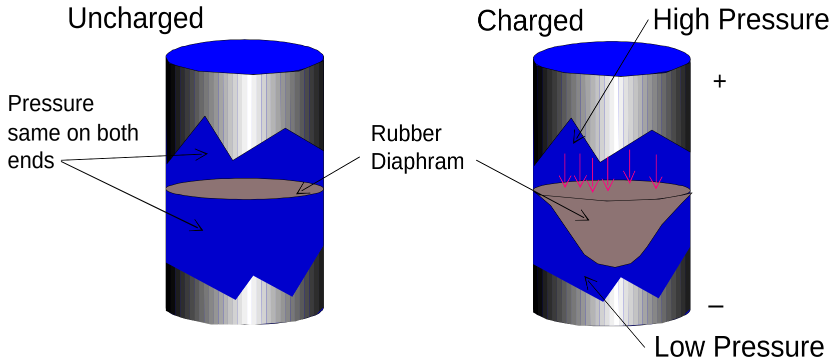
CAPACITORS

The Capacitor

The Capacitor, or electrical condenser, is a device for storing an electrical charge. In its simplest form a capacitor consists of two metal plates separated by a nonconducting layer called the dielectric. When one plate is charged with electricity from a direct-current, the other plate will have induced in it a charge of the opposite sign; that is, positive if the original charge is negative and negative if the charge is positive. The electrical size (not physical size) of a capacitor is its capacitance, this is a measure of the amount of electric charge it can hold.

In the electronic component called the resistor the reaction to voltage and current changes is instantaneous. In other words, if a voltage is placed across a resistor a current flows through the resistor instantly. The capacitor is a little different. This device stores electrons (or charges) and it takes time to push them into the device. The easiest way to understand the Capacitor is to look at its water pipe equivalent shown here.



The capacitor is equivalent to a water pipe with a rubber diaphragm stretched across the middle to block water flow as shown above. When the pressure is not the same on both ends of the pipe the diaphragm stretches and pushes back to equal the water pressure on the high pressure end. When the rubber pressure equals the water pressure the stretching stops and the capacitor is fully charged to that pressure. If the water pressure is then increased the process will continue until the capacitor is fully charged to the new pressure.

It takes time for the water to flow and charge the capacitor. If the pipes bringing the water have a high resistance it will take longer to charge the capacitor. If the diaphragm has more elasticity (fancy way to say it stretches easier) it will hold more water or it has a larger "Capacity" to hold water. If the "Capacitance" is larger it will take longer to fully charge it. The time to charge the capacitor is directly dependent on these two properties. A "time constant" for a given resistance and capacitance is equal to the

Resistance measured in ohms, times the Capacitance measured in farads. If "C" is used to represent capacitance, R for resistance, and "t" to represent the "time constant" then t = RC.
The capacitance of an electronic capacitor is measured in farads (In honor of Michael Faraday) and is determined by the formula C = q/V, where q is the charge (in coulombs) on one of the conductors and V is the potential difference (in volts) between the conductors. Michael Faraday (1791-1867), was a British physicist and chemist, best known for his discoveries of electromagnetic induction and of the laws of electrolysis.
In electronics the Capacitor acts exactly like the water pipe capacitor described above. It takes time for the electrical charges called "coulombs" to fully charge the Capacitor. The Coulomb is named after the French physicist Charles Augustin de Coulomb (1736-1806) for formulating the principle, now known as Coulomb's law, governing the interaction between electric charges. Because the voltage (pressure) across the resistor is dropping as the capacitor charges, the current decreases during charging. A time period equal to one time constant (t) will charge the capacitor to 63.2% of the full charge. The next time constant will charge the capacitor to 63.2% of the remaining charge. Each time period equal to "t" will charge the capacitor to 63.2% of the difference between the existing charge and a full charge.
You can compare this to a person trying to cross a large farm field. Lets say it takes that person 5 hours to run two thirds of the way across the field. The person becomes so tired, however, it takes that same person 5 hours to run two thirds of the remaining distance. Becoming even more tired it takes 5 hours to walk the next two thirds of the remaining distance. Now you will say the person will never get fully across the field. This may be technically true but after 10 time constants (in this case 50 hours) that person will be so close to the other end of the field it will look like the field was crossed and movement has stopped.
Take a piece of paper and start at one end. Place a dot two thirds of the way across the paper. Place the next dot two thirds across the remaining distance. Continue until the space left is too small to receive a dot. Count the dots. You probably have less than 10.

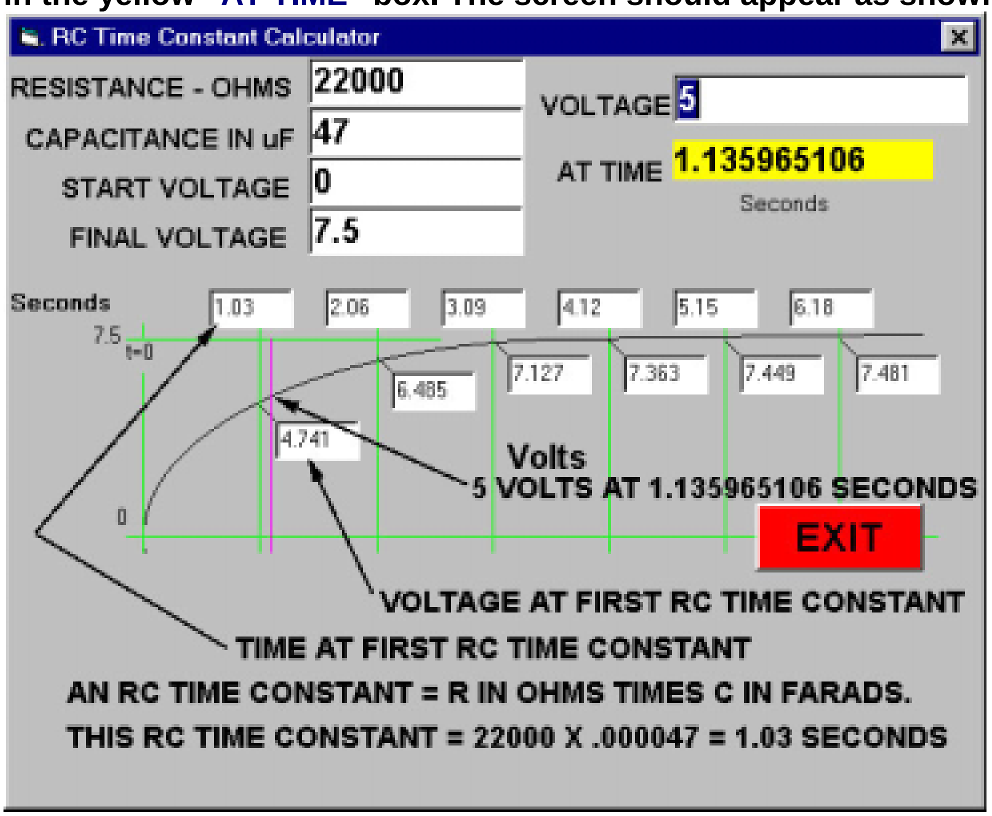
Time Constant Calculator

Because the current changes as the Capacitor is charging, the equation to calculate the voltage at any given time is not as simple as Ohm's Law. No need to worry about the mathematics, however, because there is the RC-L/R Time Constant Calculator that can be downloaded from emailschool. When this program is open it will help you calculate the components needed for any given time constant or the time constant for any given components. Download and open the program called RC.exe;

When the window opens the cursor will be blinking in a text box labeled "RESISTANCE – OHMS". Type in the value of 22000 ohms for the resistor and press the <enter> key. You will hear the calculator working and the cursor will move to the text box labeled "CAPACITANCE IN uF". Type in the value of 47 for the capacitor value in microfarads and press the <enter> key. The cursor will move to the text box labeled "START VOLTAGE". Type in 0 volts for the start voltage and press the <enter> key. This is the voltage on the capacitor at the time charging first starts. The cursor should now be in the text box labeled "FINAL VOLTAGE". Type in 7.5 volts for the final voltage and press the <enter> key. The cursor should now be in the text box labeled "VOLTAGE". Before you use this text box take a look at the curve and the labeled points on the curve.

The green vertical lines represent the RC time constants. An RC time constant is the time period equal to the total resistance in series with the capacitor multiplied by the value of the capacitor in Farads (RC). In the picture below the number over each green line is the value of time since charging started at multiples of the RC time constant. The heading on the left tells you if time is being measured in seconds, weeks, months, etc. The numbers inside the curve show the value of voltage at the time constant represented by each green line.

Type the number 5 into the voltage box and press the <enter> key. The program calculates how long it takes to reach that voltage and displays it in the yellow "AT TIME" box. The screen should appear as shown here.



The value of time that appears is equal to the exact time the voltage on the capacitor will be equal to 5 volts. The purple line will move to the position on the curve that represents this time and voltage. You may type in new voltage values and press <enter> and new times will be calculated and displayed.

Time Constant Calculator error Message

Repeat above but type in 9 volts for the "At Time" value. A message box will inform you that the voltage is outside the charging range. If you type in a value outside of the charging range a message box will inform you of your error. Change the final voltage to 10 volts and press enter. The purple line will move to the new position and the whole curve will change to satisfy these new conditions.

Capacitor Charge Curve

The number "e" in mathematics is a magic number, comparable only to pi (the ratio of the circumference of a circle to its diameter). The number "e" is most commonly defined as the limit of the expression $(1 + 1/n)^n$ as n becomes infinite. Some values of this expression for increasing values of n are included in the following table.

CALCULATIONS OF $(1+1/n)^n$

FOR INCREASING VALUES OF n

n	$(1+1/n)^n$	Numerical Value
1	$(1+1/1)^1$	2.000
2	$(1+1/2)^2$	2.250
3	$(1+1/3)^3$	2.369
5	$(1+1/5)^5$	2.489
10	$(1+1/10)^{10}$	2.594
20	$(1+1/20)^{20}$	2.653
40	$(1+1/40)^{40}$	2.684
50	$(1+1/50)^{50}$	2.691
100	$(1+1/100)^{100}$	2.705
1,000	$(1+1/1000)^{1000}$	2.717
10,000	$(1+1/10,000)^{10,000}$	2.718
∞	$(1+1/\infty)^{\infty}$	2.7182818285

An examination of the right-hand column of the above table will show that the value of the expression becomes closer and closer to a limiting value. This limiting value is approximately 2.7182818285.
The number "e" forms the base of natural, or Napierian, logarithms. It appears in the so-called exponential function, the only function having a rate of growth equal to its size, and therefore the fundamental function for equations describing growth and many other processes of change. In geometry, "e" is a necessary component of the formulas for many curves including sine waves. And in electronics "e" is the magic number that describes the charge rate of capacitors in terms of their RC time constants. For example:

$1-1/e^1$ = .63212 or 63.2%
$1-1/e^2$ = .86466 or 86.5%
$1-1/e^3$ = .95021 or 95.0%
$1-1/e^4$ = .98168 or 98.2%
$1-1/e^5$ = .99326 or 99.3%
$1-1/e^6$ = .99752 or 99.8%

Now open the time constant calculator and repeat the above example but use 0 for the starting voltage and 1 for the final voltage. Notice how the voltage at each time constant matches the numbers in the above calculations. Once again the magic number "e" shows up. This experiment also demonstrates that after 6 time constants the capacitor is 99.8% charged.
Remember the person trying to cross the field in Experiment 1? After 10 time constants he would be 99.996% of the way across the field. In other words, if the field was 1 mile long, he would have less than 3 inches to go.

Experiment 8 Nanoseconds to Weeks

Another feature in the Time Constant Calculator is the calculation of time in usable units. If the time period gets long the calculator will change from seconds to minutes. If it gets longer it will go to hours, days, even weeks to keep the numbers usable. You should realize, however, that extremely large values of resistance and capacitance are not practical in every day circuits. When the numbers entered into the Resistance Value and Capacitance In uF boxes are too high the calculator will warn you by turning those numbers red. Even though parts may be available with higher values they are not practical for RC time constant use due to leakage and size of capacitors. Open the Time Constant Calculator and start typing nines into the resistance value box. The value should turn RED when the entry exceeds 10,000,000. When the number turns red press the <enter> key. Do the same for the Capacitance in uF. The maximum value before warning should be 100,000 microfarads. Next enter starting voltage as 0 volts and final voltage as 10 volts. Type in 9 for the desired voltage and note that the time reading is in weeks. If you try to enter resistance values

greater than 100 megohms the calculator will force you back to 100 megohms. The maximum capacitance is also limited to 1 Farad.

Calculating Discharge Time

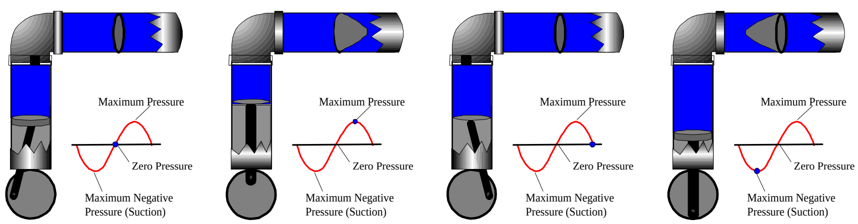
The RC Time Constant Calculator can also calculate the time it takes for capacitors to discharge. In the Resistance box enter 100000 ohms. Enter 47 uF for the Capacitance in uF and make the starting voltage 7.5 volts. Make the final voltage 1.3 volts. Press enter and the program recalculates all the new time constants. NO MATH needed when your working with this RC calculator!

Capacitors and AC Voltages

Perhaps the best way to understand AC voltage and Capacitors is to look at the analogy of an AC generator with a capacitor connected to its output. Click on the animation name called “Cap.gif” to start animation.
The wheel that revolves is the equivalent of an AC voltage generator. It pushes the water into the pipe, then it sucks the water back. This creates a positive pressure in the pipe, then it creates a negative pressure in the pipe.
The rubber diaphragm in the animation is the equivalent of a capacitor. Watch the motion of the capacitor as the generator turns. This animation will be used to explain the capacitor.

Current Leads Pressure in a Water Pipe Capacitor

In then animation there are four positions that describe the relationship of current and pressure. Those positions have been reproduced in the drawing below as “A”, “B”, “C”, and “D”.



A — Maximum Current into pipe at Zero Back Pressure

B — Zero Current into pipe at Maximum Back Pressure

C — Maximum Current back from pipe at Zero Back Pressure

D — Zero Current into pipe at Maximum Suction

In “A” the diaphragm is not stretched and there is no back pressure. At this point the piston is moving upward rapidly and water is rushing into the pipe. Current into the pipe is at a maximum.

In “B” the wheel has advanced 90 degrees. The diaphragm is stretched and back pressure is at maximum. The piston is changing direction and all water movement has stopped. Current is at zero.

In "C" the wheel has advanced another 90 degrees. The diaphragm is not stretched and back pressure is zero. The piston is moving downward rapidly and water is rushing from the pipe. Current from the pipe (negative current) is at a maximum.

In "D" the wheel has advanced another 90 degrees. The diaphragm is fully stretched and suction is at a maximum. The piston is changing direction again and all water movement has stopped. Current is at zero.
Notice that whenever the current is at zero the pressure is at a maximum, and whenever the pressure is at zero the current is at a maximum. These points occur at 90 degree intervals on the AC generator. Also it is important to note that the current must flow into the water pipe capacitor FIRST in order for the pressure to build to a maximum. This maximum occurs 90 degrees after current maximum.

Conclusion: The current leads the pressure through a water pipe capacitor by 90 degrees.
In electronics the same thing is true. The current leads the voltage through a capacitor by 90 degrees. Study the animation carefully making sure you fully understand this concept. If necessary start and stop the animation as many times as necessary to see this relationship.

Energy Stored in Capacitors.

Batteries have an internal resistance. This resistance limits the current that can be drawn from the terminals of the battery. As the batteries chemical process produces current, this internal resistance rises. Eventually the resistance is great enough to make the battery current too low for practical use. The battery must be replaced or recharged when the internal resistance rises too high.
Capacitors, however, have very little internal resistance. A capacitor can deliver large currents for short periods of time. When a capacitor is placed in parallel with a battery, the battery supplies the current to charge the capacitor. Then the capacitor can deliver large currents for short periods to satisfy peak power requirements.
In battery operated radios Capacitors are used to provide the current peaks required when audio levels such as drums are played. In this way the energy is stored in the capacitor until needed and then delivered to the audio circuits.

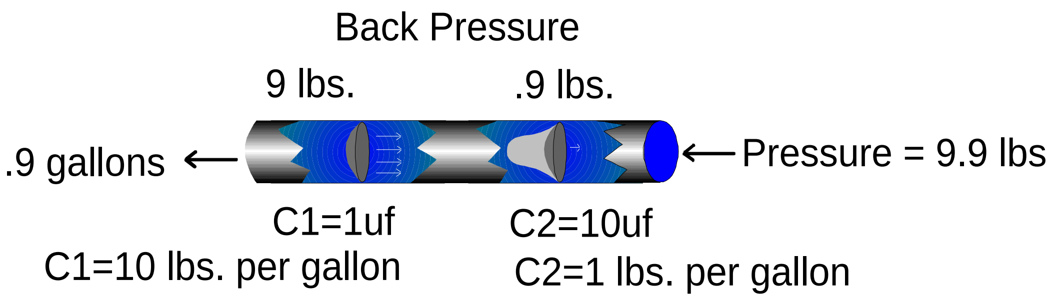
Capacitors in Series.

When capacitors are placed in series with each other the total value is less than the smallest value of capacitance. In fact the mathematics acts the same as for resistors in parallel. First, let's start using the terms micro-farad (uf) for all capacitors. Next you must download the RinParallel.exe

calculator. If you open the R in Parallel calculator and click on the "C" button. It will change to "R/L" and the calculator will be in the capacitance mode. Enter all values in microfarads as follows: For C1 enter 47 uf and for C2 enter 10 uf. The calculator will give you the result of 8.25 uf for the two capacitors in series. Experiment with the calculator and different values of capacitors. You may also enter one capacitor and the value desired for two capacitors in series and the program will calculate the value needed and give you the closest standard value at the bottom of the calculator screen.

Analogy for Capacitors in Series.

If you look at the analogy for two capacitors in series it is easier to see why the value is always less than the smallest value. Consider the two water pipe capacitors shown here.



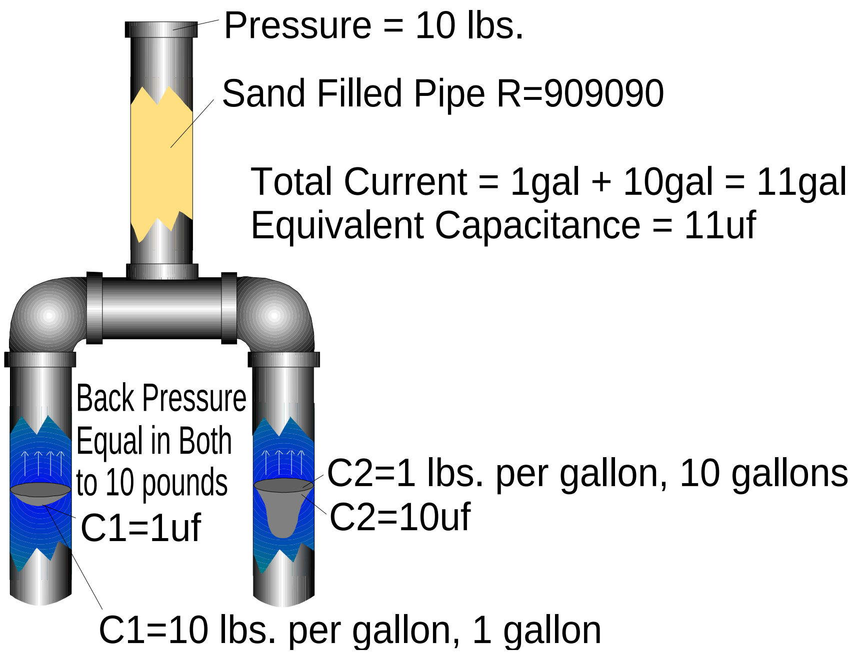
C1 is made of harder rubber than C2 and exerts a back pressure of 10 pounds per gallon. C2 would need 10 gallons of water before it would build to a back pressure of 10 pounds. The lightly shaded gray area near C2 shows how far it would stretch to equal the back pressure of C1. Therefore we say it has a larger capacity or capacitance. When they are connected in series as shown above the current flowing to stretch C1 must also flow to stretch C2. As soon as .9 gallons has left the pipe the back pressure will be equal to the pressure at the input of the pipe and current will stop (the system is charged). If C2 was removed it would take .99 gallons to equal the input pressure, but with C2 in series it only takes .90 gallons. In other words the equivalent series capacitance seems to be smaller than C1 alone.

Capacitors in Parallel.

Capacitors in parallel act exactly like resistors or inductors in series. You simply add the values to get the equivalent capacitance. For example, if a 10 uf is in parallel with a 47uf the result would be a 57uf capacitor. What would the equivalent capacitance be for a .001 uf in parallel with a.0005 uf? The answer is .0015uf.

Analogy for Capacitors in Parallel.

If you look at the analogy for two capacitors in parallel it is easier to see why the value is always equal to the sum of the individual values. Consider the two water pipe capacitors shown here.



The sand filled pipe with resistance of 909090 is the analogy to the 1 megohm resistor in parallel with the 10 megohm digital voltmeter. When the system is fully charged the back pressure in each capacitor will equal the pressure (voltage) applied to the top pipe. The amount of gallons (these are called coulombs or charges in electronics) it took to charge the system was 11 gallons. These two capacitors could have been replace with one 11uf capacitor with a back pressure of .909 lbs. per gallon filled with the same 11 gallons (.909 x 11 ≅ 10 lbs back pressure).

Quick Review:

Capacitor: **An electronic device that stores charges, passes AC voltages, blocks DC voltages, and produces a 90 degree shift between current and voltage.**

Charged Capacitor: **When the storage device pushes back as hard as the pressure pushing to charge it, current stops flowing and the capacitor is charged.**

Discharged Capacitor: **When the storage device has no charges or the rubber in the pipe is not stretched.**

RC Time Constant: **The time it takes to charge a capacitor to 63.2% of the remaining charge.**

Increasing R: **Takes longer to charge or discharge the capacitor.**

Increasing C: **Takes longer to charge or discharge the capacitor.**

90 Degrees: The difference between the current peaks and voltage peaks for a capacitor.
Capacitors in Series: If Total capacitance equals C_T, then for N capacitors in series $1/ C_T = 1/C_1 + 1/C_2 + 1/C_3 \ldots\ldots\ldots + 1/C_N$
Capacitors in Parallel: The Total capacitance equals sum of all capacitors connected in parallel.
RC Time Constant Calculator: A program that calculates time constants and time required to reach a desired voltage.
"e": A number that forms the base of natural logarithms. It appears in the so-called exponential function, the only function having a rate of growth equal to its size, and therefore the fundamental function for equations describing growth and many other processes of change.

Something to Think About:

Why does the capacitor have a voltage printed on it?

1. It takes that voltage to charge it.
2. If the voltage is exceed the capacitor could leak, get hot, and even explode.
3. If you exceed that voltage the capacitor will stop taking a charge.
4. You should always charge to this voltage for a full charge.
5. The capacitor manufacturer guarantees that the capacitor will hold a charge at this voltage.

Solve for Y to get the number of the correct answer.

Y = 3 + 5 – 4 + 2 –1 + 3 – (2x3)