Transistors

ref. Horowitz & Hill Ch. 2

Prelude

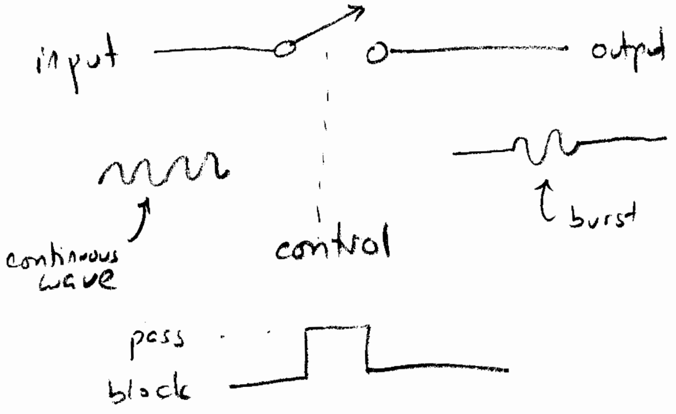
major uses of transistors

- switching } most common
- amplification }
- other, e.g., current source

kinds of electronic switches

analog, power, logic

analog switch - - either passes or blocks analog signal, ex: TV mute button



power switch

like analog, but for switching
high current, not signals
ex power on-off for instrument

logic switch

generate full swings between
two power supply voltages, typ. 0 & 5 V_{oH}

AND gate

Q = A AND B

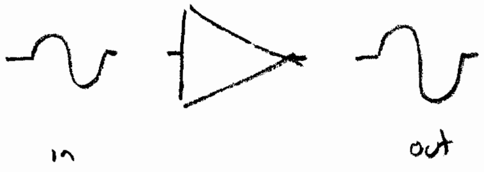
inputs		output
A	B	Q
0	0	0
0	1	0
1	0	0
1	1	1

↑ 1 = "TRUE" ⟷ voltages > 5V
0 = "FALSE $\hat{=}$ 0V ⟷ " < 0.8V

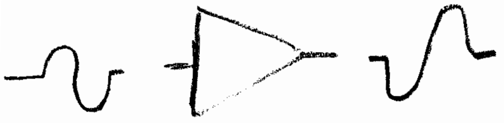
terminology for amplifiers

amplifier of gain 10
i.e., 20 dB

unity gain amplifier



"non-inverting"



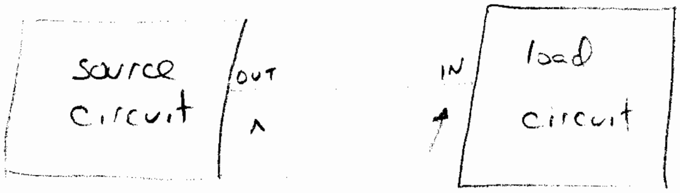
"inverting"

"follower" – like a unity-gain amplifier, but it might also add a dc offset to the output waveform

Impedances of Sources & Loads

↑ in lab
you learn to measure

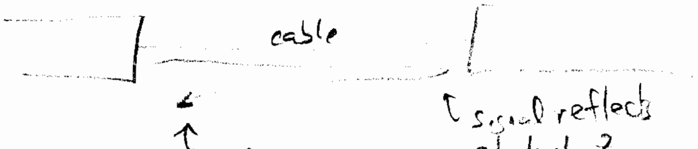
often, one connects two circuits together



usually
- you prefer $Z_{out} \ll Z_{IN}$
- to prevent "loading" of the source circuit, i.e., its output voltage diminishes due to sourcing or sinking lots of current
- ex source circuit is preamp w/ $Z_{out} = 100\Omega$
  load " is scope w/ $Z_{in} = 1M\Omega$

radio-frequency applications are exception

- desire $Z_{out} = Z_{in}$ (typically 50Ω)
- to prevent "reflections" of signal



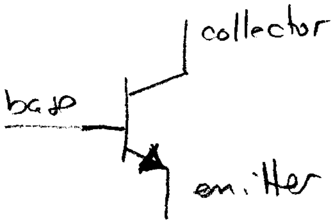
↑ signal reflects at high Z_{in}

↑ interference, due to finite λ at high freq.

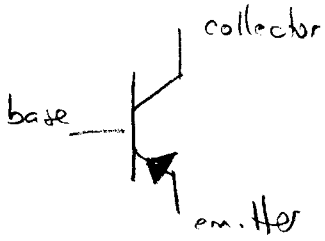
end of Prelude

Transistors - Basics

BJT = Bipolar Junction Transistor



npn
"not pointing in"



pnp

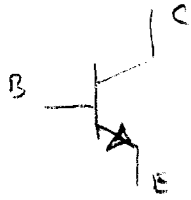
npn is more common

e.g. $\underbrace{2N}_{\text{transistor}}\underbrace{2222}_{\text{model}}$

We will use 3 models of transistor:

- "crude"
- "first model"
- "Ebers-Moll" ← a big model, but we will use only one tiny part

notation for transistors



voltages

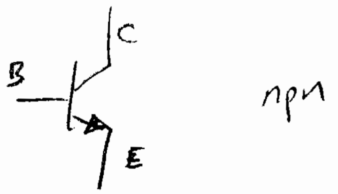
V_C, V_B, V_E	voltage on transistor terminals C, B, E
V_{CE}, V_{BE}	voltage drop between terminals
V_{CC}	positive power supply voltage
V_{EE}	negative .. .. ..

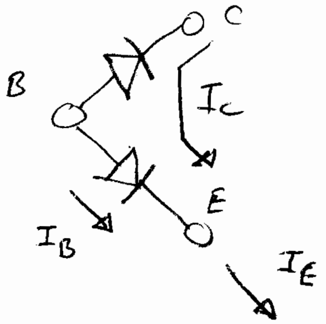
actually has nothing to do w/ the transistor itself.

currents

I_C, I_B, I_E	current flowing thru that lead of the trasistor

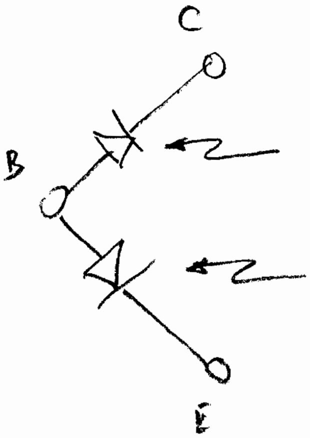
Crude Model of Transistor





$$I_E = I_C + I_B$$

- The collector current or the emitter " is usually what you use a transistor for
- The base current is much smaller, and is the input that is used to control I_C or I_E
- I_B is diode conduction, I_C is not



The C-B diode is usually reverse-biased, except in "saturation"

The B-E diode is usually forward biased, except in "cutoff"

First Transistor Model

Three modes of operation

- saturated (ON)
  I_C is big
- cutoff (OFF)
  I_C is zero

used for switches

- active region
  $I_C = h_{FE} I_B$

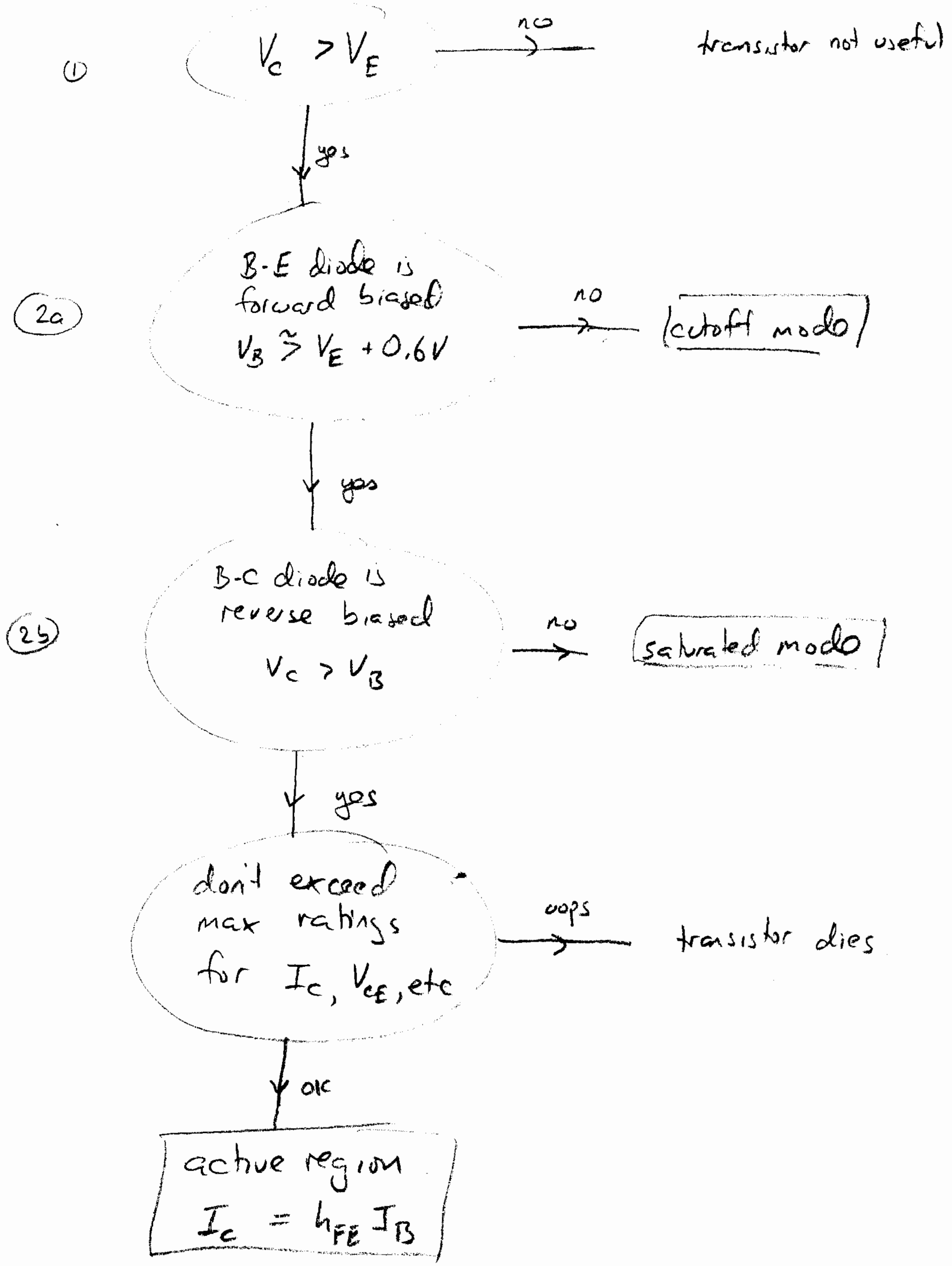
used for amplifiers

also called:

- "linear mode of operation"
- "normal"
- "small signal" applications

Rules to use transistor in active region

condition



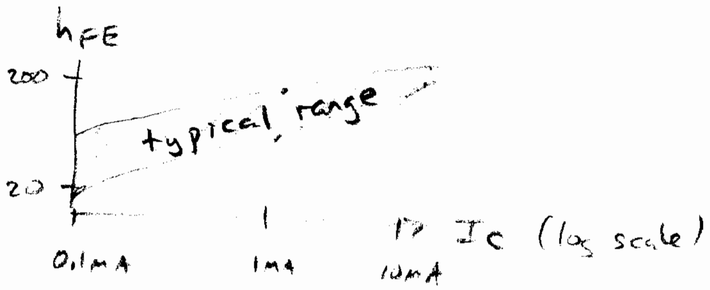
Transistor Beta

- $h_{FE} = \beta =$ "beta"

- varies from one transistor to another, mfg. variations

- typically ≈ 100

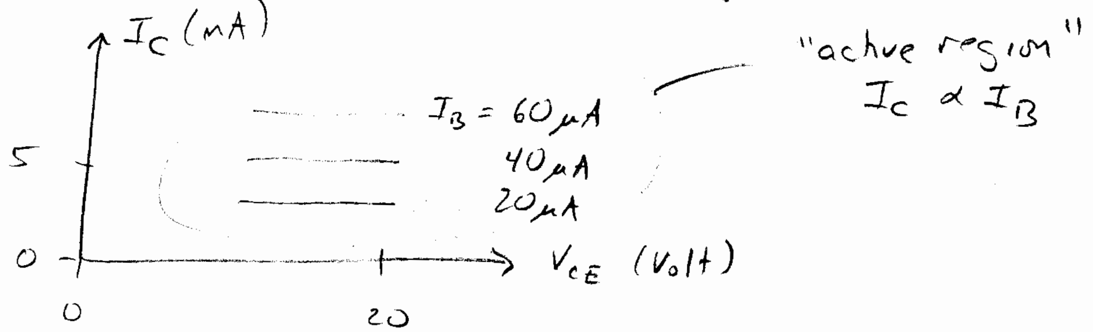
ex 2N4400 (Fig. 11, Appendix K, H&Hill)



note:
- h_{FE} such a poor parameter, the mfg provides no ± tolerance

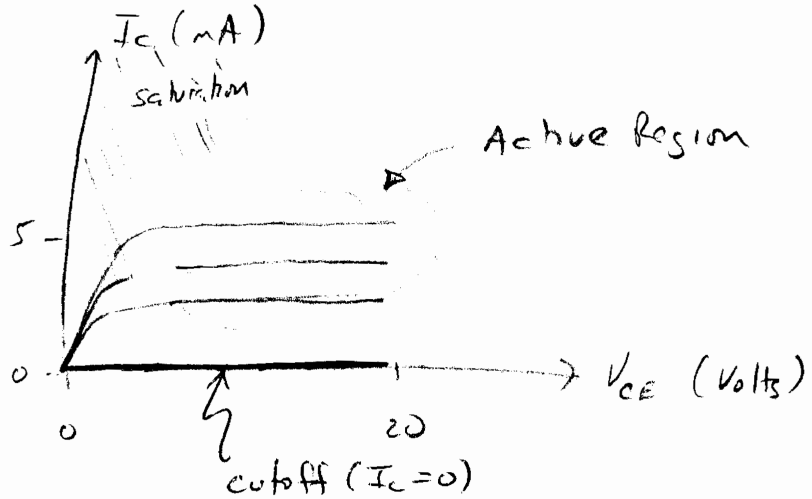
- h_{FE} actually depends slightly on I_C so $I_C = h_{FE} I_B$ isn't actually perfectly linear

- best to design circuits so they don't depend critically on h_{FE} value more on the "First Transistor Model":



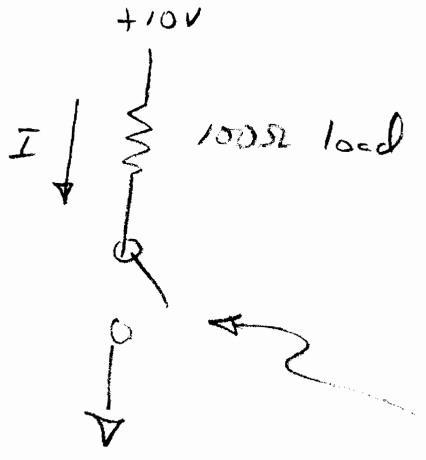
(a partial graph of NPN characteristics

now add more detail:



Using BJT transistor as a power switch

as in lab #4



replace w/ transistor

we expect a current of $I = \frac{10V}{100\Omega} = 100\,mA$

ok for BJT
like 2N2222
or 2N4400

If you need to switch lots more current,
it's better to use a "power MOSFET",
later in course.

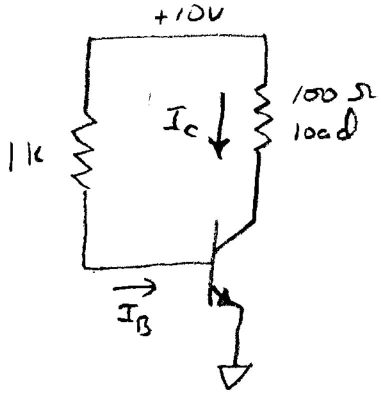
BJT Transistor Switch

ON = switch closed

use "saturated mode" by applying

lots of base current $I_B \approx 10mA$

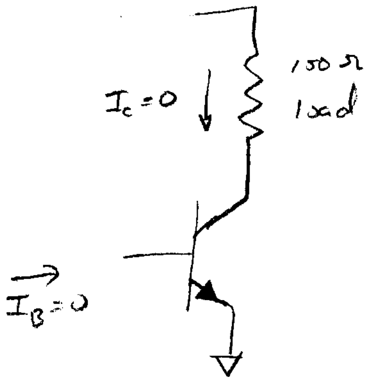
we'll show how to find this



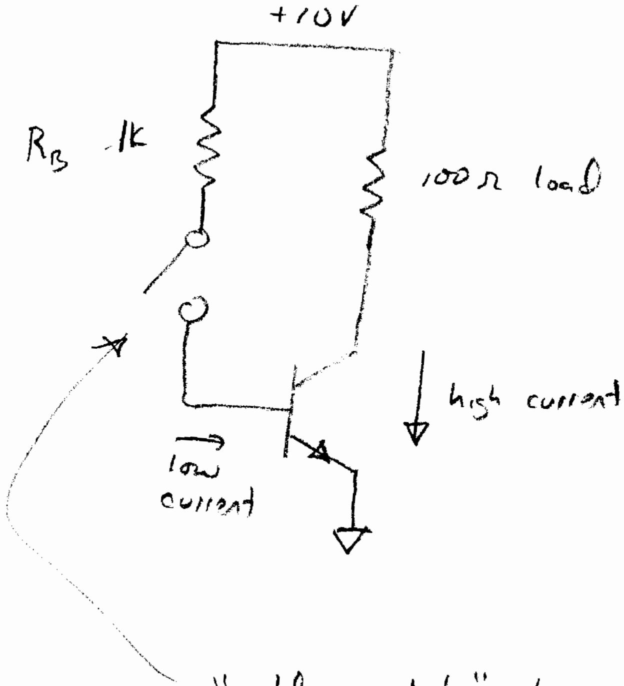
OFF = switch open

use "cutoff mode" by applying zero base current

$I_B = 0$



Complete circuit



"cold switch" to operate transistor switch

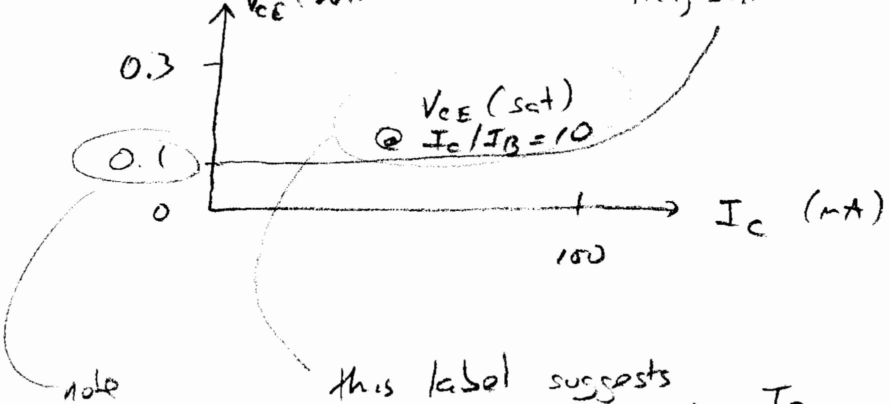
↑ advantages, it allows:

- switching bigger currents than mechanical switch's rating
- Locating control switch remotely, far from high-current circuitry

How to be sure of operating in cutoff mode?

See mfg datasheets, look for hidden label in graph:

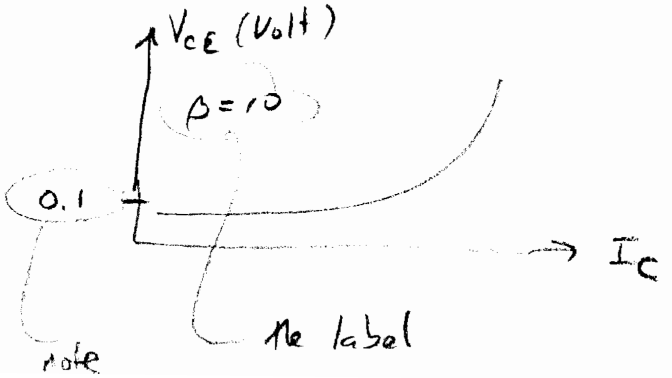
ex. 1 2N4400
Appendix K of H & Hill
in Fig. 17 for "ON voltages"
i.e., saturation



this label suggests designing so that $\frac{I_C}{I_B} \cong 10$ to achieve saturation

ex. 2 fairchildsemi.com
datasheet for 2N4400

graph "Collector - Emitter Saturation Voltage vs. Collector Current"



so, from data sheet figures:

- we desire $\frac{I_C}{I_B} \gtrsim 10$ to assure that we operate in the saturated mode
- under these conditions, we expect $V_{CE} \approx 0.1$ Volt

How to analyze:

we want to find R_B

what we know:

2 resistors ⇒ use Ohm's Law 2×

transistor in saturation ⇒ $\frac{I_C}{I_B} \gtrsim 10$ desired

$V_{CE} \approx 0.1\,V$ expected

$V_B - V_E \approx 0.6\,V$ typical

combine these to find R_B

$$R_B = \frac{\text{voltage drop across } R_B}{\text{current thru } R_B}$$

$$= \frac{10V - V_B}{I_B}$$

? 0 connected to GND

$$= \frac{10V - (V_E + 0.6V)}{I_B}$$

$$\odot \quad = \frac{9.4V}{I_B}$$

Find I_B, using $I_C / I_B \cong 10$ desired

$$I_B \cong 0.1\, I_C$$

I_c = current thru load resistance of 100Ω

$$= \frac{\text{voltage drop across load}}{100\Omega}$$

$$\cong \frac{10V - V_c}{100\Omega}$$

$$= \frac{10V - \overset{\approx 0.1 \text{ volt in saturation}}{(V_c - V_E)} - \overset{0 \text{ connected to GND}}{\cancel{V_E}}}{100\Omega}$$

$$\cong \frac{9.9V}{100\Omega}$$

$$\cong 99mA$$

$$\Rightarrow I_B \cong 0.1 I_c \cong 9.9 mA.$$

↑ plug into ⊙ above

$$R_B \cong \frac{9.4V}{9.9mA} = 949\Omega$$

↑ choose std value within 5% $1k\Omega$

$$\boxed{R_B = 1k}$$

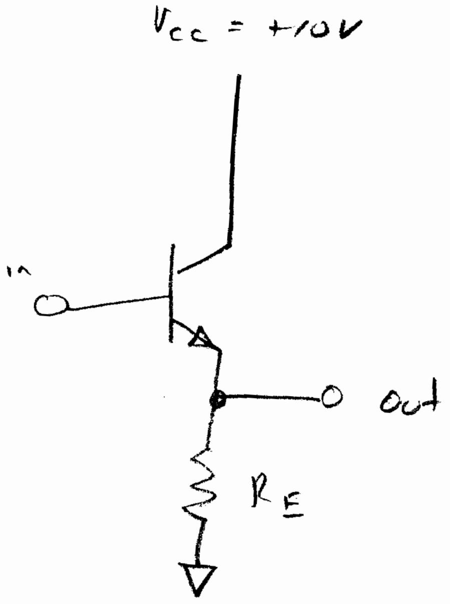
↑ the std value resistance to choose to assure operating in saturation

end of transistor switch

Now, an amplifier application of BJT

$\hookrightarrow$ operate BJT in active region

Emitter Follower



to analyze, we can use:

transistor $\Rightarrow$ use "first model" rules

resistor $\Rightarrow$ Ohm's Law (not needed here, but used later)

$$\begin{array}{ccc} V_E & = & V_B - 0.6 \text{ Volt} \\ \| & & \| \\ V_{out} & & V_{in} \end{array}$$

