Xi'an Jiaotong-Liverpool University
西交利物浦大学

MEC208 Instrumentation and Control System

2024-2025, semester 2

LAB 1: SENSORS & INSTRUMENTATION

Lab Report

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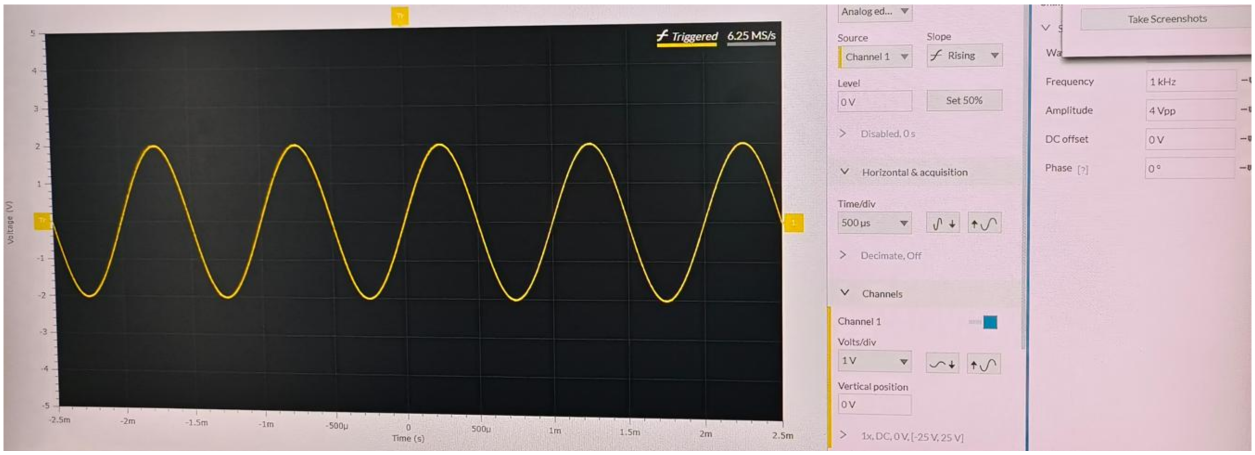
Date: 2025.03.10

Experiment 1: Basics

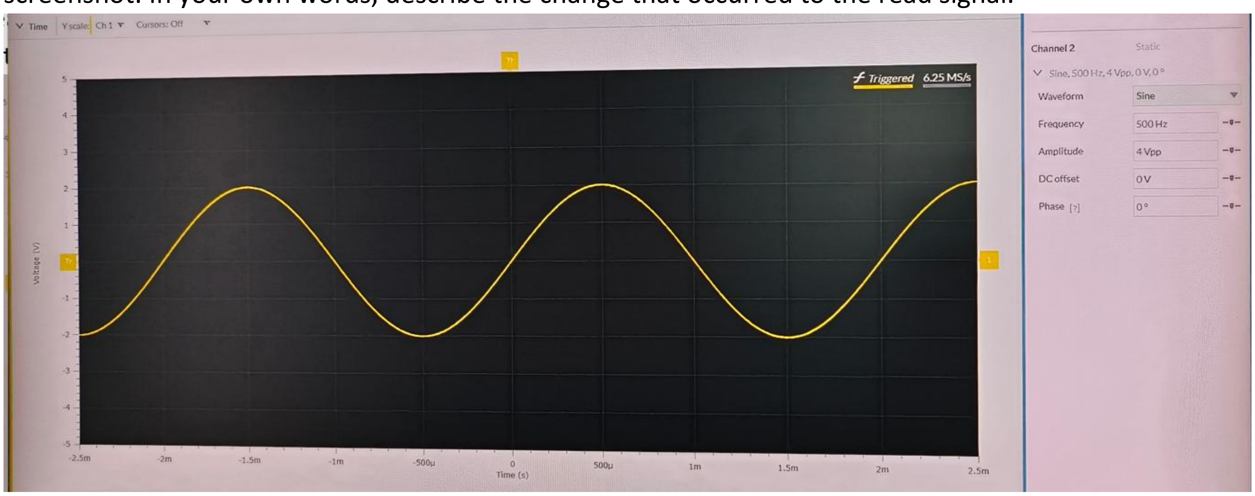
E1.1 Use the Function Generator and Oscilloscope Soft Front Panels

1) Use your function generator on your NI ELVIS III to generate a sine wave with the following specifications:
   Frequency: 1kHz Amplitude: 2V DC Offset: 0V Output Channel: 1
   Read the function generator using channel 2 of the oscilloscope. Provide a screenshot of the SFP with generated function shown.



Please note that the date shown in the picture differs from my scheduled lab date. I redid *all tasks of E1.1* on March 12, 2025, with proper registration at the IR112 office for clarity and accuracy.

2) While both SFPs are running change the frequency of the signal generated to 500 Hz. Provide a screenshot. In your own words, describe the change that occurred to the read signal.



Description:

The changes in frequency cause the period of the original sine wave become twice. Specially, the period here is 2ms.

3) Return the frequency to its initial value of 1KHz. Change the amplitude to 4V. Provide a screenshot. In your own words, describe the change that occurred to the read signal.

Description:

The changes in amplitude cause the maximum and minimum value of the original sine wave become twice, from ±2 to ±4.

4) Return the amplitude to its initial value. Change the DC Offset to 3. Provide a screenshot. In your own words, describe the change that occurred to the read signal.

Description:

The DC offset shifts the original waveform upward by 3 units, resulting in a new maximum value of +5 and a minimum value of +1.

E1.2 Use the VPS and the DMM

1) Make sure your NI ELVIS III is powered on and connected to your computer.
2) From Measurements Live website launch the SFPs of both the DMM and VPS.
3) Connect the (+) channel of the VPS to the (V) channel of the DMM using the cable and the ground of the VPS to the common ground of the DMM.

4) From the VPS SFP choose the positive power supply of +1V and a negative power supply of -1V. Click Run on both SFPs. What is the voltage read by the DMM?
   Answer:
   The volage read by DMM is 0.9941V

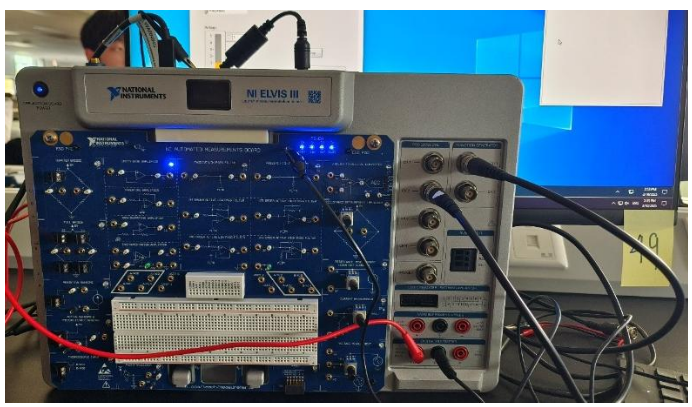
5) While both SFPs are running, unplug the Banana plug from the ground of the VPS and plug it in the (-) power supply of the VPS. What is the voltage reading on the DMM? __________.
   Answer:
   The volage read by DMM is 2.0026V after changing the wiring methods.

6) Keep the cables connected the way they are. Change the negative voltage supply of the VPS successively to -2V, -3V and -4V. What are the voltage readings on the DMM?
   Answer:
   When the negative voltage converts to -2V, the volage read by DMM is 3.0061V.
   When the negative voltage converts to -3V, the volage read by DMM is 4.0099V.
   When the negative voltage converts to -4V, the volage read by DMM is 5.0090V.

E1.3 Use NI Automated Measurements Board

- What is the voltage level you read on the DMM?
  Answer:
  The volage read by DMM is 1.0002V.

- From the LED Name control, switch the selection to various values. The corresponding LED of your choice should light up. Provide a picture of lighting the "Amplifier".



Experiment 2: Signal Chain

E2.1 Signal Chain using the NI Automated Measurements Board

1. The Light Intensity chart on your Front Panel displays the intensity of light as it changes over time.

a. What is the light intensity in your lab, measured in Volts? *(Make sure the sensor is not covered or overshadowed but rather is fully exposed to the light in the room)*

Answer:

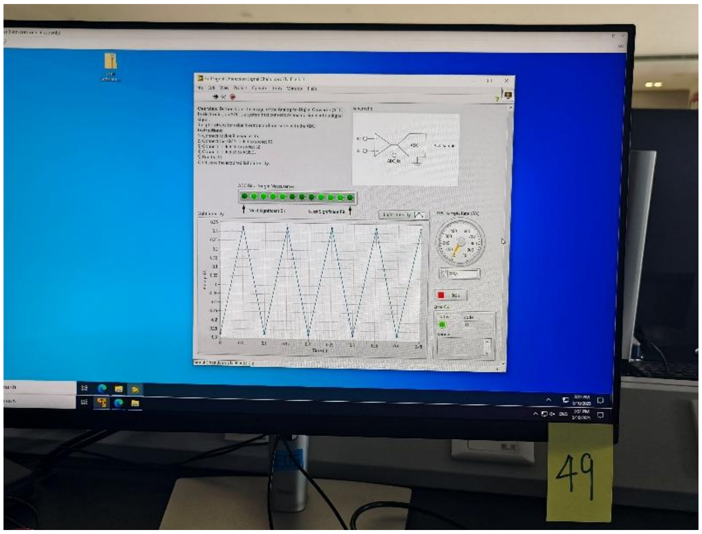
The light intensity measured in volts is 0.607V.

b. Using a light source, such as your smart phone's camera flash light, subject the sensor to light from different angles and from various distances. Provide screenshots or photos for each of the following questions.

i. What is the minimum intensity you were able to measure?

Answer:

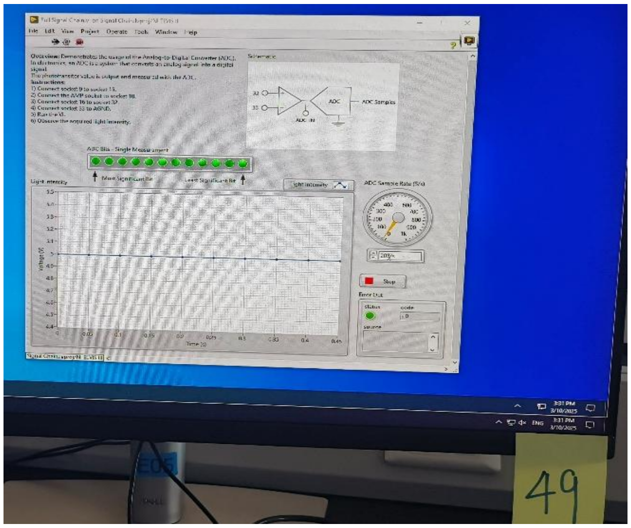
The minimum light intensity measured in volts is around 0.2V by covering the sensor, with the screenshots showing as below.



ii. What is the maximum intensity you were able to attain?

