A. Stolp
1/30/03,
1/31

## 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

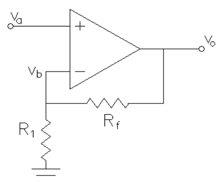
**HW #8, due F, 2/7** Ex2.21 - Ex2.26, problems 2.78, 2.84, 2.95 DO HW #8 BEFORE EXAM 1!

**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

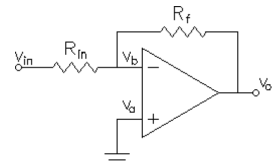
## Non-ideal (Real) Op amps, continued

### Step response

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



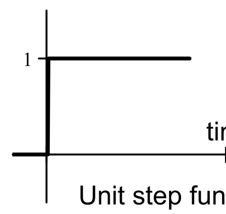

$$G = 1 + \frac{R_f}{R_1} \qquad \omega_c \cong \frac{A_o \cdot \omega_b}{G} = \frac{\omega_t}{G}$$




$$G = \frac{R_f}{R_{in}} \qquad \omega_c \cong \frac{A_o \cdot \omega_b}{G+1} = \frac{\omega_t}{G+1}$$

Essentially, an op amp amplifier is a low-pass filter so the step response is the same as for a low-pass filter.

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



Unit step function, u(t)

Laplace transform of u(t)

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

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

The Laplace transform of the output is simply the Laplace transform of the input x H(s).

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

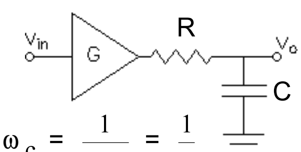
solve for the constants $K_1$ & $K_2$: $G \cdot v_{in} \cdot \omega_c = K_1 \cdot s + K_2 \cdot \omega_c + K_2 \cdot s$ $\qquad K_2 = G \cdot v_{in}$ $\qquad 0 = K_1 \cdot s + K_2 \cdot s$

$$K_1 = -K_2 = -(G \cdot v_{in})$$

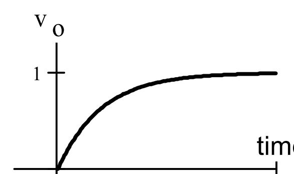
$$V_o(s) = \frac{K_1}{(\omega_c + s)} + \frac{K_2}{s} = \frac{-(G \cdot v_{in})}{(\omega_c + s)} + \frac{G \cdot v_{in}}{s}$$

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

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




With a step input, the output is just a charging capacitor. $\omega_c = \frac{1}{R \cdot C} = \frac{1}{\tau}$



Step response

The maximum slope of this function occurs at t = 0, and is: $G \cdot v_{in} \cdot \omega_c$

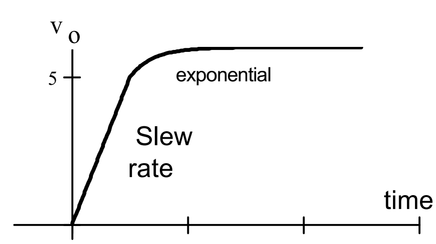
Only if: $G \cdot v_{in} \cdot \omega_c$ < SR

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 (SR)

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/µs. 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.

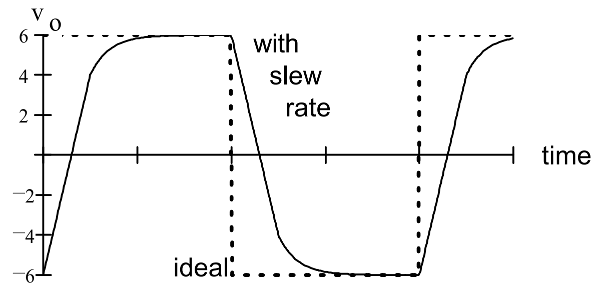
Usually the exponential part of this curve is neglected or overlooked, and you just think of the output as a straight slope until it reaches the correct output voltage.



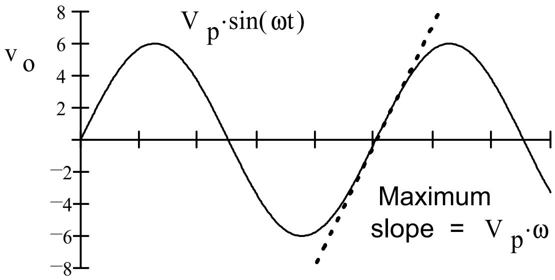
Much more common
Unit step response

## Slew Rate continued

A square wave just acts like a repeating step function:




What if your output is a sine wave?

