

Capacitors

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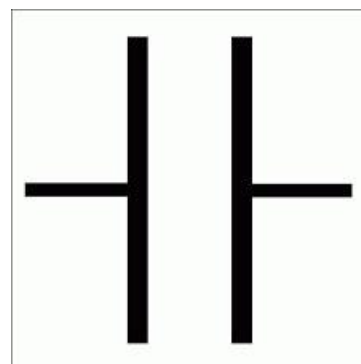
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Last year you learned about resistors, which play very important roles in electronic circuits. The line following robot circuits also contain two capacitors, but I have not had much to say about capacitors up to this point. Now that you are working on the IR module, it is time to learn how capacitors work. There are seven capacitors in the IR Module, but we will focus our attention on capacitor C6. Capacitor C6 of the IR module plays an important role in the voltage controlled oscillator (VCO) circuit that causes the IR emitter to flash on and off 38,000 times each second. In this paper you will discover why the capacitor is used in the VCO circuit.

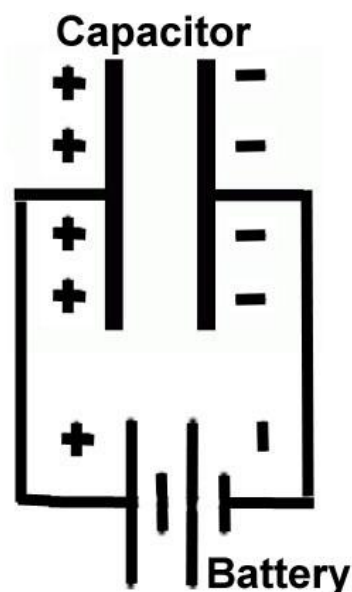
The first primitive capacitors were invented in the 1740s in Europe and were known as Leyden Jars. Scientists studying electricity at the time had to rely on static electricity for their experiments. There was a desire to store static electricity and it was found that this could be done in a glass jar, containing a metal rod inserted into the jar through an insulating cap. The famous American, Benjamin Franklin, used Leyden Jars in his experiments.

The GEAR junior group is currently working on an experiment with small Leyden Jars made from photographic film canisters. The canisters are plastic and have a snap-on plastic lid. Aluminum foil is wrapped around the bottom half of the outside of the canister and held in place with a metal wire. A metal paper clip is pushed through the cap so that it extends to the bottom of the canister interior when the lid is in place. Before snapping the cap in place, the canister is filled half-full with water. A negative charge is developed on the surface of a plastic pipe by rubbing it with cloth. Then the paper clip is passed along the surface of the pipe, which allows the electrons on the pipe surface to transfer to the inside surface of the film canister. At the same time, an equal number of electrons on the outside surface of the canister transfer to ground which results in a positive charge on the outside surface (in this case the person holding the canister is the ground, the electrons travel from the outside surface of the canister into the person). This procedure can be repeated many times to store a significant charge in the jar. When a wire is connected to the foil on the outside with its free end near the paper clip, electrons will jump across the gap causing a spark.

The symbol to the right is for a capacitor. In fact, the symbol is a good representation of a real capacitor. A capacitor consists of two metal plates that are relatively close together. However, the plates are not connected. Between the plates there is an insulator known as the **dielectric**. The insulator can be of a number of different materials: plastic (film), ceramic, air, etc. Remember an insulator is a material which does not conduct electricity.



If we connect a capacitor to a battery, as depicted in the schematic to the right, electrons will collect on the plate connected to the negative side of the battery. At the same time, electrons will leave the other plate of the capacitor and travel toward the battery's positive terminal. As a result, that plate will have a net positive charge. If we disconnect the capacitor from the battery, the capacitor will continue to contain the charges on the plates. Remember that unlike charges attract each other. The electrons on the plate to the right would like to travel toward the positively charged plate, but they cannot because of the insulating layer between the plates. Nevertheless, the oppositely charged plates will remain in that condition for a long time due to the electric field surrounding the two plates.



Now if we connect the two wires of the capacitor together, then the electrons on the negatively charged plate will travel toward the positively charged plate through the wires, which provide a pathway for discharge of the capacitor. These two characteristics of the capacitor, the ability to collect charge and the ability to discharge, are valuable in electronic circuits. They can be used for a variety of purposes.

Recall that we use the unit Ohm for resistance. For capacitance, we use the unit **Farad**, named after the famous British physicist, Michael Faraday. The Farad is a measure of the amount of charge that can be held on a capacitor when charged with one volt. *One farad is defined as the capacitance of a capacitor across which, when charged with one coulomb of electricity, there is a potential difference of one volt.* In other words, if we connected a one farad capacitor to a one volt source (DC source), the capacitor would charge until it contained one coulomb of charge. Well, we have a problem here. What is a coulomb?

Perhaps we should go back to our basic units used to measure electricity, volts and amps. Specifically, what is an amp (or ampere)? One amp is defined as the passage of one coulomb of charge past a point in a circuit in one second of time. Well, we still don't know what a coulomb is, but perhaps you can guess that it is a certain number of electrons. In fact it is a very large number of electrons, 6.241×10^{18} . That is the way an engineer or scientist would write it. Perhaps this is a more familiar form: 6,241,000,000,000,000,000 electrons. I have made an error here. Actually, a coulomb is the charge of 6.241×10^{18} protons since the unit is based on a positive charge. It is correct to state that a charge of negative one coulomb is equivalent to 6.241×10^{18} electrons.

If we connect our one farad capacitor to a one volt DC power source an excess of 6,241,000,000,000,000,000 electrons will collect on the negative plate of the capacitor. If we apply 2 volts to the same capacitor, then the negative plate will contain twice as many excess electrons. If we apply 100 volts to the same capacitor, then it will contain 100 times as many excess electrons.

Since we are on the topic of voltage, I should mention that capacitors are rated for the maximum voltage that can be applied. If a capacitor is marked as 35 volts, then we must not exceed that voltage.

The dielectric insulation of the capacitor can only withstand the rated voltage. Above that the insulation will break down and the capacitor will cease to function. It is good practice to always design your circuits with capacitors that have a maximum voltage rating well above the maximum voltage they will experience.

As it turns out, a one farad capacitor is very large. In electronic circuits we need capacitors of much less capacity. Typical capacitors are rated in units of microfarads (μF), nanofarads (nF) or picofarads (pF). There are one million microfarads in one farad, one billion nanofarads in one farad and one trillion picofarads in one farad.

As an exercise for this lesson, you will be making a capacitor with square plates that are 100 mm on a side with polyethylene film as the dielectric. We can use the equation below to calculate the capacity of a capacitor in farads.

$$C = (K)(E_0)(A/d)$$

where:

$E_0 = 8.854 \times 10^{-12}$ (or less confusing might be: 0.000000000008854) - E_0 is a constant named *permittivity of free space*

K is the dielectric constant of the insulating material, which for polyethylene is 2.25

A is the overlapping surface area of the plates in square meters,

d is the distance between the plates in meters

C is capacitance in farads

First we need to convert our measurements to meters:

100 mm = 0.1 meter and $0.1 \text{ m} \times 0.1 \text{ m} = 0.01$ meters squared, the area of our overlapping plates (A) (in our case the plates are the same area and totally overlap each other so this value is the entire surface area of one plate)

I measured the thickness of the polyethylene with my micrometer and found it to be 3.5 thousandths of an inch. We can convert that to millimeters by multiplying by 25.4: $0.0035 \times 25.4 = 0.089$ mm.

Therefore, the space between the plates, which is the thickness of the polyethylene, is 0.089 mm. We must convert that to meters by dividing by 1,000: $0.089 \text{ mm}/1000 = 0.000089$ meters thick. Therefore, d in the equation will be 0.000089 meters. Now let's calculate the theoretical capacitance of the capacitor you will make.

The equation: $C = (K)(\epsilon_0)(A/d)$

$K = 2.25$, $\epsilon_0 = 0.0000000000885$, $A = 0.01$, $d = 0.000089$

$$C = (2.25)(0.0000000000885)(0.01/0.000089)$$

$$C = 0.0000000022 \text{ farads}$$

Convert to nanofarads (nF) by multiplying by one billion:

$$C = 0.0000000022 \times 1,000,000,000 = 2.2 \text{ nF}$$

The theoretical capacitance of a capacitor with plates 100 mm X 100 mm, separated by a polyethylene film 3.5 thousandths of an inch thick will be 2.2 nF. Now you will assemble the capacitor and measure its capacitance with a meter to compare with the theoretical value.

What better way to learn about capacitors than to make one? That is what you will do now as an exercise. In order not to waste too much time, the materials for making the capacitor have been prepared for you. These are:

1. Two squares of aluminum foil, each 100 mm X 100 mm (the plates of the capacitor)
2. Two squares of polyethylene film, each 120 X 120 mm (the insulating dielectric)
3. Two short pieces of 22 gauge insulated wire
4. Some electrical tape
5. A pencil move down

Directions

1. Strip both ends of each wire
2. Using electrical tape, tape the bare end of a wire to each piece of foil, near a corner, as seen in the photo to the right.



3. Place one of the foil pieces on top of one of the film pieces – make sure the foil is centered on the film as seen in the photo to the right.
4. Now place the second piece of film on top of the foil
5. Place the last piece of foil on top of the sandwiched material
6. Carefully wrap the sandwiched material around a pencil with the foil touching the pencil. The two pieces of foil must not touch each other.
7. Wrap pieces of tape around the pencil so that the capacitor material does not unwind.



It is important that you wrap the material tightly around the pencil so that the foil pieces will be separated by only the thickness of the polyethylene film. In actuality this is very difficult to achieve, but do your best. If you wrap the sandwiched material loosely around the pencil, your capacitor will have much less capacitance than the theoretical value due to excessive space between the foil plates.

Now use a meter to measure the capacitance of your capacitor. If you did a good job, your capacitor should have a capacitance near the theoretical value.

Enter the value of the measured capacitance _____ nF

The theoretical capacitance was calculated to be 2.2 nF. **Is your measured capacitance close to the theoretical value? Yes or No (circle one).** Your measured value will probably be slightly less than the theoretical value because it is difficult to wrap the capacitor layers in a tight condition.

Congratulations, you have just made a capacitor of the film type. The plastic film called Mylar is commonly used as the dielectric in commercially made film capacitors. The capacitor you will use in the IR module for the Voltage Controlled Oscillator is a film type capacitor.

Another class of capacitors is sometimes called electrolytic or lytic (aluminum and tantalum capacitors are of this type). Electrolytic capacitors have a very thin layer of dielectric material. This material is formed on the positive (anode) plate of the capacitor by an electrochemical process known as anodizing. The word *electrolysis* is a general term used for chemical processes that are driven by application of a DC current. This process allows the manufacture of capacitors of high capacitance because the dielectric layer is very thin. If we look again at the equation for capacitance, notice that the thickness of the dielectric is d in the denominator. Therefore, the thinner the dielectric in a capacitor, the greater the capacitance.

Electrolytic capacitors have polarity requirements. If they are connected with the wrong polarity, the anodized layer will degrade, as the electrochemical reaction will be in essence, reversed. This can cause the capacitor to become shorted electrically, which can result in damage to the electronic

circuit containing the capacitor. That is why it is very important to observe the correct polarity when using electrolytic capacitors in your circuits. Remember, these capacitors are marked. Aluminum capacitors have the negative side marked and tantalum have the positive side marked.

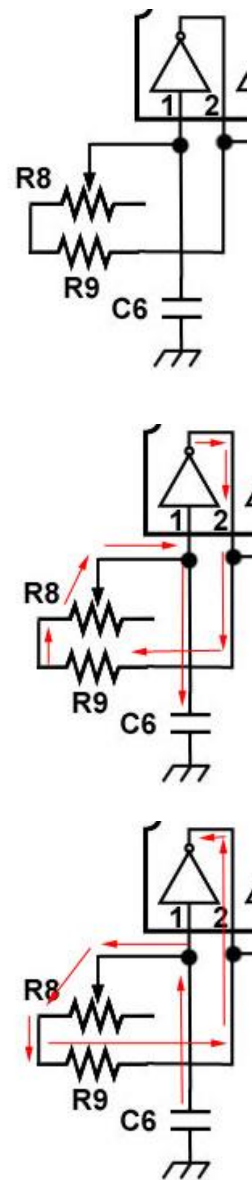
Question for you, do film type capacitors have a polarity requirement? YES NO

The schematic to the right is the voltage controlled oscillator of the IR module. The circuit includes one of the inverters of IC1, which is connected to pins 1 and 2. Pin 1 is the input and pin 2 is the output. An inverter does just what its name suggests, inverts the input. If we apply 0 volts to the input, then the output will be 5 volts. If the input is five volts, then the output will be 0 volts.

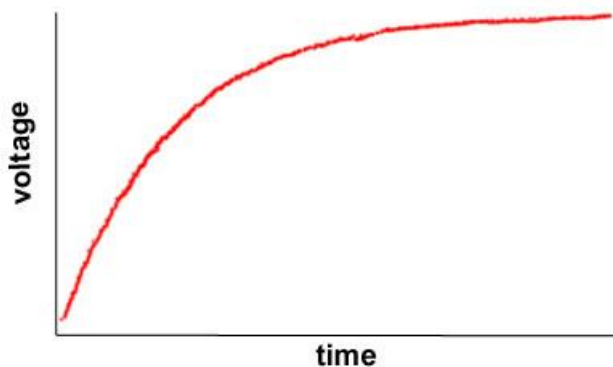
Let us take a look at what happens when power is applied to IC1. At the instant power is applied, there is 0 volts at pin 1 and a positive 5 volts at pin 2. In this condition, **positive** current will flow as marked in the second circuit to the right. It flows from pin 2 through resistor R9, then R8 and to the plate of capacitor C6, where an excess of positive charge builds. As the positive charge builds on the plate of the capacitor, the voltage applied to pin 1 begins to rise. At a certain voltage (about 3.35 volts according to IC1 data sheet) the inverter will switch the output to 0 volts. This is caused by the building voltage supplied by the capacitor. When pin 2 goes to 0 volts, then the C6 capacitor begins to discharge as seen in the third diagram to the right. Then the voltage supplied to pin 1 by the capacitor begins to drop. When the voltage drops to about 1.65 volts, the inverter switches again to output 5 volts to pin 2 and the cycle repeats. Here the capacitor is alternately charging and discharging at a rate that matches 38,000 cycles per second. That rate is controlled by the values of resistors R9 and R8 and the capacitance value of C6. If we increase the resistance in the circuit, the current flow will be reduced and it will take longer to charge the capacitor. Therefore, if we increase the resistance, we will decrease the cycle rate. If we increase the capacitance (keeping the resistance the same), it will take longer for the capacitor to charge to a given voltage level. Therefore, increasing the capacitance will also decrease the cycle rate.

How do we determine the values of resistance and capacitance to use in our circuit? In order to do that we need to understand the dynamics of a charging and discharging capacitor. To truly understand this circuit, it is necessary to apply advanced mathematics, which is not appropriate to the level of this lesson. But let us try to make some sense of this situation.

At first thought it may seem like an easy problem to solve. Is it not true that charging a capacitor is like filling a cup with water? Unfortunately, it is not. If we turn on a faucet in the kitchen and adjust the water flow to a constant rate, then the cup will fill with water at a constant rate. We can call this a linear process, which is easy to understand mathematically. The charging of a capacitor is not



a linear process. It is more like filling a tire with air. If the tire has no air pressure at all, when you first start filling it, the air rushes in quickly. But as the tire fills up, there is also an increase of pressure in the tire. This causes the rate of air flow into the tire to drop. Charging a capacitor is much like filling a tire with air. The more charge the capacitor contains, the slower it continues to charge until the voltage of the charge in the capacitor equals the voltage applied to the capacitor. At that point, the charging stops. We can say the capacitor is fully charged. And this charging rate is not linear. The fact that the process is not linear makes it more difficult to understand from a mathematical point of view. Perhaps the easiest way to come to an understanding is by taking a look at a graph. The red line represents the voltage of the capacitor as it is charging. Notice that in the beginning of the charging cycle, the voltage rises quickly. Later the rate of voltage increase is not as much. The charging can be expressed mathematically by the following equation:



$$V_c = V_s(1 - e^{-t/RC})$$

Where

V_c = voltage of the capacitor

V_s = voltage of the power supply

e = 2.718 (also known as Euler's number)

t = time (in seconds)

R = resistance in ohms

C = capacitance in farads

I don't expect you to be able to solve the above equation, but thought you might like to know about it. There is one part of the equation that we can use to help us with calculations. The term **RC** (resistance multiplied by capacitance) is known as the **Time Constant**. We can use the Time Constant in an easier equation to calculate the frequency of a voltage controlled oscillator. The equation for our circuit is at the top of the next page.

$$f = 0.92/RC$$

where:

f = frequency in Hz

R = resistance in ohms

C = capacitance in farads

Let us solve the above equation with some values I measured in the circuit on my breadboard. My oscillator was adjusted to a frequency of 38 kHz (38,000 cycles per second). The capacitor is 1 nF, R9 is 22.17 kΩ and R8 is adjusted to 1.99 kΩ, for a total resistance of 24.16 kΩ. We must convert the capacitance to farads by dividing by one billion:

$$1 \text{ nF}/1,000,000,000 = 0.000000001 \text{ F}$$

$$RC = 24,160 \times 0.000000001 = 0.0000242$$

$$f = 0.92/0.0000242 = 38,016 \text{ Hz}$$

Here we can see that the equation allows us to calculate the expected frequency of our voltage controlled oscillator by using the values of the resistors and capacitor. But I must confess that I derived this equation using the values of my capacitor and resistors. So it is no surprise that I got a good value for the frequency. To check this equation, we can try substituting another resistor on the breadboard and then check to see if the equation predicts properly the frequency. I decided to use a resistor of a much different value, 1.03 MΩ. Then I measured the frequency with my meter and found it to be 886 Hz. Let us see how close the equation will come to predicting this frequency.

$$RC = 1,030,000 \times 0.000000001 = 0.00103$$

$$f = 0.92/0.00103 = 893 \text{ Hz}$$

The measured value of 886 Hz compares favorably with the calculated value of 893 Hz, which demonstrates that the equation is valid for calculating the expected frequency of various resistor and capacitor combinations in our voltage controlled oscillator circuit.