Lecture 7: Instrumentation Amplifier

(Quiz)

0. Review

1. Inst Amp Basics

2. Common Mode Rejection Ratio
   (CMRR)

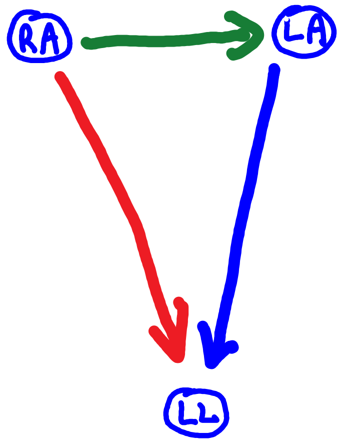
- PreLab 3 due at lab session
- Thu (Jan 30): HW3
- Fri (Jan 31): Lab 2 report

- Exam #1 (Feb 6)!
  → HW 1, 2, 3 material
  → Lectures 1-8
  → Course website will have sample exam + solutions

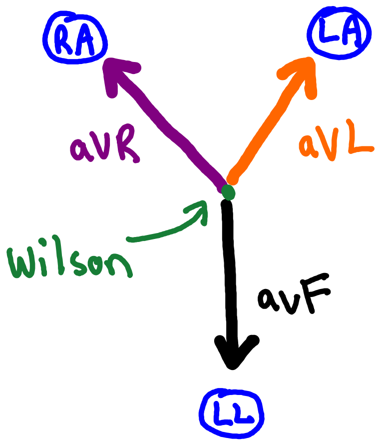
0. Review

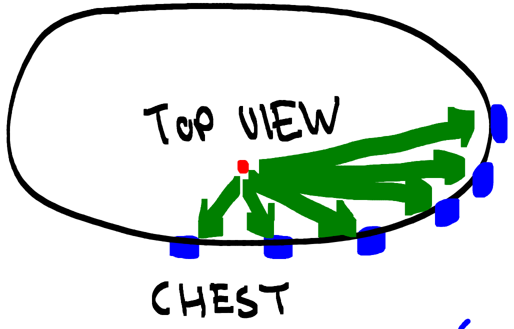
- 12-Lead ECG

(3) Einthoven's Triangle

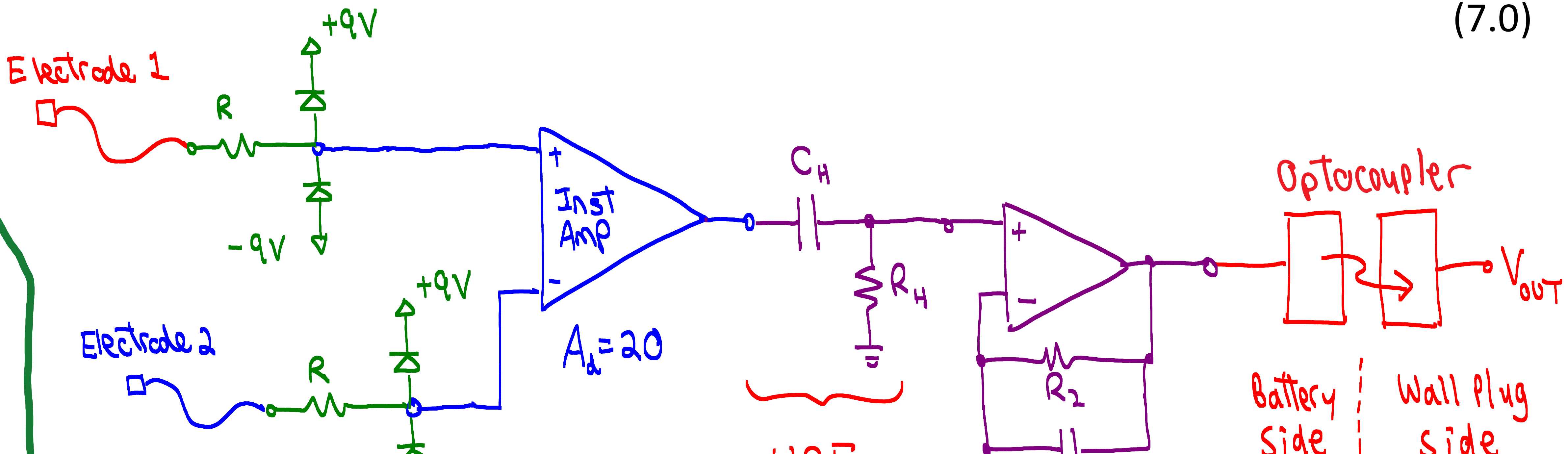


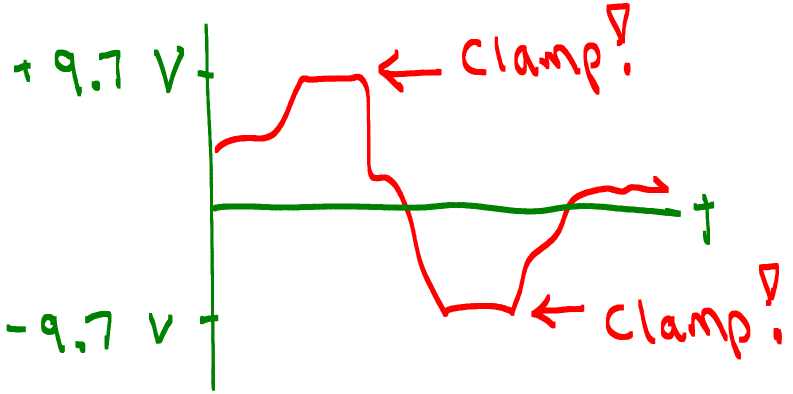
(3) Augmented



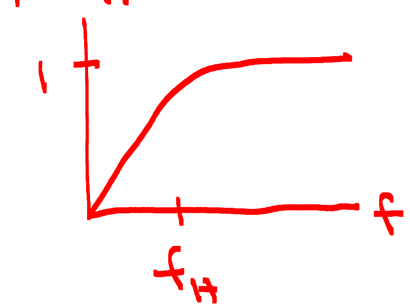


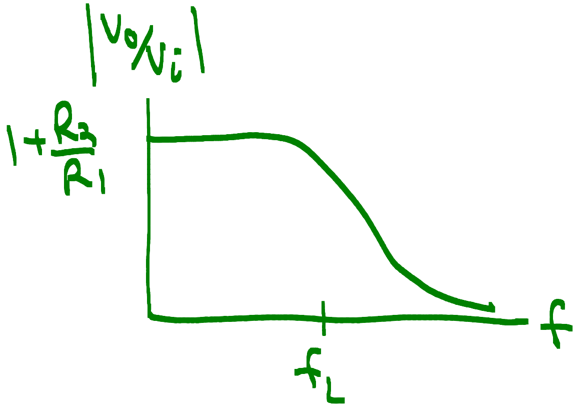
Precordial (6)





HPF

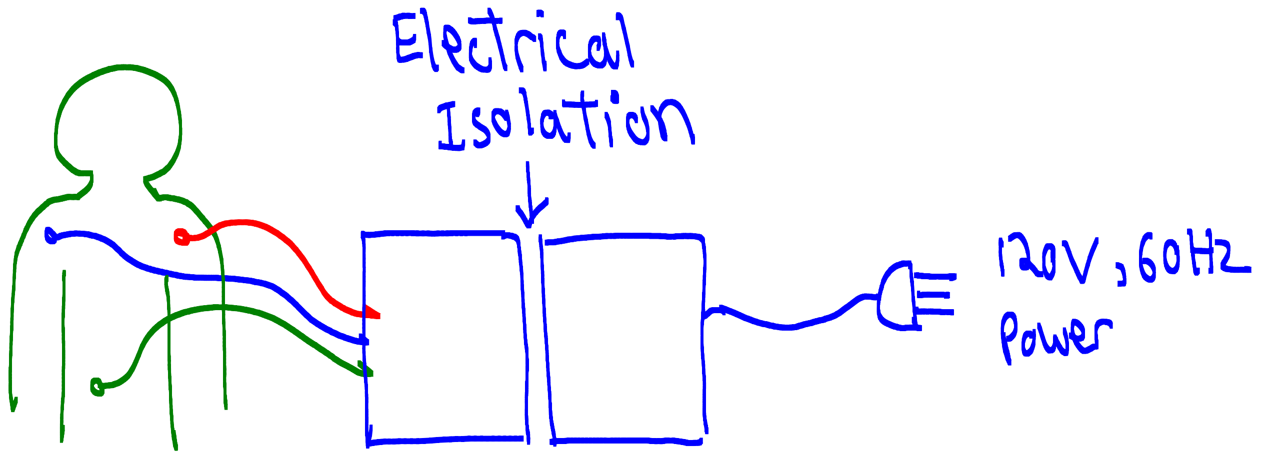




✩ Isolation

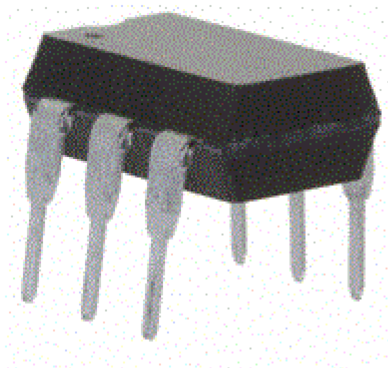
- ECG systems must minimize the possibility of the patient coming in contact with 120V power line

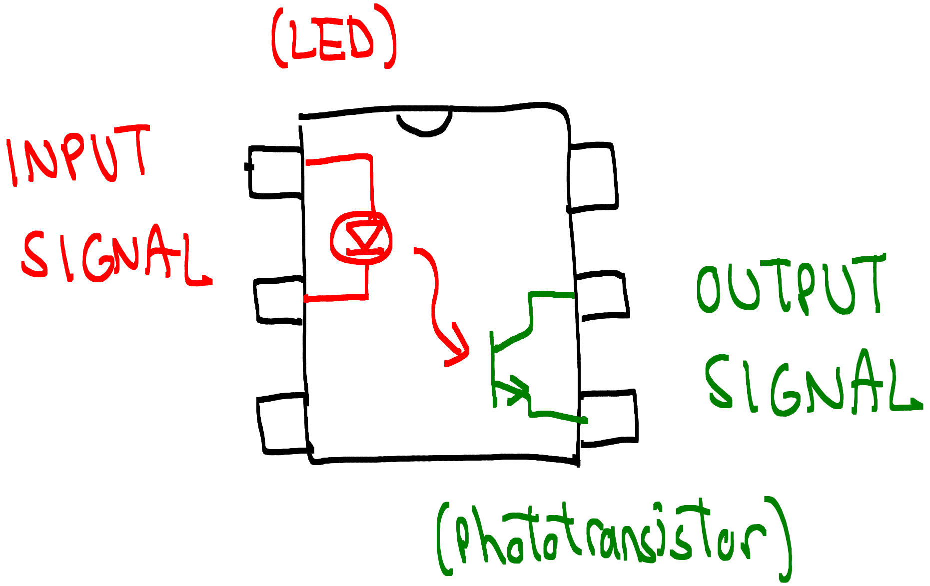
  ↑ If ECG electronics fail in some manner.



