

Name:

NetID:

Today's bench partner:

Section AB/BB:

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8	9	A	B	C	D	E	F

***Think about it...***

Signals that are “nearly” periodic occur around us every day. The buzz of the honeybee, vibrations of a car engine, and sunlight hitting a solar panel day-by-day all contain measurable signals that show repetition. What periodic signals can you think of? How might those signals be measured electronically? What engineering solution might come from having that kind of information?

# Experiment 4: Voltage-Divider-Based Motor Speed

## Laboratory Outline

This week, we continue to expand topics towards building a self-navigating car. Specifically, we will build voltage-divider circuits and “motor-drive” circuits and analyze them with the aid of a function-generator and the oscilloscope.

## Learning Objectives

- Learn to allow for tuning and discuss the need for conformity in testing conditions.
- Gain a deeper understanding of benchtop equipment designed for time-varying signals; the function generator and oscilloscope.

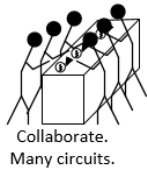
## Introduction...Meet in 1005 ECEB

Drop off your Prelab (and the Summary Sheet for today) in 1001 ECEB at a center table. One TA will check that you have completed your prelab assignment while the other will answer any questions you may have about last week's lab or today's prelab in 1005 ECEB. You will also receive a quick rundown of what is planned for today.

In order to analyze voltages that vary with time, we must use *a measurement device that can capture a time history* of those voltages. This device is called an **oscilloscope** which you gained exposure to last week. In addition, there are many situations in which we might desire to *generate a specific periodic voltage* without having to build a special circuit to do so. We can do this using what is called a **function generator** (sometimes called a *signal* generator or *waveform* generator, although these titles often imply different specific operations). Once we have mastered the use of this bench equipment, we'll continue to hone our equipment knowledge for the rest of the semester through practical use.

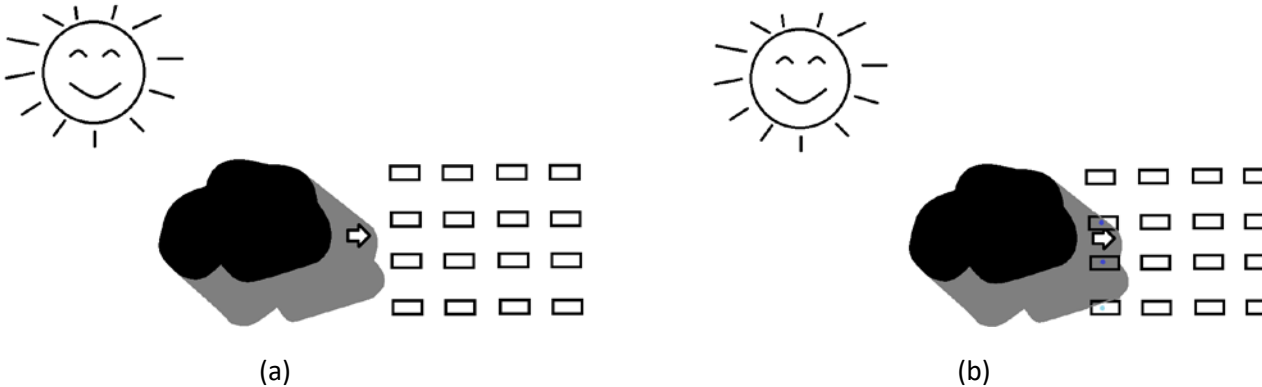
## In the Lab...Move into 1001 ECEB

When instructed, move into the breakout session of the lab. Today, you will create an array of cloud detectors and tune them for a consistent response.



## Breakout Session

Spend a little time making adjustments to your cloud detector on the bench in the middle of the room. Does it respond differently than it did at home? As a group, select LED color(s) for your array. Arrange your cloud detectors in a two-foot square of approximately 16 sensors (one per student). Pass a shadow across the array and look for uniformity in its operation. Have each student adjust his circuit as needed. All students should be involved in the discussions for improvement.



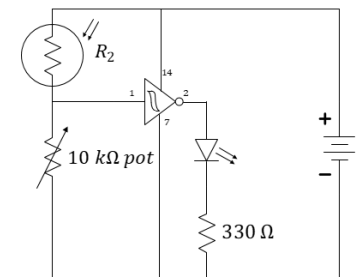
**Figure 1:** (a) Example of a cloud detector array. (b) The array lights up as the shadow covers it.

**Question 1:** Remove your potentiometer and, being careful not to alter its value, measure it on your Ohmmeter. Record its value here:  $R_1 =$  \_\_\_\_\_

**Question 2:** Comment on the values found by other students. Is there a large variation? Does the answer surprise you? Explain.

Notes:

Cloud detector circuit:



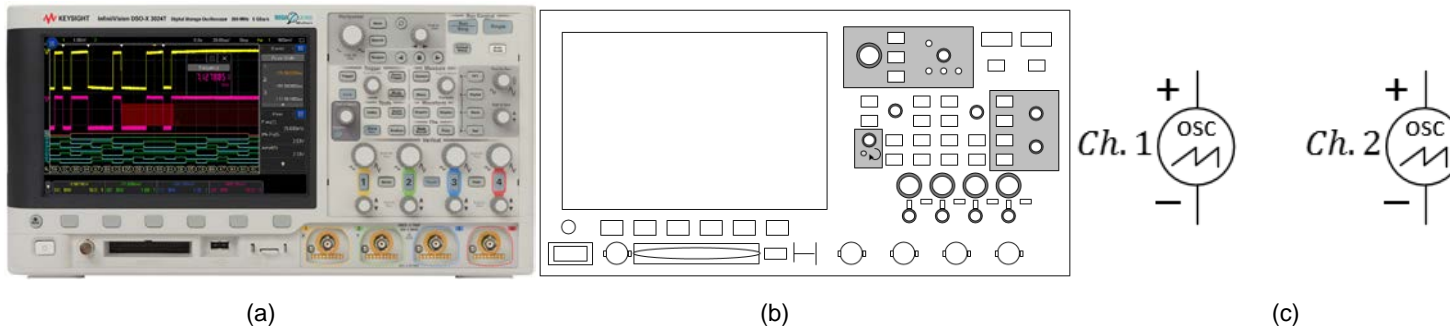


## At your Bench

Today, we will focus on voltage dividers and the production, use, and analysis of time-varying signals. Specifically, we will apply a voltage-divider to a motor-drive circuit for the car. We will learn to use the function generator to slow the car. We will learn in greater detail how the oscilloscope achieves its function to produce a quasi-static display of periodic and near-periodic signals.

## Oscilloscope

The oscilloscope (often called an “o-scope” or “scope” for short) is a measurement device that can capture a time history of a signal. At first glance, it appears to be a very complex piece of hardware. As you learn to use it, however, you will learn that most common adjustments use only a few of the controls present on the front panel of the device. The horizontal control changes the scale of the time axis allowing you to see more and less time range of the waveform as needed. The vertical control changes the scale of the voltage axis allowing you to shrink the display’s height of the waveform so that it fits within the screen or expand it to better fill the screen and make a more-accurate voltage measurement. A third menu consists of the triggering controls. The description of the trigger is less intuitive than scale so we will spend much more time investigating its key role. For now, just remember that **the oscilloscope’s trigger aids in displaying voltage waveforms in a human-readable format.**



**Figure 2:** A photo of the KEYSIGHT oscilloscope, our physical model of it, and common schematic symbols for two channels. In ECE110, often only a label (and no symbol) will be used.

The simplest way to trigger the oscilloscope is to press the **Single** button in the upper right of the oscilloscope’s front panel. The screen should go blank as the oscilloscope is *waiting for an event* to tell it something interesting has occurred. For the oscilloscope in default mode, triggering means for the oscilloscope to wait for **a voltage that rises above a set threshold.**

Notes:

### Think about it...

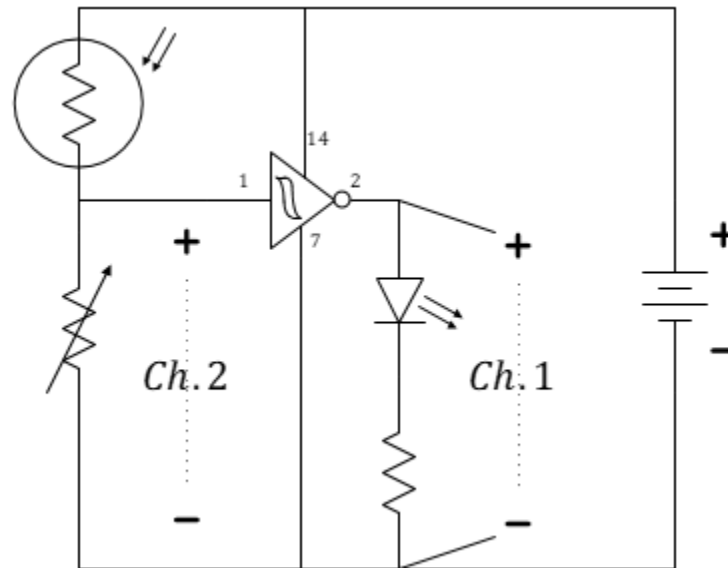
As you consider the oscilloscope’s trigger, imagine a photographer wishing to set up a camera to automatically photograph the phases of the moon by photographing it as it rises over the horizon in the East. Since the time of the moonrise will vary each day, snapping a photo every 24 hours will do no good. The photographer might rely on light from the moon to trigger the camera to snap the photo. Similar to the oscilloscope, the photographer’s system is waiting for a value to rise above a certain threshold before capturing data. The series of captured photographs will repeatedly show the moon at the same location above the horizon.



Notes:

On the oscilloscope, press the **Default** setup, then **attach Channel 1 and Channel 2** of the scope to the circuit locations shown in the schematic below.

**Turn the “Trigger” knob** clockwise until the horizontal trigger line on the oscilloscope is near 2 V.

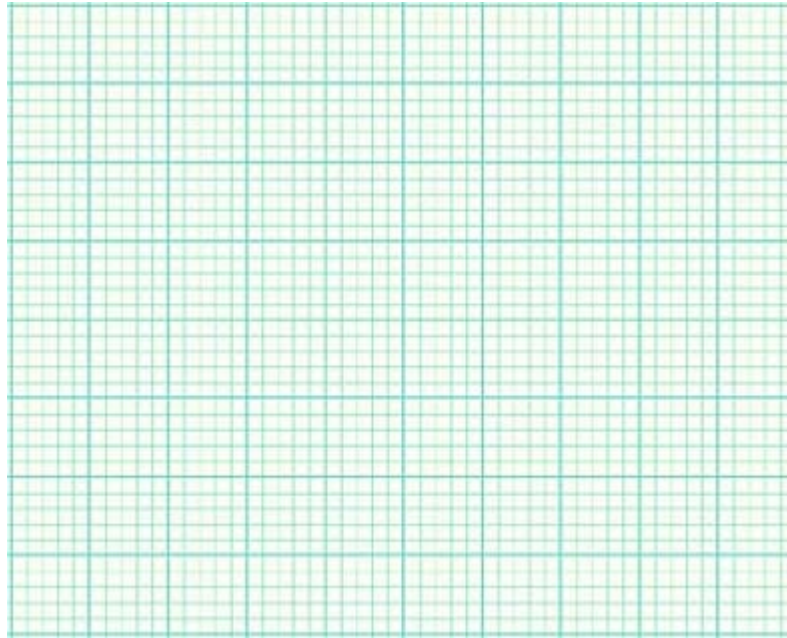


**Figure 3:** Use the oscilloscope to view the time-varying input and output of the cloud detector, Channel 1 is the output.

**Question 3:** Use the oscilloscope as shown in Figure 3 to measure the input and output of the (Schmitt trigger) inverter by using the Single run mode. Sketch in Figure 4 the waveform you see on the oscilloscope after your hand passes across the sensor. Verify that the oscilloscope’s 2-volt trigger is the value the plotted voltage reaches in the center of the screen.

**Think about it...**

If your Single mode plot doesn’t match your expectations, consider changing your time scale to 200 ms per division and trying again. Why does this matter?



*Figure 4: Plot the cloud detector's input and output. Please include time and voltage labels.*

## The Motor-Drive Circuit

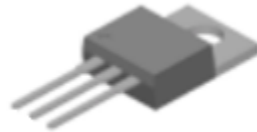
Previously, we were controlling motor speed by using a current-limiting resistor network in series with each motor. One difficulty we recognized in this method was that the resistor network had to absorb significant power. In fact, the resistors were absorbing about as much power and dissipating it as heat (waste) as the wheels were dissipating (useful) resulting in low efficiency. Furthermore, the amount of power dissipated in the resistors necessitated the use of a resistor network in order to gain a higher effective power rating. The use of a MOSFET transistors will enable us to “buffer” low-power resistive control from the higher-powered motor circuitry. In this way, we will be able to reduce cost (lower-power-rated devices) and increase efficiency (less power waste).

Find the **30N06** n-channel MOSFETs from your kit. There is an image of it below, but be sure to check the label on the device as others may look similar. The datasheet may be found at <https://cdn.sparkfun.com/datasheets/Components/General/FQP30N06L.pdf>.

Notes:

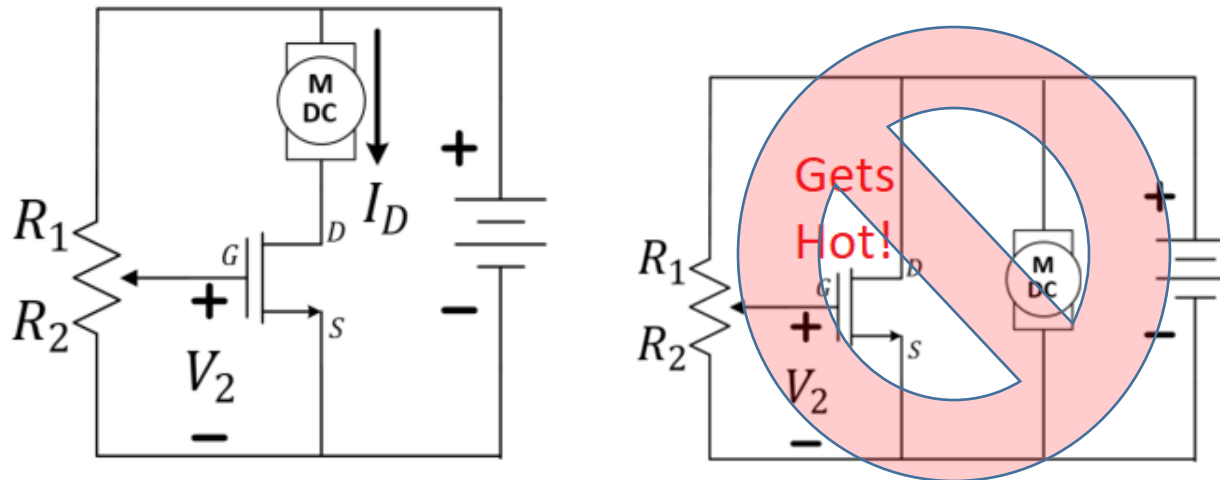
Today's modifications to the car's electronics will lead to potentially-cheaper parts, easier design, and increased efficiency.

**Question 4:** Use the datasheet to determine the drain (D), and source (S), and gate (G) pins of the 30N06 MOSFET. Label the pins on the image below correctly with D, S, and G (placing them in the correct order, of course).



**Figure 5:** Pinout of the MOSFET (you label it!).

**Build the motor control circuit** shown in Figure 2 using the **30N06** n-channel MOSFETs from your kit. Use the  $1\text{ k}\Omega$  potentiometer from your kit as well. The potentiometer is blue and has 102 printed on the side, meaning its value is  $10 + \text{two more 0s}$  to give a value of  $1000\ \Omega$  ( $10 \times 10^2\ \Omega$ ) from end to end. The knob controls a “wiper” that changes the location of the middle lead causing the values of  $R_1$  and  $R_2$  to change in relation to each other, that is, the wiper provides a single moveable “tap” dividing the resistor into two smaller resistors. Because it is formed from a single fixed-value resistor, in this case  $1\text{ k}\Omega$ , it must be true that  $R_1 + R_2 = 1\text{ k}\Omega$  always.

