇒ $r_e$ decreases

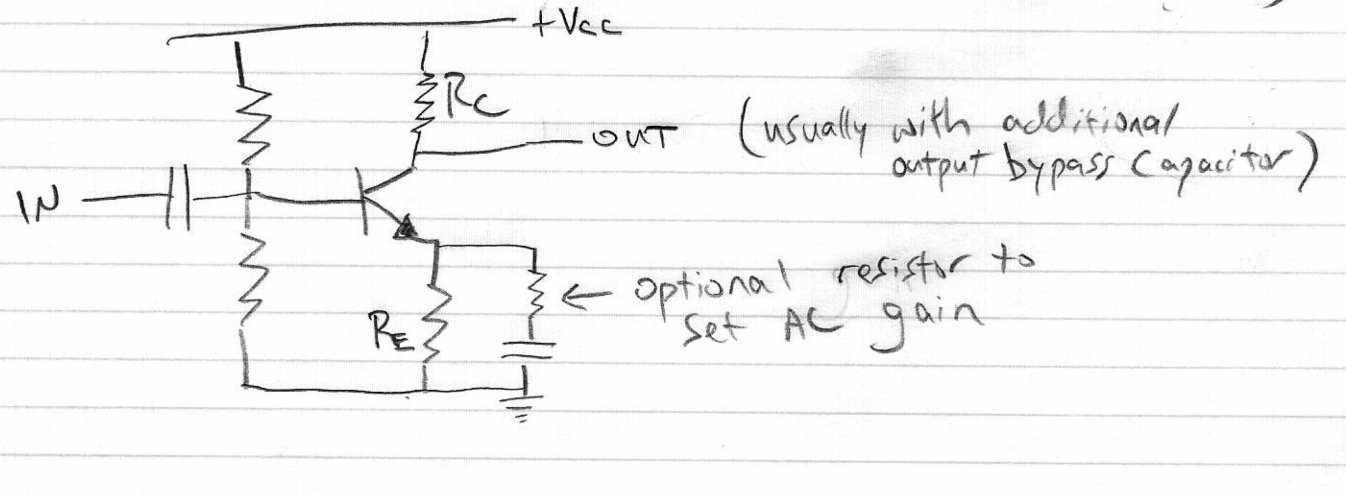
⇒ $I_C$ and temperature continue to grow

⇒ runaway condition

⇒ eventually transistor goes into saturation

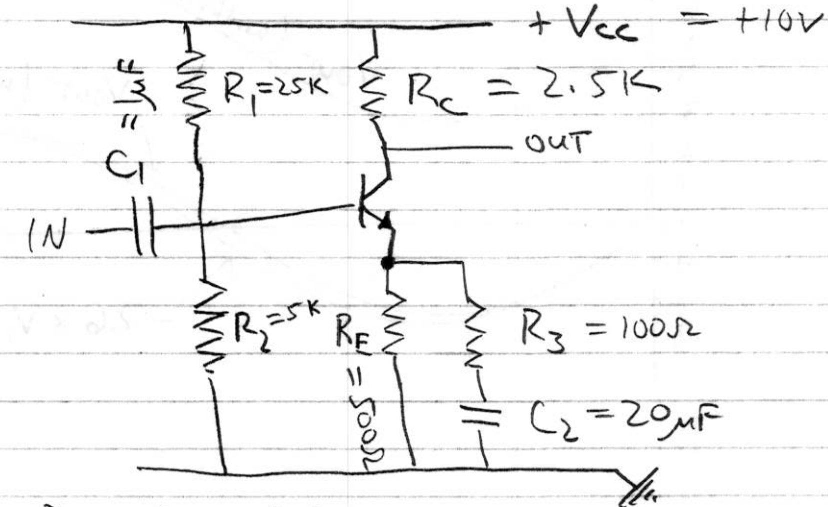
Solution: $R_E$ limits $I_C$ at DC; use bypass capacitor to increase AC gain.

(Note that ↑ temperature ⇒ ↑ $I_C$ ⇒ ↑ $V_E$ (via $R_E$) ⇒ ↓ $V_{BE}$ ⇒ ↓ $I_C$. Feedback stabilizes $I_C$.)



