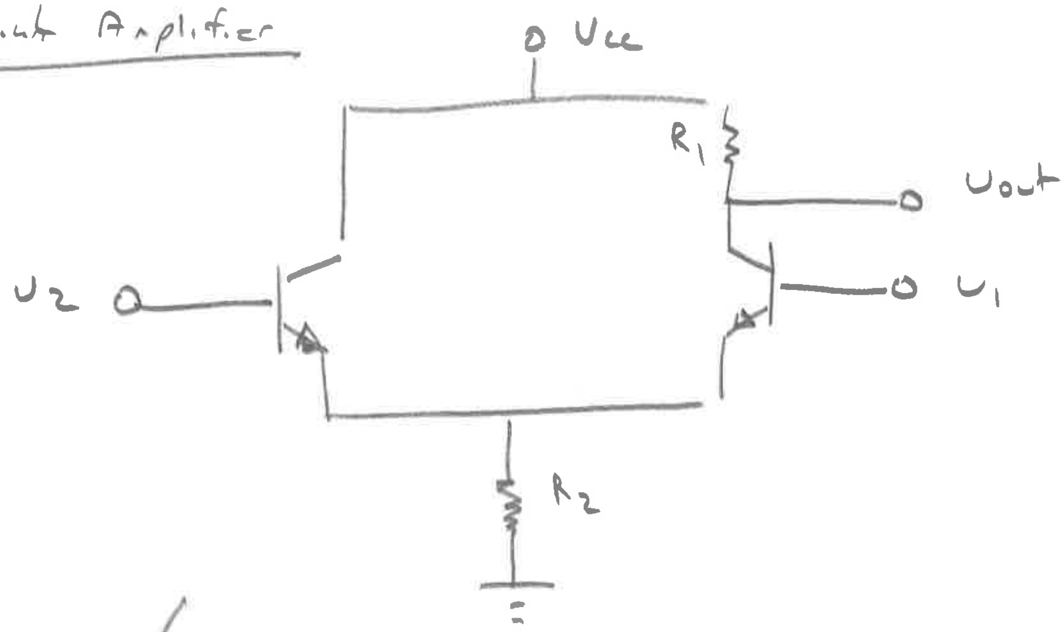
Feedback!

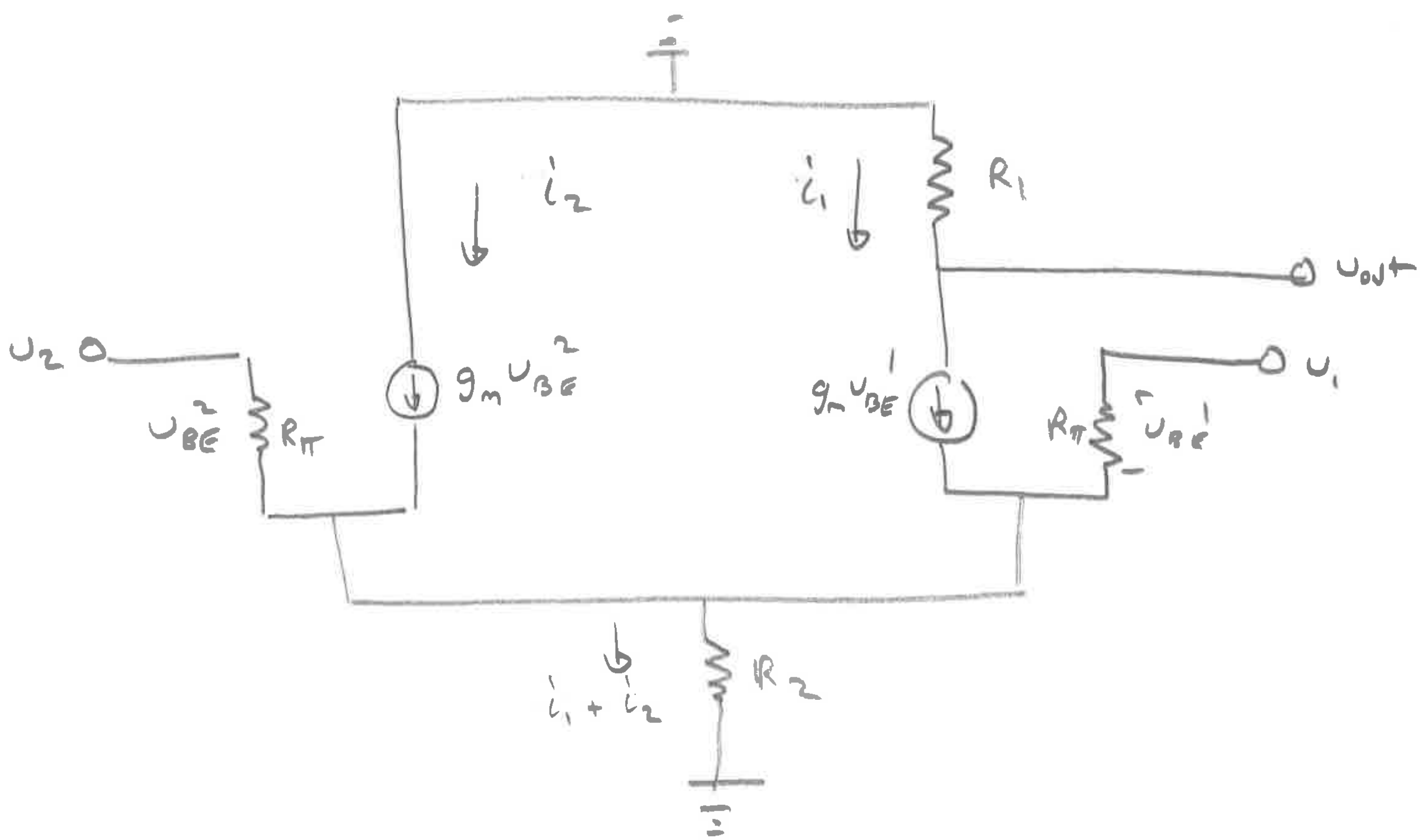
and

Op Amps

Differential Amplifier



AC Model



Case i: $\quad v_1 = v_2 = v_0 \Rightarrow \quad i_1 = i_2$

$$v_{BE}^1 = v_{BE}^2 = v_0 - R_2 (i_1 + i_2)$$

$$v_{BE}^1 = v_0 - 2 R_2 (g_m v_{BE}^1)$$

$$(1 + g_m 2 R_2) v_{BE}^1 = v_0$$

$$v_{BE}^1 = \frac{v_0}{1 + g_m 2 R_2}$$

$$v_{out} = -i_1 R_1 = -g_m v_{BE}^1 R_1$$

$$= \frac{-g_m R_1}{1 + g_m 2 R_2} v_0$$

$$= -\left(\frac{R_1}{r_E + 2 R_2}\right) v_0 = -\left(\frac{R_1}{r_E + 2 R_2}\right)\left(\frac{v_1 + v_2}{2}\right)$$

Case $v_1 = -v_2 = v_0$

$i_2 = -i_1 \Rightarrow$ current in R_2 is zero

$\Rightarrow v_E = 0$

$$v_{BE}^{1} = v_1$$

$$i_1 = g_m v_1$$

$$v_{out} = -i_1 R_1 = -g_m R_1 i_1$$

$$v_{out} = \frac{R_1}{r_E}\left(\frac{v_2 - v_1}{2}\right)$$

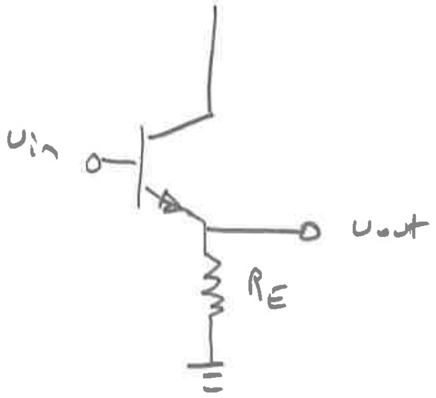
Generally:

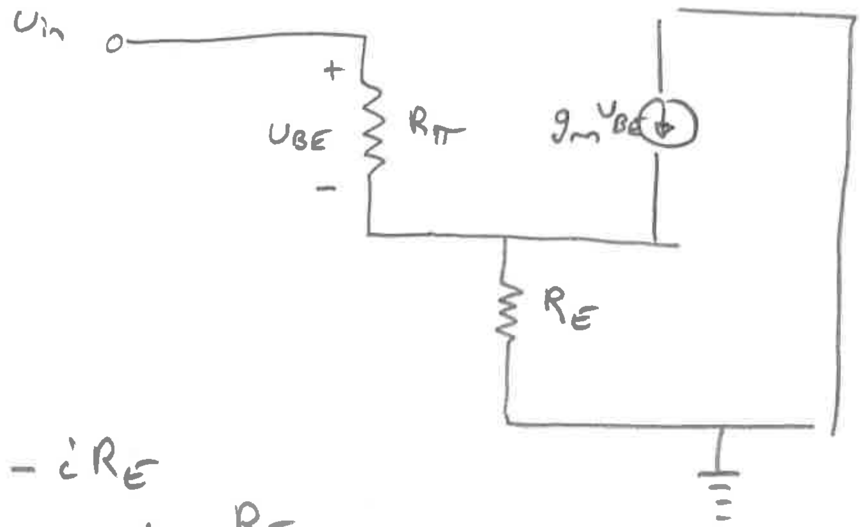
$$v_{out} = \left(\frac{R_1}{r_E + 2R_2}\right)\frac{(v_1 + v_2)}{2} + \left(\frac{R_1}{r_E}\right)\frac{(v_2 - v_1)}{2}$$

Common Mode Rejection

Differential Gain

The Follower and Feedback





① $v_{BE} = v_B - v_E = v_{in} - i R_E$

$$= v_{in} - g_m v_{BE} R_E$$

$$(1 + g_m R_E)\, v_{BE} = v_{in}$$

$$v_{BE} = \frac{v_{in}}{1 + g_m R_E}$$

$$v_{out} = i R_E = g_m v_{BE} R_E = \frac{g_m R_E}{1 + g_m R_E} v_{in}$$

$$v_{out} = \frac{A}{A+1} v_{in} \qquad A = g_m R_E \gg 1$$

$v_{out} \to v_{in}$ as $A \to \infty$

② $v_{BE} = v_B - v_E \Rightarrow v_{BE} = v_{in} - v_{out}$

v_{BE} ↑ gain device input; v_{in} ↑ input; v_{out} ↑ negative feedback

$v_{BE} \to 0$

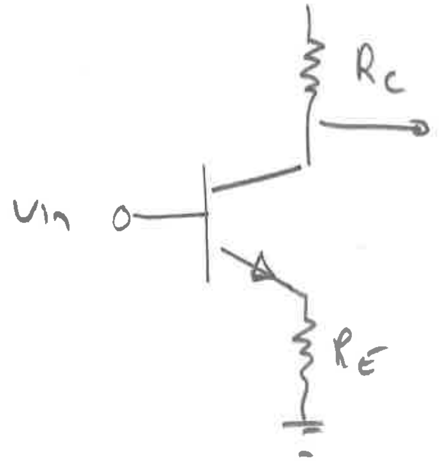
Or,

$$v_{BE} = v_{in} - v_{out} = v_{in} - \frac{A}{A+1} v_{in}$$

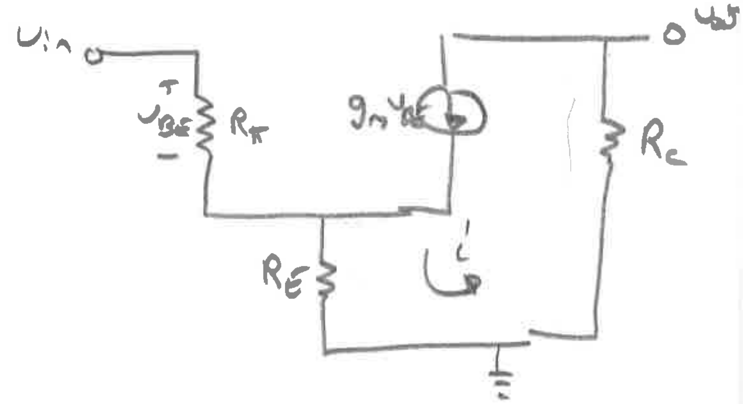
$$\boxed{v_{BE} = \frac{v_{in}}{1 + A}}$$

Negative feedback drives v_{BE} very close to zero, just near enough that large factor A puts $v_{out} \sim v_{in}$

Common Emitter Amplifier and Feedback



$\longrightarrow$



① $$v_{BE} = v_B - v_E = v_{in} - i R_E$$
$$= v_{in} - g_m v_{BE} R_E$$

$$(1 + g_m R_E)\, v_{BE} = v_{in}$$

$$v_{BE} = \frac{v_{in}}{1 + g_m R_E}$$

$$v_{out} = -R_C\, i = -R_C\, g_m v_{BE}$$
$$= -\frac{g_m R_C}{1 + g_m R_E}\, v_{in}$$
$$= \left(-\frac{R_C}{R_E}\right) \frac{g_m R_E}{1 + g_m R_E}\, v_{in} = \left(-\frac{R_C}{R_E}\right) \frac{A}{1+A}\, v_{in}$$

$$v_{out} \longrightarrow -\frac{R_C}{R_E}\, v_{in}$$

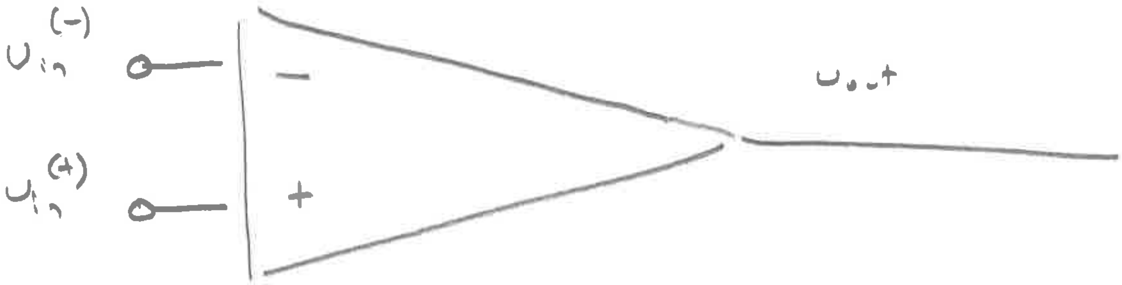
② $$v_{BE} = v_B - v_E \Rightarrow v_{BE} = v_{in} - i R_E$$
$$= v_{in} - \left(-\frac{v_{out}}{R_C}\right) R_E$$

$$v_{BE} = v_{in} - \left(-\frac{R_E}{R_C}\right) v_{out}$$

gain device input — input — negative feedback.

$$\boxed{v_{BE} \to \frac{v_{in}}{A+1} \qquad v_{out} \to \left(-\frac{R_C}{R_E}\right) \frac{A}{A+1}\, v_{in}}$$

Op - Amp

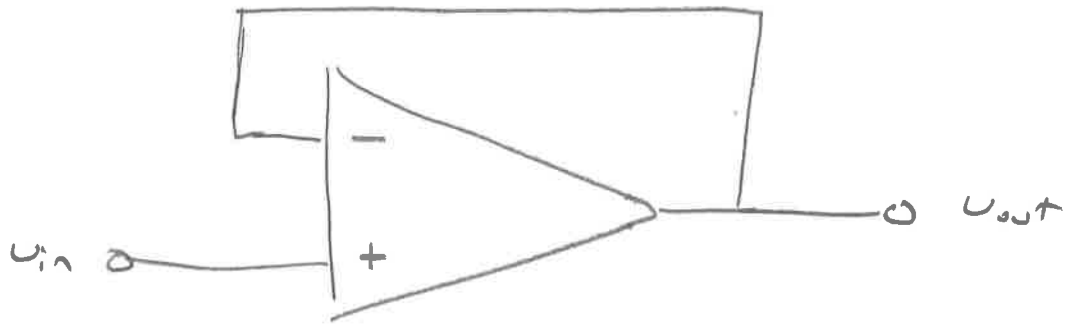


$$\boxed{v_{out} = A\left(v_{in}^{(+)} - v_{out}^{(-)}\right)} \qquad A \to \infty$$

~Infinite input impedance

With $A \to \infty$, nearly useless device until tamed by <u>negative</u> <u>feedback</u> ....

Follower



$$v_{out} = A\left(v_{in}^{(+)} - v_{in}^{(-)}\right)$$

$$= A\left(v_{in} - v_{out}\right)$$

$$(A+1)\, v_{out} = A\, v_{in}$$

$$v_{out} = \frac{A}{A+1}\, v_{in}$$

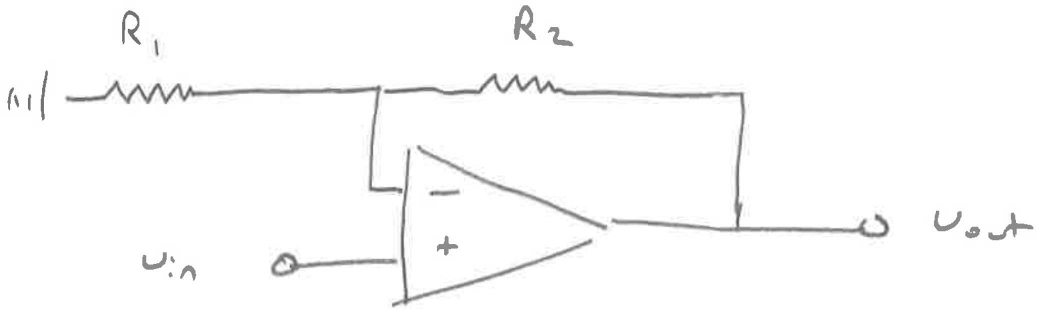
$$v_{out} \to v_{in} \quad \text{when} \quad A \to \infty$$

Notice:

$$v_{in}^{+} - v_{in}^{-} = v_{in} - \left(\frac{A}{A+1}\right) v_{in}$$

$$= \frac{v_{in}}{A+1} \to 0 \ldots$$

Non-inverting Amplifier



$$v_{out} = A\left(v_{in}^{(+)} - v_{in}^{(-)}\right)$$

$$= A\left(v_{in} - \frac{R_1}{R_1+R_2}\, v_{out}\right)$$

$$v_{out} = \left(1 + \frac{R_2}{R_1}\right)\left(\frac{A}{A+1+\frac{R_2}{R_1}}\right) v_{in}$$

$$v_{out} \longrightarrow \left(1 + \frac{R_2}{R_1}\right) v_{in}$$

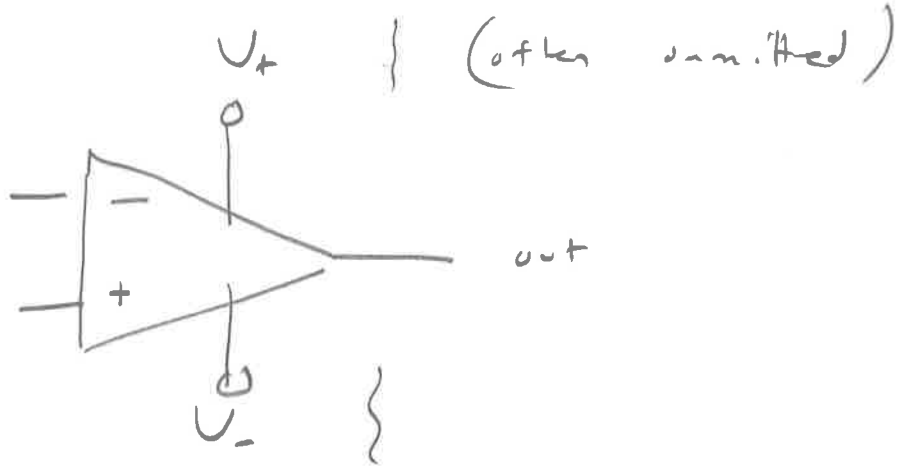
Notice:

$$v_{in}^{(+)} - v_{in}^{(-)} = v_{in} - \frac{R_1}{R_1+R_2}\, v_{out}$$

$$= \left(1 - \frac{A}{A+1+R_2/R_1}\right) v_{in}$$

$$\longrightarrow 0 \quad \text{as} \quad A \to \infty$$

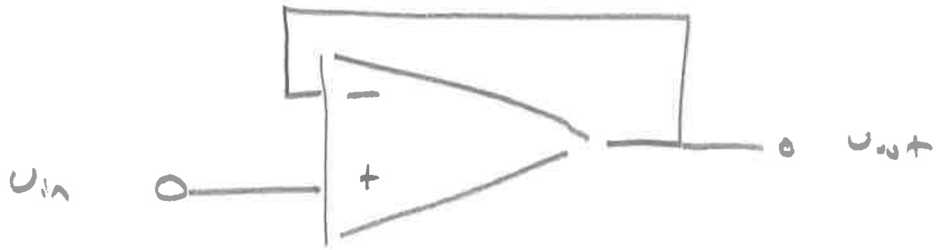
Op-Amp Rules



When negative feedback is present:

1. output does whatever possible to put $v_{in}^{(-)} = v_{in}^{(+)}$.

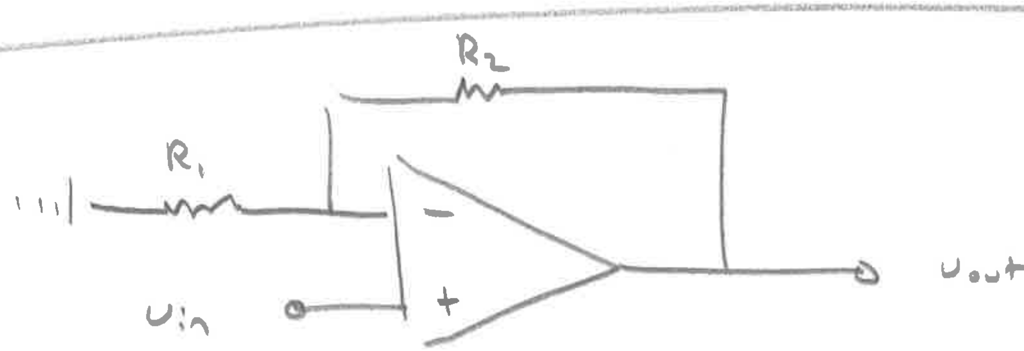
2. input terminals are ~infinite impedance $\Rightarrow$ no current into terminals.



$$U_{in}^{(+)} = U_{in}^{(-)}$$

$$\boxed{U_{in} = U_{out}}$$

$$\boxed{R_{in} = \infty}$$

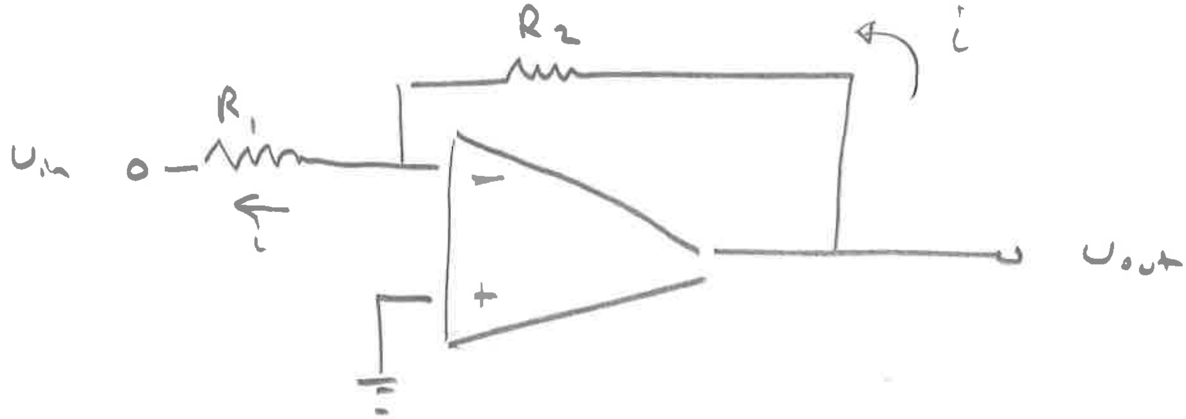


$$U_{in}^{(+)} = U_{in}^{(-)}$$

$$U_{in} = \frac{R_1}{R_1 + R_2} U_{out}$$

$$\boxed{U_{out} = \left(1 + \frac{R_2}{R_1}\right) U_{in}}$$

$$\boxed{R_{in} = \infty}$$



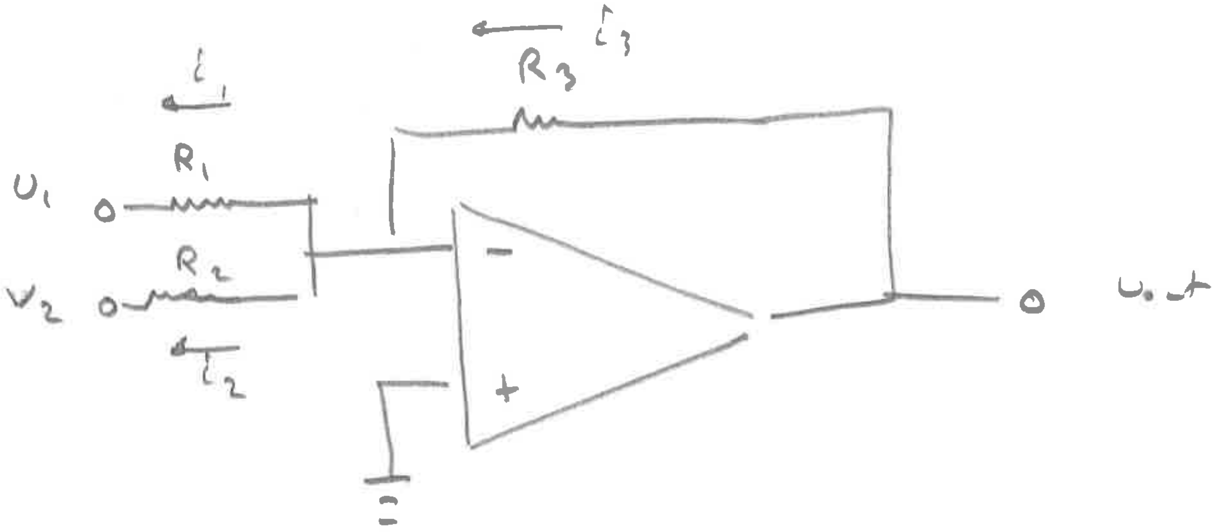
Since $v_{in}^{(-)} = v_{in}^{(+)} = 0$, we say $v_{in}^{(-)}$ is a <u>virtual</u> ground.

$$i = -\frac{v_{in}}{R_1} = \frac{v_{out}}{R_2} \Rightarrow \boxed{v_{out} = \left(-\frac{R_2}{R_1}\right) v_{in}}$$

$$\boxed{R_{in} = R_1} \quad !!!$$

Why ever do this?

1. Current sources <u>like</u> low R_{in} and hate <u>high</u> R_{in}. High quality amps use current sources...
2. $G < 1$ possible.
3. See next...



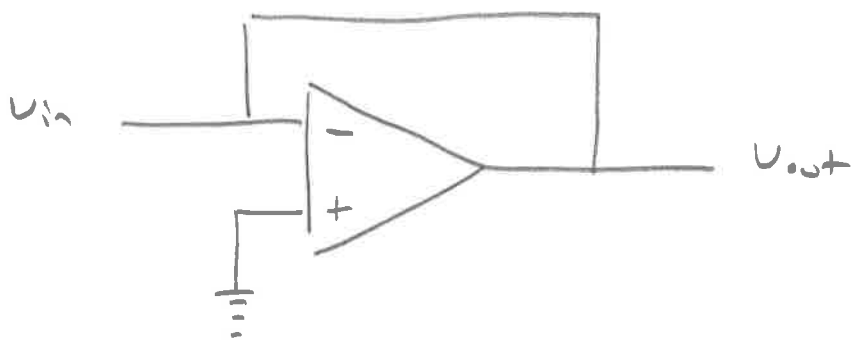
$$i_3 = i_1 + i_2$$

$$\frac{U_{out}}{R_3} = \left(-\frac{U_1}{R_1}\right) + \left(\frac{-U_2}{R_2}\right)$$

$$U_{out} = \left(-\frac{R_3}{R_1}\right) U_1 + \left(-\frac{R_3}{R_2}\right) U_2$$

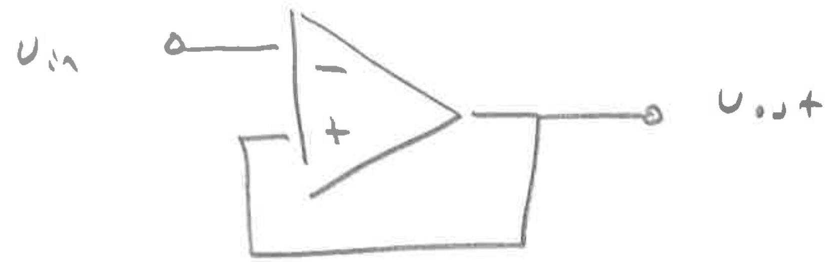
Addition (Mixer)

Problematic Circuits



$V_{in} = V_{out}$, but both are <u>shorted to ground</u>.

Problematic Circuits



Blindly following rules predicts $V_{in} = V_{out}$ ...

Not what happens ... rules apply when negative feedback is present.

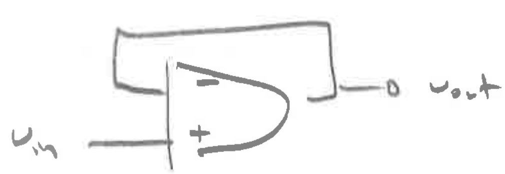
Check by putting V_{out} initially at $\pm\infty$ (or $\pm V_{cc}$) and see if it moves toward zero ...

In this case

$$V_{out} = \infty \Rightarrow V_{out} \to A \cdot \infty$$

$$V_{out} = -\infty \Rightarrow V_{out} \to A(-\infty)$$

Compare with Follower!

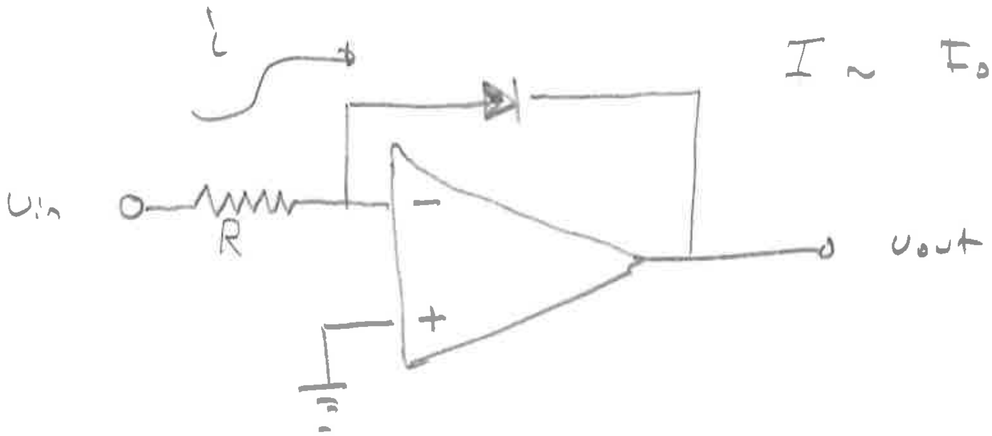


$V_{out} = +\infty$ $\quad V_{out} \to -\infty$ ($V_{out} \downarrow$)

$V_{out} = -\infty$ $\quad V_{out} \to +\infty$ ($V_{out} \uparrow$)

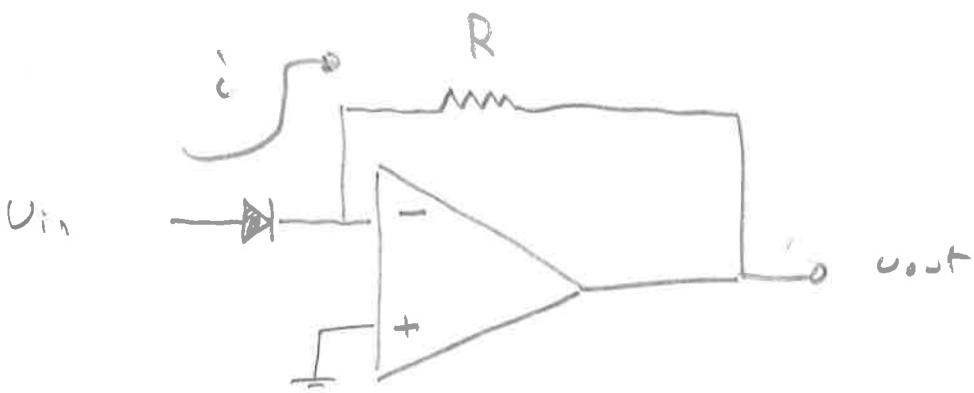
log / "anti log" amplifiers

$$I \sim I_0 \exp\left(\frac{V}{nkT}\right)$$



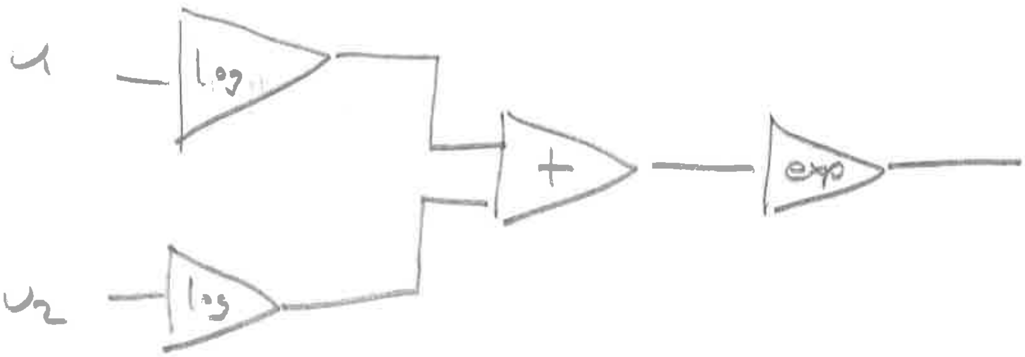
$$i = \frac{V_{in}}{R} = I_0 \exp\left(-\frac{V_{out}}{nkt}\right)$$

$$\boxed{V_{out} = -nkT \log\left(\frac{V_{in}}{I_0 R}\right)}$$



$$\boxed{V_{out} = -I_0 R \exp\left(\frac{V_{in}}{nkT}\right)}$$

Multiplier

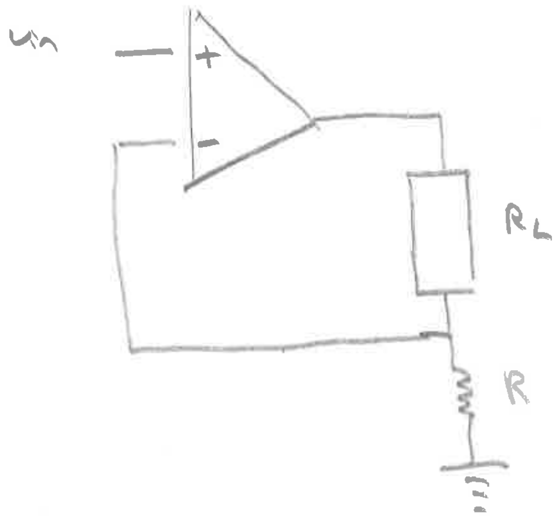


$\boxed{V_{out} \sim V_1 \times V_2}$

- Programmable Gain
- (AM modulation).

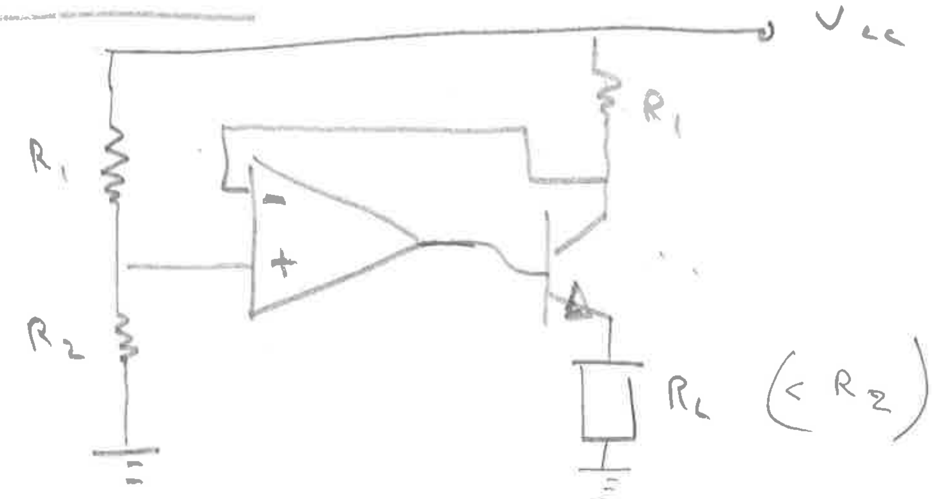
(Harder to make "4-quadrant" multiplier, w/ inputs and outputs allowed negative).

Current Sources



$$I_{out} = \frac{U_{in}}{R}$$

Ground connected:



$$I_L = \frac{V_{cc}}{R_1 + R_2}$$