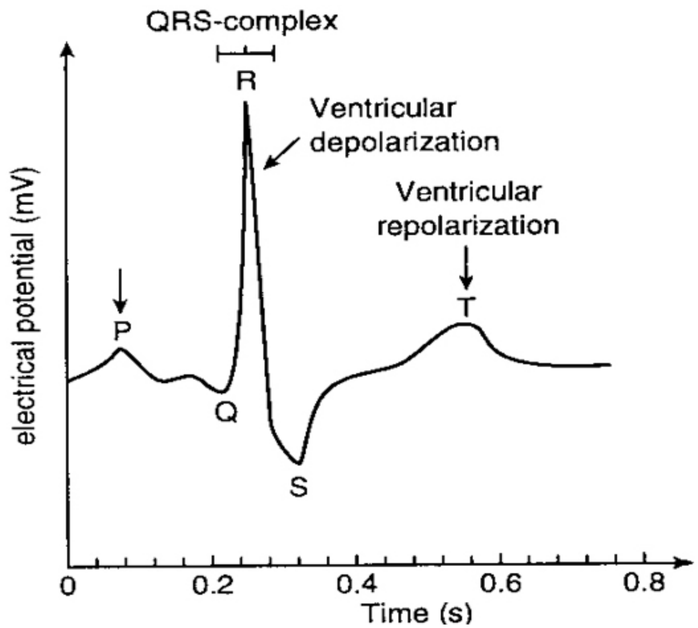
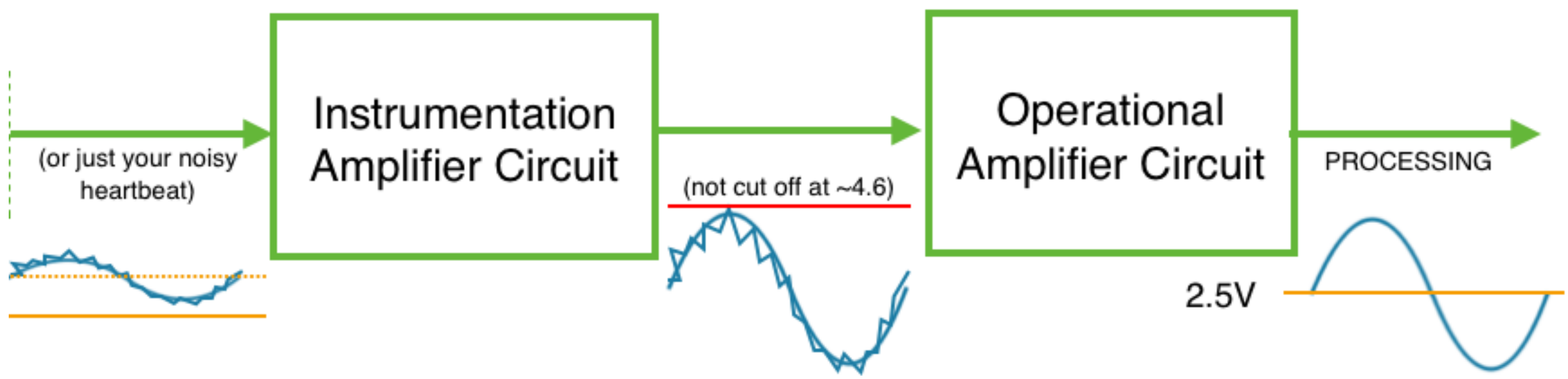
E40M

Instrumentation Amps and Noise

ECG Lab - Electrical Picture

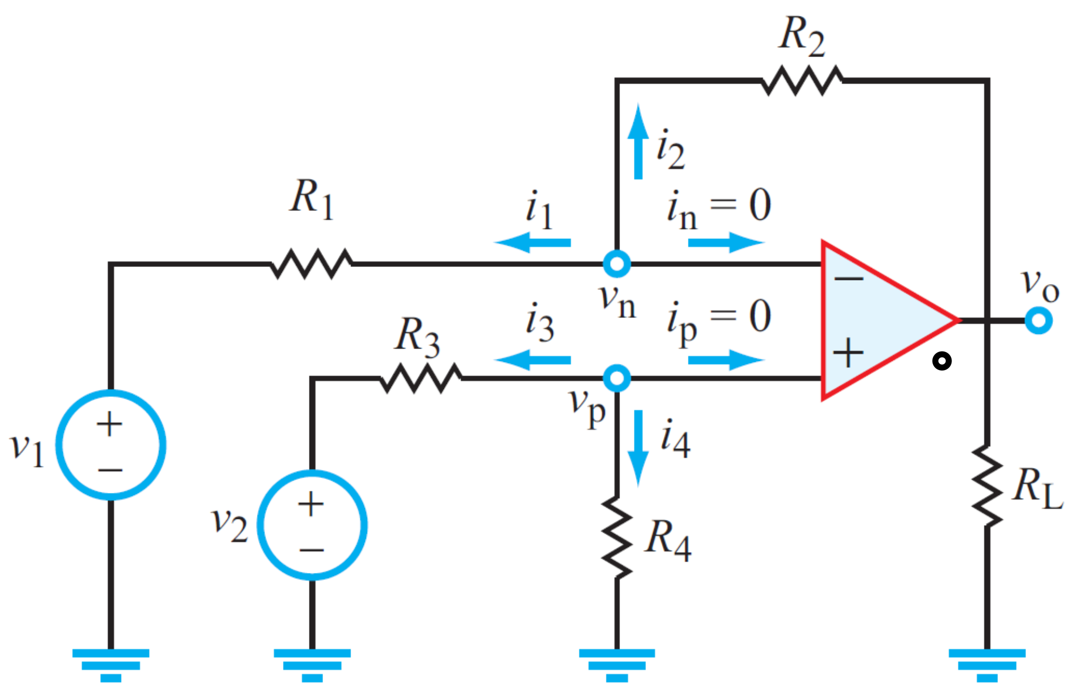


- Signal amplitude ≈ 1 mV
- Noise level will be significant
- ∴ will need to amplify and filter
- We'll use filtering ideas from the last set of lecture notes



INSTRUMENTATION AMP

Starting Point: Differential Amplifier 1.0



If $R_3 = R_1$ and $R_4 = R_2$

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

- This amplifier requires that the input voltage sources provide input currents (i_1 and i_3 are not zero) … *not* OK for the ECG project or a general-purpose instrumentation amplifier.

We Need A Differential Amplifier With No Input Current

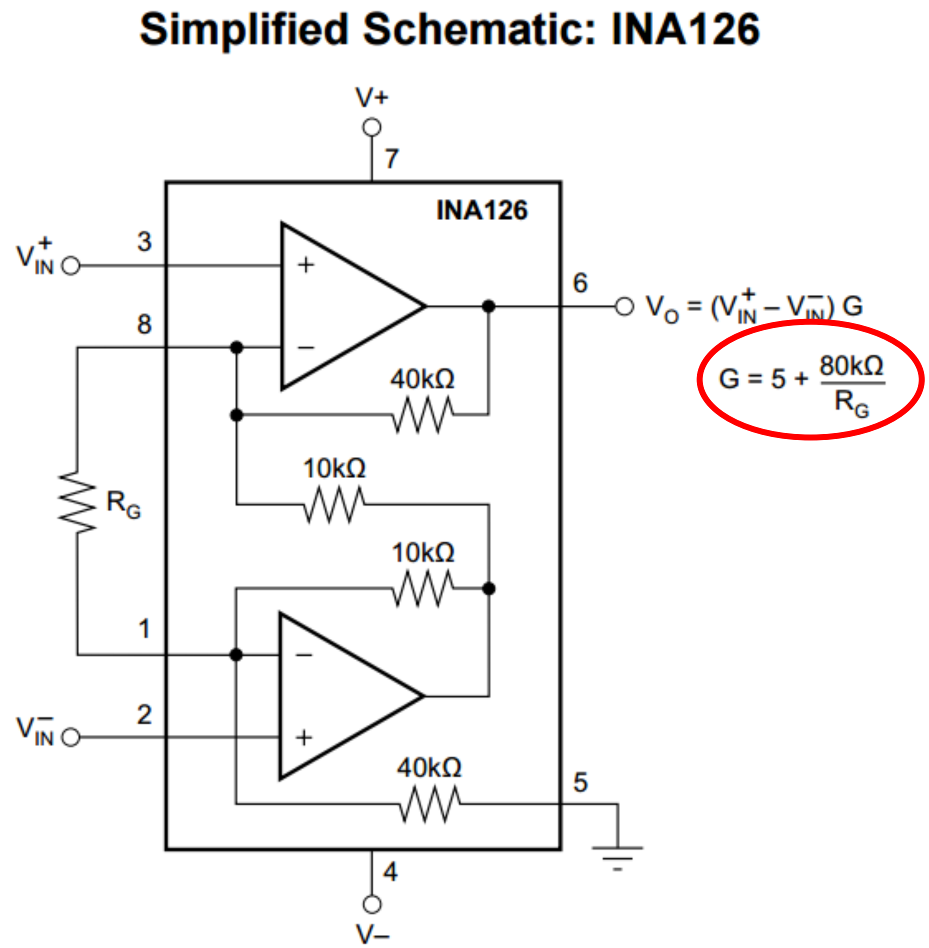
- Want really want a differential amplifier with no input current
  - Make sure the input isolation resistance isn't a problem
  - This is a common situation for many types of instruments

- There is a special part for this situation
  - Called instrumentation amplifier
  - It can be thought of as 3 amplifiers
    - Two non-inverting amplifiers (so there is no input current)
    - One differential amplifiers
  - These parts are built to match very well
    - So it is better than building the circuit yourself

Instrumentation Amp (Used in ECG Lab)

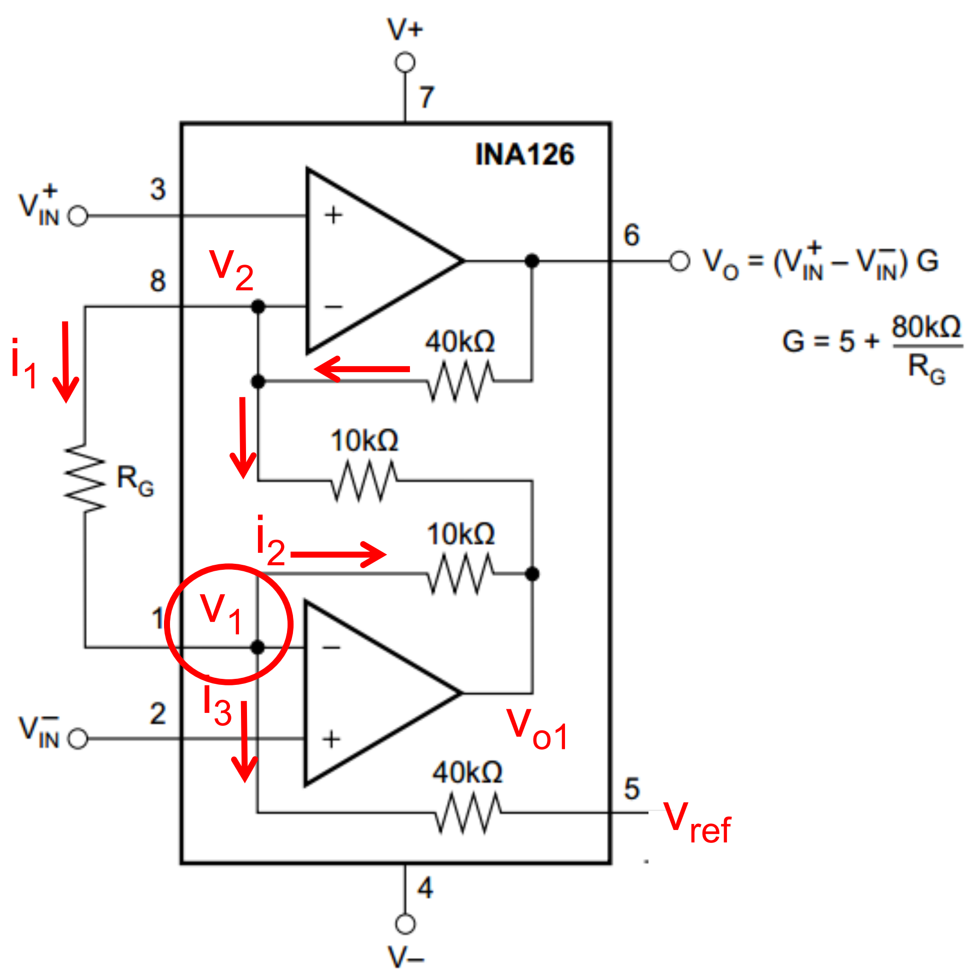
- Kind of looks like two non-inverting amplifiers
  - But they are connected together in a funny way

- Fortunately the IA can be “solved” using the Golden Rules:
  - Write KCL for ‘-’ input of the op amp
  - Find the output voltage that satisfies KCL when the voltage at the ‘-’ input is equal to the voltage on the ‘+ input



Start with KCL at Inverting Input of Op Amp #1

Simplified Schematic: INA126



- At node v_1 and assuming no op amp input current, we have

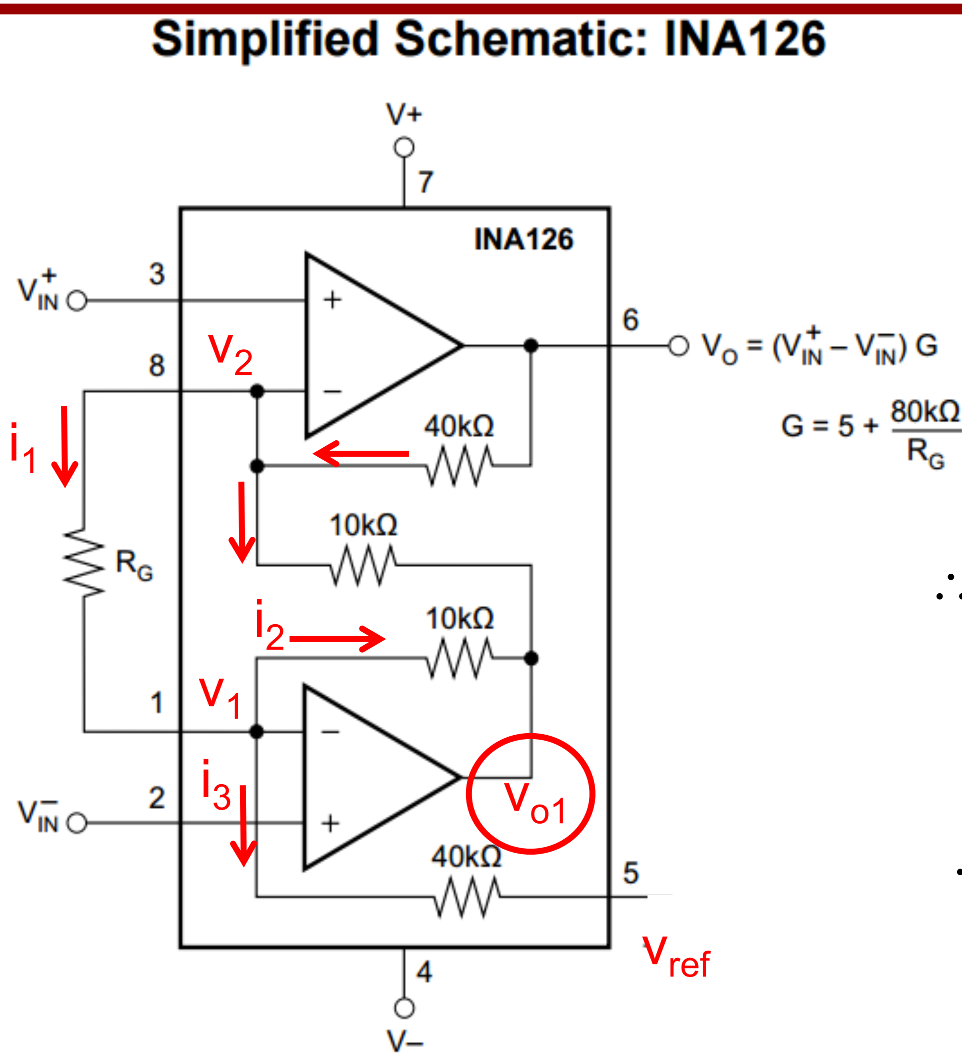
$$i_1 = i_2 + i_3$$

$$\therefore \frac{v_2 - v_1}{R_G} = \frac{v_1 - v_{o1}}{10k\Omega} + \frac{v_1 - v_{ref}}{40k\Omega}$$

- Since $v_{IN}^- = v_1$ and $v_{IN}^+ = v_2$

$$\therefore \frac{v_{IN}^+ - v_{IN}^-}{R_G} = \frac{v_{IN}^- - v_{o1}}{10k\Omega} + \frac{v_{IN}^+ - v_{ref}}{40k\Omega}$$

Now Find V_{o1} -- the Output Voltage of Op Amp #1

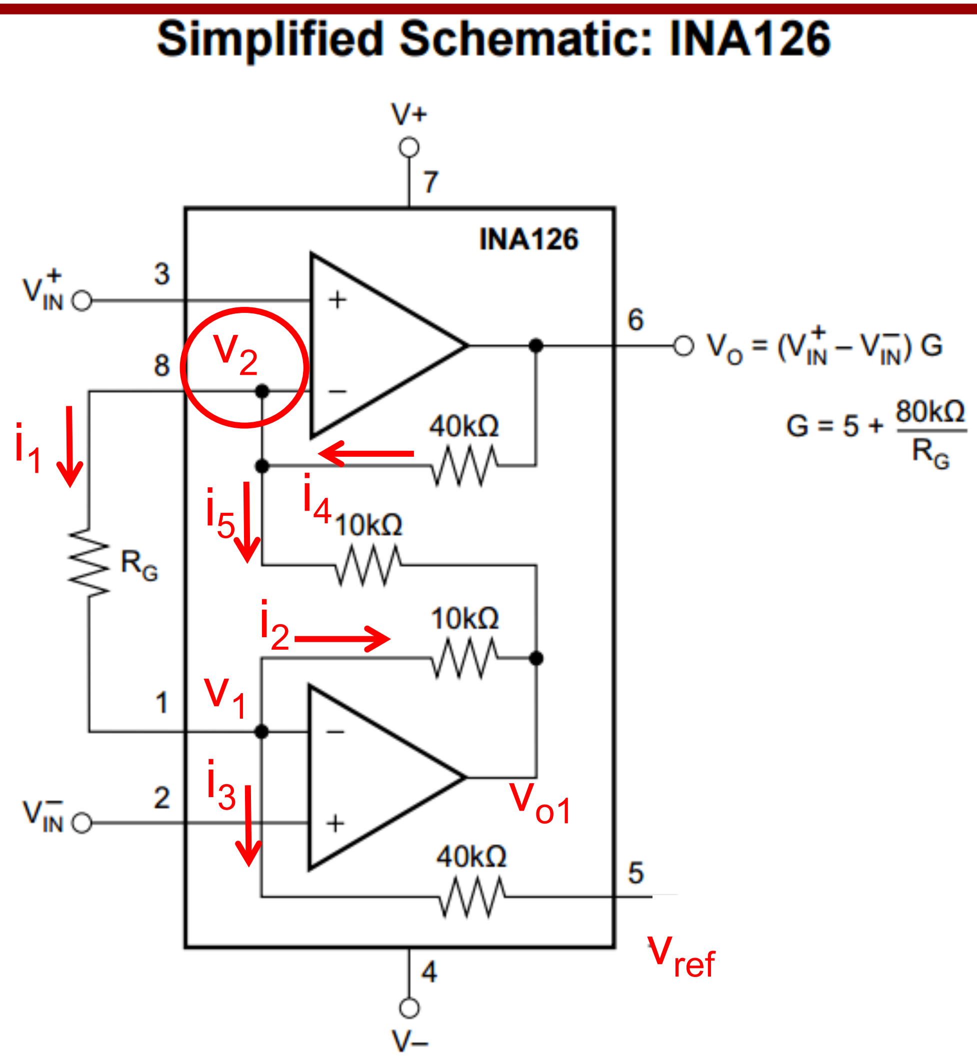


$$\therefore \frac{v_{IN}^{+} - v_{IN}^{-}}{R_G} = \frac{v_{IN}^{-} - v_{o1}}{10k\Omega} + \frac{v_{IN}^{+} - v_{ref}}{40k\Omega}$$

$$\therefore \frac{v_{o1}}{10k\Omega} = \frac{v_{IN}^{-}}{10k\Omega} + \frac{v_{IN}^{+} - v_{ref}}{40k\Omega} - \frac{v_{IN}^{+} - v_{IN}^{-}}{R_G}$$

$$\therefore v_{o1} = \frac{5v_{IN}^{-}}{4} - \frac{v_{ref}}{4} - \frac{10k\Omega\left(v_{IN}^{+} - v_{IN}^{-}\right)}{R_G}$$

Next: KCL at Inverting Input of Op Amp #2



- At node v_2 and assuming no op amp input i, we have

$$i_4 = i_1 + i_5$$

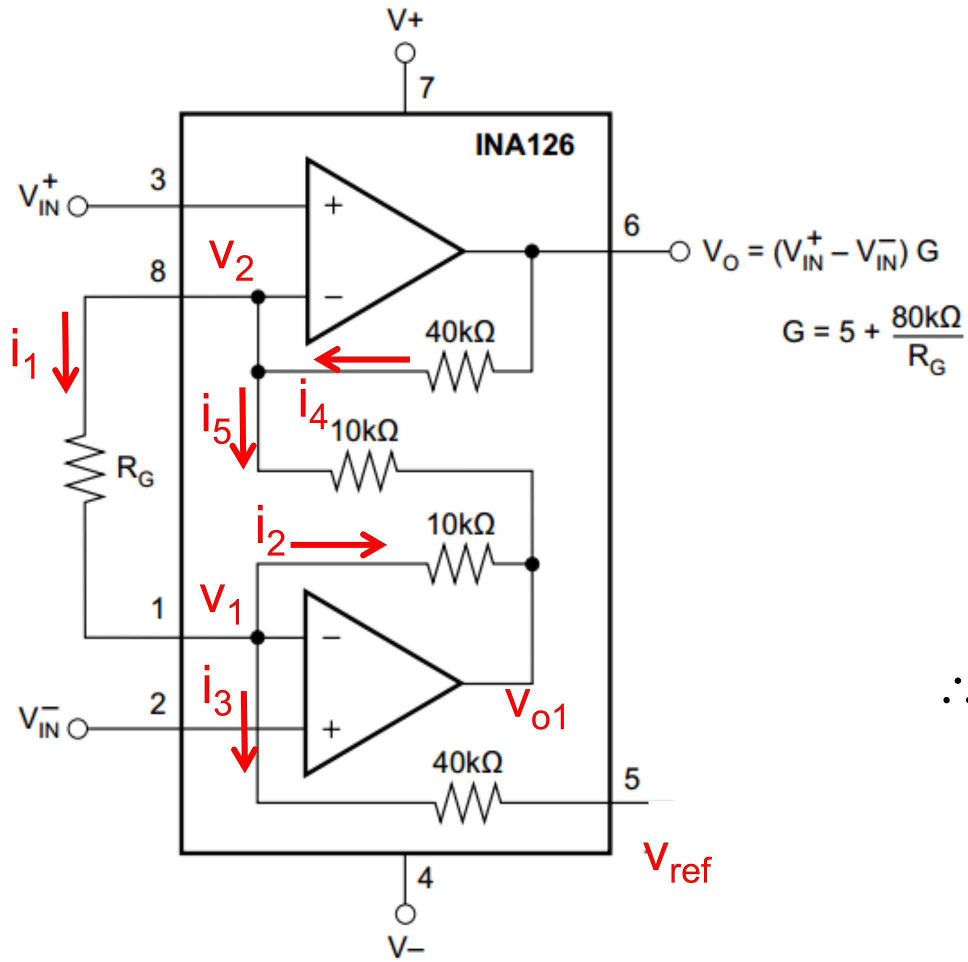
$$\therefore \frac{v_o - v_2}{40k\Omega} = \frac{v_2 - v_1}{R_G} + \frac{v_2 - v_{o1}}{10k\Omega}$$

- Since $v_{IN}^- = v_1$ and $v_{IN}^+ = v_2$

$$\therefore \frac{v_o - v_{IN}^+}{40k\Omega} = \frac{v_{IN}^+ - v_{IN}^-}{R_G} + \frac{v_{IN}^+ - v_{o1}}{10k\Omega}$$

Step n+1: Solve for V_o

Simplified Schematic: INA126



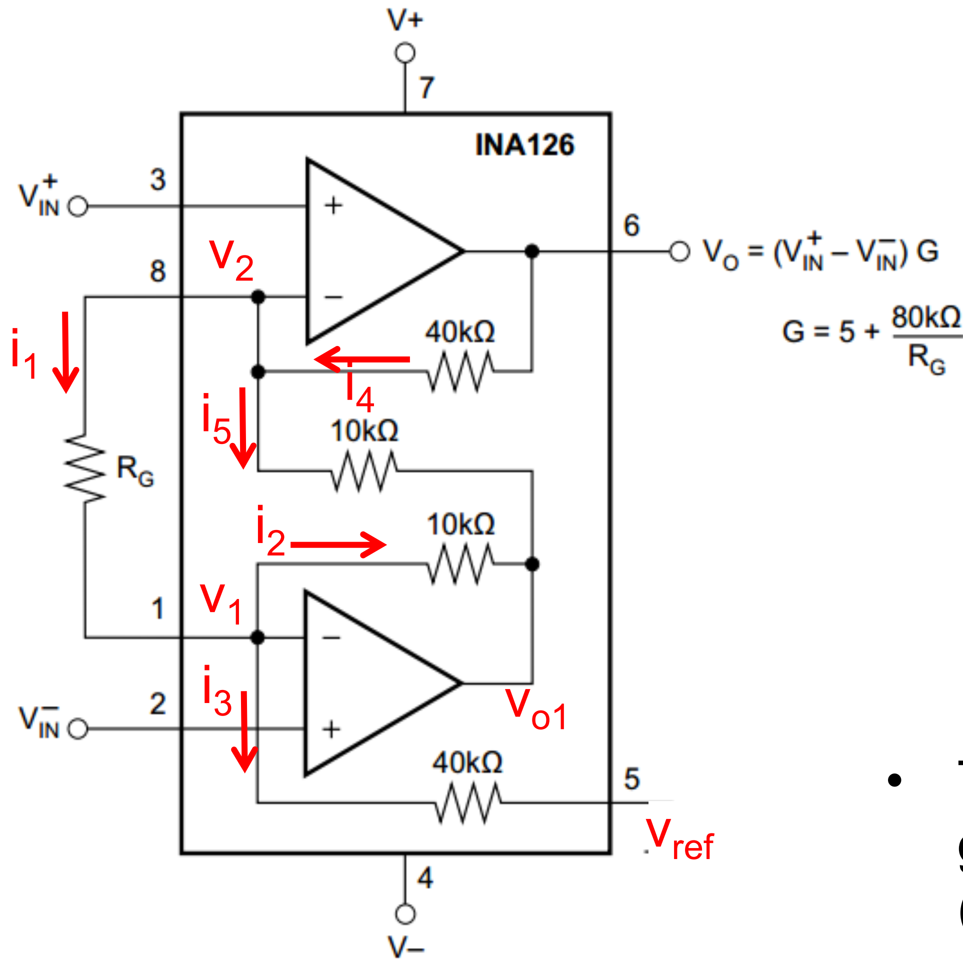
$$\therefore \frac{v_o - v_{IN}^{+}}{40k\Omega} = \frac{v_{IN}^{+} - v_{IN}^{-}}{R_G} + \frac{v_{IN}^{+} - v_{o1}}{10k\Omega}$$

$$\therefore \frac{v_o}{40k\Omega} = \frac{v_{IN}^{+}}{40k\Omega} + \frac{v_{IN}^{+} - v_{IN}^{-}}{R_G} + \frac{v_{IN}^{+} - v_{o1}}{10k\Omega}$$

$$\therefore v_o = 5v_{IN}^{+} + \frac{40k\Omega\left(v_{IN}^{+} - v_{IN}^{-}\right)}{R_G} - 4v_{o1}$$

The Finale: Combining The Results

Simplified Schematic: INA126



$$v_{o1} = \frac{5v_{IN}^{-}}{4} - \frac{v_{ref}}{4} - \frac{10k\Omega\left(v_{IN}^{+} - v_{IN}^{-}\right)}{R_G}$$

$$v_o = 5v_{IN}^{+} + \frac{40k\Omega\left(v_{IN}^{+} - v_{IN}^{-}\right)}{R_G} - 4v_{o1}$$

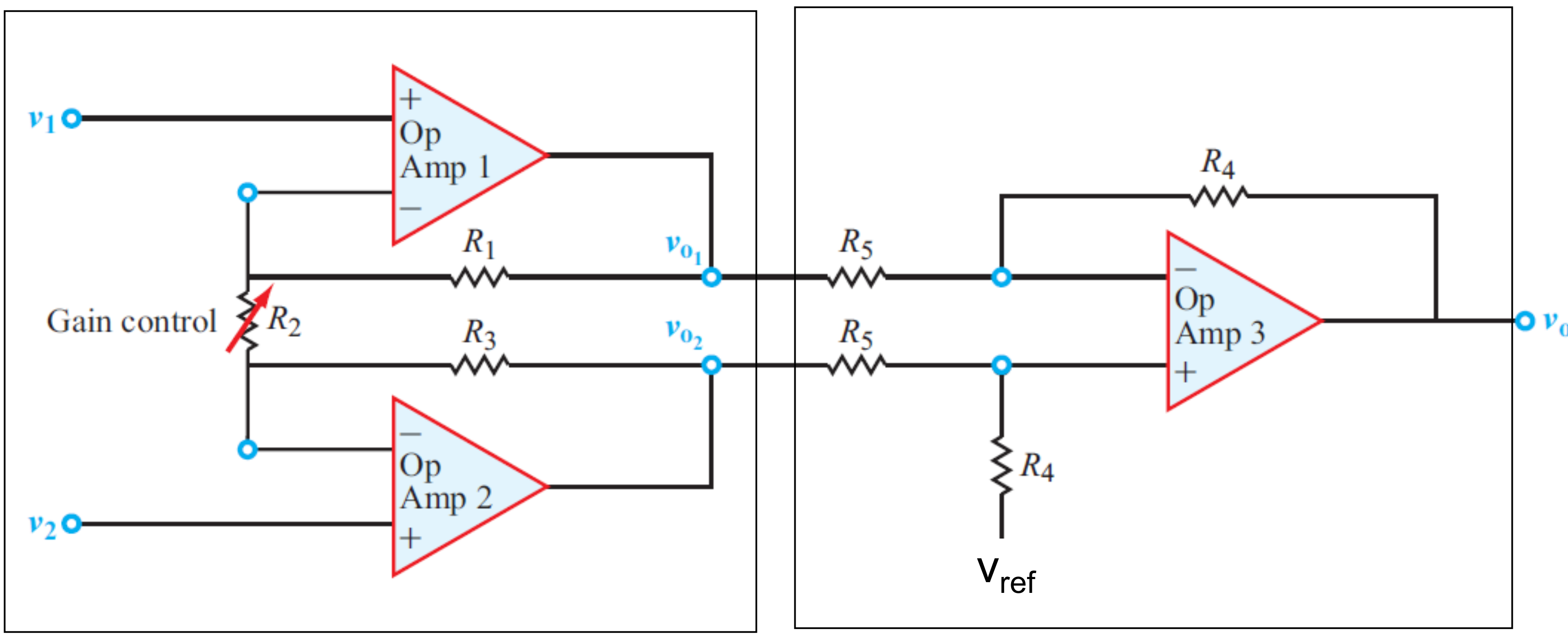
$$v_o = \left(\frac{80k\Omega}{R_G} + 5\right)\left(v_{IN}^{+} - v_{IN}^{-}\right) + v_{ref}$$

- This confirms the gain expression given in the 1NA126 data sheet! (using $v_{ref} = 0$).

Another Instrumentation Amplifier (Bonus)

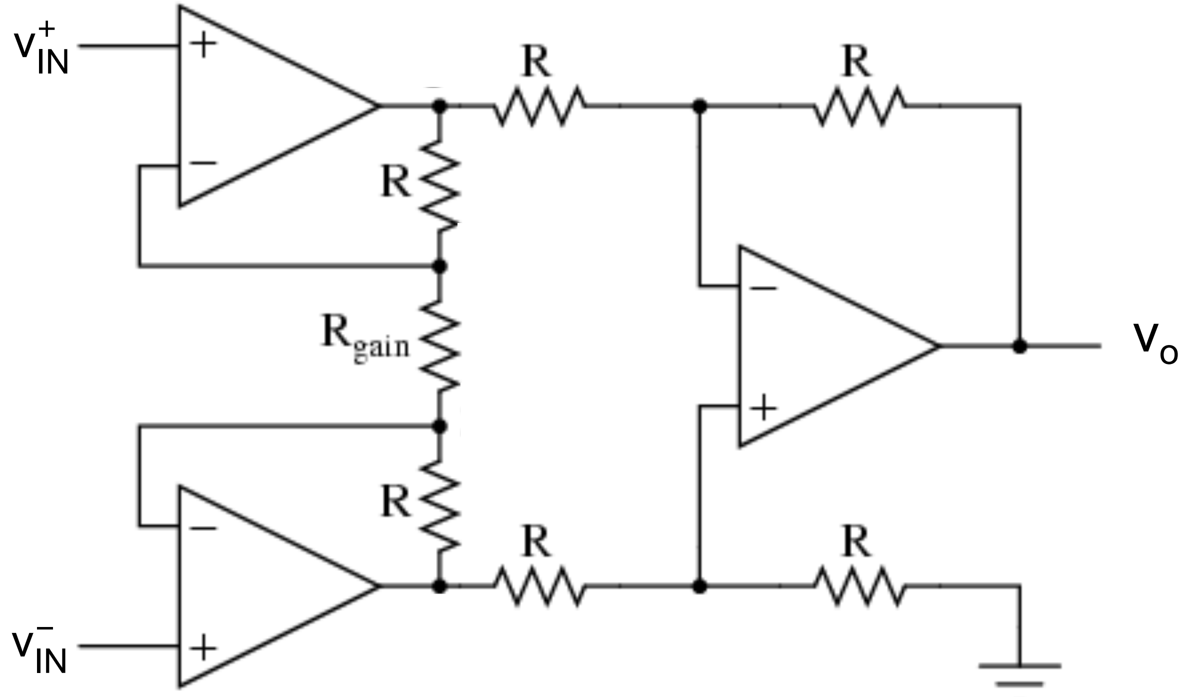
(we are not using this architecture)

- Most instrumentation amplifiers are actually built with 3 op amps.
- The analysis is quite similar to the past few pages

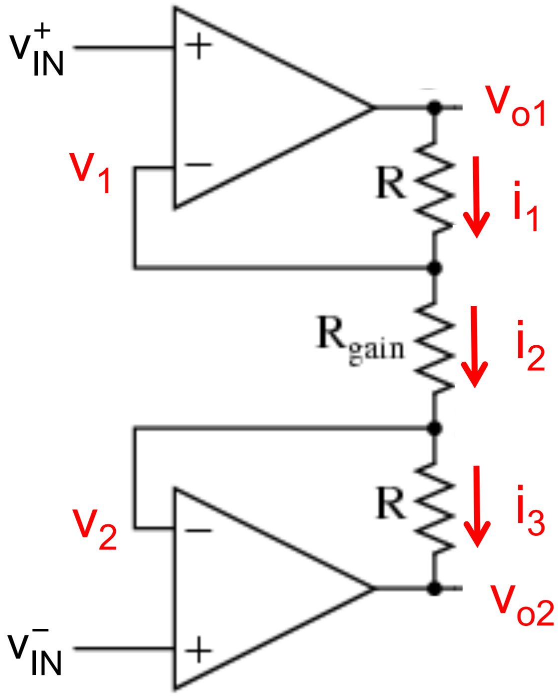


Another Instrumentation Amplifier (Bonus)

- Consider a simplified case in which all resistors are the same (except R_{gain}) and $v_{ref} = 0$.
- The analysis is quite similar to the past few pages.
- We won't cover this in class – try it yourself, you should be able to analyze this! Try it to test your understanding.



Front End of Instrumentation Amplifier (Bonus)



- G.R. #1: $v_{IN}^+ = v_1$ and $v_{IN}^- = v_2$
- KCL: $i_1 = i_2 = i_3$

$$\frac{v_{o1} - v_{IN}^+}{R} = \frac{v_{IN}^+ - v_{IN}^-}{R_{gain}} = \frac{v_{IN}^- - v_{o2}}{R}$$

$$\therefore \frac{v_{o1}}{R} = \frac{v_{IN}^+}{R} + \frac{v_{IN}^+}{R_{gain}} - \frac{v_{IN}^-}{R_{gain}}$$

$$\therefore v_{o1} = \frac{R}{R_{gain}}\left(v_{IN}^+ - v_{IN}^-\right) + v_{IN}^+$$

Similarly, $v_{o2} = \frac{R}{R_{gain}}\left(v_{IN}^- - v_{IN}^+\right) + v_{IN}^-$

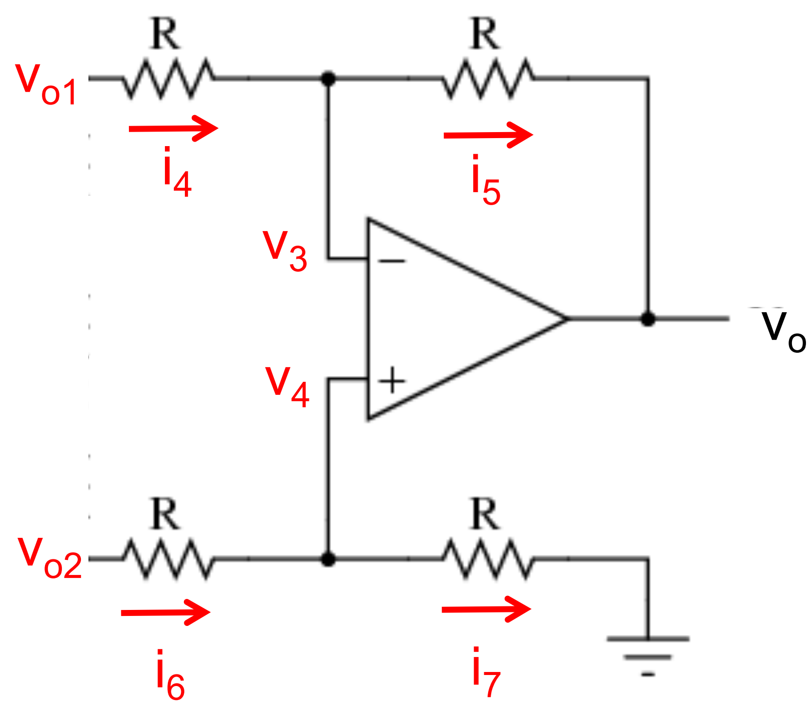
Back End of Instrumentation Amplifier (Bonus)

G.R. #2: $i_4 = i_5$ and $i_6 = i_7$

$$\frac{v_{o1} - v_3}{R} = \frac{v_3 - v_o}{R} \quad \text{so that} \quad v_o = 2v_3 - v_{o1}$$

$$\frac{v_{o2} - v_4}{R} = \frac{v_4}{R} \quad \text{so that} \quad v_4 = \frac{v_{o2}}{2} = v_3$$

Combining, $v_o = v_{o2} - v_{o1}$



Using the results from the previous page,

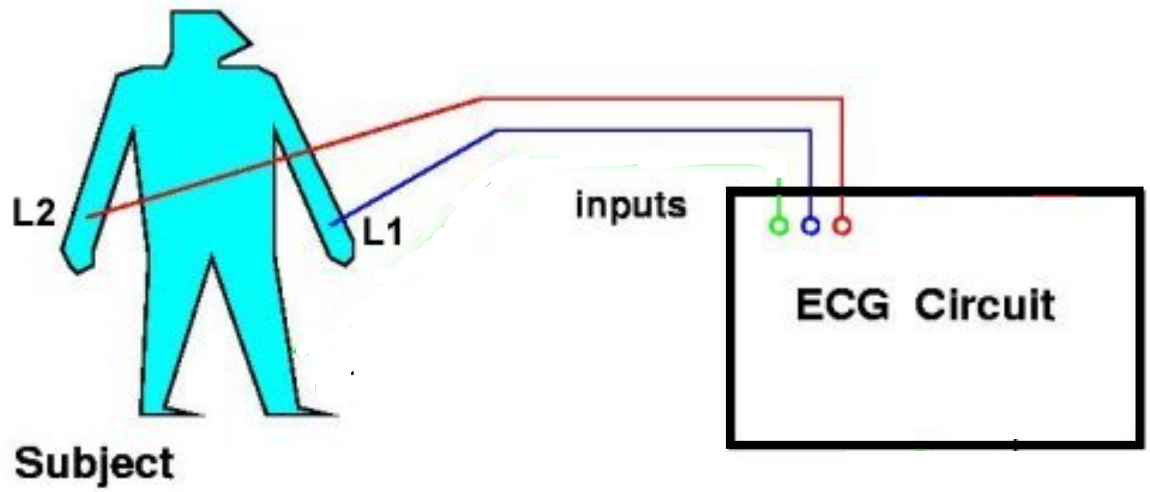
$$v_o = v_{o2} - v_{o1} = \frac{R}{R_{gain}}\left(v_{IN}^- - v_{IN}^+\right) + v_{IN}^- - \frac{R}{R_{gain}}\left(v_{IN}^+ - v_{IN}^-\right) - v_{IN}^+$$

$$\therefore v_o = \left(v_{IN}^- - v_{IN}^+\right)\left(2\frac{R}{R_{gain}} + 1\right)$$

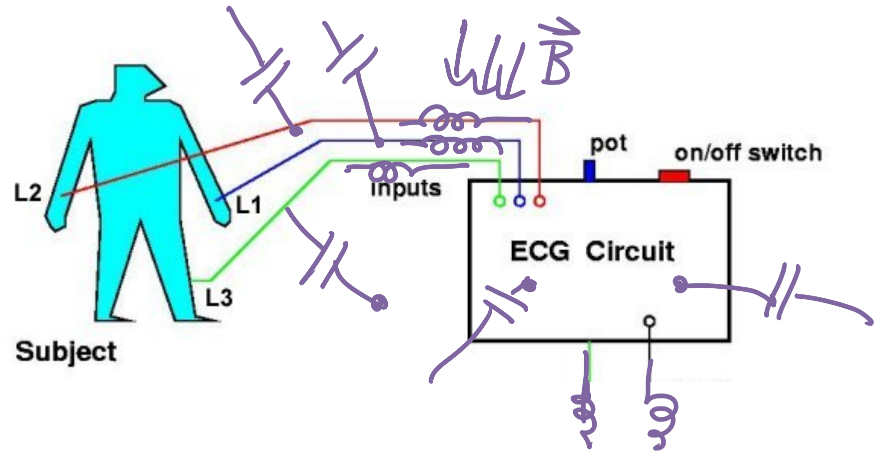
NOISE

ECG Measurement

- Need to measure the difference between L1 and L2
  - We think the circuit looks like



The Circuit Really Looks Like This:

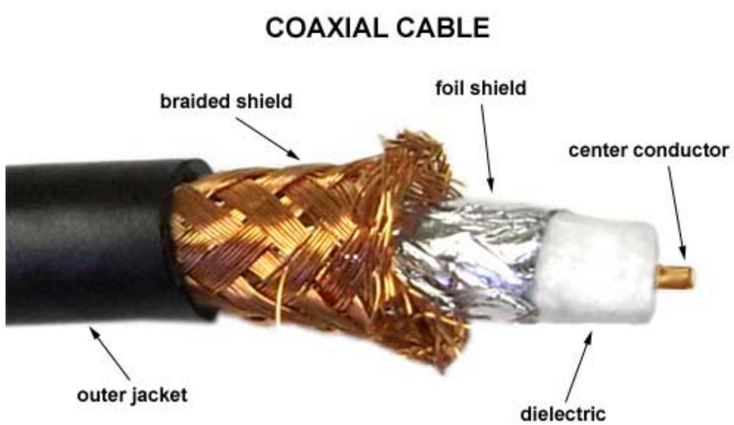


- There are many unwanted signals coupling into our circuit
  - Both capacitive (stray electric fields) and inductive (magnetic fields)
  - These signals can be larger than what we want to measure!

- How to prevent them from obscuring our signal?

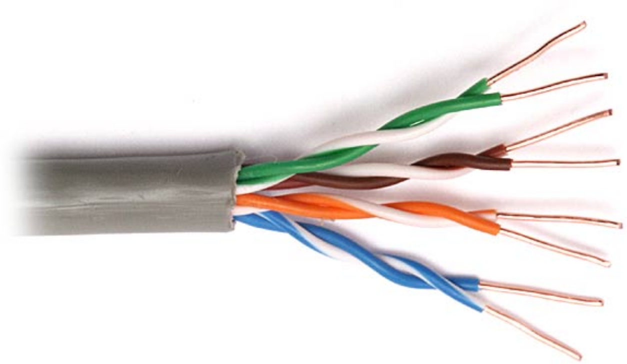
Noise Protection For Wires

- Shield the signal (literally cover it with metal)

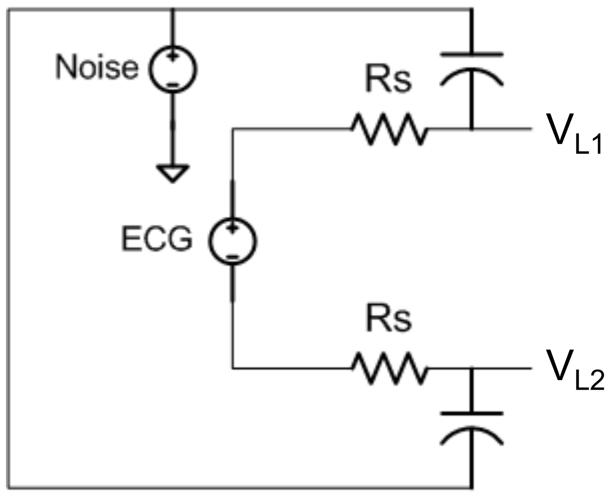


http://www.cablewholesale.com/support/technical_articles/coaxial_cables.php

- Try to make the noise common mode
  - Twist wires to each other

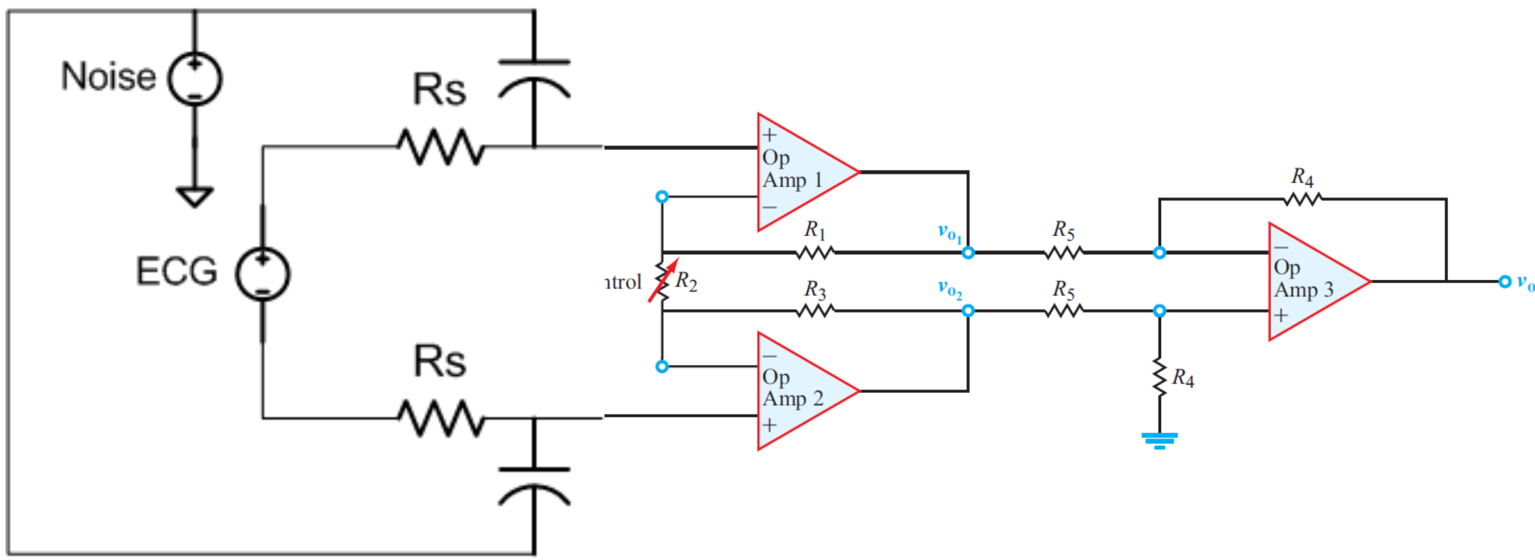


Model of the Capacitive Noise
(if it is common to both wires)



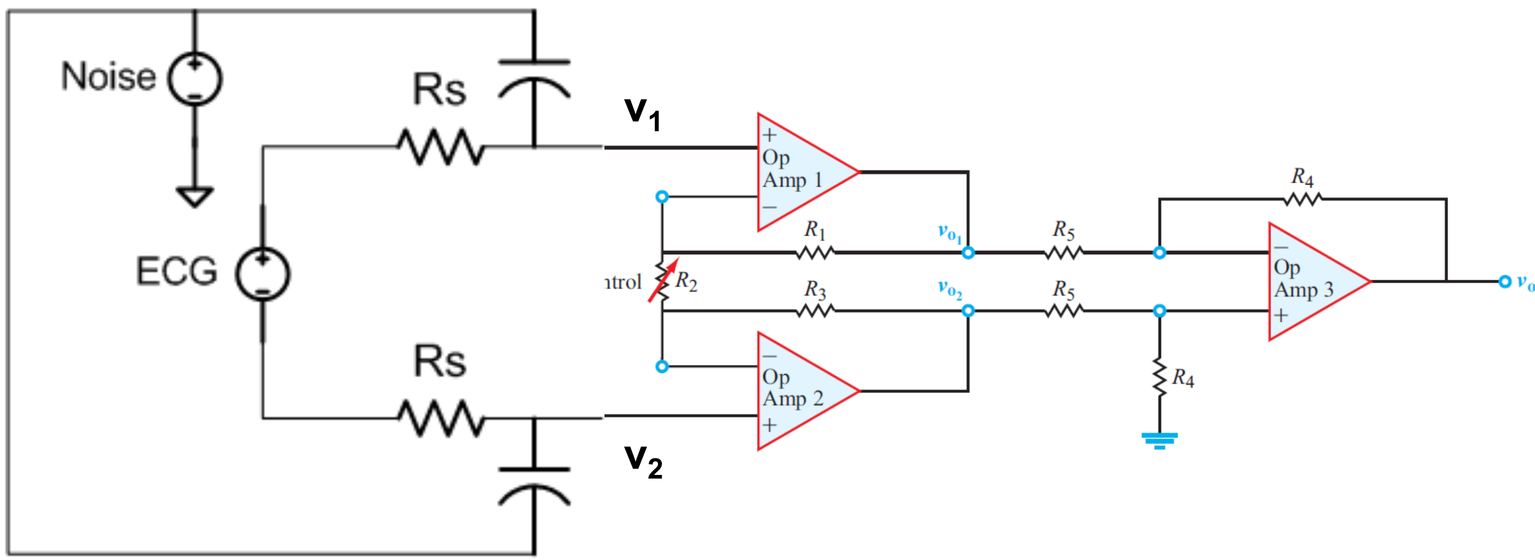
- The voltage at the two outputs will depend on ECG and Noise
  But if the capacitors and resistors are the same
  $(V_{L1} - V_{L2})$ will not depend on noise
- This is only true if the capacitance on both wires is identical
  – Which means we need a balanced differential amplifier

Balanced Amplifier



- This is a completely differential system
  - Good for reducing noise coupling

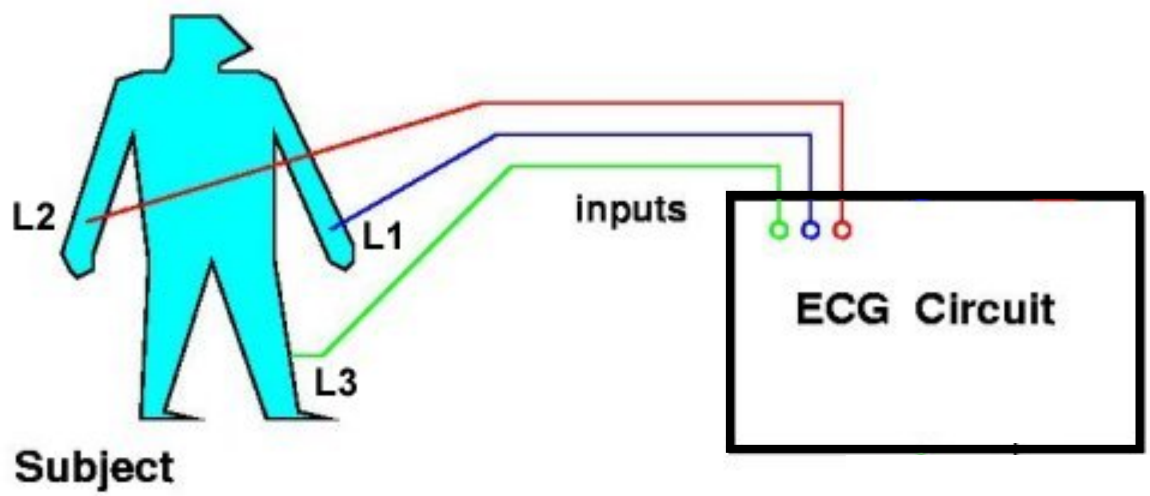
New Problem in Our Balanced Amplifier



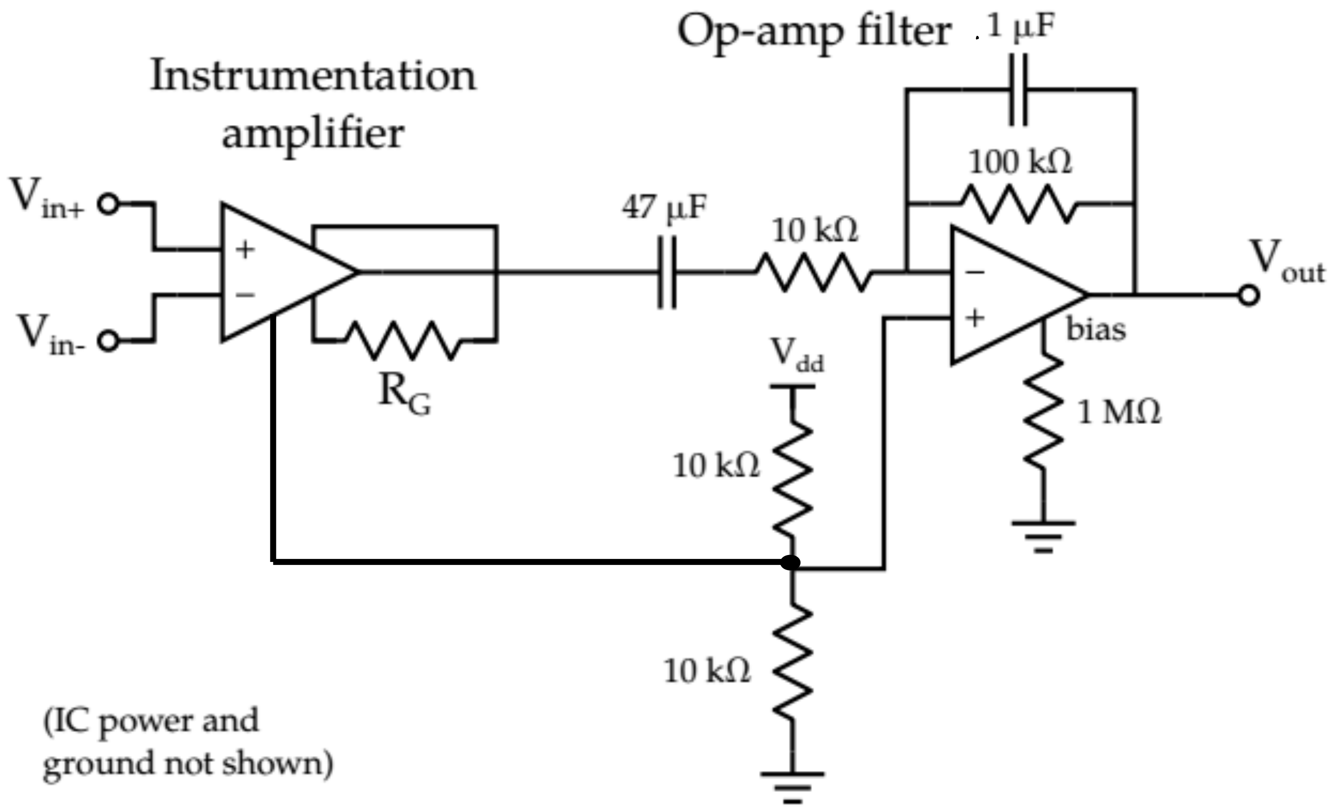
- What sets the voltage at v_1, v_2 ?
  - V_{ECG} only sets $v_1 - v_2$
  - They are not referenced to our chip's reference (Gnd)!
  - Chip won't work unless inputs are between +/- supply voltage.

The Reason for the Third Wire

- Need to measure the difference between L1 and L2
  - L3 is used to set the common-mode of the person



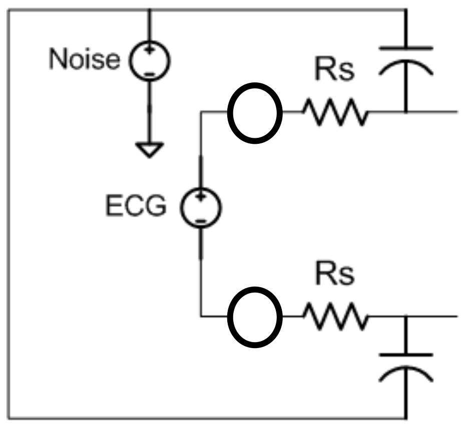
Why Does the ECG Circuit Look Like This?



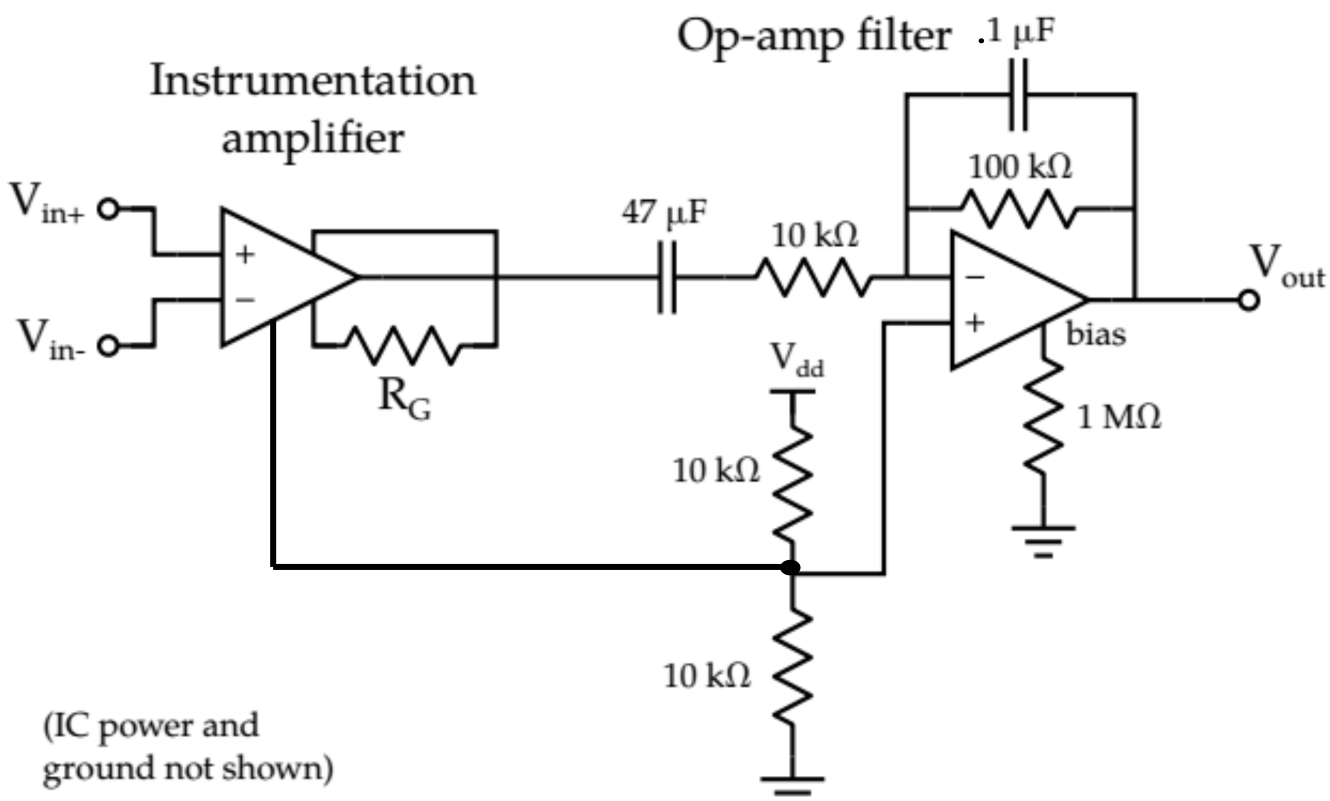
Noise: Skin Voltage

- A voltage forms when metal contacts skin
  - The size of the voltage depends on the skin condition

- This means if the conditions at the two electrodes differ
  - You can generate a voltage
    - This voltage will change very slowly with time

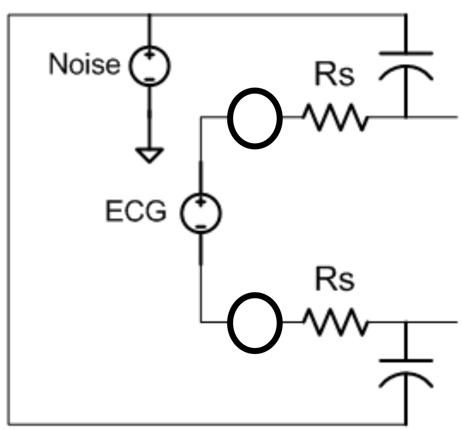


Why Does the ECG Circuit Look Like This?

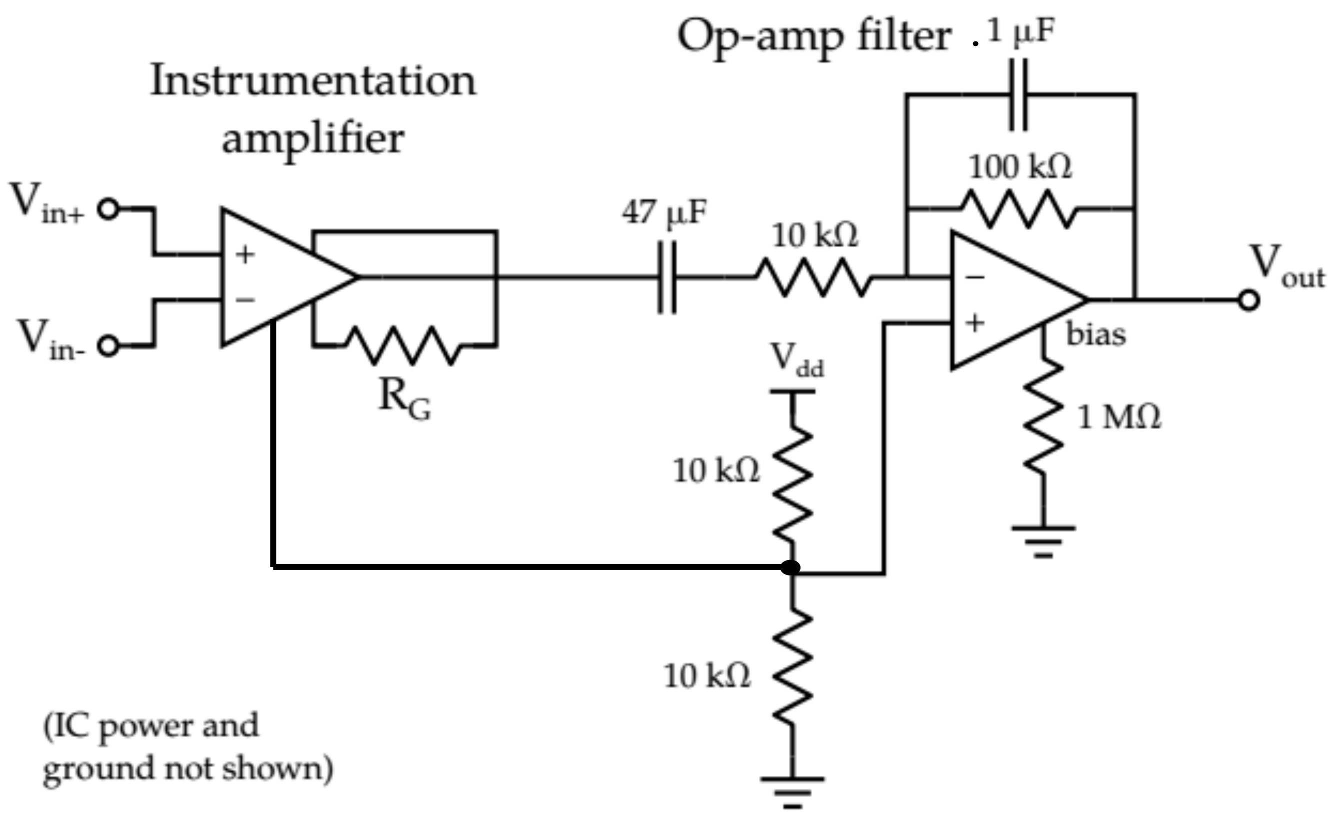


Noise: 60Hz Wall Voltage

- The main capacitive noise comes from AC power
  - 120 to 240V, 60 Hz
  - This signal can be quite large (Volts!)
    - 1000x your signal
- Differential circuit cancels most of it out
  - But some will still get through due to imperfect symmetry



Why Does the ECG Circuit Look Like This?



Learning Objectives

- Understand how an instrumentation amplifier works
  - And how to set its gain through resistor selection
- Understand what noise is
  - Other electrical signals that you don't want on your wires
  - And how to minimize their effects on your circuit through differential amplifiers and filtering
- Understand the design philosophy behind our E40M ECG circuit