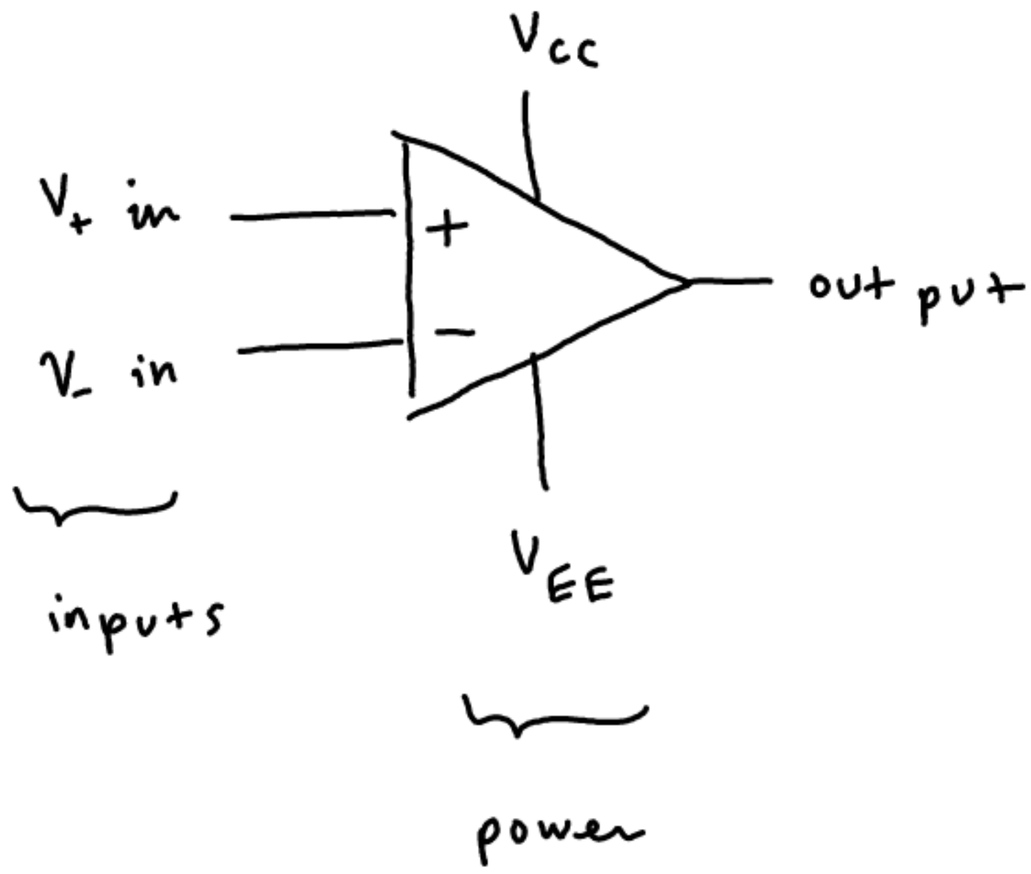
Operational Amplifier (op-amp)



2 inputs → 1 output

$$V_{out} = G_{OL}(V_+ - V_-)$$

↑ open loop gain
a very large number

This works in the active region:

where $(V_+ - V_-)$ gives $|V_{out}| \leq V_{cc}$ and V_{EE}
(below power rails)

$G_{OL} \sim 10^5 - 10^7$ so that active region is very small.

↑

not useful.

need to divide down $(V_+ - V_-)$
until it is close to zero ($\sim \mu V$)

use negative feedback

In the active region, op-amps follow the

Golden Rules

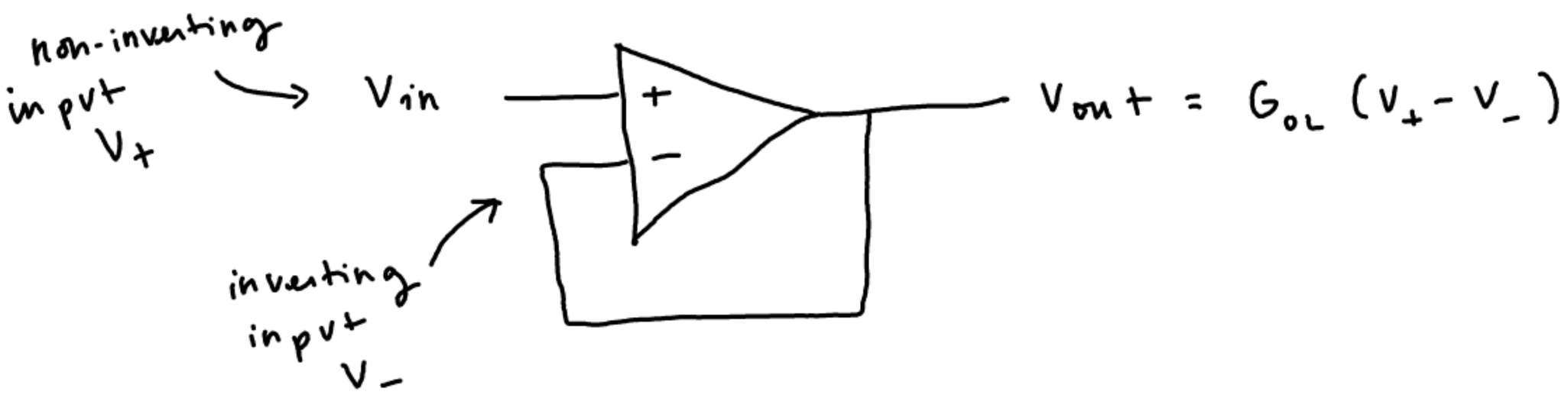
1. The output V_{out} will be whatever value makes $(V_+ - V_-) = 0$

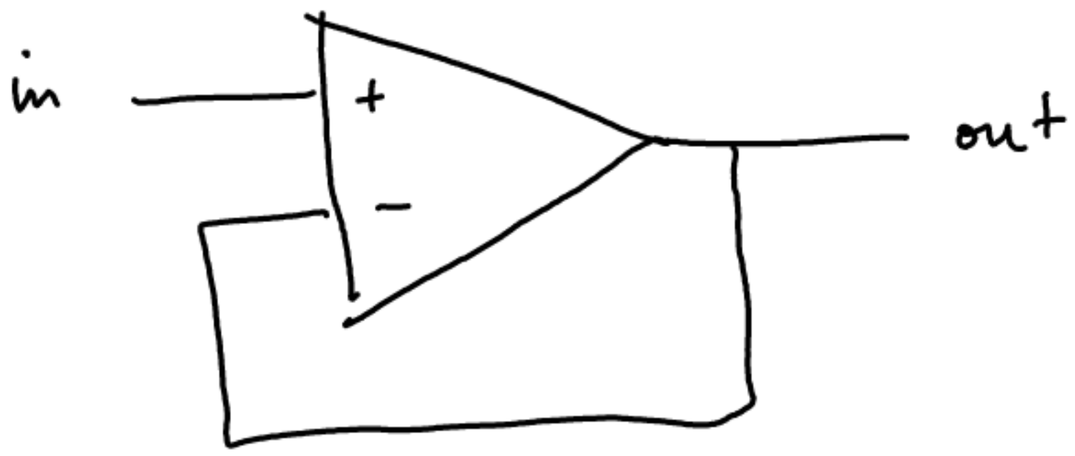
2. The inputs draw no current (very large R_{in})

We can take advantage of the rules the stay in the active region by adding feedback.

Feedback means we take some of the output and feed it back into the input.

Here is the simplest possible example, the unity gain amplifier:





if we ↑ V_{in} : ↑ ΔV

need to ↑ V_- to balance V_+

$V_{out} = V_-$ so we ↑ V_{out}

result: V_{out} follows V_{in}

to satisfy Golden Rule #1.

* why bother?
high Z_{in}, low Z_{out}

We define the closed loop gain (when we have feedback)

$$G_{CL} = \frac{V_{out}}{V_{in}}$$

for the unity gain amplifier, $V_{out} = V_{in}$
and $G_{CL} = 1$.

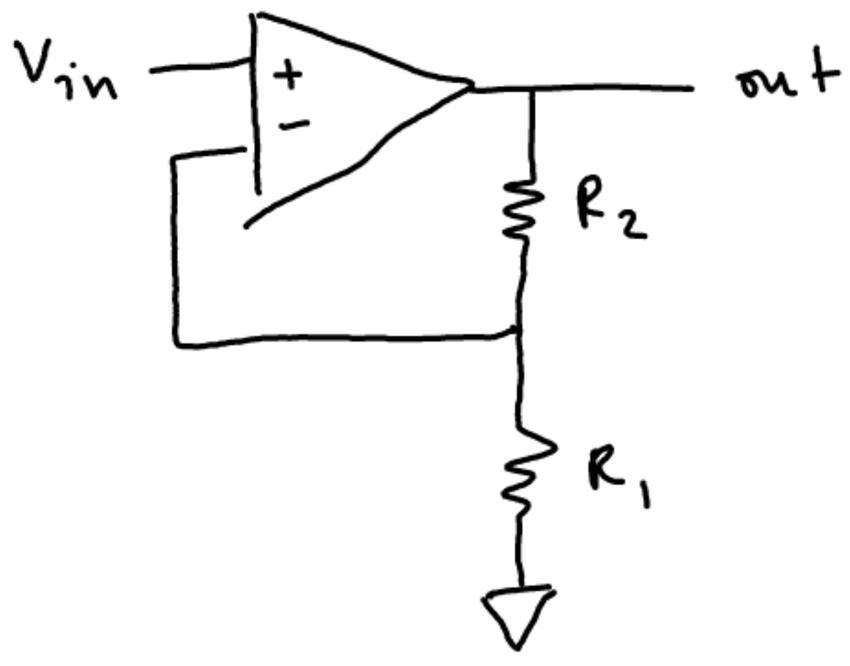
This is negative feedback blc it minimizes ΔV

↖ stabilizing

↑ attached to negative (V_-) input

inverting

Non-inverting Amplifier



(1) Full Analysis :

$$V_- = \frac{R_1}{R_1 + R_2} V_{out} \qquad V_{out} = G_{OL}(V_+ - V_-)$$

$$\downarrow$$

$$V_{out} = G_{OL}\left(V_{in} - \frac{R_1}{R_1+R_2} V_{out}\right)$$

$$V_{out}\left(1 + G_{OL}\frac{R_1}{R_1+R_2}\right) = G_{OL} V_{in}$$

for $G_{OL} >> 1$

$$G_{CL} = \frac{V_{out}}{V_{in}} = \frac{G_{OL}}{\left(1 + G_{OL}\frac{R_1}{R_1+R_2}\right)} \sim \frac{1}{R_1/R_1+R_2}$$

