BME/ECE 386 EXAM 1 (W20) NAME: Solutions

4 problems for 100 pts

Problem #1: Short Answers (25 pts)

(a) Strain Gauge (2 pts): Constantan is an alloy of which two metallic elements?

Copper and nickel

(b) True or False (2 pts): An instrumentation amplifier should have high input impedance and high common-mode gain. **If you choose false, explain why.**

False Low common mode gain A_{CM}
OR
high common mode rejection ratio (CMRR)

(c) Thermistor (2 pts): What is a common material and sign of tempco (positive or negative) of a thermistor?

Manganese oxide
Negative tempco

(d) Thermocouple (2 pts): Briefly explain the purpose of cold conjunction compensation in a thermocouple probe.

Add $\Delta S \times T_0$ $\rightarrow$ $V_{sig} = \Delta S \times (T_J - T_0) + \Delta S \times T_0$ (Cold Junction compensation)

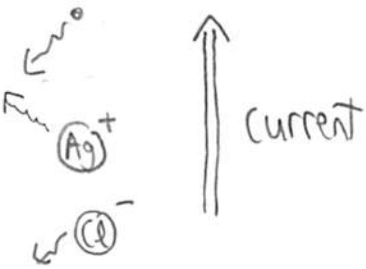
$= \Delta S \times T_J$ ← No T_0 dependence!

(e) True or False (2 pts): The output of a thermopile detector depends on $(T_{OBJ} - T_{AMB})^4$, where T_{OBJ} is the object temperature and T_{AMB} is the ambient temperature. **If you choose false, explain why.**

False $\propto T_{obj}^4 - T_{Amb}^4$

(f) <u>ECG electrodes (3 pts)</u>: What is the most common type of ECG electrode, and what chemical reactions occur to allow current to flow out of the body?

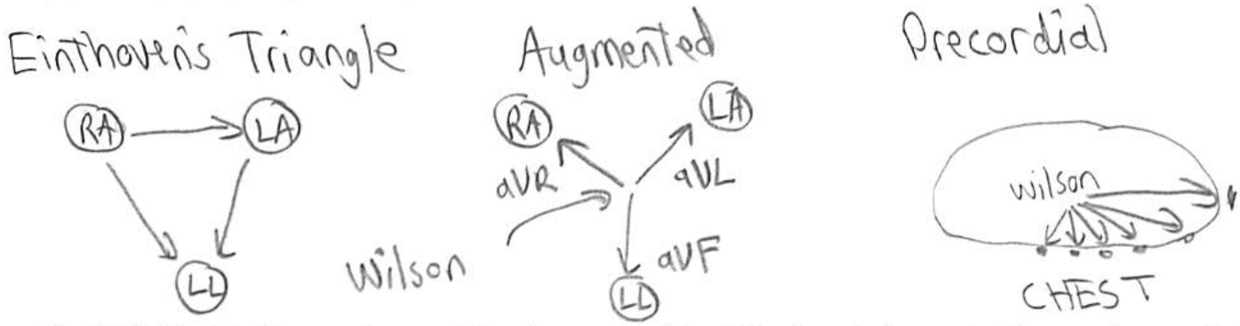
Ag / AgCl
Reduction of Ag
Dissociation of AgCl



(g) <u>Action Potential (3 pts)</u>: The action potential of a nerve involves a travelling repolarization (inward rush of Krypton atoms) followed by a travelling depolarization (outward rush of calcium ions). **Make corrections, wherever necessary, to the previous statement about the action potential in a nerve cell.**

Travelling depolarization (inward rush of sodium ions) followed by travelling repolarization (outward rush of potassium ions)

(h) <u>ECG (3 pts)</u>: Explain the positions of the lead vectors in 12-lead ECG.



(i) <u>ECG (3 pts)</u>: Choose true or false for each of the following statements. **If you choose false, then provide the correct statement.**

(i) The natural pacemaker of the heart is the Kirchhoff Current (KC) node.

(ii) In the cardiac cycle, the right atrium and left ventricle contract together, followed by the left atrium and right ventricle contracting together.

(iii) The T-wave corresponds to atrial repolarization.

(i) False sino atrial (SA) node
(ii) False L+R atria, then L+R ventricles
(iii) False ventricular repolarization

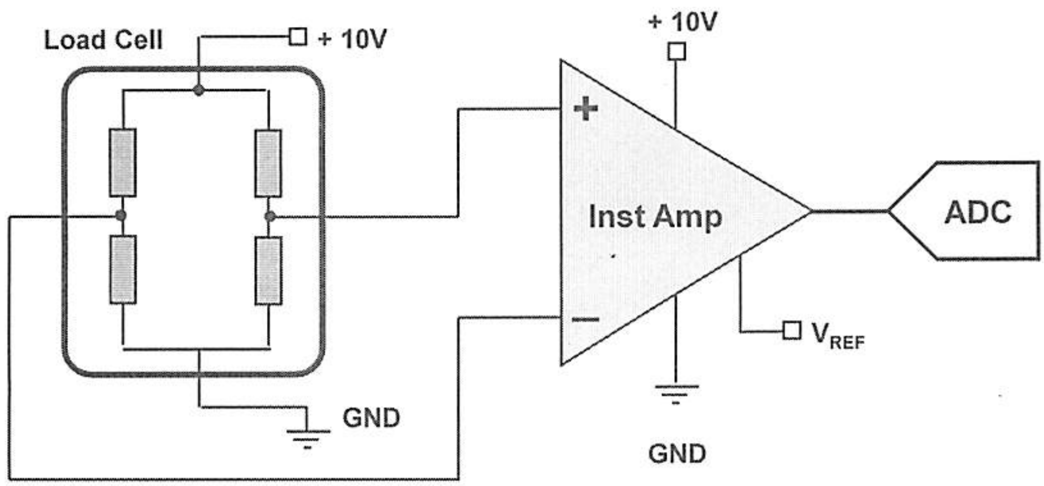
(j) <u>EMG (3 pts)</u>: Explain the smallest neuromuscular unit that can be activated and also how these units are involved in high muscle activity.

SMU (single motor unit) = [Motor neuron] + [Bundle of muscle fibers]

Higher muscle activity
→ more firings
→ recruitment of more SMUs

Problem #2: Load Cell (25 pts)

You are asked to help design a materials testing system that can both compress and stretch a sample. The customer wants to measure a maximum load of +3 kN (compress) and -3 kN (stretch) with a sensitivity of 10 N. The load cell has RO = 1.2 mV/V @ 6 kN with an excitation voltage V_S = +10V. The amplifier has a differential gain A_d = 200 and an output noise voltage V_N = 2 mV_{RMS}. The amplifier is powered by +10V and GND, so you can assume the amplifier output is limited to 1V (min) and 9V (max). The ADC has 10 bits (0 to 5V).



a) The reference voltage can be either V_{REF} = 2V or 3.5V. Which values (i.e. none, one of them, or both) satisfy all the design specs? **You must clearly explain why a V_{REF} works or does not work.** Show all work!

b) Suppose you find an ADC that operates from 0 to 10V with 14 bits. Explain whether this new ADC produces a system that satisfies all the design specs. Show all work! NOTE: You can use any relevant results from part (a) (i.e. you do not need to re-do all calculations).

(a) • Method #1 Analyze V_{Meas}

5 ← max, V_{ref}, 1 ← min

(+10)

$L = +3kN$: $V_M = 2 + \underbrace{200(10)(.0012)\frac{3kN}{6kN}}_{1.2} = 3.2V < 5$ ✓

$V_M = 3.5 + 1.2 = 4.7V < 5$ ✓

$L = -3kN$: $V_M = 2 + \underbrace{200(10)(.0012)\frac{(-3kN)}{6kN}}_{-1.2} = 0.8V > 1V$ X

$V_M = 3.5 - 1.2 = 2.3V > 1V$ ✓

$V_{ref} = 3.5V$ might be OK → need to check ΔL_{MIN}

Method #2 (extra sheet for work)

Compute $L_{max} \rightarrow V_M = V_{ref} + 200(10)(.0012)\frac{L_{max}}{6kN}$

$V_M = 5V \rightarrow L_{max} = \frac{5 - V_{ref}}{200(10)(.0012)} 6kN = \begin{cases} 7.5 \text{ kN} ✓ (V_{ref} = 2V) \\ 3.75 \text{ kN} ✓ (V_{ref} = 3.5V) \end{cases}$

(+10)

$V_M = 1V \rightarrow L_{max} = \frac{1 - V_{ref}}{200(10)(.0012)} 6kN = \begin{cases} -2.5 \text{ kN} ✗ (V_{ref} = 2V) \\ -6.25 \text{ kN} ✓ (V_{ref} = 3.5V) \end{cases}$

$\therefore V_{ref} = 3.5V$ might work, but need to check ΔL_{MIN}.

ΔL_{MIN}: $\Delta V_{ADC} = \frac{5-0}{2^{10}-1} = 4.9mV > V_N = 2mV$ Too big!

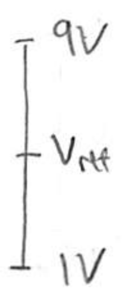
(+5) $\Delta L_{MIN} = \frac{4.9mV}{200(10V)(1.2 mV/V)} 6kN = .0122 \text{ kN} = 12.2N$ ✗

(+2) **NONE WORK!** :(

(b) New ADC! $\Delta V_{ADC} = \frac{10-0}{2^{14}-1} = 0.61mV < V_N = 2mV$ (+2)

$\Delta L_{MIN} = \frac{2mV}{200(10)(1.2)} \times 6000N = 5N < 10N$ ✓ (+3)

$\pm L_{max}$? with new ADC,



(+2)

$V_{ref} = 2V \begin{cases} \text{Max } V_M = 3.2V ✓ \\ \text{Min } V_M = 0.8V ✗ \end{cases}$

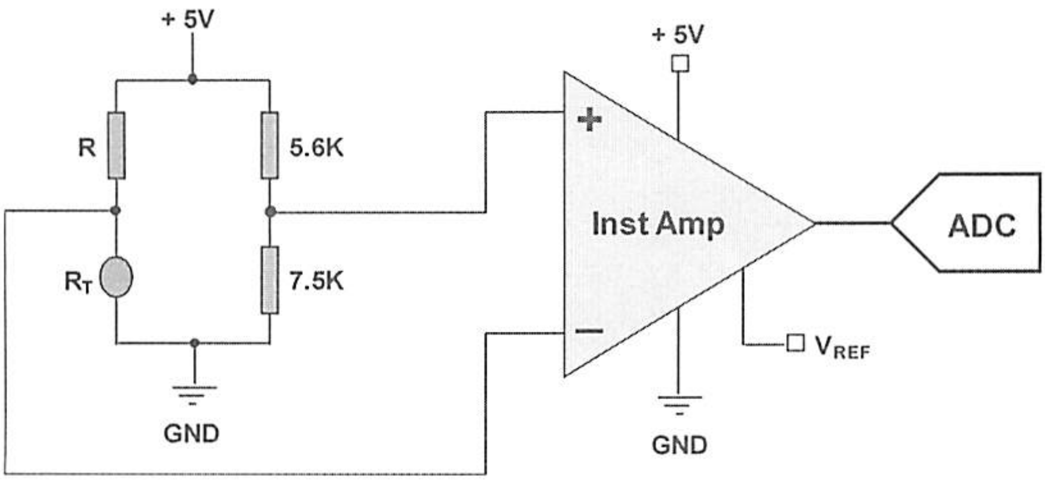
$V_{ref} = 3.5V \begin{cases} \text{Max } V_M = 4.7V ✓ \\ \text{Min } V_M = 2.3V ✓ \end{cases}$

(+1) ★ New ADC + $V_{ref} = 3.5V$ satisfy all design specs! :)

Problem #3: Temperature (25 pts)

You are asked to design a temperature measurement system that operates from 20 °C to 45 °C (e.g. for an egg incubator) with a sensitivity of 0.1 °C. You decide to use a thermistor R_T in a quarter bridge powered by +5V, as shown in the figure below. The instrumentation amplifier (A_d = 2) is powered by +5V and GND, so you can assume the amplifier output is limited to within 1V of each power supply. The reference voltage is V_{REF} = 3V. The ADC operates from 0 to 5V with 10 bits. The thermistor properties are the following:

- T = 20 °C: R_T = 12.49 kohm α = -4.51 %/°C
- T = 45 °C: R_T = 4.37 kohm α = -3.91 %/°C



a) You must choose between a bridge resistor R = 3.3 kohm or 4.7 kohm. Is an operating temperature range of 20 °C to 45 °C feasible with one, neither, or either resistor value? **If you rule out a resistor, you must clearly explain why.**

b) Suppose the amplifier has an output noise voltage of V_N = 1 mV_{RMS}. We can ignore self-heating if the temperature rise is less than the sensitivity at T = 20 °C. Can we ignore self-heating? Assume a dissipation factor δ = 7 mW/°C. Show all work!

(a) $V_M = 3 + 2 \times 5 \times \left[\underbrace{\frac{7.5K}{7.5K + 5.6K}}_{0.573} - \frac{R_T}{R + R_T} \right]$

4V
$V_{ref} = 3V$
1V

T = 45°C:

$R = 3.3K$; $3 + 10\left(0.573 - \frac{4.37K}{3.3K + 4.37K}\right) = 3.03V$ ✓

$4.7K$: $3 + 10\left(.573 - \frac{4.37K}{4.7K + 4.37K}\right) = 3.91V$ ✓

+6

(extra sheet for work)

Choose $\boxed{R = 4.7K}$ (+1)

$T = 20^\circ C$: $V_M \downarrow$ $V_M > 1V$ (+6)

$R = 3.3k$: $3 + 10\left[.573 - \frac{12.49K}{3.3K + 12.49K}\right] = 0.82V$ ✗

$4.7K$: $3 + 10\left[.573 - \frac{12.49}{4.7 + 12.49}\right] = 1.464V$ ✓ winner!

(b) • Sensitivity

$\Delta V_{ADC} = \frac{5V}{2^{10} - 1} = 4.9mV \leftarrow \Delta V_{MIN}!$ (+2)

$V_N = 1mV$

$$\frac{\partial V_M}{\partial T} = \frac{\partial V_M}{\partial R_T} \alpha R_T = \left[-10 \times \left(\frac{1}{R + R_T} - \frac{R_T}{(R+R_T)^2}\right)\right] \alpha R_T$$

$$= -10 \frac{R + \cancel{R_T} - \cancel{R_T}}{(R + R_T)^2} \alpha R_T = -10 \frac{R}{(R+R_T)^2} \alpha R_T$$

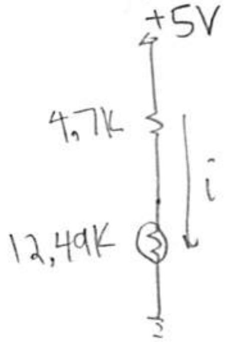
$$= -10 \frac{4.7K}{(4.7K + 12.49K)^2} (-.0451 \ /^\circ C)(12.49K)$$

$$= 0.0896 \ V/^\circ C$$ (+4)

$$\rightarrow \Delta T_{MIN} = \frac{.0049V}{.0896 \ V/^\circ C} = \boxed{0.055^\circ C} < 0.1^\circ C$$

YES!

• Self heating



$$P = \left[\frac{5V}{(12.49K + 4.7K)}\right]^2 \times 12.49K = 1.06mW$$ (+3)

$$\delta T_{self} = \frac{1.06mW}{7mW/^\circ C} = 0.15^\circ C > .055^\circ C$$ (+2) (+1)

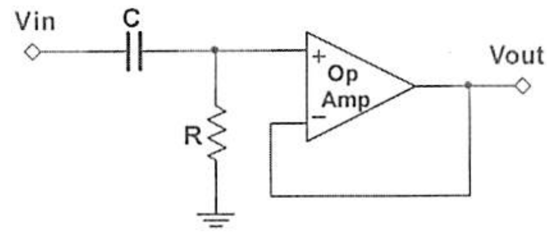
NO, we cannot ignore self heating!

Problem #4: ECG Amplifier (25 pts)

Consider an ECG system where the input PQRST waveform has a 1.5 mV amplitude R-wave. The patient's heart rate is 90 beats per minute. The patient's breathing motion also produces an input differential voltage described by a 20 mV peak-to-peak, 0.25 Hz sine wave. Power line interference produces a 3V peak-to-peak, 60 Hz common mode voltage. The instrumentation amplifier has a differential gain $A_d = 20$, CMRR = 85 dB, and $V_{REF} = 1V$.

a) Compute and sketch the instrumentation amplifier output over a 4 second interval. Label important features!

b) After the instrumentation amplifier, we want a circuit that blocks DC. Use the Golden Rules to show that the op amp output is:



$$\frac{V_{out}}{V_{in}} = \frac{jf/fc}{1+jf/fc}$$

NOTE: Make sure to clearly define fc!

c) Let us assume that the circuit from Part (b) passes a signal frequency when $|V_{OUT}/V_{IN}| > 0.9$. Let your ECG signal have frequency content that spans from 2 to 100 Hz. Suppose C = 0.33 uF. The available resistor values are R = 100 kohm, 220 kohm, 560 kohm, 820 kohm, and 1 Mohm. Which is the minimum acceptable value? Show all work!

(a) $V_{OUT} = 1 + A_d \Delta V + A_{CM} V_{CM}$

(A_d = 20; V_{CM} = $3V_{pp} \sin 2\pi f_2 t$, 60 Hz)

ΔV = $[1.5\text{ mV PQRST}] + (20 mV_{pp}) \sin 2\pi f_1 t$, .25 Hz

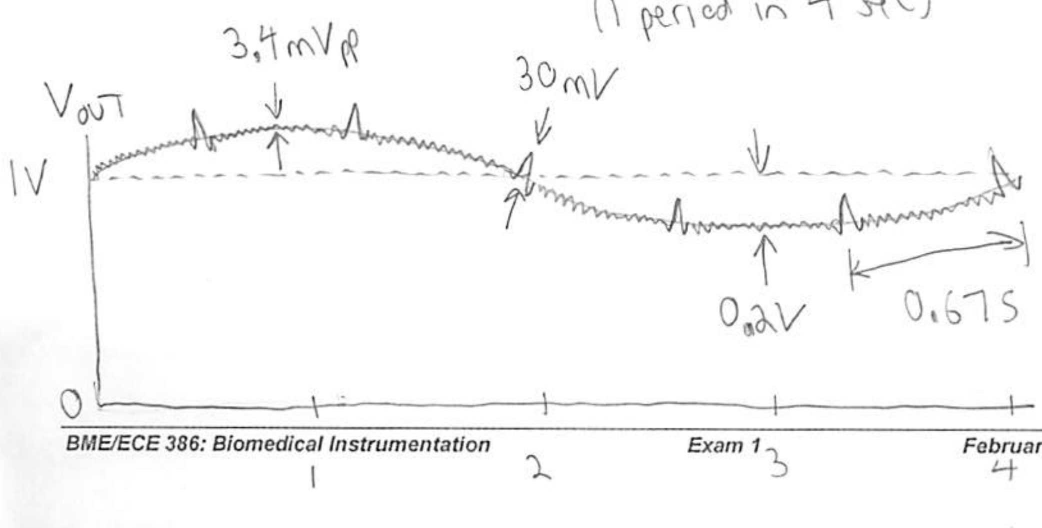
$$CMRR = 20\log_{10}\left(\frac{A_d}{A_{CM}}\right)$$

$$\rightarrow A_{CM} = \frac{20}{10^{85/20}} = 1.12\times10^{-3}$$

$$V_{OUT} = 1 + [30\text{ mV PQRST}] + [0.4V_{pp}]\sin 2\pi f_1 t + (3.4\text{ m}V_{pp})\sin 2\pi f_2 t$$

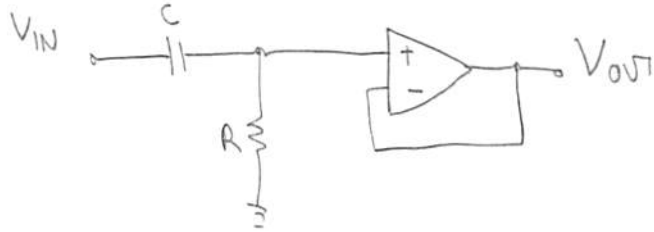
.25 Hz (slow) (1 period in 4 sec); 60 Hz (fast)

$$\frac{90\text{ beats}}{60\text{ sec}} \times 4s = 6\text{ beats}$$



+12

(extra sheet for work)



(b) $V_{OUT} = V_- = V_+$

$$= V_{IN} \frac{R}{R + 1/j\omega C}$$

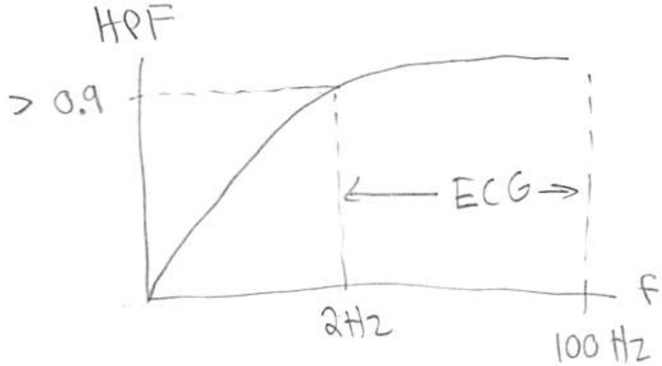
$$= V_{IN} \frac{jR\omega C}{1 + j\omega RC} = V_{IN} \frac{j2\pi fRC}{1 + j2\pi fRC}$$

Let $f_c = \frac{1}{2\pi RC}$

$$\Rightarrow \boxed{\frac{V_{OUT}}{V_{IN}} = \frac{j f/f_c}{1 + j f/f_c}}$$

(+6)

(c)



want $\left|\frac{V_{OUT}}{V_{IN}}\right|_{f=2Hz} > 0.9$

$$\frac{2/f_c}{\sqrt{1 + (2/f_c)^2}} > 0.9$$

$$(2/f_c)^2 > 0.81\left[1 + (2/f_c)^2\right]$$

$$0.19\,(2/f_c)^2 > 0.81$$

$$2/f_c > 2.065$$

$$2 \times 2\pi RC > 2.065$$

$$R > \frac{2.065}{4\pi(.33 \times 10^{-6} F)}$$

$$> 497.9K$$

Min value $\boxed{R = 560K}$

(+7)