ECE 110L Spring 2023

Laboratory 3:

Basic Electrical Measurements II and Ping))) Sensing

Contents

1 Abstract

In this laboratory exercise you will learn how to use a waveform generator, also known as a function generator, as a time varying voltage source and an oscilloscope to view and measure parameters of time varying voltages. You will learn different ways of categorizing time-varying signals. Once you are familiar with the particulars of these waveforms, you will implement a Ping sensor that uses ultrasonic waves to measure distance from the CX-Bot.

2 Objectives

After performing this laboratory exercise, students should be able to:

1. Use a waveform generator as a time-varying voltage source.
2. Use an oscilloscope and a multimeter to view and measure the parameters of a time-varying voltage waveform and understand what those parameters mean.
3. Build a 'bot that uses a Ping sensor to determine distance and moves to maintain a constant distance away from some object.

3 Background

A signal is a time-varying, measurable quantity. Examples of signals include temperature, light intensity, pressure, carbon dioxide concentration and sound intensity. Signals carry information. For example, consider a physician evaluating your health condition. What information would a physician use to make such an evaluation? It is likely that they would begin with measurements of four basic biological signals: body temperature, blood pressure, heart rate and respiration rate. The values of these (and other) signals provide information that allows the physician to assess your physical condition.

There are three primary laboratory instruments used to generate and measure time-varying signals. A **waveform generator** is used as a source of time-varying voltages. An **oscilloscope** is used to view time-varying voltages, and it may be able to measure various quantities related to those signals. A **multimeter** is also used to measure different quantities contained within time-varying voltages and currents.

Electronic sensors are devices that transform the measurement of a signal into an electrical signal. In this laboratory exercise you will explore the behavior and use of a **Ping Sensor**, which is capable of both generating and measuring signals. The Ping sensor detects objects by emitting a short, 40 kHz (ultrasonic) "trigger" pulse that travels through the air until it hits the nearest object and bounces back to the sensor. As you can imagine, the distance between the object and the sensor will determine how long it takes for this wave to return to the sensor, I.E. the width of the "echo" pulse. By measuring this aspect of the incoming waveform, the Ping sensor is able to accurately gauge the distances of nearby objects.

3.1 Waveform/Function Generator

Information about the specific waveform generator you are using is on the EGRWiki page at https://egrwiki.com/wiki/ECE_110/Equipment/Keysight_EDU33211A.

3.2 Oscilloscope

Information about the specific digital osccilloscope you are using is on the EGRWiki page at https://egrwiki.com/wiki/ECE_110/Equipment/Keysight_DSOX1202A.

3.3 Signal Characteristics

There are several signal characteristics that we can use to help quantify a signal. For periodic signals specifically, there is the period, frequency, amplitude, and phase. For time-varying signals generally, there can be maximum values, minimum values, peak-to-peak values (the difference between maximum and minimum), average values, and RMS or root mean squared values. For more information on the latter, see https://egrwiki.com/wiki/Root_Mean_Square.

3.4 Ping Sensor

Information about the specific ping sensor you are using is on the EGRWiki page at https://pundit.pratt.duke.edu/wiki/ECE_110/Equipment/Ping_Sensor.

4 Pre-Laboratory Exercises

1. **Understanding the implications of the waveform generator's internal resistance**
   Figure 1 shows two cases where the waveform generator is modeled as an ideal voltage source in series with an internal resistance. In both cases, the waveform generator or practical voltage source is demarcated with a dashed box around the instrument; the $50\ \Omega$ load is internal to the device and is therefore fixed. However, this important internal resistance will affect the voltage seen at the output of the device when there is and is not a load resistance at its output. You will need to use voltage division to determine the relationship between v_s and v_out. Also note that v_s is *not* the voltage displayed on the waveform generator! That voltage is the voltage that *should* appear at the output terminals of the device *if* there is a 50 Ω load across the terminals. v_s is always twice the value shown on the display.

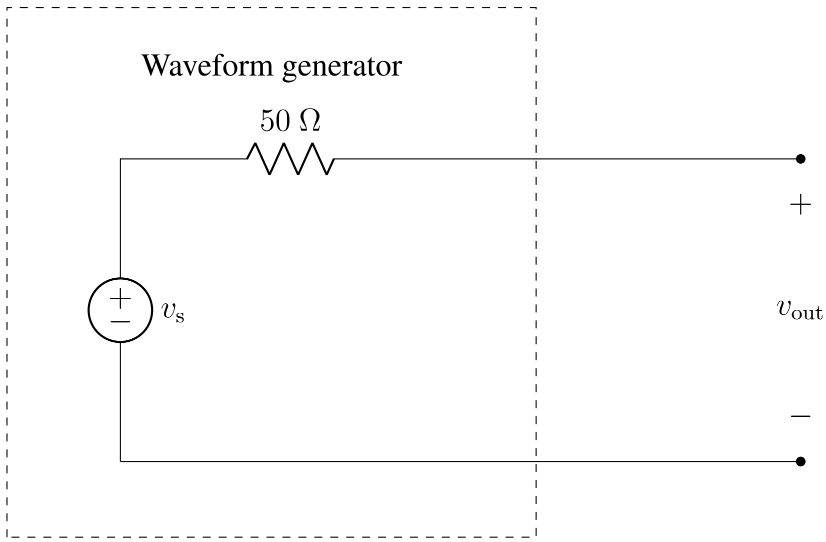
   Pre-lab Deliverable (1): Referring again to Figure 1, determine the 4 following voltages:

   (a) In Case 1, what is the peak-to-peak value of the practical internal source voltage of the waveform generator, v_s, when the value displayed on the waveform generator screen indicates that the waveform generator is set to deliver 4 volts peak-to-peak (4 $\mathrm{V_{p-p}}$)? Note that for a sinusoid, the peak-to-peak voltage is twice the amplitude, so this would indicate a desired signal of $2\ \cos(2\pi ft)$ V.

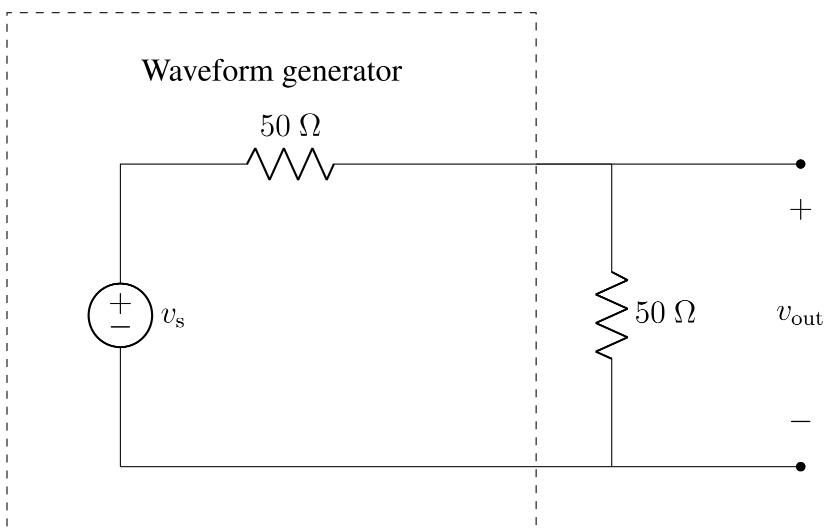
   (b) In Case 1, determine the peak-to-peak value at the output of the circuit, v_out, when the value displayed on the waveform generator screen indicates that the waveform generator is set to deliver 4 $\mathrm{V_{p-p}}$?

   (c) In Case 2, what is the peak-to-peak value of the practical internal source voltage of the waveform generator, v_s, when the value displayed on the waveform generator screen indicates that the waveform generator is set to deliver 4 $\mathrm{V_{p-p}}$. *Hint: It should be the same answer as question (a), above.*

   (d) In Case 2, with a $50\ \Omega$ resistance present at the output of the waveform generator, determine the peak-to-peak value at the output of the circuit, v_{out}, when the value displayed on the waveform generator screen indicates that the waveform generator is set to deliver 4 $\mathrm{V}_{\mathrm{p-p}}$.



(a) Case 1: Determine v_s and v_{out} for a displayed voltage of 4 $\mathrm{V}_{\mathrm{p-p}}$ and no external load.



(b) Case 2: Determine v_s and v_{out} for a displayed voltage of 4 $\mathrm{V}_{\mathrm{p-p}}$ and a 50 Ω external load.

Figure 1. Circuit diagrams depicting 2 configurations of the laboratory waveform generator. Assume that the waveform generator indicates a 4 $V_{\mathrm{p-p}}$ waveform. Note that the dashed box indicates what is internal to the waveform generator itself, namely a voltage source with a $50\ \Omega$ internal series resistance. In (a) Case 1, no load is attached to the waveform generator output. In (b) Case 2, a $50\ \Omega$ resistor is attached across the output terminals of the waveform generator.

2. **Working with resistors**
In the experimental exercises, you will eventually need a $50\ \Omega$ resistance. $50\ \Omega$ is not a standard stocked resistor value. Hence, there is no $50\ \Omega$ resistor in the laboratory components bins. The resistor values available in the laboratory are shown in Table 1 below:

Resistor Values in lab
43 Ω
100 Ω
220 Ω
470 Ω
1 kΩ
2 kΩ
4.7 kΩ
10 kΩ

Table 1. Resistors available in the laboratory

Pre-lab Deliverable (2): For the eight resistors listed above, create your own table that shows the resistor value and its color code. Assume that you are using 4-band resistors with $\pm 5\%$ tolerance. Refer to the EGRWiki page on Resistor Color Codes if you need to. You can either use the names of the colors, the colors themselves, or both. If you would like to use $\LaTeX$, here are some examples; the code for these is available at the Lab Supplements page for this lab:

Resistor	1st	2nd	3rd	4th
43 Ω	yellow	orange	black	gold

or

Resistor	1st	2nd	3rd	4th
43 Ω				

or

Resistor	1st	2nd	3rd	4th
43 Ω	yellow	orange	black	gold

or

Resistor	1st	2nd	3rd	4th
43 Ω	yellow	orange	black	gold

or

Resistor	1st	2nd	3rd	4th
43 Ω	yellow	orange	black	gold

Pre-lab Deliverable (3): Apply your knowledge of equivalent resistance to design a resistor network with an equivalent resistance of $50\ \Omega$. You will need to draw a circuit diagram of how your resistors are connected, list the individual resistor values, and show the calculations for finding your network's equivalent resistance. Be as efficient as possible!

3. **Quantifying Time-Varying Signals**
As we begin to look at time-varying signals, it will be important to understand how to quantify them. The quantities we can use depend on the nature of the signal involved.

   (a) Constants. For signals that are constant, the only real quantity of note is that constant!

   (b) Single-frequency sinusoids. For signals that look like $v(t) = A\cos(\omega t + \phi)$, we have the amplitude A, the angular frequency ω, and the phase ϕ. We can also calculate the frequency $f = \omega/(2\pi)$ and the period $T = 1/f = 2\pi/\omega$. The maximum value of the signal is A and the minimum value is $-A$. The "peak-to-peak" value (which should probably be called the "peak-to-trough value") is the difference between the maximum and minimum; in this case, that would be $2A$. The average value would be 0.

   (c) General periodic signals. For signals that repeat themselves at regular intervals (the shortest of which would be defined as the period, T), we can determine the fundamental angular frequency $\omega = 2\pi/T$, the fundamental frequency $f = 1/T$, as well as the maximum value of the signal, the minimum value of the signal, the "peak-to-peak" value, and the average value.

   (d) Aperiodic signals. For signals that do not repeat themselves, we may choose to define a time "window" for looking at signal characteristics. Within that window, we can find local maximum, minimum , "peak-to-peak", and average values. We could also keep track of the historic maximum, minimum, "peak-to-peak," and average values. We could also decompose the window into a collection of frequency components, something that will be done in ECE 280.

   (e) All signals. In addition to the metrics above, another useful value is the root mean square or RMS value of a signal. There is more information on this at https://egrwiki.com/wiki/Root_Mean_Square. Make sure you understand the difference between V_{RMS} and $V_{\text{RMS,AC}}$! In the deliverables below, these may also be referred to as RMS and RMS-AC, respectively.

   Devices capable of measuring RMS do so in a variety of ways. An application note at Keysight Technologies provides some explanation at https://www.keysight.com/us/en/assets/7018-01113/application-notes/5988-6916.pdf. Some assume that you are measuring a single frequency sinusoid and calculate the RMS value from those measurements - these can be disastrously-wrong for other types of signals! Other systems take high-speed digital samples over a window of time and use them to calculate the RMS value. Still others use analog circuitry to do the math in real time!

Pre-lab Deliverable (4): Sketch or plot the square-wave pulse signal $v(t)$ below for $-7 < t < 12$ and then determine the period, fundamental frequency, fundamental angular frequency, maximum, minimum, average, peak-to-peak, RMS, and RMS-AC value of the signal defined as

$$v(t) = \begin{cases} 0, & 0 \leq t < 2 \\ 4, & 2 \leq t < 5 \\ v(t \pm 5n), & \text{otherwise} \end{cases}$$

where n is some integer and (*spoiler alert!*) 5 is the period of the signal. This defines the signal for the period starting at zero and then states that every other window of time looks like that period.

Pre-lab Deliverable (5): Determine the period, fundamental frequency, fundamental angular frequency, maximum, minimum, average, peak-to-peak, RMS, and RMS-AC value of the signals produced by each of the two commands below. Remember that the PWM signals produced by the Arduino have a high value of 5 V and a low value of 0 V. Refer to LED Servo Monitors as needed, but remember that the graph they show is scaled in time by a factor of 100 (the actual time between pulses is 20 ms).

```
servoLeft.writeMicroseconds(1700)
servoRight.writeMicroseconds(1300)
```

5 Pre-Laboratory Assignment

The documentation for the pre-lab involves submitting a single PDF file. Your document must include your name, NetID, and the Duke Honor Code statement: "I have adhered to the Duke Community Standard in completing this assignment" at the top. **EACH INDIVIDUAL** should submit their own assignment. Your document should also include:

1. The peak-to-peak value for the internal voltage source v_s and external measured voltage v_{out} for the waveform generator when the waveform generator display shows a 4 V_{p-p} sinusoid for (a) no external load and (b) a 50 Ω external load.
2. A table of the resistor values and color codes for the eight commonly-available resistors in lab.
3. Your 50 Ω-equivalent resistive network including a diagram, individual resistor values, and equivalent resistance calculation.
4. Your sketch or plot of the square-wave pulse and your calculations of the period, fundamental frequency, fundamental angular frequency, maximum, minimum, average, peak-to-peak, RMS, and RMS-AC value of the signal.
5. Your calculations of the period, fundamental frequency, fundamental angular frequency, maximum, minimum, average, peak-to-peak, RMS, and RMS-AC values for the two servo signals.

This file should be uploaded to the ECE 110L Laboratory **Gradescope** site by the assignment deadline. Each student must submit their own **INDIVIDUAL** assignment.

6 Equipment

1. Keysight EDU33211A waveform generator
2. Keysight DSOX1202A oscilloscope
3. Keysight 34460A multimeter
4. Resistors to create a 50 Ω load
5. Breadboard, cables, and wires as necessary
6. USB cable
7. CX-Bot
8. Parallax 3-pin PING))) sensor

7 Experimental Exercise

In this experiment, you will be using the waveform/function generator to provide a time-varying voltage, which will be measured using the oscilloscope and the multimeter. Then, you will implement the Ping sensor to create a 'bot that maintains a set distance from the nearest object.

Important note 1: **DO NOT let the leads from the waveform generator touch each other!** If the waveform generator leads touch each other, either the internal fuse will blow or serious damage to the instrument will occur. It is very important that you keep this in mind at all times.

Important note 2: The following cables should be used for each instrument, respectively:

- Waveform Generator: straight black cable with alligator clips (this is an non-attenuating cable use for power sources)
- Oscilloscope: black or gray cable with probe tip spring hook. Be sure it is set to 10x, 10 MΩ. (this is used for measurements)
- Multimeter: cables with sheathed ports on one end and probes on another. You may want to also get alligator clips to connect the probes to your circuit.

Reminder: The waveform generator has an internal resistance of 50 Ω. The voltage displayed on its front panel is the voltage that would appear at its terminals if it were connected to a 50 Ω load. Under open circuit conditions, the voltage across the terminals of the waveform generator is **twice** as large as the value indicated on its front panel. This is an important concept and often misunderstood.

1. Understanding an unloaded waveform generator.

   (a) Connect the oscilloscope channel 1 probes to the leads on the waveform generator and also connect the multimeter leads (in the ports to measure voltage) to the leads on the waveform generator. Be sure all the grounds are on one node and all the not-grounds are on the other.

   (b) Set the waveform generator to produce a 10 kHz sine wave with 4 V_{p-p}.

   (c) Using the multimeter, measure and record the DCV value (average), the ACV value (RMS AC), the frequency, and the period. The period can be measured by pressing the Freq button and then toggling to measure the period with the far left button under the screen.

   (d) On the oscilloscope, press auto-scale to get a good view of the signal.

   (e) Using options with the oscilloscope Meas button, measure and record the average value, the peak-to-peak value, the DC RMS value for N cycles (RMS), the AC RMS value for N cycles (RMS AC), the frequency, and the period.

   (f) Using the oscilloscope, manually calculate the peak-to-peak value by counting the vertical divisions from the minimum to the maximum voltage and multiplying this number by the number of volts per division. The **volts per division** setting is shown in the upper left corner of the oscilloscope screen.

   (g) Using the oscilloscope, manually calculate the period of the sine wave by counting the number of horizontal divisions in one period of the sine wave and multiplying this number by the amount of time per division. The **time per division** setting is shown at the top-right-center of the oscilloscope screen.

   Checkpoint (1): Show your TA that the measured peak-to-peak voltage is approximately **twice** the peak-to-peak voltage shown on the front panel of the waveform generator and confirm that the frequencies and periods measured by the multimeter and oscilloscope generally match the setting on the waveform generator.

   Deliverable (1): For this signal, report the following values as measured from the specified devices:

   - Multimeter: DCV, ACV, frequency, and period.
   - Oscilloscope: Average, peak-to-peak, AC RMS, DC RMS, frequency, and period.

   Determine how close DCV^2+ACV^2 is to $(DC\ RMS)^2$ and comment on any potential sources of error.

2. Understanding a loaded waveform generator.

   (a) Turn channel 1 of the waveform generator off. Connect the waveform generator output leads across a 50 Ω load. Reminder: There is no 50 Ω resistor in the laboratory. You will need to use your knowledge of equivalent resistance to create a network of resistors equivalent to a single 50 Ω resistor.

   (b) Connect the oscilloscope channel 1 probes across the equivalent resistance (and waveform generator).

   (c) Connect the multimeter leads across the equivalent resistance and set the multimeter to measure AC Voltage.

   (d) Turn the waveform generator's channel 1 back on - it should still be set to generate a 4 V_{p-p} sine wave at 10 kHz.

   (e) Using the multimeter, measure and record the DCV value (average), the ACV value (RMS AC), the frequency, and the period.

   (f) On the oscilloscope, press auto-scale to get a good view of the signal.

   (g) Using options with the oscilloscope Meas button, measure and record the average value, the peak-to-peak value, the DC RMS value for N cycles (RMS), the AC RMS value for N cycles (RMS AC), the frequency, and the period. These may all still be in place from the previous experiment.

   (h) Using the oscilloscope, manually calculate the peak-to-peak value and the period.

   (i) Observe that the measured peak-to-peak voltage is approximately **the same** as the peak-to-peak voltage shown on the front panel of the waveform generator. This confirms that the voltage at the terminals of the waveform generator is **load dependent**. Whenever you use the waveform generator to provide a voltage waveform and desire a specific amplitude, you **must** use either the multimeter or the oscilloscope to set the desired voltage because the value shown on the front panel of the waveform generator is valid only for a 50 Ω load.

Checkpoint (2): Show your TA that the measured peak-to-peak voltage is approximately the same as the peak-to-peak voltage shown on the front panel of the waveform generator and confirm that the frequencies and periods measured by the multimeter and oscilloscope generally match the setting on the waveform generator.

Deliverable (2): For this signal, report the following values as measured from the specified devices:

- Multimeter: DCV, ACV, frequency, and period.
- Oscilloscope: Average, peak-to-peak, AC RMS, DC RMS, frequency, and period.

Determine how close DCV^2+ACV^2 is to $(DC\ RMS)^2$ and comment on any potential sources of error.

3. Quantifying pulse trains. You will now repeat the above process for three different pulse trains. In each case, note how the offset or the duty cycle varies and what impact that has on the measurements.

   (a) On the waveform generator, change the signal to a square wave with a frequency of 10 kHz, an amplitude of 4 V_{p-p}, a 0 V offset, and a 50% duty cycle.

   (b) Using the multimeter, measure and record the DCV value (average), the ACV value (RMS AC), the frequency, and the period.

   (c) On the oscilloscope, press auto-scale to get a good view of the signal. Then, using options with the oscilloscope Meas button, measure and record the average value, the peak-to-peak value, the DC RMS value for N cycles (RMS), the AC RMS value for N cycles (RMS AC), the frequency, and the period. These may all still be in place from the previous experiment.

   (d) Using the oscilloscope, manually calculate the peak-to-peak value and the period.

   Checkpoint (3): Show your TA the signal you are generating.

   Deliverable (3): For this signal, report the following values as measured from the specified devices:

   - Multimeter: DCV, ACV, frequency, and period.
   - Oscilloscope: Average, peak-to-peak, AC RMS, DC RMS, frequency, and period.

   Determine how close DCV^2+ACV^2 is to $(DC\ RMS)^2$ and comment on any potential sources of error.

   (e) Change the signal to a square wave with a frequency of 10 kHz, an amplitude of 4 V_{p-p}, a 2 V offset, and a 50% duty cycle. Repeat steps (b) through (d) above.

   Checkpoint (4): Show your TA the signal you are generating.

   Deliverable (4): Repeat the deliverable above for this signal.

   (f) Change the signal to a square wave with a frequency of 10 kHz, an amplitude of 4 V_{p-p}, a 2 V offset, and a 10% duty cycle. Repeat steps (b) through (d) above.

   Checkpoint (5): Show your TA the signal you are generating.

   Deliverable (5): Repeat the deliverable above for this signal.

4. Implenting the Ping Sensor. During this exercise, you will be building a 'bot that uses a Ping sensor to determine the distance between the front of the 'bot and the nearest object to the front of the 'bot. You will then use that information to determine if the 'bot should back up, stay still, or move forward. The goal will be to keep the bot at a distance of 6-10 inches from the object in front of it.

    (a) Go through the page at https://pundit.pratt.duke.edu/wiki/ECE_110/Equipment/Ping_Sensor and specifically look at the statements about getting higher resolution results as well as the "Alternate Mount" section.

    (b) Attach a three-pin Ping sensor, facing forward, such that GND is in pin 39, 5 V is in pin 37, and SIG is in pin 35.

    (c) Write a script that gets higher resolution distance values from a Ping mounted in pins 39, 37, and 35, and check it by moving your hand various distances from the sensor.

    (d) Add code to the script that will print the words "Too close" if the Ping senses an object 6 inches or nearer, "Too far" if the Ping senses an object 10 inches or more away, and "Just right" if the Ping senses an object between 6 and 10 inches away. Make sure that code is working before moving on to the next part!

    (e) Add code to the script that moves backward at full speed if the 'bot is "Too close" to an object, moves forward at full speed if the 'bot is "Too far" from an object, and stands still if it is "Just right."

    Checkpoint (6): Show your TA that your 'bot correctly responds to items placed various distances from the front of the 'bot. It should react fairly quickly to changes in the state of the Ping sensor.

    Discussion (1): With your partner, discuss improvements you might make to this code. What would be the next useful way that this code could be changed to make the 'bot respond better to changes in distance? If the 'bot were a car, what feature(s) might the passengers appreciate?

    Deliverable (6): Include your code for maintaining distance and a description of additional features that might help improve the code. You are *not* required to come up with code for the improvement, just describe your suggestion.

8 Exploration - Signals all around us.

1. Take the oscilloscope probe in one hand, expose the metal hook by pulling down on the casing with one finger of that hand, then touch the metal hook with another finger of that same hand. Touch the ground clip with your other hand.

2. With your third hand, press the autoscale button on the oscilloscope. Set the time scale to 10 ms/division if that is not what automatically happened.

3. Continuing to touch the hook, move your hand near a power receptacle or a power cord and observe the change in the waveform shown on the oscilloscope.

4. Take a picture of the oscilloscope screen to document the waveform.

Discussion (2): What is the main frequency of the waveform? Describe the waveform measured by the oscilloscope. How do you think this signal was generated? What possible implications can there be based on how the signal was generated?

Deliverable (7): Include the picture of the waveform in your lab document as well as your answers to the discussion questions above.

9 Assignment

The assignment for this laboratory involves submitting a single PDF file. Your document must include your name, NetID, and the Duke Honor Code statement: "I have adhered to the Duke Community Standard in completing this assignment" at the top. **EACH INDIVIDUAL** should submit their own assignment. The documentation for this laboratory includes answers to the following questions. This does not need to be a formal report, but it should be typed (not handwritten).

1. Suppose you connect the waveform/function generator to a circuit and the front panel display on the waveform generator reads 5 V pk-pk. But when you measure the waveform generator output voltage using the oscilloscope, you find its value is 3 V pk-pk. Explain what has happened within the context of the pre-laboratory assignment and your experiments with the output from loaded and unloaded waveform generators.
2. Tables of values from the multimeter and oscilloscope for an unloaded system with a sinusoid and a loaded system with a sinusoid and for three different rectangular waves.
3. Discussions of how close experimentally measured values for signal characteristics (RMS values, frequency, period) are to theory and potential sources of error.
4. Your Ping code for maintaining distance from the experiment (moving based on distance from an obstacle) and a description of additional features that might improve that code.
5. Picture of the signal obtained by grabbing the oscilloscope probe and both your description of the wave (includling an estimate of its main frequency) and ideas about whence it came.

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