ME 103 Experimentation and Measurements

Lab 0 - Data Collection and Uncertainty

BEFORE YOU START THIS LAB: Before beginning this lab, ensure you have submitted your **group signup form** found on Ed and the course website.

Introduction and Objectives

The purpose of this lab is for you to familiarize yourself with the lab equipment, their limitations, and how to quantify these limitations. Almost all modern measurements are taken with electronic equipment,which often takes the form of a voltage from a transducer which must then be converted into a quantity of interest. Successfully completing Lab 0 means that you are comfortable with the data acquisition (DAQ) and other lab equipment, basic circuitry, and uncertainty calculations.

Lab Objectives:

- Get hands-on experience with research quality signal generation and DAQ equipment
- Familiarize yourself with a simple LabVIEW Virtual Instrument (VI)
- Understand measurement uncertainty. Uncertainty analysis and quantification will be necessary throughout the semester, so make sure to learn this material in practice

Equipment

All equipment will be provided in the lab, which include:

- DC power supply
- DG1022 Analog waveform generator
- DDM3058 Digital multimeter
- DS1102E Oscilloscope
- National Instruments USB-6211 DAQ Extension
- Breadboard
- Coaxial cables
- Banana plugs
- Resistors of various values

Datasheets/manuals for these pieces of measurement equipment are provided in bCourses under Files > Datasheets and Manuals. They can also be found on the course website under resources! Click here

Deliverables

It is to *your benefit* to look at the questions *in advance* to know what you are measuring and why. With your group follow the steps below to complete the lab. You **must** typeset your answers in LaTeX(We recommend using Overleaf, but you can also edit locally if you prefer). Upload a single pdf file to Gradescope per team. Everyone should be contributing equally and writing on the document equally.

The lab is due 1 minute before your next lab section. For example, if you have lab on Monday at 8:00 AM, it is due the following Monday at 7:59 AM.

1 DC Measurements and Uncertainty

First, let's explore the measurement process and uncertainties of the DC power supply and digital multimeter. We will do so by constructing a simple circuit using the DC power supply and a randomly assigned $2200\,\Omega$ resistor, and then taking measurements using the digital multimeter.

1. **Preliminary Measurements:**
    - Make note of the temperature, humidity, and (atmospheric pressure if able). This is located on the left of the board as you enter Hesse 122.
    - *Reminder* to check the conditions after you have finished the lab and make note.
2. **Multimeter and DC Power Supply Setup for Voltage Measurement:**
    - Turn on the digital multimeter and insert banana plugs into appropriate inputs to measure voltage (check meter labels). Ensure the multimeter is set to measure **DC voltage**.
    - You can adjust the measurement range using the **Range+** and **Range-** buttons to suit the expected voltage.
    - Using the digital multimeter, short your wires and note the **bias error** for **voltage** (*Hint*: the expected value of the shorted value should be `0V`).

> **Bias Error** Bias (B) refers to deviations that are not due to chance alone. The simplest example occurs with a measuring device that is improperly calibrated so that it consistently overestimates (or underestimates) the measurements by X units.
>
> **Precision Error** Precision (P) refers to the repeatability of a measurement. It does not require knowledge of the true value, but rather measures how close repeated measurements are to each other.
>
> **Uncertainty**: A measure of the *expected error* in measurement that combines both the systematic and random errors. For a sample x, if B represents an estimate of bias (systematic) errors and P represents an estimate of precision (random) errors, then the uncertainty U is estimated as
>
> $$U_x = \sqrt{B_x^2 + P_x^2}$$

    - While keeping the wires shorted, note the **precision error** (*Hint: half of the smallest fluctuating digit depending on your resolution, this is* 1σ *by convention, we want* 3σ*. What should we do?*).
    - Turn on the DC power supply (large power button on left) and ensure that the current limit for both channels is set to 0 A. *We do this for safety and to ensure that we do not damage any electrical equipment.*
        - Use the knobs to adjust the voltage and current limits.
    - Set the voltage limit for channel 1 to 5.0 V but do not press the green on/off button yet (this button turns the output of the power supply on and off).
    - Use banana plugs to connect channel 1 of the power supply across a 100Ω resistor. Use Ohm's law and the setting of the power supply to predict the theoretical values for the current through the resistor and the power dissipated by the resistor.
    - Turn the power supply on. You should notice that the voltage immediately drops to 0 V. This is because the current limit is still set to 0 A, thus allowing no current to pass through the resistor.
    - Slowly increase the current limit until it reaches the theoretical value you calculated in above. You should notice that as current is allowed to flow through the resistor, the voltage across the resistor increases to the desired voltage you set previously (5.0 V).

  - **NOTE**: because we are simply dissipating power from the resistor, it may become hot to the touch after some time. We recommend that when not taking measurements, you turn the output of the power supply off or set the current limit to 0 A.

- With the digital multimeter and the power supply on, take measurements of the voltage across the resistor. **Make sure it agrees roughly with the power supply**. Why might it not be exact?
- Now, turn off the output of your power supply before reconfiguring the circuit to the one shown in **Figure 1** on your breadboard. Remember to set the current limit back to 0 A.
- Connect the power supply in a voltage divider configuration with a sense resistor of $R_2 = 15\Omega$, and a load resistor $R_1 = 2200\,\Omega$. (*Hint: look at the color bands to determine the resistance and confirm it with measurements*)

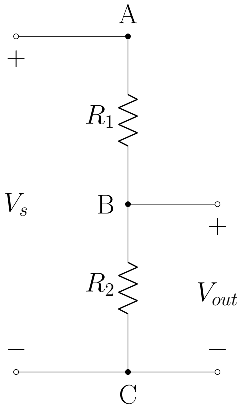


Figure 1: Voltage Divider Circuit Diagram 1. V_{bat} represents the +/− terminals of the 5V power supply, while V_{out} represents the +/− terminals of the digital multimeter. The resistor may become hot. When not measuring, disconnect the power supply.

- With the power supply connected, take **ten voltage measurements** of the **power supply** itself. Note: Press the "Single" button to take a single measurement sample instead of viewing a live measurement.
- Keeping the power supply connected, take **ten voltage measurements** across R_2. Note: Press the "Single" button to take a single measurement sample instead of viewing a live measurement.

> **Warning**: Turn off the output of your power supply before reconfiguring both the digital multimeter and your circuit to measure current. Remember to never measure current in parallel! This may cause a short circuit. Only measure current in series.

- Reconfigure your circuit to match the one below. Using this newly configured circuit, measure the **ten current measurements**. Make note of the **bias error** and **precision error** for **current**.

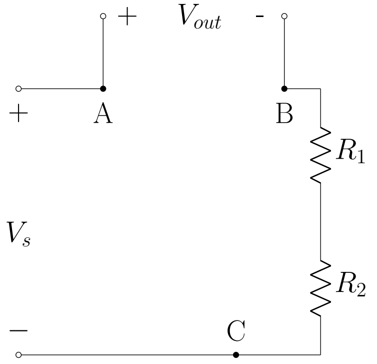


Figure 2: Circuit Diagram for Current Measurement

3. **Calculation Check**: Using the following voltage divider equation below, calculate the expected voltage V_{out}. Does your calculated result have the same order of magnitude compared to your measured values? How about the current?

$$V_{out} = \frac{R_2}{R_1 + R_2} V_s$$

Resolution is defined as the smallest change a measurement system can detect. Notice that the digital multimeter specifies a resolution of $5\frac{1}{2}$ digits. The "half digit" of resolution means that the first (most significant) digit can only be a 0 or 1. Because of the existence of resolution in a measurement system (the last digit may be rounded, truncated, or something else), the measurement is accurate to within $\pm\frac{1}{2}\times$ resolution, often called the resolution uncertainty.

2 AC Measurements and Uncertainty

In this part of the lab, we will explore the measurement process and uncertainties associated with the analog waveform generator and the oscilloscope. We will do so by constructing a voltage divider circuit and measuring alternating current through the voltage divider.

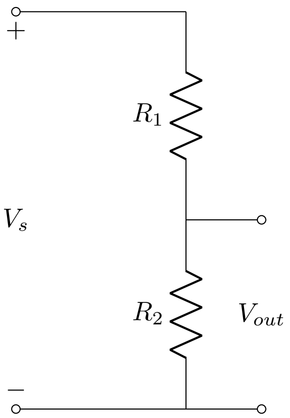


Figure 3: Voltage Divider Circuit Diagram 2. V_{bat} represents the +/− terminals of the waveform generator, while V_{out} represents the +/− terminals of the oscilloscope.