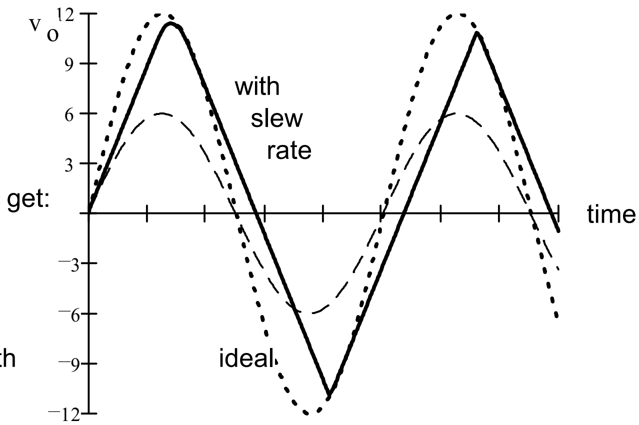



Maximum slope $= V_p \cdot \omega$ must be less than the slew rate, so: $f_{max} = \dfrac{SR}{V_p \cdot 2 \cdot \pi} = \dfrac{SR}{V_{pp} \cdot \pi}$

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

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.

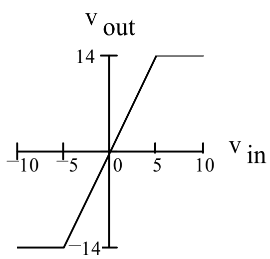
$$f_{max} = \frac{SR}{V_p \cdot 2 \cdot \pi} = \frac{SR}{V_{pp} \cdot \pi}$$ = the full-power bandwidth for sine waves

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

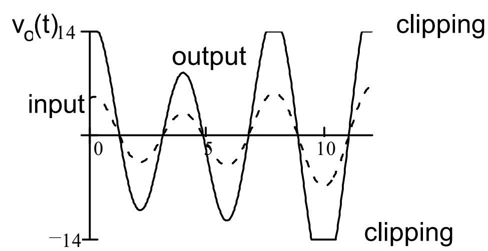
## Clipping (output saturation)

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

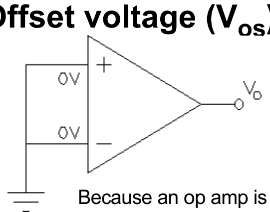



Clipping levels are functions of the output (or load) current, and are usually specified for a specific load resistor.

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

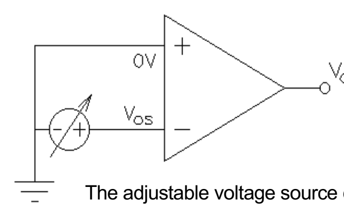
### Offset voltage ($V_{os}$)




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

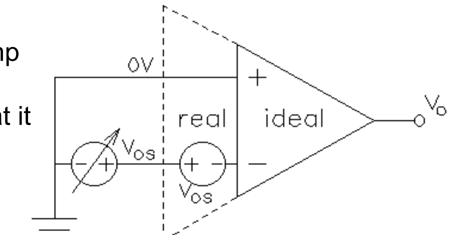
Because an op amp is a very high-gain direct-coupled (amplifies DC) amp, even very tiny and unavoidable transistor mismatches in the input differential amplifier will cause significant offsets at the output.

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.

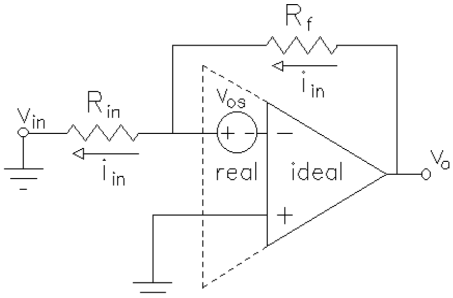
Now we can think of the real op amp as having an offset voltage ($V_{os}$) embedded within it, and beyond that it is ideal. $V_{os}$ is typically a few mV.




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.

$V_{os}$ is affected by temperature, typically drifting 10 - 20$\mu$V/$^o$C.

