Circuits and Signals: Biomedical Applications
Week 5

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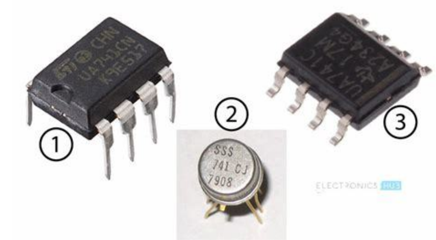
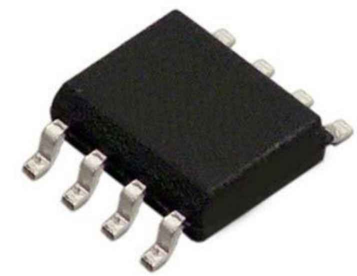
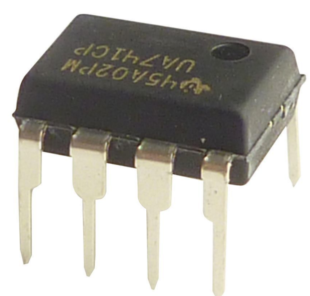
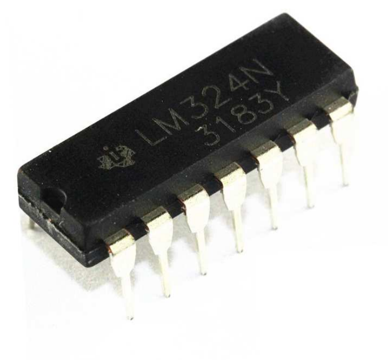
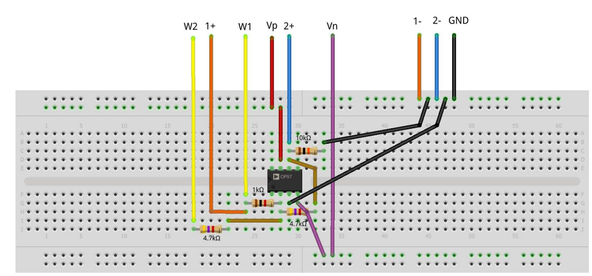
Sep 2023

Week 5 Agenda: Operational Amplifiers

- Amplifiers
- The Basic Op Amp
- Circuit Equations
- Virtual Short,
  Virtual Ground
- Negative Feedback
- Inverting Amplifier
- High Gain Amplifier
- Summing Junction
- Postive Feedback Briefly
- Non–Inverting Amplifier
- Other Amplifiers
- Saturation, *etc.*



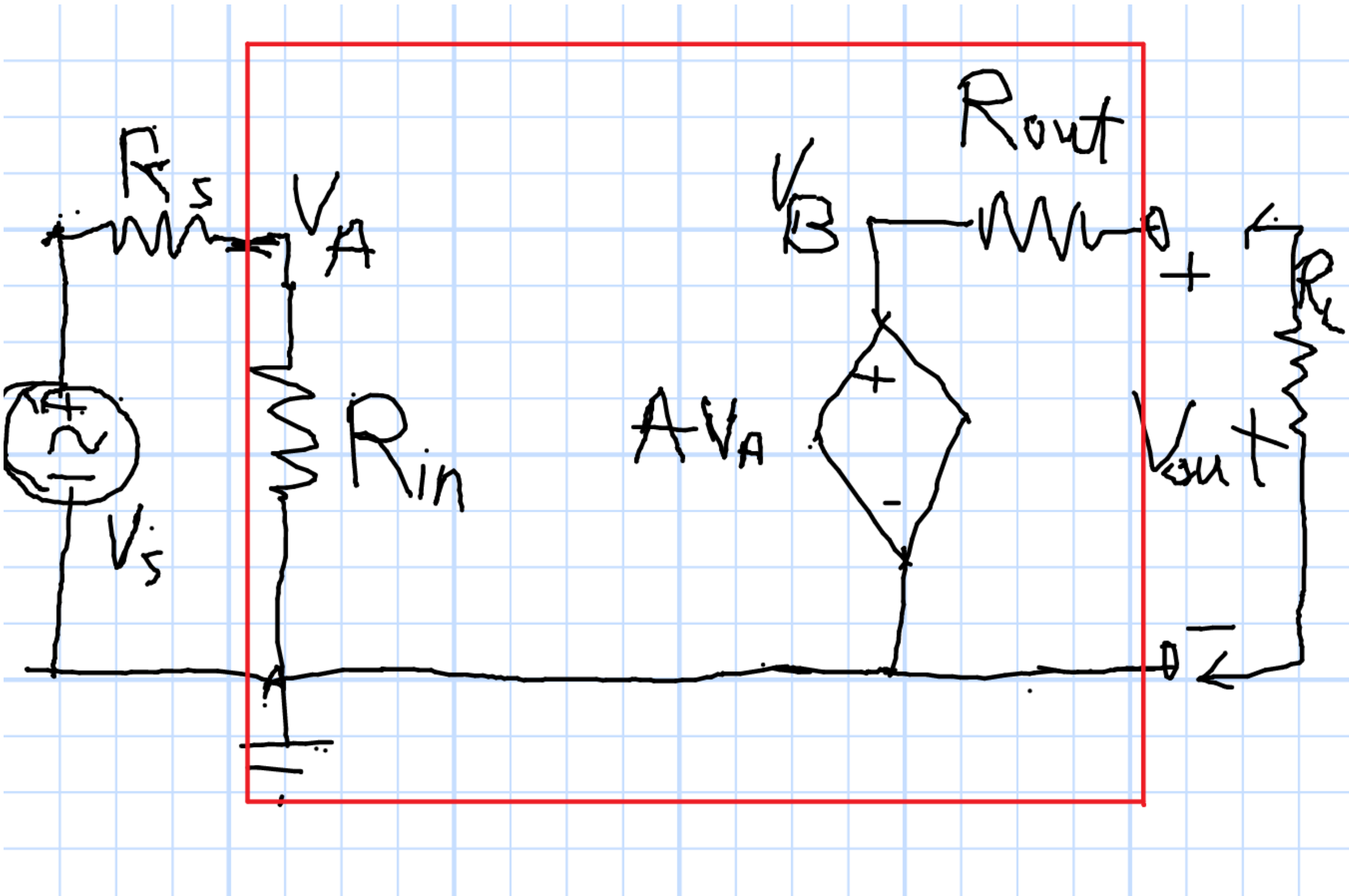






Why?

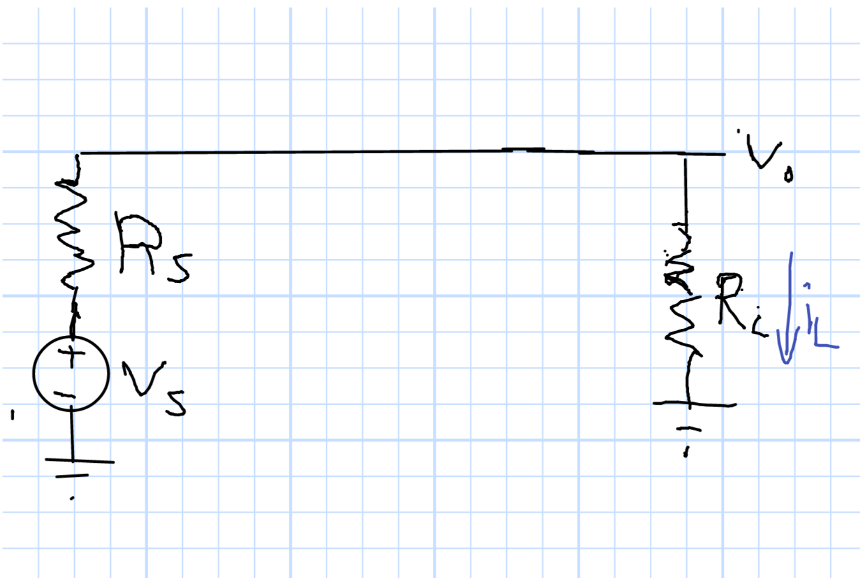
- Why Amplifiers?
  - Increase Voltage
  - Increase Current
  - Control Impedance
- Why Now?
  - Prepare for Lab
  - Nice Fit with Equivalent Circuits
- Back to Capcitors and Inductors in 2 Weeks

An Amplifier Model



We want to Choose A, R_{in}, and R_{out}

Impedance (Resistance) Choices



Voltage Divider

Maximum Voltage to Load

$$R_L \gg R_s$$

$$R_L \to \infty \text{ or } R_s \to 0$$

Maximum Power to Load

$$i_L = i_s = \frac{v_s}{R_s + R_L}$$

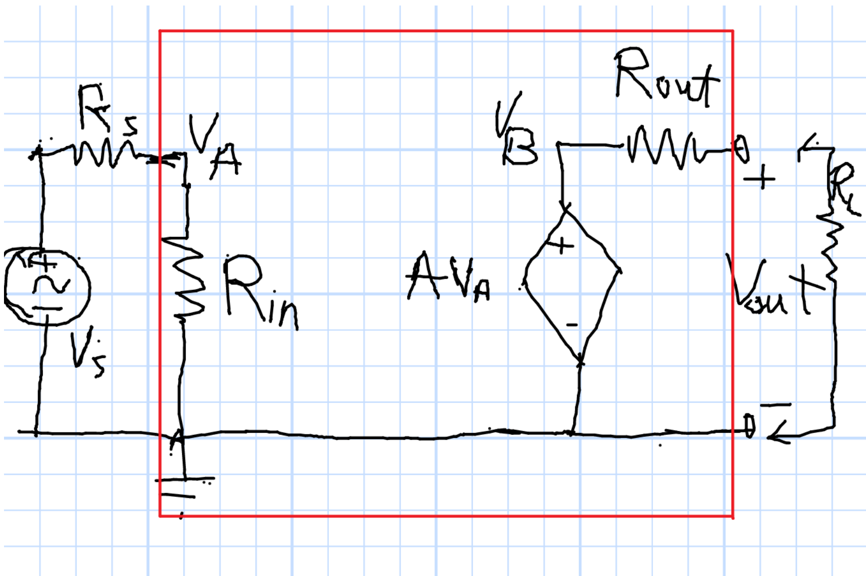
$$v_L = v_s \frac{R_L}{R_s + R_L}$$

$$p_L = v_s^2 \frac{R_L}{(R_s + R_L)^2}$$

$$R_L = R_s \qquad P_L = \frac{v_s^2}{4R_L}$$

$$P_s = \frac{V_s^2}{2R_L} \qquad P_L = P_s/2$$

Input and Output Impedance



- Mix Input and Output Choices as Needed
- Maximum Power to Load for Minimum Reflected Power

Maximum Voltage

$$R_{in} \rightarrow \infty$$

$$R_{out} = 0$$

Maximum Power

$$R_{in} = R_S$$

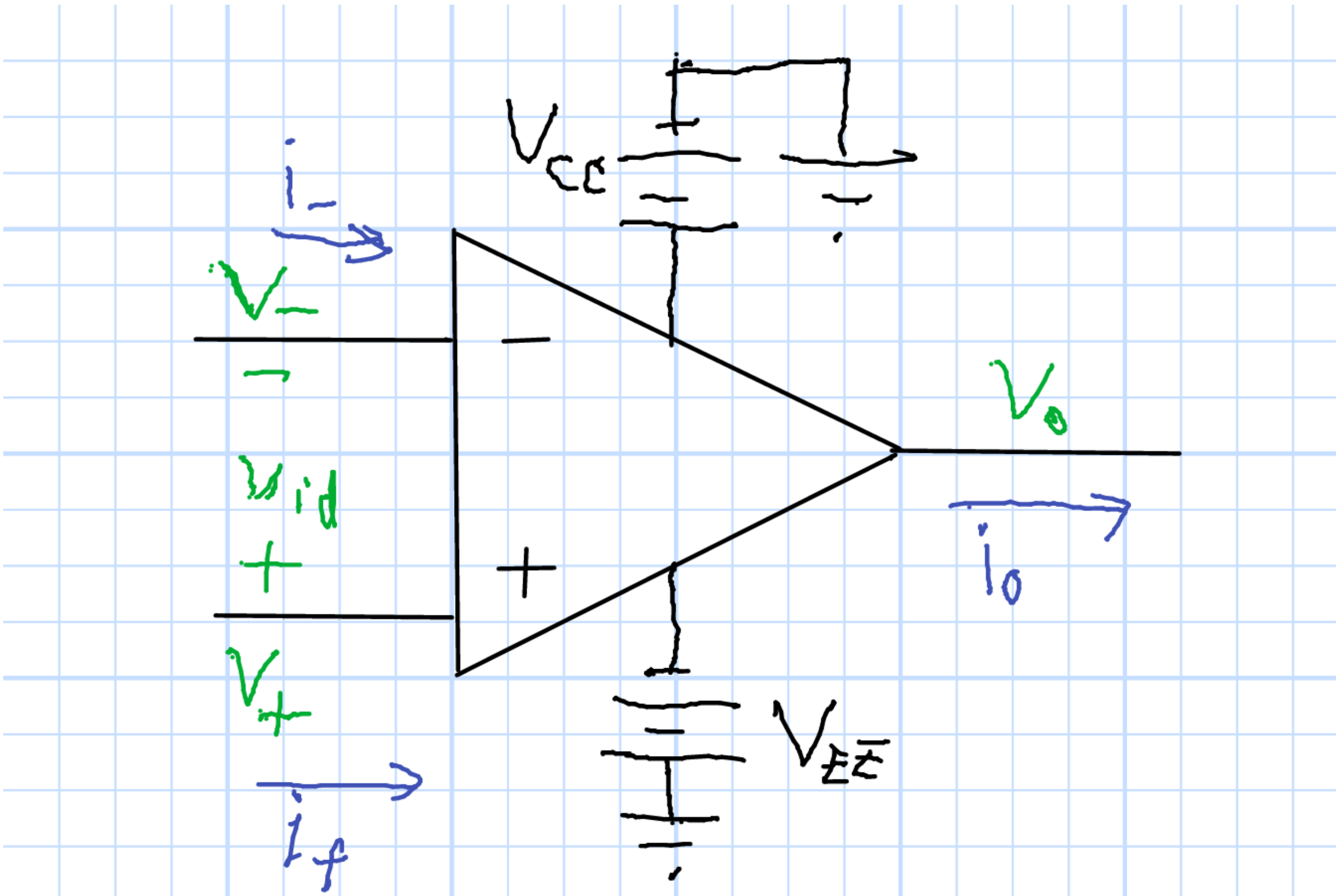
$$R_{out} = R_L$$

Maximum Current

$$R_{in} = 0$$

$$R_{out} \rightarrow \infty$$

The Operational Amplifier

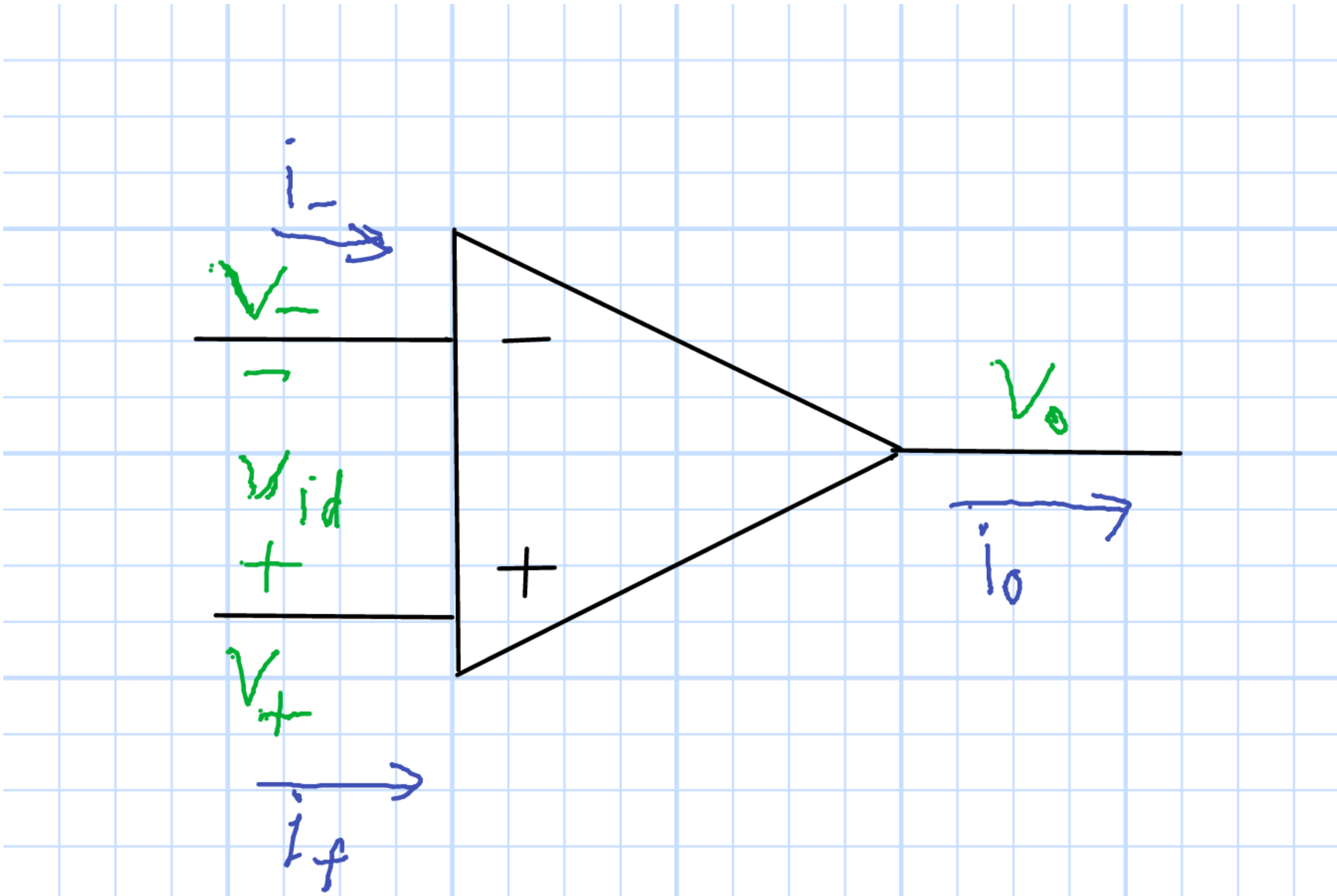


$i_+ = 0 \qquad i_- = 0 \qquad v_o = A_{OL} v_{id} \qquad A_{OL} \to \infty$

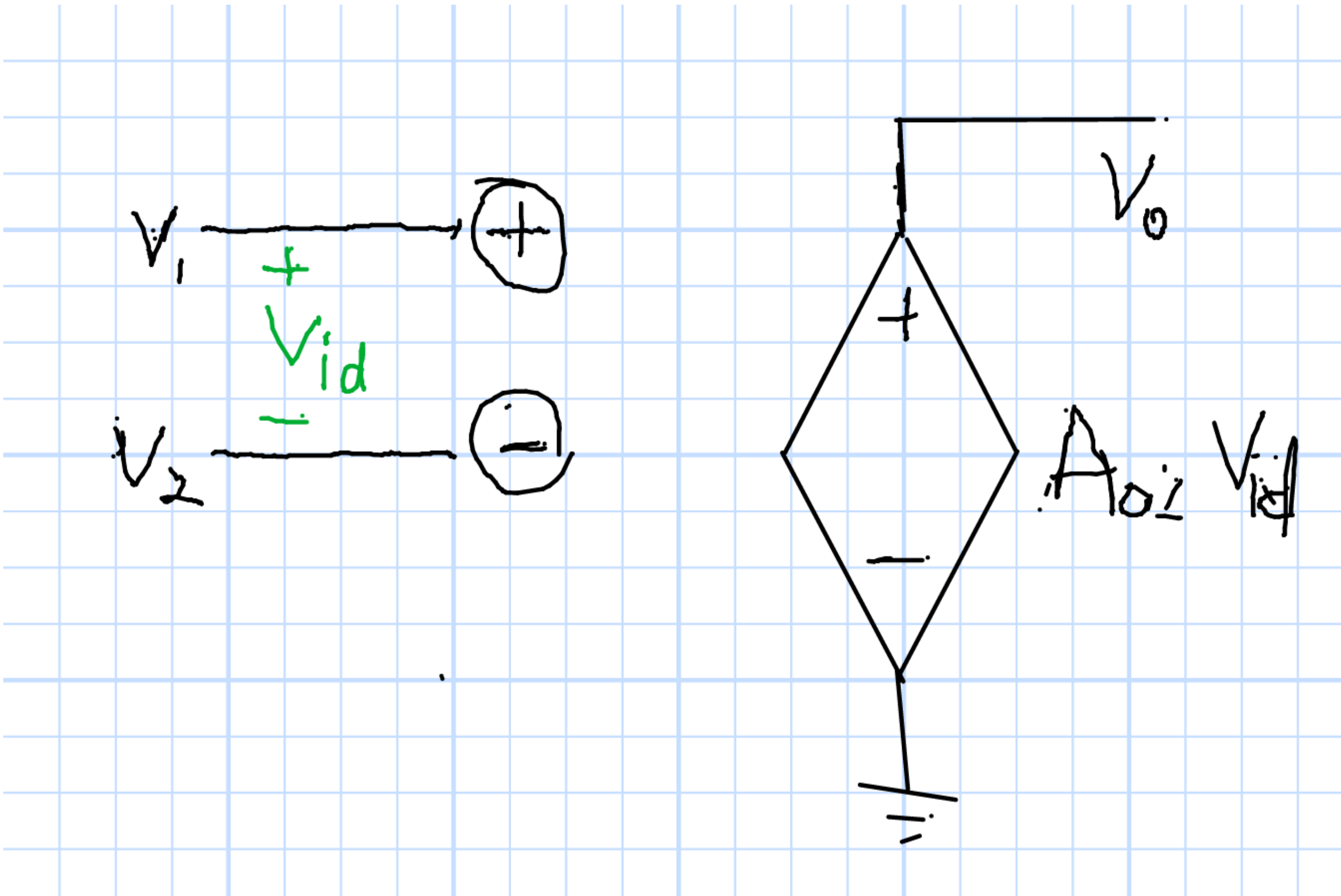
"Common Mode" $((v_+ + v_-)/2)$ Gain is Zero.

Implied Power Supplies

Often we don't show the power connections



Ideal Op–Amp Model

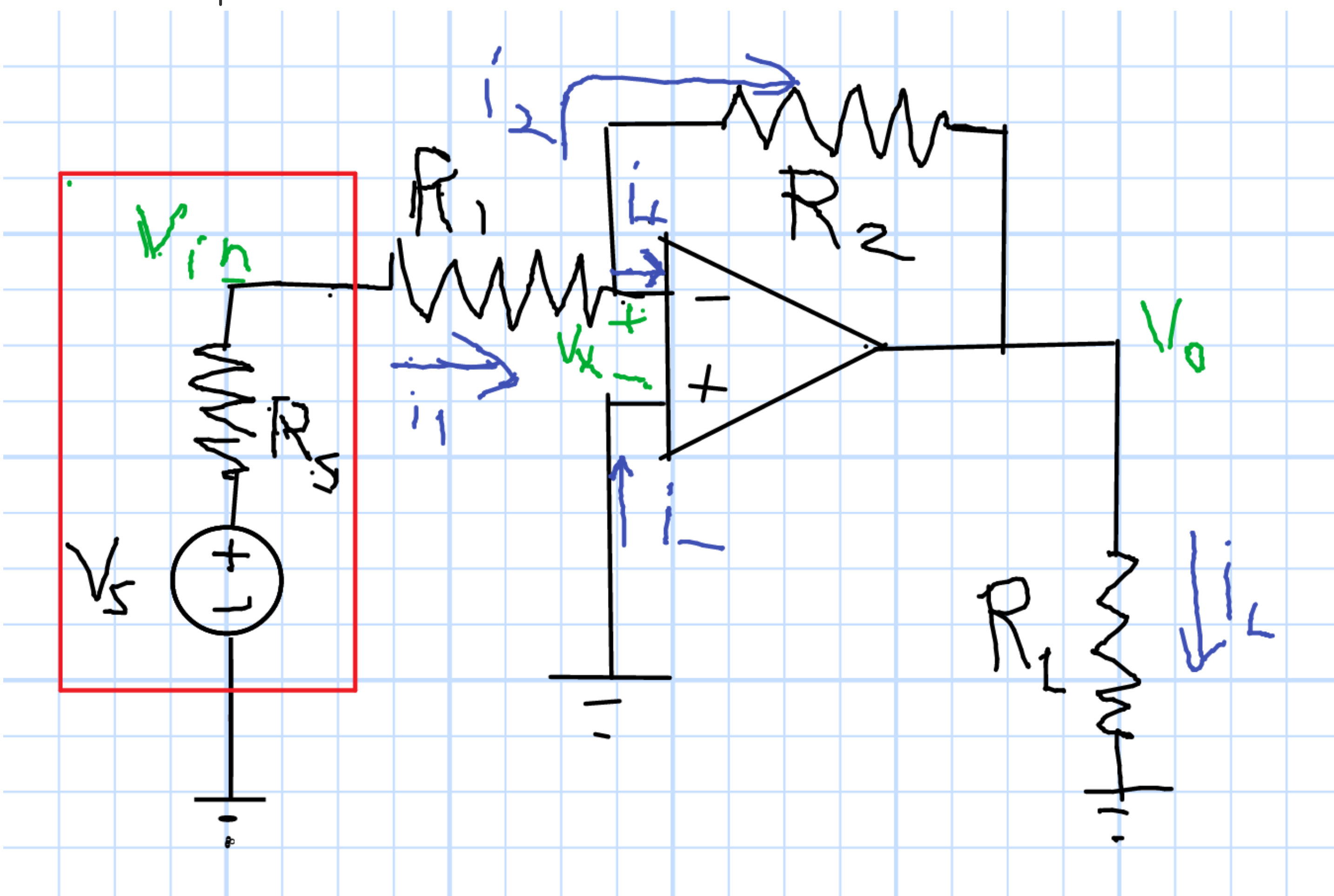


$vo = A_{OL}v_{id}$ and $A_{OL} \to \infty$ so $v_{id} = 0$. Note open–circuit inputs.

We need to build a circuit that can make this happen.

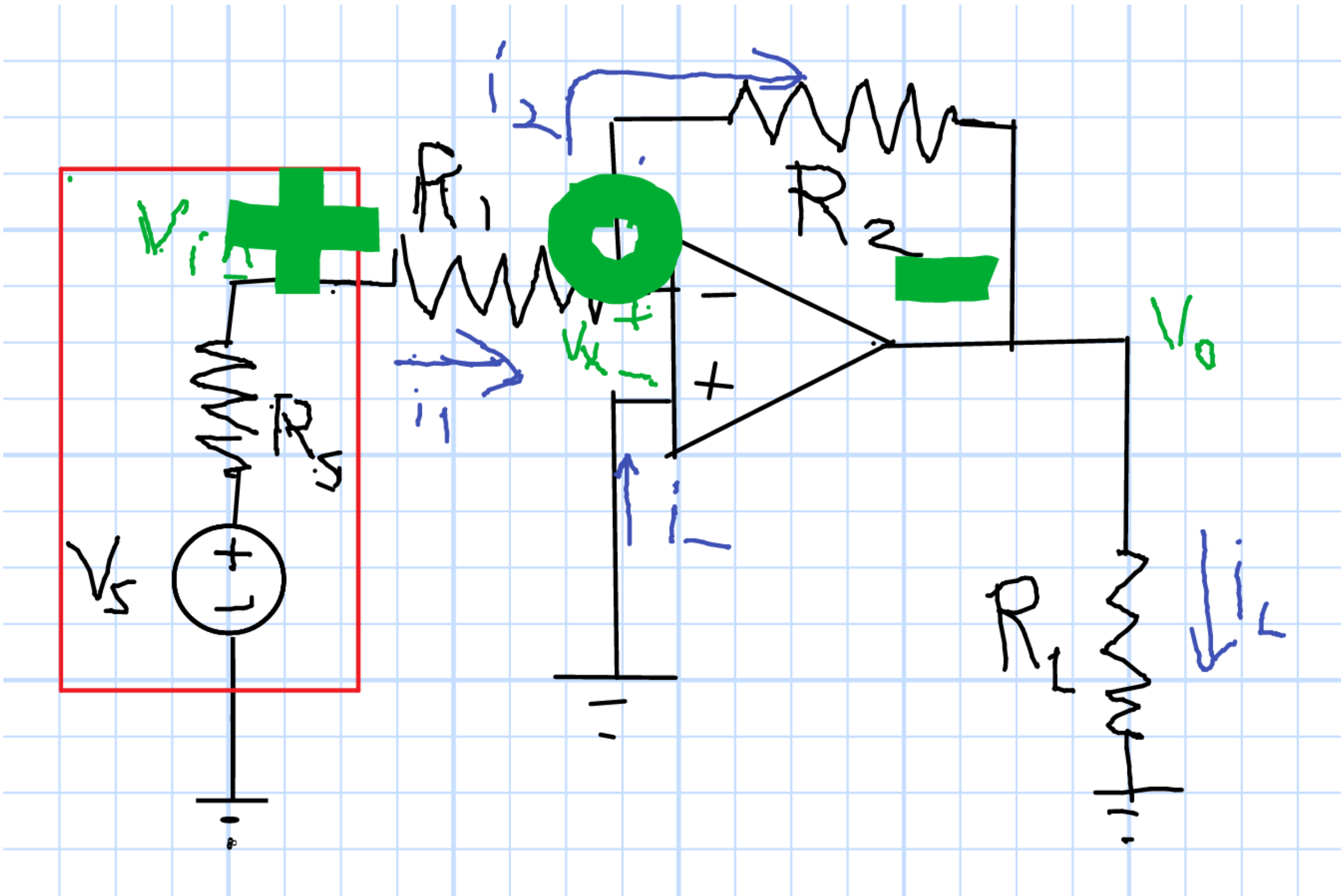
Inverting Amplifier Circuit

$i_+ = 0$, $i_- = 0$, $v_x = 0$: Virtual Ground



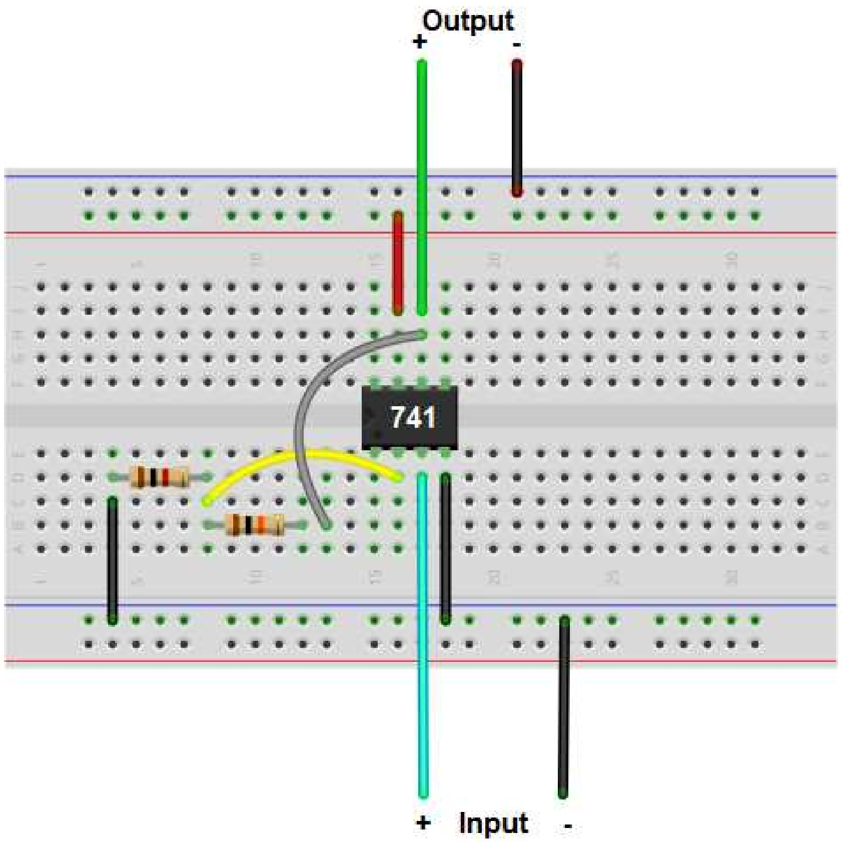
$i_1 = i_2$ so $v_0 = -v_{in}\frac{R_2}{R_1}$ or $A_v = -\frac{R_2}{R_1}$, $R_{in} = R_1$, $R_{out} = 0$

Negative Feedback

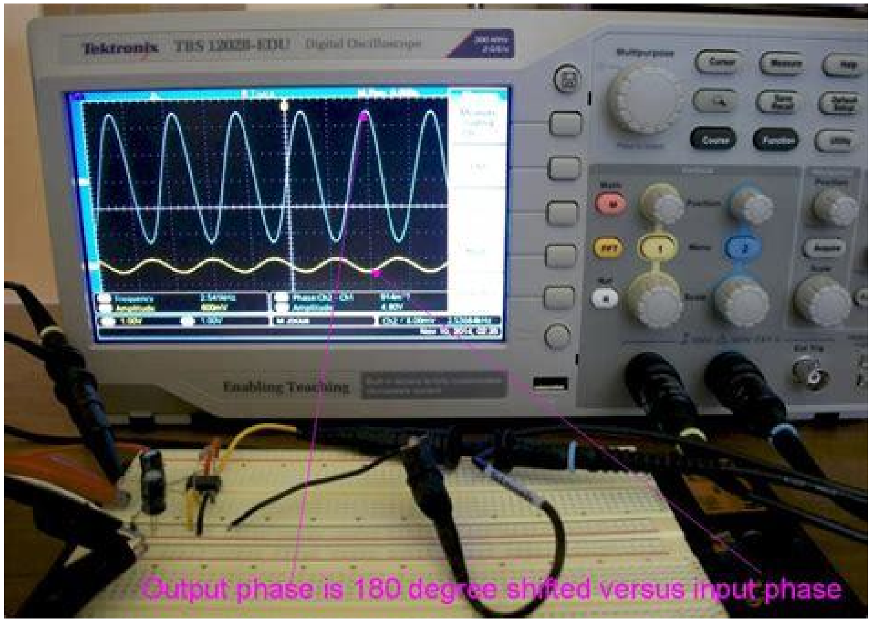


if $v_{in} > 0$, then $v_o < 0$, so v_- can be zero.
if $v_{in} < 0$, then $v_o > 0$, so v_- can be zero.

Inverting Amplifier in Lab



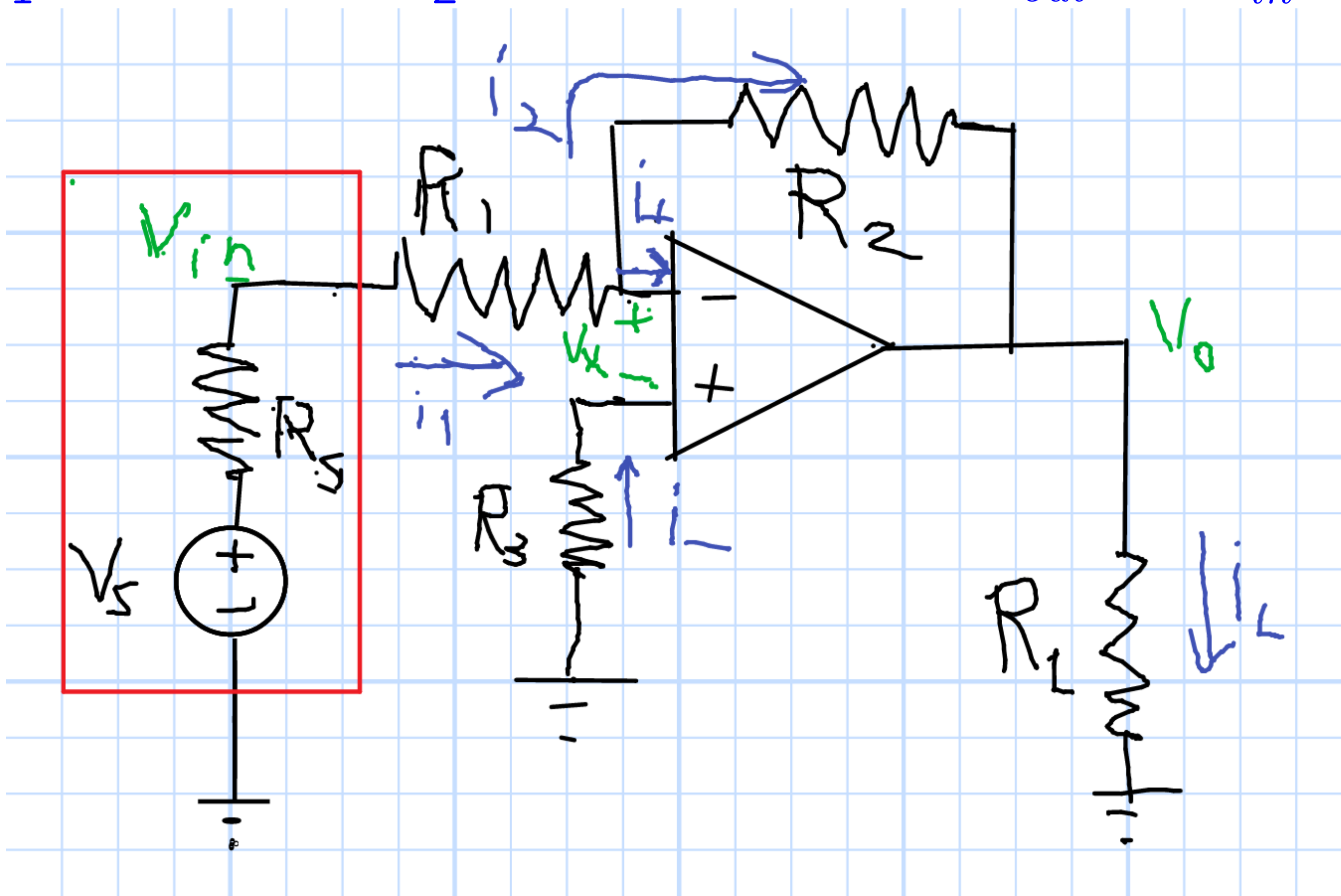
Proto–Board Connections
Power Rails
Signals



Measure Voltage (P-P)
Frequency or Period
Phase (Now 0 or 180 Deg.)

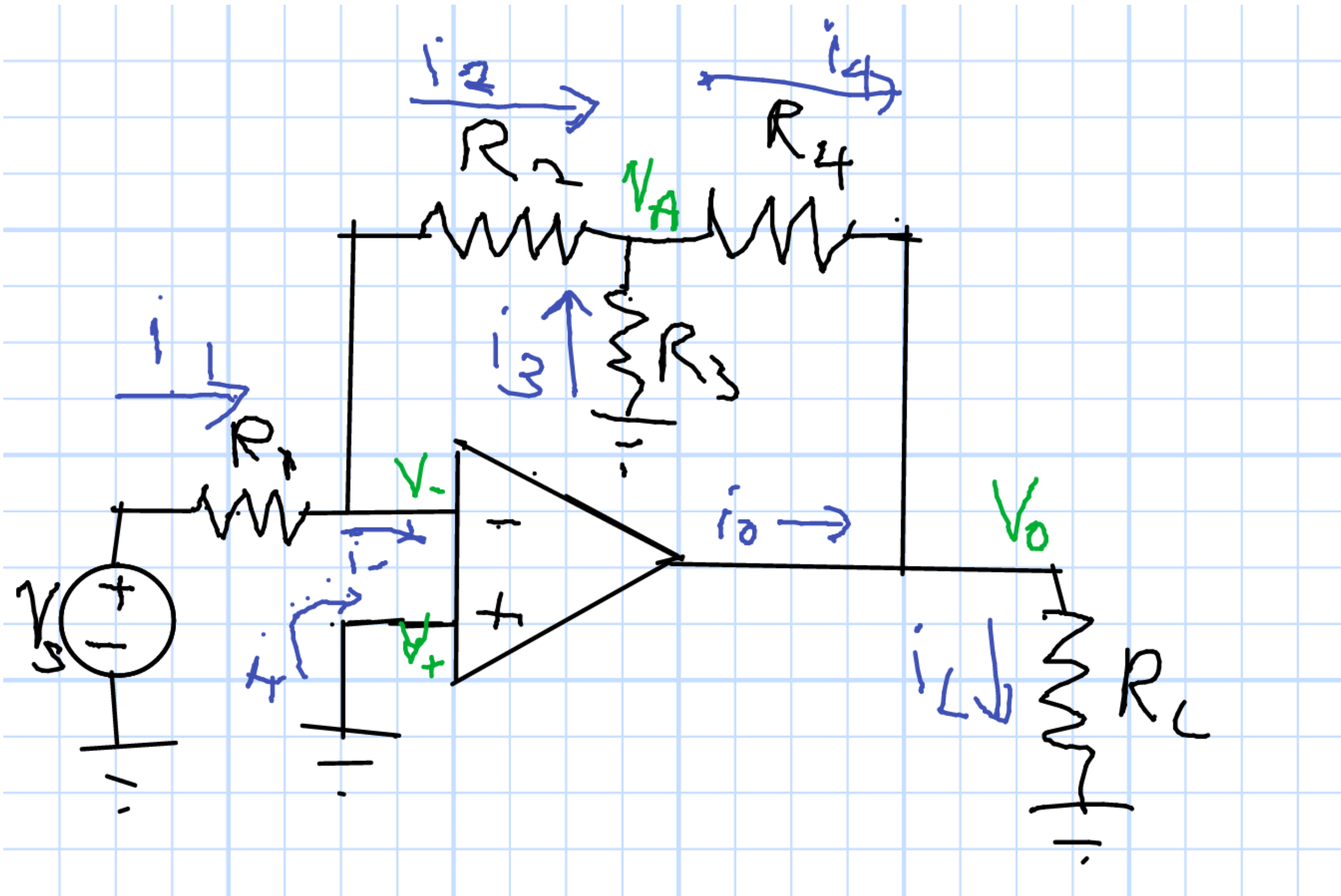
Inverting Amp Circuit?

$R_1 = 500\text{Ohm}$, $R_2 = 1\text{kOhm}$, $A_v =?$, $R_{out} =?$ $R_{in} =?$

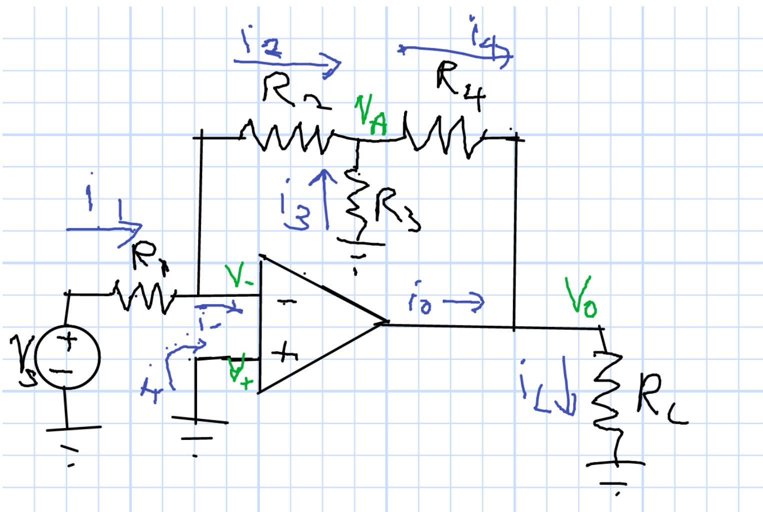


Hint: What is i_+ in R_3? What is v_+?
A virtual short circuit is different from a real one.

High Gain (1)



High Gain (2)



$$i_1 = \frac{v_s}{R_1} \qquad i_2 = i_1$$

Current Divider,
Virtual and Real Grounds

$$i_2 = i_4 \frac{R_3}{R_3 + R_2}$$

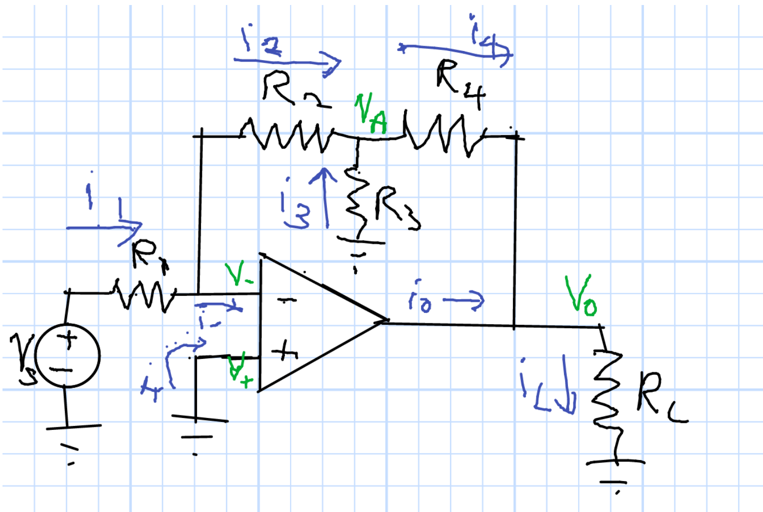
Series and Parallel Combinations

$$v_o = -i_4 \left[R_4 + (R_2 \parallel R_3) \right]$$

$$v_o = -i_2 \frac{R_3 + R_2}{R_3} \left[R_4 + \frac{R_2 R_3}{R_2 + R_3} \right] = -\frac{v_{in}}{R_1} \frac{R_3 + R_2}{R_3} \left[R_4 + \frac{R_2 R_3}{R_2 + R_3} \right]$$

$$= -v_{in} \frac{R_4 R_3 + R_4 R_2 + R_2 R_3}{R_1 R_3} = -v_{in} \left[\frac{R_4}{R_1} + \frac{R_2}{R_1} + \frac{R_2 R_4}{R_1 R_3} \right]$$

High Gain (3)



Example Values

$$R_1 = R_3 = 1\text{k}\Omega$$

$$R_2 = R_4 = 20\text{k}\Omega$$

$$R_L = 1\text{k}\Omega$$

$$v_o = -v_{in}\left[\frac{R_4}{R_1} + \frac{R_2}{R_1} + \frac{R_2 R_4}{R_1 R_3}\right]$$

$$v_o = -v_{in}\,(20 + +20 + 400) = 440 v_s$$

$$i_{in} = i_1 = \frac{v_s}{R_1}$$

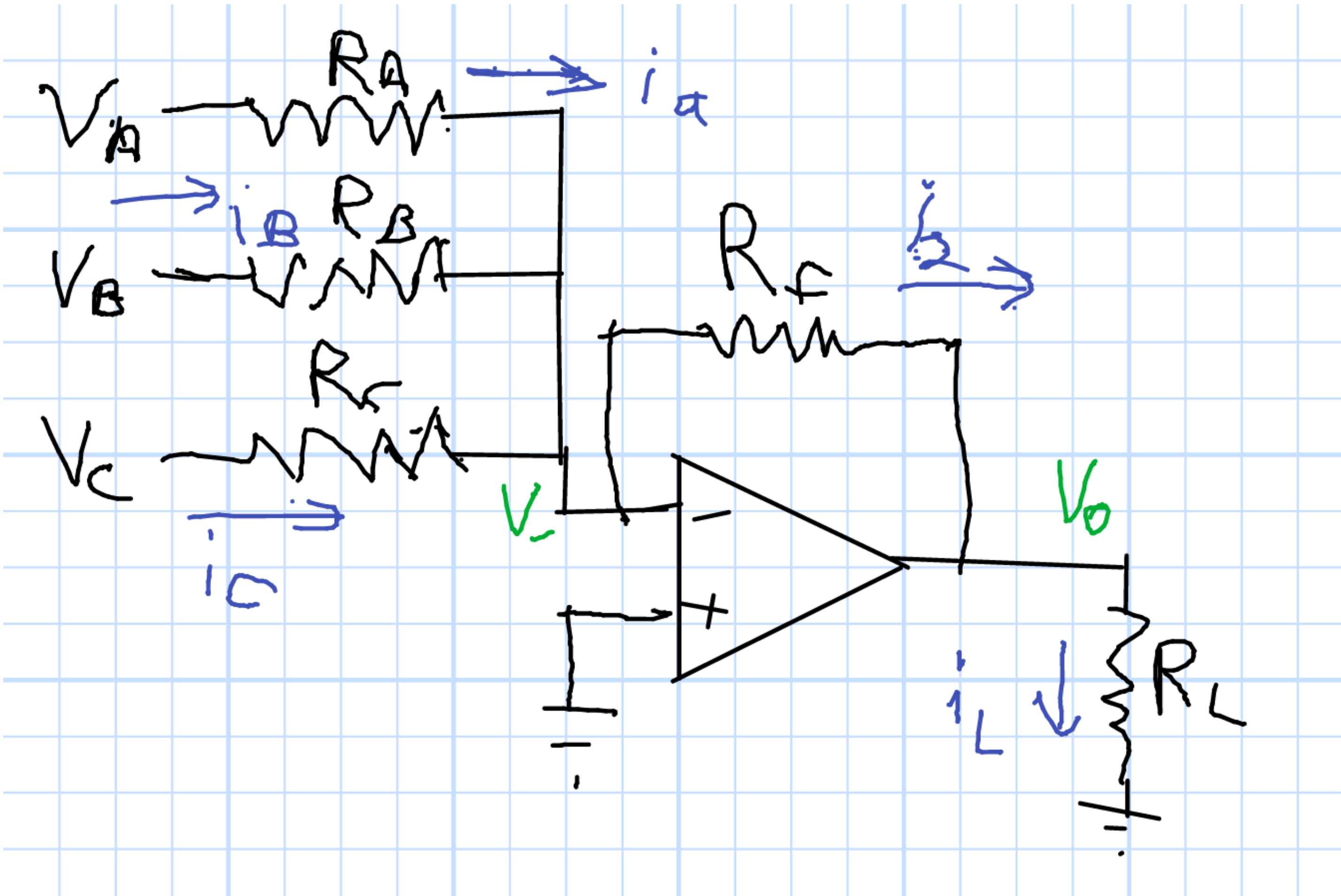
$$i_L = \frac{v_o}{R_L} = 440\frac{v_s}{R_L}$$

$$R_L = R_1 \qquad i_L = 440 i_{in}$$

Power Gain

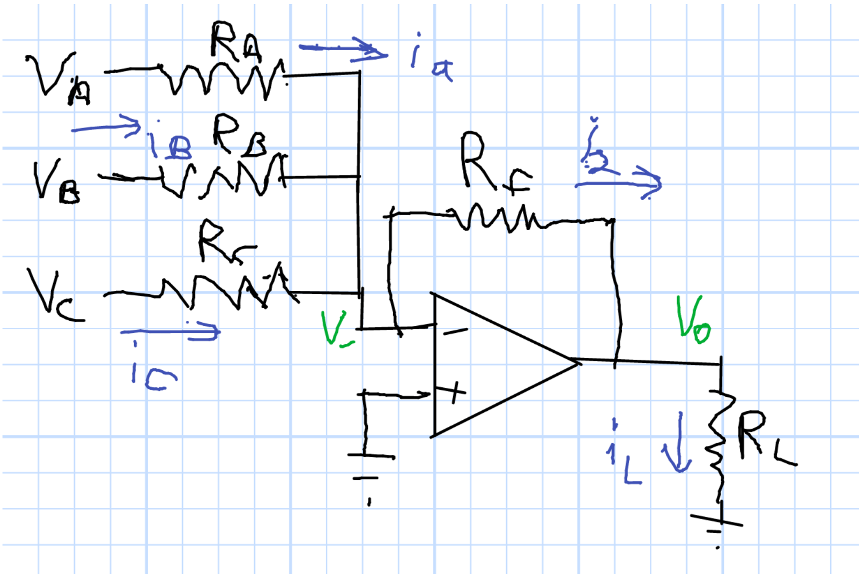
$$v_o i_L = 440^2 v_s i_{in} = 193{,}600 v_s i_{in}$$

Summing Junction



$$v_0 = -\left[\frac{R_f}{R_A}v_A + \frac{R_f}{R_B}v_B + \frac{R_f}{R_C}v_C\right]$$

Summing Junction Example



$$v_0 = -\left[\frac{R_f}{R_A}v_A + \frac{R_f}{R_B}v_B + \frac{R_f}{R_C}v_C\right]$$

V_A	V_B	V_c	V_o
0	0	0	0
1	0	0	1
0	1	0	2
1	1	0	3
0	0	1	4
1	0	1	5
0	1	1	6
1	1	1	7

$v_{A,B,C} = 0$ or 1

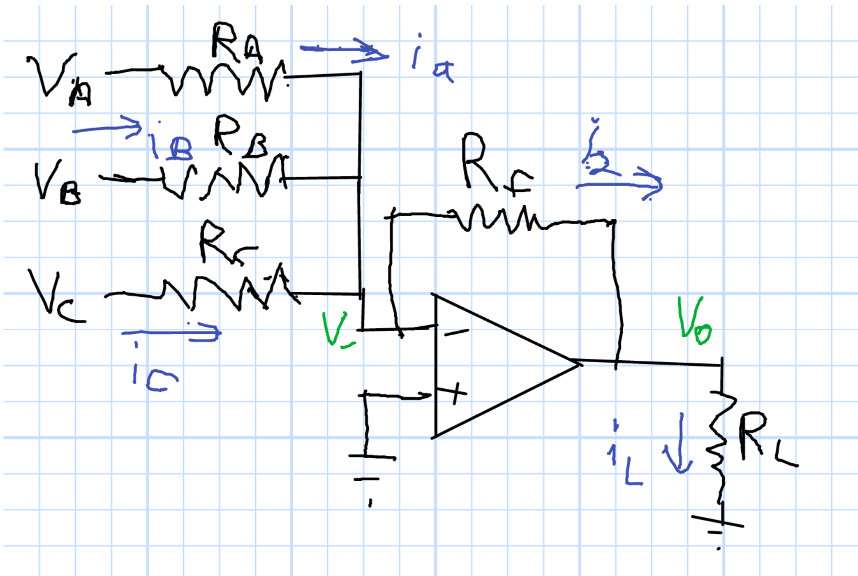
$R_f = 10\text{k}\Omega$

$R_A = 10\text{k}\Omega$ $\qquad R_B = 5\text{k}\Omega$

$R_C = 2.5\text{k}\Omega$

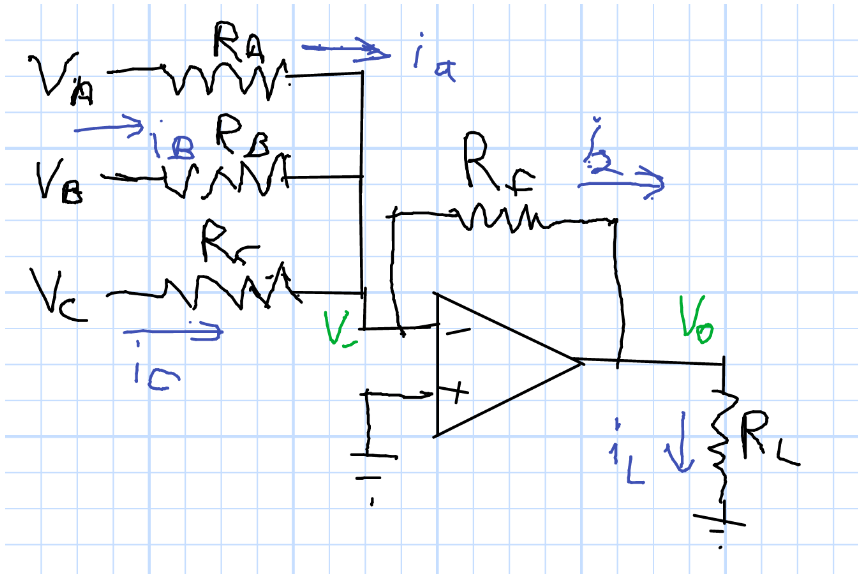
3–Bit D/A Converter

Summing Junction



Would this Work Without the Op Amp?

Summing Junction



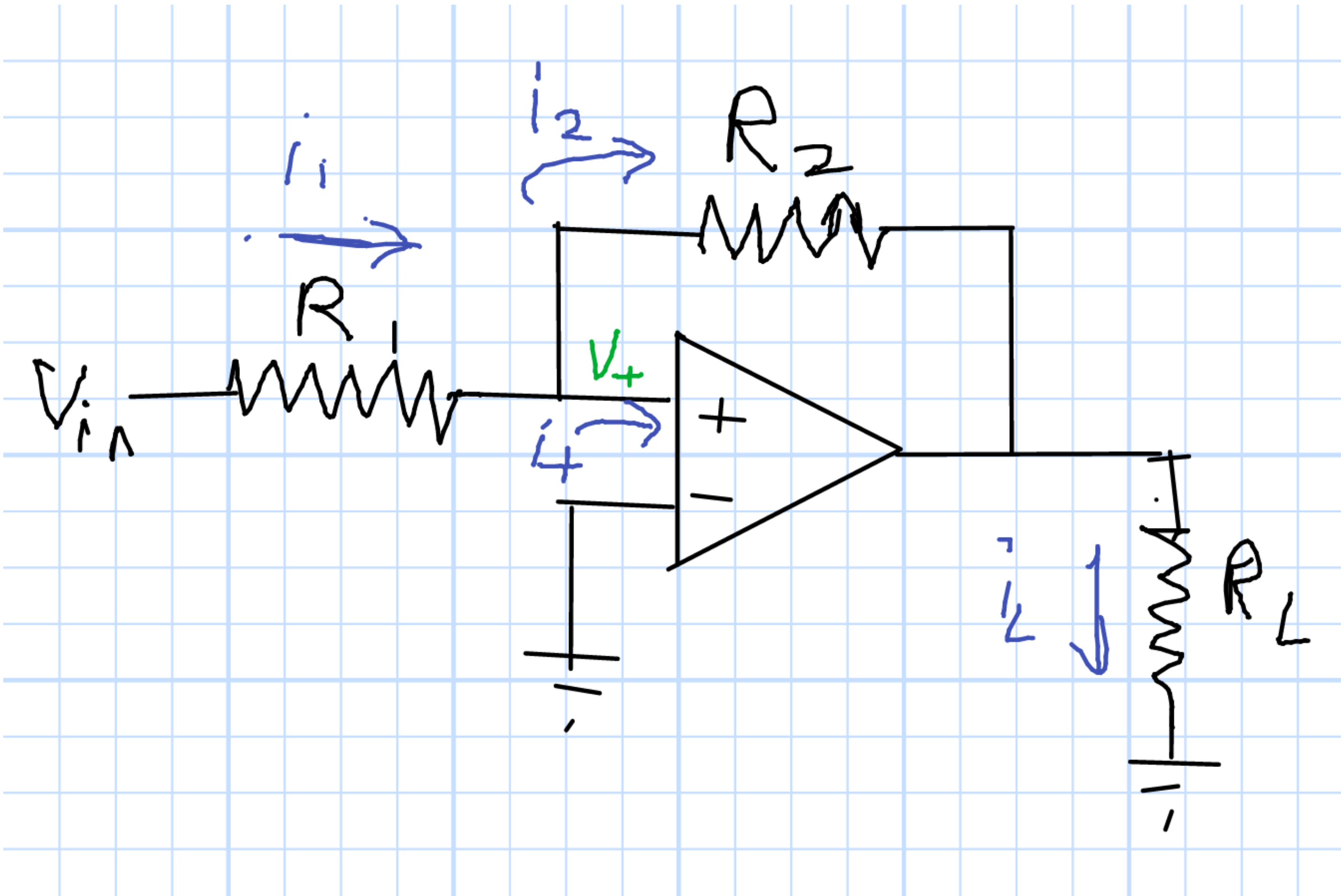
Would this Work Without the Op Amp?

No. Connect the node v_- to R_L and remove the amplifier. Calculate the voltage at that node.

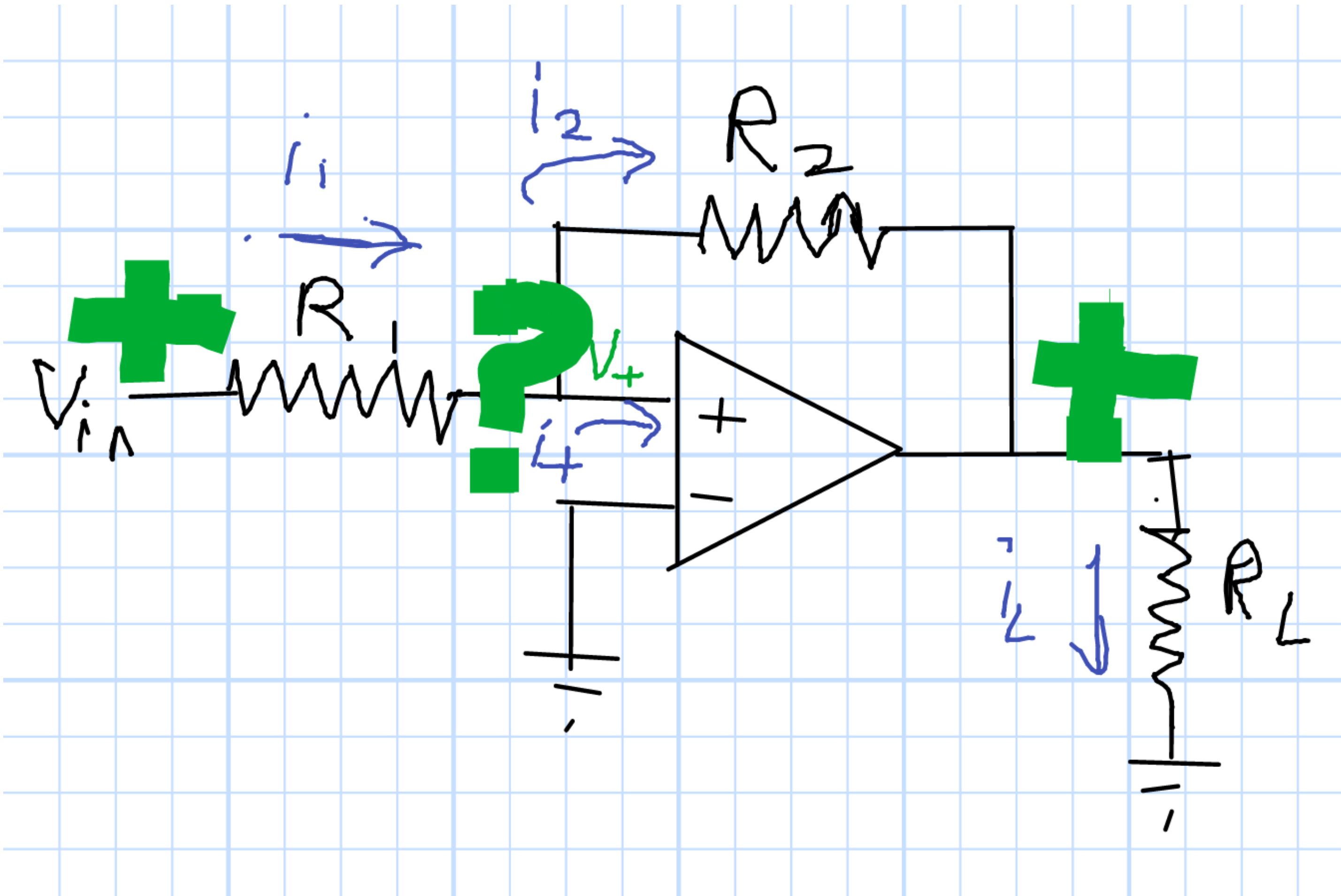
Each input circuit's voltage is affected by the other two input circuits.

The virtual ground is what makes this work.

Positive Feedback (1)



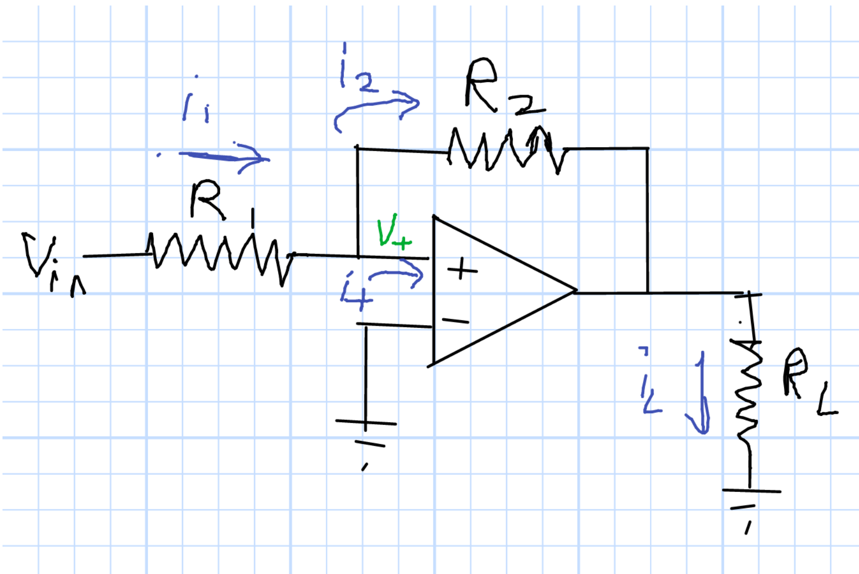
Positive Feedback (2)



v_0 and v_{in} have the same sign, so v_+ cannot be zero

v_0 "goes to the rail." $v_0 = V_{CC}$ or $v_0 = -V_{EE}$ (actually a bit less).

Positive Feedback (3)



$$v_+ = v_{in} + (v_o - v_{in})\frac{R_1}{R_1+R_2} =$$

$$v_{in}\frac{R_2}{R_1+R_2} + v_o\frac{R_1}{R_1+R_2}$$

v_o is limited by the power rails

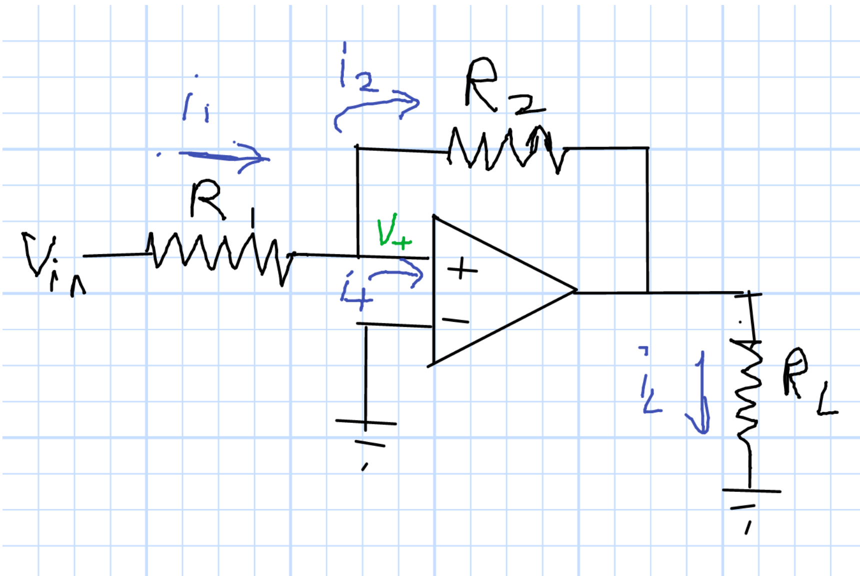
At what v_{in} does it switch?

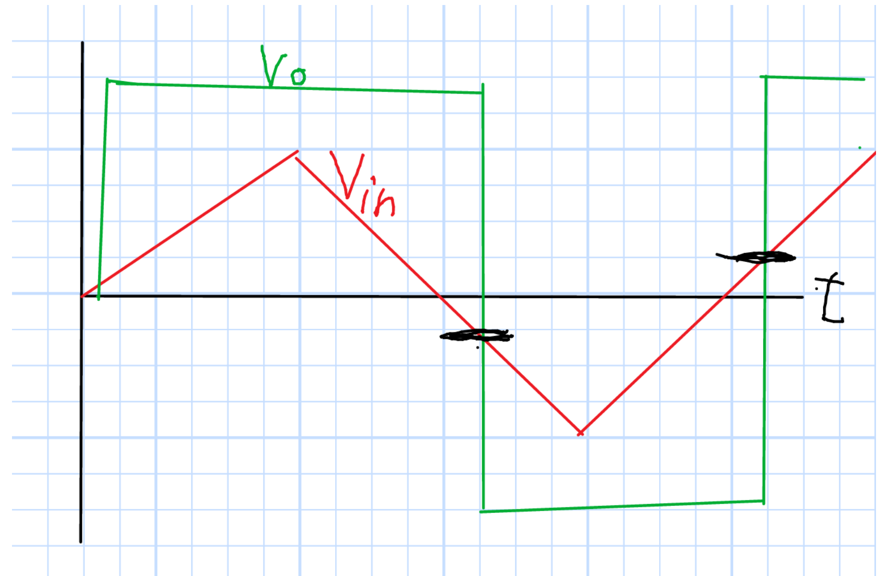
v_{id} is not zero;
Virtual ground fails.
v_+ has same sign as v_o
v_o "goes to the rail."

$$v_+ = 0$$

$$v_{in} = -v_{rail}\frac{R_1}{R_2}$$

Positive Feedback (4)





If $v_o = V_{CC}$, then it will not switch until $v_{in} < -V_{CC}\frac{R_1}{R_2}$

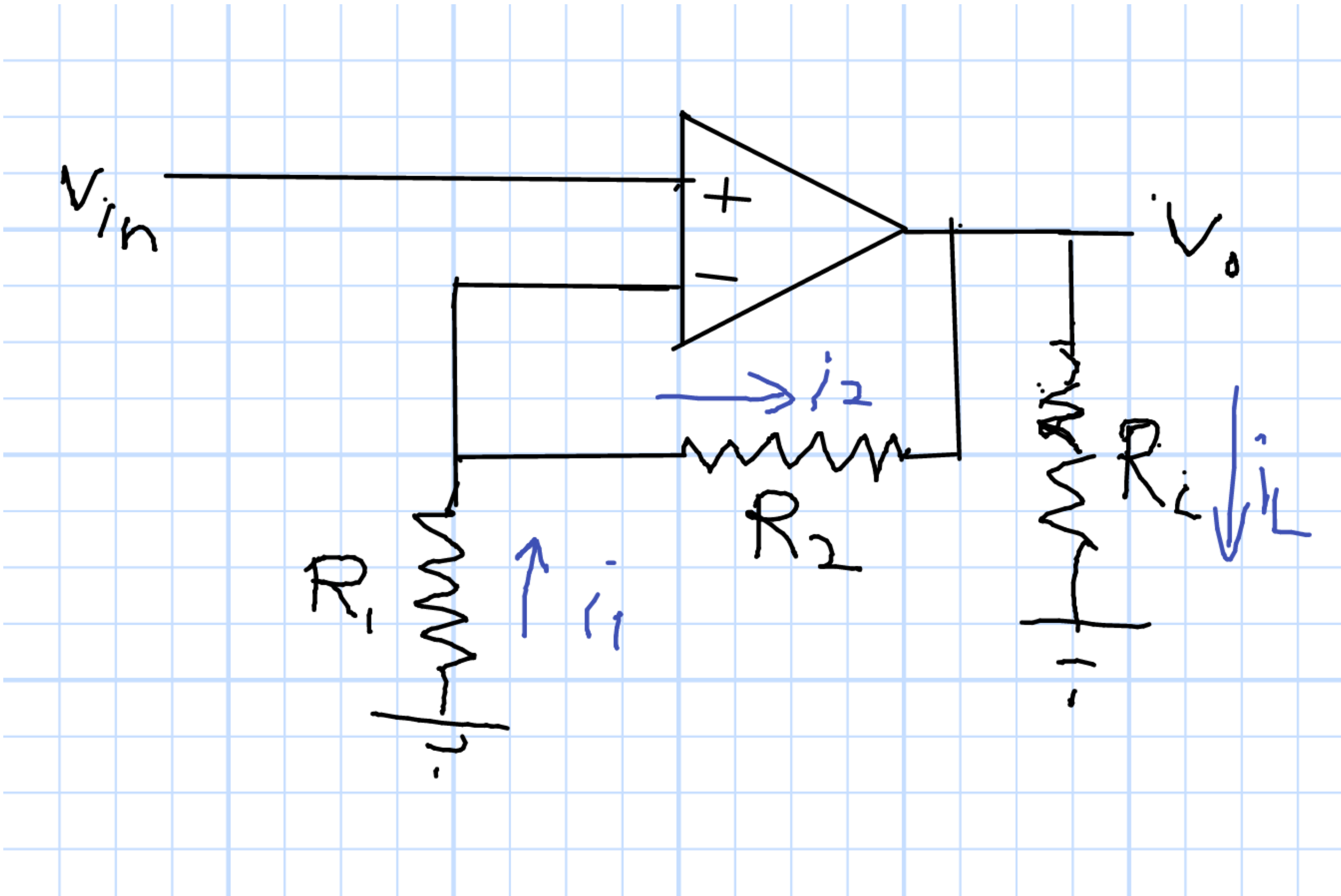
If $v_o = -V_{EE}$, then it will not switch until $v_{in} > +V_{EE}\frac{R_1}{R_2}$

The circuit is bistable.

It "remembers" how it was set until it is switched.

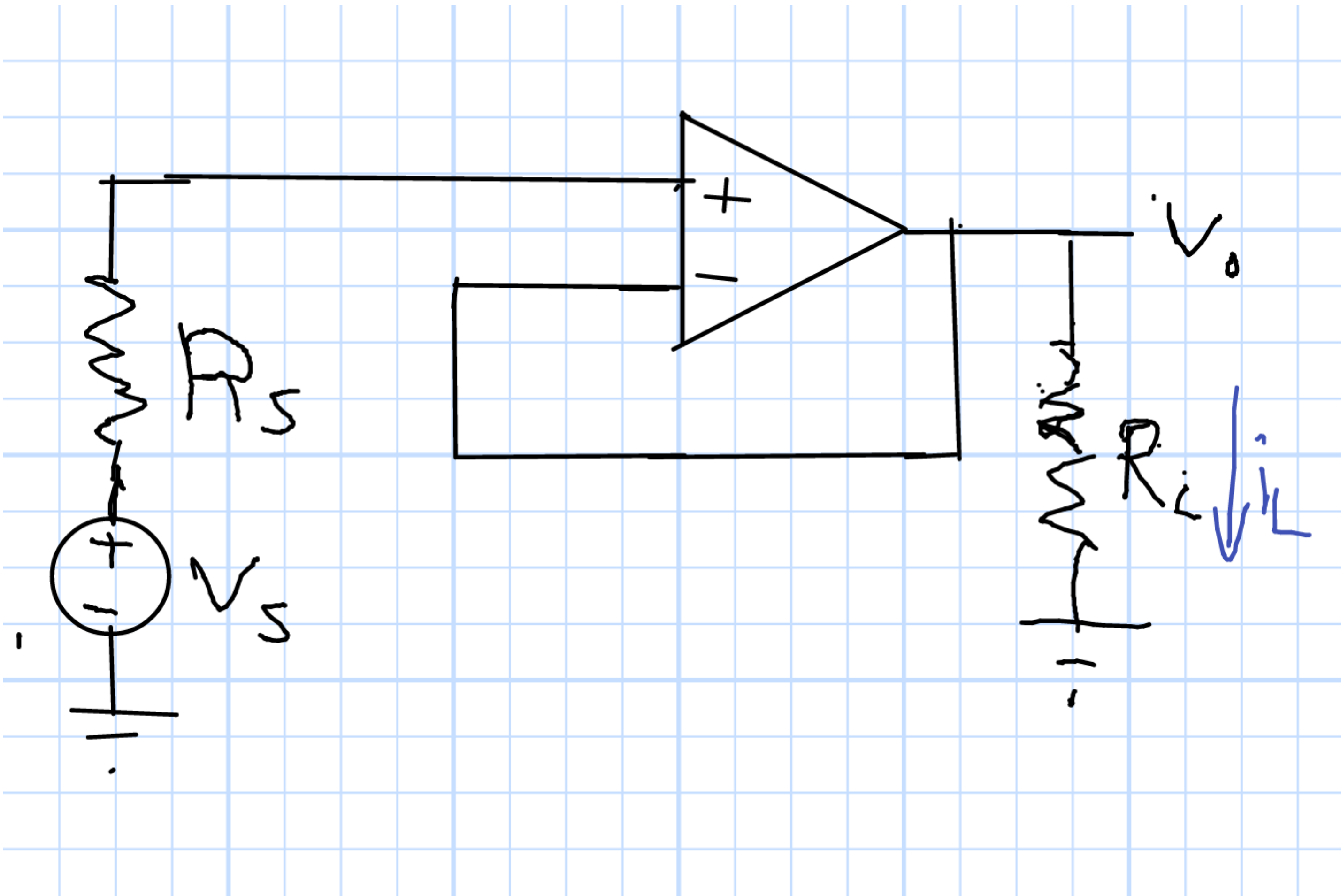
Normally, V_{in} could just be postive and negative pulses.

Non–Inverting Amplifier



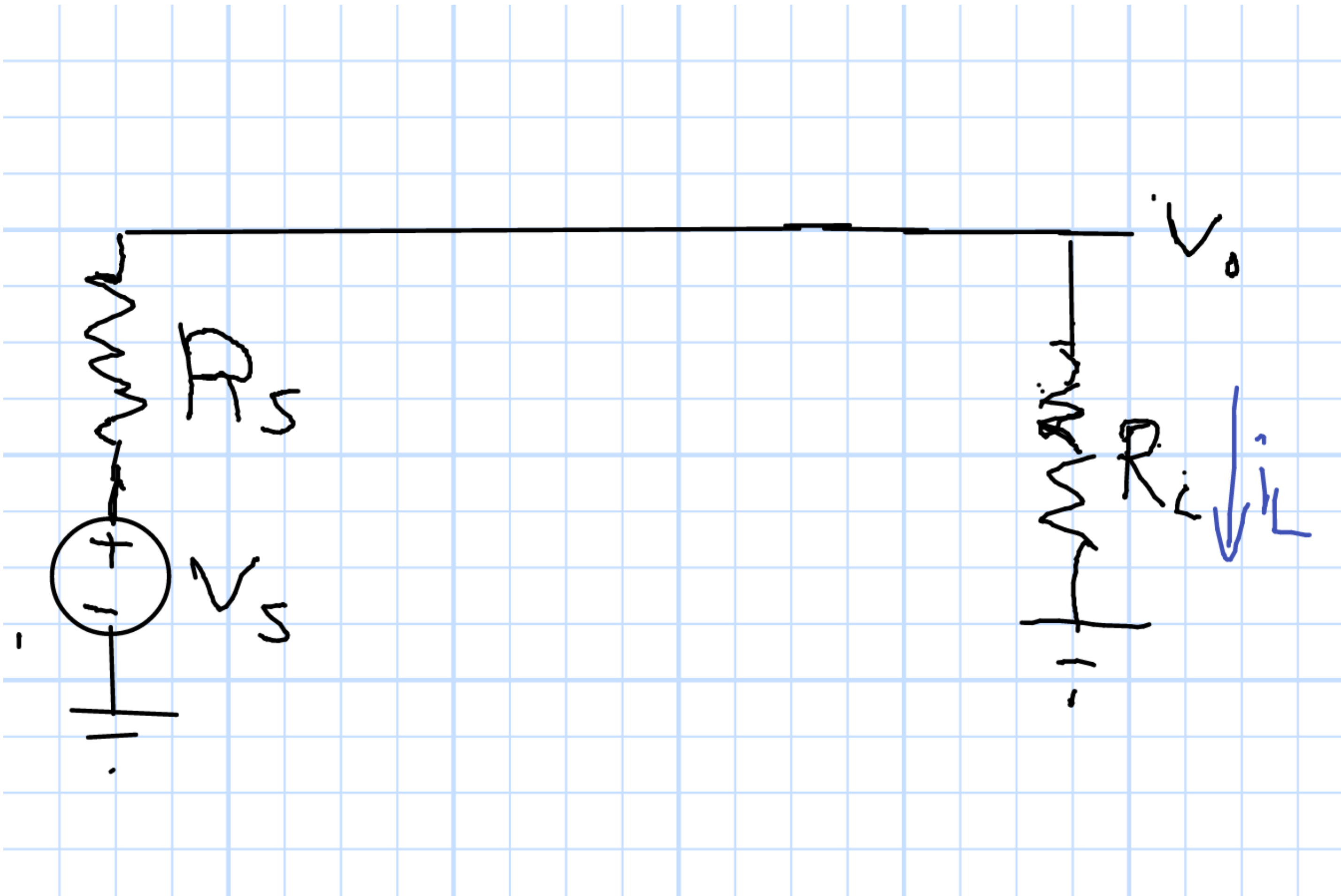
$$v_+ = v_- \qquad v_o = v_{in}\left(\frac{R_2}{R_1}+1\right)$$

Voltage Follower



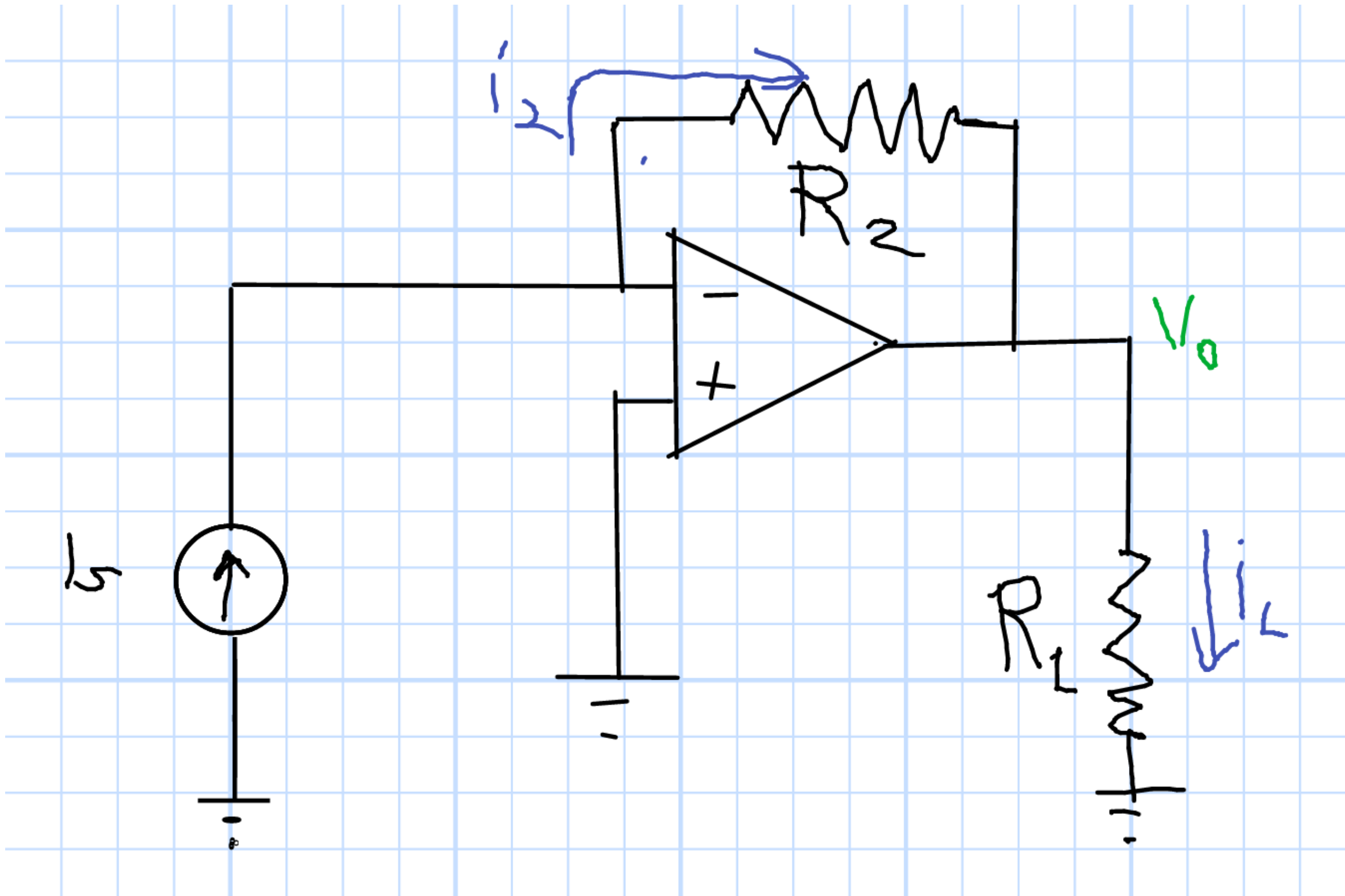
$$v_o = v_{in} = v_s \qquad i_s = 0$$

Why Voltage Follower?



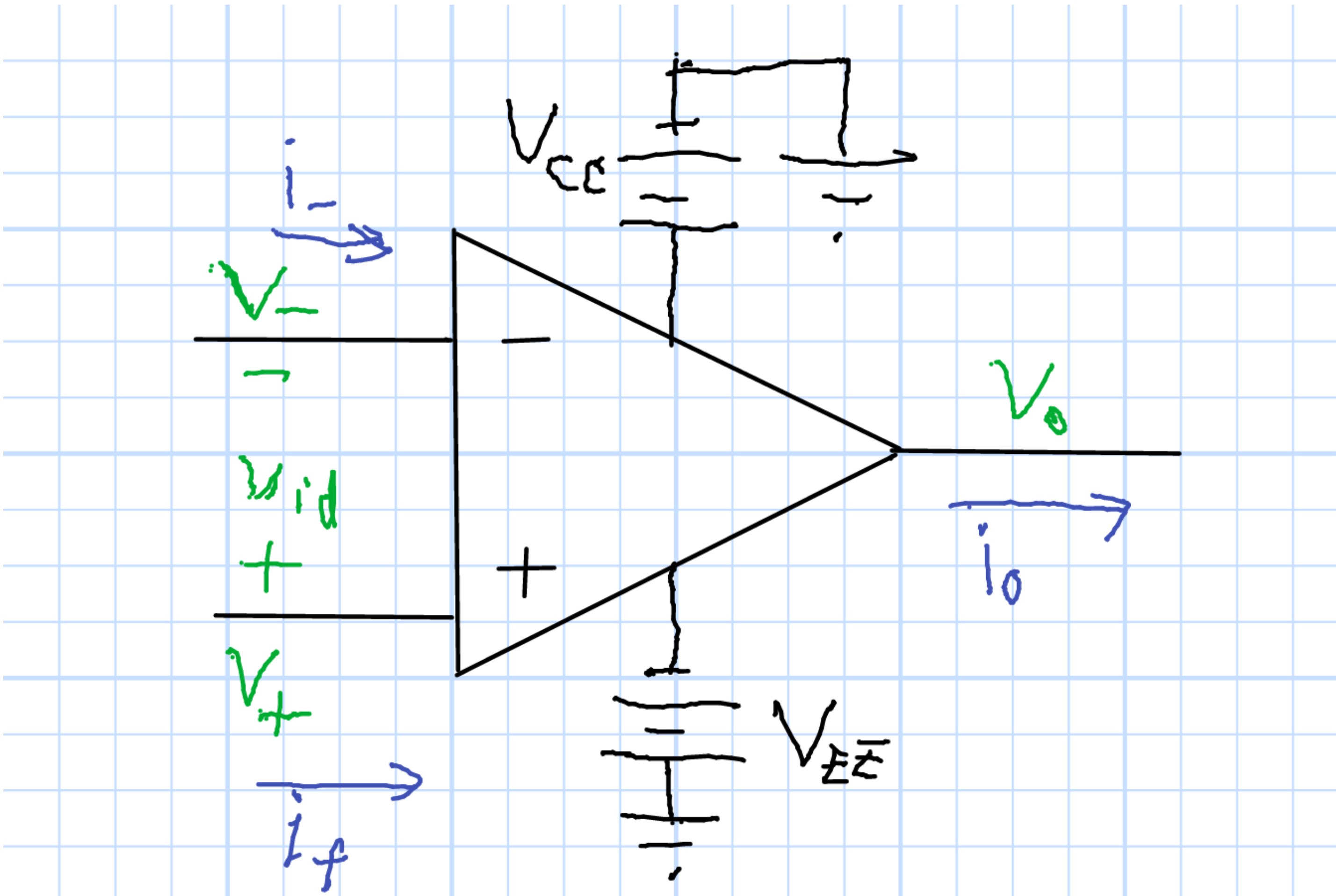
Here, $v_o = v_s \frac{R_L}{R_L + R_s}$. This is important for small R_L, large R_s.
The amplifier provides the needed current.

Transimpedance Amplifier



$v_0 = -R_2 i_s$. Useful for photodiodes among other applications

Limits on v_o

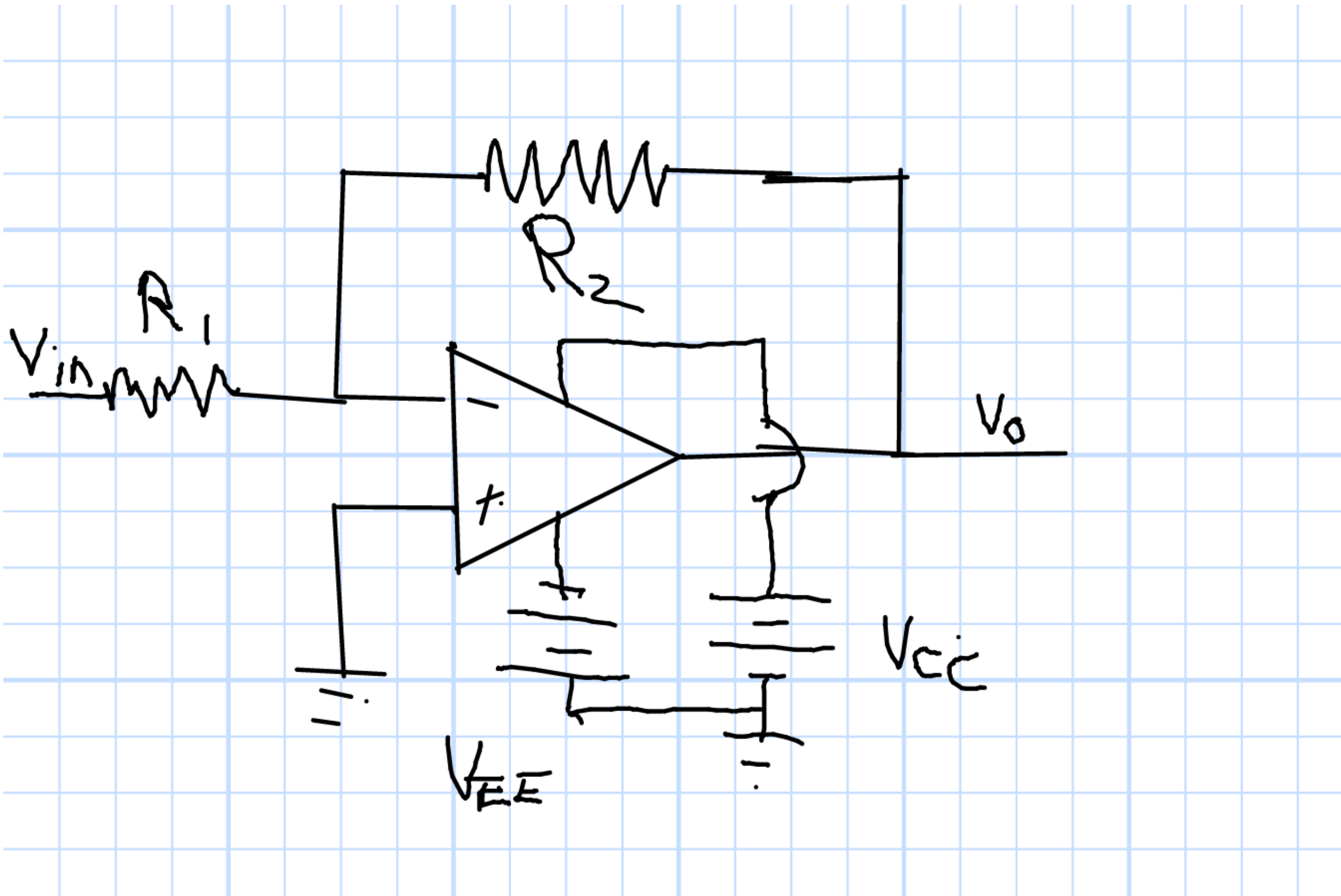


$$-V_{EE} \leq v_o \leq V_{CC}$$

Limitations

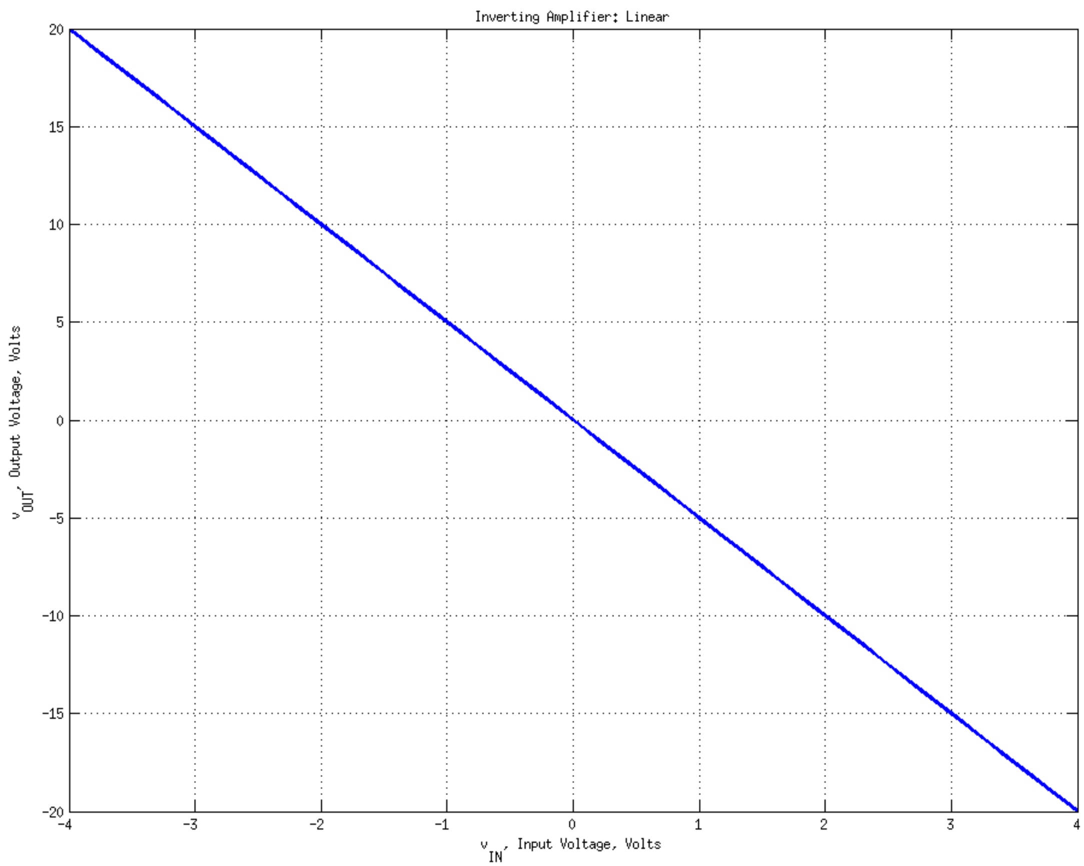
- Linear Effects
  - Input and Output Impedances
  - Finite Gain, A_{OL}
  - Gain–Bandwidth Product
- Nonlinear Effects
  - Voltage Limit
  - Current Limit
  - Slew Rate
- DC Imperfections
  - Bias and Offset Currents
  - Offset Voltage

Voltage Limits

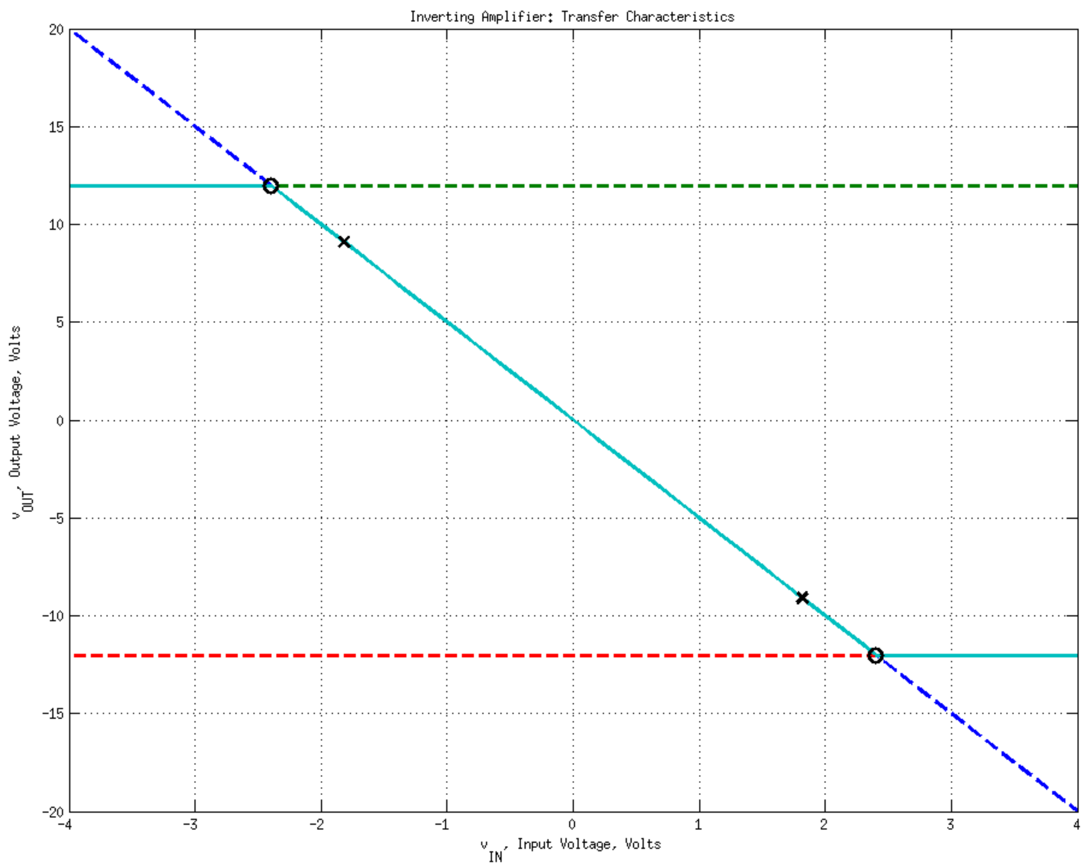


Ideal Gain: $-R_2/R_1 = -5$

New Concept: Transfer Function (Plot of output vs. input)

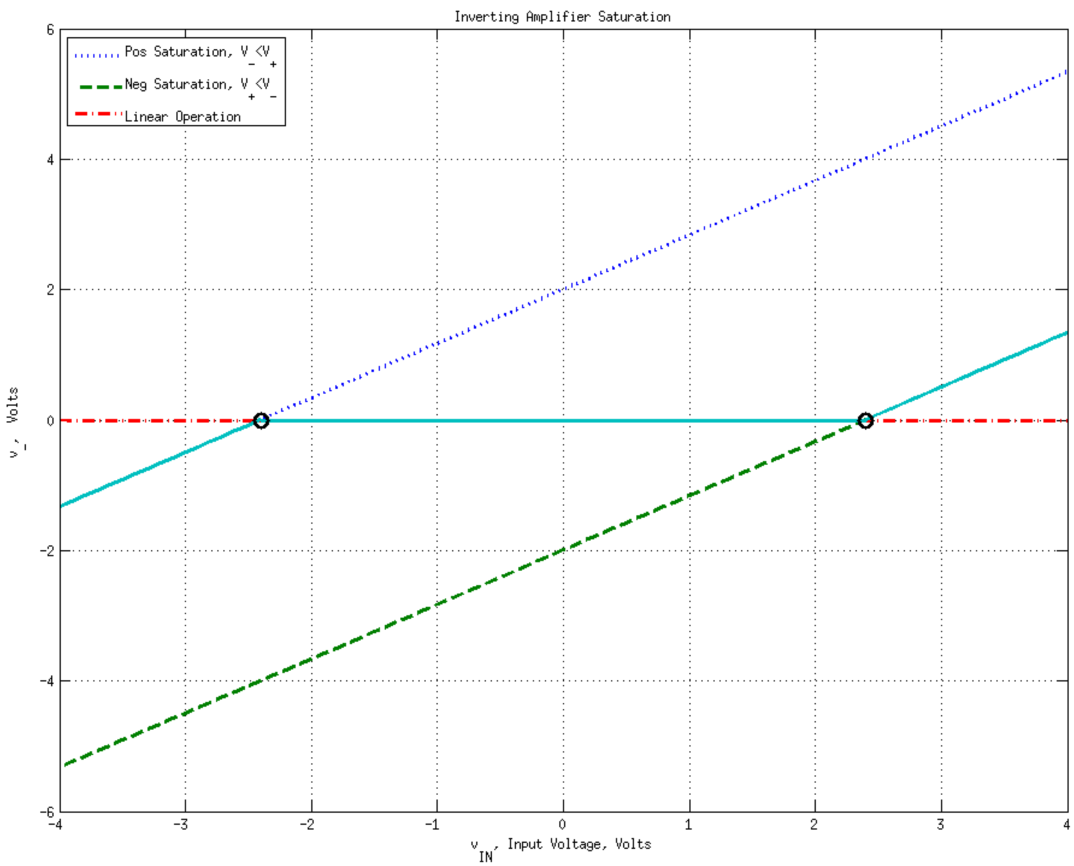


Voltage Limits Example



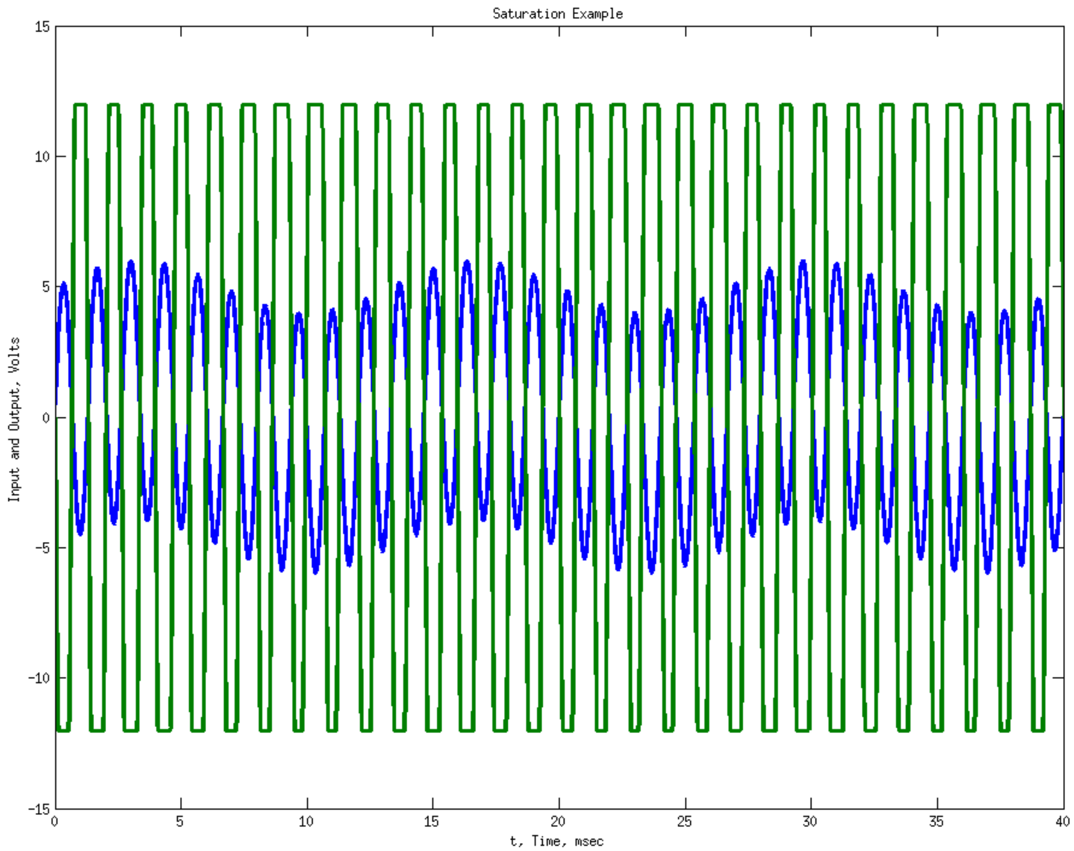
±12–Volt Power Rails. Blue dash is ideal. Cyan solid is actual.

Voltage on −Input



Virtual Ground Fails.

Gain Saturation Example



Blue in, green out. 1V at 75Hz 5V at 750Hz

$R_2/R_1 = 5000/1000$, $\pm$ 12 V rails