OPERATIONAL AMPLIFIERS

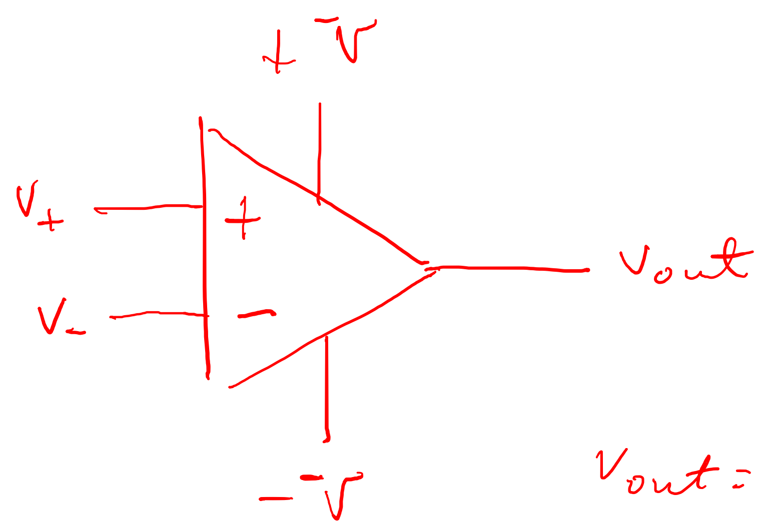
HIGH-GAIN MULTISTAGE TRANSISTOR AMPS

BJT or FET

INTEGRATED CIRCUIT:

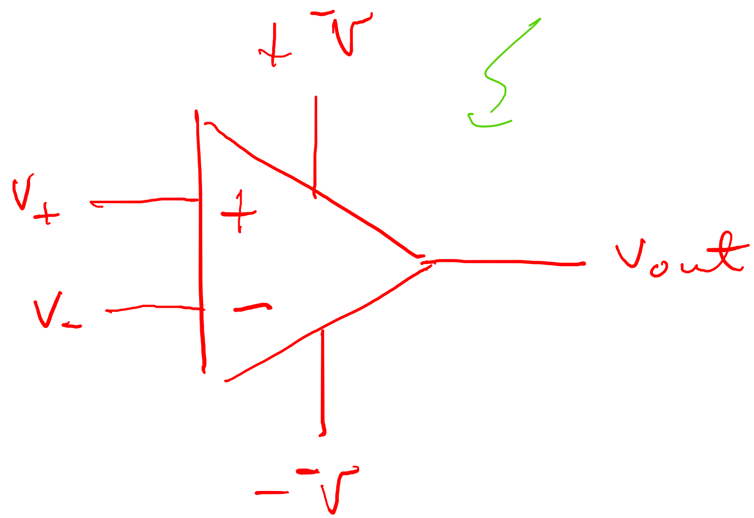
HUNDREDS OF TRANSISTORS, THIN-FILM R & C

MULTILAYER MICRO/NANOFAB

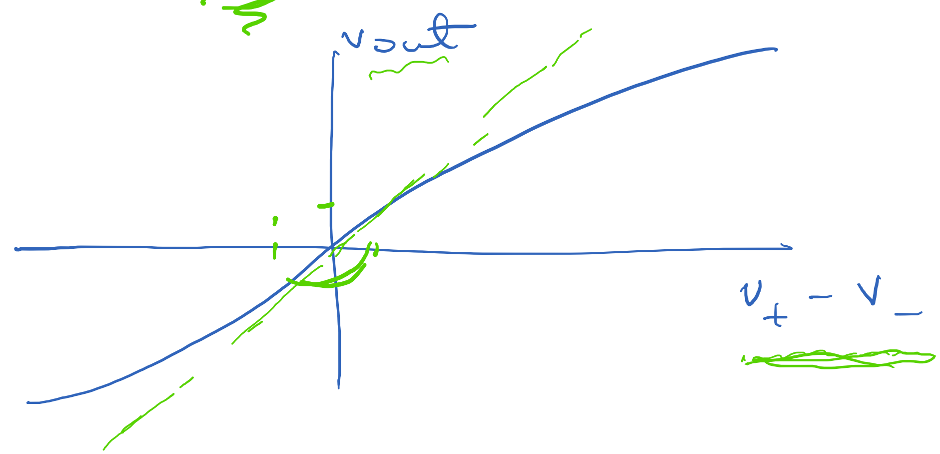


$A_0 \gg 1$

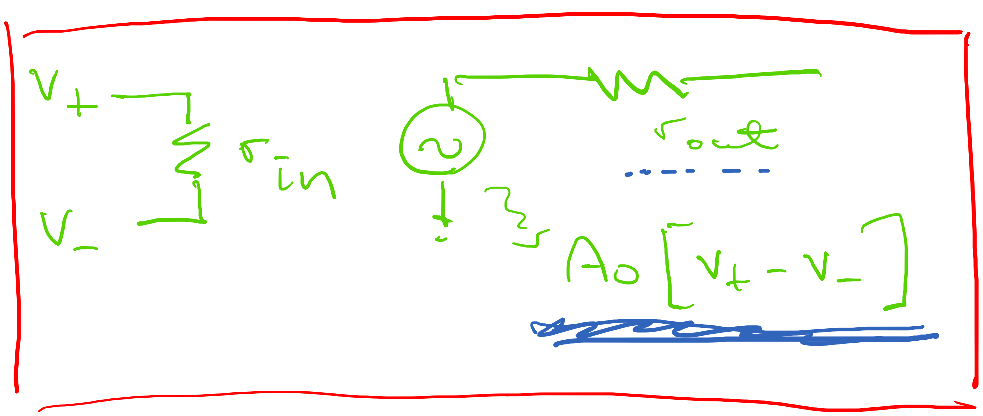
$$V_{out} = A_0 \left[V_+ - V_- \right]$$



$$V_{out} = A_0 [V_+ - V_-]$$



EQUIVALENT CIRCUIT



$r_{in} \sim 10^5 \Omega$ [BJT] → $10^{11} \Omega$ [FET]

r_{out} $10 - 10^3 \Omega$

IDEAL OP AMP:

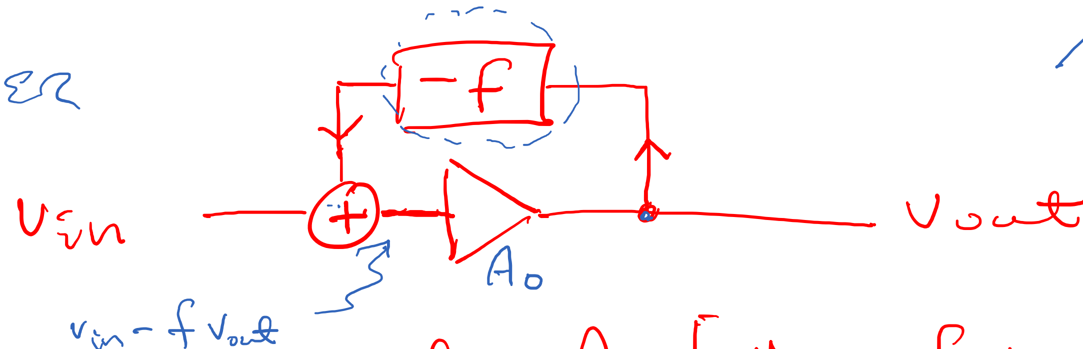
$r_{in} = \infty$; $r_{out} = 0$

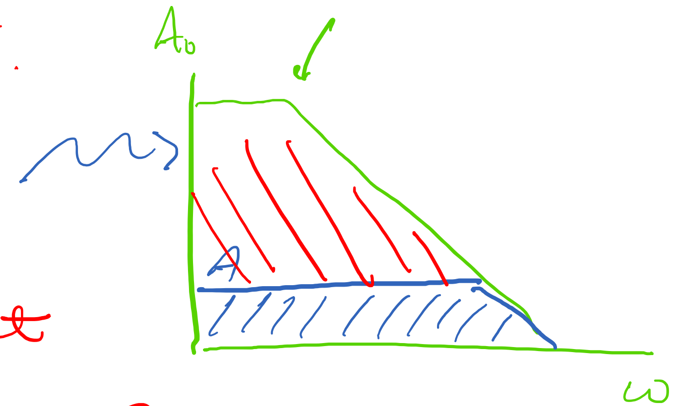
$A_0 \to \infty$

OP AMPS ARE ALMOST ALWAYS USED WITH NEGATIVE FEEDBACK

→ EXCHANGE GAIN FOR LINEARITY.

CONSIDER





$$V_{out} = A_0\left[V_{in} - fV_{out}\right] \ldots$$

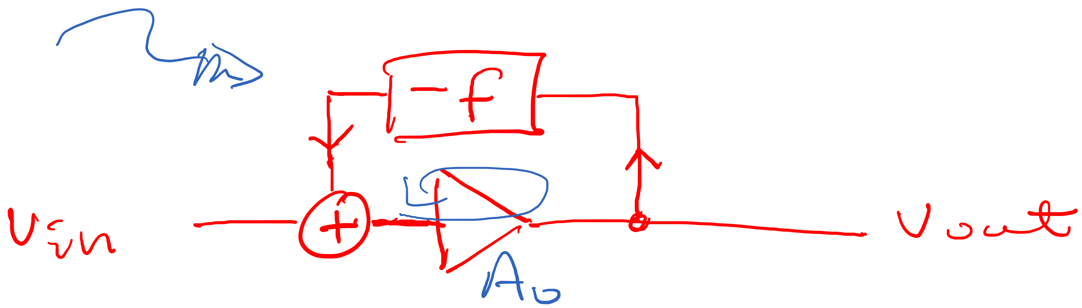
$$V_{out}(1 + A_0 f) = A_0 V_{in}$$

$$\frac{V_{out}}{V_{in}} = \frac{A_0}{1 + A_0 f} V_{in} \; ; \text{ IF } A_0 \gg 1$$

CLOSED LOOP GAIN $A \equiv \dfrac{V_{out}}{V_{in}} \approx 1/f$

INDEPENDENT OF DETAILS OF A_0's!

SOME JARGON



OPEN LOOP GAIN: A_0

$$V_{out} = A_0 \overbrace{[V_+ - V_-]}^{\varepsilon}$$

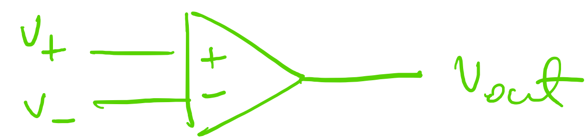
IN ABSENCE OF FEEDBACK.

CLOSED LOOP GAIN: $\frac{V_{out}}{V_{in}}$ IN CONFIGURATION W/ NEGATIVE F.B.

$$A = \frac{V_{out}}{V_{in}} \simeq 1/f$$

LOOP GAIN: $A_0 f$

"GOLDEN RULES"



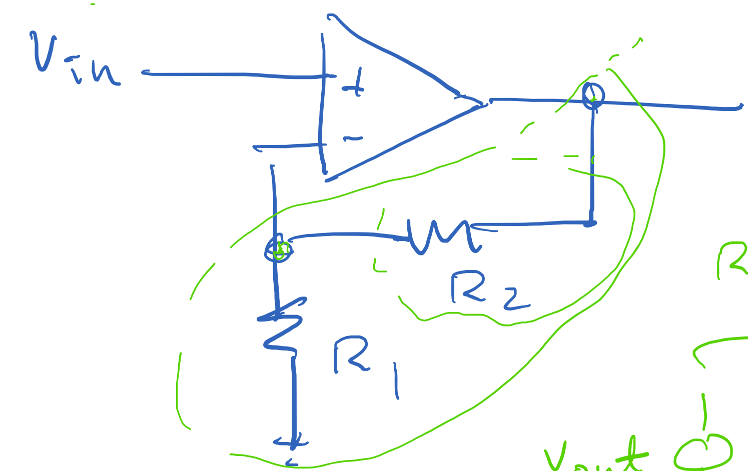
① $V_+ = V_-$

ANY NONZERO $V_+ - V_-$ ⟶ GENERATE A **HUGE** V_{out}, THAT GETS SAMPLED & FED BACK IN SUCH A WAY THAT $V_+ - V_-$ GETS PUSHED TO ZERO.

② INPUTS DRAW NO CURRENT

NONINVERTING OP AMP STAGE

"VOLTAGE FEEDBACK"

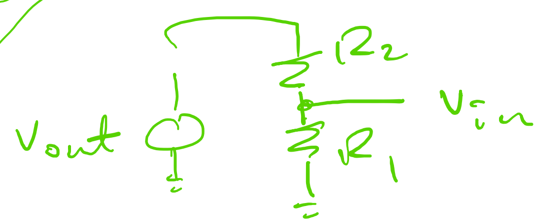


Rule 1

$V_+ = V_-$

$V_- = V_{in}$

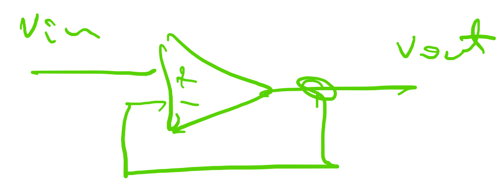
Rule 2: INV. INPUT DRAWS NO CURRENT



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

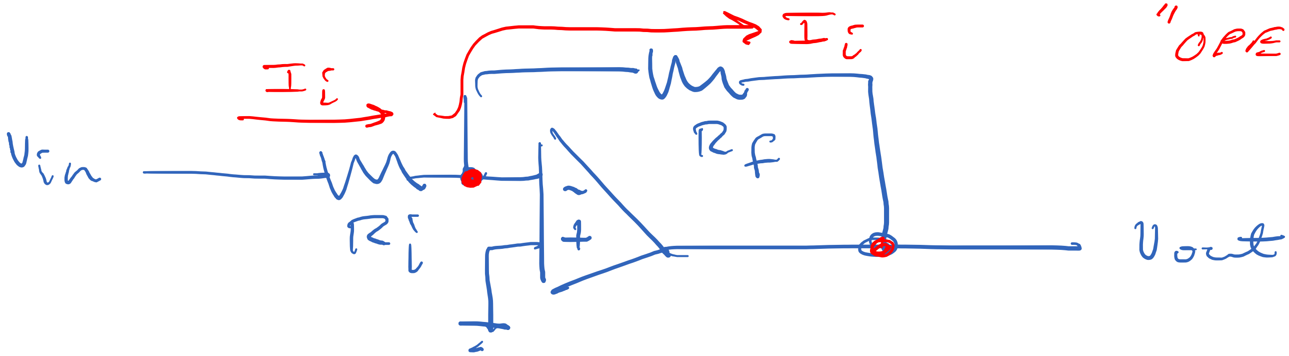
$$A = \frac{V_{out}}{V_{in}} = 1 + \frac{R_2}{R_1}$$

FOLLOWER



$A = 1$

INVERTING OP AMP STAGE



"OPERATIONAL FEEDBACK"

RULE 1 : $V_- = V_+ = 0$ "VIRTUAL GROUND"

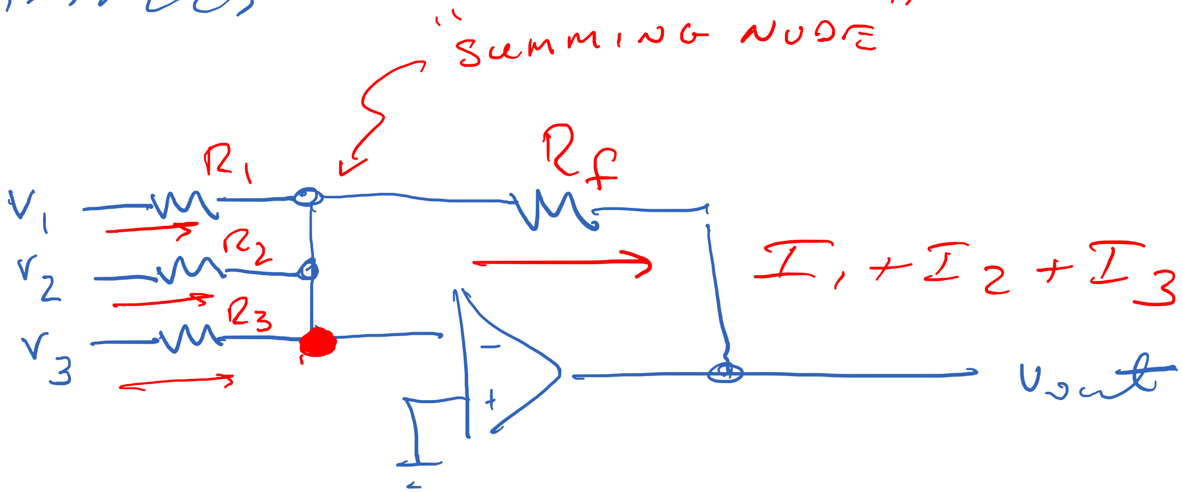
$$I_i = \frac{V_{in}}{R_i}$$

RULE 2 : INVERTING INPUT DRAWS NO CURRENT

$$\therefore \quad V_{out} = V_- - R_f I_i = -\frac{R_f}{R_i} V_{in}$$

$$\boxed{A = -R_f/R_i}$$

EXAMPLES



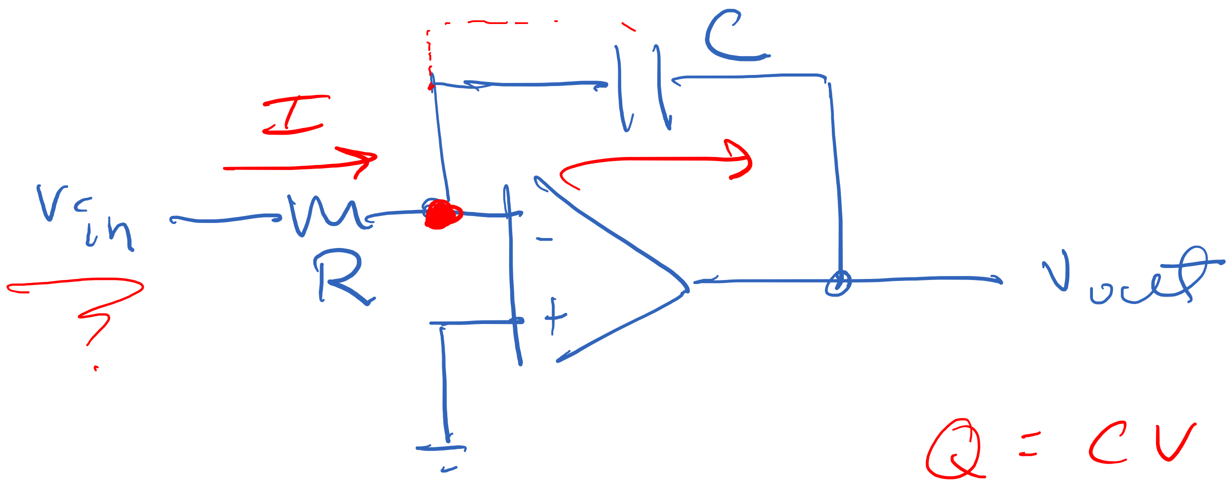
RULE 1: $V_- = V_+ = 0$ VIRTUAL GROUND

$$I_1 = \frac{V_1}{R_1} \; ; \; I_2 = \frac{V_2}{R_2} \; ; \; I_3 = \frac{V_3}{R_3}$$

RULE 2: ALL CURRENTS SUM @ INV. INPUT & FLOW ACROSS R_f

$$V_{out} = -R_f \left[\frac{V_1}{R_1} + \frac{V_2}{R_2} + \frac{V_3}{R_3} \right]$$

TIME-DOMAIN ANALYSIS

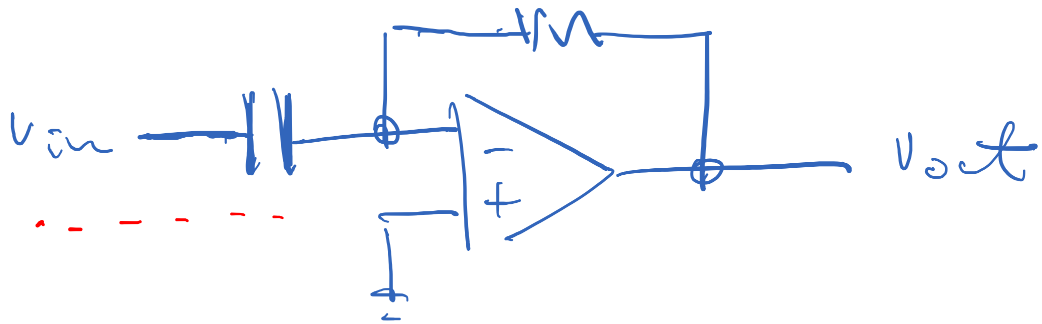


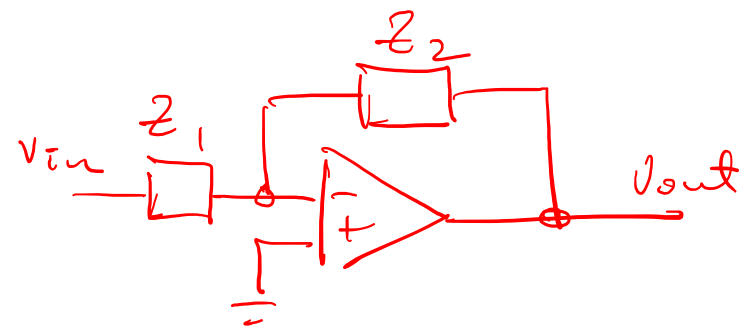
$$Q = CV$$

$$I = \frac{V_{in}}{R} \qquad I = C\frac{dV}{dt}$$

$$V_{out} = -\frac{1}{C}\int I\,dt$$

$$V_{out} = -\frac{1}{RC}\int V_{in}\,dt$$



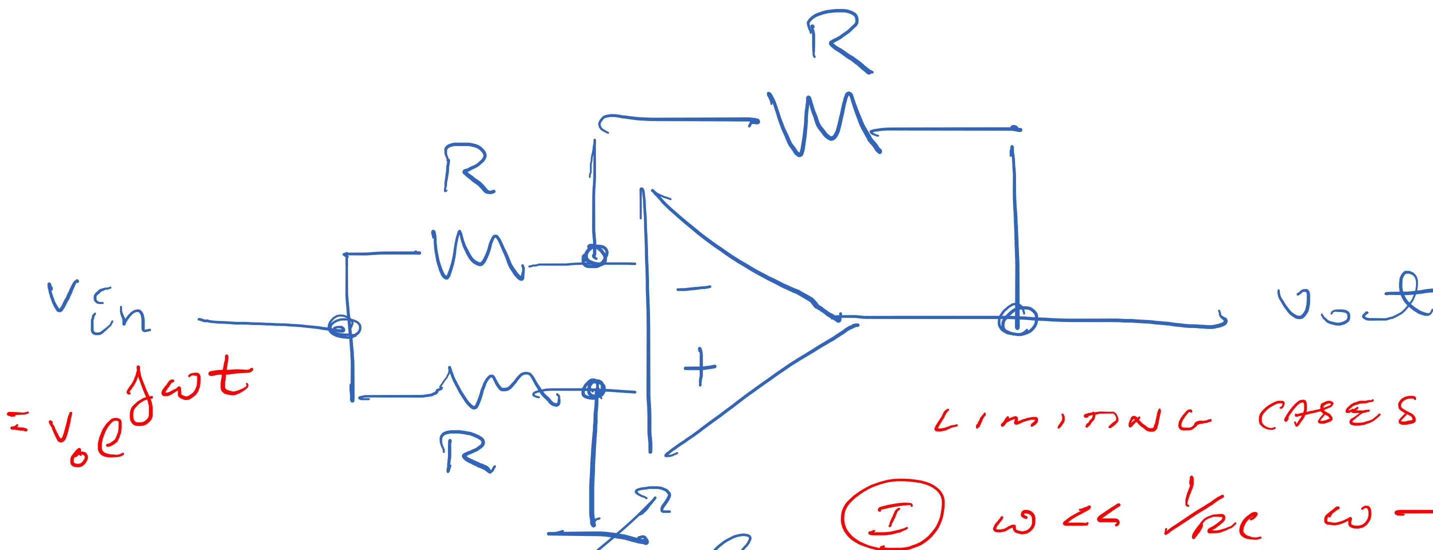


say, $V_{in} = V_0 e^{j\omega t}$

$$A = \frac{V_{out}}{V_{in}} = -\frac{Z_2}{Z_1}$$

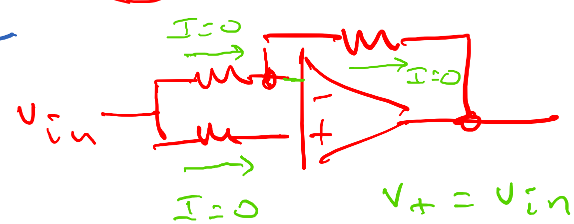
$$A = -\frac{R}{\left(\frac{1}{j\omega C}\right)} = -j\omega RC$$

HIGH-PASS FILTER.



LIMITING CASES:

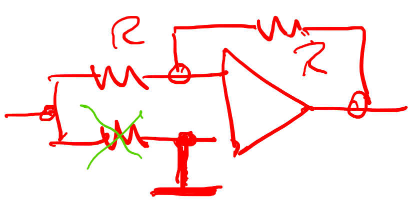
(I) $\omega << 1/RC$ $\quad \omega \to 0$



$v_+ = v_{in} = v_-$

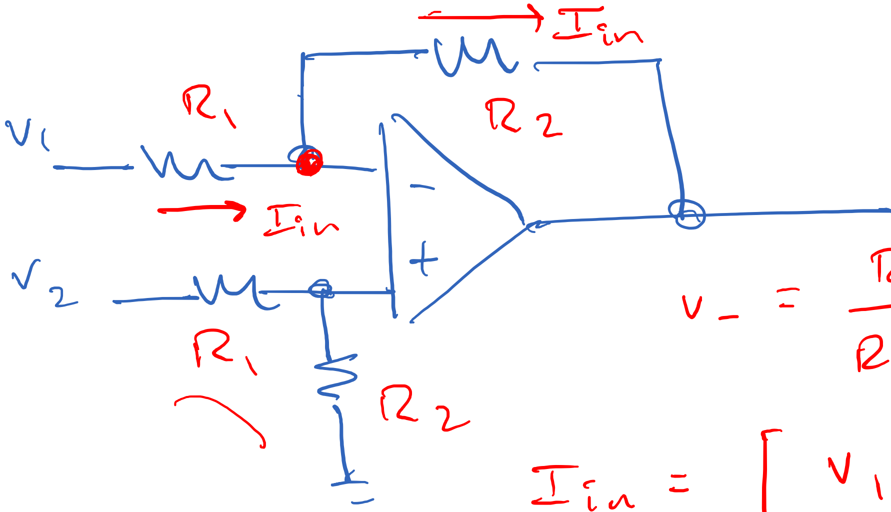
$v_{out} = v_{in} \longrightarrow A = +1$ @ $\omega = 0$

(II) $\omega >> 1/RC$ $\quad \omega \longrightarrow \infty$



$$\frac{v_{out}}{v_{in}} = -\frac{R}{R} = -1$$

$A = -1$ @ $\omega \to \infty$



$$V_+ = \frac{R_2}{R_1 + R_2} V_2$$

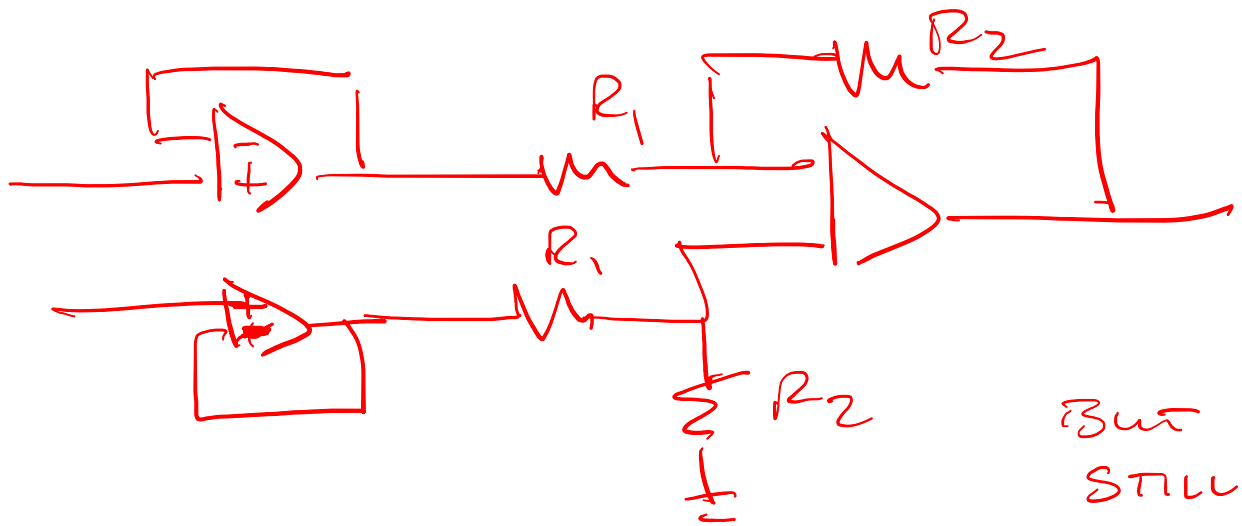
$$V_- = \frac{R_2}{R_1 + R_2} V_2$$

$$I_{in} = \left[V_1 - \frac{R_2}{R_1 + R_2} V_2 \right] \frac{1}{R_1}$$

$$V_{out} = \underbrace{\frac{R_2}{R_1 + R_2} V_2}_{V_-} - \underbrace{\left[V_1 - \frac{R_2}{R_1 + R_2} V_2 \right] \frac{1}{R_1}}_{I_{in}} \cdot R_2$$

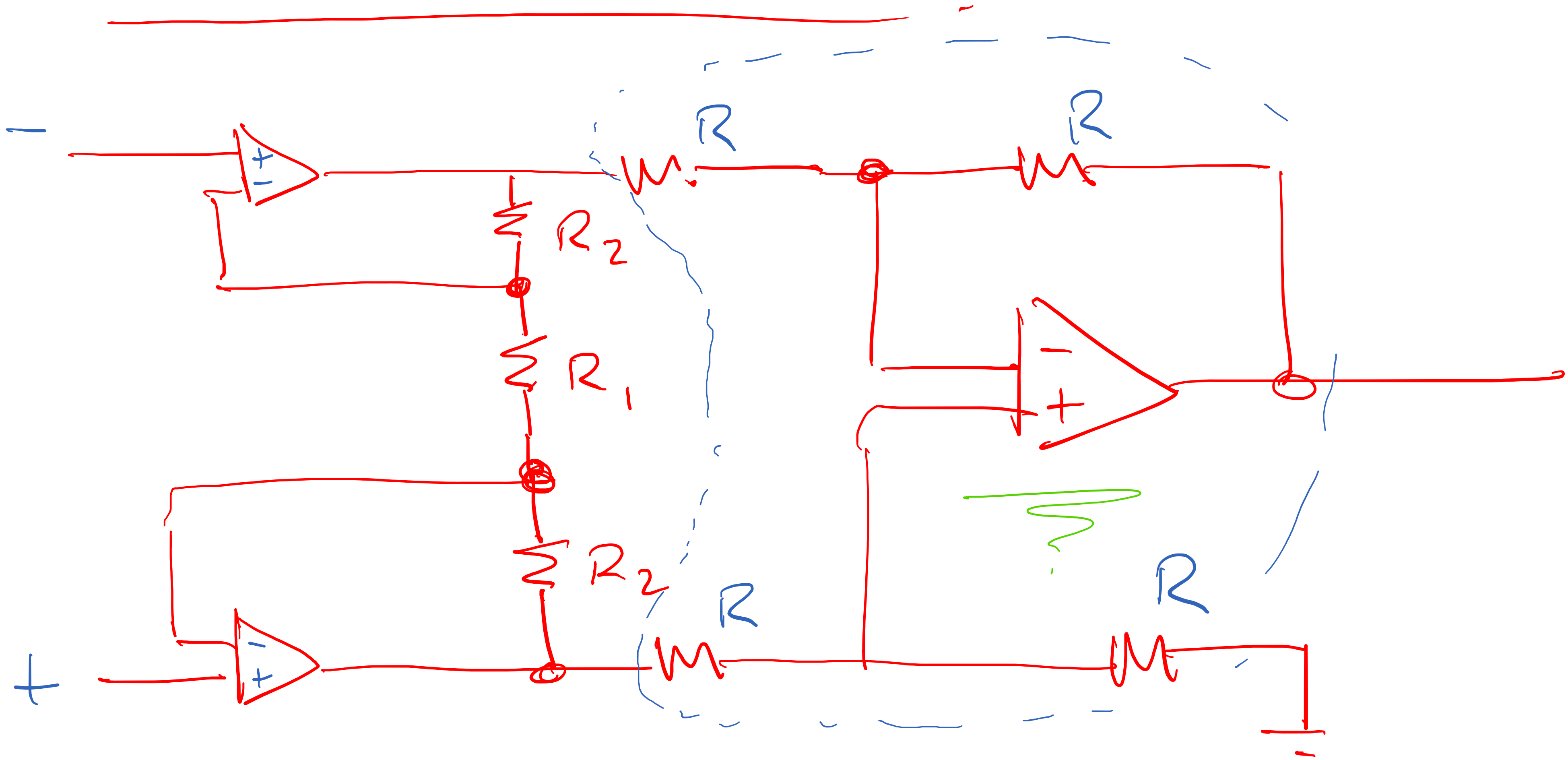
$$\boxed{V_{out} = \frac{R_2}{R_1} \left[V_2 - V_1 \right]}$$

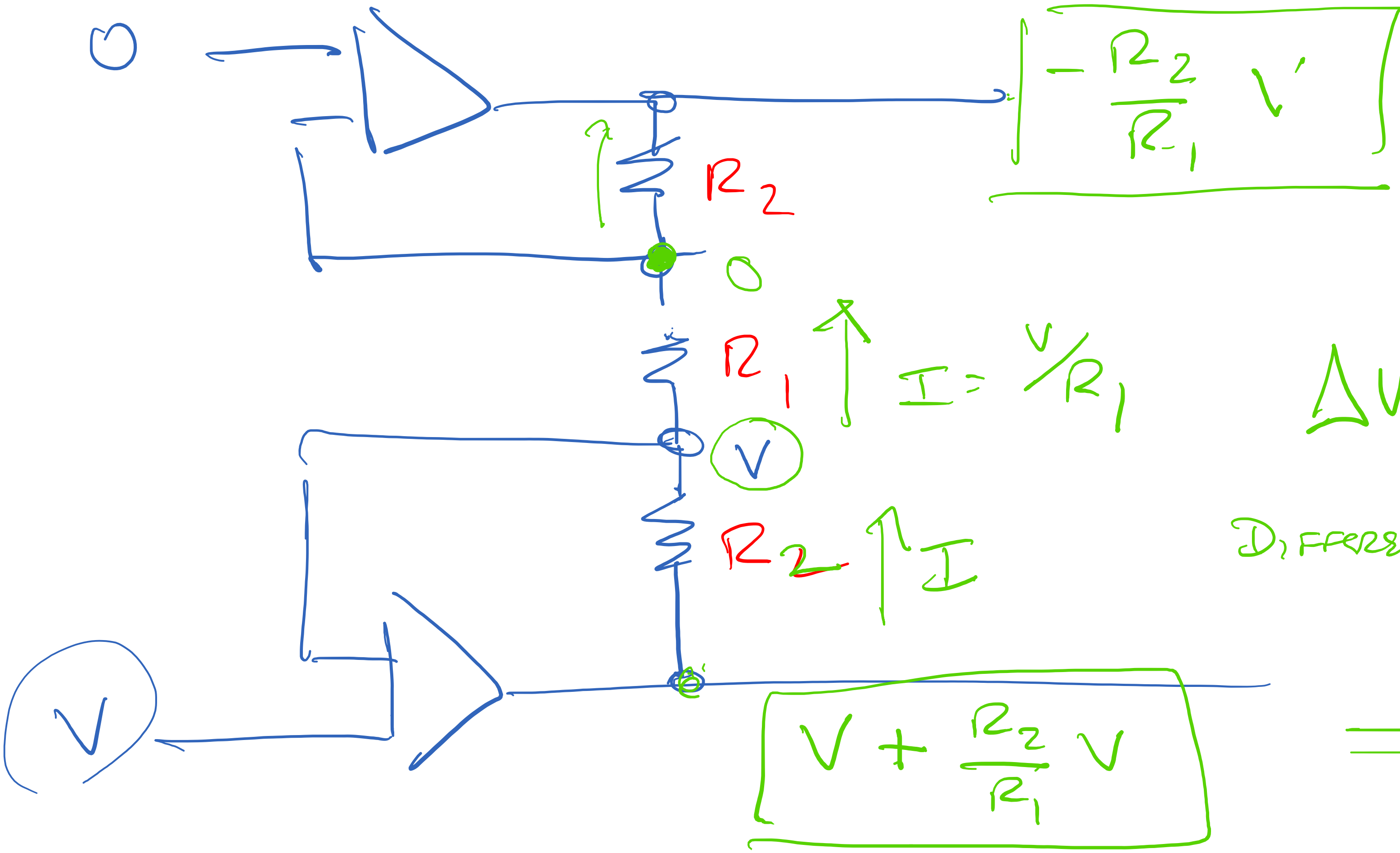
DIFFERENTIAL GAIN



BUT STILL NEED GOOD MATCH OF R'S

INSTRUMENTATION AMPLIFIER





$$\Delta V = V + \frac{2R_2}{R_1} V$$

DIFFERENTIAL GAIN

$$1 + \frac{2R_2}{R_1}$$