Answer:

The maximum light intensity measured in volts is 5V*, with the screenshots showing as below.*



iii. In your own words describe the best angle and the distance from which your light source is best detected.

Answer:

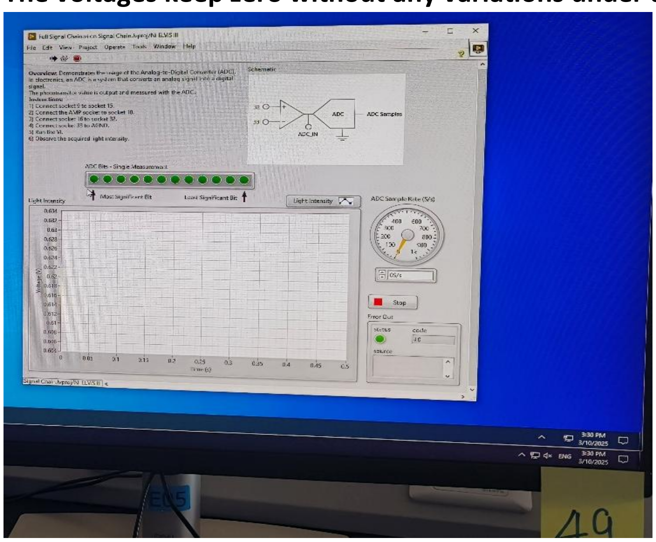
The optimal angle is directly above the sensor, perpendicular to its plane, at a height of approximately 18 centimeters.

c. From your Front Panel, set the sampling rate of your ADC successively to 0, 20, 100, 500 and 1000. With each sampling rate picked, repeat the earlier experiment. What do you notice about the chart displaying the changes in voltage?

Answer:

If the sampling rate is zero, the voltages keep zero without changing. However, as long as the ADC sampling rate is greater than zero, increasing it from 20 to 100, 500, or even 1000 does not affect the magnitude of the measured voltage. The only changes lie in density of the measured points. That means the higher the ADC sampling rate, the denser points distributed on the graph.

- ✧ **Case 1: 0 ADC sampling rate**
  The voltages keep zero without any variations under different angles.



- ✧ **Case 2: 20 ADC sampling rate**
  1. The normal lab surrounding detects a light intensity around 0.607 V.
  2. The minimum light intensity is 0.015V.
  3. The maximum light intensity is 5V.

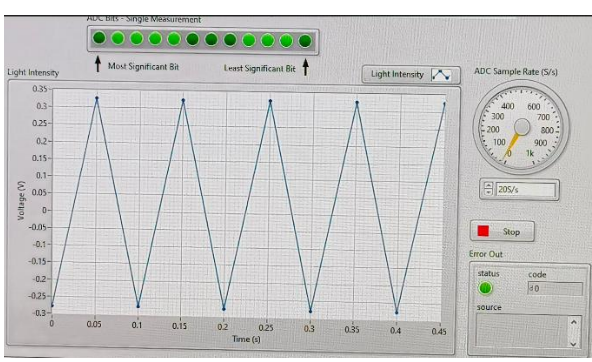


Figure: The left image represents the minimum condition, while the right image represents the maximum condition.

✧ **Case 3: 100 ADC sampling rate**

1. The normal lab surrounding detects a light intensity around 0.603 V.
2. The minimum light intensity is 0.029V.
3. The maximum light intensity is 5V.

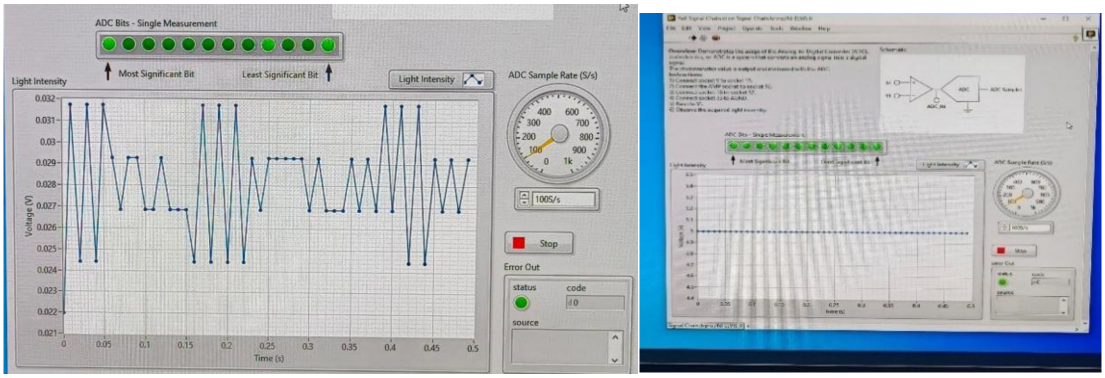


Figure: The left image represents the minimum condition, while the right image represents the maximum condition.

✧ **Case 4: 500 ADC sampling rate**

1. The normal lab surrounding detects a light intensity around 0.605 V.
2. The minimum light intensity is 0.015V.
3. The maximum light intensity is 5V.

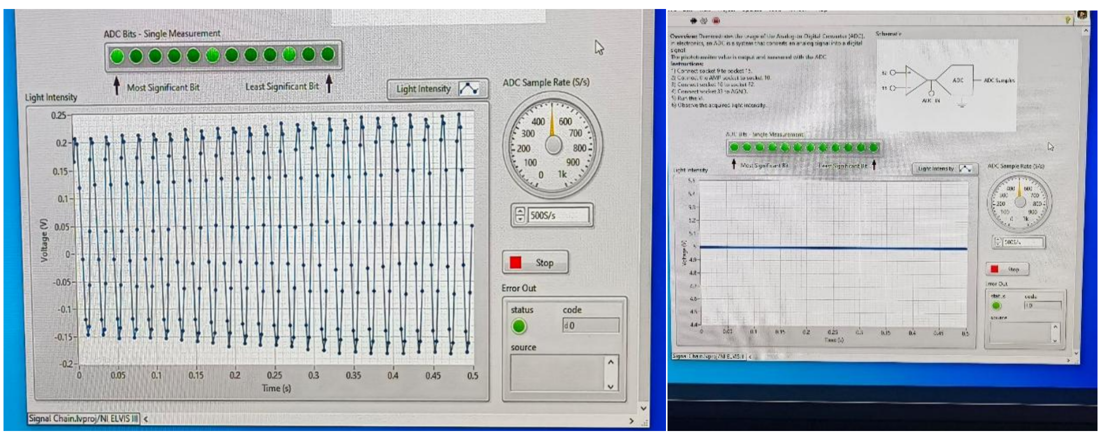


Figure: The left image represents the minimum condition, while the right image represents the maximum condition.

✧ **Case 5: 1000 ADC sampling rate**

1. The normal lab surrounding detects a light intensity around 0.607V.
2. The minimum light intensity is 0.607V.
3. The maximum light intensity is 5V.

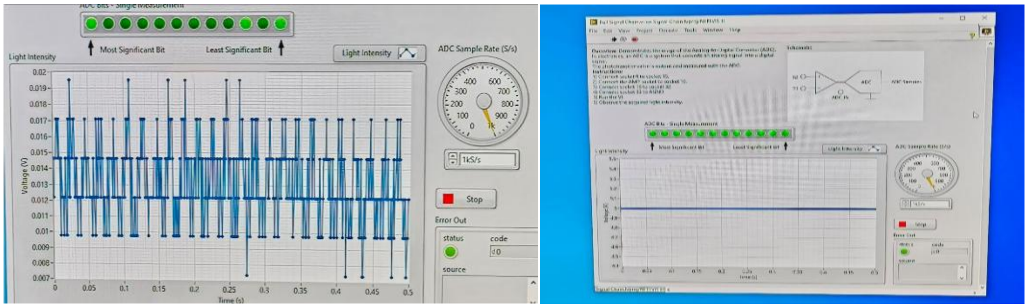
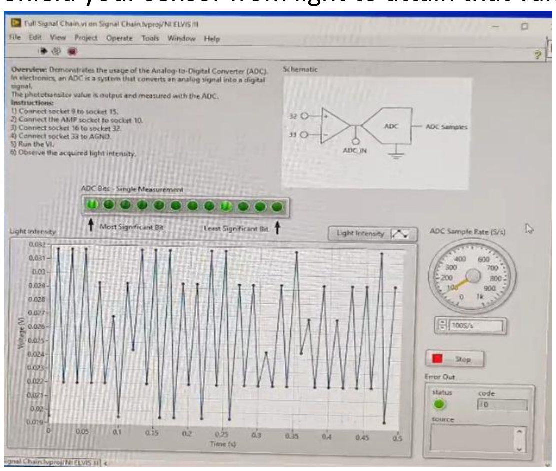
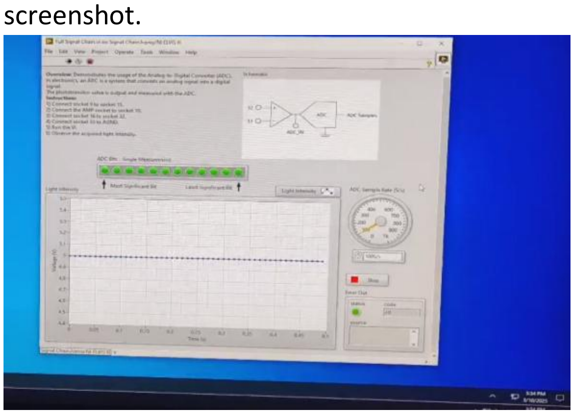


Figure: The left image represents the minimum condition, while the right image represents the maximum condition.

2. The ADC LED display provides a view of the raw digital data that is provided by the ADC to the LabVIEW VI. Each row of LEDs represents one digital voltage value composed of 12 bits of 1's or 0's. An On-LED represents the digit 1 and an Off LED represents the digit 0. The most significant bit is the sign bit indicating the sign (+/-) of measured values, the absolute decimal numbers are represented by the rest 11 bits.
   a. What is the string of 12 bits corresponding to the lowest possible voltage reading? Shield your sensor from light to attain that value. Provide a screenshot.



   b. What is the string of 12 bits corresponding to the highest possible voltage reading? Subject your sensor to the brightest light source to attain that value. Provide a screenshot.



c. What are the corresponding voltage readings to these 12-digit numbers?

Answer:

※Case 1:

The lowest possible voltage reading result is "1000 0000 1000" in binary.

