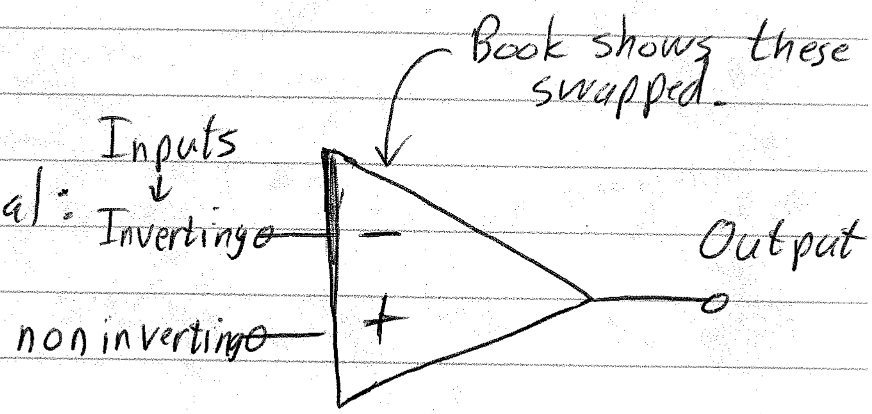
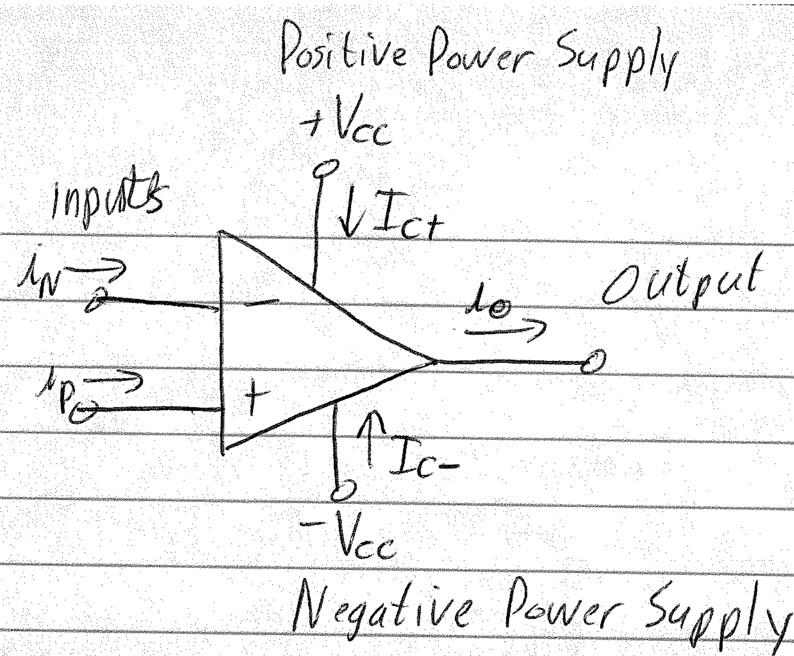
We're going to now introduce a device that you will not see in PHY 122, which contains a Dependent Source. It is the Operational Amplifier, or Op Amp. A pretty good history is in the book, page 177, so I will not repeat it here.

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:

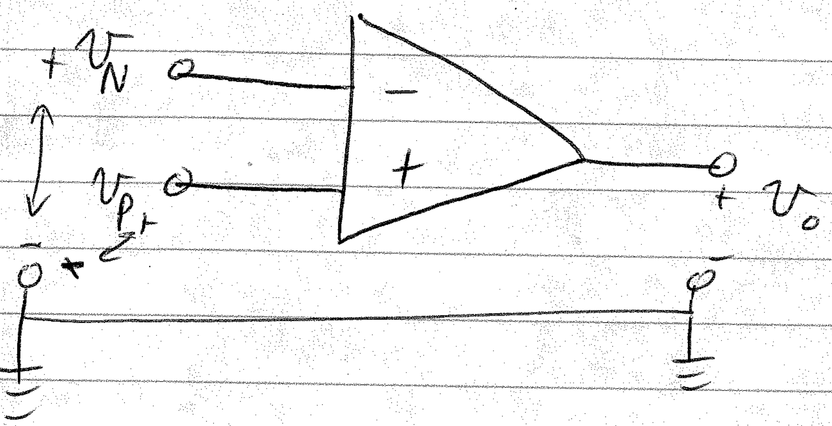


If we name currents in or out of all wires (draw and name) the we can apply KCL:

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

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 incorrect. ~~We will never~~

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



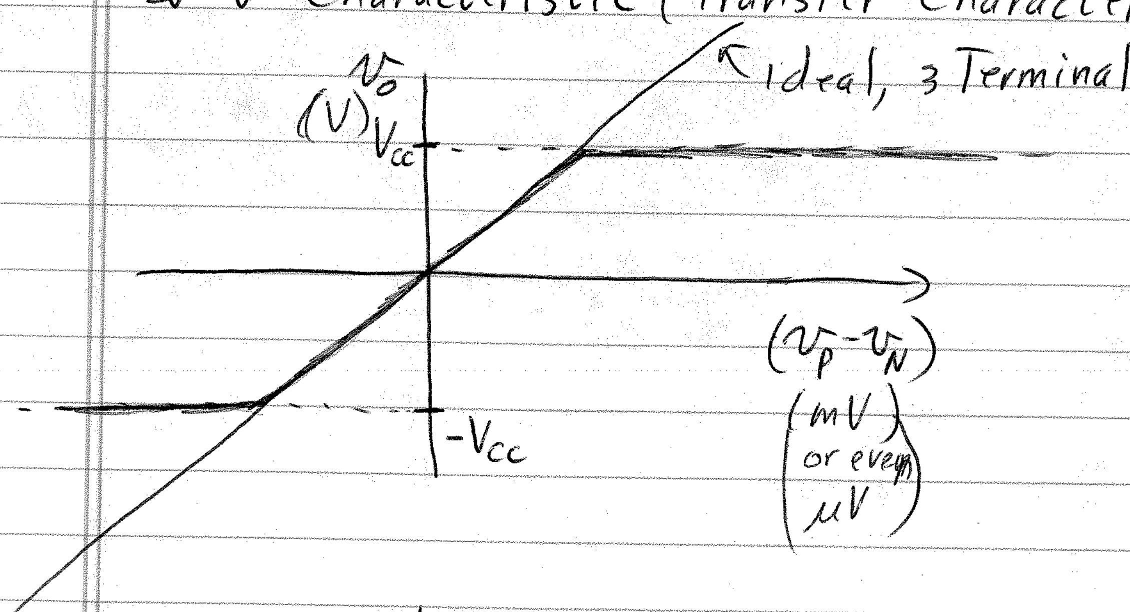
$v_o = A(v_P - v_N)$ I will also often use $(v_P = v_+)$ and $(v_N = v_-)$

or

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

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

V-V characteristic (Transfer Characteristics)



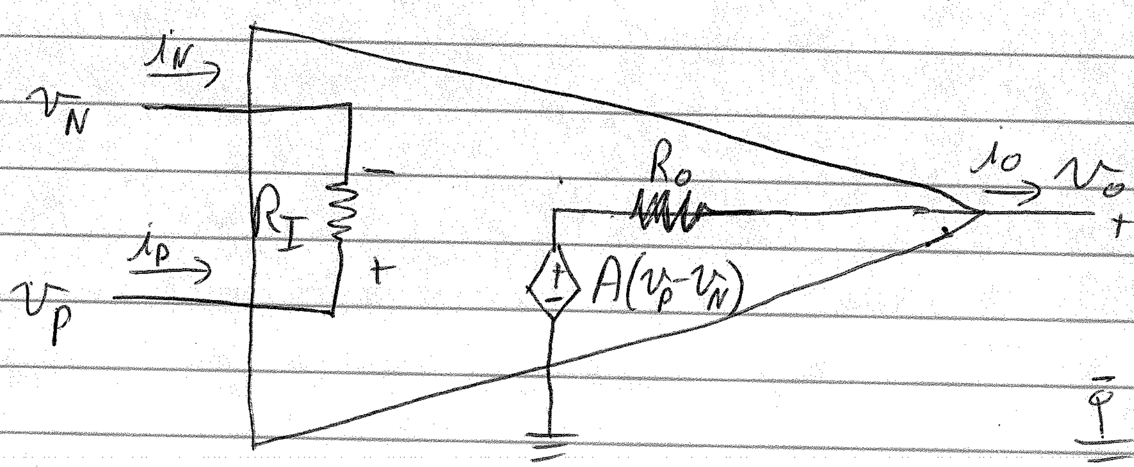
In reality, the output cannot exceed the Power Supply voltage (or maybe a little less) so there are places where the output flattens out. (draw)