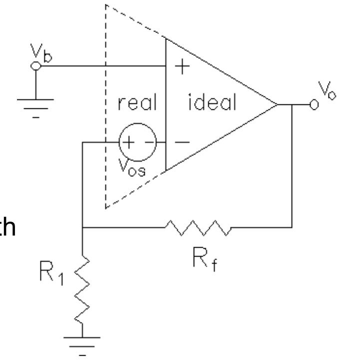
To figure out how much output you get just because of $V_{os}$, do superposition and zero the input voltage.




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

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

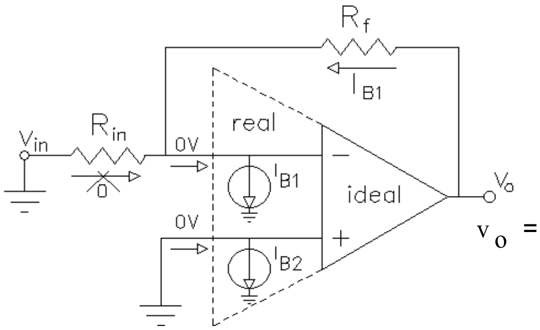
Same for both




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

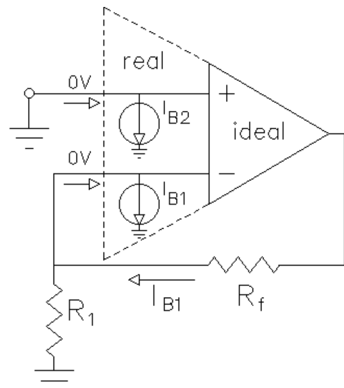
## Input bias currents ($I_{B1}$, $I_{B2}$, ave = $I_B$)

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.




$v_o = I_{B1} \cdot R_f$

Again, the two circuits are exactly the same




$v_o = I_{B1} \cdot R_f$

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

If $v_o = 0$

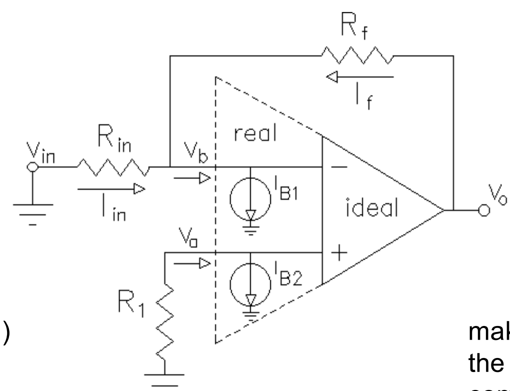
$v_b = (R_f \| R_{in}) I_{B1}$

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

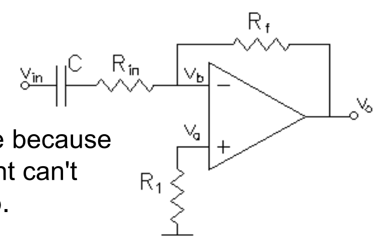
then $v_a = (R_f \| R_{in}) I_{B2}$

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

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




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, 1 - 50 pA for MOSFET op amps & varies with temp.

**Offset current ($I_{os}$)** If $I_{B1}$ not = $I_{B2}$ then you're back to the circuits above. $v_o = I_{os} \cdot R_f$

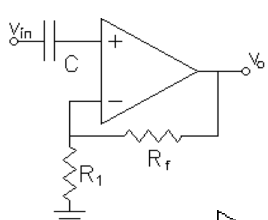
could adjust $R_1$ to compensate.

$$I_B = \frac{I_{B1} + I_{B2}}{2} \qquad I_{os} = \left| I_{B2} - I_{B1} \right|$$

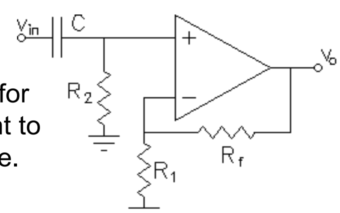
Typ. 5 - 50% of $I_B$.

**Must consider** bias currents in designs with caps.

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



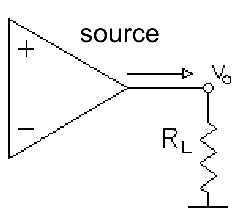

Must allow a path for the DC bias current to flow, $R_2$ in this case.

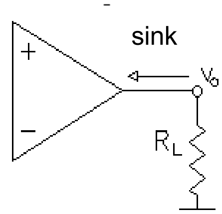



## Output Current Limits

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

Typical limits: 5 - 50 mA






That's it for op amps, next time: Diodes