※Case 2:

The highest possible voltage reading result is "1111 1111 1111" in binary.

E2.2 Measuring the Signal Directly from the Sensor

1. What is the voltage reading corresponding to the light intensity in your room?

   Answer:

   The voltage reading for the normal light intensity is 389.62 mV.

2. Using your phone's flashlight, shed light directly on the sensor. What is the corresponding DMM measurement?

   Answer:

   The voltage reading for the flash light intensity is 4.9661 V.

3. What is the DMM measurement reading if the sensor is fully shaded?

   Answer:

   The voltage reading for the flash light intensity is 12.036 mV.

4. Compare this measurement experiment with the preceding experiment you conducted. In your own words, list and justify two disadvantages that measuring the signal directly through the DMM has.

   Answer:

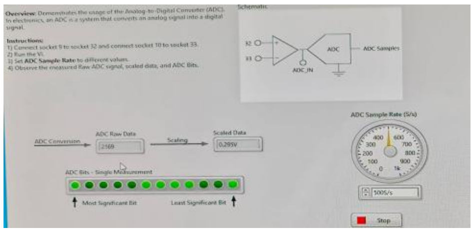
   a. DMM cannot fully describe the behavior of *dynamic system,* since it only records the instantaneous measured values.

   b. DMM also falls short in *Low Measurement Accuracy* due to its lower sampling frequency and limited resolution than that of the LabView Virtual Machine.

   c. DMM can also cause loading effect, since its input resistance can lead to lower recording values.

E2.3 Using the Analog to Digital Converter in the Signal Chain

1. Record the ADC output corresponding to the light intensity in the current room, and provide a screenshot:



Answer:
The ADC output is 2169.

2. Convert that value to voltage value (please show detailed derivations).

Answer:

- ***Step 1: 12-bits signed value to 11-bits unsigned value***

$$2169(Decimal) = 1000\ 0111\ 1001(Binary)$$

If we remove the MSB, then we have the number in 11 bits as following.

$$000\ 0111\ 1001(Binary)$$

- ***Step 2: Convert the 11-bits unsigned number to decimal value***

$$000\ 0111\ 1001(Binary)$$
$$= 1 \times 2^6 + 1 \times 2^5 + 1 \times 2^4 + 1 \times 2^3 + 0 \times 2^2 + 0 \times 2^1 + 1 \times 2^0$$
$$= 121\ (Decimal)$$

- ***Step 3: Apply formula***

From the given information, we know that

$$x = \frac{Decimal\ number * 5}{2047}$$

Where x stands for the corresponding voltage.

Since

$$Decimal\ number = 121$$

Thus, we have

$$x = \frac{121 * 5}{2047} = 0.295\ V$$

- ***Step 4: Conclusions***

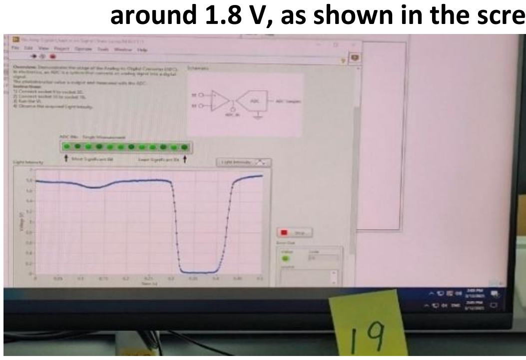
Finally, the converted equivalent voltage value is 0.295V, which shows the same value as the *Scaled Data in the screenshot*.

E2.4 Advantage of Amplifying a Signal

1. Describe how well you are able to see small changes in light intensity? For example, what is the difference in the measurement between ambient light and the measurement with the phototransistor covered? Provide screenshots.

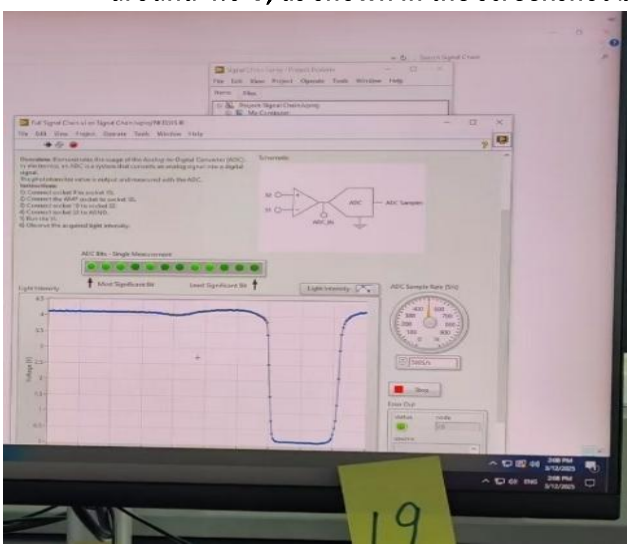
Answer:

- **I am able to observe slight changes in light intensity by *quickly passing my hand over the sensor, leading to a brief block and return of light.***
- **The difference between ambient light and the covered light measured in voltage is around 1.8 V, as shown in the screenshot below.**



Please note that the date shown in the picture differs from my scheduled lab date. I redid E2.4 task on March 12, 2025, with proper registration at the IR112 office for clarity and accuracy. Additionally, the seating positions during the two sessions differed in terms of distance from the window and overhead lights, resulting in variations in light intensity. As a result, the data obtained in this session may have some numerical differences compared to the previous measurements.

2. Repeat the above experiment but this time include the Non-Inverting Amplifier in the signal chain using the same wiring you did earlier, in the first experiment. Provide screenshots. Now how well are you able to see small changes in light intensity? What is the difference in the measurement between ambient light and the sensor being covered?
   Answer:
   - **This time, I introduced a non-inverting amplifier as did in E2.1.**
   - **I am able to observe slight changes in light intensity by *quickly passing my hand over the sensor, leading to a brief block and return of light.***
   - **The difference between ambient light and the covered light measured in voltage is around 4.0 V, as shown in the screenshot below.**



3. In your own words describe the impact the amplifier had on the signal acquisition.
   Answer:

To discuss the impacts of amplifier on the signal conditioning, we need to consider both the benefits and the weakness of it.

※ **Case 1: Pros**
   - ***Lower Noise disruption:***
     Compared to these two experiments, it is obvious that introducing the amplifier effectively reduces the noise level, resulting in less output ripple effects.
   - ***Difference Amplification:***
     Although the images in the E2.1 section show a significant difference between the maximum and minimum values, the actual voltage variation is only about 1.8V, which

is relatively small. However, with the amplifier, this range expands to approximately 4V at full brightness—twice as large as without amplification.

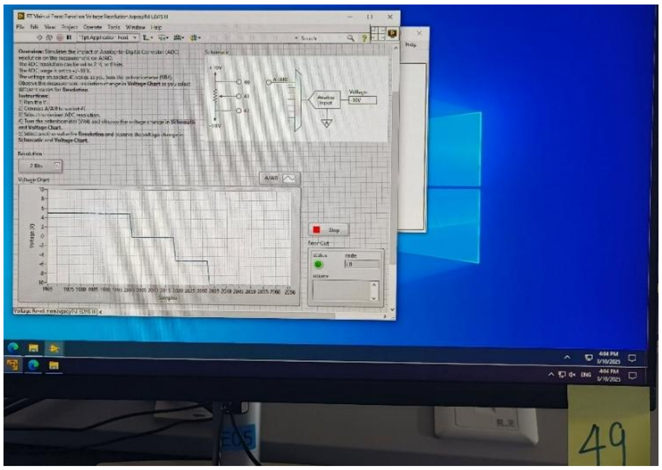
- *Accuracy & Sensitivity:*
  The amplifier can amplify and sense the small signals to make it capturable by instruments.

※ **Case 2: Cons**

- *Non-linearity:*
  The amplifier can bring about some non-linearity distortions.
- *Inherent Error:*
  The amplifier's gain may potentially push the magnified results beyond its calibrated operating range, causing clipping and limiting the output value.

E2.5 The Impact of Resolution on Reading a Signal

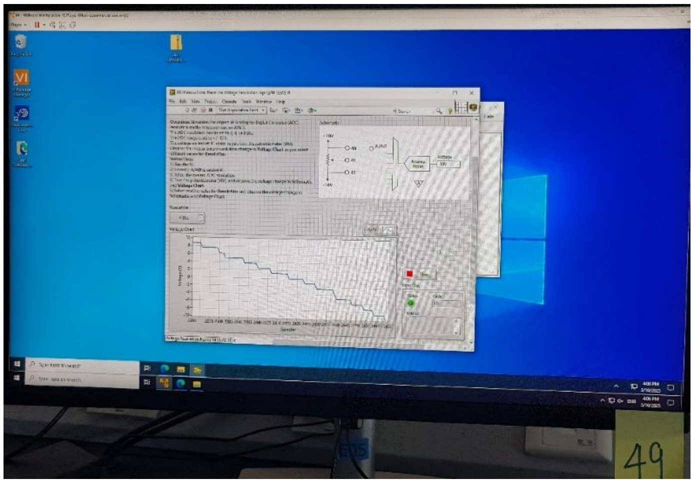
1. Set the resolution to 2 bits. Turn the potentiometer wiper up and down slowly. What is the minimum change in voltage captured by the chart or Voltage Box in the schematic? Provide a screenshot.
   Answer:



2. List all the possible voltage readings that can be done at 2-bit resolution:
   Answer:
   The results range from 5, 0, -5 to -10, with 5 volts as one step.
   The unit step value can be verified by the formula that

$$\frac{\mathbf{5-(-10)}}{\mathbf{2^2-1}} = \mathbf{5}\boldsymbol{v}$$

3. Change the resolution to 4 bits. What is the minimum amount of voltage change that can be captured by the chart or the Voltage Box in the Diagram? Provide a screenshot.
   Answer:

