

Stuff Exam 1 Friday, 2/7/03

Chapters 1 & 2, Lectures through 1/31

HWs 1 - 8 Understand problems.

Try some old exams (Web HW page).

We will move to EMCB 101 on Monday 2/3

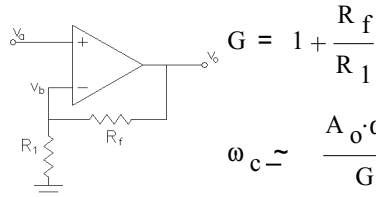
HW #8, due F, 2/7 Ex2.21 - Ex2.26, problems
2.78, 2.84, 2.95 DO HW #8 BEFORE EXAM 1!**HW #9, due M, 2/10**

Ch. 3, Ex3.1 - Ex3.5, Repeat Ex3.1 - Ex3.5 using the 0.7V drop model of the diode. Ex3.4c book ans. wrong, should be: -5V

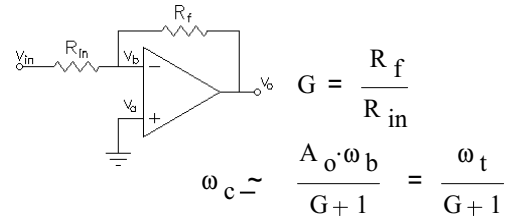
Non-ideal (Real) Op amps, continued

Step response

The step response is the output when the input is a step function.



$$\omega_c \approx \frac{A_o \cdot \omega_b}{G} = \frac{\omega_t}{G}$$

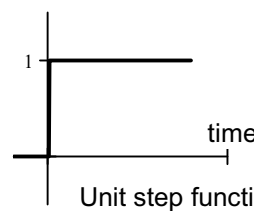


$$\omega_c \approx \frac{A_o \cdot \omega_b}{G + 1} = \frac{\omega_t}{G + 1}$$

Essentially, op amp amplifiers are low-pass filters. The step response will also be the same as for a low-pass filter.

$$H(\omega) = \frac{G}{1 + \frac{j\omega}{\omega_c}} \quad \text{So:} \quad H(s) = \frac{G}{1 + \frac{s}{\omega_c}}$$

The Laplace transform of the output is simply the Laplace transform of the input $\times H(s)$.

Laplace transform of $u(t)$

$$\mathcal{L} u(t) = \frac{1}{s}$$

$$\mathcal{L} v_{in} u(t) = \frac{v_{in}}{s}$$

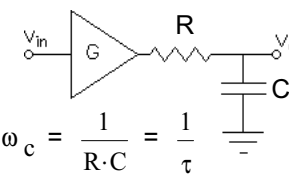
$$V_o(s) = H(s) \cdot V_{in}(s) = \frac{G \cdot v_{in}}{\left(1 + \frac{s}{\omega_c}\right) \cdot s} = \frac{G \cdot v_{in} \cdot \omega_c}{(\omega_c + s) \cdot s} = \frac{K_1}{(\omega_c + s)} + \frac{K_2}{s} = \frac{K_1 \cdot s + K_2 \cdot (\omega_c + s)}{(\omega_c + s) \cdot s}$$

$$\text{solve for the constants } K_1 \text{ \& } K_2: \quad G \cdot v_{in} \cdot \omega_c = K_1 \cdot s + K_2 \cdot \omega_c + K_2 \cdot s \quad K_2 = G \cdot v_{in} \quad 0 = K_1 \cdot s + K_2 \cdot s$$

$$V_o(s) = \frac{K_1}{(\omega_c + s)} + \frac{K_2}{s} = \frac{-(G \cdot v_{in})}{(\omega_c + s)} + \frac{G \cdot v_{in}}{s} \quad K_1 = -K_2 = -(G \cdot v_{in})$$

$$\text{Take the inverse Laplace transform to get } v_o(t) = \left(-G \cdot v_{in} \cdot e^{-\omega_c t} + G \cdot v_{in} \right) \cdot u(t) = G \cdot v_{in} \cdot (1 - e^{-\omega_c t}) \cdot u(t)$$

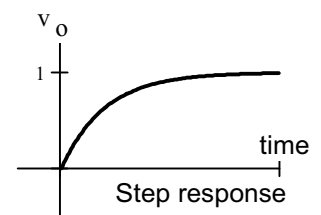
That should be no surprise. We could get the same transfer function from an ideal amp and a simple RC filter.



With a step input, the output is just a charging capacitor.

The maximum slope of this function occurs at $t = 0$, and is:

$$G \cdot v_{in} \cdot \omega_c$$



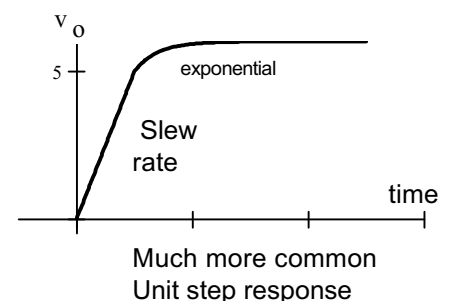
Only if: $G \cdot v_{in} \cdot \omega_c < SR$

However, there is also an absolute maximum slope for the op amp which is usually more limiting than this exponential curve. We'll look at the slew rate next.

Slew Rate

The op-amp output voltage can only change so fast. The maximum rate of change is called the slew rate (SR) and is usually specified in $V/\mu s$. You've already seen this slew rate in the lab. So if you try to make the output step too big it will look like this instead of the exponential shown above.

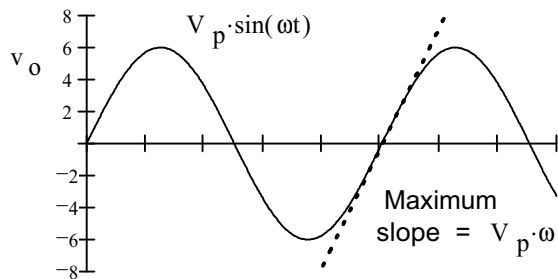
Usually the exponential part of this curve is neglected or overlooked, and you just think of the output as a straight slope until it reaches the correct output voltage.



Slew Rate continued

A square wave just acts like a repeating step function:

What if your output is a sine wave?



$$\text{slope} = \frac{d}{dt} V_p \sin(\omega t) = V_p \omega \cos(\omega t)$$

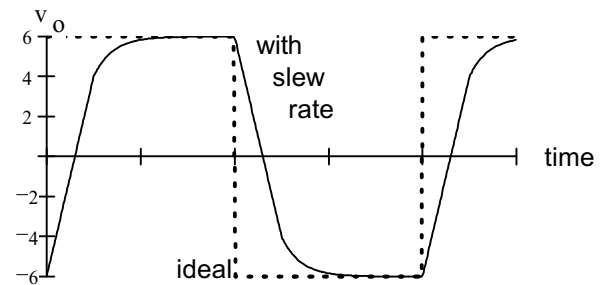
maximum slope is $V_p \omega$, where $\cos(\omega t) = 0$

Try to double the V_p and look what you get:

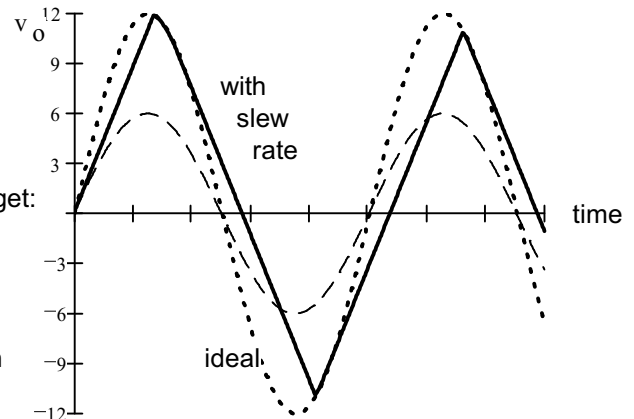
The slew rate limits the useful frequency response if the output voltages are large.

$$f_{\max} = \frac{SR}{V_p \cdot 2\pi} = \frac{SR}{V_{pp} \cdot \pi} = \text{the full-power bandwidth}$$

Typ. $SR = 1 - 30 \text{ V}/\mu\text{s}$, but can go to 100s



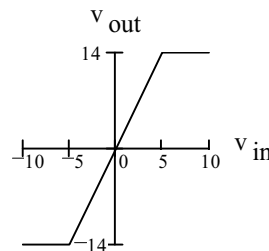
$$f_{\max} = \frac{SR}{V_p \cdot 2\pi} = \frac{SR}{V_{pp} \cdot \pi}$$



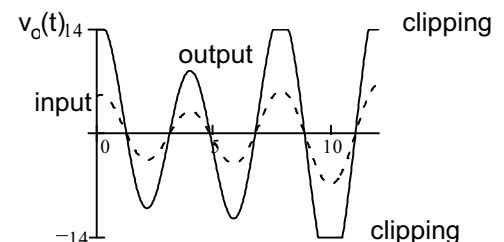
Clipping (output saturation)

Another problem that shows up when the output voltages are large.

Typically, op amps clip when the output voltage gets to within 1 to 2V of the power supply voltages.



Transfer characteristic

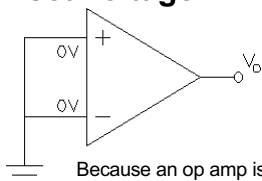


Clipping levels are functions of the output (or load) current, and are usually specified for a specific load resistor.

Some op amps, like the LM324, are designed to be useful in circuits with only one power supply. Their negative clipping voltage should be equal to the negative power supply voltage so that the negative power supply can be ground.

DC imperfections

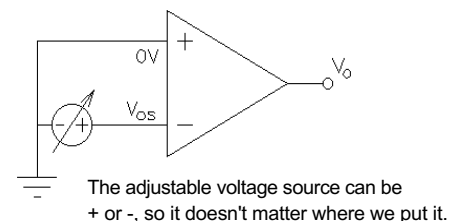
Offset voltage



v_o should = 0, but almost never does in a real op amp.

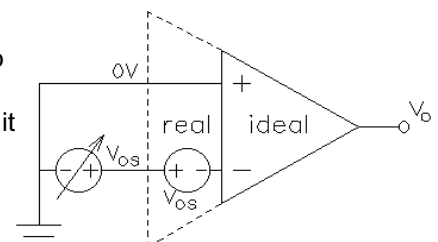
Because an op amp is a very high-gain direct-coupled (amplifies DC) amp, even very tiny and unavoidable transistor mismatches in the input differential amplifier will cause significant offsets at the output.

Let's put a little adjustable voltage source outside the op amp and adjust it so that the output is 0.



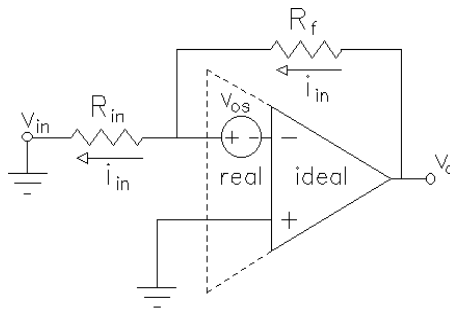
The adjustable voltage source can be + or -, so it doesn't matter where we put it.

Now we can think of the real op amp as having an offset voltage (v_{os}) embedded within it, and beyond that it is ideal. v_{os} is typically a few mV.



Some op amps, like the LM741, have extra terminals (offset null terminals) which allow you to adjust out some or all of the offset voltage.

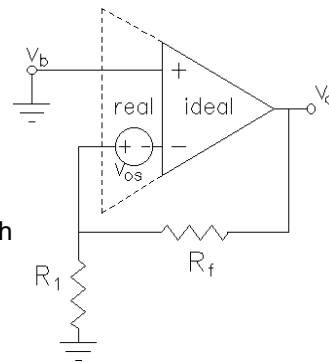
To figure out how much output you get just because of v_{os} , do superposition and zero the input voltage.



$$i_{in} = \frac{v_{os}}{R_{in}} = \frac{v_o - v_{os}}{R_f}$$

$$v_o = \frac{R_1 + R_f}{R_1} \cdot v_{os}$$

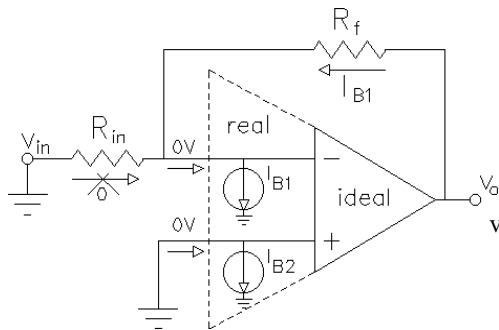
Same for both



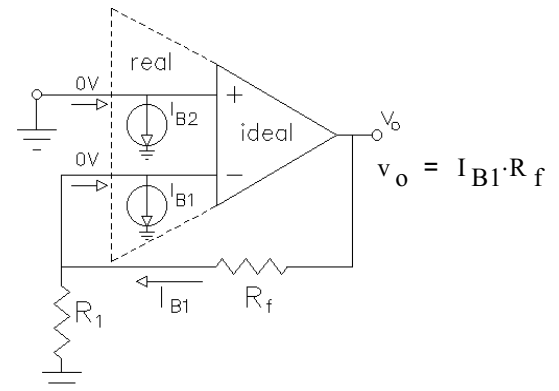
If you look carefully at this circuit, you'll see that with the input zeroed, it is exactly the same as the inverting amp.

Input bias currents

The currents into an op amp really aren't 0, as in the ideal case. But oddly, they don't really depend much on the input voltage. These input currents are pretty constant bias currents, and so can be thought of as sources.



Again, the two circuits are exactly the same



The cure (if $I_{B1} = I_{B2}$):

If $v_o = 0$

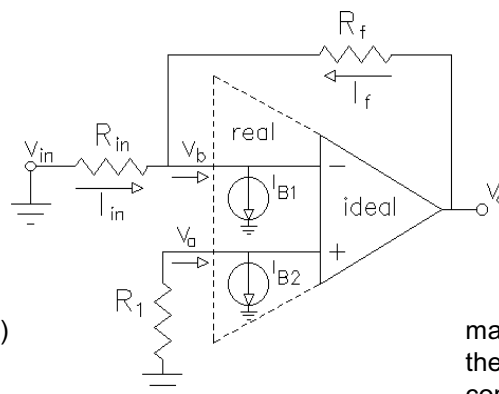
$$v_b = (R_f \parallel R_{in}) I_{B1}$$

$$\text{if } R_1 = (R_f \parallel R_{in})$$

$$\text{then } v_a = (R_f \parallel R_{in}) I_{B2}$$

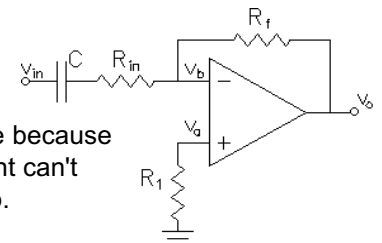
So: make $R_1 = (R_f \parallel R_{in})$

$$R_f \parallel R_{in} = \frac{1}{\frac{1}{R_f} + \frac{1}{R_{in}}}$$



want $v_o = 0$, so let's assume it is

make $R_1 = R_f$ here because the DC bias current can't come through cap.



Typ. $I_B =$
 10 - 100 nA for BJT
 10 - 100 pA for FET op amps & varies with temp.
 1 - 50 pA for MOSFET

Offset current If $I_{B1} \neq I_{B2}$ then you're back to the circuits above. $v_o = I_{os} \cdot R_f$

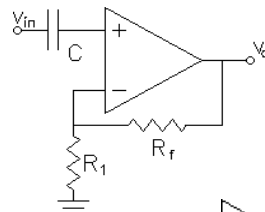
could adjust R_1 to compensate.

$$I_B = \frac{I_{B1} + I_{B2}}{2}$$

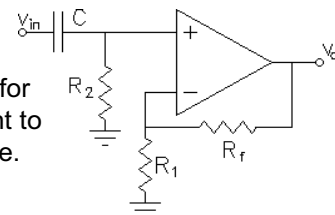
$$I_{os} = |I_{B2} - I_{B1}| \quad \text{Typ. 5 - 50\% of } I_B$$

Must consider bias currents in designs with caps.

Why won't this circuit work with a real op amp?



Must allow a path for the DC bias current to flow, R_2 in this case.



Output Current Limits

Op amp output currents are quite limited. The "source" limit may be different than the "sink" limit.

Typically 5 - 50 mA

