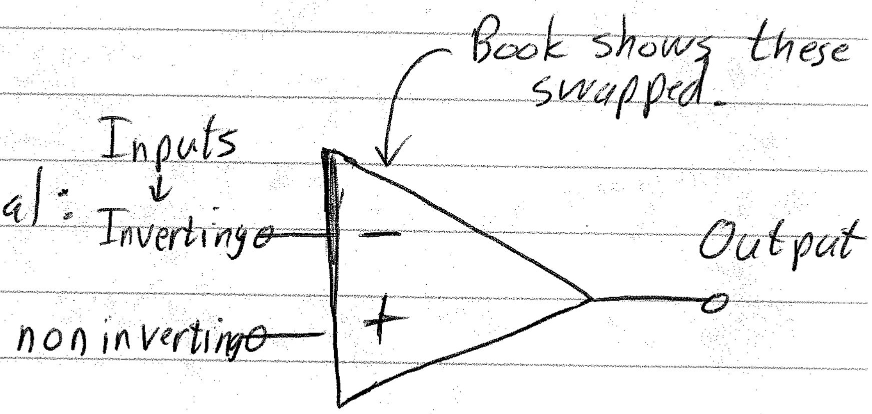
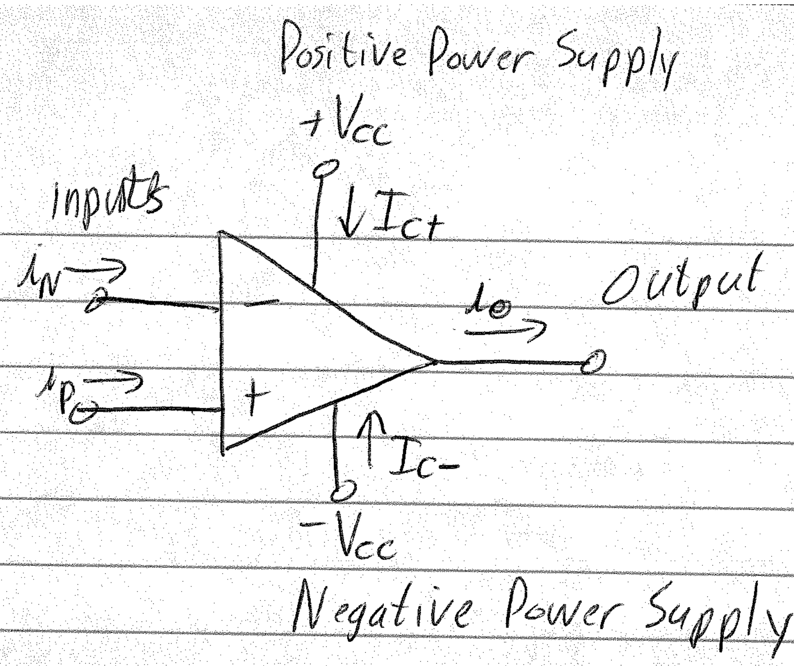
We're going to now introduce a device that you will not see in PHY 122, which contains a Dependent Source. It is the Operational Amplifier, or Op Amp. A pretty good history is in the book, page 177, so I will not repeat it here.

Symbols:

Three Terminal:
(the one we will use most often)



This contains a Dependent Source, so can insert energy into the circuit that contains it, so must be getting that energy from somewhere. It is implicit in the 3 Terminal model, and made explicit in the 5 Terminal model:

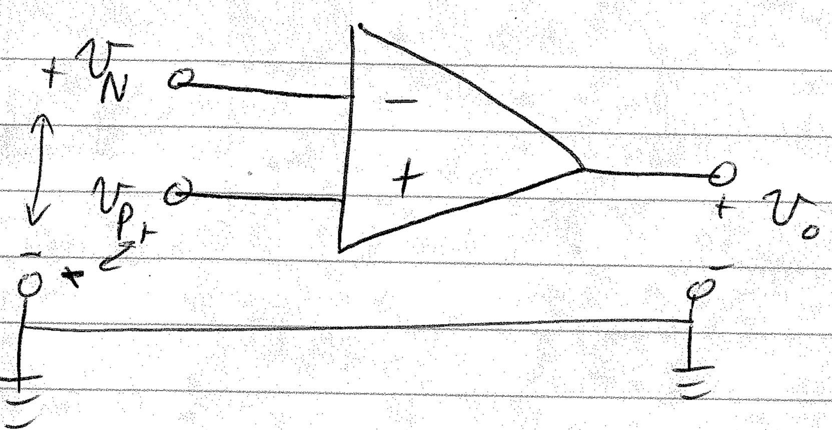


If we name currents in or out of all wires (draw and name) the we can apply KCL:

$$i_o = I_{C+} + I_{C-} + i_p + i_N \quad \text{(correct KCL)}$$

The 3 Terminal model does not include I_{C+} or I_{C-}, ~~since~~ giving us $\cancel{i_o = i_p + i_N}$ which implies that the output current comes from the inputs, which is <u>incorrect</u>. ~~We will never~~

The output voltage of an op amp is proportional to the difference between the two input voltages:



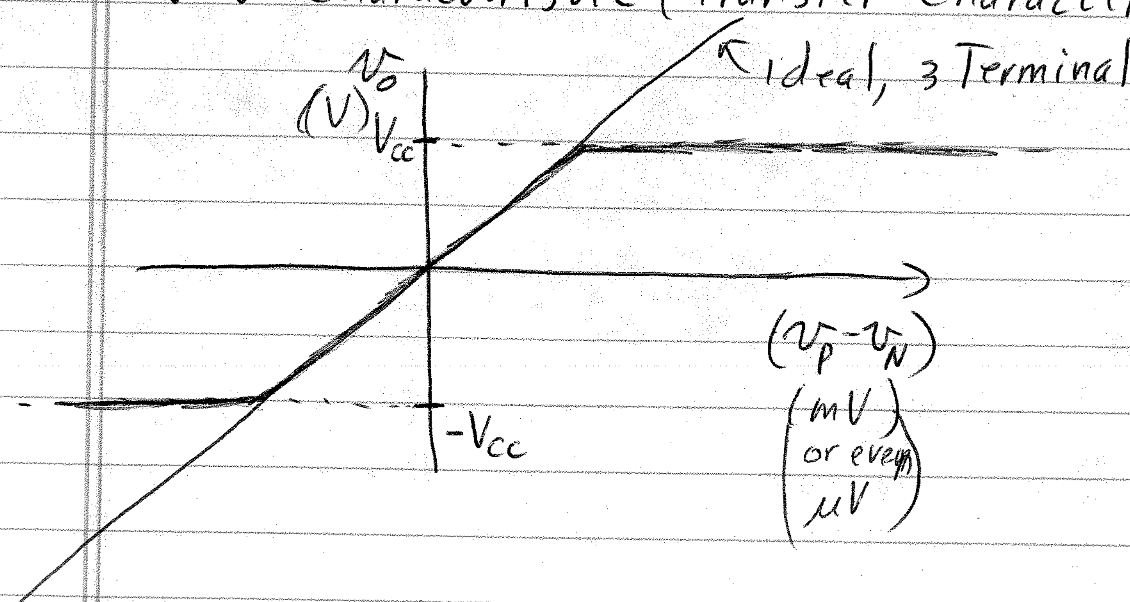
$v_o = A(v_P - v_N)$ I will also often use $(v_P = v_+)$ and $(v_N = v_-)$

or

$v_o = A(v_+ - v_-)$

A (called the Open-Loop Voltage Gain) is very large, typically $> 10^5$.

IV-V characteristic (Transfer Characteristics)



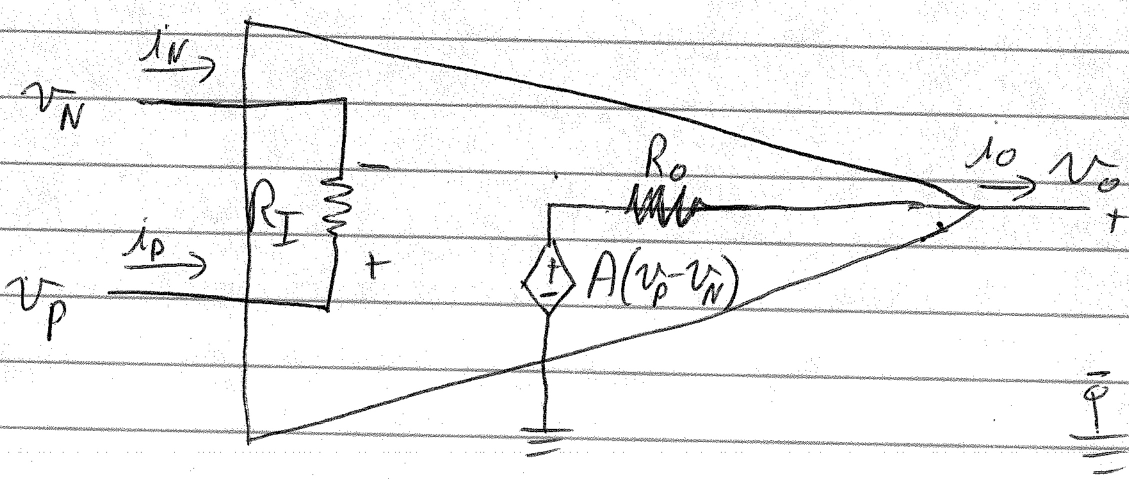
In reality, the output cannot exceed the Power Supply voltage (or maybe a little less) so there are places where the output flattens out. (draw)

3 modes: + and - <u>Saturation Modes</u>

and <u>Linear Mode</u> in between.

<u>Usually</u> we use Op-Amps for the Linear Mode, but sometimes we actually want it to be in saturation, more on that later.

Ideal Op Amp Model, in linear range:



Parameters:	Range
R_I	$10^6 \le R_I \le 10^{12}\ \Omega$
R_o	$1\text{-}10 \le R_o \le 100\ \Omega$
A	$10^5 \le A \le 10^8$

To operate in Linear Mode, the output is limited to $+V_{cc}$ and $-V_{cc}$, so

$$\cancel{+V_{cc} \leq (v_p - v_N)}$$

$$-V_{cc} \leq A(v_p - v_N) \leq V_{cc}$$

or $$-\frac{V_{cc}}{A} \leq (v_p - v_N) \leq \frac{V_{cc}}{A}$$

Since A is very large we take the $\lim_{A \to \infty}$

$$-0 \leq (v_p - v_N) \leq 0$$

This means $v_p - v_N = 0$
or $\underline{v_p = v_N}$

(The Ideal Op Amp will work to make $v_p = v_N$)

Also, since R_I is very large, we take the $\lim_{R_I \to \infty}$, which makes the inputs open ckts.

$$\underline{i_p = 0}, \quad \underline{i_N = 0}$$

Golden Rules for an Ideal Op Amp with resistive negative feedback (more on that later)

1) $i_p = i_N = 0$

2) $v_p = v_N$