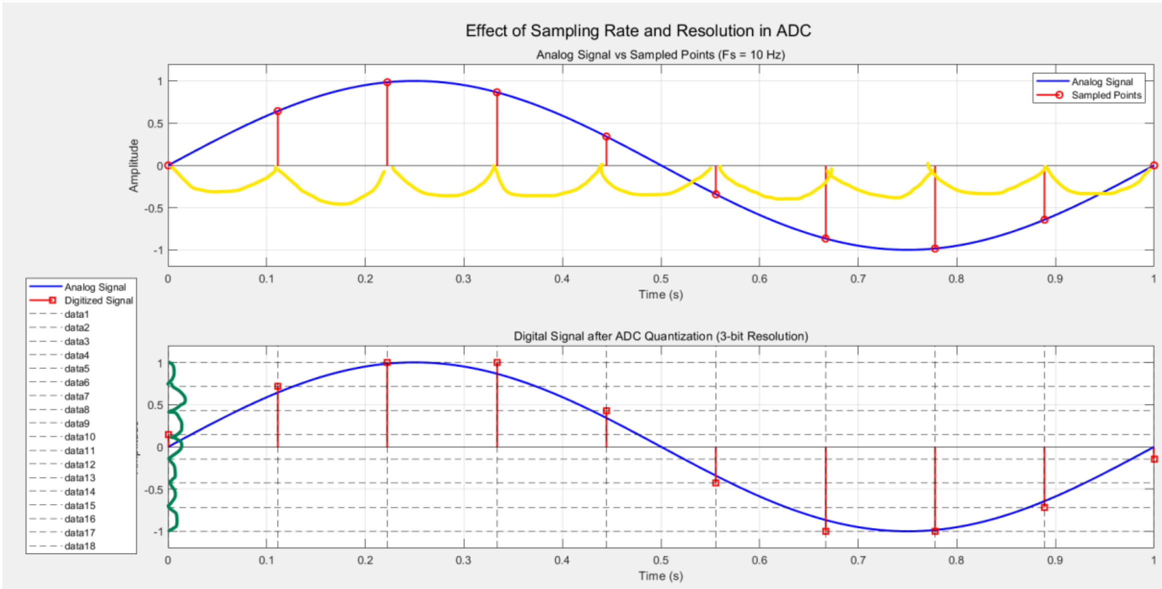


4. What is the total number of voltage readings that can be done at 4-bit resolution?
   Answer:
   The results range from
   8.75,7.5,6.25,5.0,3.75,2.5,1.25,0.0, −1.25, −2.5, −3.75, −5.0, −6.25, −7.5, −8.75 to −10, with 1.25 volts as one step.
   The unit step value can be verified by the formula that
$$\frac{8.75-(-10)}{2^4-1}=1.25v$$

5. In your own words, describe how a change in resolution under a fixed range impacts the analog to digital conversion.
   Answer:
   a. **The construction of digital signal is considered be of higher quality if the modified signal resembles the original analogue signal in a larger degree.**
   b. **The higher resolution, the denser the data points locate on the graph, capturing more information from the analog signal and leading to more accurate ADC conversion.**
   c. **However, higher resolution may also increase conversion time and require more processing power, which could be a trade-off in time-sensitive applications.**

Conclusion

1. Indicate whether each of the following is true or false. [T/F]
   a. The higher the resolution in bits the larger the resolution in volt. **T**
   b. The higher the sampling rate the more accurate your digital representation of an analog signal. **T**
2. In your own words, describe resolution and sampling rate of an ADC.
   Answer:
   The relation of resolution and sampling rate in ADC can be interpreted in the following diagram plotted in MATLAB.



a. **Resolution is defined as the minimum measurable value of a signal, and this concept focuses on the *__accuracy of the value__* *shown in green on y axis of the figure*.**
b. **Sampling Rate is defined as the minimum collecting period of the signal, and this concept focuses on the *__accuracy of the time__*, *shown in yellow on x axis of the figure*. The appropriate sampling rate must satisfy the *Nyquist-Shannon Sampling Theorem*, which states that the sampling frequency should be at least twice the highest frequency component of the signal to prevent waveform aliasing.**
c. **Maintaining both high resolution and high sampling rate enhances ADC performances.**

Experiment 3: Temperature and Strain Measurement

E3.1 Temperature Measurement with a Thermocouple

1. Observe the change in the sensor reading when touching the glass bead at the end of the wire.
2. Write down the sensor reading before and while touching the thermocouple with your hand. Provide screenshots.

Answer:

- **Case 1: Without touching**

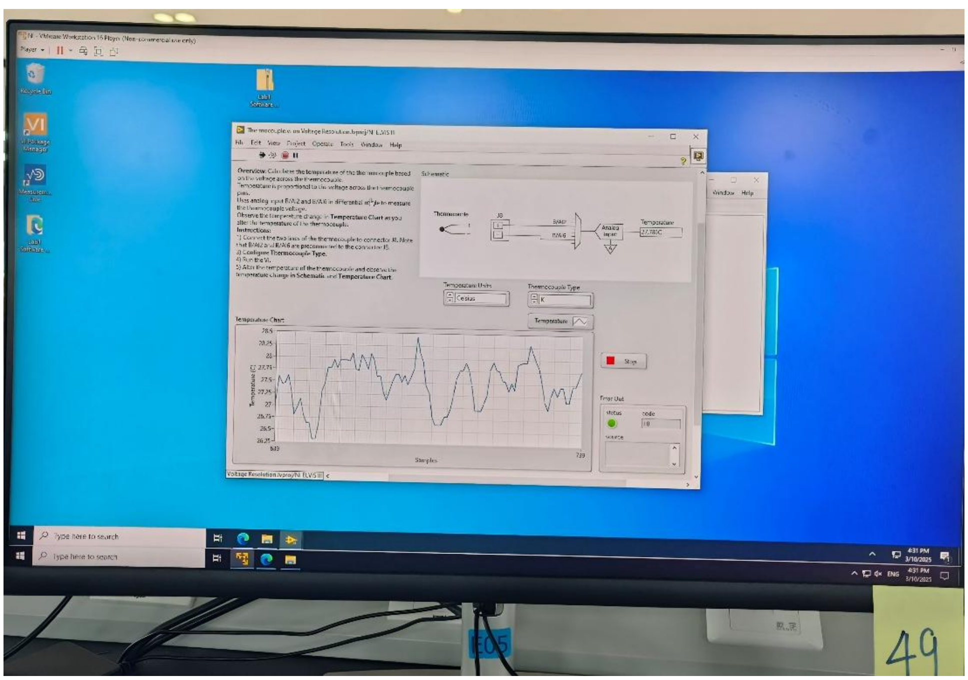
The sensor reads the temperature of the surrounding about 27.35℃.

- **Case 2: After touching**

The sensor reads the temperature of the surrounding about 38℃.

3. How long does it take for the sensor reading to stabilize after touching it?
   Answer:
   It takes the sensor 4.21s to stabilize after touching it.

4. Write down the sensor noise level at room temperature. Provide a screenshot. How much change in temperature does the noise cause?
   Answer:



To analyze the noise level, we should analyze from three dimensions, which are range, mean and standard deviation. To get these two parameters, we should collect a data set. For example, I collected 20 points distributed on the curve, and write a C code to find the corresponding Range and Standard deviation of the data sample.

- **Code Format**

```c
#include <stdio.h>
#include <math.h>
#define SIZE 20
// Function to calculate mean
double calculate_mean(double data[], int size) {
    double sum = 0.0;
    for (int i = 0; i < size; i++) {
        sum += data[i];
    }
    return sum / size;
}

// Function to calculate standard deviation
double calculate_standard_deviation(double data[], int size, double mean) {
    double sum = 0.0;
    for (int i = 0; i < size; i++) {
        sum += pow(data[i] - mean, 2);
    }
    return sqrt(sum / size); // Population standard deviation
}

// Function to calculate range (max - min)
double calculate_range(double data[], int size) {
    double min_value = data[0];
    double max_value = data[0];
    for (int i = 1; i < size; i++) {
        if (data[i] < min_value) {
            min_value = data[i];
        }
        if (data[i] > max_value) {
            max_value = data[i];
        }
    }
    return max_value - min_value;
}

int main() {
    double data[SIZE] = {
        27.87580645, 28.5, 27.68709677, 27.15, 28.5, 27.26612903, 27.9193548
        26.78709677, 26.74354839, 26.75806452, 26.8, 28.13709677, 28.0790322
        27.89032258, 26.65, 27.84677419, 26.3, 28.29677419
    };
    double mean = calculate_mean(data, SIZE);
    double std_dev = calculate_standard_deviation(data, SIZE, mean);
    double range = calculate_range(data, SIZE);
    printf("Mean: %.6f\n", mean);
    printf("Standard Deviation: %.6f\n", std_dev);
    printf("Range: %.6f\n", range);
    return 0;
}
```

- **Mean & Range & Standard Deviation**

```
Mean: 27.560000
Standard Deviation: 0.667943
Range: 2.200000

D:\C_Language\ABC\x64\Debug\ABC.exe (进程 22368)已退出，代码为 0。
要在调试停止时自动关闭控制台，请启用“工具”->“选项”->“调试”->“调试停止时自动关闭控制台”。
按任意键关闭此窗口. . .
```

The sensor noise level at room temperature is reflected by the standard deviation (0.6679°C), indicating typical fluctuations around the mean. The range (2.2°C) shows the maximum temperature variation due to noise. This suggests that temperature readings can fluctuate by approximately ±0.67°C around the mean, with occasional peaks reaching up to ±1.1°C.

5. What filter would you use to reduce the noise but not affect the signal due to real temperature changes? Explain why.

Answer:

I would choose Low-Pass Filter (LPF), especially RC.

Reasons:

- **Noise signals are often high frequency components, so we have to eliminate them by LPF.**
- **The temperature signals measured in volts are low-frequency components, and we have to keep them.**

E3.2 Temperature Measurement with an RTD

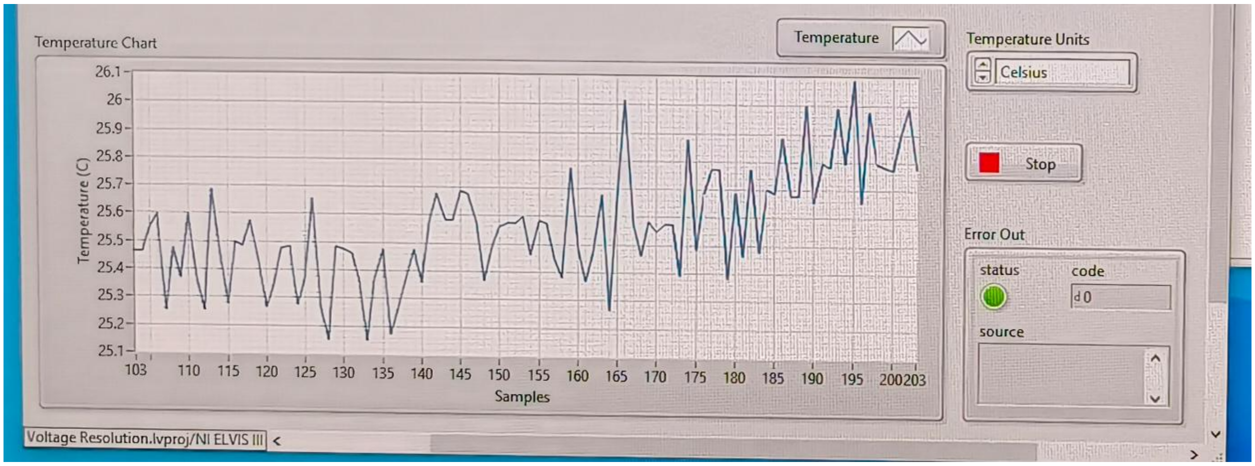
1. Observe the change in the sensor reading when touching the glass bead at the end of the wire.

2. Write down the sensor reading before and while touching the RTD with you hand. Provide a screenshot.

Answer:

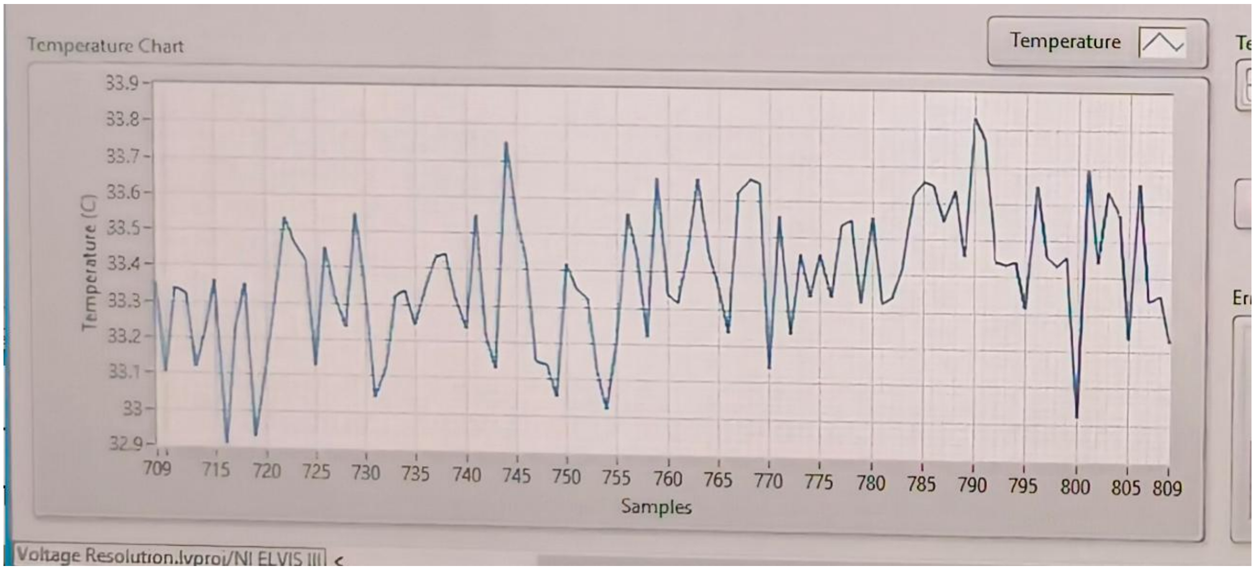
✧ **Case 1: Without touching**

The sensor reads the temperature of the surrounding about 25.6℃.



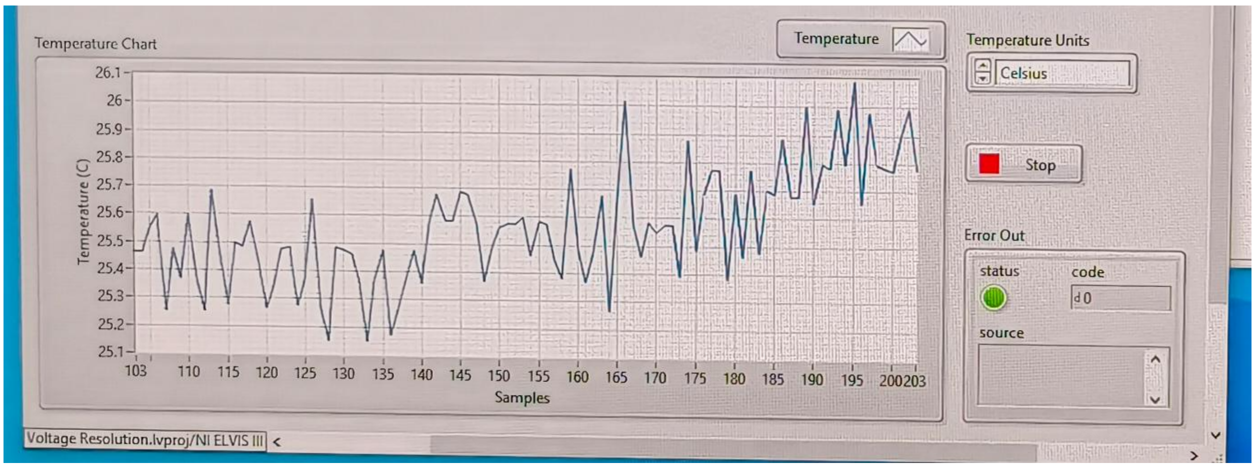
✧ **Case 2: After touching**

The sensor reads the temperature of the surrounding about 33.4℃.



3. How long does it take for the sensor reading to stabilize after touching it? Is this sensor slower or faster in its reaction to a temperature change compared to the thermocouple in the previous experiment?
   Answer:
   It takes about 5.15s for the sensors to stabilize after touching it.
   RTD has a higher sensitivity and reacts faster than the thermocouple.

4. Write down the sensor noise level at room temperature. Provide a screenshot. How much change in temperature does the noise cause?
   Answer:



<u>Due to methodological continuity with previous studies, the code implementation and procedural details are omitted here for brevity, with emphasis placed solely on the presentation of results.</u>

- **Mean & Range & Standard Deviation**

```
Mean: 25.589819
Standard Deviation: 0.422803
Range: 0.997738

D:\C_Language\ABC\x64\Debug\ABC.exe (进程 23360)已退出，代码为 0。
要在调试停止时自动关闭控制台，请启用"工具"->"选项"->"调试"->"调试停止时自动关闭控制台"。
按任意键关闭此窗口. . .
```

The sensor noise level at room temperature is reflected by the standard deviation (0.4228°C), representing typical fluctuations around the mean. The range (0.9977°C) indicates the maximum variation due to noise. This suggests that temperature readings can fluctuate by approximately ±0.42°C around the mean, with occasional peaks reaching up to ±0.5°C.

5. How does this noise level compare to the thermocouple?
   Answer:
   RTD introduces a lower noise level compared to the thermocouple.

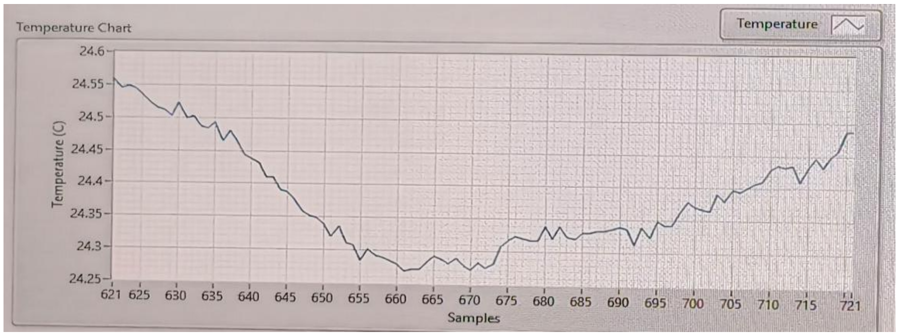
E3.3 Temperature Measurement with a Thermistor

1. Write down the sensor reading before and while touching the thermistor with your hand. Provide screenshots.

   Answer:

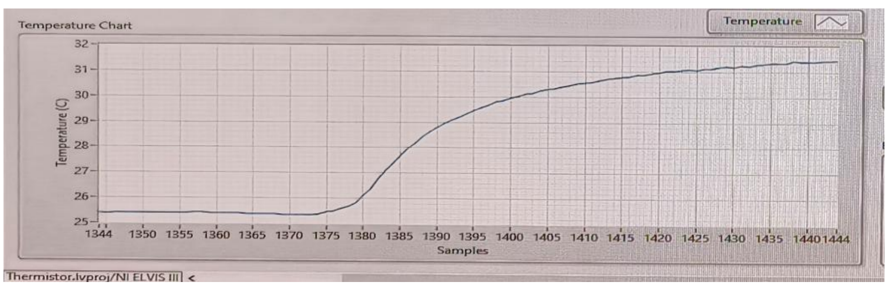
   ✧ **Case 1: Without touching**

   The sensor reads the temperature of the surrounding about 24.35℃.



   ✧ **Case 2: After touching**

   The sensor reads the temperature of the surrounding about 31.40℃.



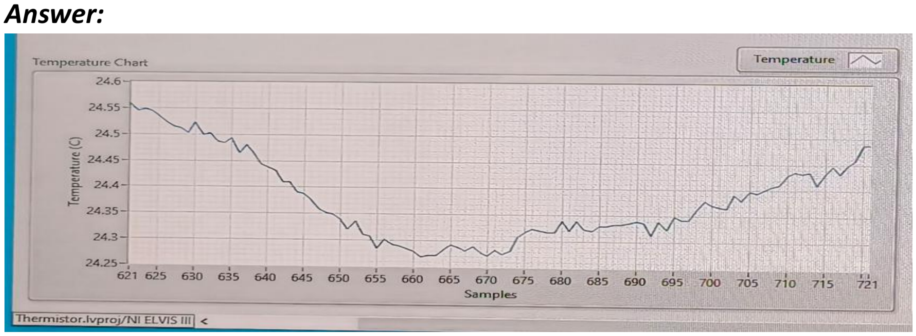
2. How long does it take for the sensor reading to stabilize when touching it?

   Answer:

   It takes about 4.86s for the sensors to stabilize after touching it.

3. Write down the sensor noise level at room temperature. Provide screenshots. How much change in temperature does the noise cause?

   Answer:



<u>Due to methodological continuity with previous studies, the code implementation and procedural details are omitted here for brevity, with emphasis placed solely on the presentation of results.</u>

- **Mean & Range & Standard Deviation**

```
Mean: 24.421470
Standard Deviation: 0.097962
Range: 0.332102

D:\C_Language\ABC\x64\Debug\ABC.exe (进程 18696)已退出，代码为 0。
要在调试停止时自动关闭控制台，请启用"工具"->"选项"->"调试"->"调试停止时自动关闭控制台"。
按任意键关闭此窗口. . .|
```

The sensor noise level at room temperature is represented by the standard deviation (0.09796°C), indicating minimal fluctuations. The range (0.3321°C) shows the maximum variation due to noise. This suggests that temperature readings typically vary by ±0.098°C around the mean, with occasional peaks reaching up to ±0.166°C.

4. How does this noise level compare to the thermocouple and RTD?
   Answer:
   The thermistor has the lowest noise level compared to the thermocouple and RTD. Its standard deviation (0.09796°C) is significantly smaller than that of the RTD (0.4228°C) and thermocouple (0.6679°C), indicating more stable readings. Additionally, its range (0.3321°C) is much smaller than the RTD (0.9977°C) and thermocouple (2.2°C), meaning less variation in measurements.

Conclusion

1. Which of the three temperature sensors was most affected by noise? How much of a swing in temperature did this cause? How could you overcome this noise?
   Answer:
   The thermocouple is mostly affected by noise.
   Thermocouple causes a swing in temperature in the lab surrounding to change from 26.3℃ to 28.4℃ (27.35℃±1.05℃).
   There are *three main ways* to overcome this noise.

- **Use a Low-Pass Filter to filter the high-frequency AC noise.**
- **Use a combination of instrumentation amplifier and non-inverting amplifier *<u>as displayed in E2.1</u>* to amplify the signal while suppressing noise.**
- **Apply differential measurement (*Taught in EEE211*) instead of single-ended measurement to reduce noise effects.**

2. Which of the sensors reached the peak temperature fastest, when touching it? What would this mean for a real-world measurement system?
   Answer:
   <u>Thermocouple</u> reached the peak temperature fastest after touching it. It means that thermistors can be applied to engineering that demands fast response. As taught in the lecture slides, we have learnt the concept of *Cogeneration*, and there is a component called furnace which utilizes thermocouple. For example, in industrial furnaces used for metal processing,

thermocouples are employed to monitor furnace temperatures during melting, annealing, and heat treatment processes. Accurate temperature monitoring equipment like thermocouple ensures that metals achieve the desired properties and quality.

3. In your own words, describe the difference in construction, connection, and behavior between the three sensors.
   Answer:

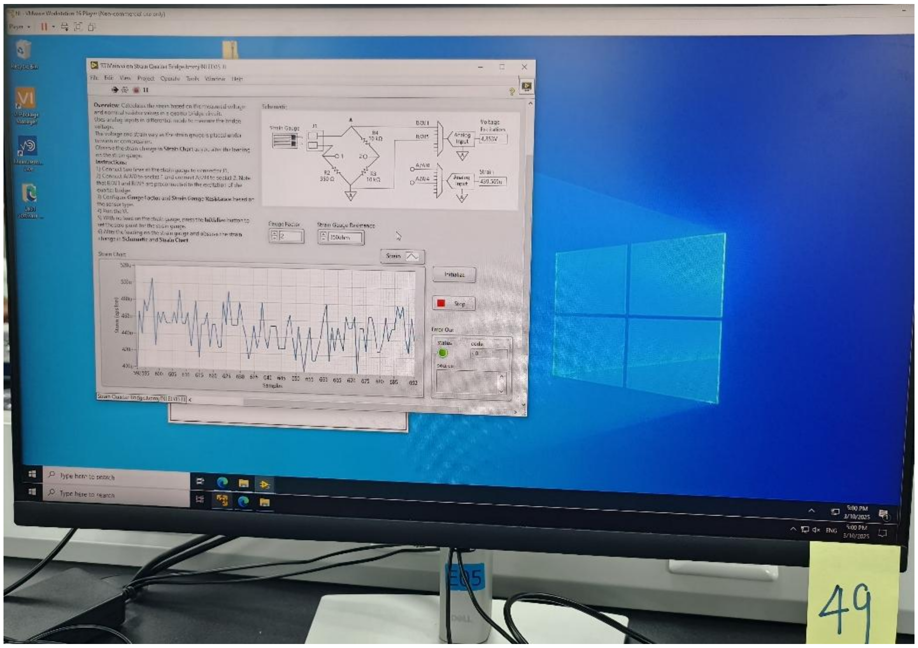
Comparison	construction	connection	behavior
Thermocouple	1. Made by two different types of metal, connected together by a junction. 2. A temperature-related potential occurs at the junction. 3. Thermoelectric effect.	2 wires connecting	Higher temperature measurement range Cold junction compensation Enduring Industry high temperature measuring
RTD	1. Mainly made by Platinum	2 wires connecting Or 3-4 wires connecting	$RT = R0(1 + \alpha T)$ Linearity only in a finite temperature range Mid sensitivity Higher long-term stability Higher cost (Pt-detectors) Higher accuracy Lab measuring
Thermistor	1. Made by Semiconductor	2 wires connecting	R $\propto$ +T (PTC) or R $\propto$ -T (NTC) Non-linearity High sensitivity Lower long-term stability Used as thermal switch

E3.4 Strain Measurement with Quarter Bridge

1. Observe the change in the sensor reading when carefully flexing the sensor.

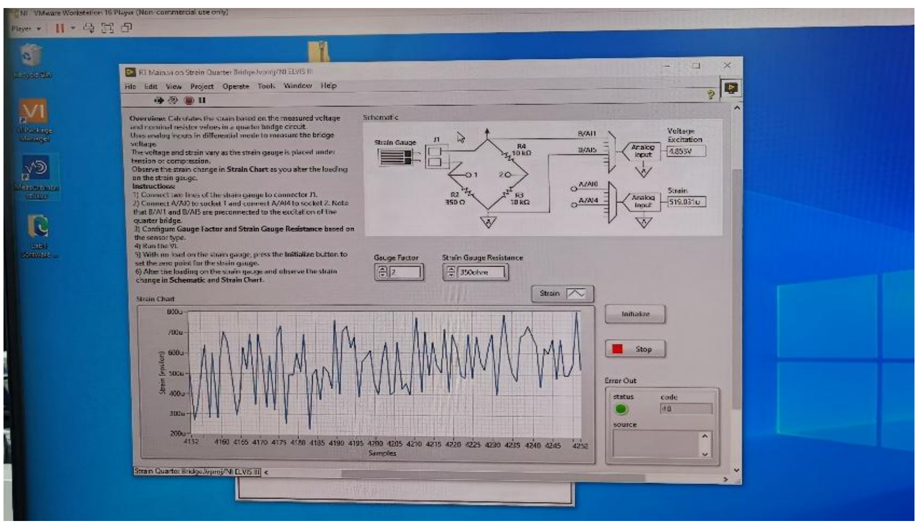
2. Write down the sensor reading before and while flexing the metal foil gauge with your hand. Provide screenshots.
   Answer:
   - **Case 1: Without bending**

   The sensor reads the strain about 460μ.



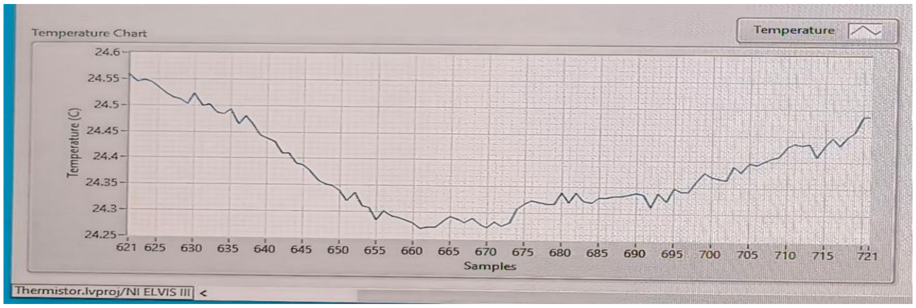
✧ **Case 2: After bending**

The sensor reads the strain about 519μ.



3. How long does it take for the sensor reading to take affect? Compare this to the RTD temperature sensor in the previous lab.
   Answer:
   It takes about 4.07s for the sensors to stabilize after touching it.
   Strain Gauge has a higher sensitivity and reacts faster than the RTD.

4. Write down the sensor noise level? What filter would you use to reduce the noise?
   Answer:
   Let us analyze the sensor noise level under the case that the strain gauge is not bent. Similar to analysis in previous cases, I will also collect 20 points on the curve and calculate the mean, standard deviation and range to demonstrate.



<u>Due to methodological continuity with previous studies, the code implementation and procedural details are omitted here for brevity, with emphasis placed solely on the presentation of results.</u>

- **Mean & Range & Standard Deviation**

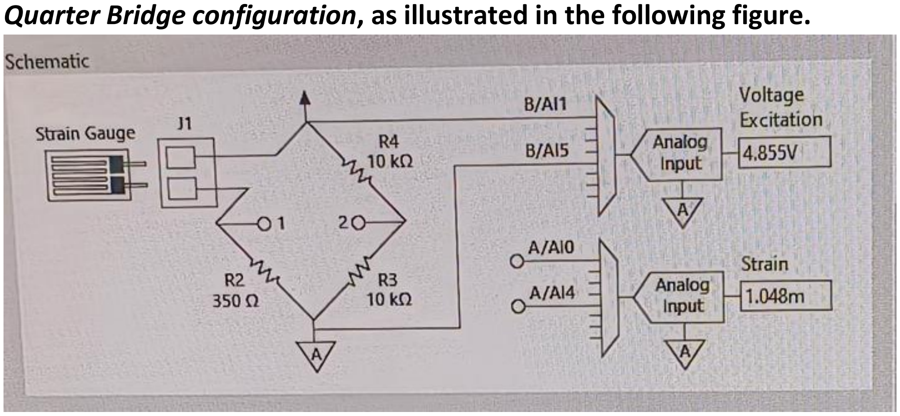
```
Mean: 450.556213
Standard Deviation: 31.520829
Range: 100.828402

D:\C_Language\ABC\x64\Debug\ABC.exe (进程 2500)已退出，代码为 0。
要在调试停止时自动关闭控制台，请启用“工具”->“选项”->“调试”->“调试停止时自动关闭控制台”。
按任意键关闭此窗口. . .
```

The sensor noise level at room temperature is reflected by the standard deviation (31.52 με), indicating significant fluctuations around the mean. The range (100.83 με) represents the maximum variation due to noise. This suggests that strain readings typically vary by ±31.52 με around the mean, with occasional peaks reaching up to ±50.41 με.

5. Use the breadboard of the Automated Measurements Board and add some extra wires in between the strain gauge and the J1 connector (i.e. make the connection path between the strain gauge and the J1 connector go through at least 1 extra wire per lead). How does the additional lead wire affect the sensor reading when no strain is applied? How does it affect the measurement when applying strain?

Answer:

Based on the circuit diagram provided in the Lab Manual, our circuit can be classified as a *Quarter Bridge configuration*, as illustrated in the following figure.

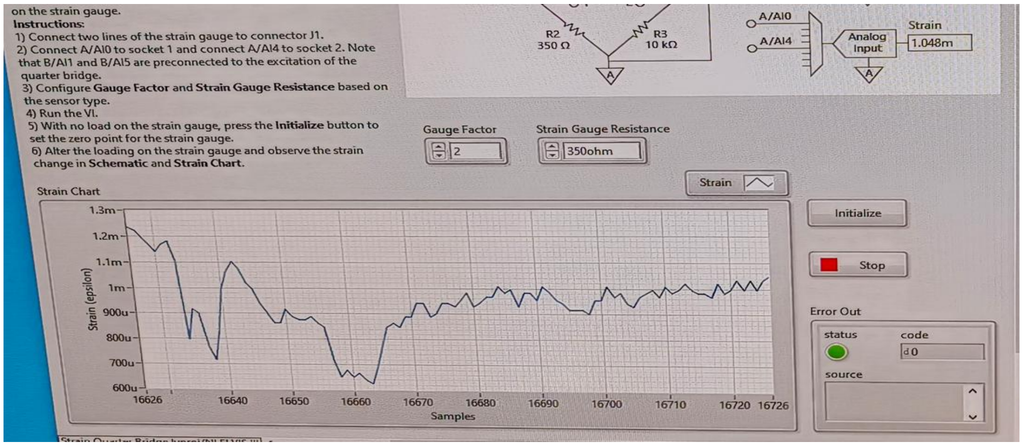


To analyze this problem, we consider two scenarios: without an additional wire and with an additional wire.

- **Case 1: Without an Additional Wire**

✧ **Measurement Values**

Without adding an extra wire to the breadboard, the measured strain value is approximately 1.048m.



✧ **Electric Bridge**

Initially, we do not apply strain manually, then the electric bridge is balanced, and we assume that the resistance of Strain Gauge $J1$ is $R1$, that means:

$$\frac{R1}{R2} = \frac{R3}{R4}$$

✧ **Output Voltage**

Then, after introducing the strain, the resistance of $R1$ has been changed to $R1 * (1 + G\varepsilon)$, thus the output voltage will be:

$$Vout\_I = Vs * [\frac{\mathrm{R1} * (1 + \mathrm{G}\varepsilon)}{\mathrm{R1} * (1 + \mathrm{G}\varepsilon) + \mathrm{R2}} - \frac{1}{2}]$$

With mild assumption, $R1 = R2 = R3 = R4$.

Then, we have:

$$Vout\_I = Vs * [\frac{(1 + \mathrm{G}\varepsilon)}{(1 + \mathrm{G}\varepsilon) + 1} - \frac{1}{2}] \approx Vs * \frac{\mathrm{G}\varepsilon}{4}$$

✧ **Sensitivity**

We know that sensitivity is defined as the slope of the output characteristics. Thus, in this experiment, we have:

$$Sensitivity = \frac{\Delta\varepsilon}{\Delta \mathrm{t}}$$

From the lecture, we know that:

$$\varepsilon = \frac{\Delta \mathrm{R}/\mathrm{R}}{\mathrm{G}}$$

Where

R stands for the resistance of the strain gauge.

G stands for the Gauge Factor of the strain gauge.

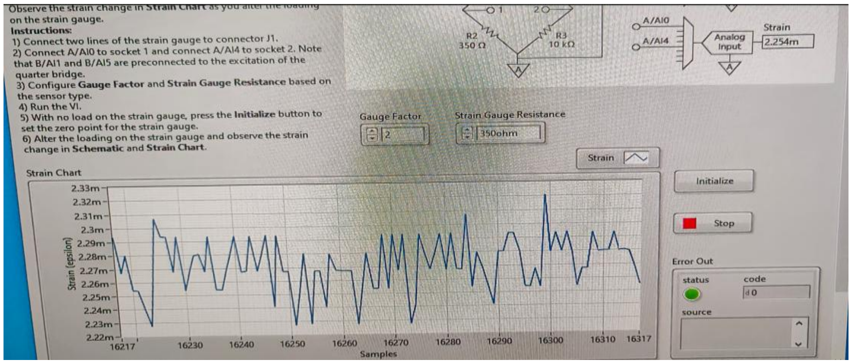
Thus, we have:

$$Sensitivity = \frac{\Delta\varepsilon}{\Delta \mathrm{t}} = \frac{\Delta \mathrm{R}}{R * \mathrm{G} * \Delta \mathrm{t}}$$

- **Case 2: With an additional wire**

✧ **Measurement Values**

Without introducing a wire to the breadboard, our measured strain value is around 2.054m.



- ✧ **Electric Bridge**

At the beginning, before applying any strain manually, the bridge is unbalanced because the extra wire adds resistance (r) to the strain gauge. Thus, we assume the resistance of J1 is $R1 + r$, that means:

$$\frac{R1 + r}{R2} \neq \frac{R3}{R4}$$

- ✧ **Output Voltage**

Then, after introducing the strain, the resistance of R1 becomes $(R1 + r) * (1 + G\varepsilon)$, thus the output voltage will be:

$$Vout\_II = Vs * [\frac{(\mathrm{R1} + \mathrm{r}) * (1 + \mathrm{G}\varepsilon)}{(\mathrm{R1} + \mathrm{r}) * (1 + \mathrm{G}\varepsilon) + \mathrm{R2}} - \frac{1}{2}]$$

With mild assumption, $R1 = R2 = R3 = R4$.
Then, we have:

$$Vout\_II = Vs * [\frac{(1 + \mathrm{G}\varepsilon)}{(1 + \mathrm{G}\varepsilon) + \frac{R2}{R1 + r}} - \frac{1}{2}]$$

Compared to $Vout\_I$ shown in Case 1, the denominator becomes smaller, since

$$\frac{R2}{R1 + r} < 1$$

which leads to an increase (*Positive Shift/Offset Voltage*) in the total $Vout$.

- ✧ **Sensitivity**

However, when an additional wire is introduced, the sensitivity is affected and can be expressed as:

$$Sensitivity = \frac{\Delta\varepsilon}{\Delta \mathrm{t}} = \frac{\Delta \mathrm{R}}{(\mathrm{R} + \mathrm{r}) * \mathrm{G} * \Delta \mathrm{t}}$$

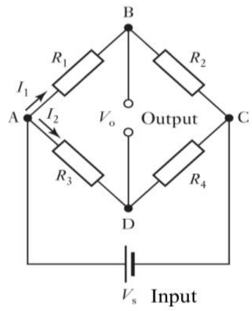
Hence, the presence of an additional wire reduces the overall sensitivity.

Conclusion

1. In your own words, describe the impact of using a bridge to perform a resistance measurement. What are the differences between bridge types and their uses?

- ***Answer for Bridge Circuits Impacts:***

  A bridge circuit (Wheatstone Bridge) provides both advantages and disadvantages to measurements as well.



- Pros
  - ✧ **Measurement Correction**
    A way of eliminating the temperature effect to use a Wheatstone Bridge, correcting the thermo-electric potential by compensation circuit.
  - ✧ **Signal Conversion**
    The Wheatstone bridge can be used to convert a resistance change to a voltage change
  - ✧ **High Sensitivity**
    The bridge circuit can detect very small changes in resistance.

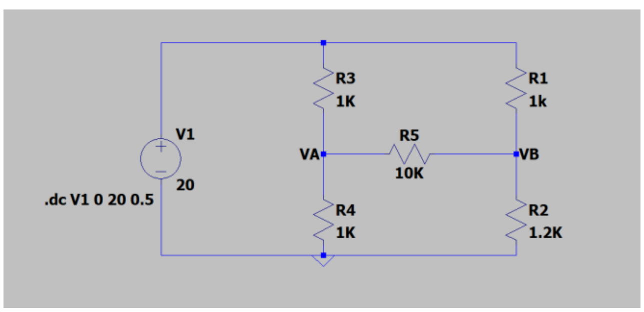
- Cons
  - ✧ **Loading Effect**
    Ideally, when $R2$ is a sensor experiencing a resistance change δR, the Wheatstone Bridge becomes unbalanced, and the output voltage is determined solely by the bridge parameters (resistances), and an output voltage variation is:

$$\delta Vo \approx Vs * \frac{\delta R}{R1 + R2}$$

However, when a load resistor (R_5) is introduced at the output terminal, it affects the output voltage, making δVo no longer only subject to bridge inner parameters ($R1, R2, R3, R4$), and creating a *Positive Shift/Offset* to the output voltage.

To further demonstrate my findings, I performed *LTSpice* simulations under different load resistance values, assuming $R2' = 1.2K\Omega$, while $R1 = R3 = R4 = 1K\Omega$, and $R5$ is a resistor with unfixed values。

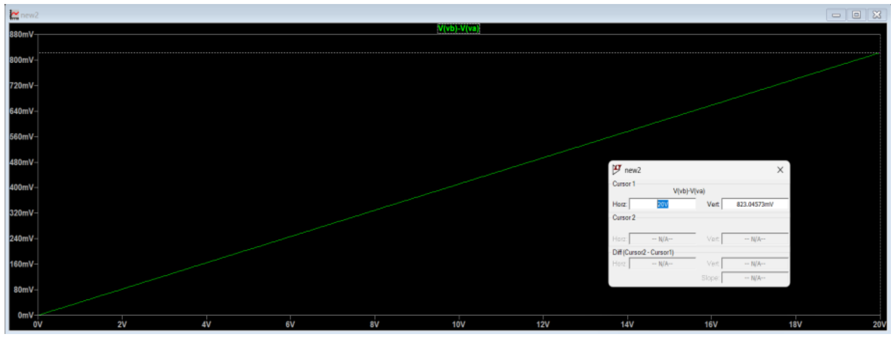
➢ **Circuit schematic**



Since I set the source voltage at 20V, therefore, what I would like to observe and compare is the $Vout$ under 20V.

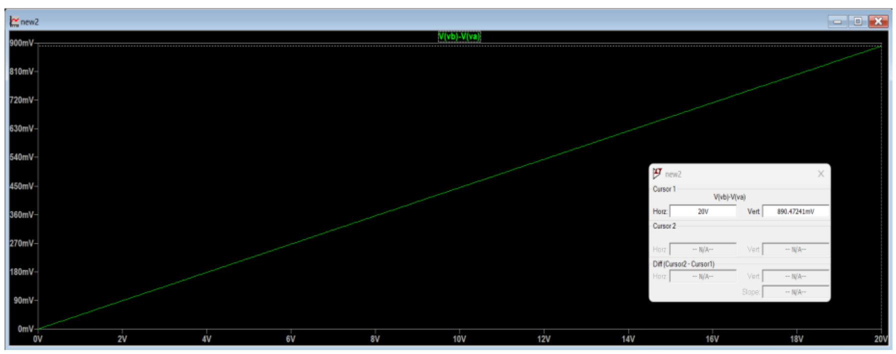
<u>Due to methodological continuity, the circuit schematic and procedural details are omitted in the following 4 cases for brevity, with emphasis placed solely on the presentation of results.</u>

➢ **Case 1: $R5 = 10k\Omega$**



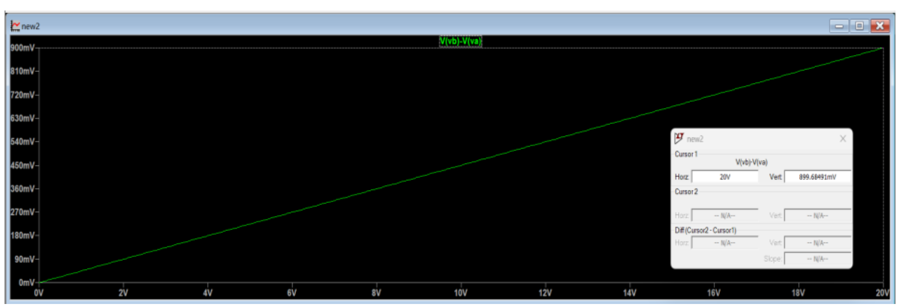
Measured output voltage: $Vout = VB - VA = 823mV$.

➢ **Case 2: $R5 = 50k\Omega$**



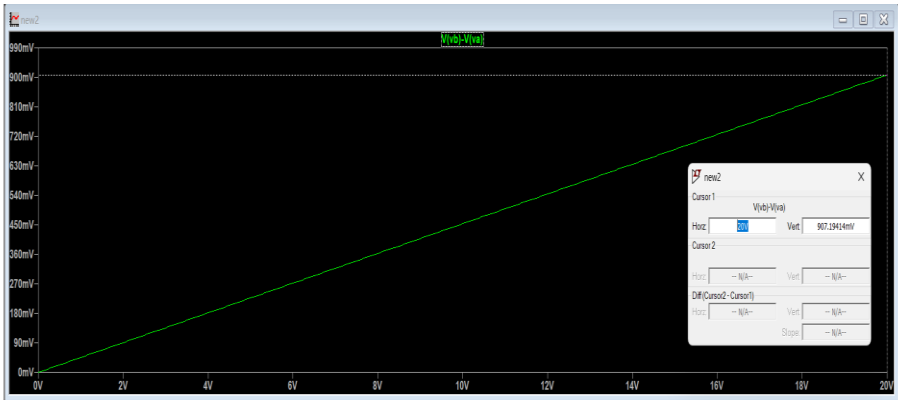
Measured output voltage: $Vout = VB - VA = 890mV$.

➢ **Case 3: $R5 = 100k\Omega$**



Measured output voltage: $Vout = VB - VA = 899mV$.

➢ **Case 4: $R5 = 500k\Omega$**



Measured output voltage: $Vout = VB - VA = 907mV$.

- **Key Observations**

➢ **Rate of Change in $Vout$**

Initially, a small increase in $R5$ results in a significant increment in $Vout$, but when $R5$ increases beyond $100k\Omega$, its impact diminishes, suggesting a gradual approach to an ideal case.

➢ **Comparison to Ideal Case**

Ideally, the output voltage variation is derived as:

$$\delta Vo \approx Vs * \frac{\delta R}{R1 + R2}$$

However, when $R5$ is low, δVo increases significantly. Based on our simulation, for $R5 \geq 100k\Omega$, δVo becomes negligible, making it a practical design choice.

- **Brief Summary & Potential Solutions**

The simulation results clearly demonstrate the loading effect in a Wheatstone Bridge circuit. A load resistor introduces an extra current draw at the output node, altering the expected voltage division across the bridge resistances. In real-world applications, minimizing the loading effect is crucial for accurate measurements. To mitigate the errors, using a high $R5$ $(\geq 100k\Omega)$ ensures the bridge output remains accurate.

✧ **Initial Offset Voltage**

The bridge will produce a small nonzero voltage even when no strain or temperature change is applied due to manufacturing techniques. Effective methods including software compensation, offset-nulling circuits, and buffered offset nulling help minimize initial offset voltage.

- ***Answer for Bridge Circuits Types and Differences:***

  There are three main methods using bridge circuits to perform resistance measurement.

  ➢ **Case 1: Single active gauge plus one 'dummy' gauge bridge**
    - **1 active & 1 dummy for compensation**
    - $Vout = Vs * G * \epsilon * 0.25$
    - **Used in scenarios with low requirement of measurement accuracy, since the factor 0.25 is still too small to catch slightly-changed signals.**

- Also used in static or lower frequency applications
- Highest SNR
- Medium Sensitivity for Temperature, since 1 dummy gauge offers temperature compensation.

➢ **Case 2: Two active gauges and two 'dummy' gauges bridge**
- 2 active & 2 dummy for compensation
- $Vout = Vs * G * \epsilon * 0.5$
- Used in scenarios with moderate requirement of measurement accuracy, since the factor 0.5 is still small to catch slightly-changed signals.
- Medium SNR
- Lowest Sensitivity for Temperature, since 2 dummy gauges offer temperature compensation.

➢ **Case 3: Four active gauges bridge**
- 4 active & 0 dummy for compensation
- $Vout = Vs * G * \epsilon * 1$
- Used in scenarios with moderate requirement of measurement accuracy, since the factor 0.5 is still small to catch slightly-changed signals.
- Lowest SNR
- Highest Sensitivity for Temperature, since no dummy gauges provide temperature compensation.

2. In general, how did the strain gauge compare in performance to the temperature sensors in the previous lab? (consider signal-to-noise ratio and response time of the sensors). How would this affect how the sensors are implemented in real-world systems?

Answer:

- **Parameters Comparisons**

Instruments \ Comparisons	SNR	Response Time
Thermocouple	Lowest	Shortest or Second Shortest
RTD	Medium	Longest
Thermistor	Second Highest	Medium
Strain Gauge	Highest	Shortest or Second Shortest

Notes:

- ***Although the Strain Gauge shows the highest standard deviation, this results from its larger absolute measurement values and wider range. In fact, its Signal-to-Noise Ratio (SNR) is the highest among the four sensors.***
- ***Response Time ≠ Stabilization Time: Response time typically refers to the time needed to reach 90% of the final value, while stabilization time refers to when the reading becomes steady. Therefore, their rankings may differ slightly.***
- ***We conducted three measurements for both the thermocouple and the strain gauge. In one case, the strain gauge had a shorter response time, while in the other two, the thermocouple responded faster. Therefore, we cannot conclusively determine which one is consistently faster.***

- **Effects**

- **SNR**

Signal to Noise Ratio (SNR) is defined as:

$$SNR = \frac{p_{signal}}{p_{noise}}$$

The formula suggests the higher SNR, the better effect the sensor performs in noise cancelling.

From the analysis, the Strain Gauge exhibits the highest SNR, indicating it has a better capability of reducing noise. Such trait makes Strain Gauges competitive and high-demanding for the industry. For instance, strain gauges are used to detect slight deformations in structural health monitoring of bridges and aircraft. Its applications in infrastructure and Aeronautical Engineering significantly guarantees the safety of the commuting of the ordinary.

Moreover, other three sensors also have wide applications in our life. RTDs, with their high SNR, ensure precise and stable temperature measurements in medical and industrial settings, while thermistors balance SNR and sensitivity for household appliances, and thermocouples, despite their low SNR, are widely used in high-temperature environments like furnaces and engines due to their durability.

- **Response Time**

In addition, the strain gauge also exhibits the quickest response time among our measurement, and as such, is appropriate for applications where rapid detection of physical changes is needed. One common example is electronic weighing scales, which utilize strain gauges for detecting small deformations and providing real-time weight output.

Furthermore, the thermocouple also reacted promptly in two out of three trials, with equal performance. It is also commonly used in kitchen ovens, where it reacts promptly to changes and helps regulate heat cycles for effective and even cooking.

And for the remaining sensors, RTDs are commonly employed in medical thermometers for accurate body temperatures, and thermistors are used for stable and effective temperature control in air conditioners and fridges.

3. Discuss factors that would influence your strain measurement, and how to overcome them.
   Answer:
   - **Factor 1: Instrument Aging Effect (*System Error*)**
     Some strain gauges have been in use for many years, leading to reduced sensitivity to physical bending. To solve this problem, students can fetch a new one from the lab office.
   - **Factor 2: Operating Error (*System Error*)**
     Students may bend the wrong position on the strain gauge rather than the gauge itself, or apply too little force to make the gauge readings change. To address this issue, students should improve their experiment methods. They need to look pinpoint the accurate location of the gauge and apply appropriate force to bend it and observe the changes.

- **Factor 3: Electromagnetic Interference (*Random Error*)**
  Strain gauge readings may fluctuate due to surrounding electromagnetic noise, especially if the sensor wires are not properly shielded or are placed near power equipment. To minimize this issue, use twisted-pair shielded cables, keep the wires away from high-power devices, and implement proper grounding in the circuit.

Discussions and Conclusions of the whole experiment

(Discuss your observations/findings, different sensor characteristics, influencing factors, possible solutions etc.; conclude the measurement system; summarize what you have learned from this lab)

Answer:

This lab session provides a deep insight into the Instrumentation, successfully answering the basic principles of temperature sensors and signal conditioning. It also provides a comprehensive understanding of the essential components of a measurement system, including sensors, signal conditioning, ADC conversion, and data processing, all of which are crucial for ensuring accurate and reliable measurements.

From E1.1 to E1.3, I come to understand that signals can be modulated and measured by DMM, and find the position of amplifier in the breadboard.

In E2.1 to E2.5, I first compared ADC with DMM, finding that ADC performs better than DMM in dynamic measuring environment. I also explored the ADC process, understanding the roles of sampling and resolution, and distinguishing the differences between them. Finally, I discovered that the measurement accuracy can be improved by using an amplifier.

In E3.1 to E3.4, I understand the difference of the four instruments in temperature sensing by comparing response time and Signal-to-Noise Ratio (SNR). By comparing the parameters, Strain Gauge performs the best among all four sensors, while other three sensors have their own usages. This helped me understand how to select the appropriate sensor based on different industrial requirements.

Moreover, I encountered several measurement errors during the lab. For instance, I had to replace the strain gauge four times due to quality issues and operational errors. Additionally, when I was measuring room temperature by thermocouple, it initially showed 33℃, which was inaccurate. However, after reconnecting the wires and tightening the screws, I finally measured the correct temperature of around 25℃.

In summary, this lab not only practices our hands-on ability, but also fosters team work spirit. Since students were randomly assigned into groups of two, most were unfamiliar with their lab partners. This required team members to break the ice and cooperate effectively—for example, one student could take photos while the other adjusted the wiring setup—to maximize efficiency and successfully complete the experiments.