Let's go through HH design example for common emitter amplifier with large AC gain:

(Hayes & Horowitz, page 115)




① choose $I_C$ (quiescent) ~ few mA;
choose $R_C$ to center $V_{OUT}$, given $I_C$
e.g. $V_{CC} = +10V$, $I_C = 2mA \Rightarrow R_C = 5V/2mA = 2.5K$

② choose $R_E$ to put $V_E \sim 1V$, for temperature stability
$\Rightarrow R_E = 1V/2mA = 500\Omega$

③ choose $R_1 // R_2$ such that $R_{IN}(\text{transistor}) \sim \beta \cdot R_E \gg R_1 || R_2$, so that the transistor does not load the bias network appreciably $\Rightarrow R_1//R_2 \ll 50K$

④ choose $R_1, R_2$ to put $V_B$ at $V_E + 0.7V = 1.7V$
$\Rightarrow$ use e.g. $R_2 = 5K$, $R_1 = R_2 \cdot \frac{8.3}{1.7} = 25K$
then $R_1 // R_2 \simeq 5K \ll 50K$

⑤ choose $R_3$ (if any) for AC gain
e.g. $R_3 = 100\Omega \Rightarrow \text{gain} = -R_C / (r_e + (R_E // (R_3 + Z_{C_2})))$

$\approx -R_C / (r_e + R_E // R_3)$

$\approx -2.5K / (\frac{25mV}{2mA} + 500\Omega // 100\Omega)$

$\approx -2.5K / 96\Omega \simeq -26$

⑥ choose $C_2$ for $f_{3dB} = \frac{1}{2\pi R C_2}$, where $R = R_3 + r_e = 113\Omega$.
So e.g. $20\mu F \Rightarrow f_{3dB} = 70Hz$

⑦ choose $C_1$ for $f_{3dB}$, where $R = R_1 // R_2 // \beta \cdot (R_E // R_3)$
$\sim 5K // 25K // 10K \sim 3K$

70 Hz to match (6) $\Rightarrow 0.75\mu F$, so we'll use $1\mu F$.

Let's try it in LTspice...

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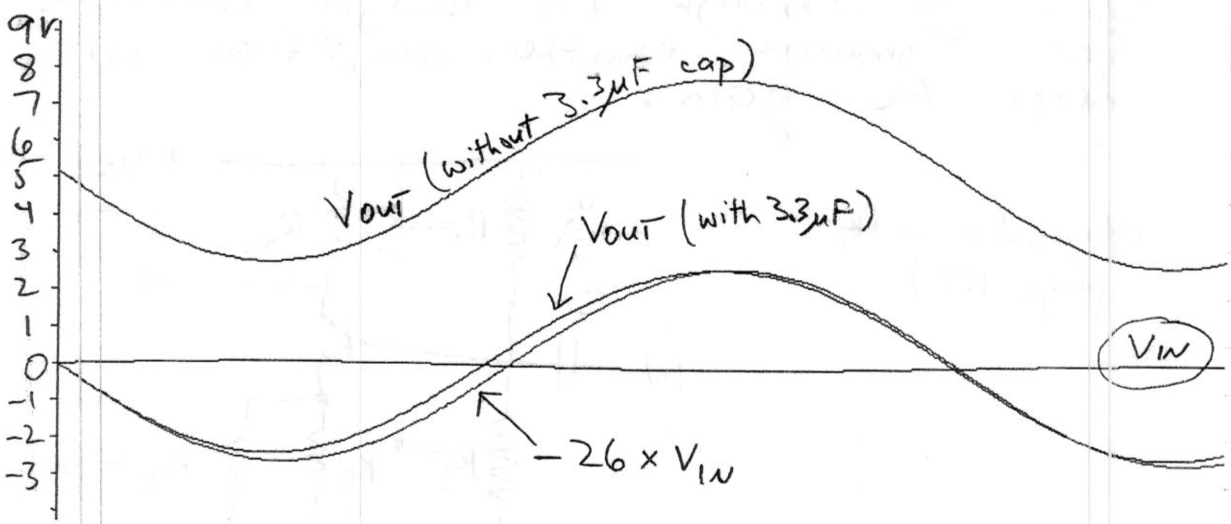
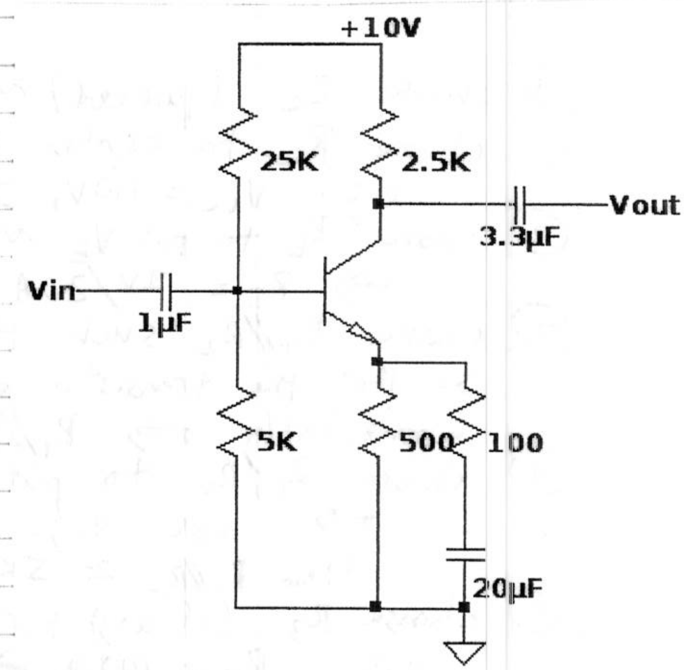
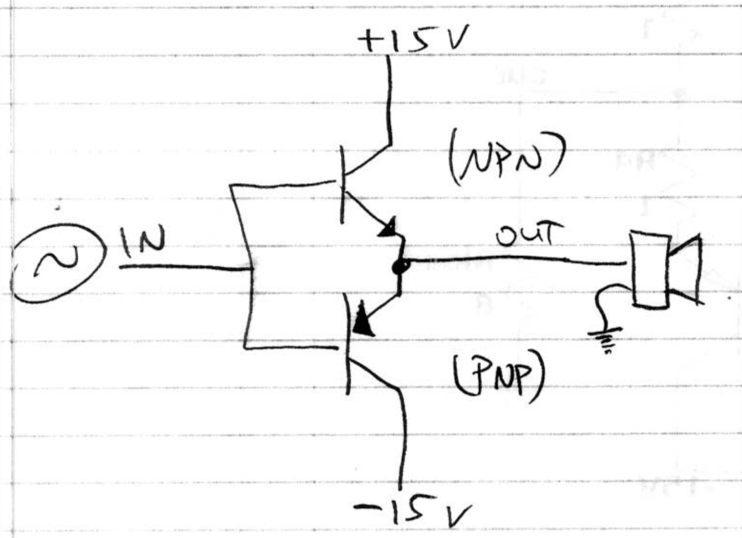
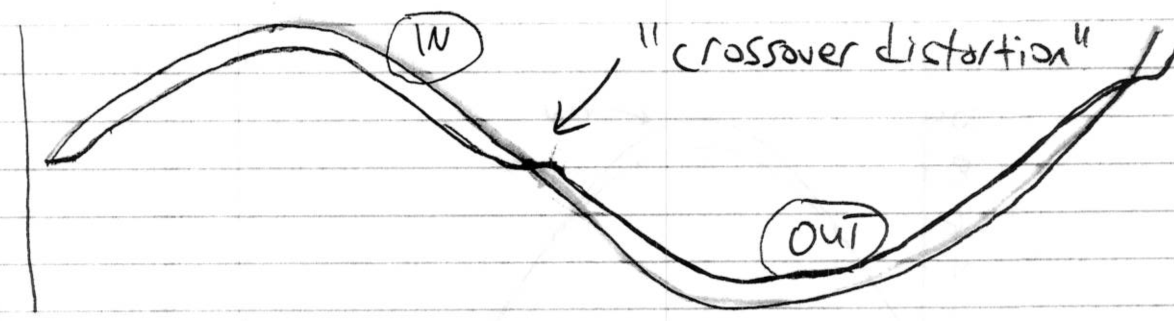


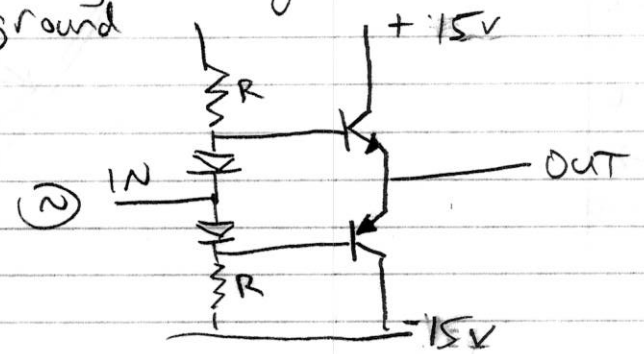
Now suppose you want to drive a big current through a speaker. HH example (§ 2.15, page 91, figure 2.54) shows problem with using an emitter follower: either you amplify only the positive half of the waveform, or else you bias the follower such that its quiescent power >> its useful power.

Solution: push-pull follower



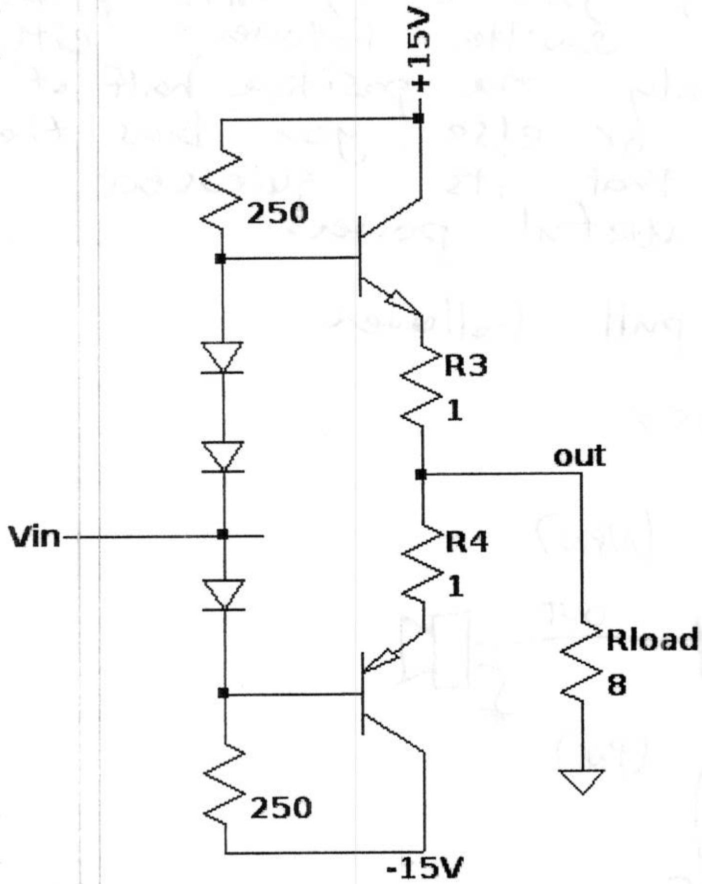



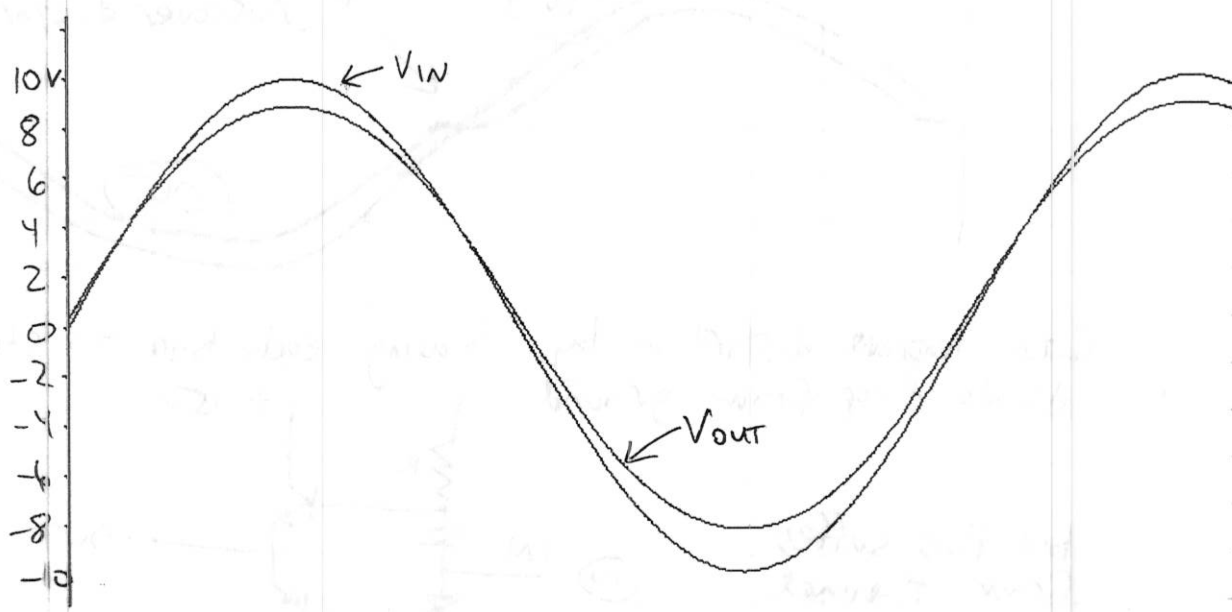

Can improve distortion by biasing each base to stay one diode drop from ground




but this suffers from thermal runaway problem

So in practice, your push-pull buffer probably looks something like this:



Next Monday, we'll look at a couple of additional BJT circuits, then we'll study Field Effect Transistors.

Note that I put LTspice models online for nearly all of the circuits in these notes.

due Thursday, 2010-10-21

# HOMEWORK for WEEK 6: (Borrowed from Harvard course)

Design a circuit that will deliver two outputs: one that looks like the input (except for a DC offset), and one that looks like an inverted version of the input (except that the DC level is whatever you think best). Such a circuit is called a "phase splitter."

Here are the specifications:

- power supply: $+25V$
- quiescent $I_c$: $2.5 mA$
- $R_{OUT}$ for signal source feeding your circuit: $\leq 100\Omega$
- $f_{signal} \geq 50$ Hz

Once your design is complete, evaluate the following, at signal frequencies:

- input impedance
- output impedance, at in-phase terminal (emitter)
- output impedance, at inverted-phase terminal (collector)
- largest input signal that can pass through your circuit without clipping

Now add a circuit fragment that will lower $R_{OUT}$ at the collector.

- What is the new $R_{OUT}$?