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: ~~R~~ 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.

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

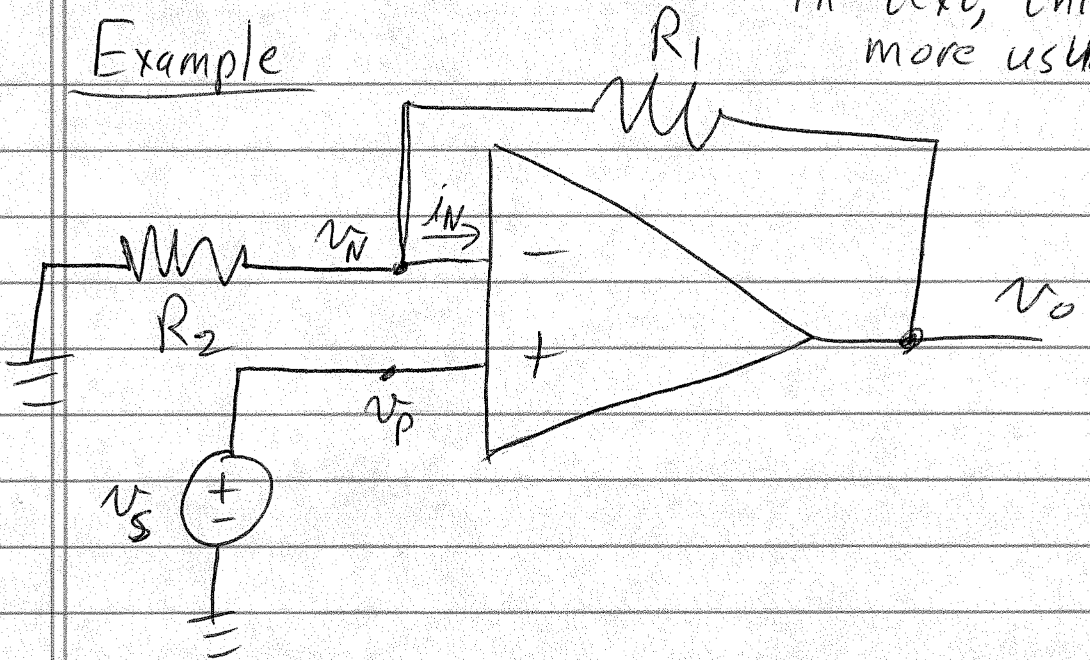
Golden Rules for an Ideal Op Amp with resistive negative feedback (more on that later)

1) $i_p = i_N = 0$

2) $v_p = v_N$

Drawn differently in text, this is the more usual way.

Example



Analyzed differently in text, I'm going to apply a pretty standard, general, approach.

1.) There is resistive ~~feed~~ negative feedback (resistor from output to $-$ input) so Golden Rules apply.

