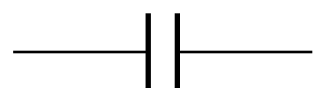
Name___________________________

Unit 5 : Introduction to Capacitors

In this short unit, you will work a bit with a device known as a capacitor. If you are already an electronics expert and know all about capacitors, please don't give away too many surprises to your partners, and make sure they make the circuits!

The small (about 3 cm in diameter, 1 cm high) green shrink-wrapped disks are electronic devices known as capacitors. You are going to attempt to discover why they behave in their own peculiar way in circuits with batteries and bulbs. With these capacitors, use two batteries in series (3 V total) and one of each of the bulbs (one round and one oblong). **Do not use the power supplies** because voltages greater than 5 V will destroy the capacitors, which are not cheap! Later, you will use other less expensive varieties--including some you make yourselves!

You are also asked to draw diagrams of your circuits. To do this, you need to know what a capacitor symbol looks like (with connections to left and right):



The symbol looks similar to that of a battery, but for the capacitor, the two bars are of equal length.

Guidebook Entry V.1: Series Bulb and Capacitor

a) Connect a bulb (either variety) to the batteries (which I will from now on refer to as a single battery for convenience) to recall how bright it normally is, and to make sure it is working. Then, disconnect the battery, and connect the bulb and a green capacitor in series. Finally, reconnect the battery. Record your observations, including a circuit diagram.

b) Disconnect the battery--what happens?

c) Now take the two clips that were connected to either end of the battery, and connect them together. What happens?

You should have clearly seen that the capacitor is a very different circuit element from anything we've used in this course so far. If you haven't observed this, check with an instructor now.

Guidebook Entry V.2: Parallel Bulb and Capacitor

a) Connect a bulb (either variety) and a capacitor in parallel. Then connect the parallel combination to the battery. Draw a circuit diagram, and record your observations.

b) Based on what you saw in the series case, what do you predict will happen when you simply disconnect the battery?

c) Disconnect the battery, and record your observations. Was it what you expected?

d) Reconnect to the battery, and let the circuit stabilize. Based on what you saw in the series case, what do you predict will happen when you disconnect the battery and promptly connect the two leads that used to go to the battery to one another?

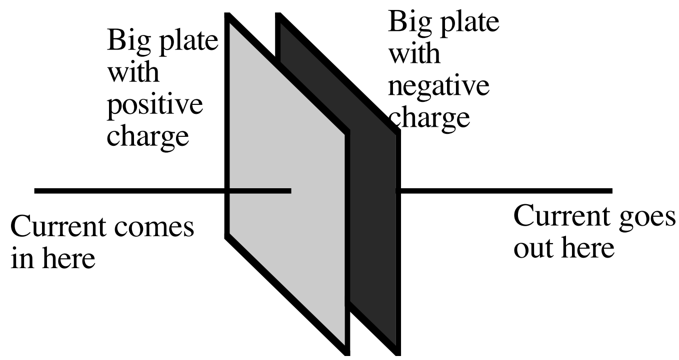
e) Test your predictions for part d) and record your observations. Was it what you expected?

Guidebook Entry V.3: Dependence on Bulb Type

a) The round bulbs are lower resistance models relative to the oblong bulbs. In other words, when connected to the same battery, the round bulbs draw a lot more current than the oblong bulbs. See what difference this makes on the time dependence of the effects you have seen. Use whatever capacitor circuit you like to investigate this. Draw your circuit, describe your test, record your results, and see if you can explain what is happening.

b) Before you go on to the next page, explain in your own words how you think the capacitor works. You may use any analogies you like if helpful.

A capacitor works by storing the electrical stuff that is the substance of electric current. This stuff, which we call charge, comes in two flavors, positive and negative. And much like the poles at the end of a magnet, opposites attract and likes repel. If we want to store some of this charge, the only [electrically] useful way to do it is by storing the two types of charges separately (ordinary matter already has essentially equal amounts of positive and negative charge). We need then separate places to store the positive and negative charges. In addition, all the positive charge in that storage place will be repelling one another, requiring a large voltage (the electrical equivalent of a fluid pressure) to keep it in place. A well designed capacitor gets around some of this by making the storage places very large, and locating the positive and negative areas close to one another, so as to take advantage of the attraction between the opposite charges on the plates. An example is sketched below. This also explains the symbol for the capacitor–two parallel conducting plates.



To help you get a better idea of how this works, we will have you build some capacitors, and see how the capacitance (a larger capacitance means you can store more charge for the same voltage) depends on the area of the storage regions and on how close together we place them.

Guidebook Entry V.4: Making and Measuring Capacitors

The technique we will use for making capacitors is to place two sheets of aluminum foil parallel to one another. This geometry for a capacitor is called a parallel plate capacitor. You will use an electronic multimeter with a capacitance scale to measure the capacitance. To make sure that the foils stay parallel to one another, and don't touch, place them within a thick textbook. When you cut out your foil, make sure to make connection tabs that stick out of the pages in different places so they don't touch. These then must be clip-lead connected to the wires stuck into the appropriate holes in the meters.

a) How do you think the capacitance will depend on the area of the plates? Will larger areas mean larger or smaller capacitances? Discuss your prediction with your partners, and write your reasoning below.

b) Make at least three different sets of foils with different areas. Place each set in the textbook about 20 pages apart, and measure the capacitances (press the book down to make sure the foils are flat and parallel). How does the capacitance depend on area? Did it agree with your prediction? Make a table of your data, and graph it, attaching your results below.

c) How do you expect capacitance to depend on the spacing between the plates? Discuss with your partners and explain your conclusions.

d) Make the measurement of capacitance versus spacing. Number of pages makes a convenient measure of separation. [Note: when the spacing becomes very small, the capacitance is greatly affected by how much you press on the book, so data with only one or a few pages separation might not be very reliable.]

e) Try to find a mathematical expression that gives the dependence of the capacitance on area and separation of the plates. See if you can even get the units and constants right (capacitance is measures in farads, with prefixes of micro, nano, and pico which correspond to ten to the -6,-9, and -12 powers).

f) Can you think of a way of building a much larger capacitor without using a much larger book? Brainstorm with your partners, and if you have time, try building one.

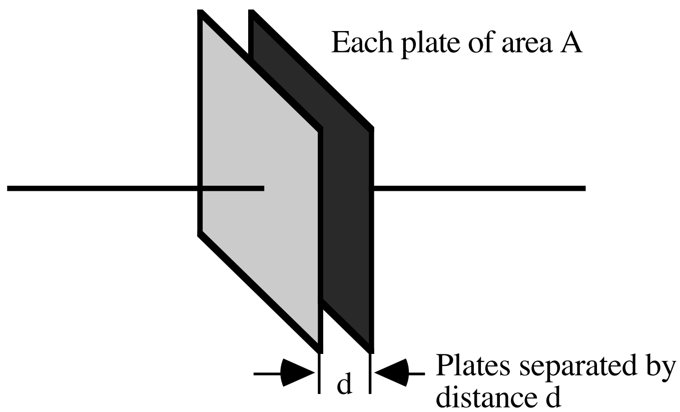
Now that you have made your own capacitors, it is a good time to look at a few commercially made capacitors, and see how they compare.

Guidebook Entry V.5: Measuring Capacitance

a) Take a couple of the capacitors (NOT the green ones you started with) on the equipment cart and measure their capacitance with the meter. Can you find any markings on the capacitor that seem to relate to the measured values? Record below your values and the markings.

b) Look again at the green capacitors we started with. What value is marked on them? Is this large or small compared to the ones you made? The commercial ones? Typically how much larger or smaller (in terms of the ratio of capacitances)?

You should have found in the previous exercises that the capacitance depended linearly on the area of the plates, and inversely on the separation of the plates. In other words, if I have two plates forming a capacitor



with spacing of d and each plate of area A, then the capacitance is proportional to A/d.

We described the electric current to be a flow of charge, and that charge is what builds up on the capacitor plates. So, if some current is flowing in through a capacitor lead, the plate to which that lead is connected will have the charge on it changing such that the total charge Q on that plate is related to the current I through the equation

$$I = \frac{dQ}{dt}.$$

This charge Q has units of Coulombs (abbreviated Coul. or C), such that Amperes are Coulombs/second. Conversely, one can find the charge on the plate at any time by integrating the current:

$$Q(t) = \int_0^t I\,dt \ .$$

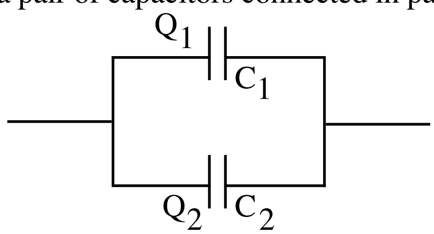
In a later unit we will verify the fact that the capacitance as we measure it with our meters relates to the charge and voltage through the relationship

$$C = Q/V \ .$$

We can take this relationship to be the definition of the capacita
(although we have not yet shown that the voltage is proportiona
charge on a capacitor). In the next activity, you will use this rel
predict what happens when you connect two capacitors in parall
what equivalent single capacitance results.

Guidebook Entry V.6: Parallel and Series Capacitors

Consider a pair of capacitors connected in parallel, as shown.



If the voltage across C_1 is V, then what must the voltage across C_2 be?

Since charge is the integral of the current, then current conservation implies charge conservation. In other words, whatever charge is stored on the two capacitors must have all come in through the same wire. If that is so, and charges Q_1 and Q_2 are stored on the left-hand plates of C_1 and C_2 respectively, what is the total charge that must have come in on the left hand wire?

Now, knowing that the capacitance is defined as C = Q/V, what must the effective capacitance of these two capacitors in parallel be?

Take two capacitors (with capacitances you can easily measure) of near equal value. Measure and record their capacitances.

Connect them in parallel. Using your formula above, what do you predict the effective capacitance should be?

Measure the capacitance of the parallel combination. Does it agree with your prediction?

You should have found a formula that looks like the formula for series resistors. It is therefore plausible that the formula for series capacitors looks like the formula for parallel resistors. Making this guess, predict the effective capacitance for your two capacitors in series.

Make the series connection and measure the capacitance. Does it agree with your prediction?

Session 2: Charge and Current in Capacitors

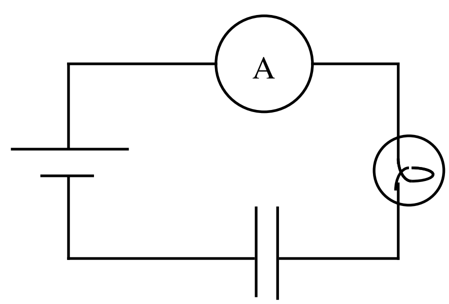
In this session, we will consider briefly how current flows in capacitors, and thereby try to understand more completely how charge is stored in a capacitor.

We are told that capacitors have no connection between the two terminals. Yet somehow current seems to flow through them--we were able to light a bulb with a capacitor in series. This seems to contradict our experience that current will only flow when there is a complete circuit! Let us use our meters to measure what is actually happening.

Guidebook Entry V.7: Current Flow in a Capacitor

Does current really flow through a capacitor? To answer this question, let's first look at the resistance of a capacitor. Take one of the small commercial capacitors and measure the resistance of it with the BK digital meter. What value do you get?

If the resistance of a capacitor is very large or infinite, then how can we actually get a light bulb to light through one? Is current actually flowing? To answer this, connect an ammeter (**use the Simpson meter** on the 500 mA scale) in series with the [small]capacitor as shown.



Describe what the current readings are after connection to the battery.

Try measuring the resistance of one of the green 1 or .47 F capacitors. What does the meter do?

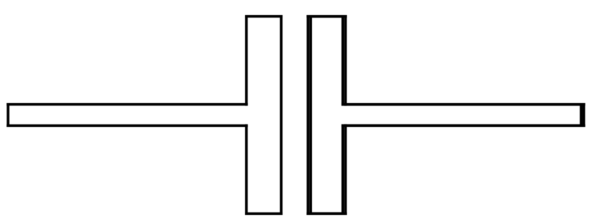
The resistance meter works by passing a small current through the resistor, and seeing what voltage difference that requires. Why might it be difficult for the meter to measure that capacitor with a very large capacitance?

Electrical current comes from the motion of electrical charges--ions or electrons--through the conductors. Virtually all of the electrical current that you have dealt with is the motion of nearly free electrons in metals. An important exception is within the battery, where ion motion is critical to the operation of the battery. Electrons have a negative charge, so motion of electrons to the left in a conductor produces the equivalent of positive charge moving to the right, which is a current to the right.

We claimed earlier that capacitors worked by building positive charge on one surface, and negative charge one the other plate in equal amounts. In fact, all metals consist of equal mixes of negative and positive charges, but only some of the negative charges can move. In the next activity, we will consider conceptually and experimentally whether the equal balance of positive and negative charges makes sense.

Guidebook Entry V.8: What and where is this charge?

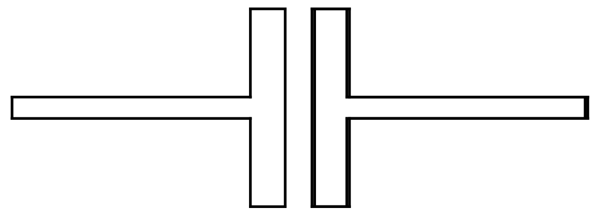
Shown below is a blown up sketch of a capacitor. Imagine the leads go off to the left and right as part of a larger circuit, probably containing at least a battery. Sketch in equal numbers positive and negative charges (you can use + and - marks) on each plate. That is, for example, put 5 + marks on the left plate, 5 + marks on the right plate, 5- marks on the left plate, and 5- marks on the right plate.



Now redraw the charges on the sketch below in a way that accomplishes the following:

1) There are the same total number of positive charges and the same number of negative charges, since they can't be destroyed.
2) There are the same number of positive charges on each plate as above, since they cannot move.

3) There is a net positive charge (positive less negative charges) on the left that is equal in magnitude to a net negative charge on the right.



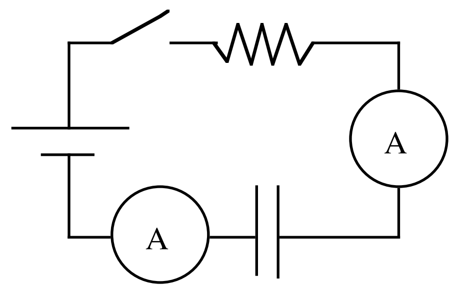
How many negative charges moved onto the right plate in your figure?

How many negative charges moved off the left plate in your figure?

These moving charges represent a current. Draw in arrows representing the current flow on both the left and right leads of the capacitor figure above. Is the current on the left lead the same as that on the right lead?

Can you tell from the leads whether the current is actually flowing through the capacitor or just building up on the plates? In other words, can you explain how it can seem as if current flows through the capacitor (and lights a bulb, for example) when no charges actually can move from one plate to the other?

Now, lets check to see if the current through either lead really does balance as we claimed. Build the circuit below with a resistor of somewhere between 100 and 1000 Ω. Use two digital meters on the current setting on either side of the capacitor. Make sure the meters are set to the current setting just above V/R.



Monitor the ammeters and write down the current values at several different times as the capacitor charges.

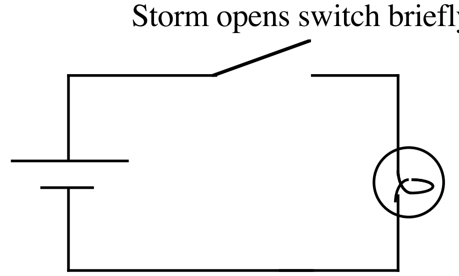
Does it appear that each plate charges equally?

Many of you have asked "yes, but what good are capacitors." Capacitors are used either because they store charge, or because they take time to charge and discharge. In the latter case they are often used in electronic timing circuits of various types. As charge storage devices, they might be used for memory purposes (charged = 1, discharged = 0), or to save charge to release very quickly (as in a photographic electronic flash). In the next example, we will investigate another extremely common use of capacitors.

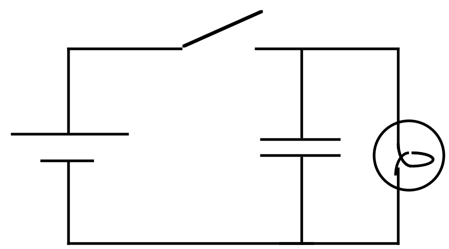
Guidebook Entry V.9: A Practical Capacitor Application

Imagine that we have a light that serves an important purpose--perhaps it is lighting a hospital operating table. The power in the hospital suffers from very brief black-outs of duration of less than a second due to a terrible electrical storm. We can simulate this with the following circuit:

Storm opens switch briefly



Build this circuit, making use of an oblong bulb. Use the switch to simulate these brief blackouts. This would not be a desirable working situation even for a physicist, let alone for someone performing brain surgery! Let's see if we can give the patient and the surgeon a fighting chance. Add one of the green capacitors to the circuit as shown.



Now describe what happens when you briefly flip the switch.

Explain why this works this way, and why it doesn't turn off the bulb as it did in series.

The circuit you examined in the above exercise is not so practical in an operating room, but exactly that concept *is* used in many applications. For example, your digital clock can survive a brief (few seconds) power outage and still remember the time, thanks to a circuit like that.

Now that you have a good notion of charge conservation on capacitors, let's return to a problem to which we just guessed the answer, and now solve that analytically. Just as we did with the parallel capacitors (and analogous to our series and parallel resistor cases) we define the effective capacitance as the total charge supplied (say by a battery) divided by the total voltage difference over the combination.

Guidebook Entry V.10: Series Capacitors

Draw a circuit with C_1 and C_2 in **series** with a battery of V_0. Do the two individual capacitors store the same charge as one another, or do they each have the same voltage difference across them? Why? Check your answer with an instructor.

Use your answer to the above question to help you write expressions for the *total* voltage difference and the *total* charge in terms of the voltage difference and charge on each capacitor.

Now use $C_{eq}=Q_{total}/V_{total}$ to derive an expression for C_{eq} in terms of C_1 and C_2.

You should have found these rules for series and parallel capacitors:

$$1/C_{series} = 1/C_1 + 1/C_2$$

and

$$C_{parallel} = C_1 + C_2 \quad .$$

Compare this mathematical result with your earlier observations and guess for the series case: that parallel capacitors increase the capacitance and series capacitors decrease it. Does it agree? Give a calculated example for each.

Now verify your understanding of series and parallel capacitors by drawing a circuit that includes at least one set of series and one set of parallel capacitors.

Choose several capacitors (same number that you used in your example above) of roughly equal capacitance. Measure their capacitances and write those values below.

Build the circuit you designed with your capacitors, and calculate the equivalent capacitance using parallel and series rules.

Now measure the capacitance of your circuit. Does it agree with your calculation? If not, find your mistake!

Name________________________________

Session 3: Charge, and Charge Conservation

In this session, we will use our large (half farad) capacitors with a new device known as a digital oscilloscope to make some quantitative charge measurements. In the process, we will learn a bit about how voltage and charge are related in capacitors, and verify the important principle of charge conservation. We will then apply these principles to discover the time dependence of the charging and discharging process in a capacitor.

The oscilloscope is a voltage measuring device. Since we want to measure current or charge, we first need to have a good method of measuring current flow with the oscilloscope. The easiest way to do this is to include a resistor in series with our circuit and measure the voltage across the resistor.

Before you do any measurements, it is good to get the oscilloscope set roughly right. Turn the oscilloscope on with the button on top. After the self-test is finished, press the autoset button on the top row of the front panel. The oscilloscope will now be ready to make graphs of voltage (vertically) versus time (horizontally). Adjust the time scale with the farthest right of the three large knobs on the front panel to its maximum scale by turning it counterclockwise (which gives a scale of 5 seconds per centimeter). Adjust the vertical scale (left most knob) to read about one volt per centimeter. Don't hesitate to ask for help; this is a complicated instrument!

Guidebook Entry VI.4: Measuring Current with the Oscilloscope

First, you should try duplicating graphs of voltage versus time for charging and discharging capacitors. Using a half Farad capacitor and two 1.5 volt batteries in series with a bulb, connect the oscilloscope connections across the capacitor. Charge and discharge the capacitor, and verify that you are getting reasonable graphs before moving on. If you have any trouble, ask for help.

Next, we need to know what size resistor we need to produce usable voltages. To do this, use a current meter in series with two batteries and an oblong bulb to see how large a current we will be dealing with. Write your result below.

We would like the voltage across our measuring resistor to be small relative to our battery voltage of 3 V. However, a very small voltage will be hard for the oscilloscope to measure. Let's choose about a half volt as a compromise. What resistance will produce half a volt when the current you measured above passes through it?

We have a variety of resistors. Pick one that is comparable (a factor of two or so) to your value in the previous section.

Now you should verify that the oscilloscope can measure a voltage that is proportional to the current. Build a circuit that includes the battery, the resistor, a light bulb, and the current meter in series. Use the oscilloscope to measure the voltage across the resistor. Record the voltage from the computer and the current from the ammeter, and verify that they are proportional. Explain how you test for this proportionality!

Does your result agree with Ohm's law and your measured resistance?

What is the conversion factor that converts volts measured by the oscilloscope across the resistor into current in

Amperes? You will use this value again in the next activity.

In the last session we observed some direct effects of charged objects such parallel plates, which were essentially charged capacitors. We claimed that the current that flowed to charge those capacitors was really a flow of individual charges. If this is true, then the current must be the time rate of change of charge on one of the capacitor plates:

$$I = dq/dt$$

where I is the current in the circuit and q is the charge on the plate. No current flows *through* the capacitor, of course: current flowing in the circuit results in a pile-up of charges on the capacitor plates. If we measure our current in Amperes, and our time in seconds, then the charge as defined by the above equation is in Coulombs. We can also consider this as the time rate of charge passing any point in a circuit, just as we did for fluid flow.

We can then turn this around, and find the charge on a capacitor by doing the inverse operation of differentiation, i.e. *integration*. This is simply the area under the current-as-a-function-of-time graph. The oscilloscope will not do this directly, but it will calculate an average value using the "mean" command. This is in an on-screen menu that you access by hitting the "measure" button on the top row. The integral is just the total time per sweep times the average value.

First we will see how the charge stored depends on the charging process. To do this, we will charge the capacitor two ways--once through a light bulb, and once through a resistor. Since the light bulb does not behave Ohmically, there will be a qualitative difference between the two charging graphs. You will see if the charge stored depends just on the final voltage or also on this charging process.

Guidebook Entry VI.5: Charge on a Capacitor--Dependence on Charging Process

Here you will again look at the process of charging a capacitor, only now you can look more quantitatively. You no longer need the current meter, since the oscilloscope will measure voltage as a function of time and you can easily translate this to current versus time. Explain below how you will actually do this, including a circuit diagram and your voltage to current conversion factor.

With the series circuit of two batteries, a capacitor, a switch, our resistor, and a light bulb, measure the current (as indicated by the resistor voltage) vs. time while charging the capacitor. (Make sure that the capacitor is fully discharged first.) Sketch the oscilloscope trace below.

When a capacitor has stored the maximum possible charge on its plates (for a given voltage), we say that the capacitor is "fully charged". How much charge should the capacitor hold when it reaches the battery voltage (i.e. when it is fully charged) as predicted by C=Q/V.

Use the measurement mode to measure the integral of the voltage across the resistor (which indicates the current) from the time that you start charging until the capacitor is fully charged. What is the result of this integration?

Using your conversion factor from GE VI.4, convert your integral value to Coulombs. Is it reasonably close to your prediction for the stored charge?

You should notice that your discharging graphs looks almost linear for most of the process with a light bulb. Now remove or short out the light bulb so that the charging of the capactitor will occur through the resistor alone. Discharge the capacitor by connecting a single clip lead across its connectors for about 10 seconds, and then take a set of charging data like you did above. How does the shape of the I versus t graph differ from the data with a light bulb? Sketch it.

Calculate the total charge on the capacitor in this circuit by integrating the curve. How close is it to the value that you got before?

Guidebook Entry VI.6: Charge on a Capacitor--Charging versus Discharging

Next you will measure the current that flows *out* of the capacitor after it is charged (either through a bulb, or just through your resistor). Discuss how to do this with your partners, and explain below how you plan to do this.

What do you expect to see when you do the experiment? Sketch your prediction for I vs. t.

Now run the experiment, and record your observations. Also paste in your graph. Compute the amount of charge which flowed out of the capacitor. How does it compare to the amount of charge supplied by the battery in the charging process?

You should have observed that all the charge supplied by the battery (in charging up the capacitor) appeared again in the form of current flowing from the discharging capacitor, at least within our measuring uncertainty of about 10% or so. This is an example of *conservation of charge*.

We found in earlier activities that Ohm's law, and implicitly therefore the notion of resistance itself, depended on the current through a conducting material being proportional to the voltage applied. We know that this is true for some materials (like Nichrome and pencil leads) and not true for other materials (light bulb filaments).

We have a similar situation with capacitance. The rule for capacitors that is equivalent to Ohm's law is C=Q/V, which for some reason has never been seen as adequately distinguished so as to deserve a name. This definition of capacitance depends on this linearity between charge and voltage. We had simply accepted this in the last unit, but now that we have a method of measuring the total charge stored on a capacitor, we have the techniques necessary to verify the logic of defining a capacitance, which you will do in the next activity.

Guidebook Entry VI.7: Charge on a Capacitor--Charge versus Voltage

We need to have a source of voltage to force charge onto a capacitor. To remind yourselves, write below the equation relating stored charge to the voltage on a capacitor.

Consider our typical circuit of battery, resistor, and capacitor in series. As you have observed, no current flows in the circuit after the capacitor is fully charged. With your capacitor fully charged, measure the voltage across each element in your series circuit. What is the voltage across the capacitor now? Across the resistor? Across the battery? Does Ohm's law still work? Discuss this with your partners and an instructor.

By now you should be practiced at measuring the charge on a capacitor. Discharge your capacitor, then measure the charge supplied to it by one battery. What is the voltage across the fully charged capacitor? Record your results below.

How does the charge stored by a capacitor connected to one battery compare to your previous measurement of the charge stored by a capacitor connected to two batteries?

How does the charge stored in a capacitor seem to relate to the voltage across the capacitor?

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In general, the capacitance depends only on the geometry of the capacitor - not on the applied voltage or the stored charge or the type of metal used for the plates. It can, however, depend on any material placed between the plates to keep them from shorting out (connecting). After we learn a bit more about electric fields and potential differences, we will be able to calculate (at least in principle) this constant simply from the geometrical measurements of the capacitor.

Guidebook Entry VI.8: A Discharging Capacitor

Draw a circuit diagram for a charged capacitor that is discharging through a resistor.

We know that the amount of charge we can store on a capacitor is directly proportional to the voltage across that capacitor, with the proportionality constant $C = q/V$. Also, the current I out of the capacitor is the time rate of change of the charge on the capacitor, or $I = -dq/dt$ (the minus sign indicating the current flow implies discharge, or q getting smaller). When we discharge a capacitor, the only elements in the circuit are the capacitor and the resistor. The capacitor is the repository of stored energy which causes the current to flow. Therefore, the voltage applied across the resistor is the capacitor voltage (somewhat as if the capacitor is acting as a battery in the circuit--you could have seen this applying a Kirchhoff loop rule). We therefore have two expressions for the voltage, that across R ($V=IR$) and that across C ($V=q/C$). Use these together to show that dq/dt is proportional to -q.

We've seen before that when the derivative of a function is proportional to the function that exponential solutions satisfy this, functions like we saw for a draining tube $h = h_o e^{-t/\tau}$. Write an analogous expression for the charge on a discharging capacitor, and find τ in terms of R and C.

Argue now that V is also a decreasing exponential function with the same characteristic time τ. This is important, since we can measure V with our computers, not Q.

Verify the relationship τ = RC for two resistances with a **big green capacitor (0.5 Farad).** For suitable resistances, use a couple of small resistors with values between 1 and 10 ohms. Measure the resistance with the digital multimeter. Use the oscilloscope to measure the characteristic time τ from the resulting exponential graph. The easiest way to do this is to measure the half time, or half-life $T_{1/2}$ and use the relationship $T_{1/2} = \tau \ln(2)$ (which you derived for draining fluid a few weeks ago).

Sketch your circuit below, and include the placement of the oscilloscope probes. Does the oscilloscope measure the voltage across the capacitor (which is proportional to the charge on the capacitor)? Does it measure the voltage across the resistor (which is proportional to the current through the resistor)?

Now measure the characteristic time for two different resistances:

C	R	measured $T_{1/2}$	[illegible]	τ ($\tau_{1/2}/\ln 2$)	RC

Do your results agree well with RC? How might you account for any discrepancy?