Module 006: What is a Capacitor?

Notes:

Prerequisites: Use of the function generator and the oscilloscope.

Capacitance is a property of anything that can hold charged particles in some amount of isolation (insulated from) the environment. Your body has a great amount of capacitance as your cat, dog, or (former) friend knows when you touch them after walking across a carpeted floor during a dry, cold winter. One of nature's most spectacular displays demonstrates the ability of the ground and surrounding atmosphere to store enormous amounts of electrical energy. If the energy of lightning could be harvested a single strike contains the equivalent energy content as 150 gallons of petroleum.

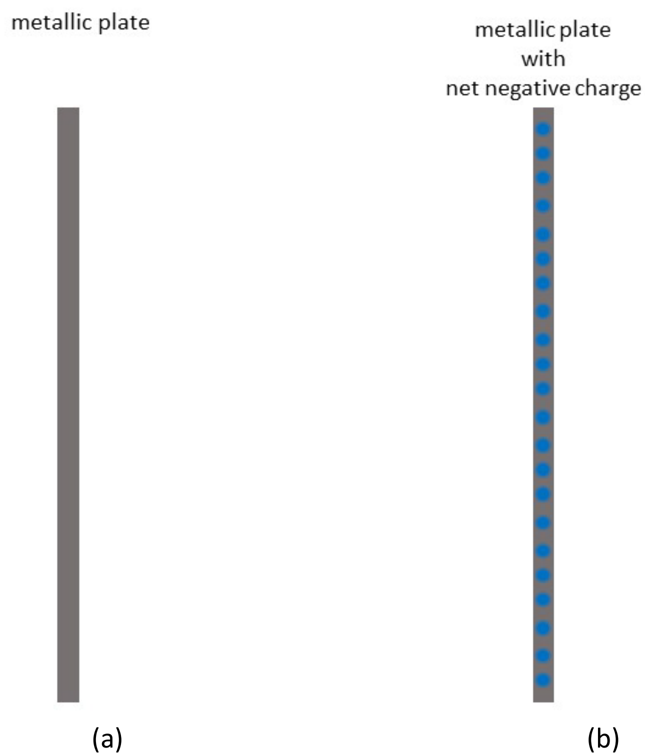

Figure 1: Capacitance is the measure of the ability of conducting shapes to hold charge to store potential electric energy.

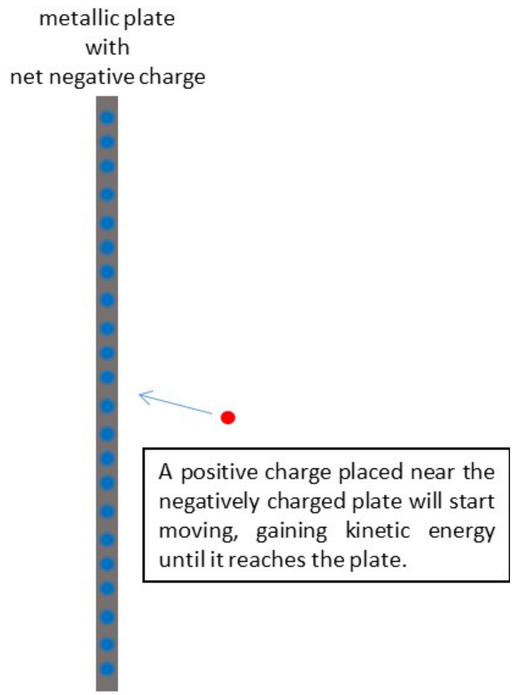

Figure 2: Potential electric energy comes about due to the interactions of a charged conductor with ions of an opposite charge.

So what makes an electronic device a 'capacitor'? A capacitor is anything that is capable of storing electrical energy through a separation of charges, usually two sheets of metal separated by some insulator. One attribute seems to be the ability to assemble and hold a large amount of charge isolated in one location so when you need some electrical energy you can discharge some of the charge to light and LED, power a small motor, etc… During the lecture you learn about an instrument named the Leyden jar – this is an example of a device designed to store a lot of electrical energy in a small space (at least, considering the methods of fabrication available at the time).

The Leyden jar was covered by metallic foil on part of the outside ***and*** on the corresponding part of the inside of the jar. The key feature of this configuration was that there two pieces of metal *electrically isolated* from one another by insulating glass while still positioned very close to one another. The jar was usually corked but pierced by a metal rod connected by a metallic chain to the inside conductor. The metal rod was used to both charge and discharge the Leyden jar.

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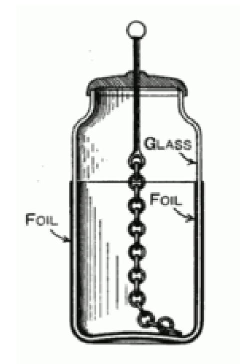

Leyden Jar – the Leyden jar is not named after a person – at least not directly. It was first invented in 1745 by Pieter van Musschenbroek at the University of Leiden in the Netherlands. The name Leiden was anglicized as Leyden.

Notes:

The Leyden-jar capacitor can be charged by touching one of the plates with a material known to contain an excess of electrons (often obtained by rubbing two different types of materials together. For a brief explanation, look at http://soft-matter.seas.harvard.edu/index.php/Triboelectric_series). Once the plate is charged, the potential energy is stored until the plate is discharged by touching another conducting material.

If a second metallic plate is moved close to the charged plate the (electric) *field* between the plates is intensified and mostly confined to the area between the plates – hence the two-plate geometry of the Leyden jar and most other capacitors. This potential energy can be tapped by connecting a device – a light bulb for, example – between the metallic rod at the top and the outer conducting foil. Alternately, if a positively-charged particle is placed near the plate, it will move towards the plate because the charge on the plate influences any nearby charged particles.

Capacitors that are used for various purposes in electrical circuits are all designed using the same basic geometry – two pieces of conducting material separated by a non-conducting material. To understand what circuit designers mean when they say capacitance let's look at the simplified view of the geometry of a capacitor as two parallel metallic plates. This is the same picture you will see in your physics, circuits, and electromagnetics classes. It is this geometry depicted in the circuit symbol for the capacitor (see Figure 3).

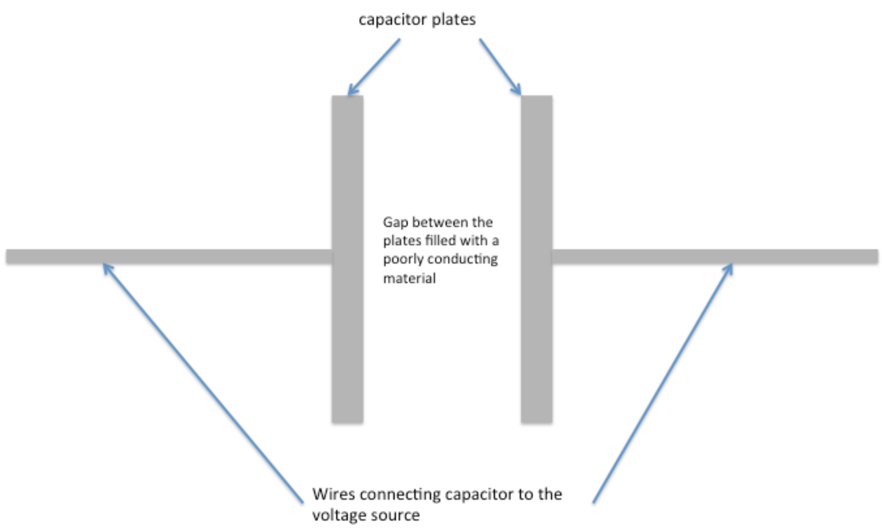

Figure 3: Basic geometry of a capacitor

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When the capacitor is hooked up to a voltage source, the electrons flowing from the voltage source start piling up on one of the capacitor plates while be attracted away from the other plate. Initially, the voltage across the plates is 0 volts until the charges start accumulating. As electrons exit one plate, they leave behind positively-charged vacancies. As electrons simultaneously gather on the other plate, it might *appear* to the rest of the circuit that electrons are flowing through the gap even though no electron will breach it (see Figure 4).

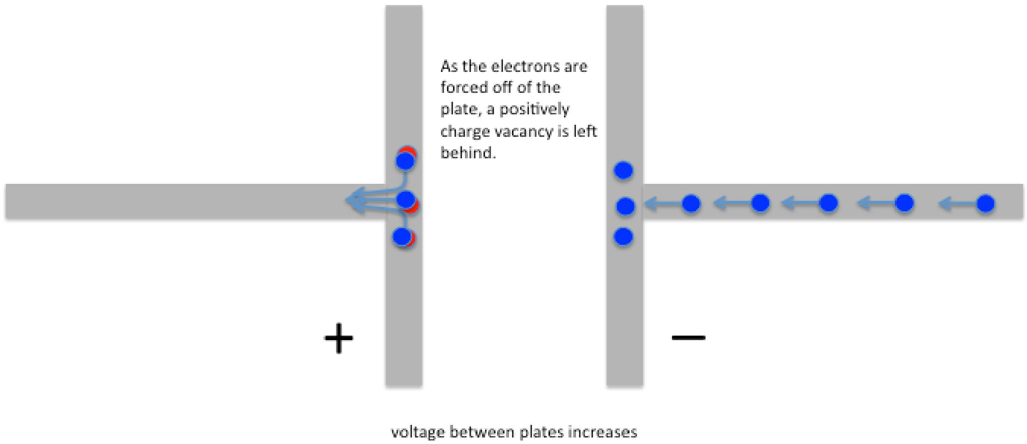
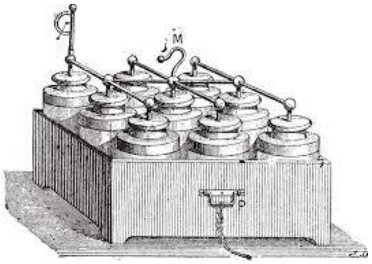


Figure 4: Electrons are flowing onto the rightmost plate pushed along by a voltage source connected to the capacitor.

This process continues but as more electrons accumulate (on the right plate of Figure 4), it becomes more difficult to add more electrons because of the presence of the other negative charges already on the plate. The accumulated charge sets up a voltage across the gap so that the force needed to add more electrons increases. The process slows down and, in each time interval, fewer and fewer electrons are added. Fewer positively-charged vacancies are created. The increase in voltage also slows down.

After a finite time interval the voltage cross the capacitor matches that of the source (see Figure 5 for a 1-volt charge) the process stops. If the voltage source remains constant, current will no longer flow, and the voltage across the capacitor remains constant as well. If the source is disconnected from the capacitor the stored charge should remain and can be stored to be used to deliver power at a later time. Storing charges in a bank of Leyden Jars was one of the first ways scientists used to store electrical energy.



A bank of nine Leyden Jars used to store electrical energy circa 1895

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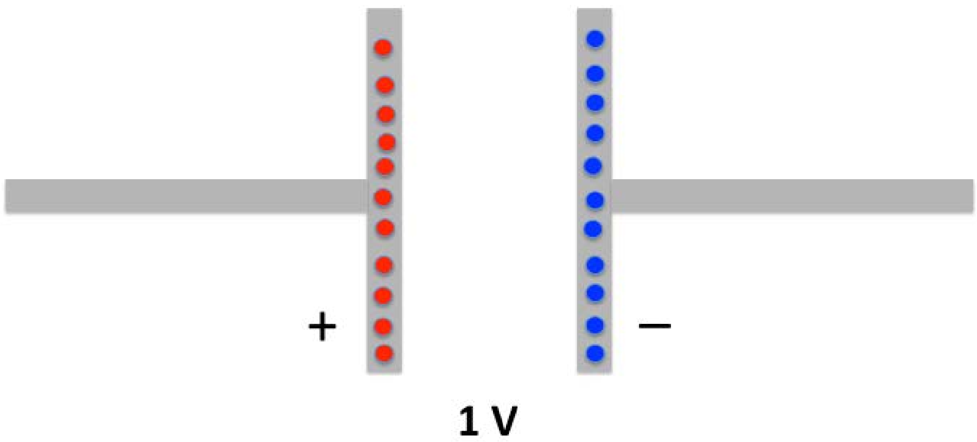


Figure 5: The capacitor is fully charged when the charges on the plates have created a voltage that is the same as the charging voltage source (assumed to be a 1-volt battery in this case).

Capacitance is defined as the amount of charge that any given geometry of conductors can hold for a given voltage. Mathematically this can be expressed as $C = Q/V$ or alternately, $Q = CV$. Since most capacitors at steady-state are maintaining an amount of charge that is nowhere near the limit of the material, the capacitor has a linear relationship between the total number of electrons and the voltage across the plates. Since the number of electrons on one plate equals the number of positively charged vacancies on the other plate, Q in this equation refers to the amount of charge on either plate. Since capacitance is not negative $Q = |Nq|$ where N is the total number of charges and q is the charge of each electron ***or*** positively charged vacancies. The unit of capacitance, like resistance, reflects the basic definition of the units. Since the I-V relationship for a resistor is $V = RI$ the constant *R* is measured in Ohms which is equal to *(Volts/Amps)*. The I-V relationship of the capacitor is $I = C\frac{dV}{dt}$. This is a differential equation that shows that the voltage and current have a time dependence. Recognizing that the current is really $I = \frac{dQ}{dt}$ the relation is written as $\frac{\Delta Q}{\Delta t} = C\frac{\Delta V}{\Delta t}$ where the derivatives have been replaced with the delta Δ notation. The relationship can be expressed as *Q=CV* making 1 *Farad* equal to 1 *Coulomb/Volt*.

What is a Capacitor?

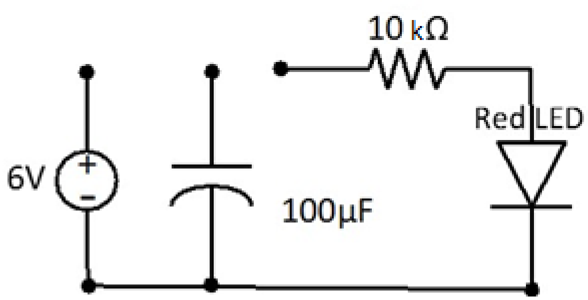
Procedures

Energy Storage Devices

While there are many different types of capacitors used in electronic circuits, the concept of a thing *having* capacitance applies to all matter. Some structures are better at storing electrical energy than other things. In the next section you will play with different parameters of a capacitor. First let's look at how electrical energy is stored. You will be using a capacitor, one like you might find in your computer or other electronic equipment.

This section will also give you respect for some safety issues that are associated with using capacitors. Before flat screen televisions there were TVs that used Cathode Ray Tubes (CRT) as the method of projecting the image. Older models used some very high voltage, high power capacitors that were so effective at holding their charge that repairmen servicing a broken TV had to make certain to discharge all the capacitors before starting their repair work. There are many stories of people dying from touching the terminals of a capacitor that was assumed to be "discharged" but still retained its charge even after the power was removed weeks before. The little capacitors in our kit are pretty safe.

- ✓ On a breadboard use build the following circuit using a red Light-Emitting Diode (LED), a $10\ k\Omega$ resistor, and an electrolytic capacitor with a labeled capacitance of $100\mu F$ (10e4). Below is the schematic and a suggested layout on the breadboard.



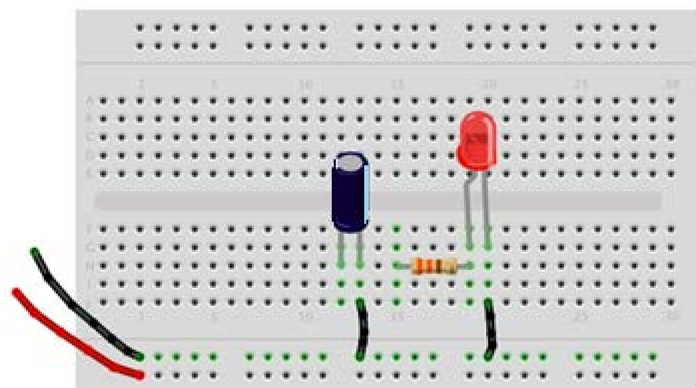
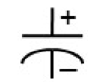


Figure 6: Circuit Schematic and Breadboard implementation for charging/discharging a capacitor.

This circuit is incomplete because you will connect it in two different configurations.

What is a Capacitor?

Notes:



Symbol for the Electrolytic capacitor. It has a polarity – one lead is considered positive and the other negative (shorter lead). If it is charge with the wrong polarity IT WILL self-destruct. If you are lucky it will do so with a loud pop.

Notes:

Step 1: Charge the Capacitor

- ✓ Set the power supply voltage to 6V.
- ✓ Connect the power supply to the breadboard as shown in the figure above – along the breadboard's power buses.
- ✓ Connect the capacitor circuit to the 6V supply

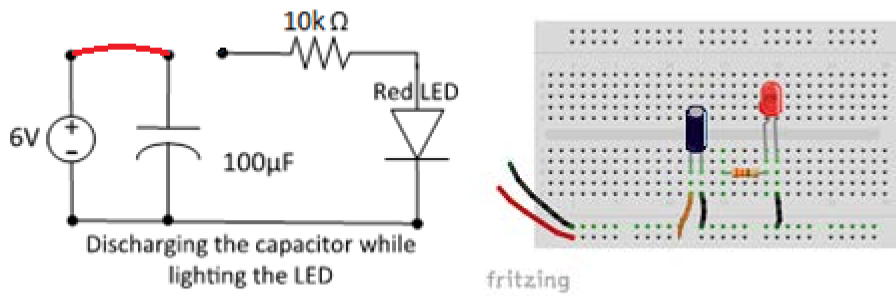


Figure 7: Charging the Capacitor.

- ✓ Disconnect the 6V and return the circuit to its original disconnected state.

The capacitor should be charged. Since the capacitor is outwardly undemonstrative let's check with a voltmeter.

Answer Question 1.

Step 2: Light the LED

The capacitor is now holding enough charge such that the voltage across the leads is near 6 V. Later in the semester you will study diodes. The LED is a special diode that lights up when the voltage across the terminals of the device reaches a certain value. Since the LED takes so little current to light up it is ideal for hobbyist projects and is fast becoming the primary mode of lighting. A red LED draws larger currents when it has about 1.7 volts across it.

- ✓ Connect the capacitor to the LED making certain the polarities line-up as shown in the schematic (the longer wire of the LED should be on the "left" in the physical diagram).

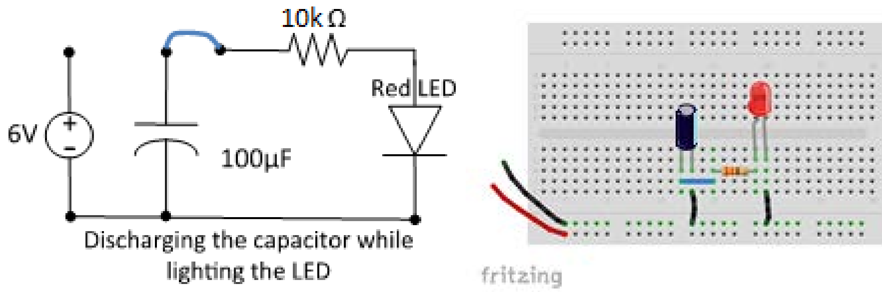


Figure 7: Discharging the Capacitor.

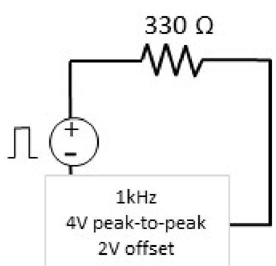
Answer Questions 2 and 3.

Effect on time-varying signals

Besides storing energy the capacitor has another characteristic that is exploited in many circuit designs. The capacitor has time-dependent behavior – mathematically this means that the I-V relationship includes a derivative $I = C\frac{dV}{dt}$ where *C* is the capacitance. If the time variation of the signal is fast enough the capacitor cannot fully charge and discharge completely. Let's see how this affects a square wave. The square wave is a difficult signal to produce because it requires abrupt changes in voltage. Realistic physical constraints prevent sudden changes in voltage, so the square wave is often used to show the characteristics of the transient (time-varying) behavior of circuits.

If a resistor is connected to the signal generator, from Ohm's Law you would expect to see the square wave supplied by the signal generator and the current flowing through the resistor $I = \frac{V}{R}$ so let's test how the individual components, the resistor and capacitor, affect the square-wave.

- ✓ Build a new circuit with only the resistor.



Notes:

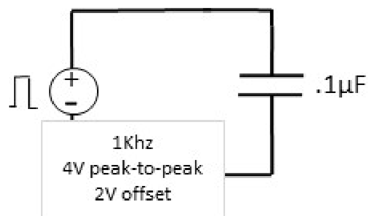
Though more and more signal processing can be done inside the computer, hardware filters are still used to modify a signal like that coming from the terminals of your car's radio antenna.

Notes:

- ✓ Probe the voltage across the resistor with channel 1 of the oscilloscope.

Answer Question 4.

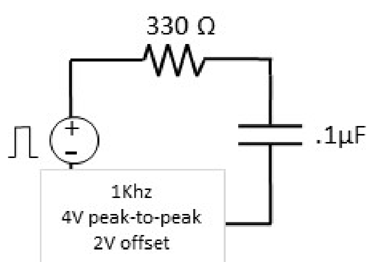
- ✓ Now take out the resistor and put the square wave signal across one of the capacitor that comes in your kit. Use the one labeled **104**. In the weird and wacky world of capacitor labeling the number 104 means that the capacitance is 10*10000 picoFarads. What does pico mean as a prefix?



- ✓ Probe the voltage across the capacitor with channel 1 of the oscilloscope.

Answer Question 5.

- ✓ Now put the resistor and the capacitor in series and connect the square wave signal.



- ✓ Probe the voltage across the capacitor with channel 1 of the oscilloscope.

Answer Question 6.

The resulting waveform when the capacitor is included in the circuit has rounded corners. Where the square wave was crisp and square across the resistor, all the transitions are smoothed when the capacitor is added. When the resistor and the capacitor are both in the circuit the amount of smoothing changes. With larger values of resistance or capacitance it takes longer for the voltage to reach the DC values of 4 or 0V. In fact, by judicious choice of *R* and *C* you can control this time interval.

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Increase the frequency of the square-wave while watching what happens on the oscilloscope.

Answer Question 7.

Experiment with making a capacitor

The devices we call capacitors are optimized through the choice of the most suitable **material and geometry**. All capacitors are built using two conducting “plates” in close proximity separated by different materials depending on the type of capacitor. The main factors that determine capacitance involve characteristics that affect how much charge can be stored:

i. The surface area of the plates A – often they are both the same size. The larger the area the more charge that can be stored.
ii. The distance between the plates *d* – the closer the plates are the more the positive charges mitigate the forces the electrons exert on each other so more charge can be accommodated.
iii. The material in-between the plates can affect the ability of the capacitor to store charge as well. The material property is characterized by a parameter called the permittivity ϵ that is a measure of how deformable the molecules inside the material are when subjected to electromagnetic forces generated by the charges on the capacitor plates. You will learn more about this concept in your physics and engineering classes.

With easy to use materials – metal plates or aluminum foil and paper – you will explore how the size of the plates and the separation affects the capacitance.

Unfortunately, your ECE 110 lab bench equipment cannot directly measure the capacitance of a device. Such equipment exists but learning to estimate the capacitance of devices without special equipment is valuable as you might not have the proper equipment out in the field. You need a capacitor and your eyes are too old or cannot read the markings, or you forgot the somewhat cryptic labeling convention.

✓ Build a circuit similar the one used in the previous section except replace the resistor with a 1MΩ resistor and remove the capacitor. The capacitor is to be replaced by one that you build.

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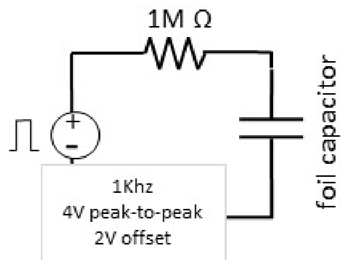

- ✓ Cut two pieces of aluminum foil the size of a sheet of paper. Make a capacitor by inserting a piece of paper between the two pieces of foil. Ta da! a capacitor.
- ✓ Attach an alligator clip to each piece of foil. The placement is irrelevant but be sure that the pieces of foil DO NOT touch and the alligator clips do not short.
- ✓ Attach the alligator clips to banana cables which have adapters attached that allow the ends to connect to the breadboard. Insert the foil capacitor into the circuit.
- ✓ Apply the 1kHz, 4V peak-to-peak square wave with a 2V offset as the power source as before.
- ✓ Probe the voltage across the capacitor on channel 1 of the oscilloscope.

Hopefully, you see a similar waveform on the oscilloscope. The capacitance is related to the distance between the plates. Push down on your capacitor and describe what you observe happening to the waveform on the oscilloscope.

Answer Question 8.

- ✓ Using the same circuit but cut your capacitance in half. HINT: Capacitance of a parallel plate capacitor is given by $C = \epsilon \frac{A}{d}$ where "permittivity", ϵ, and distance between the plates, d, are not as easy to change as area, A. Just cut the area of the foil in half.

Answer Question 9.

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Module 006: What is a Capacitor?

Question 1: Using the DMM, measure the voltage across the capacitor and record the value.

Question 2: Describe what you observed during the discharge of the capacitor. That is, explain the behavior of the LED with respect to time.

Question 3: Measure the voltage across the capacitor and record the value. It might not be zero. Can you explain this considering that the red LED draws much less current when operated below 1.7 volts?

Question 4: Draw or plot the waveform across the resistor. Comment if you can.

Notes:

Question 5: Draw or plot the waveform across the capacitor on top of the one you drew in the previous question. How are they different? Explain the difference. *This is a tricky question because, mathematically the voltage across the capacitor should follow the voltage of the function generator so that the differences between the two would be imperceptible.

Question 6: Draw or plot the waveform across the capacitor (now with a resistor in the circuit) on top of the one you drew in the previous question. Describe the difference in the plots.

Question 7: Describe what you see as the frequency changes and provide an explanation.

Question 8: Explain what you observe as you press on the capacitor. Plot the waveform obtained with no pressure and a wave form obtained while pressing down on the foil.

Question 9: When you are not pressing on the foil capacitor how does the waveform of the smaller capacitor compare to that obtained in Question 8? Explain the difference.

What is a Capacitor?