2.) Apply KCL at inverting input.

$$\frac{v_N - 0}{R_2} + \frac{v_N - v_o}{R_1} + \cancel{i_N}^{\,0} = 0$$ but $i_N = 0$ by G.R. 1

$$\left(\frac{1}{R_2} + \frac{1}{R_1}\right) v_N - \frac{1}{R_1} v_o = 0$$

$$\frac{R_1 + R_2}{R_1 R_2} v_N - \frac{1}{R_1} v_o = 0$$

$$\frac{1}{R_1} v_o = \frac{R_1 + R_2}{R_1 R_2} v_N$$

$$v_o = \cancel{R_1} \frac{R_1 + R_2}{\cancel{R_1} R_2} v_N$$

$$v_o = \left(1 + \frac{R_1}{R_2}\right) v_N$$

3.) Use $v_N = v_p$: Lookat v_p: $v_p = v_s$, so

$v_N = v_s$, so

$$v_o = \left(1 + \frac{R_1}{R_2}\right) v_s$$

(Output) = G (Input)

$$G = \left(1 + \frac{R_1}{R_2}\right)$$

feedback R or R_f

input R or R_I

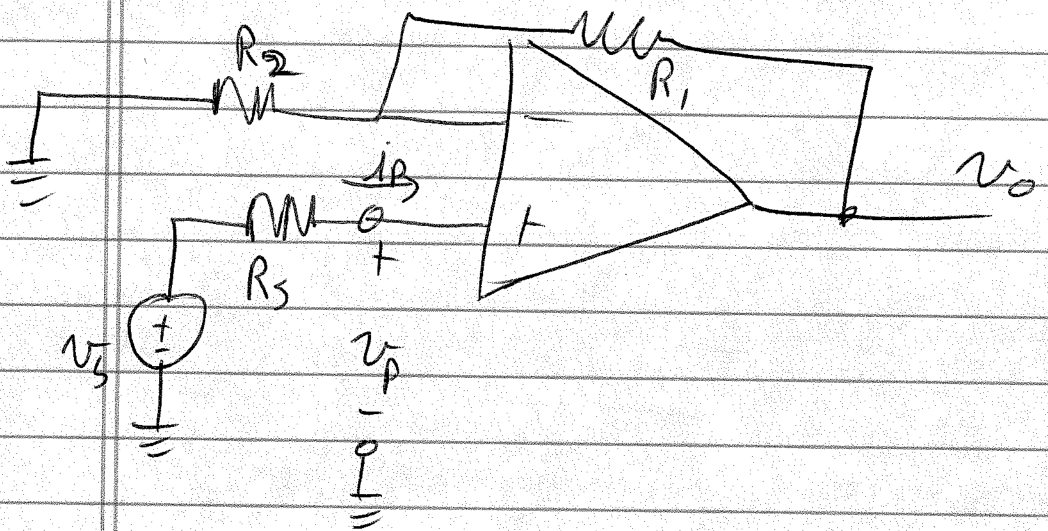
$$G = \left(1 + \frac{R_F}{R_I}\right)$$

G is positive, so Non inverting

Can choose $\frac{R_F}{R_I}$ to be about anything we want, usually limit it to be $< 1{,}000$

G is called the Closed Loop Gain, because R_1 has "Closed the Loop" to provide feedback

What if we have a Practical Source providing the input instead of an Ideal Src?



KVL: $R_s i_p + v_p - v_s = 0$

but $i_p = 0$, so $R_s(0) = 0$, or

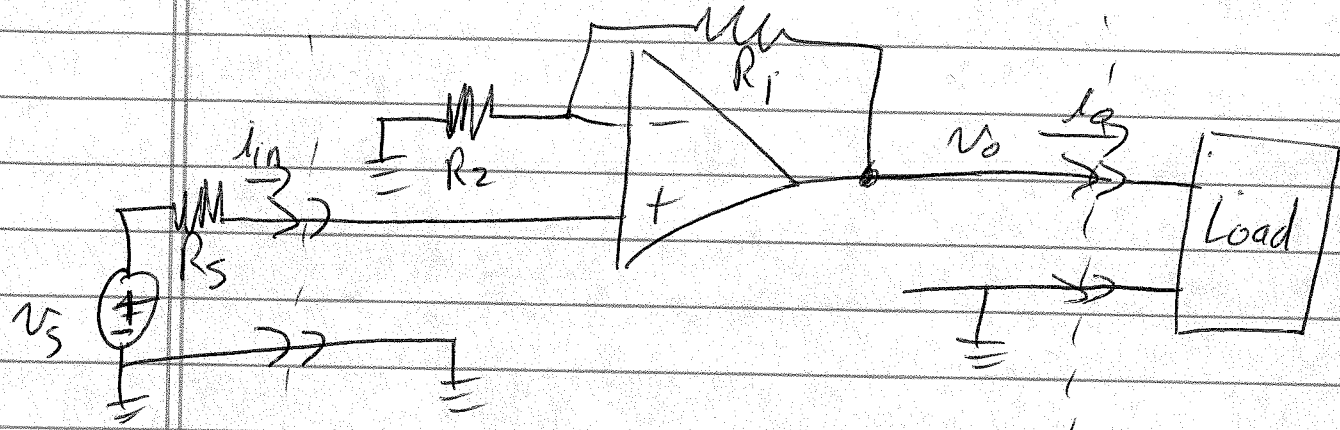
$$0 + v_p - v_s = 0$$
$$v_p = v_s \quad \text{as before}$$

~~No in~~ Equivalent of $i_p = i_N = 0$ are the words,

GR 2: No current flows in or out of the inputs of an Ideal Op Amp. (always true)

GR1 With resistive feed back, an Ideal Op Amp works to make $v_p = v_N$.

What are the Thevenin Input + Output Equivalents?



input 

For all inputs, $i_{in} = 0$, so

$$R_{in} = \frac{v_S}{i_{in}}$$

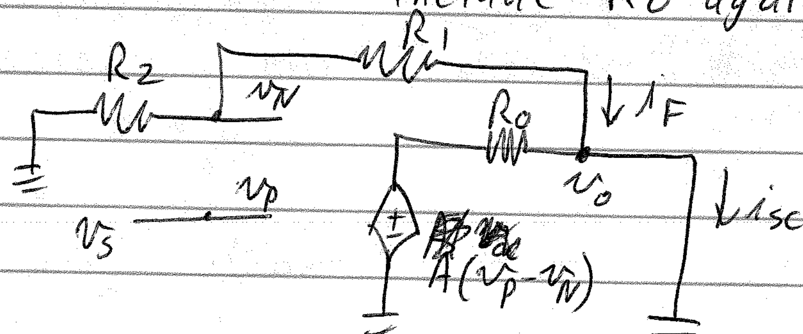
$$\underline{R_{in} = \frac{v_S}{0} = \infty}$$

output

We know v_{oc} already,

$$\underline{v_{oc} = \left(1 + \frac{R_1}{R_2}\right) v_S}$$

To put a short ckt in we have to include R_o again:



Inv Input: $\frac{v_N}{R_2} + \frac{v_N - v_o}{R_1} = 0$ but $v_o = 0$, so $v_N = 0$

$$\underline{i_F = 0}$$

$$A(v_p - v_N) = A v_S$$

$$i_{sc} = \frac{A v_S - 0}{R_o} = \frac{A}{R_o} v_S$$

So $R_s = \dfrac{v_{oc}}{i_{sc}} = \dfrac{\left(1+\frac{R_1}{R_2}\right)\cancel{v_s}}{\frac{A}{R_o}\cancel{v_s}}$

$= \dfrac{R_o}{A}\left(1+\dfrac{R_1}{R_2}\right) \leftarrow$ call this G

~~for the case $\left(1+\frac{R_1}{R_2}\right) \ll A$ (say .01A)~~

~~we can~~ ignore

$R_s = R_o \dfrac{G}{A}$ in most cases $G \ll A$,

so $R_s \ll R_o$

or $\underline{R_s \approx 0\ \Omega}$

So the Thev. Eq. output is: