ECE 2100 Lecture notes Wed, 1/22/03

A. Stolp
1/20/03

HW #4, due F, 1/24 Ch 1: 34, 37, 43
Exercises: 2.1, 2.2, 2.4, 2.5
For hints etc., see lecture notes for F, 1/17

HW #5, due W, 1/29 Ch.2:
problems 6, 8a-e, 10, 15, Ex2.4 - Ex2.9
Ans: 6: -1, -3.00V, -2.7V to -3.3V

HW #6, due F, 1/31 Ch.2:
Ex2.10 - Ex2.16, problems 2.22, 2.30

Stuff

Problem Sessions:
W, 11:50 - 12:40 am, WBB 212 (tall brick geology building)
F, 10:45 - 11:35 am, MEB 1208 (by SW entrance)

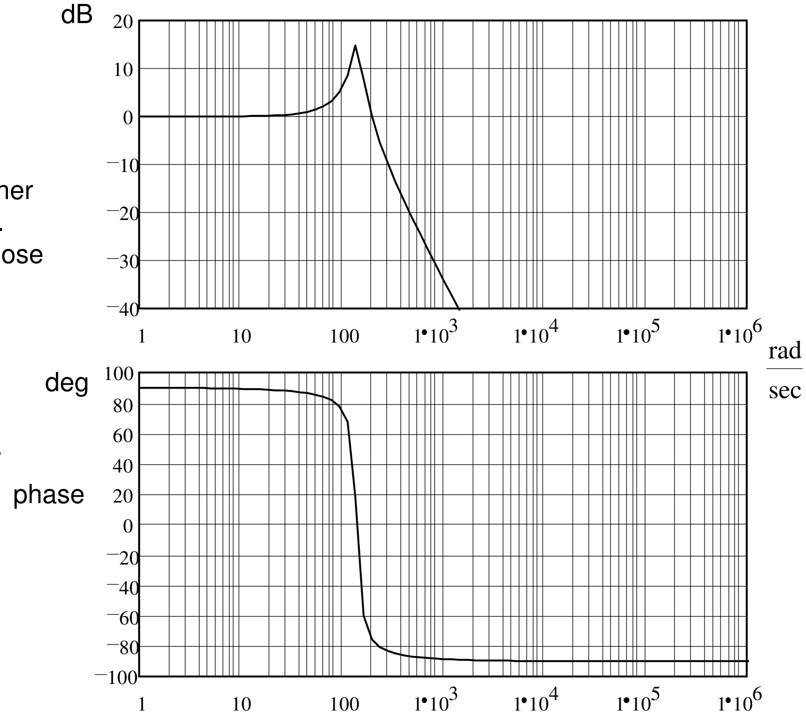
Clean up some loose ends

Bode Plots

The Bode plots that we've covered in class are the simplest types and will do for our purposes. We are primarily interested in the design of amplifiers and analysis of the low and high corner frequencies. The poles and zeroes are usually far apart.

When poles and zeroes are too close to each other they can interact or even result in complex poles. Complex poles result in resonance effects like those shown at right.

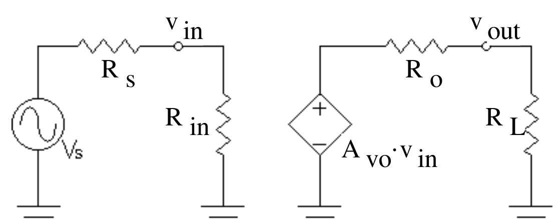
If poles and zeroes are simply close but not complex, the effects of each simply add or subtract. That can throw off your assumptions (like the -3dB) around the corner frequency, etc..

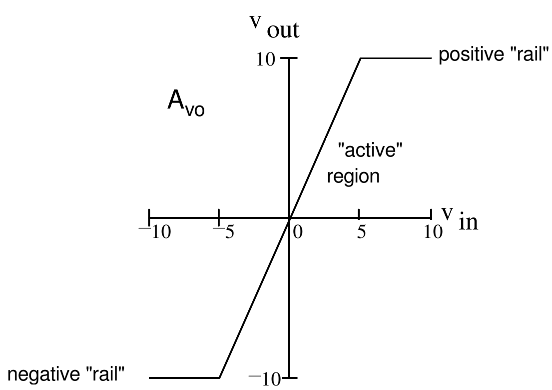


If asked in a future classes if you have "covered" Bode plots, answer only a qualified "yes" or you may be expected to know more than you do.