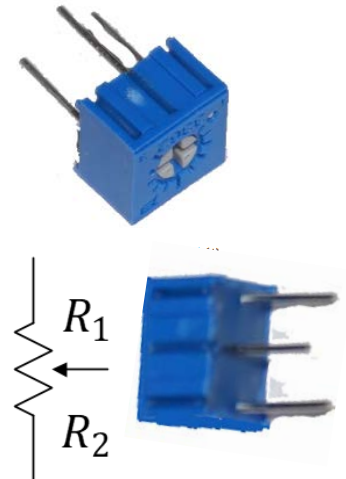


**Figure 6:** The voltage-divider-based motor-drive circuit (on the left). **Avoid the wiring mistake on the right!**

Notes:

Do you see that big hunk of metal on the MOSFET? That’s a “heat sink”. It helps dissipate heat. If you think your MOSFET is **getting hot**, 1) **don’t touch it**, 2) unplug your battery, and 3) figure out what you wired wrong!

Potentiometer:



$$R_{pot} = R_1 + R_2$$

In this design, **the MOSFET acts as a switch**. There is a high impedance (think “resistance”) looking into the gate (“G”) pin and therefore the voltage-divider circuit on the left is relatively unaffected by the presence of the MOSFET and can be analyzed as though the rest of the circuit were not present. However, the MOSFET monitors the “output” of the voltage divider and behaves like a switch. When the voltage,  $V_2$ , across  $R_2$  becomes high enough, current  $I_D$  will begin to flow driving the motor. When the voltage across  $R_2$  is small, the current will be zero and the motor will be stopped.

Use the oscilloscope to monitor  $V_2$  as you adjust the potentiometer that determines the balance between  $R_1$  and  $R_2$  and, therefore, controls  $V_2$ .

**Question 5:** At what voltage  $V_2$  does the motor begin to turn?

**Question 6:** At what minimum voltage  $V_2$  does the motor appear to run near full speed?

**Question 7:** What is the voltage from drain-to-source at the same motor speed as in Question 6? (This will be useful later when estimating efficiency,  $\eta$ !)

## Oscilloscope Triggering

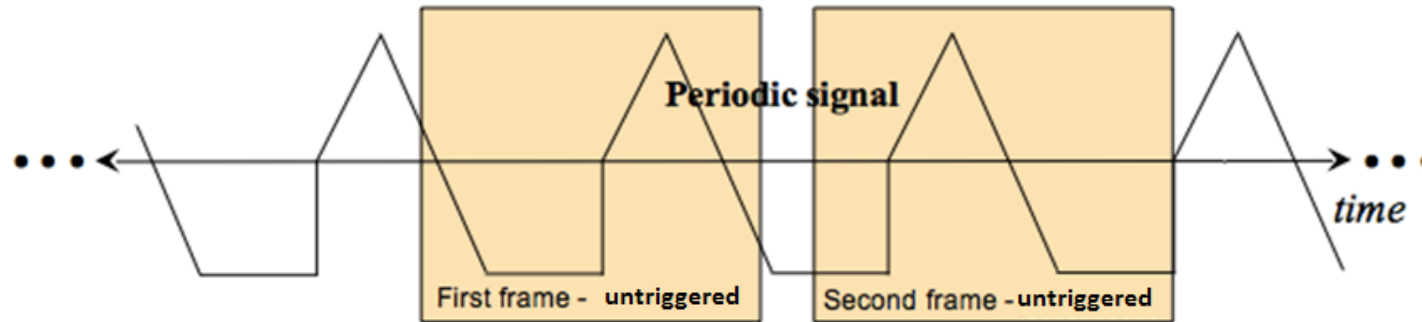
### Without Triggering

Suppose we input a periodic signal into channel 1 of the oscilloscope. Without triggering, each plotted **frame** (*a short time-sweep of the voltage*) will begin at arbitrary point in the waveform and, with each sweep, the signal will jump around on the time axis so fast that the plot will just look like garbage. The explanation is simple. Refer to the figure below. For the first frame, the computer inside the oscilloscope will collect a waveform (frame) starting at an arbitrary point in time. A second frame is also collected starting at a later, but at a point in time unrelated to the period of the periodic signal. The second frame will be an arbitrarily-time-shifted version of the first. It is this arbitrary time shift between consecutive frames that causes the waveform to appear on the oscilloscope placed at random time intervals. If only the oscilloscope had some way of estimating the period of the waveform, it might be able to produce a stable display of one or more periods. So we note that many “basic” period

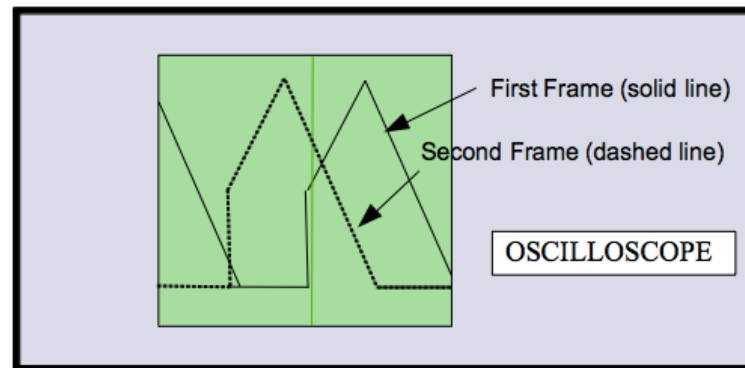
### Notes:

Note that the efficiency of this motor-control scheme can be calculated as  $\eta = \frac{I_D V_m}{I_{bat} V_{bat}}$  where  $V_m$  is the motor voltage and  $I_{bat}, V_{bat}$  are the battery's current and voltage.

waveforms (like sinusoids, square waves, and triangular waveforms) do something specific only once or twice each cycle...like transitioning across a certain voltage value.



(a)



(b)

**Figure 7:** Two frames of an un-triggered periodic signal shown in time (a) and plotted simultaneously (b).

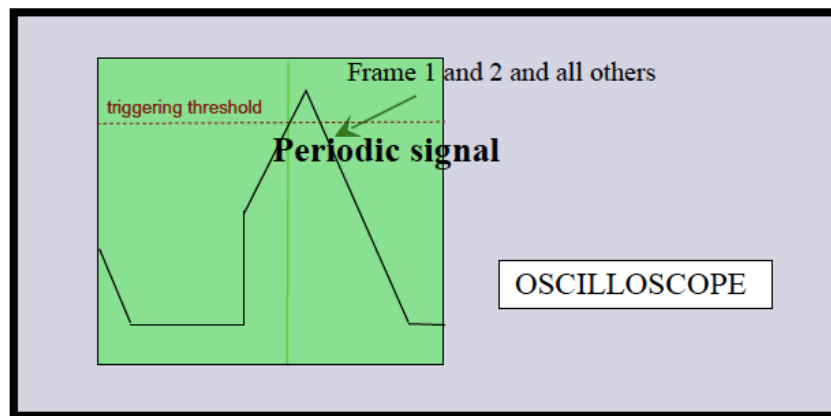
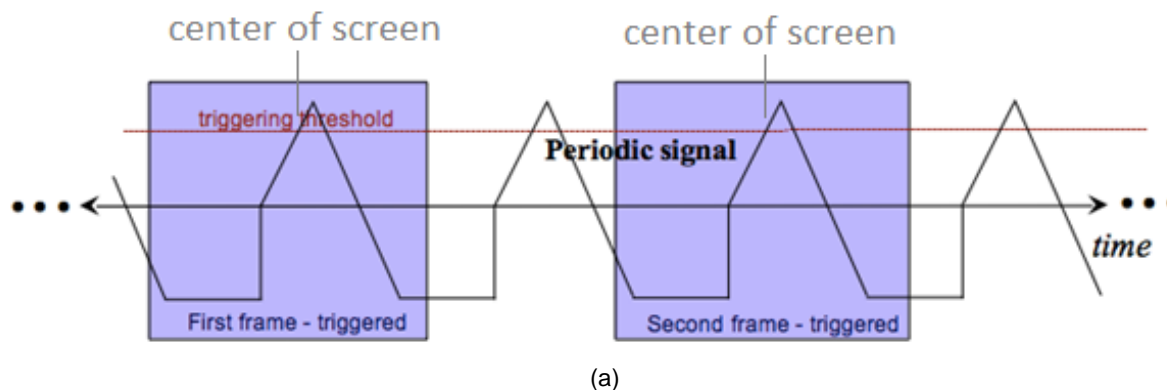
#### Continuous Triggering (Run)

Continuous triggering allows the user to specify how the oscilloscope draws and redraws a signal on the screen. Our oscilloscopes are digital scopes. A digital scope reads the analog signal (**analog**: *continuous in time and continuous in amplitude*) applied to each channel and converts it into a series of binary numbers sampled in time that represents the original signal.



These numbers are stored in memory continuously with new numbers always replacing the old. Continuous triggering is used to tell the oscilloscope how to display the signals in a manner that underscores the periodic nature of the waveform.

The oscilloscope does not actually estimate the waveform's period (although it could). It does something clever with a "trigger". The **trigger** is a *voltage threshold that we choose*. We specify a particular voltage level and the oscilloscope starts to sketch a new frame when the voltage waveform again crosses that threshold.

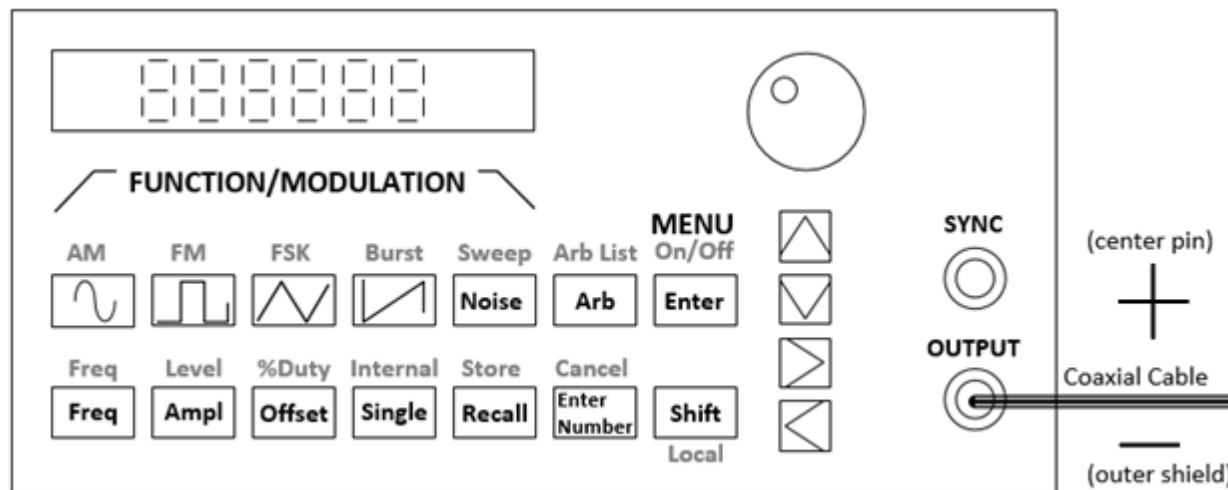


**Figure 8:** Two frames of a triggered periodic signal shown in time (a) and plotted simultaneously (b).

Since the signal is periodic, each frame will be nearly identical (even if several periods are missed between frames!). Therefore, the oscilloscope display overlays similar frames and the image it shows will be steady. With a steady display, the parameters of the waveform (amplitude, frequency, offset, etc.) will be easy to measure.

## Function Generator

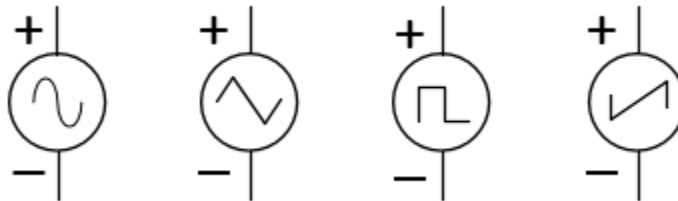
A function generator is a piece of equipment that outputs an electrical voltage waveform that can vary in time, in contrast to the DC power supply that can only output a constant voltage. The output waveform of our function generator is periodic. The waveform's shape can be chosen from a predetermined "function" list. Besides the waveform's shape, the front panel buttons allow the user to alter other parameters of the waveform like frequency, amplitude, offset, and duty cycle.



**Figure 9:** The front panel of the HP33120A function generator. At the BNC output, the center pin is the positive voltage reference while the outer shield is the negative (often the "ground" reference).

The waveform output is generated inside the device from functions stored in memory in digital form. The list of binary numbers that specify the waveform are applied to a Digital-to-Analog (D/A) converter and output as an analog waveform through the bottommost BNC connector that is labeled OUTPUT. The circuit symbols for several different functions are provided in Figure below.

The SYNC port is used to synchronize the “clocks” of multiple devices. We will not use it in ECE110. Be careful not to accidentally confuse it with the OUTPUT port.



**Figure 10:** Circuit symbols for the sine, triangular, square, and sawtooth waveforms, respectively.

When discussing periodic signals, we often refer to parameters like amplitude and frequency and period. **Amplitude** is the height of the voltage (commonly in units of volts or millivolts). It might be given as the peak-to-peak height (the difference between the largest voltage the waveform takes and the smallest voltage) or, often for a signal that symmetrically takes on positive and negative voltages, the zero-to-peak voltage (half of the peak-to-peak). **Period** is the amount of time, often in seconds, it takes for a signal to complete one cycle and return to its starting point. Frequency is the rate at which the periods (or cycles) appear measured in cycles/second or “Hertz”. Frequency is actually just the inverse of the period.

Two other parameters are quite common as well. A periodic signal like a sinusoid or square wave is generated by a device like the function generator to be symmetrical around 0 volts (takes on evenly positive and negative voltage values relative to its “ground” reference). Adding a “**DC-offset**” to the signal can shift it upwards or downwards. Often the goal is to shift the signal upwards so that the voltage produced always falls between 0 volts and the peak-to-peak amplitude. For a square-wave signal, **duty cycle** is the ratio of the time in each period the signal is at its maximum value divided by the amount of time in one period. For a duty cycle of 1%, the waveform almost never leaves its minimum value and for a duty cycle of 99%, the waveform is nearly always at its maximum value. A duty cycle of 50% is what most people think of as a square wave signal. A signal in which the duty cycle is adjustable, often in response to some outside stimulus, is referred to as a pulse-width modulation (PWM) signal.

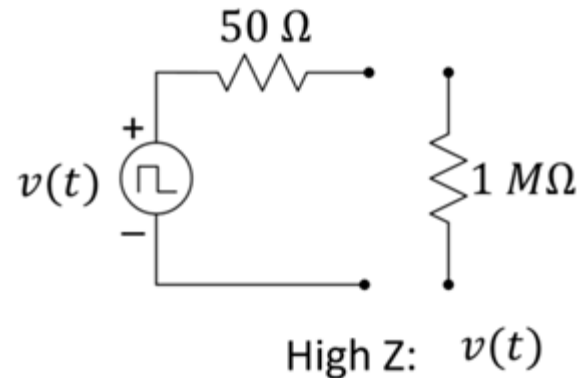
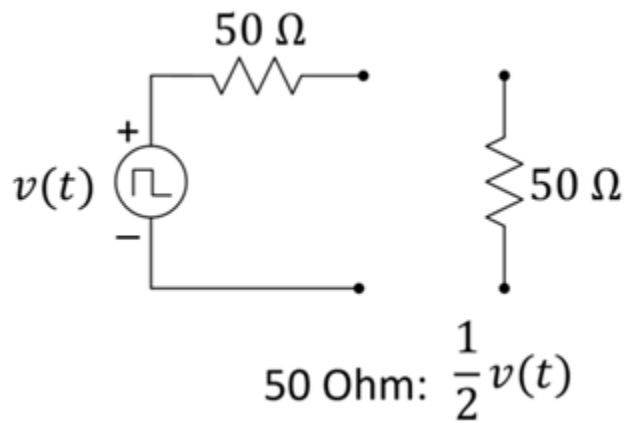
Setup the Function Generator (HP33120A) to output a square wave with a frequency of  $1000\text{ Hz}$ , a  $5\text{ V}$  peak-to-peak amplitude, and an offset of  $2.5\text{ V}$ . Here are the instructions:

Set the following parameters of the output by pressing the corresponding button and turning the large knob if necessary.

- ✓ **Function** – press the button on the function generator that shows a **square wave**.
- ✓ **Amplitude** – Press the *Ampl* button. This shows you the default amplitude value in the display. To quickly change the amplitude, turn the dial in the upper right corner. Alternately, fine tuning can be accomplished by pressing the up/down arrows. Either control changes the digit blinking on the display. A different digit can be made to blink by using the left/right arrow keys.
- ✓ **Frequency** – Press the *Freq* button. Adjust settings with the dial or arrows.
- ✓ **Offset** – Press the *Offset* button. Adjust settings with the dial or arrows.

Validate your signal by connecting it to the oscilloscope (there are BNC-to-BNC cables in the cabinet). Are you surprised by what you see? READ ON! ...

There is one hidden problem with the function generator. We cannot treat it as an ideal voltage-signal generator. It turns out that it was designed to have a  $50\ \Omega$  internal resistance. This cannot be changed, but the designer of the function generator also recognized that the most typical “loads” the function generator would see would be either  $50\ \Omega$  (an equipment *standard*) or a much larger resistance like  $1\text{ M}\Omega$  (another equipment standard and the default value on our oscilloscope). In their wisdom, the designer of the function generator has allowed us to select the device to be in either the default **50 Ohm** mode or in the so-called **High Z** (high-impedance) mode. Nothing physically changes within the function generator while changing between these two modes, however, the digital display will report either the generated voltage,  $v(t)$ , or half of that voltage,  $\frac{1}{2}v(t)$ . See the figure below.



**Figure 11:** Deciding when to use the High Z vs. 50 Ohm setting of the function generator.

## Switching between 50 Ohm and High Z modes

If you want the displayed value of the function generator's to match the voltage read by a high-resistance device, you need to set the function generator to "High Z". Do this by pressing this series of keys on the function generator: **Shift, Enter, >, >, >, V, V, >, Enter**. The function generator will now show the voltage value of the "ideal internal source". *You must do this each time you use the function generator because the 50 Ohm default setting will report  $\frac{1}{2}v(t)$ .*

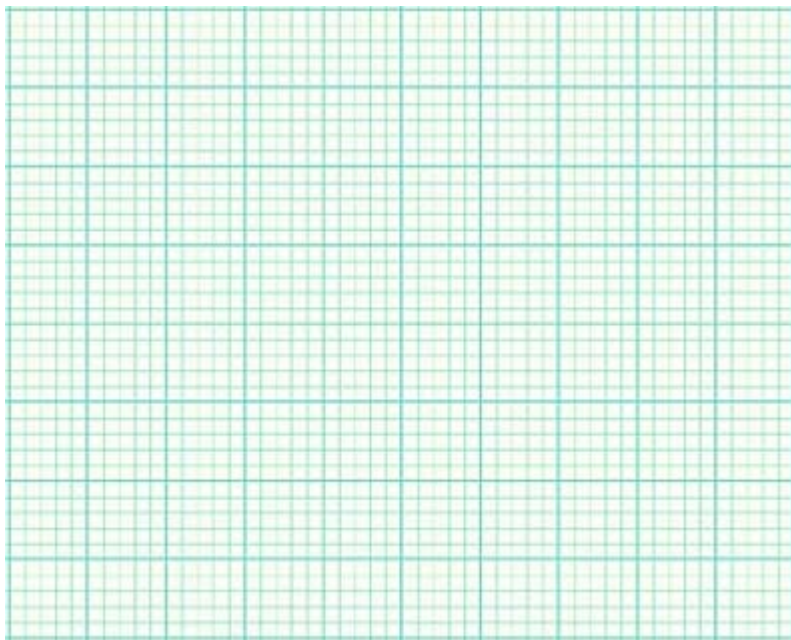
**Question 8:** Configure the function generator and the oscilloscope so that they agree with each other with respect to the anticipated resistance. Sketch the signal seen on the oscilloscope on the figure below.

Notes:

In 50-Ohm mode, the function generator will display a value only 50% of the open circuit amplitude because that is what you would see across a 50-Ohm load. In High-Z mode, the function generator will display the open-circuit voltage because that is what you would see when measuring across a high resistance.

## High Z

This can serve as a bookmark for you. How to set High Z on the function generator.



*Figure 12: The output of the function generator square wave.*

### ***Explore More! Modules***

Explore More! Modules provide students with options to investigate new concepts! As time allows, do one or more of the modules before returning to the laboratory's core procedure.

This week, we highly recommend the following ***Explore More! Modules***:

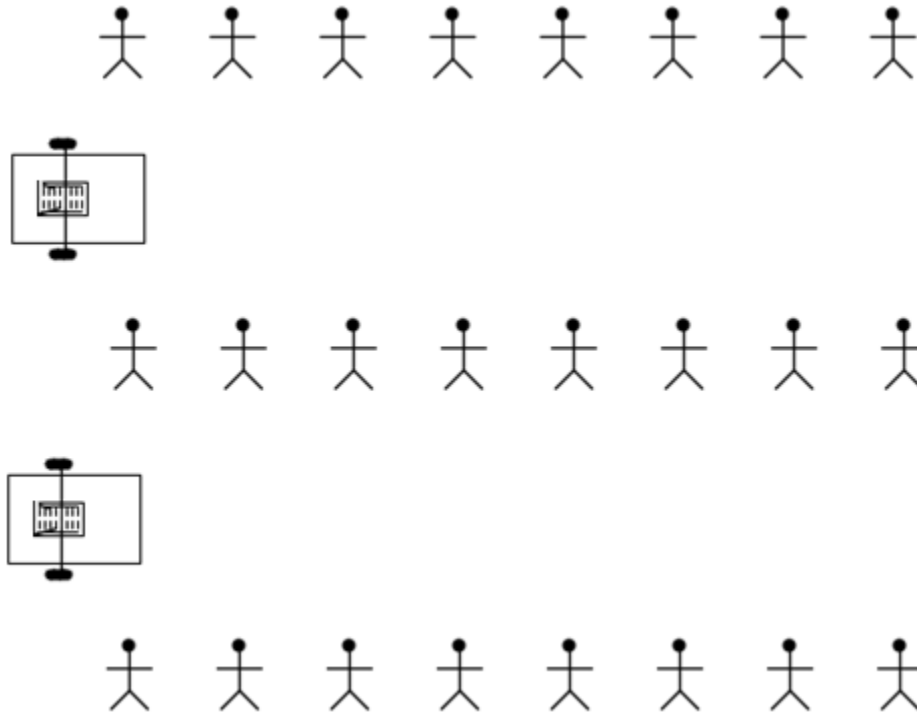
<b><i>Explore More! Arduino as an Oscilloscope</i></b>	<b><i>Explore More! The Oscilloscope's XY Mode</i></b>	<b><i>Explore More! Non-Ideal Behavior of the Bench Equipment (DC)</i></b>
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At the end of the semester, you will earn points towards your total semester lab score by having completed a minimum of 12 modules. If you wish to be eligible for a Course Aide position in the future, please consider doing more and impressing us with your command of the material and your ability to aid your classmates.

## Breakout Discussion Session

Return to the breakout session when instructed by the TA.

With both motors configured as in Figure 6, (the same circuit  $\times$  2), make your car race straight through a straight-line obstacle course.



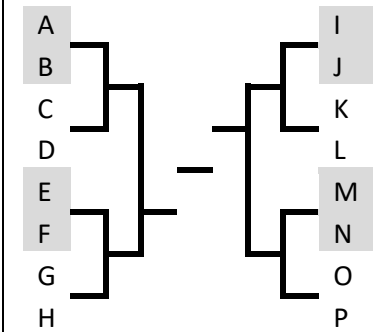
**Figure 24:** Head-to-head car race using the MOSFET motor-drive circuits with potentiometer control.

In a breakout of 8 students, discuss the ease (or difficulty) of adjusting your car to navigate the path.

**Question 9:** Comment on the ease or difficulty of adjusting your car to navigate the path. Compare your efforts to earlier efforts with or without the tethered switches.

Notes:

Competition Bracket  
(use only as time allows)



When instructed, return your borrowed equipment and clean up your benchtop.

Do NOT tear down your MOSFET-based motor-drive circuit. You were provided an extra breadboard with the car chassis and that should remain in your locker at this point forward to reduce future build times.

**As a group, complete the Lab 4 Summary.**

Submit your lab summary and two modules (if not submitted earlier) before leaving for the day. Thank you!



# Lab 4 Summary (To be submitted at the end of the laboratory session)

**Question 10:** Describe a procedure for determining the efficiency,  $\eta$ , of the voltage-divider controlled motor-drive circuit (Figure 6). Assume all power consumed by the motor is useful and all power used elsewhere is waste.

**Question 11:** Explain how the oscilloscope’s trigger causes multiple time captures of a periodic signal to look like a static image. Put a simple example of a periodic signal in the figure below to help illustrate your explanation.

Notes:

Name:

NetID:

Section AB/BB:

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(circle one)

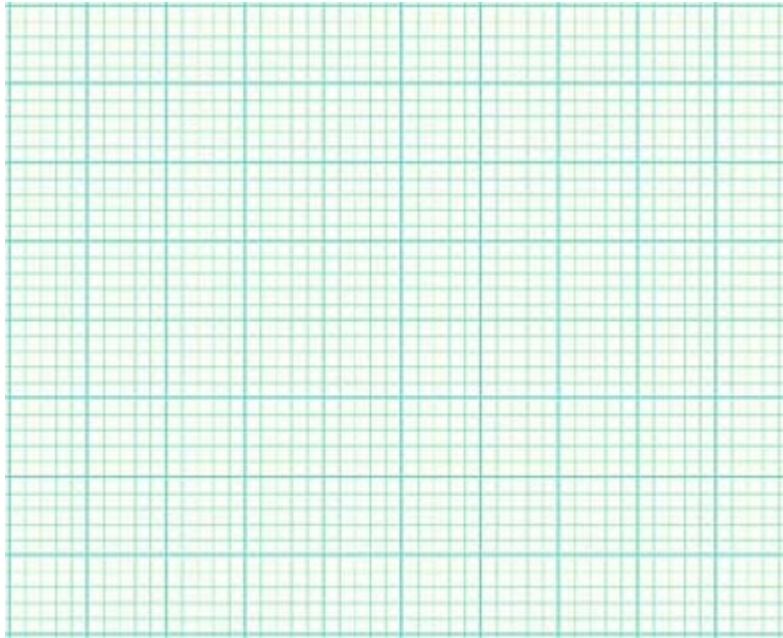
Bench:

A B C D E F G H I J K L M N O P

(circle one)

Return your borrowed equipment, clean up your benchtop, and submit your lab summary before leaving for the day. Thank you!

Notes: \_\_\_\_\_



**Figure 14:** Illustration of the oscilloscope's trigger operation.

**For TA use only:**

- Prelab Check: full/half/zero credit
- Student was engaged and active throughout the lab, sharing duties with partner, not distracted by phone, homework, etc.

TA initials: \_\_\_\_\_

TA initials: \_\_\_\_\_

Lab grade (reasons for deductions and/or total points awarded):

\_\_\_\_\_/8