Lab Report 1

Prepared by: Heidi Eren

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Executive summary (5 pts):

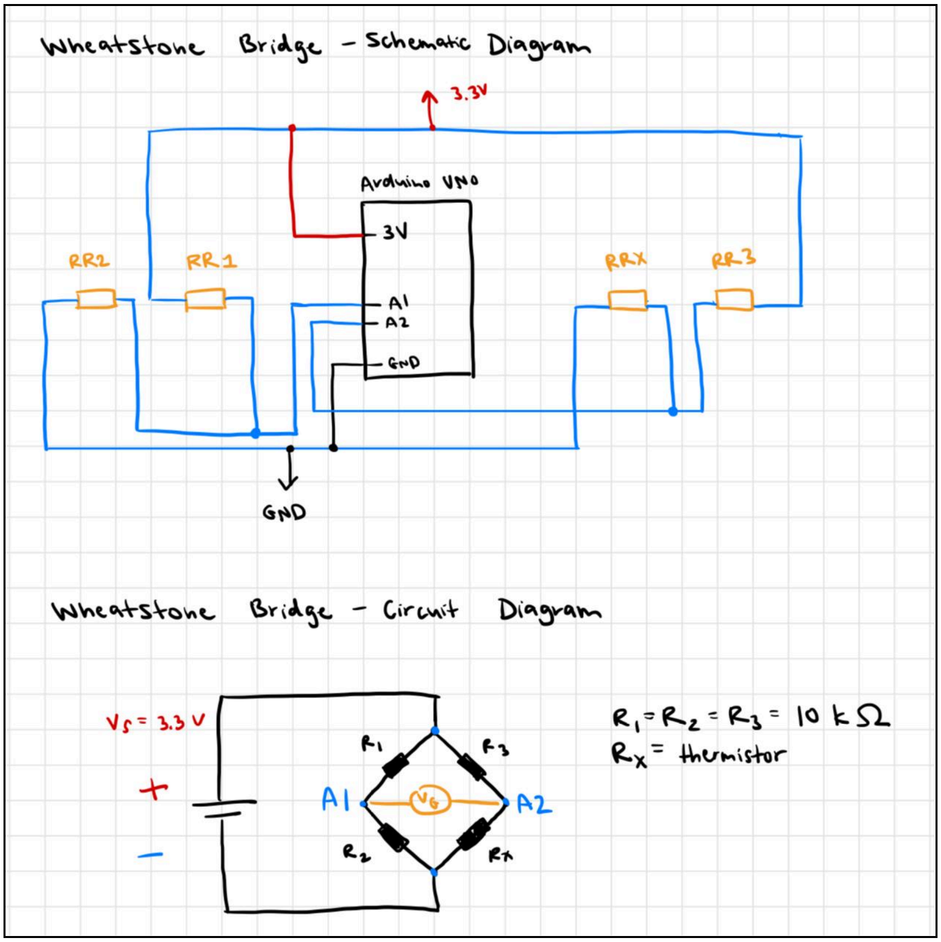
Describe what you are trying to accomplish/demonstrate. What is the purpose of this test?

The purpose of this experiment is to demonstrate an understanding of the Wheatstone bridge circuit by collecting real-time signal processing data using a physiological (temperature) sensor. By curve fitting the Steinhart-Hart equation, the measured resistance values are interpolated with known temperatures to calculate the calibration points, or Steinhart-Hart coefficients, in order to compute the temperature readings of the system. By evaluating all, 10-, and 100-time point intervals for the moving average at standard increments of temperature measured from the thermistor, the level of noise in the system can be observed to gauge the variability in hardware tolerances and data processing that ultimately influences the accuracy and precision of the results.