Clipping

All real amplifiers will clip the output signal if the input is too big. Only one part in the model can possible account for the clipping-- a nonlinear A_{vo}.





Clipping level at the output (v_{out}) is less than that of A_{vo} ($\pm$ 10V) because of the R_o, R_L voltage divider.

The maximum allowable $v_{in} = \dfrac{10 \cdot V}{A_{vo}}$

The maximum allowable v_s is greater than this because of the R_S, R_{in} voltage divider.

Operational Amplifiers (Op amp) Chapter 2 of the textbook **Start with lecture for F, 1/17**

It's very difficult to make v_a & v_b close enough without using some negative feedback. Negative feedback makes the op-amp maintain $v_a \simeq v_b$ for itself. With the proper negative feedback the op-amp keeps $v_a \simeq v_b$ so close that you can usually assume that $v_a = v_b$. Without this negative feedback the op-amp output will almost certainly be at one of its limits, either high or low, i.e. NOT in its active, or linear, range. Incidentally, circuits without negative feedback are also useful, but the output is either high or low (digital) and not linearly related to the input. These types of circuits are called nonlinear circuits.

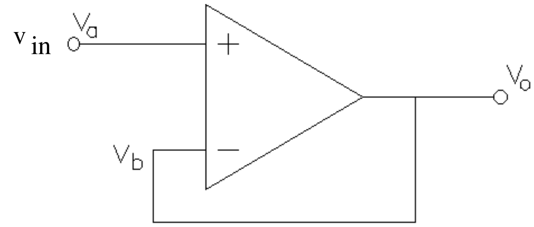
The op-amp has very high input impedance. The input currents are almost zero. As long as you use reasonable resistor values in your circuits (say 100Ω to 1MΩ), you can neglect the input currents.

The output impedance of IC op amps is not that great, but negative feedback makes it look much smaller than it really is, and it's often neglected.

Op-amps amplify DC as well as AC.

Active (Linear) Op amp Circuits

Voltage follower



Negative feedback, the entire v_o is fed back.

$v_a \simeq v_b = v_o$ OR: $v_o = v_a = v_{in}$

Normally the approximate equal sign is left out.

Also known as a buffer. This is very useful as a current amplifier.
Very little (usually negligible) current flows in and significant current can flow out.

Notice that he power supply connections are not shown. They are "understood" to exist.

Negative feedback

What if: $v_a := 1 \cdot V$ & $v_o := 0 \cdot V$ because they're connected: $v_b := 0 \cdot V$ $100000 \cdot (v_a - v_b) = 100000 \cdot V = v_o$

So the op amp wants to make the output 100000V, and will "turn up" the output voltage as fast as it can.
Very soon the output will reach 1V and the process will stop.

What if: $v_a := 1 \cdot V$ & $v_o := 3 \cdot V$ $v_b := v_o$ $100000 \cdot (v_a - v_b) = -200000 \cdot V = v_o$

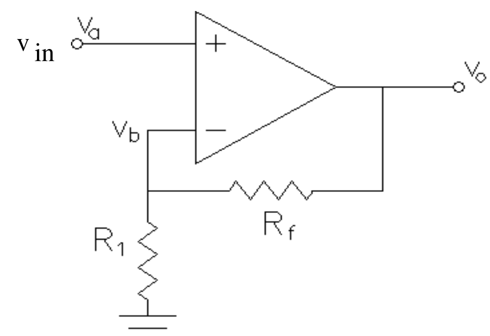
Now the op amp wants to make the output -200000V, and will "turn down" the output voltage as fast as it can.
Again, the output will soon reach 1V and the process will stop. This is how negative feedback works.

Negative feedback is an important concept. It is used in almost all systems, including all natural systems. A very simple example is the heating system in your house. If the air temperature is too low the thermostat detects a difference between its setting and the air temperature and turns on the heater. When the air temperature reaches the set temperature the thermostat turns off the heater—negative feedback.