$$G_{CL} \sim 1 + \frac{R_2}{R_1}$$

(2) Simple Model Analysis

$V_+ = V_-$ to stay in active region

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

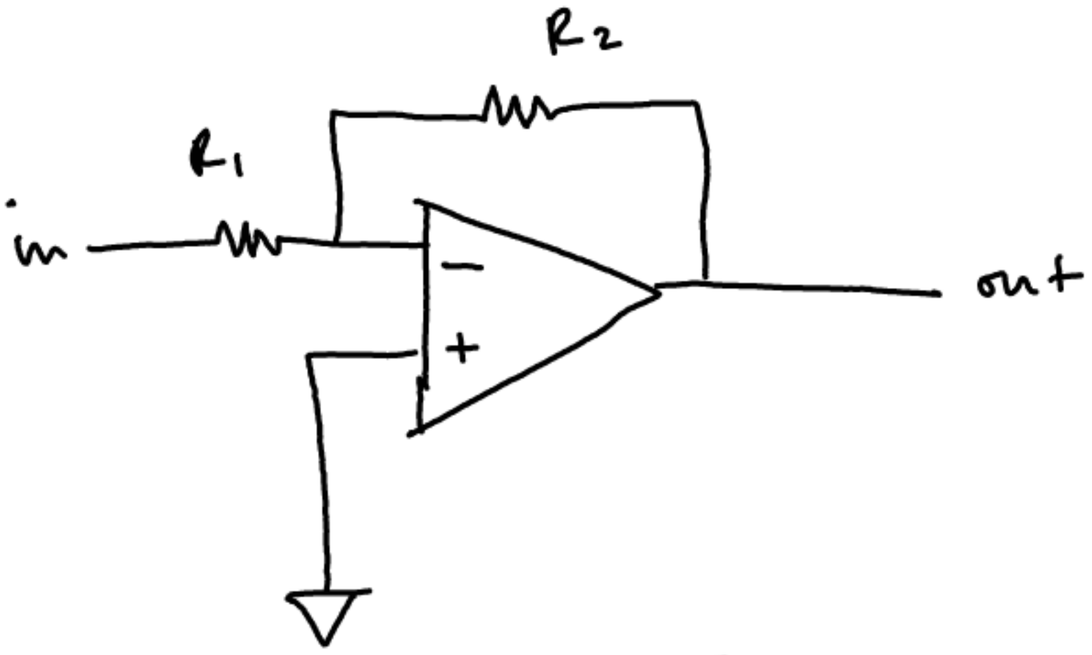
$$G_{CL} = \frac{V_{out}}{V_{in}} = \frac{R_1 + R_2}{R_1} = 1 + \frac{R_2}{R_1}$$

same result
much faster.

non-inverting amp gain is always positive
and always > 1

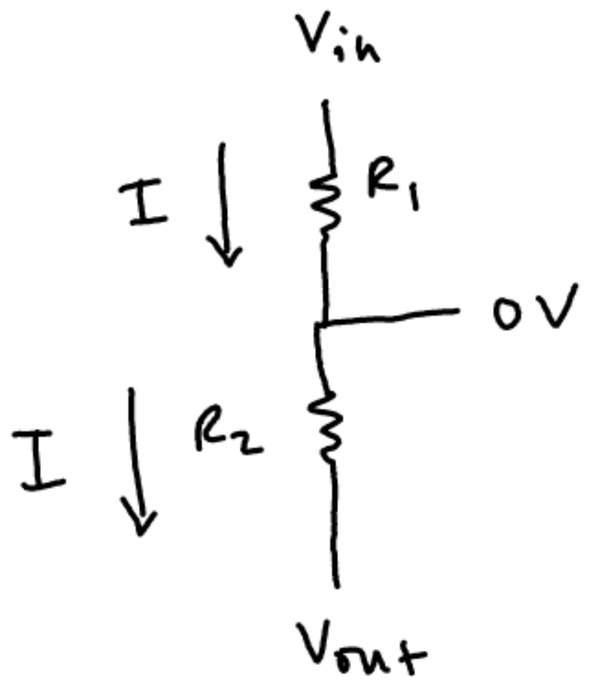
$$\boxed{G_{CL} = 1 + \frac{R_2}{R_1}}$$

Inverting Amplifier



Now the input is on the inverting terminal.

The top can be unfolded:



the mid point is zero by Golden Rule #1.

$(V_+ = V_-)$

By Golden rule #2, no current goes into the V_- terminal even though it's at 0V.

$$\Delta V_{R_1} = I R_1 = V_{in} \rightarrow I = V_{in}/R_1$$

$$\Delta V_{R_2} = -V_{out} = I R_2 \rightarrow I = -V_{out}/R_2$$

$$\frac{V_{in}}{R_1} = -\frac{V_{out}}{R_2}$$

$$G_{CL} = \frac{V_{out}}{V_{in}} = -\frac{R_2}{R_1}$$

negative gain can be < 1