EE 42/100
Lecture 9: Op-Amp Based Circuits

Rev A 2/9/2012 (9:08 AM)

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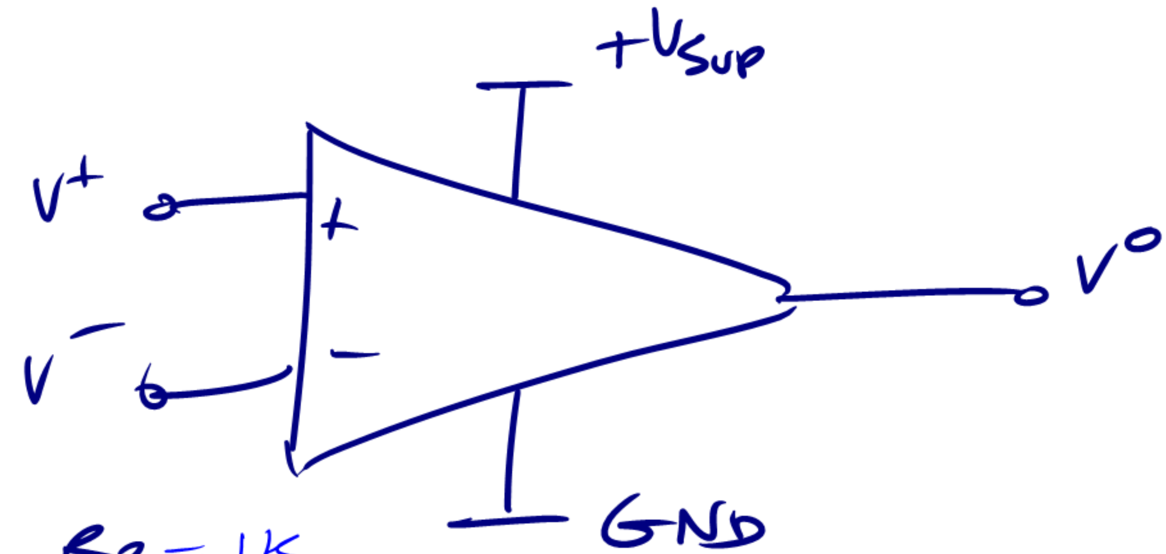
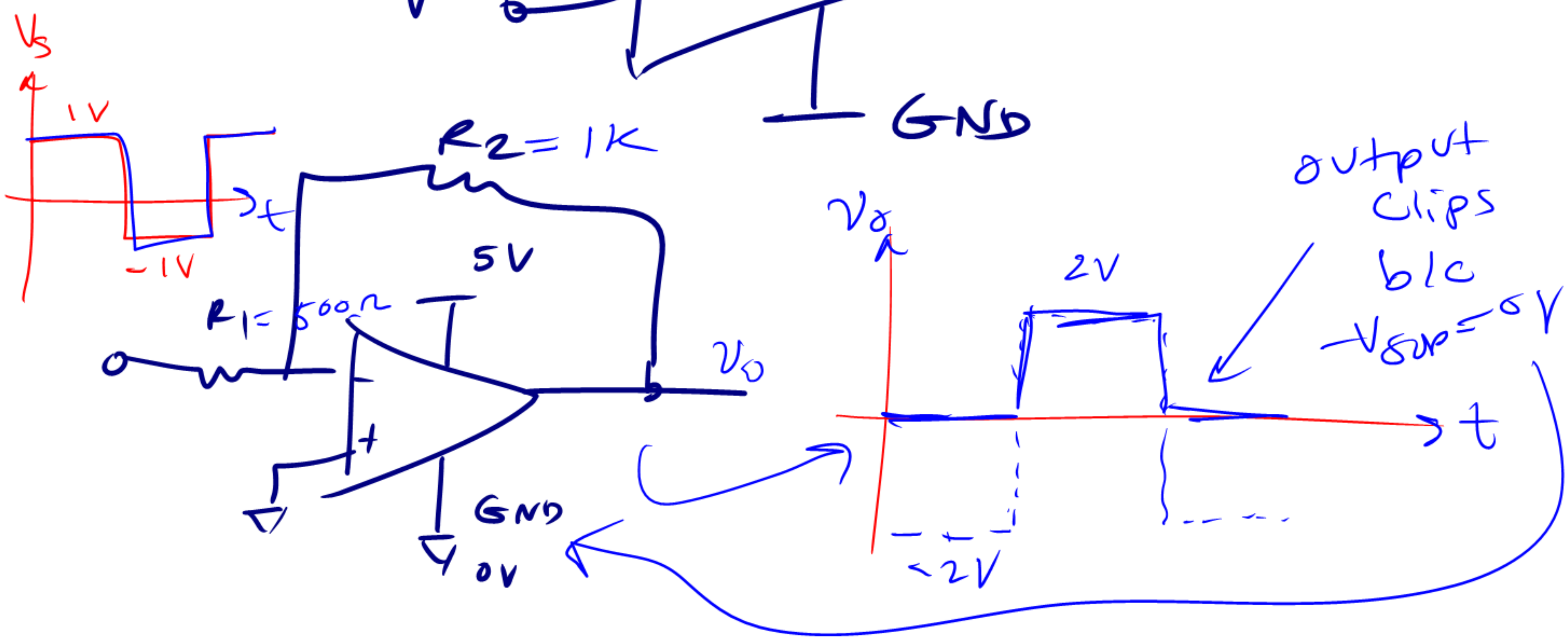
TI's op-amp in Lab:





Ideal Op-Amp: Golden Rules

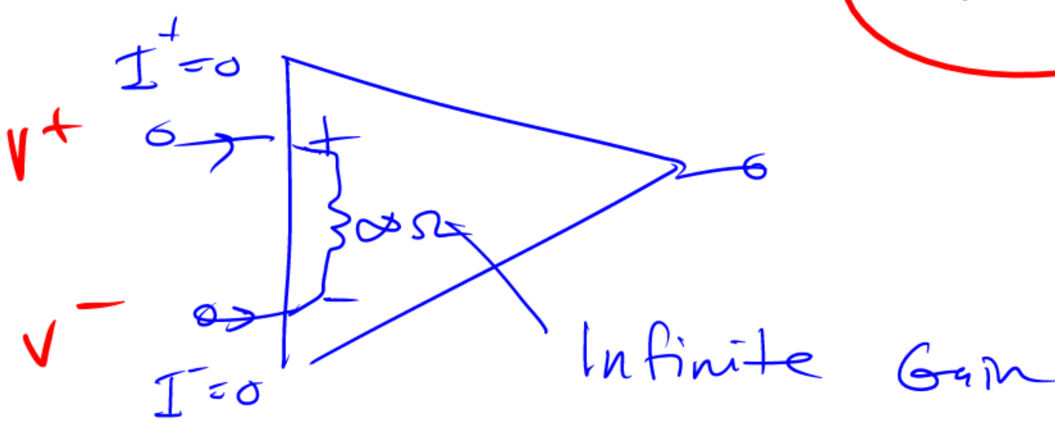
- The ideal op-amp model introduced thus far is useful for circuit simulation, but too complicated for hand analysis. In fact, since the gain of the op-amp is so large, we can make several simplifying assumptions:

Both inputs are at the same voltage.
No current flows in or out of either input.

- As a consequence of the first rule, the input impedance of the amplifier is nearly infinite. Even if the amplifier has a relatively modest input impedance, when feedback is applied, or in “closed loop" configuration, the input impedance is driven to very high values.

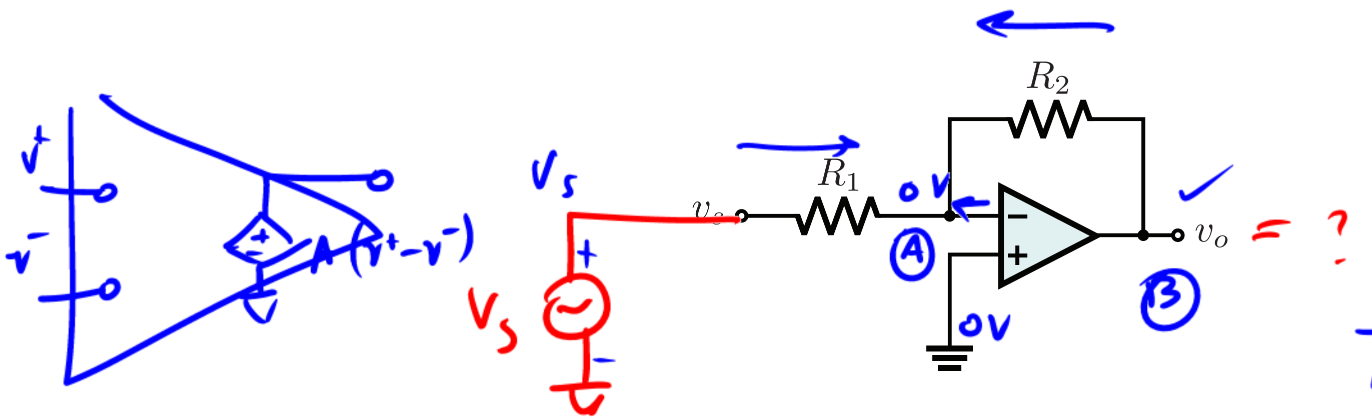
$V^+ = V^-$

WHEN WE USE NEGATIVE FB



$V^+ - V^- = 0\,V$

Example Calculation: Inverting Amplifier



$v^+ = v^-$

KCL @ A

$$\frac{V_s}{R_1} - \cancel{I} + \frac{V_o}{R_2} = 0$$

0

- Let's redo the calculations for the so-called "inverting amplifier" using the Golden Rules
- By the first golden rule, the inverting input of the op-amp must be at ground potential ($v^+ = v^-$), which is often called a "virtual ground". That's because this voltage moves very little as an input signal is applied.
- Write KCL at the input of the op-amp (which is at the virtual ground potential):

$$\boxed{\frac{v_s}{R_1} = -\frac{v_o}{R_2}}$$

- Note that the term for the input current of the op-amp is missing, due to the golden rule. Then we have

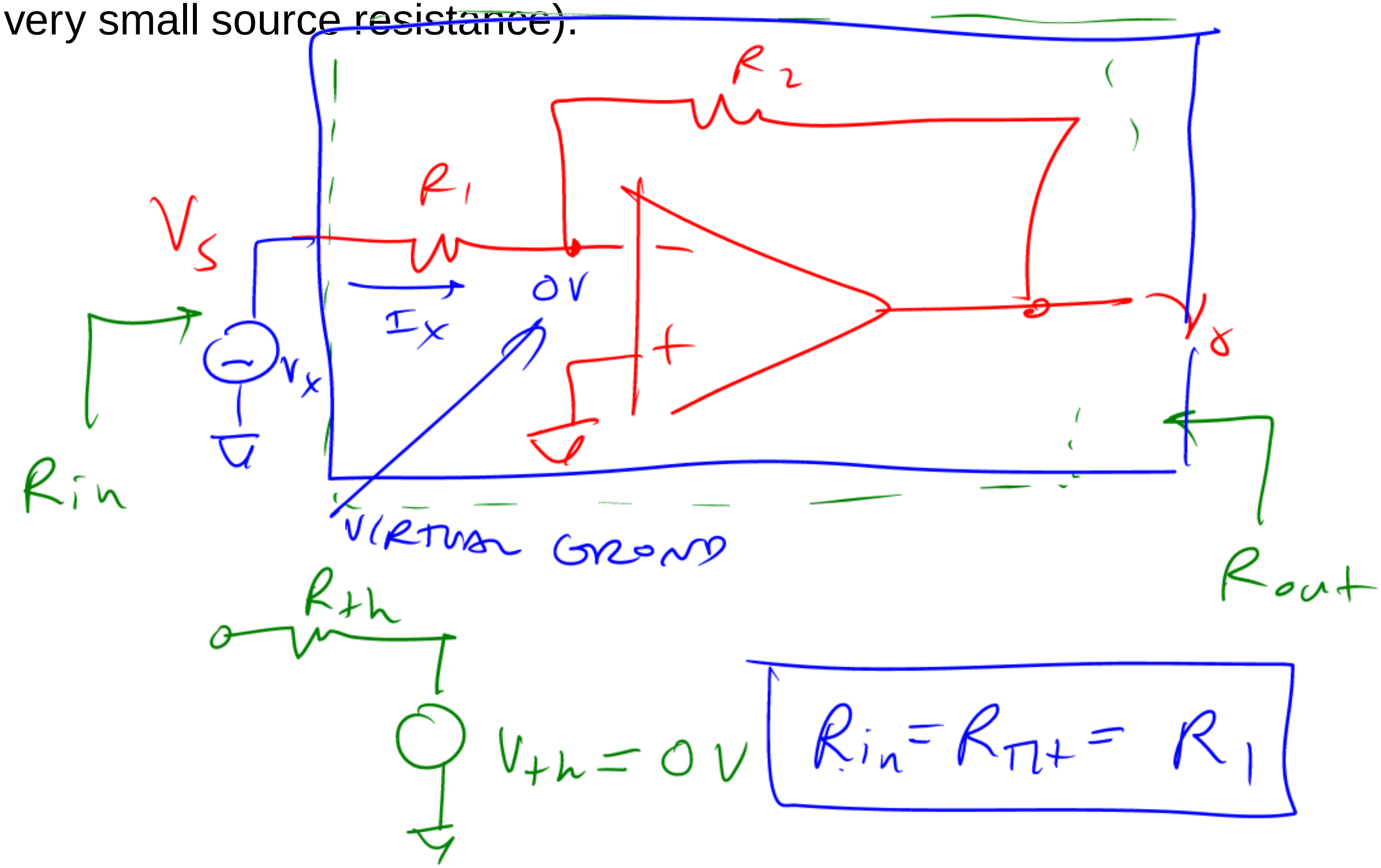
$$G = -\frac{R_2}{R_1}$$

$$\frac{v_o}{v_s} = \frac{-R_2}{R_1}$$

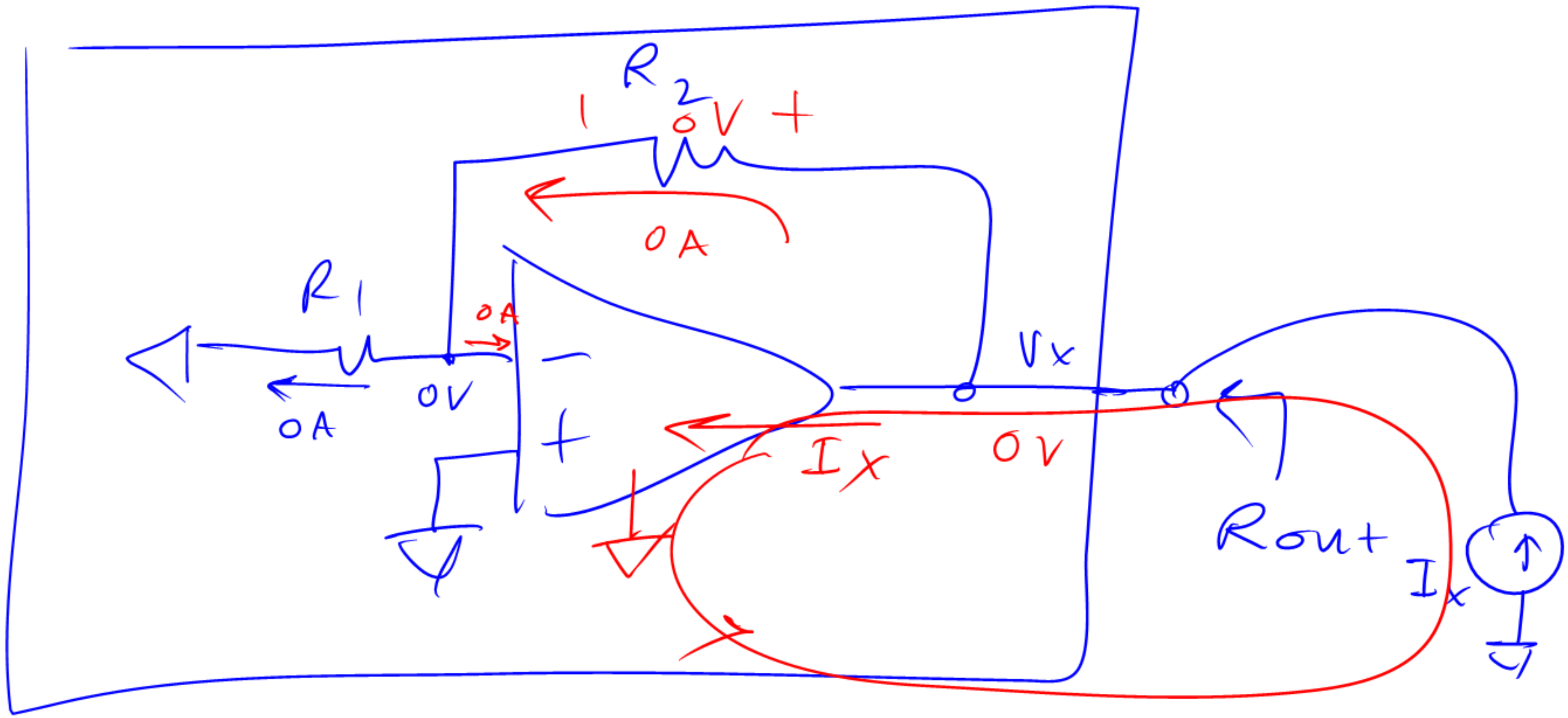
TRANSFER FUNC

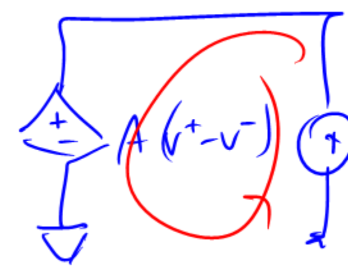
Inverting Amp Input/Output R

- Since the input of the amplifier is at a virtual ground, the voltage source v_s only "sees" the resistance R_1, which is approximately the input resistance of the circuit.
- At the output, the action of the feedback lowers the output resistance, and so the output looks like a nearly ideal voltage source, which means that the op-amp has transformed the voltage source into a nearly perfect voltage source! In other words, the op-amp buffers the source and presents it as a nearly perfect source (with very small source resistance).



$V_{th} = 0\,V$ $\boxed{R_{in} = R_{Th} = R_1}$

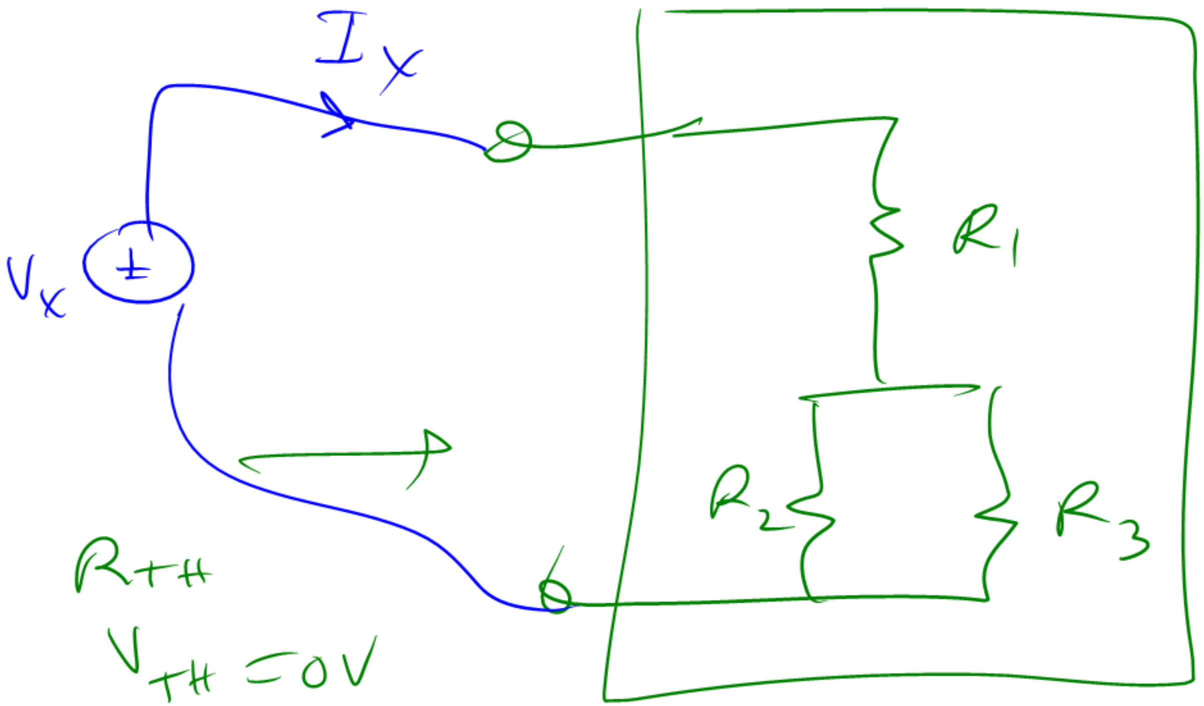




$$R_{out} = \frac{V_x}{I_x} = 0\,\Omega$$

OUTPUT RESISTANCE $= 0\,\Omega$

EXAM SAMPLE



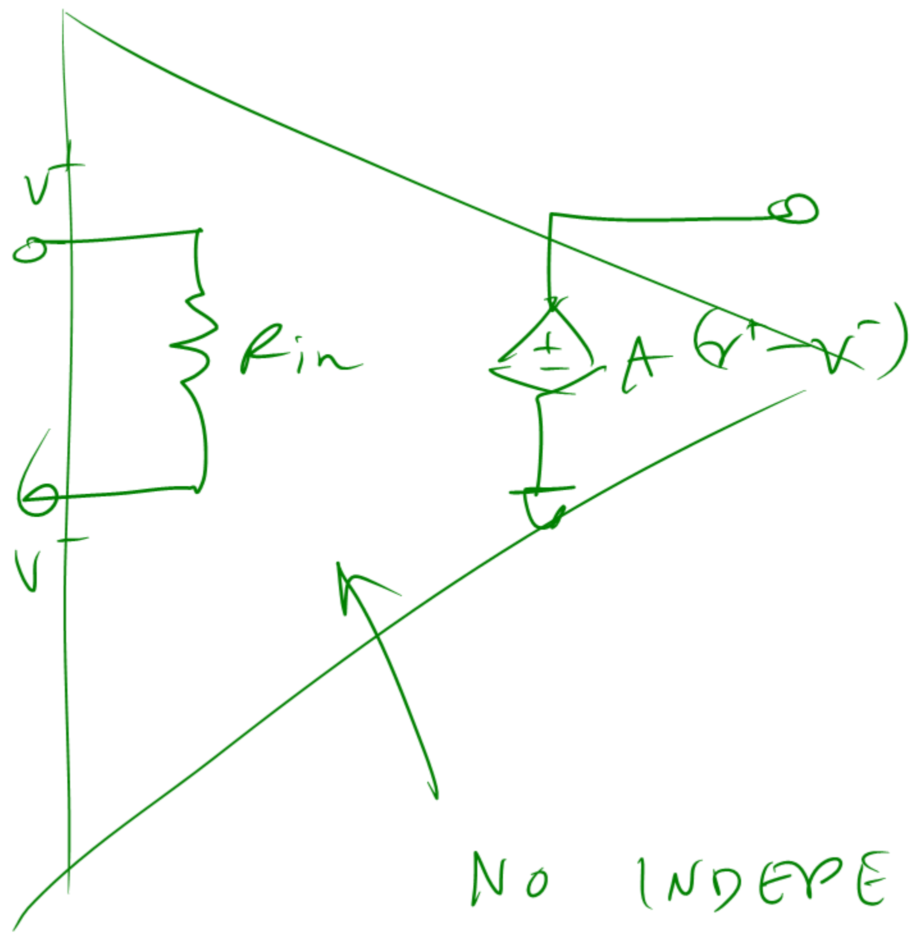
$$R_{TH} = \frac{V_X}{I_X}$$

R_{TH}

$V_{TH} = 0V$

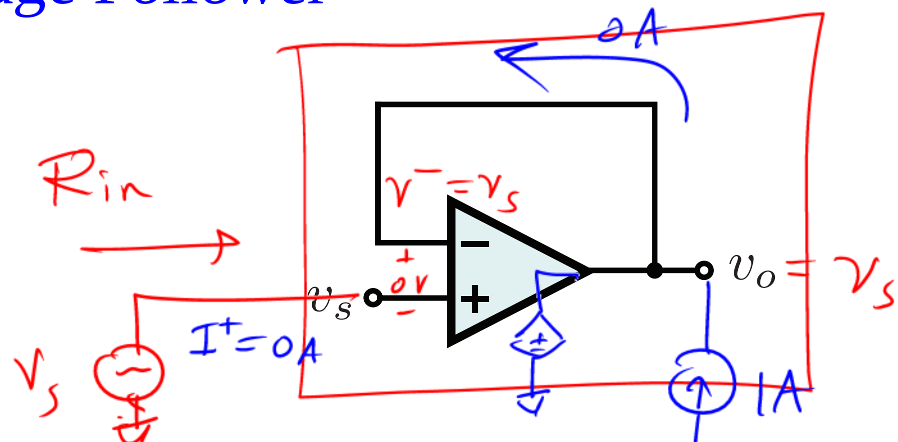
$$R_{TH} = R_1 + R_2 || R_3$$

MODEL OF OP-AMP



NO INDEPENDENT SOURCES INSIDE !

Voltage Follower



$R_{in} = \frac{V_s}{I^+} = \infty\,\Omega$

$R_{out} = 0\,\Omega$

- This is the idea behind the voltage follower, which has an input-output relation that at first seems trivial:

$$v^s = v^+ = v^- = v_o$$

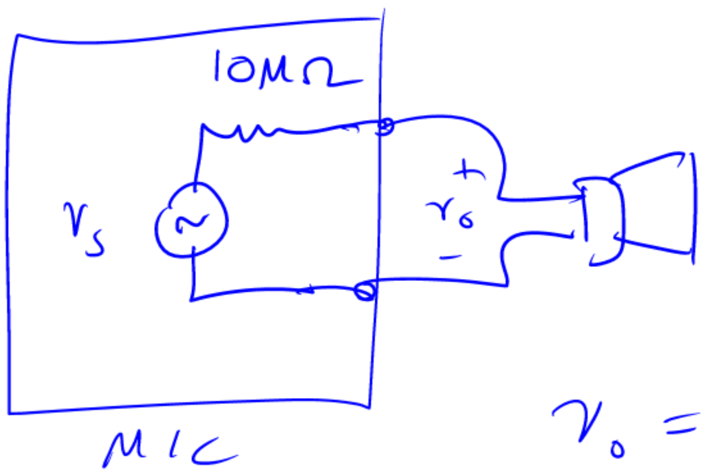
- Which means the output voltage is just the same as the input voltage, or it *follows* the input. But notice that the input impedance seen by the source is nearly infinite, since no current flows into the op-amp. This means that the op-amp does not load the source in this configuration. Likewise, the output impedance is very low, which means that an imperfect source can be buffered and made to appear as an ideal voltage source.

ALSO KNOWN AS:

A UNITY BUFFER

Microphone Example

- A crystal microphone has a source resistance of 10 $M\Omega$. We wish to drive a speaker with has an impedance of only 8Ω. Last lecture we realized that using a simple linear amplifier is not practical, because of the loading issues.
- But a voltage buffer followed by an amplifier solves these problems.



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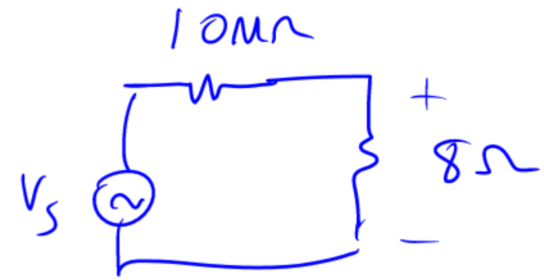
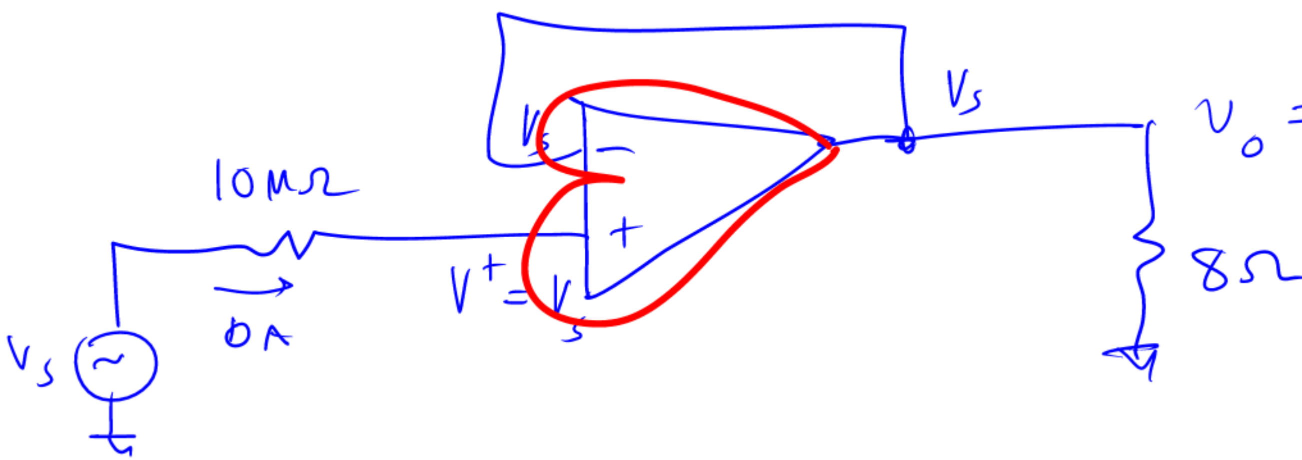
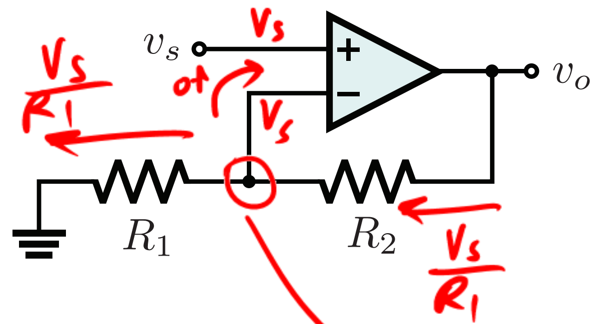


$$v_o = \frac{8\Omega}{10M\Omega + 8\Omega} v_s \simeq 8 \times 10^{-7} v_s$$



$v_o = V_s$

Non-Inverting Amplifier



$\swarrow I_{R_2}$

$V_o = V_s + \left(\frac{V_s}{R_1}\right) \times R_2$

$$\boxed{V_o = V_s\left(1 + \frac{R_2}{R_1}\right)}$$

$\underbrace{\left(1 + \frac{R_2}{R_1}\right)}_{\text{GAIN} > 0}$

- For the non-inverting amplifier, we still apply feedback to the negative terminal. The input is supplied to the positive terminal.
- Applying the first golden rule as before, we have

KCL

$$\frac{V_s}{R_1} + \frac{V_s - V_o}{R_2} = 0$$

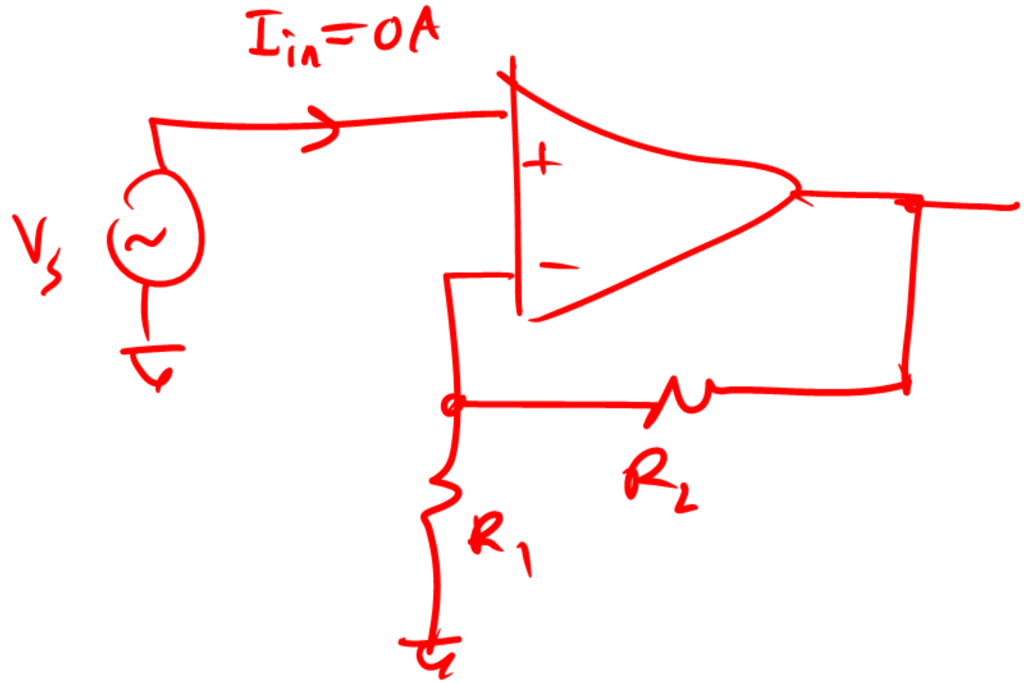
$$v^- = v^+ = v_s$$

- Now applying the second golden rule, since the input current of the op-amp is zero, there is a perfect voltage divider from the output of the op-amp to the negative terminal

$$v^+ = v_o \frac{R_1}{R_1 + R_2}$$

- Which means that

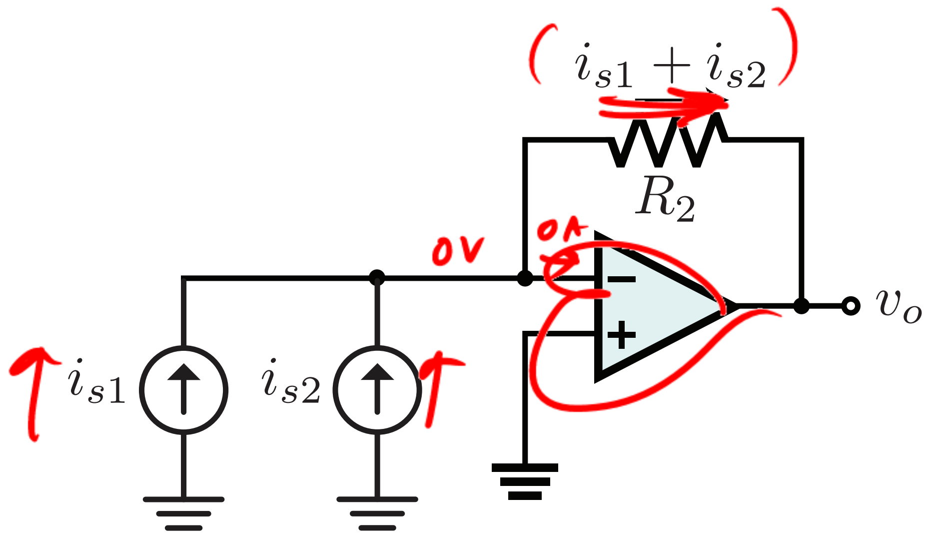
$$\frac{v_o}{v_s} = 1 + \frac{R_2}{R_1}$$



$$R_{in} = \frac{V_s}{I_{in}} = \infty\,\Omega$$

$$R_{out} = 0\,\Omega$$

Current Summing Amplifier



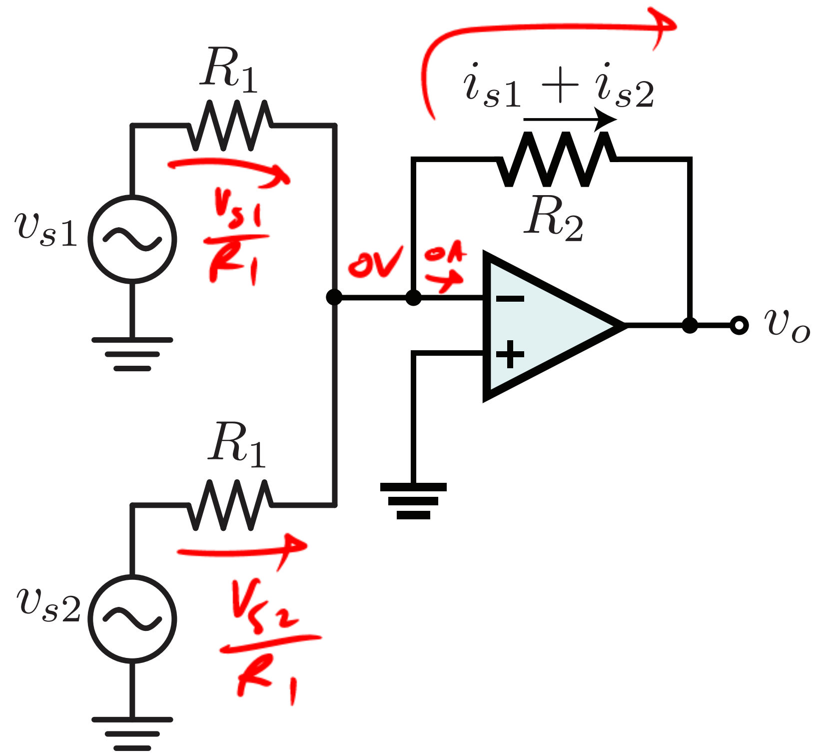
- An important observation is that in the inverting amplifier, the current injected into the negative terminal of the op-amp is routed to the output and converted into a voltage through R_2. If multiple currents are injected, then the *sum* of the currents is converted to a voltage.

$$V_o = \cancel{V^-} - (i_{s1} + i_{s2}) \cdot R_2$$

0V

$$= -(i_{s1} + i_{s2}) R_2$$

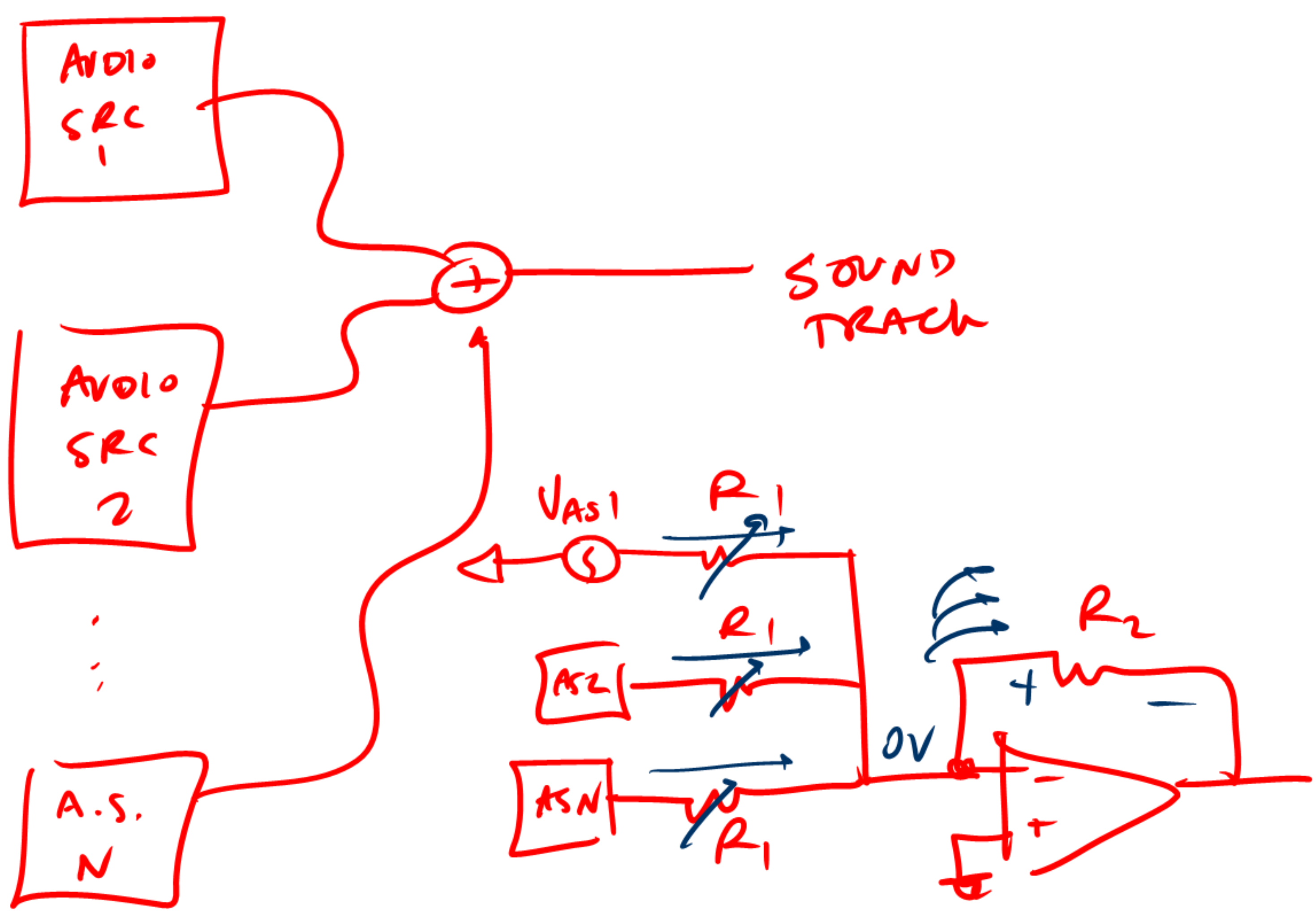
Voltage Summing Amplifier



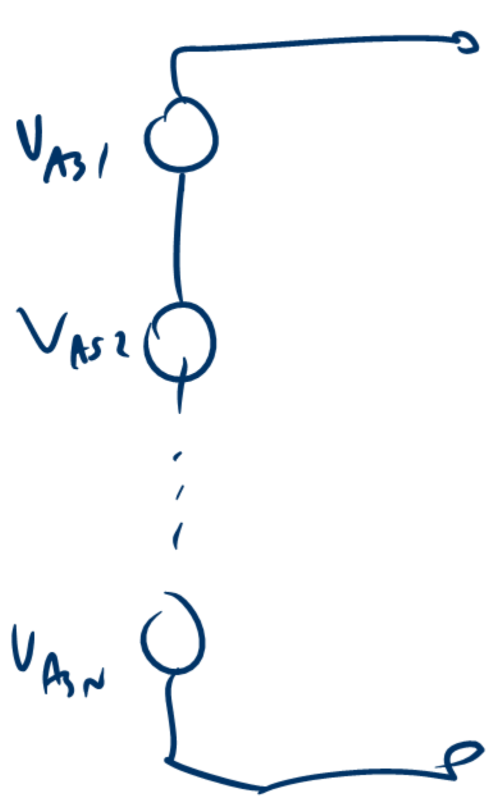
- Each source is converted into a current and then summed in a similar fashion as the currents. Note that the virtual ground means that no current is "lost" when the currents are put in parallel (due to the output resistance).

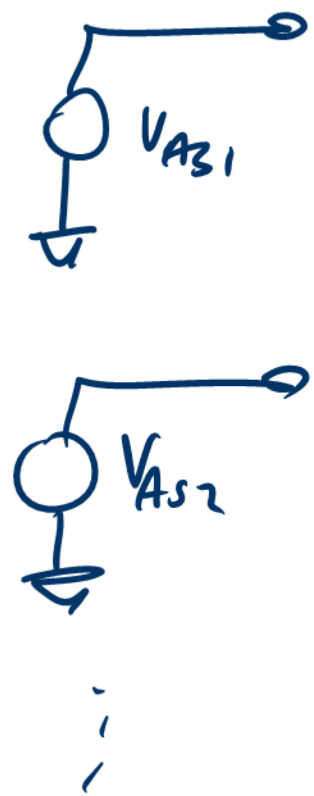
$$v_o = -(i_{s1} + i_{s2}) \cdot R_2 = -\left(\frac{v_{s1}}{R_1} + \frac{v_{s2}}{R_1}\right) \times R_2$$

$$= -\frac{R_2}{R_1}(v_{s1} + v_{s2})$$

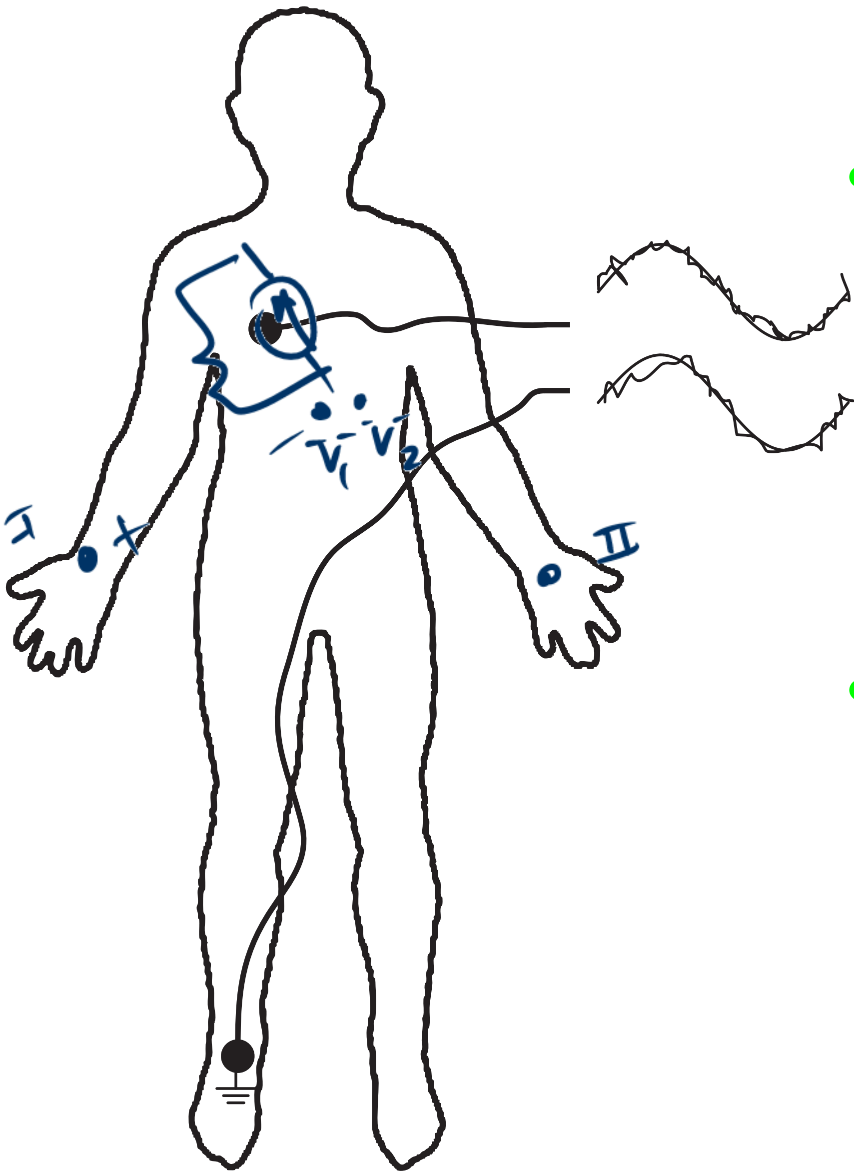


AUDIO SRC 1
AUDIO SRC 2
A.S. N
+
SOUND TRACK
VAS1
S
R1
AS2
R1
ASN
R1
R2
0V
+
−
−
+

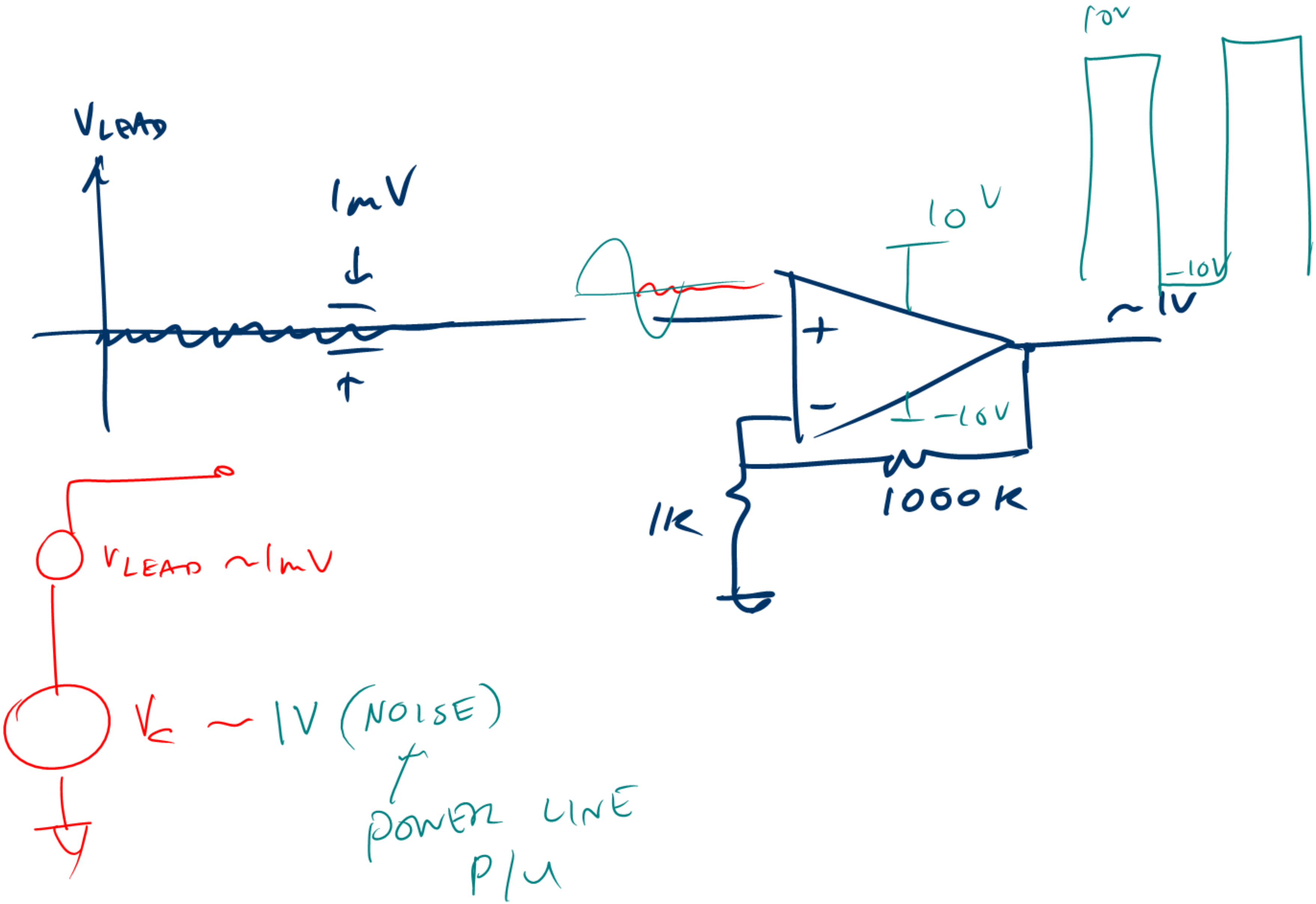

V_{AS1}
V_{AS2}
V_{ASN}


V_{AS1}
V_{AS2}

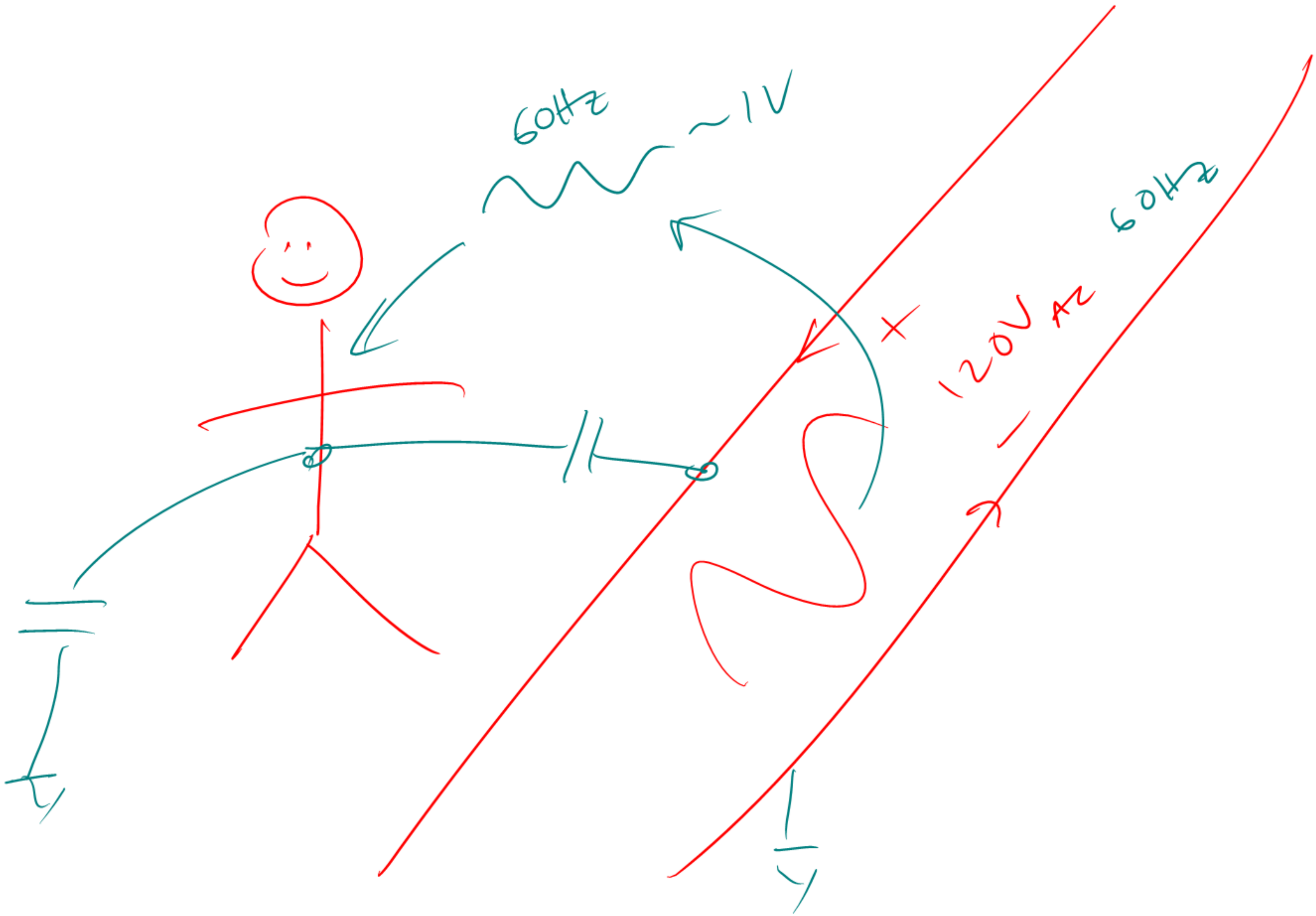
Differential Amplification and Noise



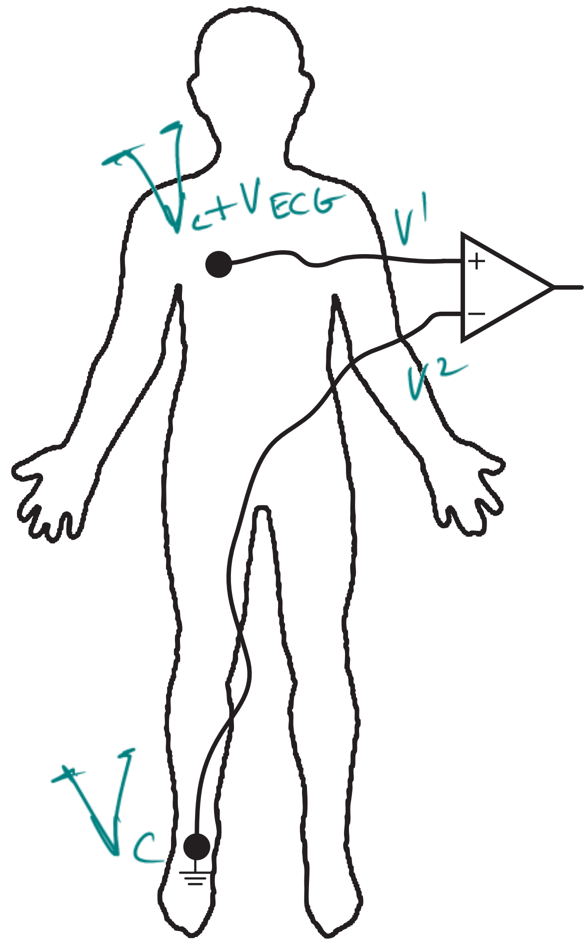
- In many systems, the desired signal is weak but it's accompanied by a much larger undesired signal. A good example is the ECG measurement on the human body. The human body picks up a lot of 60 Hz noise (due to capacitive pickup) and so a very weak ECG signal (mV) is accompanied by a large signal ($\sim 1V$) that we wish to reject.
- Fortunately the noise pickup is in *common* with both leads of the ECG because the body is essentially an equipotential surface for the noise pickup. If we take the difference between two points, it disappears.



V LEAD
1mV
10V
10V
-10V
~1V
+
-
-10V
1000K
1K
V LEAD ~1mV
Vc ~ 1V (NOISE)
POWER LINE
P/U


60Hz
~1V
+
120V AC
60Hz
-

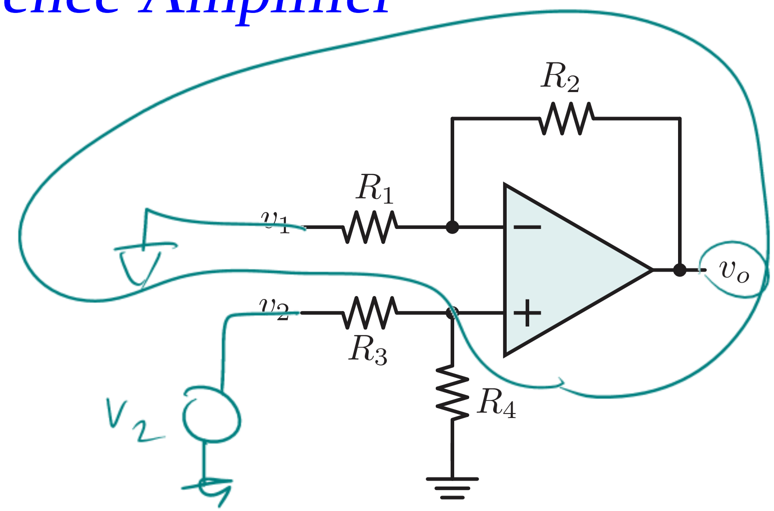
Common-Mode and Differential-Mode Gain



$$
\begin{aligned}
v_o &= V^1 - V^2 \\
&= \cancel{V_c} + V_{ECG} - \cancel{V_c} \\
&= V_{ECG}
\end{aligned}
$$

- We thus need an amplifier that can detect a small *differential mode* voltage in the presence of a potentially very strong *common mode* voltage.

Difference Amplifier



NON-INVERTING AMP

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

- Using superposition, we can quickly calculate the transfer function. For port 1, the amplifier is simply an inverting stage $V_2 = 0V$

$$\boxed{v_o^1 = v_1 \frac{-R_2}{R_1}}$$

- For port 2, it's a non-inverting stage, except we only tap off a fraction of v_2

$$\boxed{v_o^2 = v_2 \frac{R_4}{R_3 + R_4}(1 + \frac{R_2}{R_1})}$$

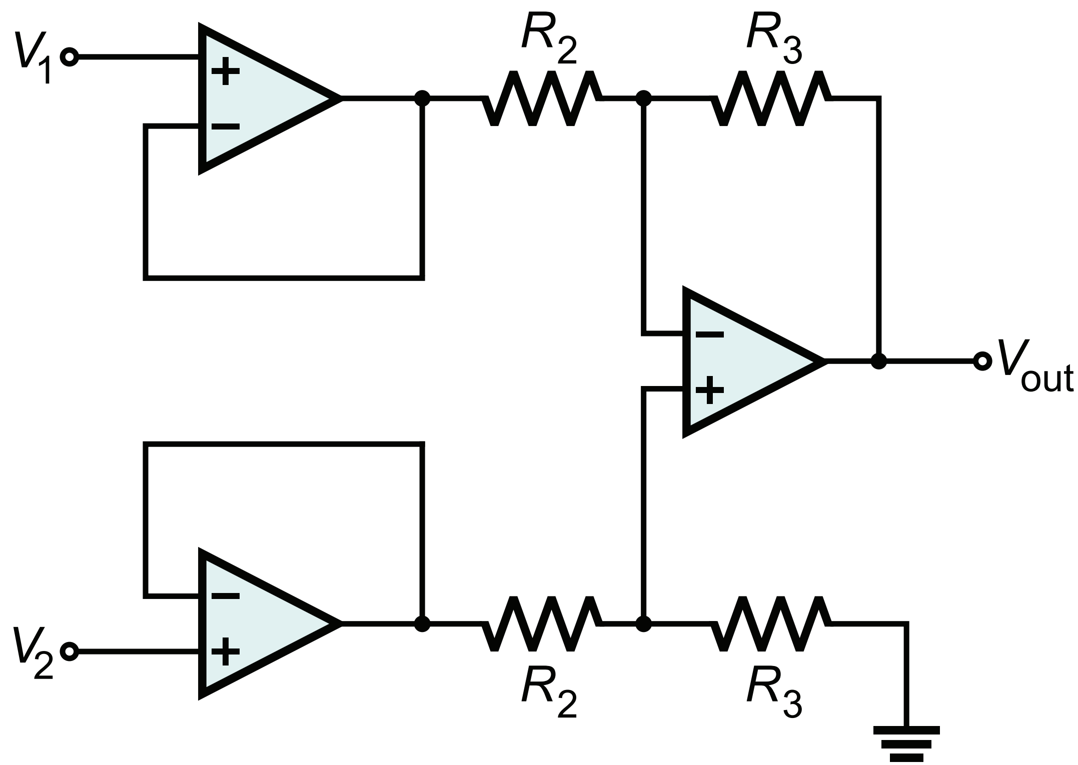
$V^+ = \frac{R_4}{R_3 + R_4} V_2$

$V_o = G \cdot V^+$

- Take the sum and set $R_1 = R_3$ and $R_2 = R_4$, we have

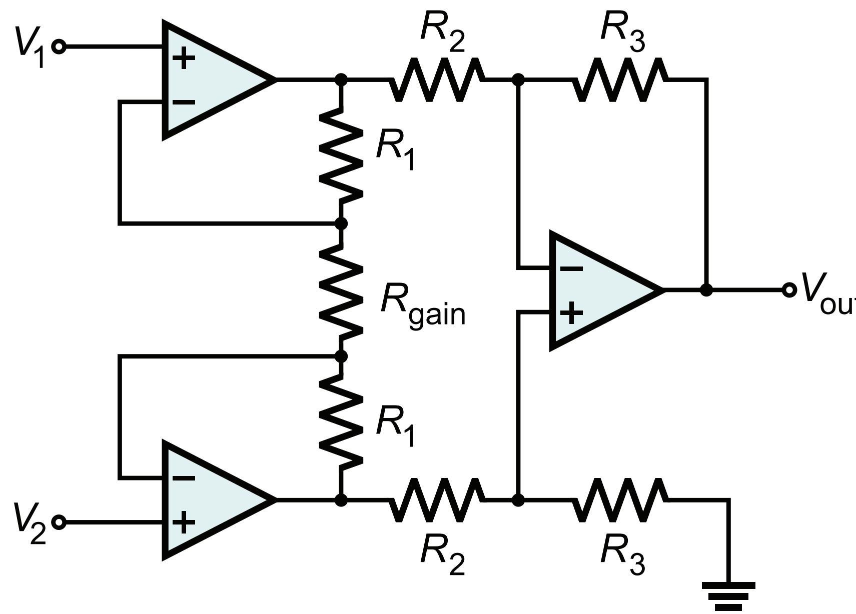
$$\boxed{v_o = \frac{R_2}{R_1}(v_2 - v_1)}$$

Instrumentation Amplifier



- Two unity-gain buffers are used to buffer the input signal. A difference amplifier is used to provide a gain of R_3/R_2.

Instrumentation Amplifier Version 2



$$v_o = \left(1 + \frac{2R_1}{R_{gain}}\right)\frac{R_3}{R_2}(v_2 - v_1)$$

- The input buffers now have gain due to the fact that the circuit is configured as a non-inverting amplifier. Why is the resistor R_{gain} appear between the amplifiers?
- *Subtle:* Note that we could simply put in two resistors to ground, but a more elegant way to realize it is to put in between the top and bottom. For balanced inputs, the resistor is split in two and grounded in the middle (another virtual ground). For unbalanced inputs, no current flows and the resistor is not there, so there's no common-mode gain!