Incidentally, a real op amp does have a limit as to how fast it can change its output voltage. This maximum is called the "slew rate" (SR) of the op amp and is generally specified in V/μs.

Noninverting Amplifier

Same type of negative feedback, but now only a fraction of v_o is fed back.



$$v_a \simeq v_b = \frac{R_1}{R_1 + R_f} \cdot v_o \quad \text{OR:} \quad v_o = \frac{R_1 + R_f}{R_1} \cdot v_{in} = \left(\frac{R_f}{R_1} + 1\right) \cdot v_{in}$$

You can get whatever gain you want just by selecting the right resistor values.

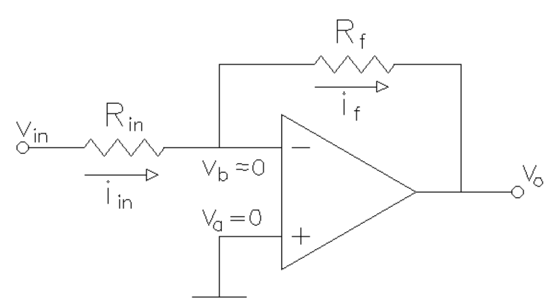
Remember the + 1

These calculations are only valid If the op amp is in its **active** region. If v_{in} is too big, the output will be clipped and v_a will NOT equal v_b. It is only reasonable to assume that the circuit might be in the active region if there is **negative** feedback. Look for a connection from the output to the inverting (-) input.

This amplifier is called "noninverting" because the output is not inverted with respect to the input.
You can tell this at a glance if you see that the input is connected to the noninverting (+) input.

Inverting Amplifier

You still have negative feedback, but now the v_{in} is also connected to the same op-amp input.



$v_b \simeq v_a = 0V$, it's connected to ground

$i_{in} = \dfrac{v_{in}}{R_{in}}$ But this current can't flow into the op amp, so it must flow up through R_f (the feedback resistor).

$$i_{in} = \frac{v_{in}}{R_{in}} = i_f = \frac{v_b - v_o}{R_f} = \frac{0 - v_o}{R_f} = \frac{-v_o}{R_f}$$

OR: $v_o = -\frac{R_f}{R_1} \cdot v_{in}$ The - sign means "inverting".

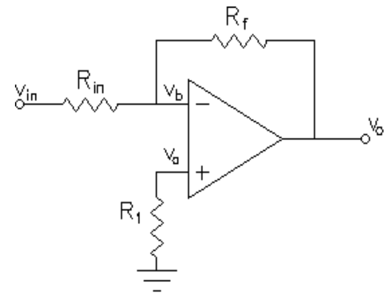
You can tell this at a glance that this is an inverting amp if you see that the input is connected to the inverting (-) input.

Again, you can get whatever gain you want just by selecting the right resistor values.

Usually the noninverting input is hooked to ground through a resistor such that:

$$R_1 \simeq \frac{1}{\frac{1}{R_{in}} + \frac{1}{R_f}}$$

This doesn' t affect our ideal calculations above, but does make real op amps appear more like ideal ones. We' ll revisit this again when we talk about the non-ideal effects and how to deal with them.

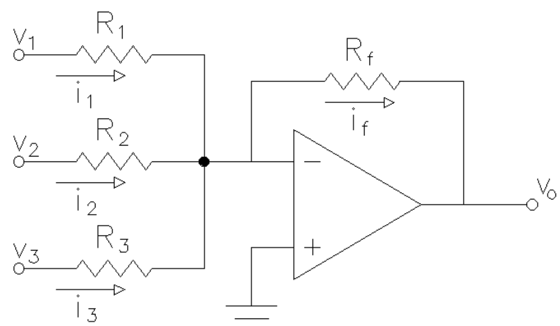


Summer

This is a variation of the inverting amp.

$$\frac{v_1}{R_1} + \frac{v_2}{R_2} + \frac{v_3}{R_3} = i_f = \frac{v_b - v_o}{R_f} = \frac{-v_o}{R_f}$$

OR: $v_o = -\left(\frac{R_f}{R_1} \cdot v_1 + \frac{R_f}{R_2} \cdot v_2 + \frac{R_f}{R_3} \cdot v_3\right)$

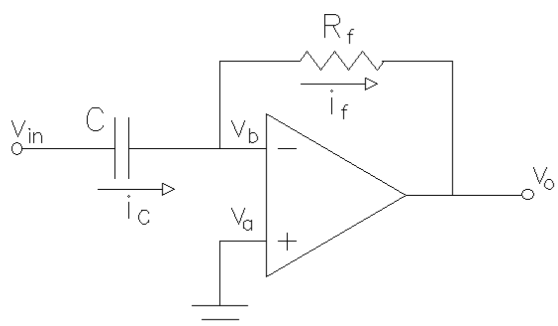


Differentiator

Another variation of the inverting amp.

$$i_C = C \cdot \frac{d}{dt} v_{in} = \frac{-v_o}{R_f}$$

OR: $v_o = -R_f \cdot C \cdot \frac{d}{dt} v_{in}$



Integrator

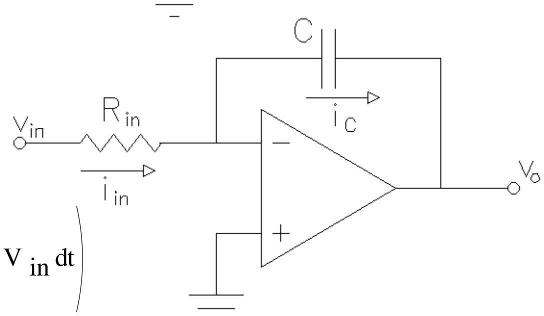
Another variation of the inverting amp.

$$i_{in} = \frac{v_{in}}{R_{in}} = i_C = C \cdot \frac{d}{dt}(-v_o)$$

integrate both sides

$$\frac{1}{R_{in}} \cdot \int V_{in}\, dt = C \cdot (-v_o)$$

OR: $v_o = -\frac{1}{R_{in} \cdot C} \cdot \left(\int V_{in}\, dt\right)$



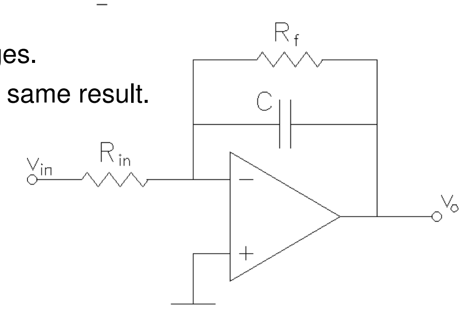
This is a nice circuit, but impractical in real life.

The slightest DC voltage at v_{in} will make the output drift to one of the rail voltages.

Even if you hooked v_{in} to ground, imperfections in the op amp would cause the same result.

A practical variant is the running average or **Miller Integrator**.

R_f allows the capacitor charge to leak off.



This and all the previous circuits could also be looked at in terms of steady-state AC analysis:

$$i_{in} = \frac{v_{in}}{Z_{in}} = i_f = \frac{-v_o}{Z_f}$$

OR: $v_o = -\frac{Z_f}{Z_1} \cdot v_{in}$

The - sign means a 180º phase change.

Active Filters

By using various networks of resistors and capacitors in place of Z_1 and Z_f you can make all sorts of excellent filters without using inductors. That' s good because real inductors are expensive and not nearly as ideal as real capacitors.

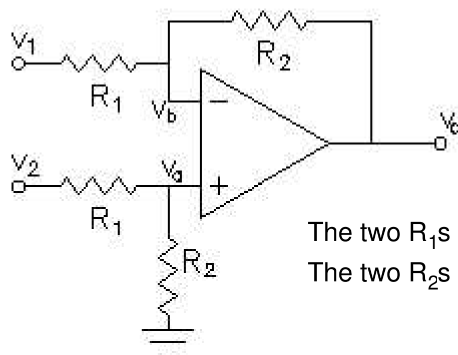
In the case of the Miller integrator:

$$v_o = -\frac{Z_f}{Z_1}\cdot v_{in} = -\frac{\left(\dfrac{1}{\dfrac{1}{R_f}+j\cdot\omega\cdot C}\right)}{R_{in}}\cdot v_{in} = -\frac{\left(\dfrac{R_f}{1+j\cdot\omega\cdot C\cdot R_f}\right)}{R_{in}}\cdot v_{in} = -\frac{R_f}{R_{in}}\cdot\frac{1}{\left(1+j\cdot\omega\cdot C\cdot R_f\right)}\cdot v_{in}$$

A single-pole low pass filter with: $\omega_C = \dfrac{1}{C\cdot R_f}$

A good reference: *Active Filter Cookbook* by Don Lancaster, published by Howard W. Sams & Co..

Differential amplifier



The two R_1s are equal in value.
The two R_2s are equal in value.

$$v_a = \frac{R_2}{R_1+R_2}\cdot v_2 = v_b$$

$$v_b = \frac{R_2}{R_1+R_2}\cdot\left(v_1-v_o\right)+v_o$$

They must be equal $\quad \dfrac{R_2}{R_1+R_2}\cdot\left(v_1-v_o\right)+v_o = \dfrac{R_2}{R_1+R_2}\cdot v_2$

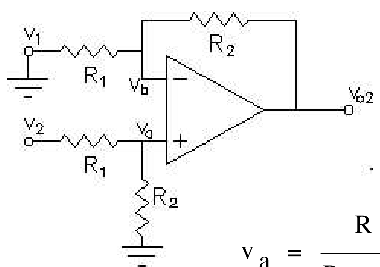
$$R_2\cdot\left(v_1-v_o\right)+v_o\cdot\left(R_1+R_2\right) = R_2\cdot v_2$$

$$R_2\cdot v_1 - R_2\cdot v_o + v_o\cdot R_1 + v_o\cdot R_2 = R_2\cdot v_2$$

$$R_2\cdot v_1 + v_o\cdot R_1 = R_2\cdot v_2$$

OR: $\quad v_o = \dfrac{R_2}{R_1}\cdot\left(v_2-v_1\right)$

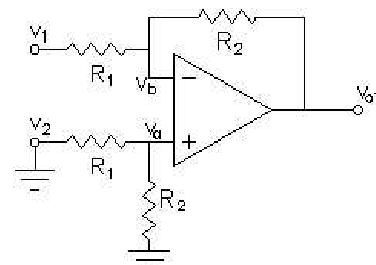
Or, Calculated by superposition:



$$v_a = \frac{R_2}{R_1+R_2}\cdot v_2$$

What remains is just a noninverting amplifier

$$v_{o2} = \frac{R_1+R_2}{R_1}\cdot v_a = \frac{R_1+R_2}{R_1}\cdot\left(\frac{R_2}{R_1+R_2}\cdot v_2\right) = \frac{R_2}{R_1}\cdot v_2$$



$$v_a = 0$$

What remains is just an inverting amplifier

$$v_{o2} = -\frac{R_2}{R_1}\cdot v_1$$

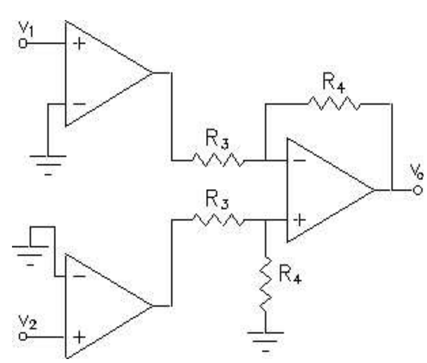
Together: $\quad v_o = \dfrac{R_2}{R_1}\cdot\left(v_2-v_1\right)$

Input resistance problem

Input resistance for v_2 is: $\quad R_1+R_2$

Input resistance for v_1 is: $\quad R_1$ but may change if v_2 changes.

What if $v_a = v_1$? Then $v_b = v_1$ and then the input resistance for v_1 is ∞!

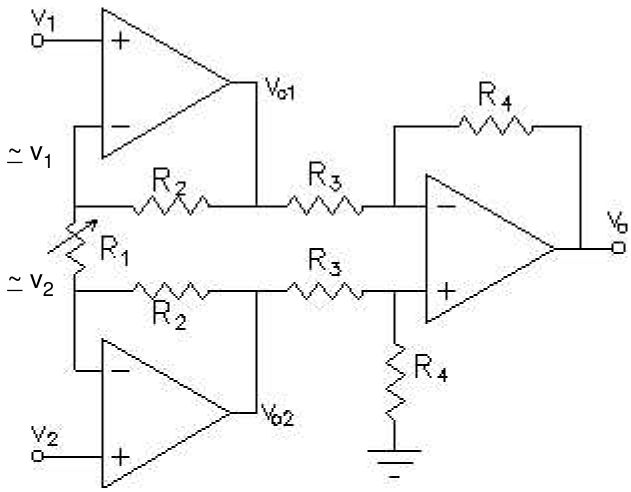


One cure for this variable input resistance is to buffer both inputs, and this will indeed make a good differential amplifier.

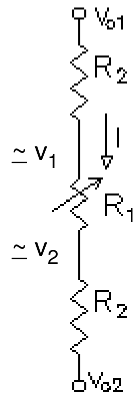
However, varying the gain of this amplifier would involve changing two resistors at a time.

Instrumentation amplifier

The circuit below is only slightly more complex, but offers a simple way to change the gain.



To find the gain of the left part of the circuit:



$$v_{o1} - v_{o2} = I\cdot\left(R_2 + R_1 + R_2\right)$$

and: $v_1 - v_2 = I\cdot R_1$

so:

$$\frac{v_{o1} - v_{o2}}{v_1 - v_2} = \frac{I\cdot\left(R_2 + R_1 + R_2\right)}{I\cdot R_1}$$

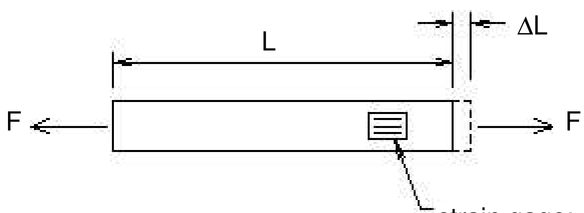
$$= 1 + \frac{2\cdot R_2}{R_1} = \frac{v_{o2} - v_{o1}}{v_2 - v_1}$$

$$v_o = \left(1 + \frac{2\cdot R_2}{R_1}\right)\cdot\frac{R_4}{R_3}\cdot\left(v_2 - v_1\right)$$

Uses

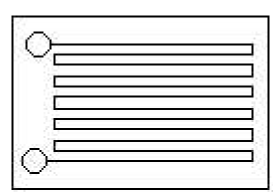
So where might you use one of these instrumentation amplifiers? Here' s an example of where I personally used one. The objective was to add force sensing to a robot gripper. The sensors were called "load cells" and are based on a full wheatstone-bridge of strain gages. Lets look at stain and strain gages first:

Stain is the stretch of a material under stress (forces)



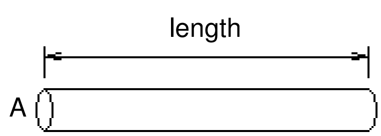
strain = $\frac{\Delta L}{L}$

stress = $\frac{F}{A}$ A = cross-sectional area



A strain gage is a thin backing material with a wire and two contacts.

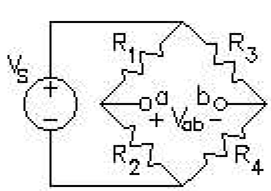
recall:



$$R = \rho\cdot\frac{\text{length}}{A}$$

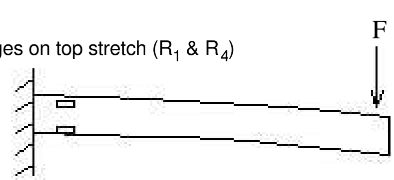
So, as the wires in a strain gage are stretched, the resistance goes up

4 strain gages are usually wired into wheatstone bridges, like the one shown below, where each of the resistors is a strain gage attached to a beam. This helps cancel temperature dependencies.



Two strain gages on top stretch (R_1 & R_4)

Beam:

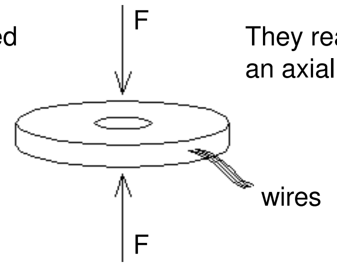


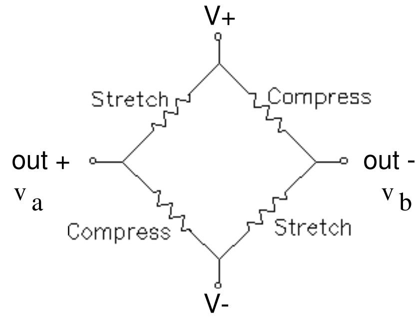
Two strain gages on bottom compress (R_2 & R_3)

A load cell generally contains 4 strain gages in a full bridge

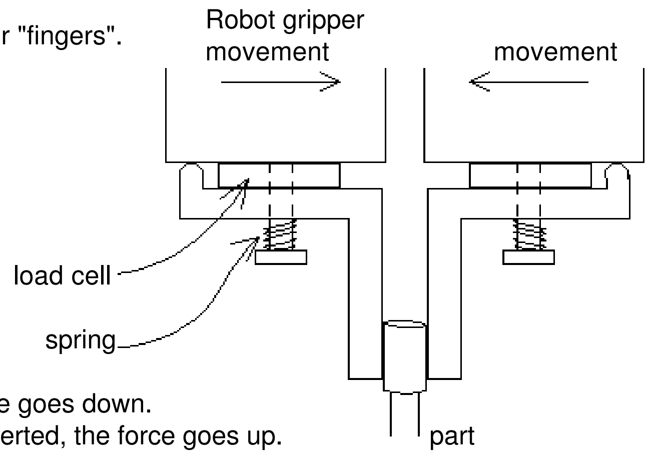
The load cells we used were shaped like washers

They react to an axial force





Two load cells were placed under the gripper "fingers".



If the gripper has a part, the load-cell force goes down.
if the part hits something as it' s being inserted, the force goes up.

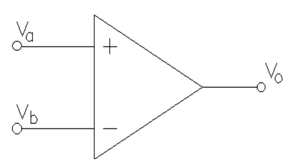
I used an instrumentation amplifiers to amplify the differential voltage (V_{ab}) from each load cell.

Nonlinear Circuits

You may get the idea from the previous circuits that $v_a = v_b$ in all cases, but that is not always true-- the op amp is not always in its active region. Not only that, but you can make useful circuits even if the op amp can only switch between the two rail voltages.

Comparator

Without negative feedback the op amp is simply a comparator.

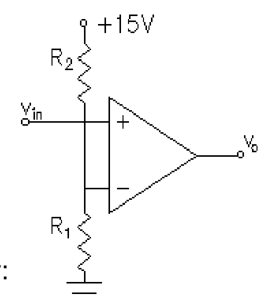


If $v_a > v_b$ then v_o = L+, the positive output limit (+ rail).

If $v_a < v_b$ then v_o = L-, the negative output limit (- rail).

You now have a digital output that tells you which voltage is greater.

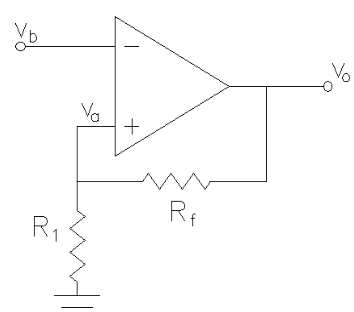
one of the two voltages typically comes from a voltage divider:



If $v_a \simeq v_b$ the output will switch at the slightest noise on the inputs. The next circuit will fix that.

Schmitt Trigger

Now we' ve got some positive feedback. This causes a "toggle" action or hysteresis in the switching. As soon as the output switches, the switching level changes as well.



The switching level is: $\dfrac{R_1}{R_1 + R_2} \cdot v_o$ + if v_o is + , - if v_o is -

There are other ways to make Schmitt triggers, but all have some positive feedback.

Other Nonlinear Circuits

You' ll see more in the Nonlinear Op Amp Circuits lab.

References for practical circuits

IC Op-Amp Cookbook by Walter G Jung, published by Howard W. Sams & Co..

The Art of Electronics by Horowitz and Hill published by Cambridge University Press

 Next time: Non-ideal effects