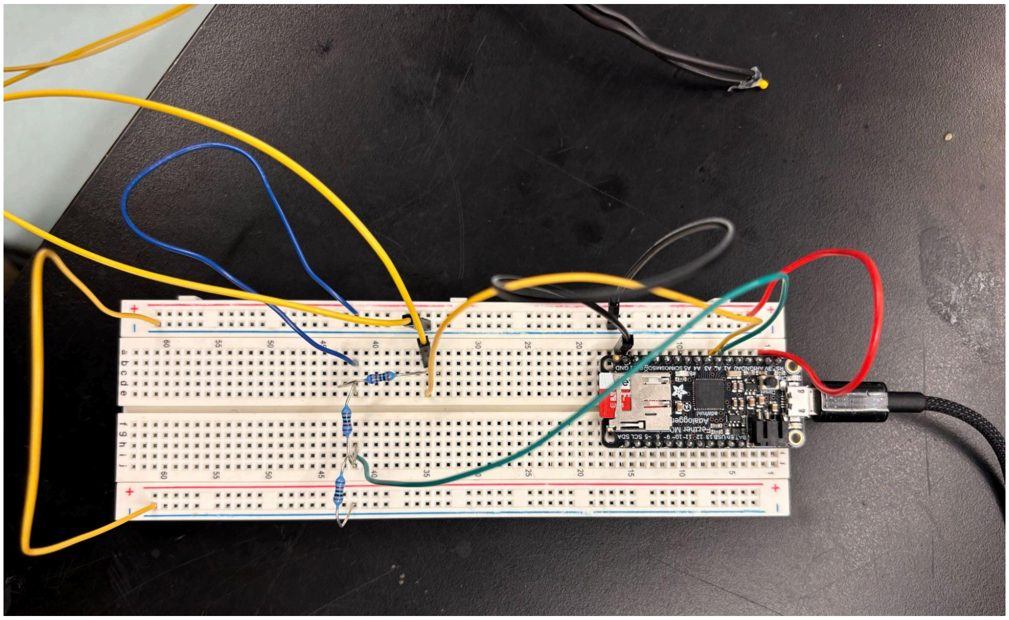
Procedure:

1. Build a circuit to measure temperature using a thermistor. Use a Wheatstone bridge to measure the change in resistance and an Arduino for data acquisition.

2. **Sketch a circuit diagram of the circuit (5 pts):**



3. **Take a photo of the circuit (3 pts):**



4. In the Arduino IDE, add your equation to calculate resistance from a known Wheatstone bridge output voltage. Output that calculated resistance to the serial monitor. (**You will upload your final code to Canvas**).

5. In the place of the thermistor (in the hardware), place a 5.6 kΩ resistor. Ensure that the calculated resistance is approximately 5.6 kΩ.

6. In the place of the thermistor (in the hardware), place a 15 kΩ resistor. Ensure that the calculated resistance is approximately 15 kΩ.

7. Replace the 15 kΩ resistor with the thermistor. Ensure the calculated resistance (roughly) matches the resistance expected at room temperature (~11 kΩ).

8. In the Arduino IDE, add your Steinhart-Hart equation to calculate temperature from a known resistance. Output that calculated temperature (along with resistance) to the serial monitor. (**Upload any files, i.e. .xls, that were used to calculate these coefficients) (7 pts)**.

9. Using the water bath, measure the water temperature at 5 temperatures. *Be careful not to let the metal leads touch the water.* At each temperature, collect approximately one minute of data using 1. No averaging; 2. A moving average of 10 time points; 3. A moving average of 100 time points. **Fill in the tables below. Submit any data files that were used to generate these results (10 pts).**

Bad resistors (+/- 5% tolerance)

Temperature	Metric	No average	10-point moving	100-point moving

			average	average
25 °C	Max	**29.01**	**27.04**	**26.83**
	Min	**24.78**	**25.32**	**23.94**
	Var	**0.11**	**0.070**	**0.16**
35 °C	Max	**38.31**	**36.38**	**36.07**
	Min	**33.7**	**34.9**	**29.92**
	Var	**0.090**	**0.020**	**0.70**
37 °C	Max	**53.52**	**37.98**	**36.66**
	Min	**22.96**	**33.07**	**26.49**
	Var	**0.82**	**0.12**	**1.40**
38 °C	Max	**50.1**	**39.57**	**38.46**
	Min	**25.86**	**37.05**	**27.74**
	Var	**0.67**	**0.075**	**1.73**
40 °C	Max	**46.46**	**40.42**	**39.80**
	Min	**33.70**	**38.23**	**28.34**
	Var	**0.43**	**0.067**	**2.08**

10. Replace all 10 kΩ resistors with 10 kΩ resistors with lower tolerance.

11. Using the water bath, measure the resistance and temperature of the circuit at 5 temperatures. At each temperature, collect approximately one minute of data using a moving average of 10 time points. **Fill in the table below. Submit any data files that were used to generate these results (10 pts).**

Good resistors (+/- 0.5% tolerance)

Temperature	Metric	No average	10-point average	100-point average
25 °C	Max	**30.09**	**27.38**	**26.97**
	Min	**24.33**	**25.27**	**26.19**
	Var	**0.15**	**0.04**	**0.0054**

35 °C	Max	**38.69**	**36.24**	**36.01**
	Min	**33.52**	**35.49**	**35.72**
	Var	**0.067**	**0.0099**	**0.0040**
37 °C	Max	**56.71**	**38.63**	**36.63**
	Min	**21.87**	**34.61**	**35.94**
	Var	**1.26**	**0.13**	**0.015**
38 °C	Max	**49.22**	**38.75**	**37.72**
	Min	**28.47**	**36.63**	**37.31**
	Var	**0.60**	**0.058**	**0.012**
40 °C	Max	**46.56**	**42.54**	**40.61**
	Min	**33.79**	**39.41**	**40.12**
	Var	**0.25**	**0.057**	**0.010**

Notes and recommendations:

All questions are short answers.

1. Describe the circuit you used to measure temperature (2 pts). What is the function of the Wheatstone bridge? (1 pts)

   The circuit used to measure temperature is known as Wheatstone bridge. It has four resistors that form two voltage dividers in parallel, so the same resistance values result in a voltage flow of 0 across the bridge. By comparing the voltage changes across the known resistors, the unknown resistance of the fourth resistor can be determined. As the smallest changes in voltage are measured, low values of resistance can be determined at a higher degree of precision.

2. Discuss the curve-fitting process. Why was the curve-fitting necessary? Why not just use the table provided in the data sheet? (2 pts)

   The curve-fitting process forms an equation that can describe the observed data. In this case, the Steinhart-hart equation utilizes curve-fitting to calculate the coefficients based on a dataset containing the standard resistance of the thermistor over a range of temperatures. This is necessary because even the smallest fraction of a degree in temperature makes a significant difference. The provided table only includes temperature values to the nearest degree, which may not result in accurate measurements when comparing the measured resistance. Hence, the Steinhart-hart equation interpolates the observed resistance values to ensure that the most accurate temperature values are obtained.

3. Did the moving average increase accuracy or precision of the result? (1 pt) How many points should be used for the moving average (why)? (2 pts) At what point would you reach diminishing returns, and why? (2 pts)

   The moving average increases the precision of the result because with a greater number of samples being measured, the closer the range of temperature values will be to each other. Rather than comparing individual temperature values, the moving average ensures that outliers do not affect the overall range of results, especially since random fluctuations from noise can easily influence the temperature readings. Based on this lab, 10 samples should be used for the moving average because it ensures that sufficient temperature values are being measured to outweigh the fluctuations recorded. As shown in the tables above, the moving average values within the 10-time point interval had a variance of 0.1 or less (regardless of the resistor), which means the averaged values were very close in magnitude to each other. This validates the precision of the temperature readings during the time frame. However, if we increase the number of time points measured to compute the moving average, the precision will decrease because despite the measurements being close to each other, it can stray further away from the true value. A greater number of time points also increases the likelihood of capturing more outliers that deviate the overall average of the values. The 100-time point interval in the table resulted in the variance of around 1 for the bad resistors, which is significantly higher than the 10-time point interval variance. With a greater number of time points, the likelihood of fluctuations and noise being measured in the data can increase significantly, which shifts the moving average towards a more inaccurate value.

4. Describe the effect of replacing the “standard tolerance” resistors with precision resistors and compare it to using a moving average. (3 pts) For what applications would you recommend using precision resistors? (1 pts) For what applications would you not recommend using precision resistors? (1 pts)

   When replacing the “standard tolerance” resistors with precision resistors, it was evident that the precision increased. A smaller tolerance indicates less variability in the observed resistance value (from 10kΩ), which subsequently results in more accurate temperature calculations. During the measurements, the variance of temperature values was much lower for the precision resistors than the standard tolerance resistors. There were less fluctuations in the measurements using the precision resistors, which suggests that there was less bias in hardware tolerancing because they have a lower tolerance of +/- 0.05% whereas the “standard tolerance” resistors have a higher tolerance of +/- 5%. With less bias influencing the moving average, the measured temperature values would be closer to each other, so the precision would be greater. Replacing the “standard tolerance” resistors with precision resistors is similar to replacing the time points for the moving average from none to 10. By increasing the number of time points, there is greater precision in the temperature values without comprising the outliers, which minimizes the variability and increases the consistency of the results.

   For precision resistors, I would recommend blood oxygenation applications or movement sensors for motor disease progression because there are not many well-established predictive devices for these applications, so ensuring that accurate readings with the least amount of hardware tolerancing bias would be crucial for obtaining and analyzing the observed measurements. For the “standard tolerance” resistors, I would recommend body temperature applications because there are a plethora of predictive devices with known sources of error, so when analyzing the measurements from these sensors, the bias can be easily accounted for.

5. Identify any other sources of noise or error present within the circuit. How could they be reduced or eliminated? (5 pts for at least 3 correct answers)

One simple source of error in the circuit is the sensor setup. A jumper wire or wire leads of the sensor could easily not be pressed into the terminal strip, causing a short circuit and cutting the connection. This can be addressed by checking over the setup and ensuring that all wires and pins are firmly pressed into the breadboard.

Another source of error in the circuit could be the rounding or number of significant figures (defined or specified) in the calculations. Using Arduino outputs or Excel solver may round certain measurements to a specific decimal place, which can affect the accuracy of the temperature readings as they can be susceptible to the smallest of changes. For example, one of my calculated coefficients for the Steinhart-hart equation was off by 0.0001th place, which resulted in very inaccurate temperature readings. Hence, by ensuring that any values or calculations are correctly rounded or defined to the exact significant figures, the error in data processing can be minimized.

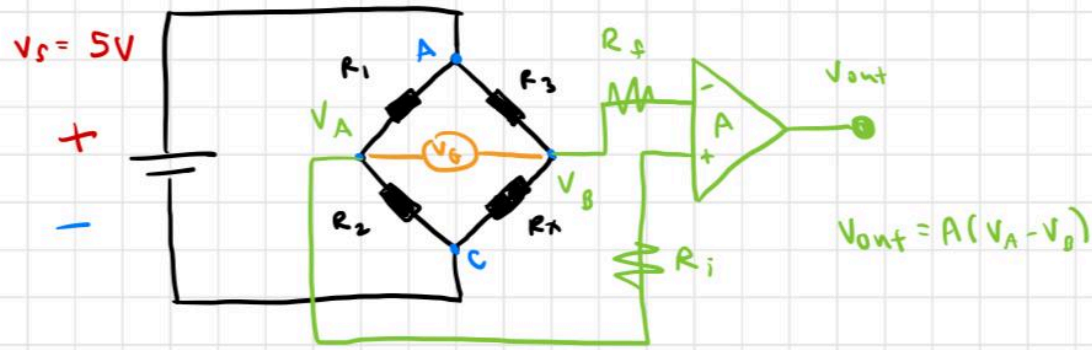
Another source of error that I encountered was the Wheatstone bridge setup, where the A1 and A2 nodes were flipped. Because the resistance was not perfectly equal (due to standard noise or fluctuations in resistors), the voltage across the bridge was not zero. Based on the voltages of the resistors, there was a current that flowed from A1 to A2. However, the circuit was wired so that the current flow was from A2 to A1. This affects the coded voltage difference that in turn, incorrectly calculates the resistance of the thermistor. With inaccurate resistance values, the resulting temperature readings were inaccurate as well. This error in data acquisition can be eliminated by ensuring that current flow from the two nodes are properly accounted for and wired correctly in the circuit.

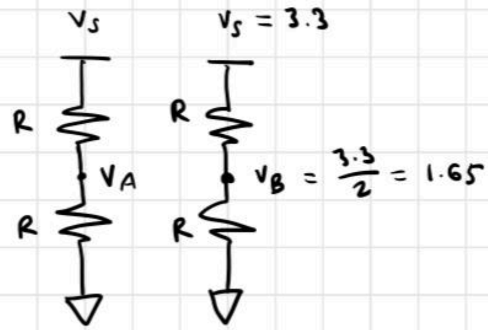
The most established source of noise in the circuit are the resistors. Because of hardware tolerancing compounded with the thermal noise from connectivity, the Vdiff often ranged from 0.05 to 0.5 V due to this discrepancy between the resistors (V1 and V2 values). Even with lower tolerances from the precision resistors, the variability in the measured voltage was evident, which produces noise in the data. To reduce this, high precision resistors with a tolerance of 0.01% can be used to minimize the level of noise from hardware tolerancing coupled with thermal noise.

6. **BONUS:** A Wheatstone bridge is typically implemented in combination with a differential amplifier. **What would be the ideal gain of the amplifier to take advantage of the full scale of the Arduino? Show your work. (3 pts)**

A differential amplifier would help amplify the voltage difference across the resistors in a Wheatstone bridge. If we assume that the Arduino input voltage cannot be changed, it is assumed that Vs = 3.3V. Given that the maximum Vdiff is around 0.5V (based on the precision resistors from this experiment) and assume that the R1 & R3 resistors can be changed to 1.5kΩ, the ideal gain would be 6.6:

Wheatstone bridge with differential amplifier





$$V_A = \frac{V_s \cdot R_v}{R + R_v}$$

$$V_{out} = \frac{R_f}{R_i}(V_A - V_B)$$

Assume $V_s = 3.3V$ (supply voltage cannot change):

$V_{diff} = 0.5\,V$

$$G = \frac{V_s}{V_{diff,max}} = \frac{3.3\,v}{0.5\,v} \approx 6.6 \checkmark$$

$$V_{out} = \frac{R_f}{R_i}(V_A - V_B) \qquad V_{out} = G \times V_{diff} \qquad G = \frac{R_f}{R_i}$$

For target $V_{diff} = 500\,mV$ or $G = 6.6$:

Set $R_i = R_3 = 1.5\,k\Omega$
$R_f = R_4 = 10\,k\Omega$

$$G = \frac{R_f}{R_i} = \frac{10}{1.5} = 6.6 \checkmark$$

Because the Arduino at full scale has an input voltage of 5V, the amplifier can amplify the maximum Vdiff from the Wheatstone bridge to 5V. Given the maximum Vdiff to be around 0.5V (based on the precision resistors from this experiment) and the R1 & R3 resistors can be changed to 1kΩ, the ideal gain would be 10:

Assume $V_S = 5\,V$ (supply voltage can be changed):

$V_{diff} = 0.5\,V$

$$G = \frac{V_S}{V_{diff,max}} = \frac{5\,V}{0.5\,V} \approx 10$$

$V_{out} = \frac{R_f}{R_i}(V_A - V_B)$ $\quad V_{out} = G \times V_{diff}$ $\quad G = \frac{R_f}{R_i}$

For target $V_{diff} = 500\,mV$ or $G = 10$:

Set $R_i = R_3 = 1\,k\Omega$

$R_f = R_4 = 10\,k\Omega$

$$G = \frac{R_f}{R_i} = \frac{10\,k\Omega}{1\,k\Omega} = 10 \checkmark$$