$$\Rightarrow \boxed{V_{out} = V_{in} - 0.6 \text{ Volt}}$$

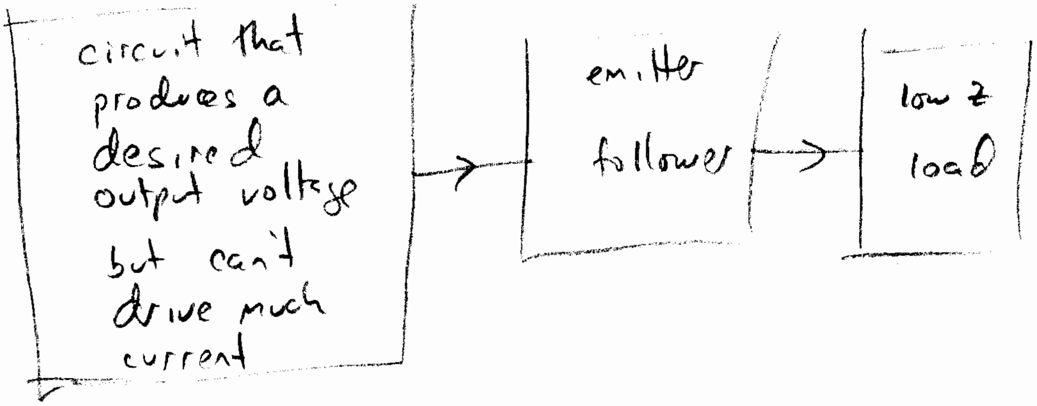
- this circuit has <u>no voltage</u> gain
  (it merely applies a dc bias to the output voltage)

- it can provide current gain,

because it has $\frac{\text{input impedance}}{\text{output \ \ "}} > 1$

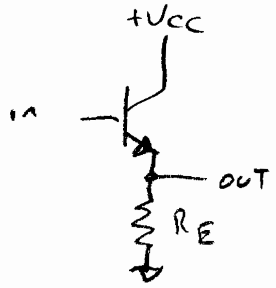
- you will measure in lab 4
- calculated below

useful to:
- drive low Z loads
- add to the output of a voltage source to make it "stiffer", i.e., less affected by "loading"



demo multisym :
- demonstrate "clipping" with emitter follower
- terminology: "rails"

Calculate impedances of emitter follower for ac signals



output impedance Z_{OUT}

easy, because circuit output is connected directly to a power supply by a single resistor R_E

$\Rightarrow Z_{OUT} = R_E$

input impedance Z_{IN}

harder

$$Z_{in} = \frac{V_{in}}{I_{in}}$$

$$= \frac{V_B}{I_B}$$

however, here we need an impedance for ac signals only recall notation for ac signals:

if $$V(t) = \underset{\substack{\uparrow \\ \text{dc} \\ \text{bias}}}{2V} + \underset{\substack{\uparrow \\ \text{ac} \\ \text{amplitude}}}{5V} \sin(\omega t)$$

$$v(t) = 5V \sin \omega t$$

↑ lower case denotes ac portion of signal

same for $i(t)$

so we seek

$$z_{in} \equiv \frac{v_B}{i_B}$$

find a relation between v_B, i_B using "first model" rules + Ohm's Law

$$I_E = I_C + I_B$$

$$\uparrow \quad I_C = h_{FE} I_B \quad \text{in active region}$$

$$\uparrow \quad I_E = \frac{V_B - 0.6V}{R_E} \quad \text{Ohm's Law for } R_E$$

combine →

$$\frac{V_B - 0.6V}{R_E} = (1 + h_{FE}) I_B$$

keep only ac portion

$$\frac{v_B}{R_E} = (1 + h_{FE}) i_B$$

$$\Rightarrow Z_{in} = \frac{v_B}{i_B}$$

$$= (1 + \underbrace{h_{FE}}_{\gg 1}) R_E$$

$$\boxed{Z_{in} \simeq h_{FE} R_E}$$

so $Z_{in} \gg Z_{out}$ by factor of $h_{FE} \sim 100$

for emitter follower

Transistor Current Source

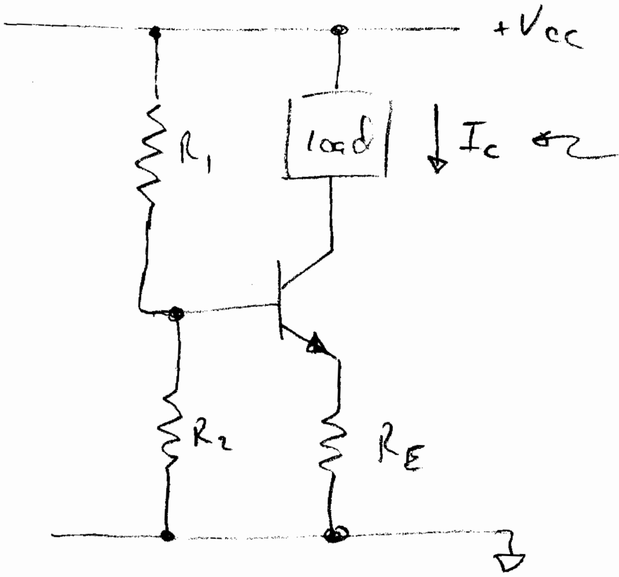
recall: "current source" provides constant desired value of output current, regardless of the voltage it must output

previous current source we considered (Lab 1)

voltage source + big resistor

Pros: easy

Cons: very sensitive to load impedence



← the current we wish to control

To analyze:

- Transistor "First Model" Rules for active region
- Resistors: voltage divider or Ohm's Law

transistor rules:

$$V_E = V_B - 0.6\,V$$

$$I_E = I_C + I_B$$

$$= (1 + h_{FE}^{-1}) I_C$$ in active region

$$\cong I_C$$

Ohm's Law for RE

$$I_E = \text{current thru } R_E$$

$$= \frac{V_E - 0}{R_E}$$

Combine:

$$\boxed{I_C \cong \frac{V_B - 0.6\,V}{R_E}}$$ output current thru Load

voltage divider R_1, R_2 is used to establish V_B

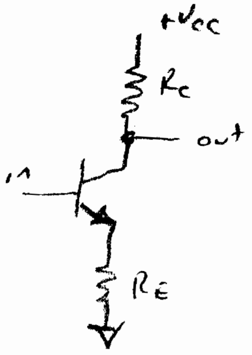
note: good circuit design:
the desired output I_C
depends sensitively only on the
supply voltage & resistances,
which are good parameters,
not on transistor parameters
h_{FE} which are not reliable

Common Emitter Amplifier

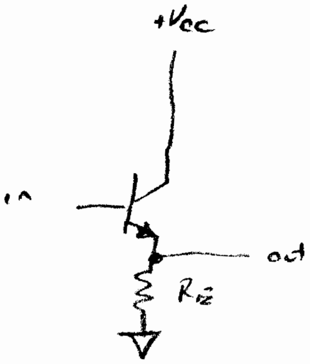
- a voltage amp, uses BJT in active region
- used mainly for AC signals

Compare to Emitter Follower

Common Emitter



Emitter Follower



Purpose:	voltage gain	drive a low-Z load
Details:	has collector resistor	has none
	output on collector	output on emitter
	$Z_{in} \approx Z_{out}$	$Z_{in} >> Z_{out}$

Parameters of interest for amplifiers

Gain ← most Important

Maximum Output (Amplitude or Power)

Freq. Response (e.g., gain is constant ± 3dB for 20Hz < f < 20kHz)

Z_{in}

Z_{out}

Power Consumption

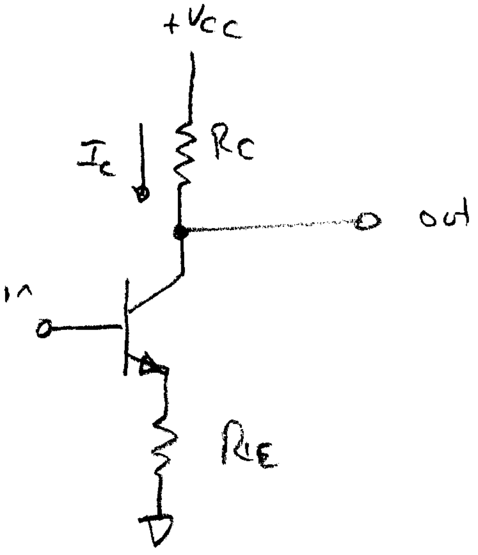
Analyze common emitter amp to find AC gain $A_v = \frac{v_{out}}{v_{in}}$

First, assess what's involved

- collector resistor ⇒ Ohm's Law
- emitter " ⇒ " "
- transistor ⇒ First Model
- node at output ⇒ Kirch. Current Law

↑ here, we ignore if output is connected only to a high Z load

Next, write corresponding equations



collector resistor: $(V_{cc} - V_{out})/R_c = I_C$ (1)

emitter: $(V_E - 0)/R_E = I_E$ (2)

transistor (First Model, active region): $\left.\begin{array}{l} V_E = \underset{\uparrow = V_{in}}{V_B} - 0.6\text{ Volt} \end{array}\right\}$ (3)

$I_E = I_C + I_B$ (4a)

$= I_C(1 + h_{FE}^{-1})$ (4b)

Then, find V_{out}, V_{in}

$V_{out} = V_{cc} - I_c R_c$ from (1)

$v_{out} = -i_c R_c$ ac part

$$V_{in} = V_B$$

$$= V_E + 0.6 \text{ Volt} \qquad \text{from (3)}$$

$$= I_E R_E + 0.6 \text{ Volt} \qquad \text{from (2)}$$

$$= I_C(1+h_{FE}^{-1}) R_E + 0.6 \text{ Volt} \qquad \text{from (4b)}$$

$$v_{in} = i_C(1+h_{FE}^{-1}) R_E \qquad \text{ac part}$$

Finally, calculate gain for ac signals:

$$A_V = \frac{v_{out}}{v_{in}}$$

$$= - \frac{\cancel{i_c} R_C}{\cancel{i_c} R_E(1+h_{FE}^{-1})}$$

↑ good that amplifier's gain does not depend on an amplitude like i_c

$$= - \frac{R_C}{R_E(1+h_{FE}^{-1})}$$

↑ $h_{FE} \approx 100$, $h_{FE}^{-1} \approx 0.01$

Good circuit design:
The most important circuit parameter (here, gain) depends sensitively only on reliable parameters (here, resistances) not on bad parameters (h_{FE})

Result:

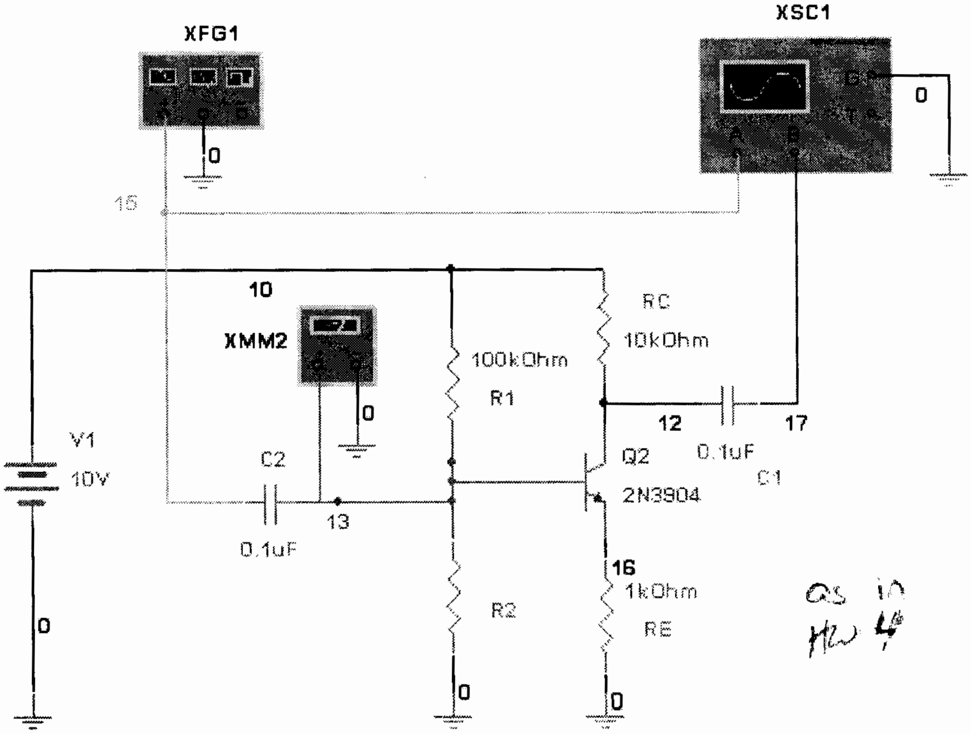
$$\boxed{A_v \cong -\frac{R_C}{R_E}}$$ AC gain of common-emitter amp

↑ note: gain < 0

⇒ inverting amp.

multisym demo

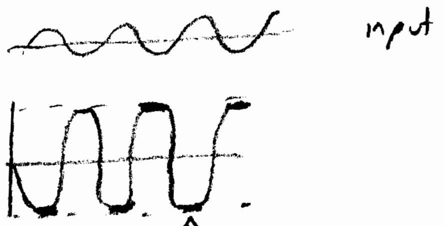
1. demonstrate gain = $-R_C/R_E$
   ↑ inverted
2. " clipping



as in HW 4

demo: clipping of CE amp

1) increase input amplitude, observing clipping on output, equally at top & bottom of waveform



↖clipping ⇔ flattened waveform at peak

2) vary biasing resistor R2, observe output clips first on its top or bottom, not equally on top & bottom, if R2 is not chosen optimally

(you will do this in hw 4)

Common-Emitter Amp -
How to choose biasing resistors

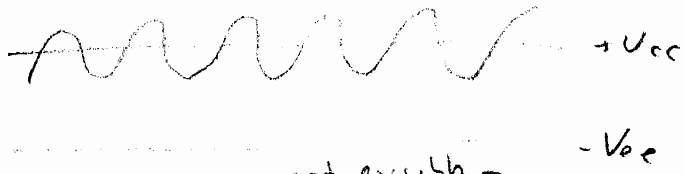
- The biasing resistors establish the dc bias of the transistor's base, which in turn establishes the dc bias of the transistor's emitter & collector.

- Discuss. Which poses a greater problem: the dc bias of base
  or " " " " collector?

Consider that the output waveform (on the collector) has a larger amplitude than the input waveform on the base, due to gain.

Also consider that all waveforms must fit "within the rails", i.e. between the + & - power-supply voltages.

possible



not possible — clipping will occur instead

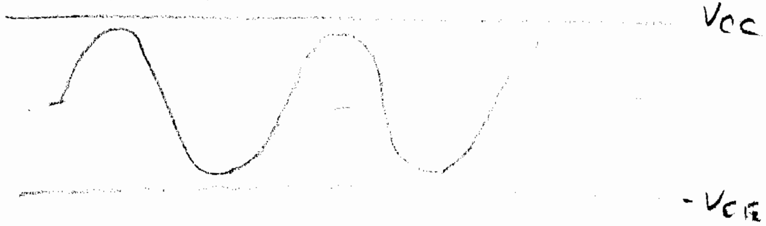
The output amplitude is bigger, so it poses the greater problem to fit its wave form between the rails.

Discussion of bias, continued

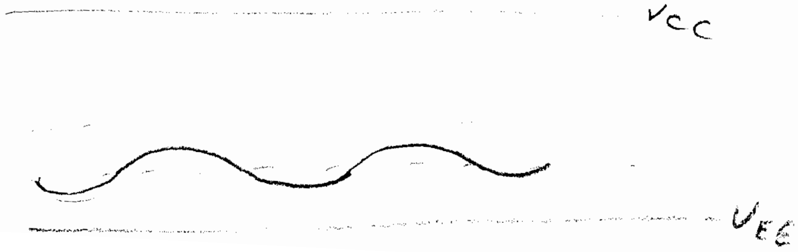
- So, given a choice of centering the output waveform or centering the input " between the rails, we choose to center the output waveform so that we make maximum use of the available power supply

- Note that the dc bias on the input (base) and output (collector) are *not* the same. (This is a commm student error.)

output – (centered between rails)



input (not necessarily centered)



Discussion of b~~[illegible]~~iased

- in HW4, you will calculate value of R2 to achieve a bias on the base that yields a collector bias that's halfway between the rails.

- how you'll do it (problem 1(a), HW4) work backwards, including these steps
  - you desire $V_C = \frac{V_{cc} - 0}{2}$ (halfway between rails)
  - Ohm's Law for $R_C \rightarrow I_C$ value
  - Transistor Model $\Rightarrow I_C \approx I_E$ yields I_E value
  - Ohm's Law for $R_E \rightarrow V_E$ value
  - Transistor Model $\Rightarrow V_B \simeq V_E + 0{,}6V$ yields V_B value
  - Voltage divider R_1, R_2 must be designed to provide this desired V_B

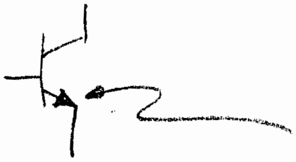
You will then use Multisym to test your predicted value of the optimal R_2

Beyond the "First Transistor Model"

"Ebers-Moll" - a big model

- we'll use only one part of it:

Transistor's Intrinsic Emitter Resistance



inside the BJT
there is an
"intrinsic emitter resistance"

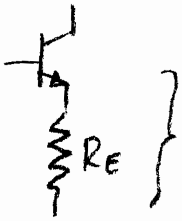
$$r_e \cong \frac{25}{I_c(\text{mA})}$$

depends on Temp

ex. if $I_c = 1\,\text{mA}$, $r_e = 25\,\Omega$

This intrinsic emitter resistance appears in series with any components connected to the emitter.

ex.



behaves like $R_E + r_e$

So the gain of a C.E. Amp is really

$$A_V = -\frac{R_C}{R_E + r_e}$$

How to get more gain from a C.E. Amp

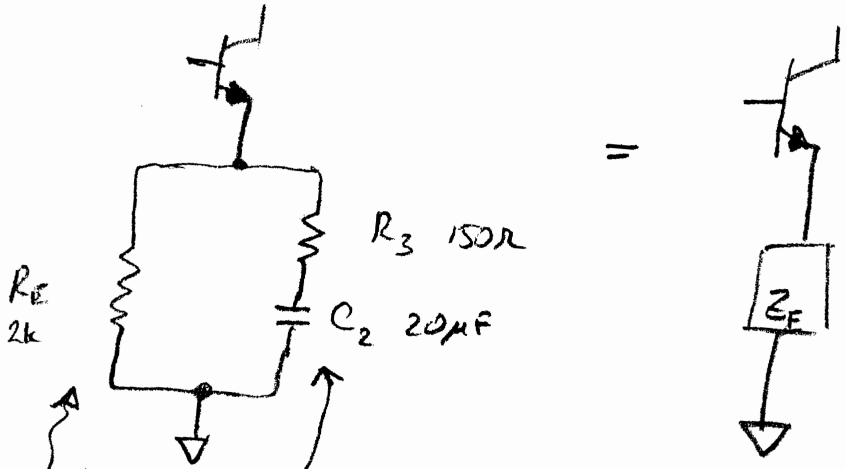
- Two obvious ideas are bad:
  - make R_E small

    (bad because dc, i.e., quiescent current, will depend critically on r_e, temp ⇒ unstable).
  - make R_C big

    (bad because $Z_{out} \approx R_C$ for C.E Amp, & we prefer a small Z_{out}, as always).
- Clever trick: "emitter-bypass"

  you'll do it in the Transistor II lab.

emitter bypass



capacitor blocks dc, allows ac to pass

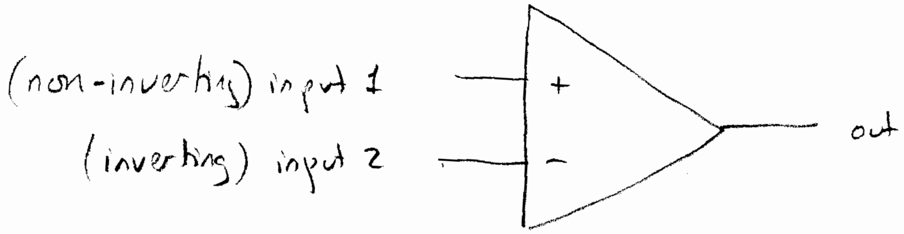
big emitter resistor provides stable dc (quiescent) current

this combination provides a big ac gain $A_v = -\frac{R_c}{R_3 + r_e}$

but a stable dc operation

multisim demo

Differential Amplifiers

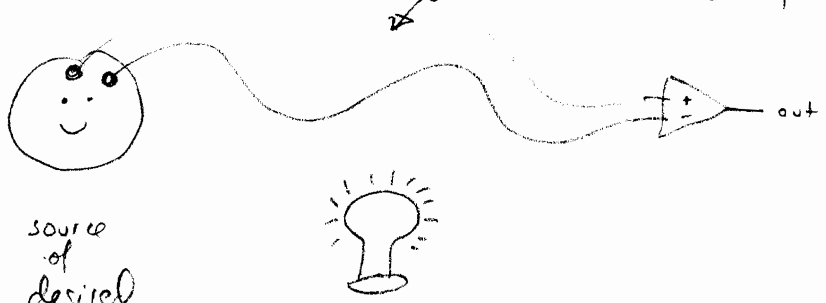


$$V_{out} = A_v^{diff} \left(V_{in1} - V_{in2} \right)$$

↑ differential gain

Q. Why use a differential amp?

A. To eliminate "common-mode noise", i.e., features in the input waveforms that are identical for both inputs



wires act like antennas, receiving "pickup noise"

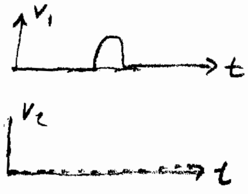
source of desired signal

source of 60-Hz, influences both inputs equally
"common-mode"

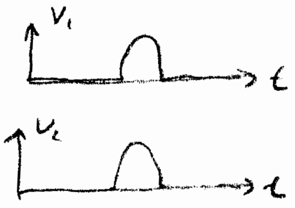
CMRR - common-mode rejection ratio

a figure of merit for how good a differential amplifier is

define:



"normal mode" inputs

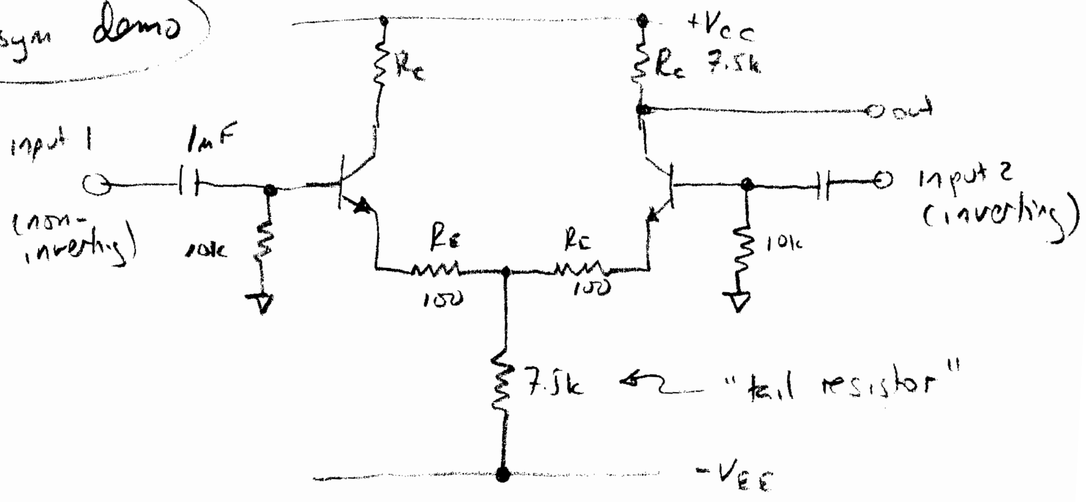


"common mode" inputs

$$\text{CMRR} = \text{ratio} \; \frac{\text{amplifier output for normal mode input}}{\text{'' \quad '' \quad '' common '' \quad ''}}$$

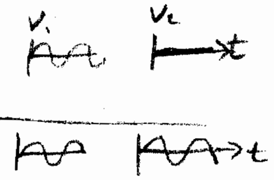
$$= \frac{A_v^{diff}}{A_v^{common}}$$

multisym demo



differential amplifier demo, cont.

$$\text{CMRR} = \frac{\text{output for normal mode}}{\text{'' \quad '' \quad common mode}}$$



$$= \frac{2.72\,\text{V}}{0.0485\,\text{V}}$$

$$= 56$$

$$20 \log_{10} 56 = 35\,\text{dB}$$

For comparison, a really good differential amp. has CMRR $= 10^6 \rightarrow 120$ dB

Q. why isn't the common-mode gain zero?

A. $A^{\text{common}} \sim R_C/R_T$ & R_T is finite
$A^{\text{diff}} \sim R_C/2R_E$
} see text.

show differential amplifier for biomedical use