- Refer to the **Figure 3**. Suppose you want to build a voltage divider with voltage ratio $\frac{V_{\text{out}}}{V_{\text{in}}} = \frac{1}{11}$ using $R_1 = 1k\Omega$. Determine the correct choice of R_2 and then ask the lab GSI for the correct resistor value.
- Physically construct the voltage divider you designed in step 1 on the white breadboard.
- Configure the analog waveform generator:
  - Set channel 1 to produce a 50 Hz sinusoidal waveform
  - Set peak-to-peak voltage $V_{\text{pp}} = 4$ V
  - Ensure the waveform type is sine wave to simulate alternating current.
- Connect the waveform generator to your circuit:
  - Turn on the oscilloscope. Use channel 1 of the oscilloscope to probe V_{out}.
  - You may need to adjust the horizontal and vertical scales to more easily see the signals.
  - If the oscilloscope doesn't appear to be in sync with your signal, set the Trigger mode to slope.
- Now we are going to measure the peak-to-peak voltage using the cursor measurement function:
  - Press "Cursor" in the oscilloscope menu. Rotate the knob to manualm, and press it in to confirm. Position Cursor A at the positive peak of the channel 1 waveform.
  - Position Cursor B at the negative peak of the same waveform.
  - Record the ΔY measurement displayed in the top right corner.
  - Capture a screenshot or photograph of the oscilloscope display showing the cursors and measurement.
  - Repeat these steps for Channel 2 of the oscilloscope, which you will use to probe V_{in}, however, use "Measure" in the oscilloscope menu, select voltage, and scroll to verify V_{pp}.
  - You have now learned two ways to verify the peak-to-peak voltage of a measured waveform.

- In the “TRIGGER” section of the oscilloscope, go to MENU and set the Mode to Edge. Then under Slope change the trigger detection from ”Rising Edge” to ”Falling Edge” (upward or downard pointing arrow, respectively). Note how the waveform display shifts.

3 Exploring LabView

In this part of this lab, you will explore the quantization effect while also familiarizing yourself with the LabVIEW software. We will measure **voltage** using the DAQ, with current obtained through calculations.

Our setup is now essentially the same as it was in Part 1 i.e. , except that we are instead using the DAQ as our measurement device instead of the our digital multimeter. You will be using the 2200Ω and 15Ω for R_1 and R_2 respectively. You will be putting $V_s = 5V$ across the circuit from the power supply like before. The benefit is that using the DAQ in combination with LabVIEW allows for customizable data collection, data visualization, and data storage/file exports.

Quantization Effect
When you run the VI, you should see that the power supply voltage and output voltages displayed on the graph. Zoom in significantly to the signals until you can see small steps between distinct voltage levels (this might take several zooms).

The effect you are seeing is known as the **quantization effect** (or discretization effect). When an analog signal (like a voltage) is converted into a digital signal (for computer processing), quantization always occurs because the digital device has a finite number of bits. The resulting step size is called resolution and can be calculated as

$$\text{Resolution}_{DAQ} = \frac{span}{2^N}$$

where the span is the range of values a system can measure and N is the number of bits (bit depth).

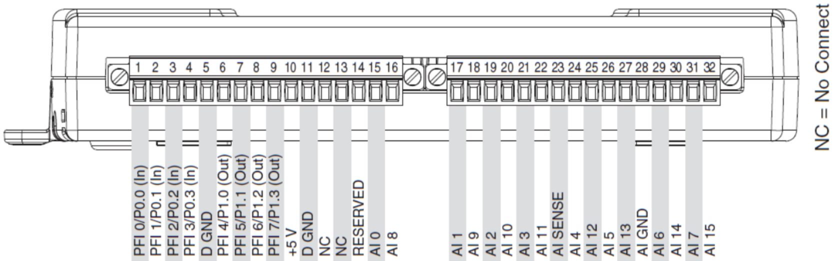


Figure 4: USB-6211 pinout

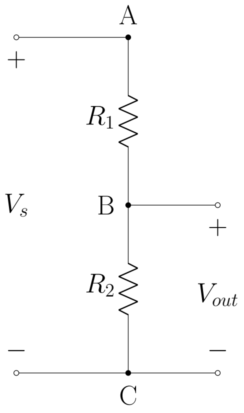


Figure 5: Voltage Divider Circuit Diagram for the DAQ.

1. **Set up the DAQ for voltage measurement:**
    - Connect the common ground (Node C) to analog input ground (`AI GND`) channel (refer to the USB-6211 pinout, which can be found in the manual on bCourses and above).
    - Connect a wire from node A to the `AI 1` (Analog Input 1) channel on the DAQ. This will measure the input voltage from the power supply.
    - Node B should be connected to the `AI 2` input channel, and is used to measure the output voltage.
    - Turn on the power supply set to 5V through the circuit, slowly increasing the current until the voltage reaches 5.0 (this is a sensitive adjustment, going too far will fry your circuit).
    - Open the `ME103 LAB0 0 SP26.vi` on the desktop in LabVIEW, and press the "Run" arrow in the top left corner.
    - record/screenshot the voltage measurement readings displayed in LabVIEW.
2. **Save and analyze data:**
    - Export all recorded voltage measurement data, including the following zero calibration data, as a CSV file from LabVIEW.

      Note: To save the voltage measurement data, right click on the LabVIEW graph. Go to `Export > Export Data to Excel`, and rename/save the file in a secure place.

      While it is possible to save files on to the cloud. It is *recommended* to bring a flashdrive to each lab, in the event that the internet connection is unstable. These computers are quite old.
3. **Zero-Offset calibration:**
    - Disconnect the circuit voltage source and connect the `AI1` to `AI GND` input channel on the DAQ.
    - Measure and record several voltage readings around zero volts.

4 Questions

Section 1 Questions

1. With the digital multimeter, you measured the bias error and precision error at your specific range. Using this, what is the uncertainty of the voltage for your very first measurement.

   SOLUTION: Looking at the oscilloscope, the steady state error is going to be the difference between the shorted wires which we get as 0.009`mV`. As for the precision error, for digital instruments, the "precision error" is usually taken as ±1/2 of the least significant digit at the chosen range. In other words, it is $\frac{1}{2}$ of the smallest number at that specific range (in our case the range is 200`mV`), our last digit fluctuates between 0.008`mV` and 0.009`mV`, so the range is 0.001`mV`, and half of that is ±0.0005`mV`, which is our precision error.

   We can then calculate uncertainty as follows

   $$u_v = \sqrt{B_v^2 + P_v^2} = \sqrt{0.009^2 + 0.0005^2} = \pm 0.009\texttt{V}$$

2. Predict the theoretical values for the current through the R_2 and the power dissipated by the resistor. You may or may not find the following equation helpful

   $$V_{out} = \frac{R_2}{R_1 + R_2} V_s, \quad V = IR$$

   SOLUTION: Starting with the voltage divider equation, the voltage across R_2 can be written as

   $$V_{R_2} = \frac{R_2}{R_1 + R_2} \cdot V_{in} = \frac{15}{2200 + 15} \cdot 5 = 0.034 \text{ V}$$

   The current through R_2 is then found through Ohm's law as

   $$I_{R_2} = \frac{V_{R_2}}{R_2} = \frac{0.034}{2215} = 0.0023 \text{ A}$$

   The power dissipated by the resistor is

   $$P_{R_2} = V_{R_2} I_{R_2} = 0.0000782\,\texttt{[W]}$$

3. Find the 95% confidence interval of the sample mean of the power supply voltage data (10 samples). *Hint: Would you use a normal distribution?*

   SOLUTION: Taking ten measurements of voltage across the power supply, we get:

   $$[4.9985, 4.9992, 5.0001, 5.0003, 5.0008, 5.0012, 5.0015, 5.0019, 5.0023, 5.0027]$$

   Since we only have $n =$ **10 samples** < 30, we need to use the t-distribution to find our critical value at a significance level $\alpha = 0.05$. Note the $DoF = n - 1 = 9$. The critical value from a t-table for a 2-tailed cdf is $t_{0.975,9} = 2.262$.

   To set up our confidence interval for the mean, we use $CI = \overline{x} \pm t_{1-\frac{\alpha}{2},n} \frac{s}{\sqrt{n}}$. To find the mean, we do

   $$\overline{x} = \frac{1}{n} \sum_{i=1}^{n} x_i = 5.00065$$

   The sample standard deviation can be calculated as

   $$s = \sqrt{\frac{\sum_i (x_i - \overline{x})^2}{n - 1}} = 0.001384$$

Then, the standard error of the mean can be found as

$$SE = \frac{s}{\sqrt{n}} = \frac{0.001384}{\sqrt{10}} = 0.0004375$$

Constructing the confidence interval now, we have

$$\overline{x} \pm t_{1-\frac{\alpha}{2},n-1} \frac{s}{\sqrt{n}} = 5.00065 \pm (2.262)(0.0004375) = 5.00065 \pm 0.000989$$

Taking into account the s.f., we should be keeping 5 since our data has 5 s.f. Therefore, we are 95% confident that the sample mean of the power supply voltage data is

$$\overline{x} = 5.0007 \pm 0.0010$$

4. Look at the measurements you took of the voltage. Why would they differ? Would this variation be categorized as systematic or precision uncertainty?

   SOLUTION: The measurements of voltage could potentially differ for a variety of reasons, including: fluctuations in environmental conditions (especially temperature); electrical noise in Hesse Hall maybe EMI; varying internal resistances in power supply and/or multimeter. These variations are categorized as precision uncertainty.

5. Why do we measure current in series? Why not parallel like voltage?

   SOLUTION: If we want to measure current, we want to find the current through a particular branch, in our case it is the current through R_2, which requires it to be in series. An ammeter has ideally 0 resistance so if we connected it in parallel with R_2, we will create a short allowing all the electrons to flow through the ammeter and not the resistor.

6. Calculate the mean voltage measurement and mean current measurement, and use those to calculate an estimate of the power dissipated by the resistor. If only this single calculated value of power dissipated is reported, what characteristic of your measurements would not be captured?

   SOLUTION: Let $\overline{V}_{R_2}$ and $\overline{I}_{R_2}$ be the sample means of the n voltage and current measurements across $R_2 = 15\ \Omega$. The power estimate is

$$\hat{P} = \frac{\overline{V}_{R_2}^2}{R_2} = \overline{V}_{R_2} \cdot \overline{I}_{R_2}.$$

   Reporting only $\hat{P}$ conveys the *point estimate* of expected power but fails to capture the *uncertainty* (spread/variability) in measurements.

Section 2 Questions

7. What is the ΔY for the peak to peak voltage of R_2 on the bitmap.

   SOLUTION:

$$Vin = 4Vpp$$

   (what we set the waveform generator to)

$$Vout(R2) = Vin\frac{R2}{R1+R2} = 4\frac{1k\Omega}{11k\Omega} \approx 0.72\ V_{pp}$$

   ΔY represents the voltage across $R2$:

$$\Delta Y_{R2} = 0.72\ V_{pp}$$

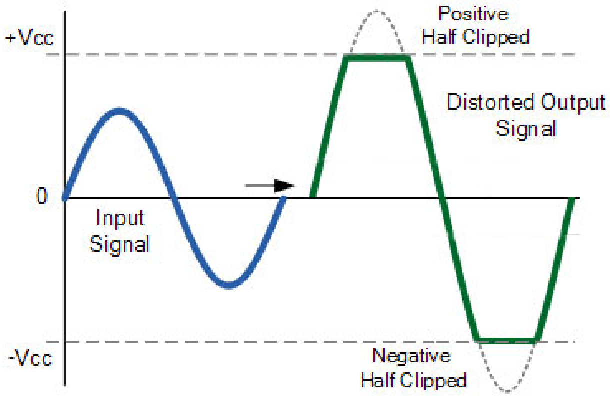
8. Does the ΔY measurement make sense based on the input from the waveform generator? Submit a bitmap.

   SOLUTION: Should depict a bitmap reporting a similar V_{pp} to the theoretical value calculated above.

9. Why might changing the trigger from "Rising Edge" to "Falling Edge" detection be beneficial?

   SOLUTION: Accept any attempt at an explanation since this question isn't very clear–changing the edge allows you to look at the features of a slower waveform ($< 5Hz$) much quicker than scrolling on the oscilliscope. Merely for convenience.

10. Suppose you are now sampling a signal using the maximum input range of the DAQ to measure a 30V peak-to-peak sinusoidal signal. Sketch what you think the measured voltage vs. time graph would look like.



   SOLUTION: Waveform will look clipped at ± 10 V on the negative and positive ends, with the actual waveform reaching ± 15 V.

11. Now suppose you attempt to use a voltage divider to fully capture the signal in question 10. How could you minimize the impact of the quantization effect on your measurement? In other words, how would you design your voltage divider so that the resolution is the smallest possible fraction of the amplitude of the signal?

   SOLUTION: To minimize quantization error relative to signal amplitude, maximize the *fraction of DAQ input range* used:

$$\text{Resolution fraction} = \frac{\text{Resolution}_{\text{DAQ}}}{\text{Signal Amplitude}} = \frac{\frac{\text{span}}{2^N}}{V_{\text{pp}}} = \frac{\text{span}}{V_{\text{pp}} \cdot 2^N}$$

   Design voltage divider with attenuation k such that:

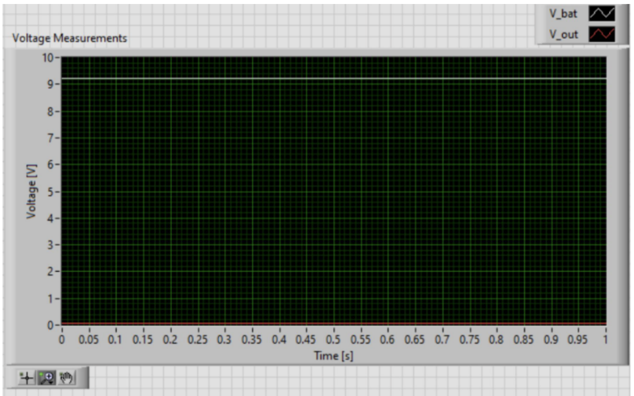
$$k \cdot 30\,\text{Vpp} = \pm 10\,\text{V} \quad \Rightarrow \quad k \approx \frac{1}{3}$$

   Any voltage divider that provides a 1/3 gain is acceptable.

Section 3 Questions

12. When you run the VI, you should see an uncalibrated Voltage vs. Time graph. Take a screenshot and submit this plot.

   SOLUTION: should be like photo below except at 5V instead of 9.



13. Refer to the datasheet for the NI USB-6211 DAQ Extension on bCourses. If the maximum input range is used, what is the resolution of the DAQ?

    SOLUTION: The maximum range of is 20`V` as the device lists ±10`V`, it has 16-bit resolution so resolution of the DAQ is

    $$Resolution_{DAQ} = \frac{20}{2^{16}} = 3.05 \times 10^{-4}\texttt{V}$$

14. List two general ways to improve resolution, i.e. decrease the numerical value of the resolution (hint: refer to the formula for quantization uncertainty).

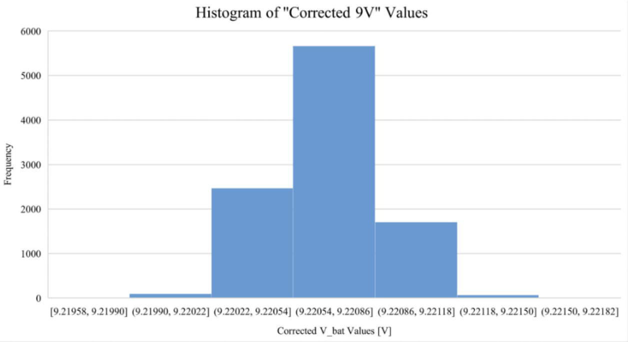
    SOLUTION: Just by observation, note that by increasing either the number of bits or decreasing the voltage span of the DAQ, we can improve the overall resolution.

15. Import your saved LabVIEW data into Excel. Create a column titled "Calibration" for your shorted circuit data, and a column titled "5V" for your data measured when the power supply is connected. What is the standard deviation of the calibrated data? Think: Would you use `STD.S` or `STD.P` in Excel? What's the difference?

    SOLUTION: We are using `STD.P` because we are dealing with a n > 30, allowing us to assume a Gaussian distribution.

16. Calculate the mean of the calibration data. Then subtract this mean from each measurement in the "5V" column to correct for the DAQ's zero-offset error. Present the result in a new column named "Corrected 5V". Use this to plot the distribution of your calibrated data. Does the data suggest that the Voltage is Gaussian? Do the bars represent the resolution of the DAQ?

    SOLUTION: should be like photo below except at 5V instead of 9. Half points for a x axis that does not have 5 s.f.



17. Find the 95% confidence interval of the population mean of the output voltage data.

    SOLUTION: From the empirical rule for Gaussian distributions, we know the critical z–value for a 95% confidence interval is $z^* = 1.96$, and

    $$CI = \mu \pm \left(z^* \cdot \frac{\sigma}{\sqrt{n}} \right).$$

    Based on μ, the average output voltage across R_2 and its standard deviation, σ, and $n = 10000$.

18. Is there a difference between DAQ and multimeter voltage and why?

    SOLUTION: Any comment on the additional noise with DAQ measurements vs. added noise filtering on the multimeter recieves full points.