✩ An optocoupler (or photocoupler) is a common way to achieve galvanic isolation

↑ no electrical connection





→ Information is transmitted by light, not electricity! } Commonly used to electrically isolate a circuit from high voltage.

(Lots of other applications...)

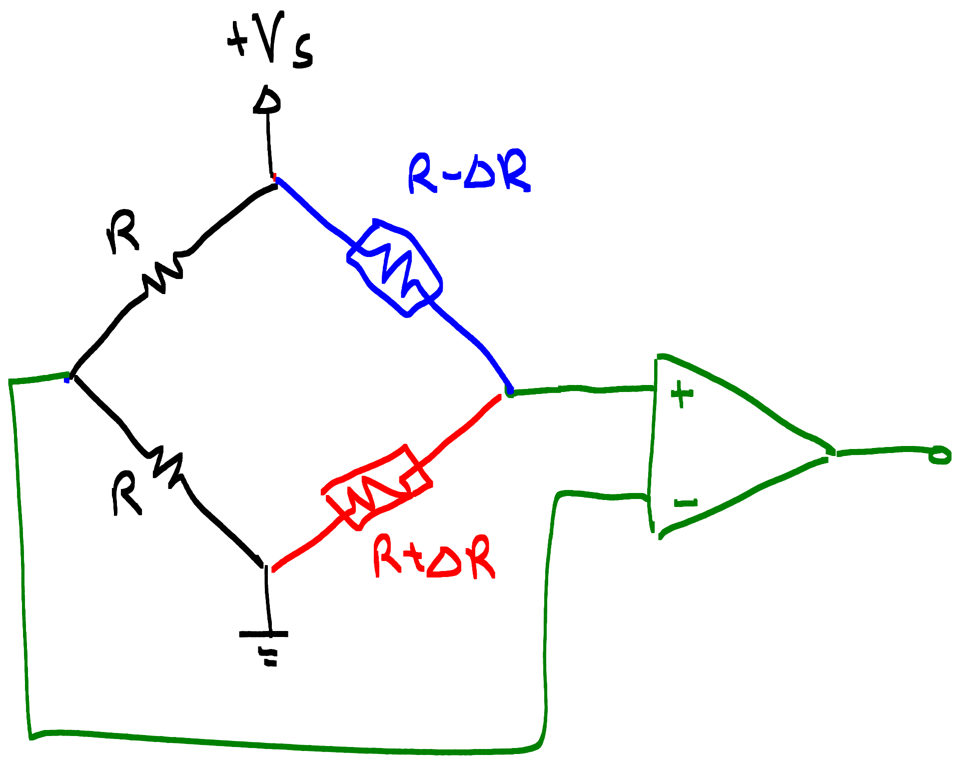
1. Instrumentation Amplifier Basics

A. Differential Amplifier

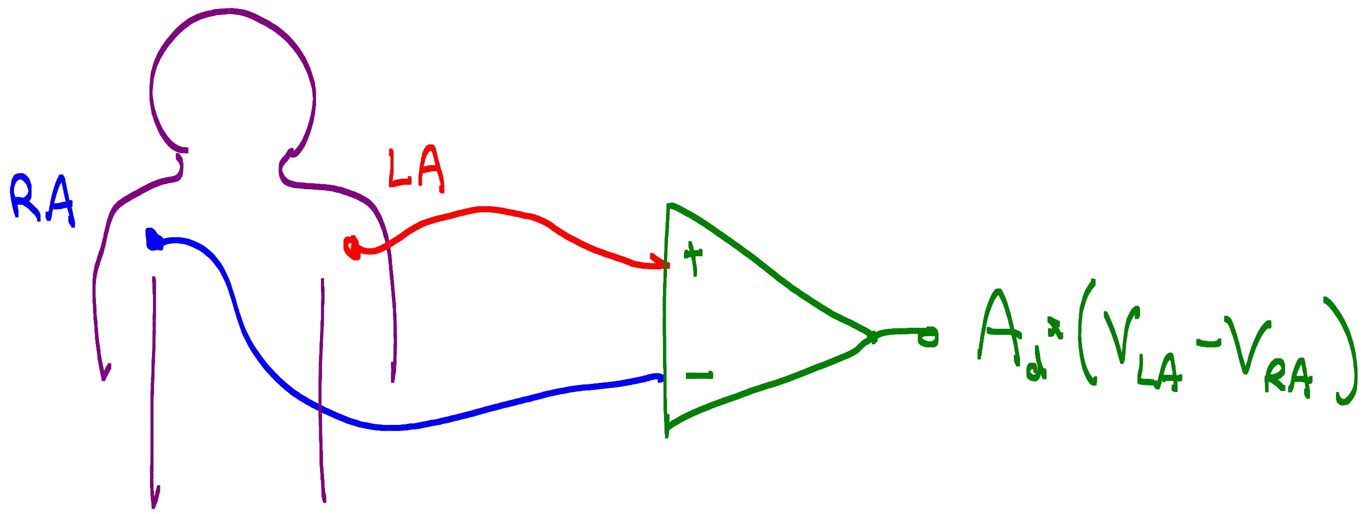
- Many sensors produce a differential output voltage

Ex:

strain Gage



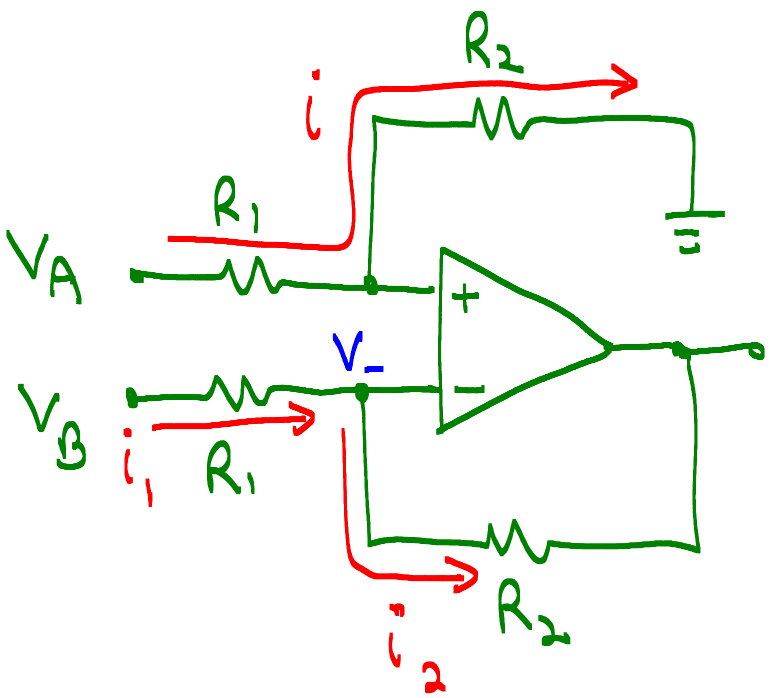
- In ECG, we want to amplify the voltage between 2 electrodes



$\Rightarrow$ Need a differential amplifier!

B. Single Op-Amp Differential Amplifier

Simplest type of diff amp:



$$V_{OUT} = \frac{R_1}{R_2}(V_A - V_B)$$

KCL at node V_-:

$$i_1 = i_2 + 0$$

Golden Rule #2

$$\frac{V_B - V_-}{R_1} = \frac{V_- - V_{OUT}}{R_2}$$

$$\frac{R_2}{R_1} V_B - \left(1 + \frac{R_2}{R_1}\right) V_- = -V_{OUT}$$

$$V_{OUT} = \left(1 + \frac{R_2}{R_1}\right) V_- - \frac{R_2}{R_1} V_B$$

Golden Rule #1: $V_- = V_+ = i R_2 = \frac{V_A}{R_1 + R_2} R_2$

$$\Rightarrow V_{OUT} = \frac{\cancel{R_1 + R_2}}{R_1} \cdot V_A \frac{R_2}{\cancel{R_1 + R_2}} - \frac{R_2}{R_1} V_B$$

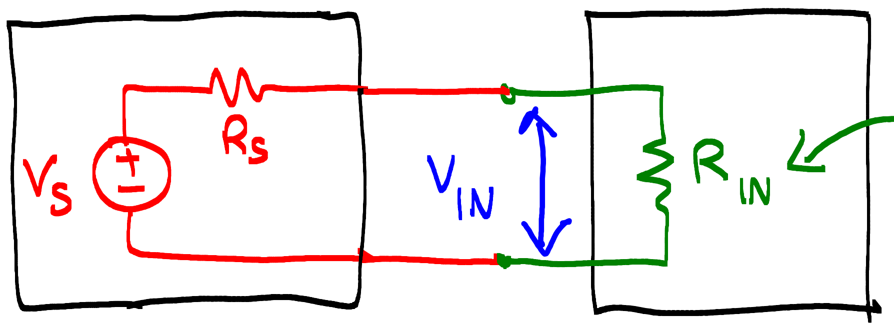
$$= \frac{R_2}{R_1}(V_A - V_B) \checkmark$$

- Major drawback of single op amp diff amplifier is modest input impedance (typically ~10K).

Who cares?

1. Sensor can be viewed as a voltage source V_s with output impedance R_s ← Thevenin!

Sensor Amplifier



Input impedance of amplifier

2. Amplifier looks like a resistor R_{IN} to the sensor

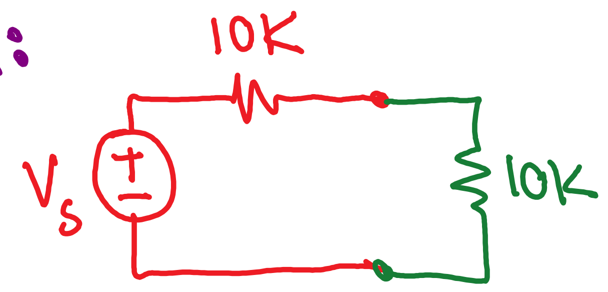
☆ $$V_{IN} = V_s \frac{R_{IN}}{R_{IN}+R_s}$$

→ R_s and R_{IN} form a voltage divider!

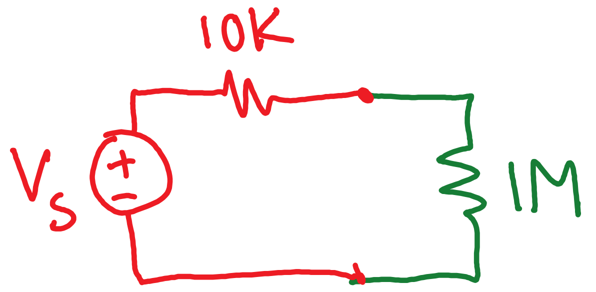
⇒ Many sensors have $R_s \sim 10K\Omega$ (even 1M!)

⇨ Need large input impedance (e.g. $R_{IN} > 100M$) to minimize signal loss!

Ex:

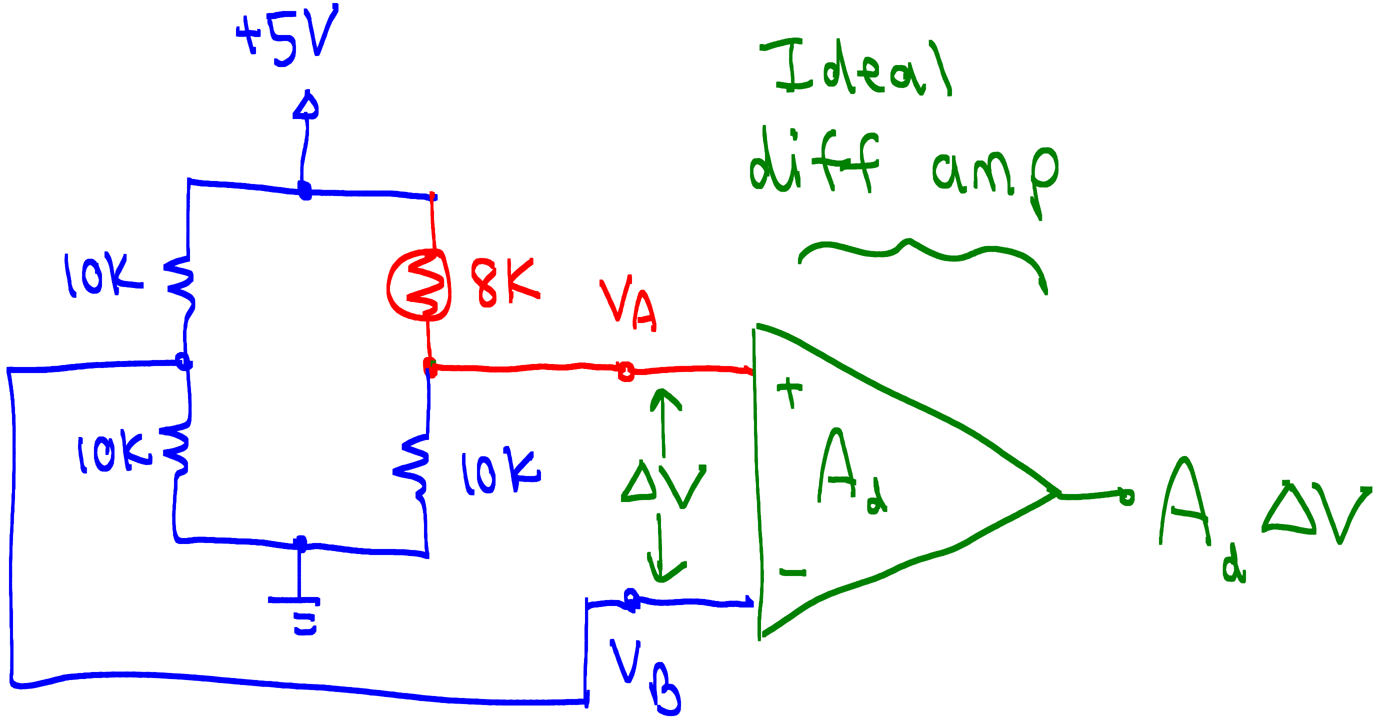


$$V_{IN} = V_s \frac{10K}{10K+10K} = 0.5 V_s$$



$$V_{IN} = V_s \frac{1M}{1.01M} = 0.99 V_s$$

Example Thermistor Circuit



- By itself, the bridge produces

$$V_A = \frac{5V}{8K+10K} \times 10K = 2.78V$$

$$V_B = \frac{5V}{10K+10K} \times 10K = 2.5V$$

$\rightarrow \quad \Delta V = 2.78 - 2.5 = \boxed{0.28V}$

- Ideally, a diff amplifier ($A_d = 2$) produces: $A_d \Delta V = 2 \times .28$

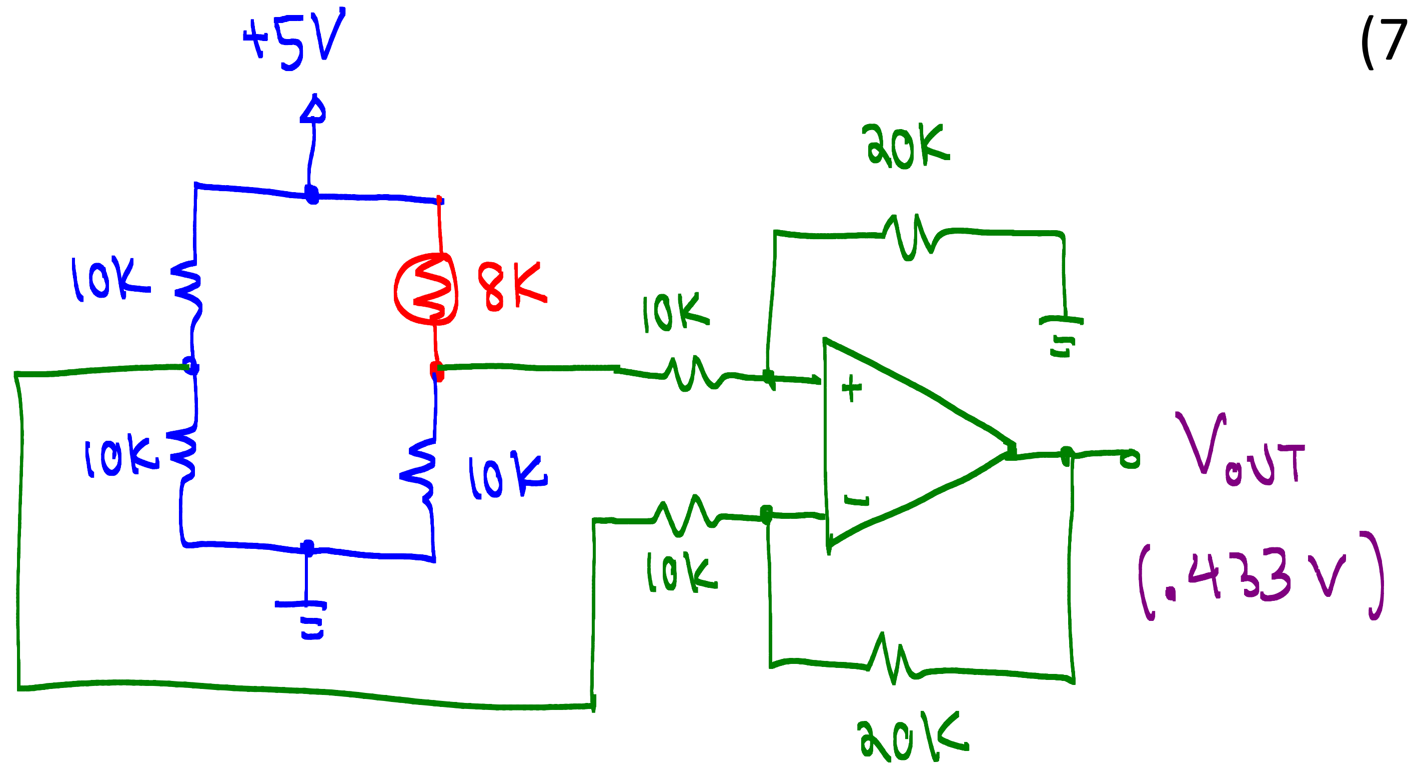
$$= \boxed{.56V}$$

single op amp diff amplifier does NOT produce this!

- Now consider using a single op amp diff amplifier.

Turns out $V_{OUT} = 0.433V$ ← 23 % error!

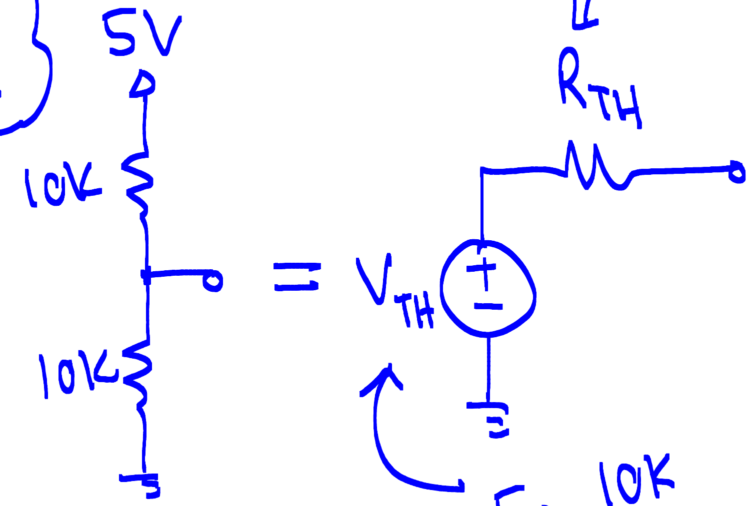
☹



Derivation:

① Thevenize the bridge!

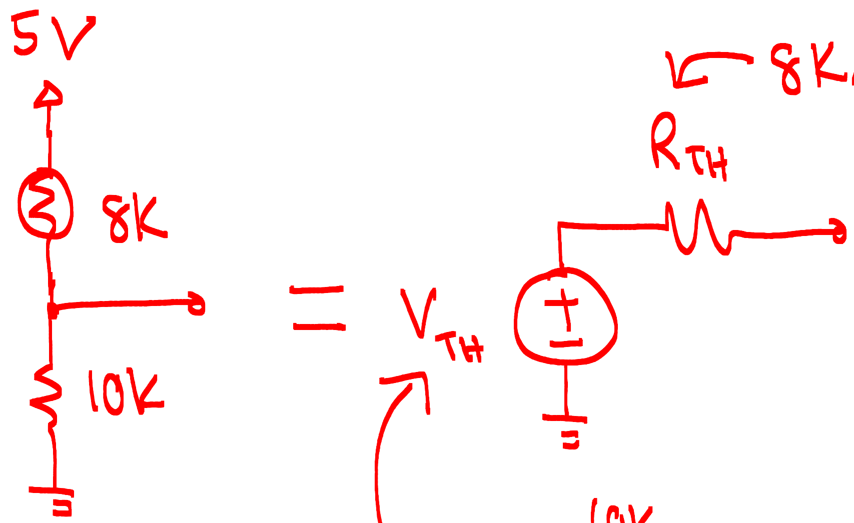
LEFT SIDE



R_{TH}: $10K // 10K = \underline{\underline{5K}}$

V_{TH}: $5 \times \frac{10K}{10K+10K} = \underline{\underline{2.5V}}$ (open circuit voltage)

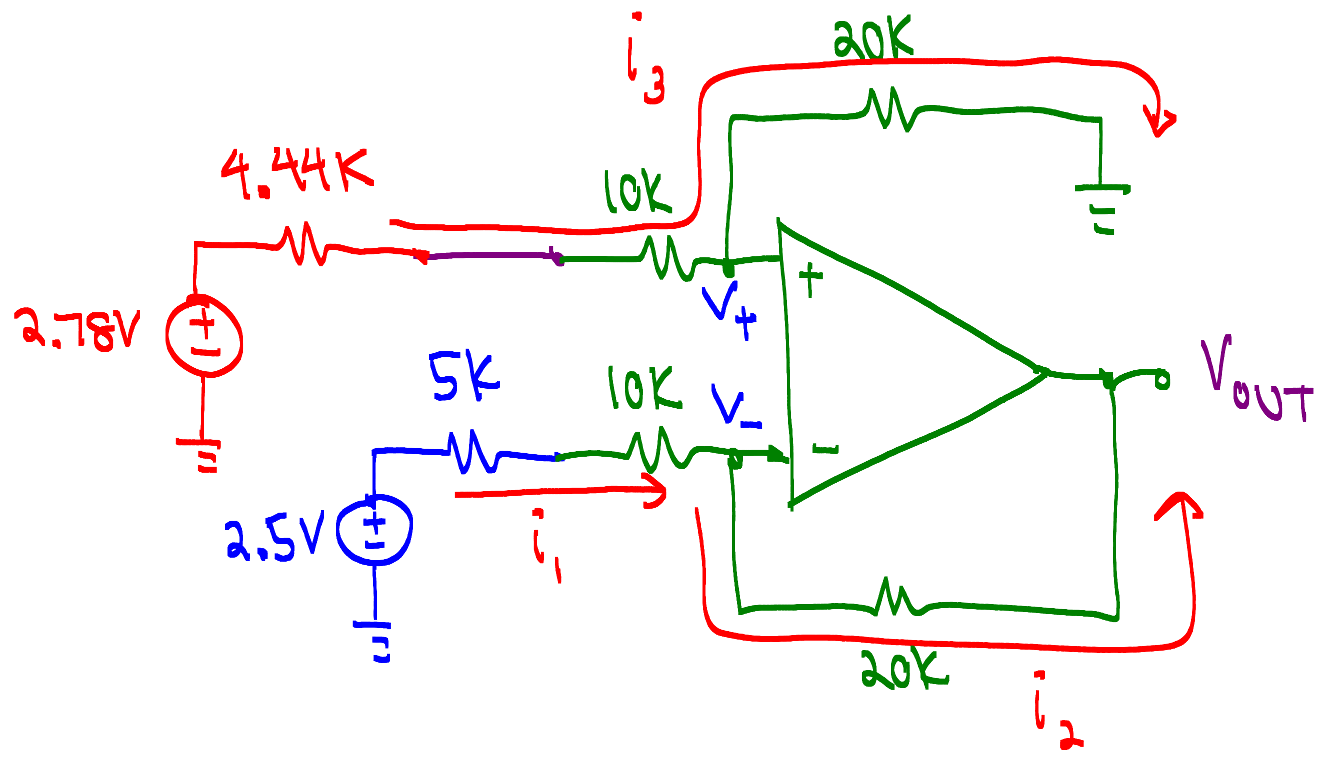
RIGHT SIDE



R_{TH}: $8K // 10K = \underline{\underline{4.44K}}$

V_{TH}: $5 \frac{10K}{10K+8K} = \underline{\underline{2.78V}}$

② Use Golden Rules on new circuit:



KCL at node V_-: $i_1 = i_2$

$$\frac{2.5 - V_-}{5K + 10K} = \frac{V_- - V_{OUT}}{20K}$$

$$\Rightarrow V_{OUT} = V_- - 20K \, \frac{2.5 - V_-}{15K}$$

Rule #1: $V_- = V_+ = i_3 \times 20K$

$$= \frac{2.78 - 0V}{4.44K + 10K + 20K} \times 20K$$

$$= 1.614V$$

$$\Rightarrow V_{OUT} = 1.614 - 20K \cdot \frac{2.5 - 1.614V}{15K}$$

$$= \boxed{0.433V}$$

23 % error :(

(ideal value = 0.56V)

- An instrumentation amplifier is a very high quality diff amplifier

① HUGE input impedance (~ GΩ)

↳ No signal loss! :)

② Large common mode rejection ratio (CMRR)

↑?

APPLICATIONS

Weigh scales

ECG and medical instrumentation

Transducer interface

Data acquisition systems

Industrial process controls

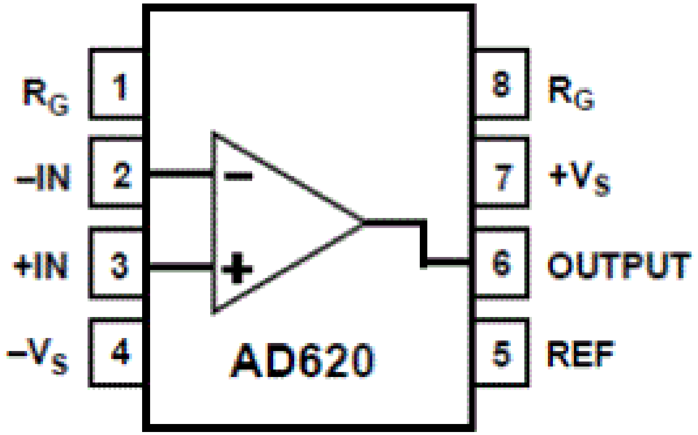
Battery-powered and portable equipment

ANALOG DEVICES

Low Cost Low Power Instrumentation Amplifier

AD620

There many other kinds! ↗



2. Common Mode Rejection Ratio (CMRR)

- Ideal output of inst amp:

$$V_{OUT} = V_{REF} + A_d \Delta V$$

"Differential Gain" (A_d)

$\Delta V = V_1 - V_2$ "Differential input"

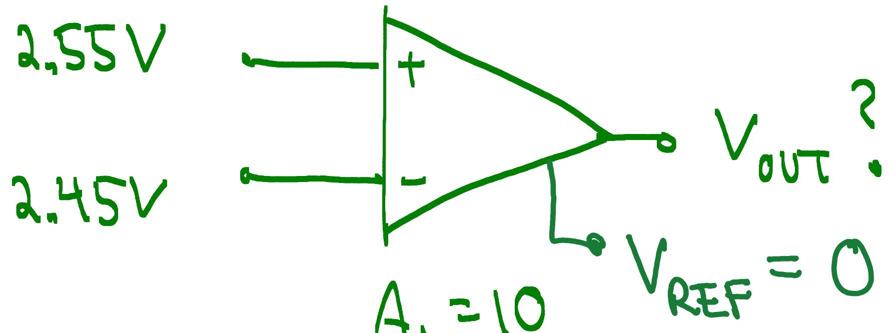
- In reality, an extra "error" term exists!

$$V_{OUT} = V_{REF} + A_d \Delta V + A_{CM} V_{CM}$$

Want this tiny! — "Common Mode Gain" (A_{CM})

$V_{CM} = \frac{V_1 + V_2}{2}$ "Common Mode Input"

Example



$A_d = 10$

$A_{CM} = 0.01$

① Determine inputs:

(Differential) $\Delta V = 2.55 - 2.45 = 0.1V$

(Common Mode) $V_{CM} = \frac{2.55 + 2.45}{2} = 2.5V$

② Compute V_{OUT}:

$$V_{OUT} = V_{REF} + A_d \Delta V + \overbrace{A_{CM} V_{CM}}^{\text{error term}}$$

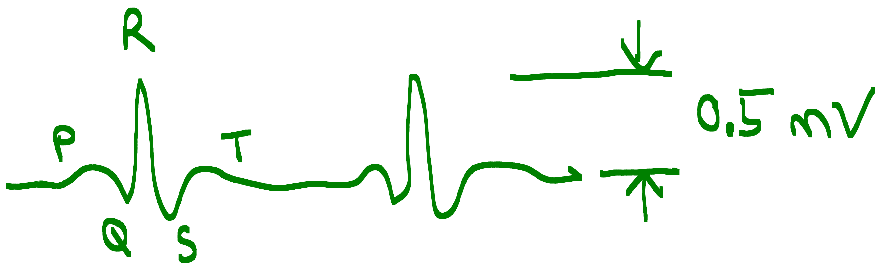
$$= 0 + \underbrace{10 \times 0.1}_{1.0} + \underbrace{.01 \times 2.5}_{.025} = \boxed{1.025V}$$

- Common Mode Rejection Ratio (CMRR)

$$\boxed{CMRR = 20\log_{10}\left(\frac{A_d}{A_{CM}}\right)}$$

← Good inst amp has CMRR > 100 dB!

$\frac{A_d}{A_{CM}} = 10^5$



Example:

ECG input is PQRST waveform with 0.5 mV peak R-wave. Power line interference causes common mode voltage with 1 V_{pp} amplitude.

If $A_d = 30$ and CMRR = 80 dB, what is V_{OUT}?

① Inputs: $\Delta V = [0.5\,mV\ PQRST]$

$V_{CM} = 0.5 \sin 2\pi f_0 t$

← 60 Hz

② A_{CM}: $CMRR = 20\log_{10}\frac{A_d}{A_{CM}}$

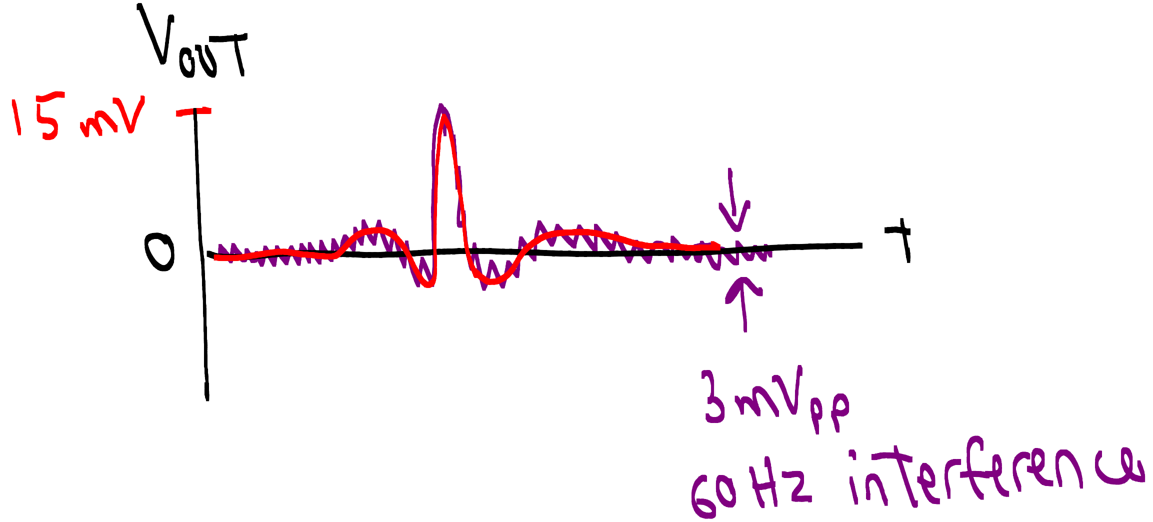
$\rightarrow \frac{A_d}{A_{CM}} = 10^{CMRR/20} \Rightarrow A_{CM} = \frac{30}{10^{80/20}} = \underline{\underline{.003}}$

③ output: $V_{OUT} = A_d \Delta V + A_{CM} V_{CM}$ ← assume $V_{REF} = 0$ if none given

$$= 30 \times (0.5\,mV\ PQRST) + .003 \times 0.5 \sin 2\pi f_0 t$$

$$= (15\,mV\ PQRST) + \underbrace{.0015}_{1.5\,mV} \sin 2\pi f_0 t$$

60 Hz



NOTE: