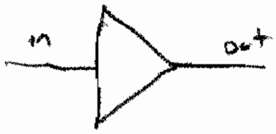
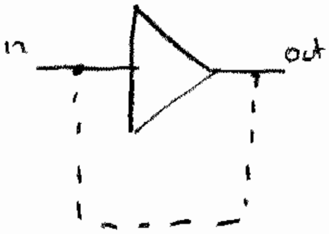
Horowitz & Hill Chap 4 Op-Amps

Feedback Concept



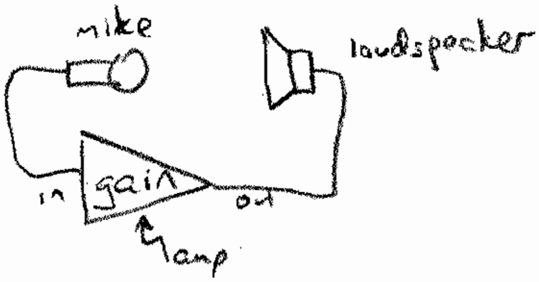
amplifier with no feedback



amplifier with feedback
(some of the output is
applied to the input)

positive feedback:

- feedback causes the input to be enhanced
- ex.



- a waveform travels around the loop (including sound wave in air) becoming bigger each time
- result: whistling noise, i.e., oscillation at the frequency where gain is highest.

negative feedback

- feedback causes the input to be diminished
- results in less overall gain,
  but:
  - better frequency response
  - better linearity
  - avoids oscillation

in general, negative feedback is desirable for amplifier circuits

positive feedback is used for oscillators

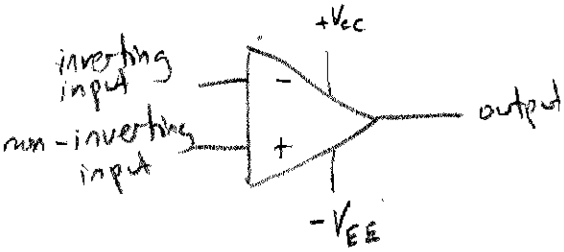
Op-Amps

"Operational Amplifiers"

It's a differential amplifier, on a chip

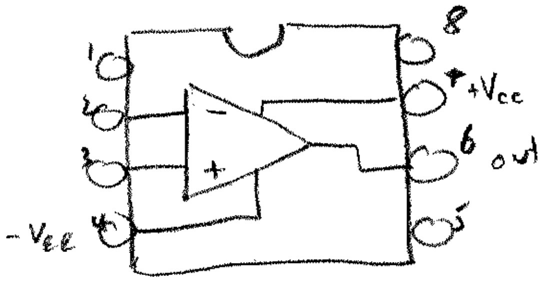
"chip" = "IC" = "Integrated Circuit"

Schematic symbol



↑ power supply voltages are typically ±12V or ±15V

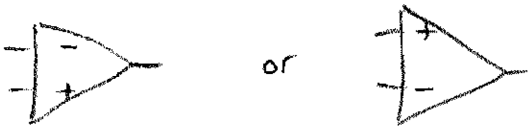
Pin diagram



8-pin DIP package

some pins on chip are not used

it's okay to draw the symbol upside down



Major things to know about opamps

- it's a differential amplifier
- high input impedance
  (inputs draw little current)
- low output impedance
  (output can source current, although not as much as a power transistor)

Open-loop behavior

If you do not provide external feedback, an op-amp's output will simply swing to one of the power-supply "rails":

If $V_+ > V_-$, $V_{out} \to +V_{CC}$

If $V_+ < V_-$, $V_{out} \to -V_{EE}$

This is like a comparator (see later in this chapter).

Three Op-Amp Rules (ideal op amp)

⓪ Check for feedback loop

- If you provide an external feedback network with negative feedback, then rule ① below will apply.
- Otherwise, the open-loop behavior mentioned above occurs

① $V_{OS} = 0$

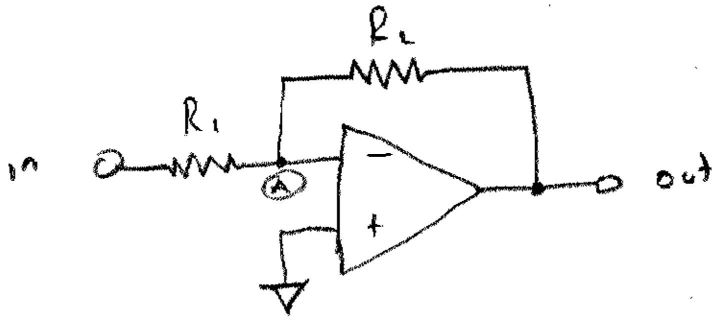
- The difference between the two input voltages $V_{os} \equiv V_+ - V_-$ will be zero.
- This is achieved through the negative feedback mechanism — the op-amp's output voltage will swing to whatever output " is required to achieve $V_+ = V_-$ on the inputs.

② $I_{bias} = 0$

The two inputs draw no current

exception to rule ①.
The output voltage cannot exceed the power supply voltages. Clipping of the output waveform will occur.

Inverting Amplifier



To analyze, we will follow our usual strategy:

- identify components & nodes
- write equations for these
- combine to eliminate variables
- solve for the desired parameter

What is the desired parameter?

For amplifiers, gain is the most important parameter.

other parameters of interest include: input impedance
output "
frequency response
power-supply requirements

Here we will solve for gain:

$$A_v = \frac{V_{out}}{V_{in}}$$

identify components & nodes:

Opamp ⇒ 3 rules

resistors ⇒ Ohm's Law or voltage divider rule

node A ⇒ Kirchoff's current law

Rule ⓪ ✓ neg. feedback is provided thru R_2

Rule ① $V_+ = V_-$

here we see that $V_+ = 0$ because that input of the opamp is connected directly to ground

another name for V_- here is V_A because that input of the opamp is connected to node Ⓐ.

$\Rightarrow V_A = 0$

Rule ② op-amp inputs draw no current.

here we combine this with Kirchoff's current law for node Ⓐ to see that: all the current flowing thru R_1 into node Ⓐ must also flow out of node Ⓐ thru R_2

i.e. $I_{R_1} = I_{R_2}$

Ohm's Law:

$$I_{R_1} = \frac{V_A - V_{in}}{R_1}$$

$$I_{R_2} = \frac{V_{out} - V_A}{R_2}$$

examine the circuit diagram to see why this is the correct voltage drop across the resistor

we've now exhausted our list of components & nodes that required equations

$\Rightarrow$ next step is to combine the equations, eliminating variable to yield an expression for the desired quantity, $\frac{V_{out}}{V_{in}}$.

$$I_{R_1} = I_{R_2}$$

$$\frac{V_A - V_{in}}{R_1} = \frac{V_{out} - V_A}{R_2} \quad ; \text{ use } V_A = 0$$

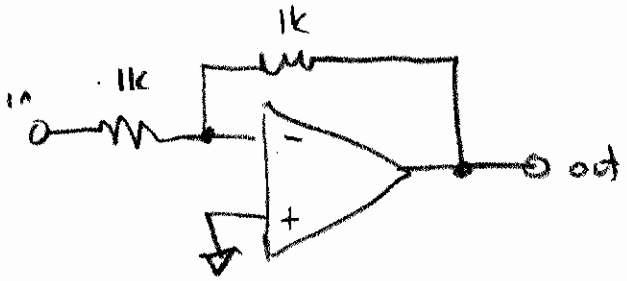
$$-\frac{V_{in}}{R_1} = \frac{V_{out}}{R_2} \quad ; \text{ rewrite}$$

$$\boxed{\frac{V_{out}}{V_{in}} = -\frac{R_2}{R_1}}$$

Note: you should be able to duplicate this kind of analysis yourself.

multisym demo

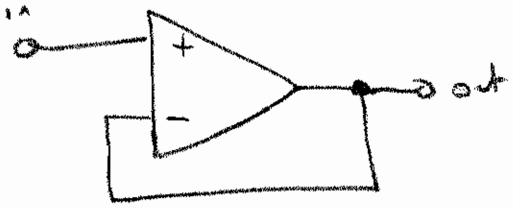
Unity Gain Inverter



$$\frac{V_{out}}{V_{in}} = -1$$

discuss usefulness of this.

Follower



Analyze: list components & nodes:
op-amp. nothing else

list equations:

⓪ neg feedback ✓

① $V_+ = V_-$

Here, $V_- = V_{out}$

Here, $V_+ = V_{in}$

Because these inputs are connected directly to the circuit input & output

② next page

② op-amp inputs draw no current

Here, the only significance of this is that the circuit's input impedance will be the same as the op-amp's (since they are directly connected)

⇒ amplifier circuit's $Z_{in} \to \infty$ which is a good thing

From rule ① →

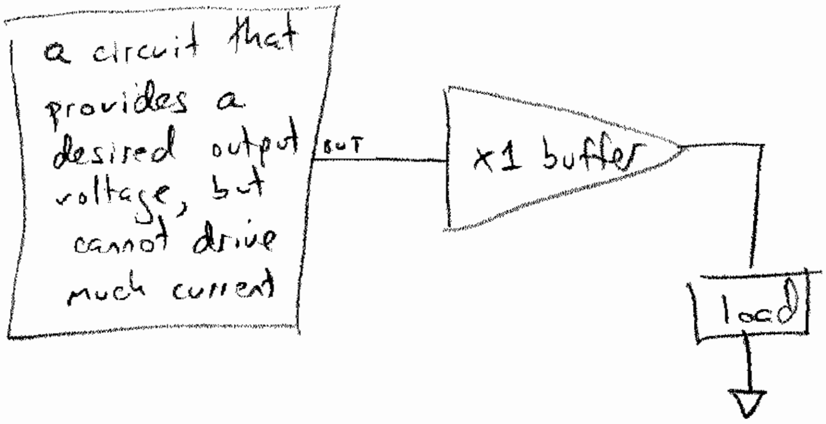
$\boxed{V_{out} = V_{in}}$ "follower"

Discuss comparison to emitter follower

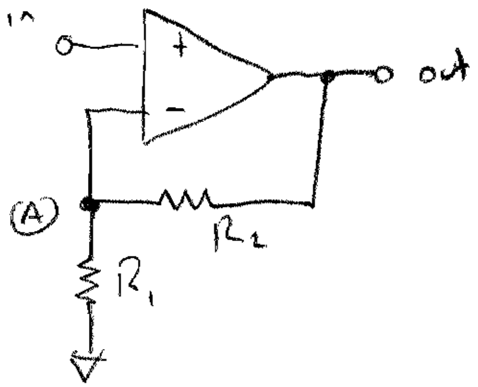
Discuss use: • has: high Z_{in}

low Z_{out}

• use it as a "buffer"



Non-inverting Amp



Analyze:

identify components & nodes:

op amp ⇒ 3 rules

2 resistors ⇒ Ohm's Law or Voltage Divider rule

node Ⓐ ⇒ Kirch. Current Law

easier, here

write equations

rule ⓪ ✓ neg feedback thru R_2

rule ① $V_+ = V_-$

Here, $V_- = V_A$

Here, $V_+ = V_{in}$

$\Rightarrow V_{in} = V_A$

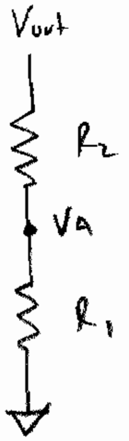
rule ② op-amp inputs draw no current

combine with Kirchoff's Current Law

⇒ all current thru R_2 must also flow thru R_1

we could use Ohm's Law for the two resistors, although doing so here would ultimately just re-derive the voltage divider rule, so we'll just use the ~~vo~~ " " " directly

Redraw the R_1 - R_2 network like this:



where we have exploited the fact that no current flow from node Ⓐ to the op-amp - input

use voltage divider rule:

$$V_A = V_{out} \frac{R_1}{R_1 + R_2}$$

combine with Rule 1 result $V_A = V_{in}$ →

$$V_{in} = V_{OUT} \frac{R_1}{R_1 + R_2}$$

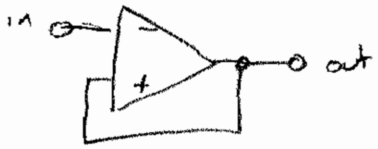
$$\boxed{\frac{V_{OUT}}{V_{in}} = 1 + \frac{R_2}{R_1}}$$

gain is pos ⇒ non-inverting

discuss how gain < 1 is not achievable here

Bad Op-Amp Circuits

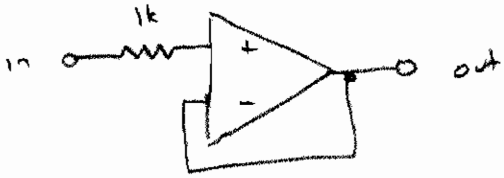
①



Q. Will this work as a buffer?

A. No. Although op-amp rule #1 would indicate that $V_{out} = V_{in}$ as desired for a buffer, this circuit has a fatal flaw because feedback is positive, violating rule #1.

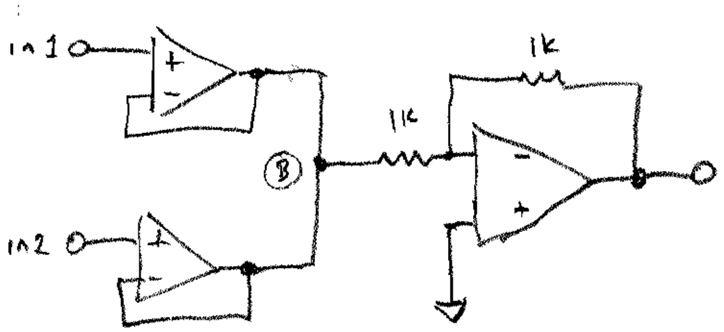
②



Q. Will this work as a buffer?

A. Yes, but the circuit has a non-fatal design error: The 1k resistor serves no purpose. A resistor is useful only if current passes through it, but because of op-amp rule #2 no current will flow through this one, so that no voltage drop will appear across it. You might as well replace it with a wire.

③

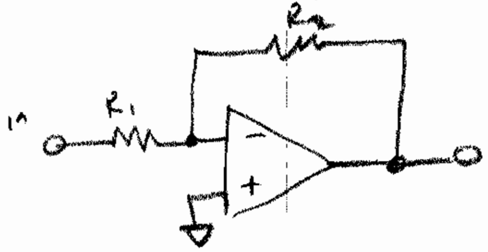


Q. will this circuit work as a voltage adder?

A. No - design has a fatal design error: two outputs are connected directly together at node Ⓑ.

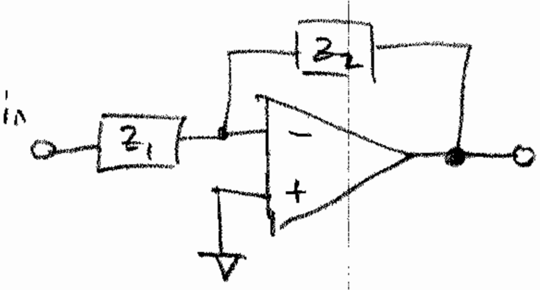
Active Filters using Op-Amps

First, recall inverting amp, using resistors:



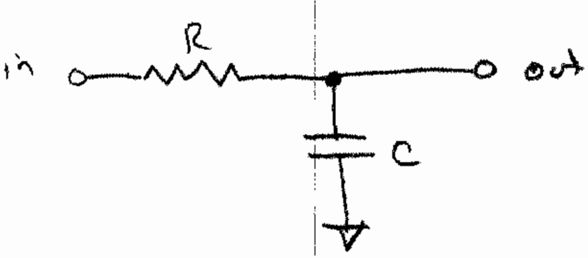
$$V_{out} = -\frac{R_2}{R_1} V_{in}$$

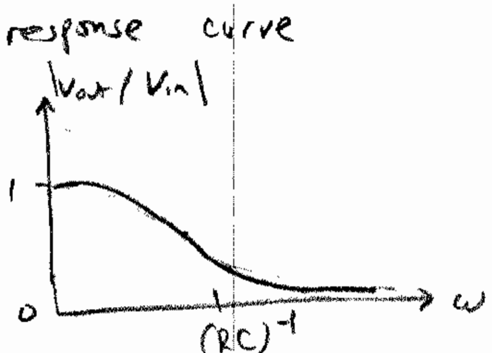
Generalize this, using impedances:



$$V_{out} = -\frac{Z_2}{Z_1} V_{in}$$

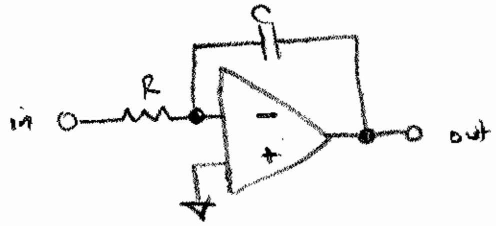
Next, recall passive low-pass filter





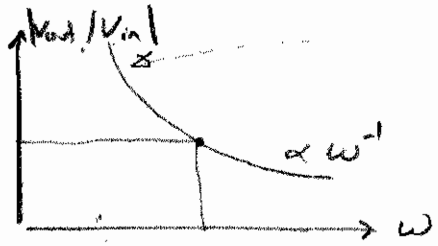
two attempts to design an active low-pass filter

(1)



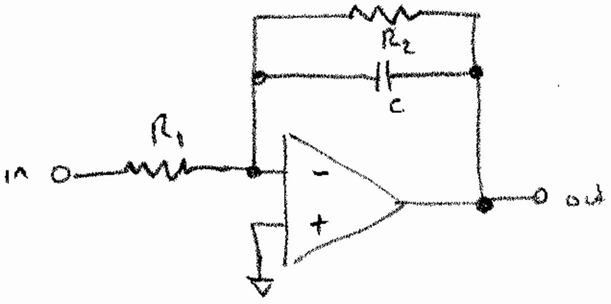
$$V_{out} = -\frac{Z_C}{Z_R} V_{in}$$
$$= -\frac{1}{j\omega RC} V_{in}$$

response curve:

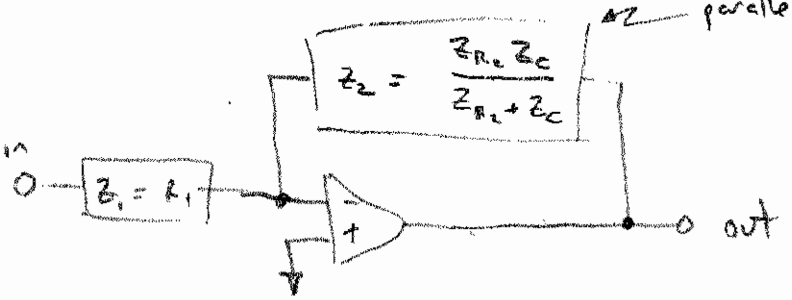


not good: gain → ∞ instead of
gain → const
at low frequency

(2) improve design by adding resistor to feedback loop



which looks like



$$Z_2 = \frac{Z_{R_2} Z_C}{Z_{R_2} + Z_C}$$

$$Z_2 = \frac{Z_{R_2} \; Z_c}{Z_{R_2} + Z_c}$$

$$= \frac{\frac{R_2}{j\omega C}}{R_2 + \frac{1}{j\omega C}}$$

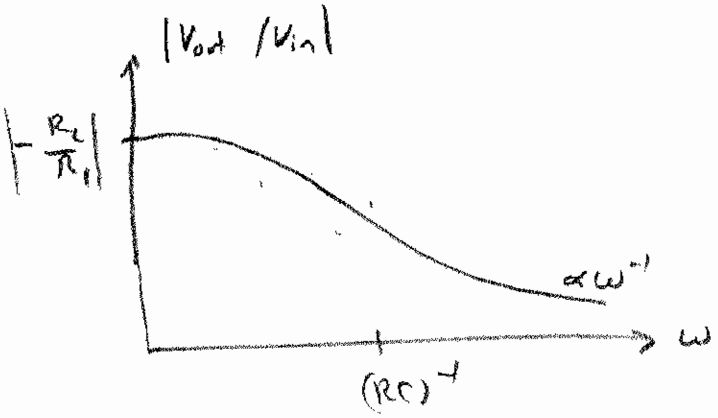
$$= \frac{R_2}{j R_2 \omega C + 1}$$

$$V_{out} = - \frac{Z_2}{Z_1} V_{in}$$

$$\frac{V_{out}}{V_{in}} = - \frac{R_2}{R_1} \left(\frac{1}{j\omega R_2 C + 1} \right)$$

$$\left| \frac{V_{out}}{V_{in}} \right| \to \begin{cases} \to -\frac{R_2}{R_1} & \text{as } \omega \to 0 \\ \to \frac{1}{\omega} & \text{as } \omega \to \infty \end{cases}$$

(a constant, that's what we want)



Putting stuff in the feedback loop of an op-amp

Next, we will examine three circuits involving a diode junction where we will make an undesirable feature of the junction (diode drop & the temperature sensitivity of the diode drop) vanish. We'll do this by putting the diode junction in the feedback loop of an op amp.

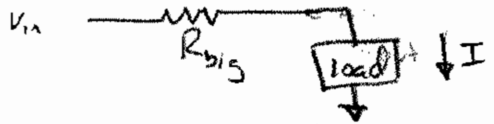
The three circuits we'll examine that do this:

- current source
- power booster
- active rectifier.

Op-Amp Current Source

First, recall three earlier ways of making a current source:

(1) Big resistor in series w/ voltage source

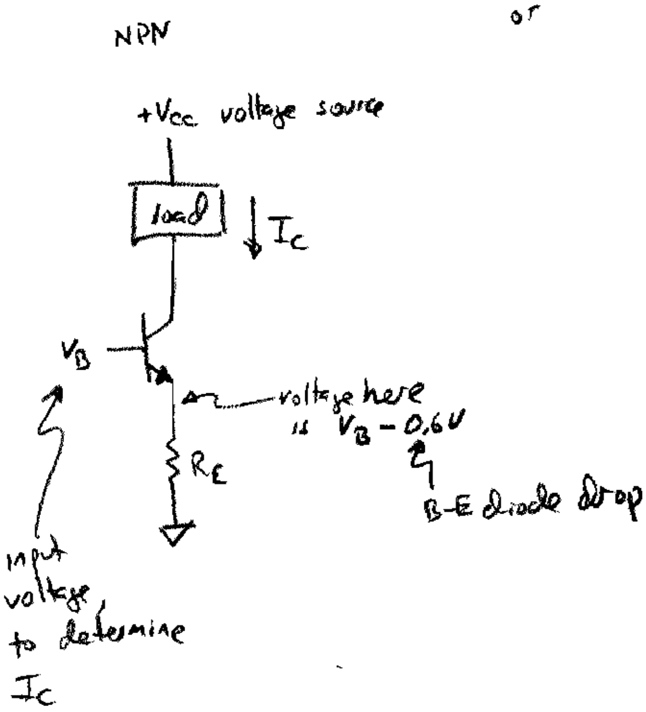


a simple resistor converts voltage source at input into current output

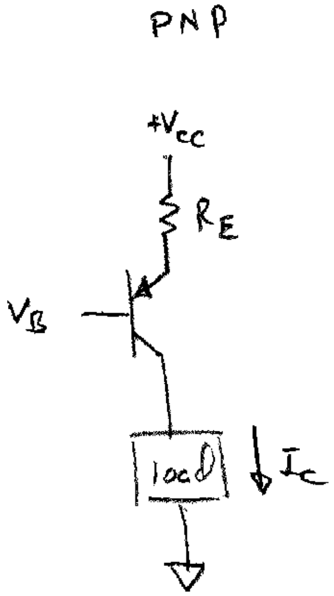
Pros: simple

Cons: poor compliance - (I_{out} will diminish a lot if connected to a high Z load)

(2) BJT & resistor combined w/ voltage source.



or



Here, I_c is the regulated output current

$$I_c = \frac{(V_B - 0.6 \text{ Volt})}{R_E}$$ from Ohm's Law for R_E

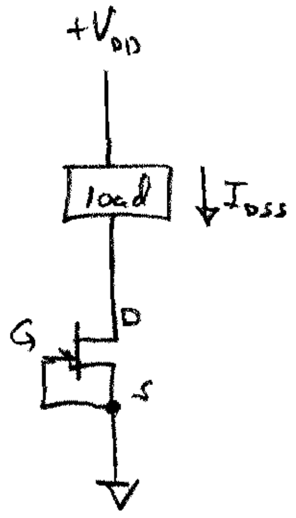
B-E diode drop

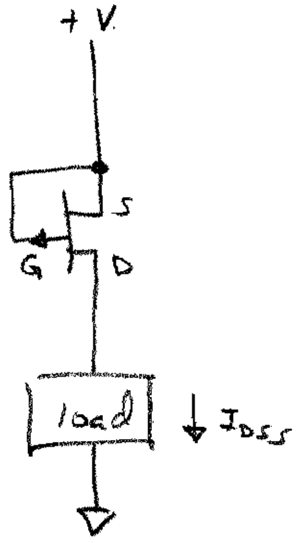
Pros: . Improved Compliance
. Adjustable output current, by adjusting input voltage applied to V_B

Cons: . current depends on B-E diode drop which depends on temp
. more complex than the simple "big resistor" current source

(3) JFET current diode, combined with voltage source

n-JFET or p-JFET



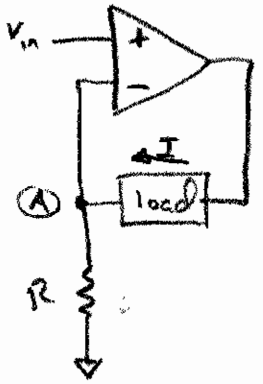


Here, I_{DSS} is the regulated output current

Pros: simplicity. Only one component, just like the simple "big resistor" current source

Cons: Very poor temperature dependence (I_{DSS} varies 0.4% per °C) next, two op-amp current source designs:

(1) simple op-amp current source



to analyze: identify components & nodes & rules

opamp rule (0) neg feedback is ok

(1) $V_A = V_{in}$

(2) no current flows into − input of opamp

node Ⓐ → kirchoff current law

combine w/ rule (2) result

⇒ all current I thru load must flow thru resistor *

resistor → Ohm's Law

current thru resistor = $\frac{V_A - 0}{R}$

combine w/ rule (1) result

⇒ current thru resistor = $\frac{V_{in}}{R}$ **

combine * & ** above ⇒

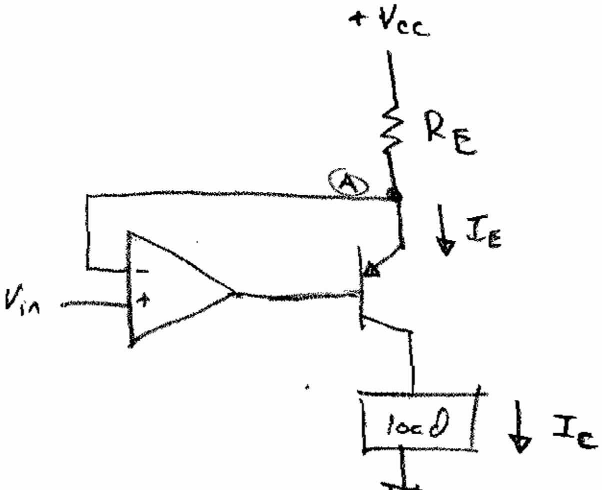
$\boxed{I = \frac{V_{in}}{R} \text{ is current thru load}}$

Pros: no B-E diode drop

Cons:
- inconvenient that neither side of load can be connected directly to GND or power-supply voltage — for many applications this would not be useful
- I thru load can't be very big because op-amps can output only milliamps of current

(2) Op-Amp with BJT Current Source

this circuit is like the earlier BJT current source, except that the B-E diode drop problems are eliminated by putting the BJT's B-E diode junction in the feedback loop of an op-amp.



to analyze: identify components & nodes & rules

Op Amp Rule (0) ok - neg feedback thru transistor

(1) $V_A = V_{in}$

(2) no current into - input of op-amp

Node Ⓐ → kirchoff's current law
combine w/ rule (2) result
⇒ I_E = current thru R_E

Ohm's Law → current thru $R_E = (V_{cc} - V_A)/R_E$

combine w/ rule (1) result & node Ⓐ result →

$$I_E = \frac{V_{cc} - V_{in}}{R_E} \quad *$$

Transistor → $I_c \approx I_E$

combine with * →

$$\boxed{I_c \approx \frac{V_{cc} - V_{in}}{R_E}}$$

↑ is current thru load

Pros: I thru load:
- doesn't depend on B-E diode drop; temp dependence of B-E diode drop has no effect
- can be big, multiple Amps, because a transistor supplies current

Cons: Complexity

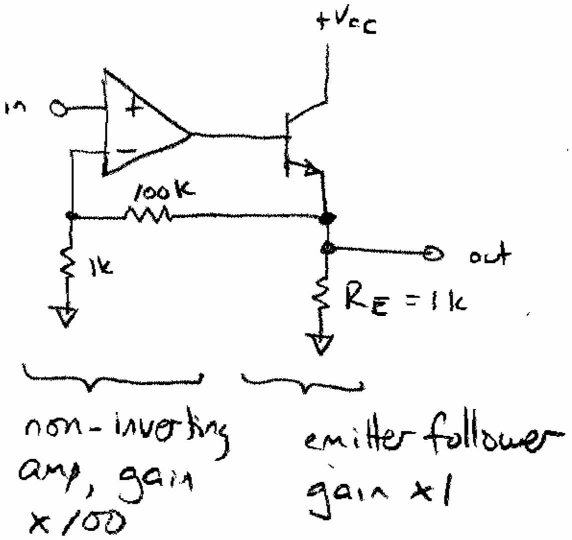
Power Booster

Another example of placing a B-E diode junction in the feedback loop of an op-amp.

Power Booster = Voltage Amplifier capable also of sourcing/sinking large currents, as would be required by a low Z load like a loudspeaker

Problem:
- Emitter Follower can drive Amps of current but has no voltage gain. It also has an unwanted B-E diode drop
- Op-Amp can provide voltage gain, but can source/sink only milliAmps of current

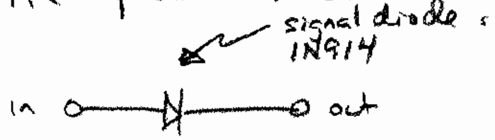
Solution: Combine Emitter Follower & Non-inverting op-amp amplifier, placing the BJT's B-E junction in the op-amp feedback loop

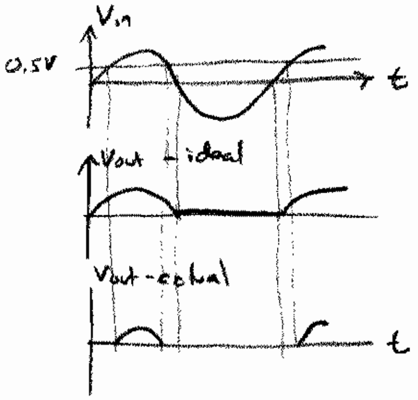


Active Rectifier

Another example of placing a B-E diode junction in the feedback loop of an op-amp.

Problem with passive rectifier : the diode drop



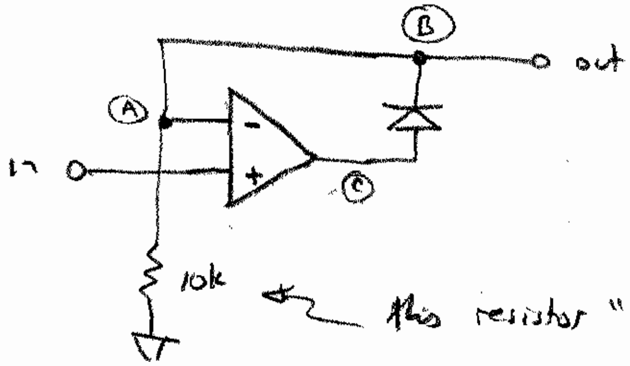


← the actual waveform is lacking the portion of the input waveform between zero & 0.5 Volt

even worse, if $|V_{in}| < 0.5$ Volt, the passive rectifier will have zero output!

Solution

place the diode in the feedback loop of a non-inverting op-amp circuit.

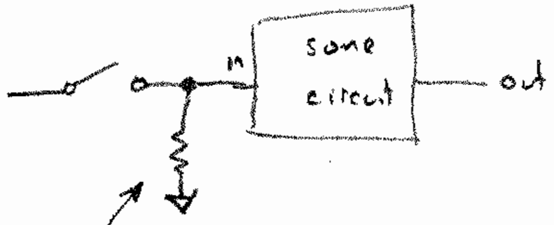


← this resistor "ties an input to ground" aside: using a resistor to tie an input to ground

this is a use of resistors we haven't seen before.

problem: if a circuit's input is sometimes unconnected, its output, will be unpredictable

solution: tie input to ground w/ resistor:

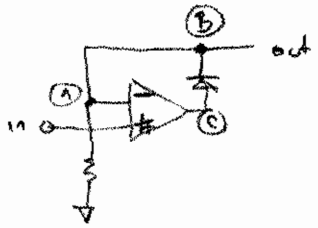


circuit input will be established at zero volts if the circuit otherwise has no input.

now back to the active rectifier

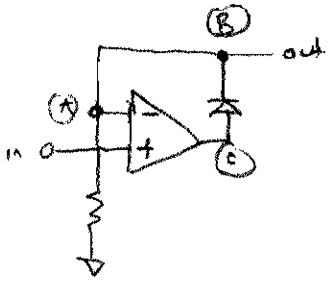
to analyze: identify components & nodes & rules

diode: two cases:
- if forward biased by more than 0.5 volts:
  - diode conducts
  - voltage drop across diode of 0.5 Volt
- otherwise - no conduction



op-amp:

Rule (0)
- If diode conducts, satisfied external feedback thru diode
- If diode does not conduct, not satisfied



op-amp has no feedback, so Rule (1) will not apply, & op-amp output will swing to rails $+V_{cc}$ or $-V_{ee}$ depending on which op-amp + or - input is more positive.

Rule (1)
- If diode conducts, $V_- = V_+$

note: V_- is connected directly to V_{out} ⇒ $V_- = V_{out}$

V_+ is connected directly to V_{in} ⇒ $V_+ = V_{in}$

$\Rightarrow \quad V_{out} = V_{in}$

- If diode does not conduct, Rule(1) does not apply. See above.

Rule ② no current flows into - input of op-amp nodes Ⓐ,Ⓑ : Kirchoff's Current Law:

for this circuit, we won't actually need the results of Rule (2) or Kirchoff's current law

resistor :

ties op-amp - input to ground,
so that " " " will be at zero volts
if the diode does not conduct.

combine these results:

<u>two cases</u>

If $V_{in} > 0$, diode conducts *

$V_{out} = V_{in}$

If $V_{in} < 0$, diode does not conduct

$V_{out} \to -V_{EE}$

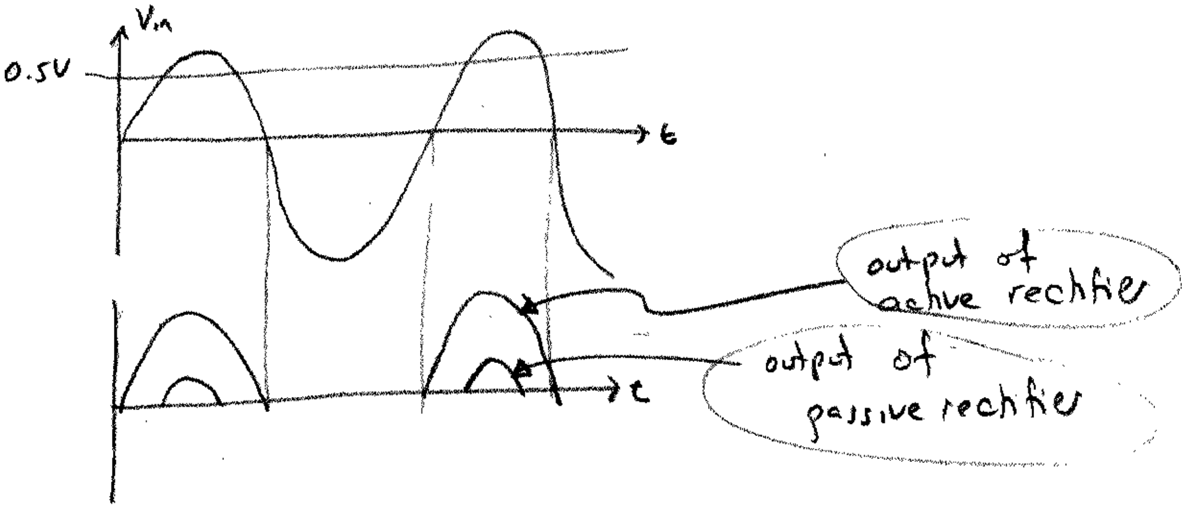
* Internal to circuit, $V_c = V_{in} + \underset{\uparrow\,\text{diode drop}}{0.5}$ Volt

is the op-amp's output voltage, which the " " provided in order to satisfy Rule (1).

active rectifier result:

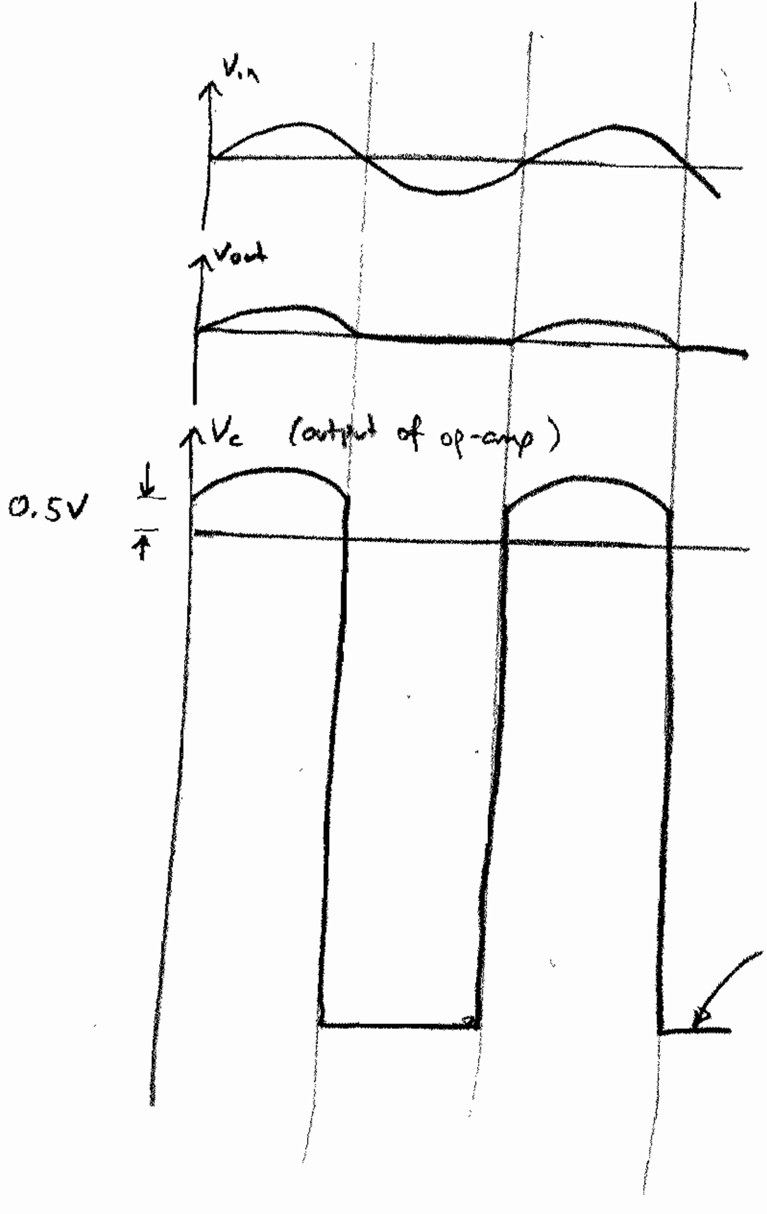
$$V_{out} = \begin{cases} V_{in} & \text{if } V_{in} > 0 \\ 0 & \text{if } V_{out} < 0 \end{cases}$$

* note the advantage of this circuit, as compared to passive rectifier, that the diode drop does not affect the output voltage!



active rectifier (continued)

Let's look at what the op-amp's output (internal to circuit) does:



op-amp output goes into negative saturation when there is no ext feedback & the − input of opamp is more positive than the + input

Real-life limitations of op-amps

until now, we have assumed ideal behavior of op-amps.

However, op-amps do not perfectly obey rules ① & ②.

Does it matter?

For some circuit applications yes, others no.

You must understand these limitations when you design a circuit, and ask yourself whether they will affect your design.

Let's look at the various limitations:

1. Finite Slew Rate dV/dt
2. Input Bias Current I_B
3. Input Offset Voltage V_{os}

there are others, also, but these are the most important.

1. Finite Slew Rate

voltage at an op-amp's output can change no faster than the op-amp's "slew rate"

Finite Slew Rate (cont.)

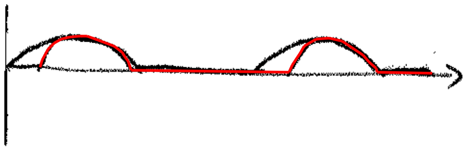
op-amp	slew rate	comment
741	0.5 V/μs	
411	15.0 V/μs	
"damn fast"	6000 V/μs	expensive

Q. when does slew rate matter?

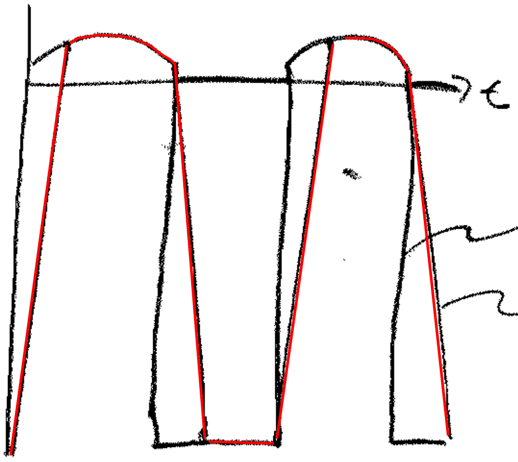
A. • when voltage changes are large & sudden (as in active rectifier)

• or when frequencies are high (above audio frequency)

For Active Rectifier:



actual circuit output (red) will differ from ideal (black)



ideal waveform (∞ slew rate)

actual waveform (finite slew rate)

demo

2. Input Bias Current I_B

Rule (2) isn't perfectly satisfied: <u>inputs to op-amp actually draw non-zero current I_B</u>

op-amp	I_B	comment
741	100,000 pA	(BJT input)
411	50 pA	(FET input)

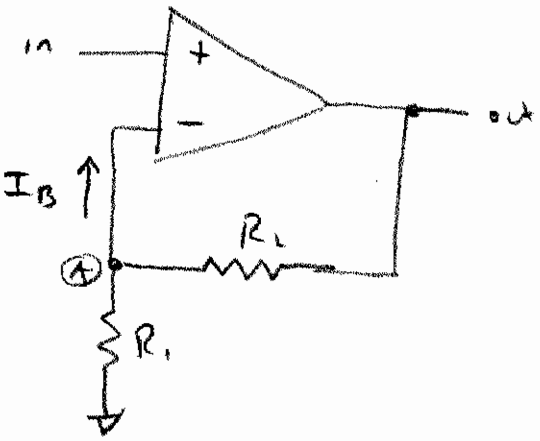
↑ much better

Q. When does Input Bias Current matter?

A. When small currents flow thru feedback network, the unwanted I_B can be significant. This can easily happen if you use Mega-Ohm resistors instead of kilo-Ohm ..

Input Bias Current (cont.)

example: non-inverting amplifier



the unwanted current I_B from node Ⓐ into op-amp input must flow thru R_1 and/or R_2, and this will cause an unwanted voltage drop across R_1 & R_2 due to Ohm's law

⇒ output voltage of circuit will not obey the expected $\frac{V_{out}}{V_{in}} = 1 + \frac{R_2}{R_1}$

The discrepancy will be most severe if:

- desired voltages (your signal) are small (μV or mV)
- resistors R_1 & R_2 are big ($M\Omega$)

so that desired currents at node Ⓐ are small (~ nano-Amp)

3. Input Offset Voltage V_{os}

Rule (1) isn't perfectly satisfied:

instead of ideal $V_+ = V_-$ at inputs of op-amp,

what happens is $V_+ = V_- + \underset{\text{input offset voltage (due to manufacturing variations)}}{V_{os}}$

Op-Amp	V_{os}	comment
741	2 mV typ. 6 mV max	
411	0.8 mV typ 2.0 mV max	costs $1
LTC-1150	0.005 mV max	"precision op-amp" costs $7

two choices if you need a very low V_{os}:

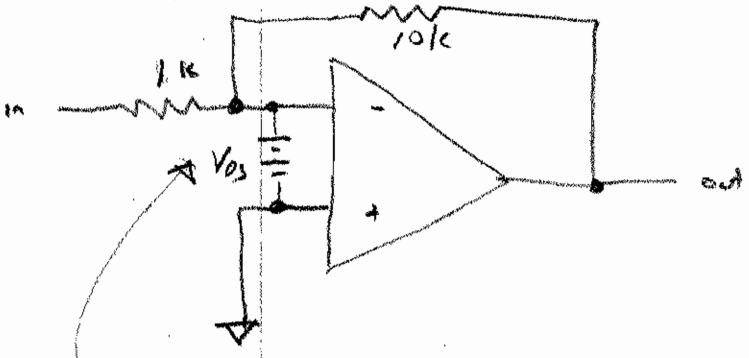
- buy an expensive precision op-amp
- add "trim-pot" between pins 1 & 5

Input Offset Voltage (continued)

Q. When does V_{os} matter?

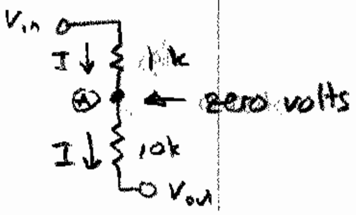
A. When your signal is small (μV or mV)

example: inverting amplifier



the effect of $V_{os} \neq 0$ is like having a fixed voltage drop from a battery between the op-amp's - and + inputs

ideal ($V_{os}=0$)



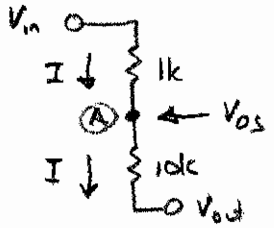
$V_{out} = 0 - (I)(10k\Omega)$

$\uparrow$

$I = \frac{V_{in}-0}{1k\Omega}$

$\Rightarrow V_{out} = -\left(\frac{10k\Omega}{1k\Omega}\right)V_{in}$

actual ($V_{os} \neq 0$)



$V_{out} = V_{os} - (I)(10k\Omega)$

$\uparrow$

$I = \frac{V_{in}-V_{os}}{1k\Omega}$

$\Rightarrow V_{out} = -\left(\frac{10k\Omega}{1k\Omega}\right)V_{in} + 2V_{os}$

Input Offset Voltage (continued)

example, continued

so, the circuit output voltage
will have a constant DC bias of $2V_{os}$
which is undesired

since $V_{os} \sim 1mV$, this is not a
big problem if your expected output
voltage is big ($\sim 1V$)

but it is a problem if your expected
output voltage is a few mV or
smaller – then you must buy a
precision op-amp or trim the
chooper op-amp with a trim-pot.

Comparators

- A chip that compares two analog input voltages to determine which is more positive

- Used in:
    - analog circuits, typically as a trigger
    - analog-to-digital conversion

Comparator

Recall Op-Amp behavior:

Q. what happens if you do not provide external feedback

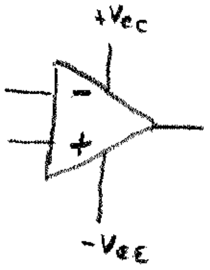
A. The op-amp is then just a high-gain differential amplifier. Its output will:

$$V_{out} \to \begin{cases} +V_{cc} & \text{if } V_+ > V_- \\ -V_{EE} & \text{if } V_+ < V_- \end{cases}$$

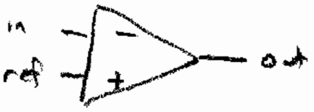
Comparator
- is like an op-amp but it is intended to be used without a feedback network. It will behave as described above

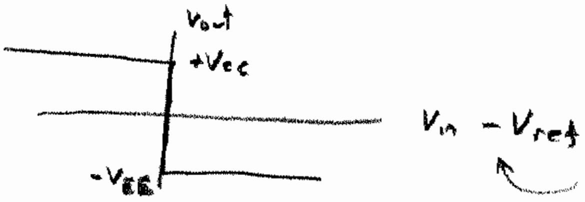
- useful to determine which of two signals is larger

- LM311 is a popular comparator.



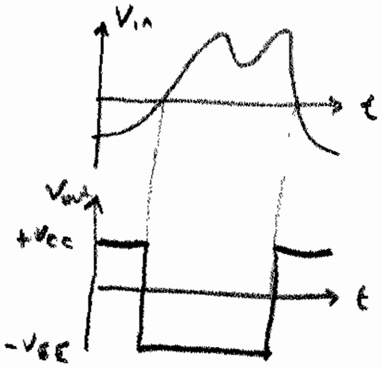
It has one peculiarity you must know about if you use one: it has an "open-collector output"





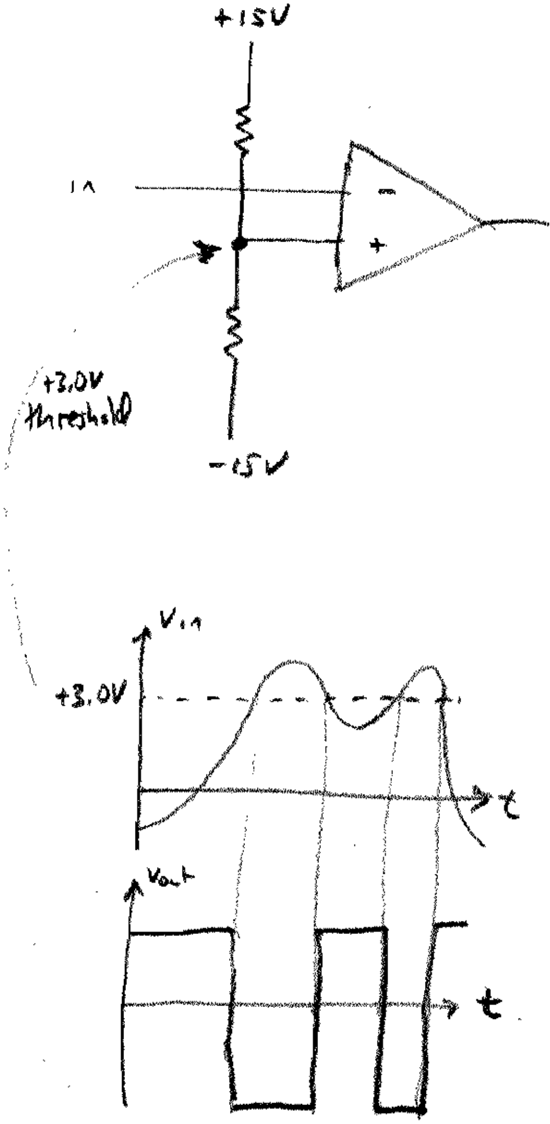
difference of two input voltages

example: provide an output signal that indicates whether an input voltage is pos. or neg, i.e., $V_{in} > 0$ or $V_{in} < 0$.

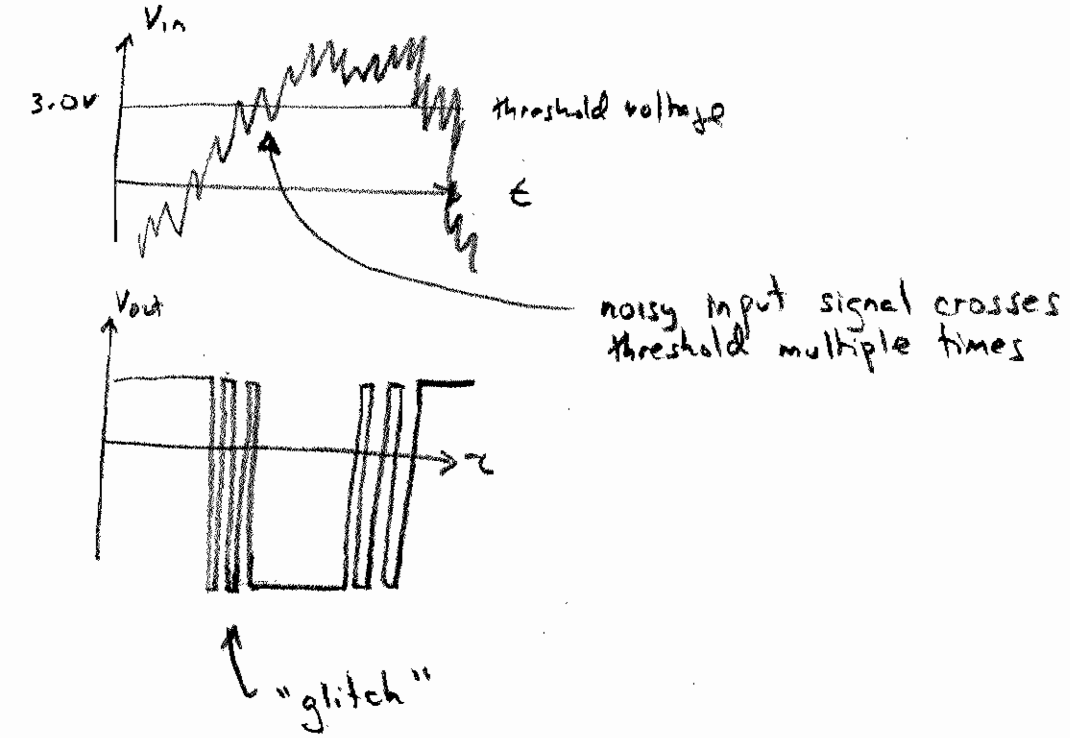


← here, zero volts is the threshold

you can choose another voltage as the "threshold" or reference voltage for a comparator



A complication for comparators : Noisy input signals

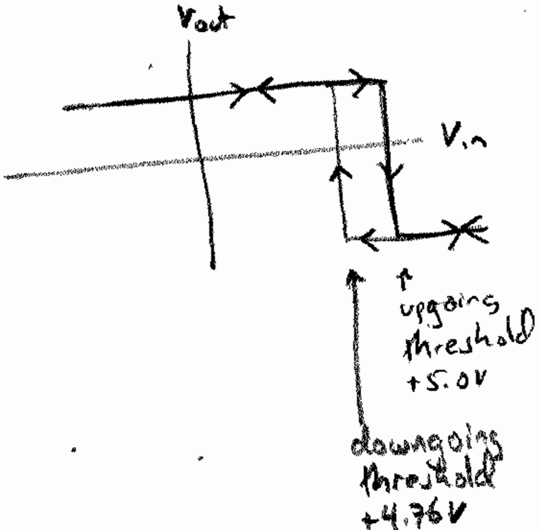


Schmitt Trigger Input

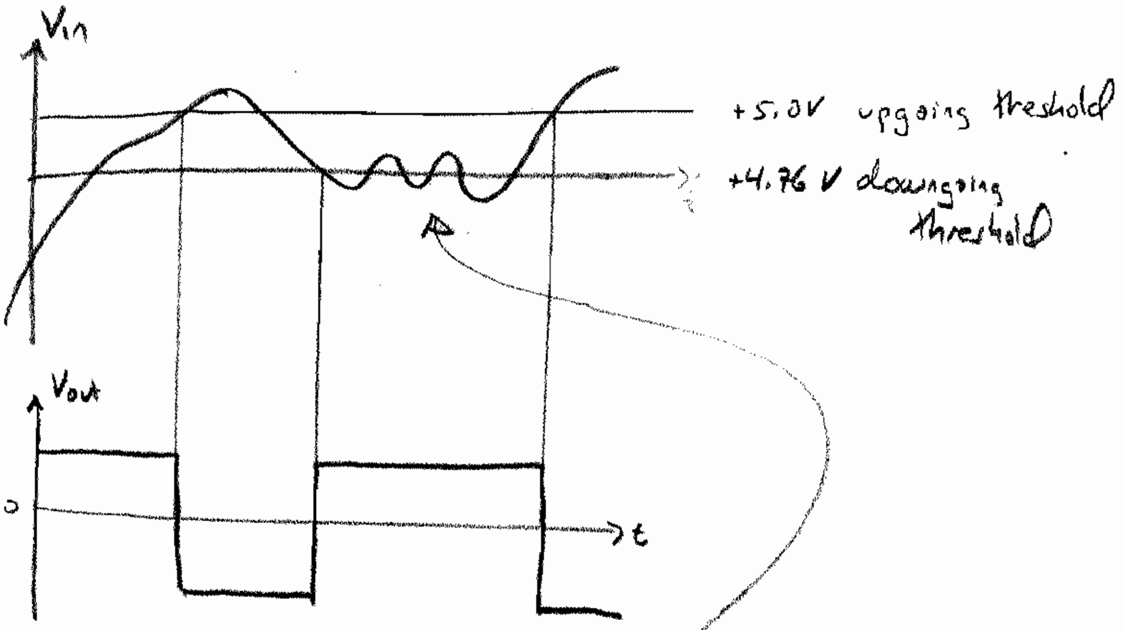
a feature built into some comparators & logic chips to reduce glitches

the trick: use two different thresholds for input:

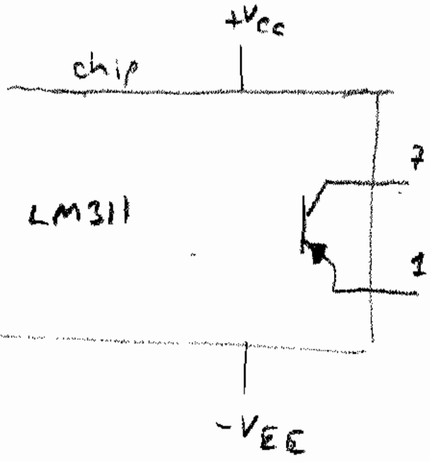
- upgoing threshold +5.0V
- downgoing " +4.76V



Schmitt trigger input for comparator, continued



small amplitude noise does not cause a change in output voltage aside: about "<u>open-collector outputs</u>"



the manufacturer did not "finish" the circuit inside the chip. You must finish it by adding external parts, typically like this: