training chart manual

SECTION a

FUNDAMENTALS OF ELECTRICITY AND MAGNETISM

Delco Remy

reluctance is analogous to resistance in an electrical circuit.

There is an equation for an electromagnetic circuit that is similar to Ohm's Law for the electric circuit. This equation for the magnetic circuit can be expressed as follows:

$$\text{Number of Magnetic Lines is proportional to } \frac{\text{Ampere-Turns}}{\text{Reluctance}}$$

Although it will not be necessary for us to study this equation in detail, there are two important facts that should be observed. The first observation is that the number of magnetic lines, or strength of the field, is directly proportional to the ampere-turns. In an electromagnet, the field strength will be increased if the current in amperes flowing through the coil is increased.

The second observation is that the number of lines or field strength is inversely proportional to the reluctance; that is, if the reluctance increases the field strength decreases. Since most magnetic circuits consist of iron and short air gaps, the reluctance of such a series circuit is equal to the iron reluctance added to the air gap reluctance.

The effect of an air gap on the total reluctance of a circuit is very pronounced. This is true because air has a much higher reluctance than iron. To illustrate this fact, consider a magnetic circuit with a short air gap that has a field strength of 10,000 lines of force. If the length of the air gap is doubled, the reluctance will almost double, and the field strength will be reduced to approximately 5,000 lines of force. Although the air gap represents only a very short segment of the total magnetic path, increasing the air gap from say .1 inch to .2 inch may cut the field strength almost in half.

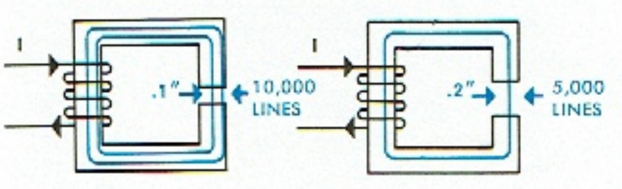
The subject of electromagnetism can be summarized in the following statements.

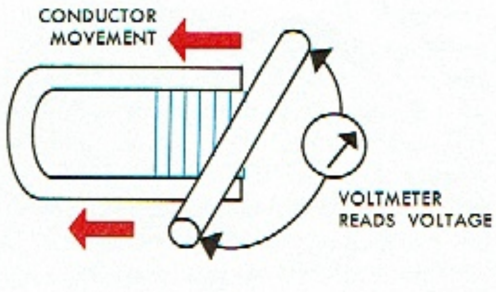
1. Electricity and magnetism are related, because a magnetic field is established around a conductor that is carrying current.
2. An electromagnet has an N pole at one end and an S pole at the other end of the iron core, much like a bar magnet.
3. Every magnetic field has a complete circuit that is occupied by the lines of force.
4. The amount of flux created by an electromagnet is directly proportional to the ampere-turns, and inversely proportional to the reluctance.

electromagnetic induction

In the year 1831, a very important discovery was made in the field of electricity when it was observed that a conductor moving across a magnetic field would have a voltage or electromotive force (emf) induced in it. This principle is called electromagnetic induction, and is defined as the inducing of a voltage in a conductor that moves across a magnetic field.

To illustrate this principle, consider a straight wire conductor that is moving across the magnetic field of a horseshoe magnet. If a sensitive voltmeter were connected to the ends of the





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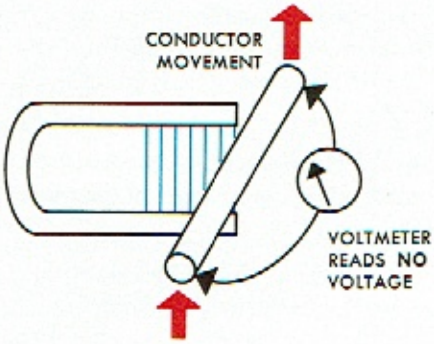
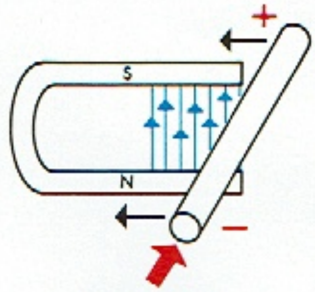


straight wire, the voltmeter needle would indicate a small voltage when the wire is being moved across the magnetic field. However, if the wire is moved parallel with the lines of force, no voltage will be induced. The conductor must cut across the lines of force in order to induce a voltage.

In our study of electricity, we have observed that voltage has polarity, that is, positive and negative. We have also stated that current flows from the positive terminal of a voltage source through the external circuit and then back to the negative terminal of a voltage source. It is important to note that the wire cutting across the magnetic field becomes a source of electricity, and must have a positive end and a negative end, just like a battery has a positive post and a negative post. However, unlike the battery, we will now see that the polarity at the ends of the wire can change, and is dependent upon the relative direction of wire movement and the direction of the magnetic field.

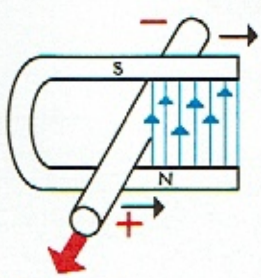
To determine the polarity at the ends of a conductor and the consequent direction of current flow, consider a straight wire moving to the left across a magnetic field as shown. With this direction of motion, the magnetic lines are striking the wire on the left side, and this side of the wire is called the **leading** side. By applying the Right Hand Rule for an Induced Voltage, the voltage polarity and current flow direction can be determined as follows: Grasp the conductor with the fingers on the leading side of the wire, and pointed in the direction of the magnetic lines of force. The thumb will then point in the direction of current flow.



CURRENT FLOW

In this example, current is seen to flow into the page, or away from the reader, as indicated. This means that the polarities at the wire ends must be as shown in order to meet the condition that current flows from the positive side of a source through the external circuit and returns to the negative side of the source. The cross in the circular end of the wire in the previous illustration indicating direction of current flow should not be confused with the positive voltage polarity marking (+) at the other end of the wire in this illustration.

When the direction of motion of the conductor is changed to move toward the right, the right side of the conductor becomes the leading side. By applying the Right Hand Rule, the current is seen to reverse its direction from the previous illustration, and to flow out of the page or toward the reader. This means that the voltage polarities at the wire ends have reversed, showing that the voltage polarity and current flow direction are determined by the relative direction of wire movement and the direction of the lines of force. By applying the Right Hand Rule, the direction of current flow and the voltage polarity required to cause current to flow in this direction are easily determined.

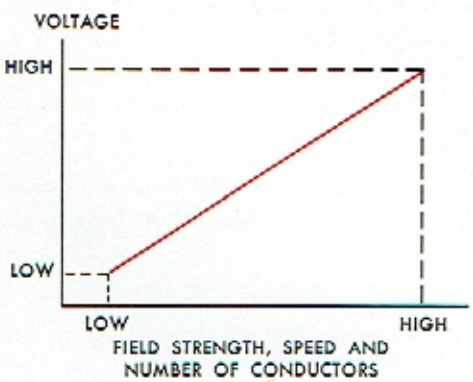


CURRENT FLOW

In the previous examples, if, instead of moving the wire to the left, the magnetic field is moved to the right across a stationary conductor, the same voltage and current flow will be induced into the wire. The same holds true for moving the field to the left across the conductor, because in each case the leading side of the conductor and the magnetic field direction are unchanged. It can, therefore, be concluded that a voltage will be induced in a conductor cutting across a magnetic field when there is **relative motion** between the two. Either the conductor can move, or the magnetic field can move.

Now that we have observed the factors that determine the polarity of the induced voltage and the direction of current flow, let's consider the factors that determine the **magnitude** of the induced voltage. These factors can be listed as follows:

1. The strength of the magnetic field.
2. The speed at which lines of force are cutting across the conductor.
3. The number of conductors that are cutting across the lines of force.



If the magnetic field is made stronger, such as by using a larger horseshoe magnet, more lines of force will be cut by the conductor in any given interval of time and the induced voltage will be higher.

If the speed increases at which the lines of force are being cut, more lines of force will be cut in any given interval of time and the voltage will be higher.

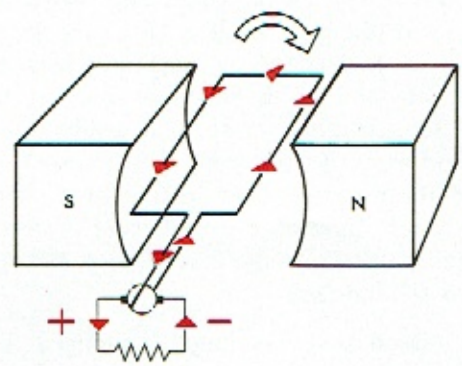
If the straight wire conductor is wound into a coil which is then moved across the field, all the loops of wire are in series and the voltage induced in all the loops will add together to give a higher voltage.

To summarize, the stronger the field, the greater the speed, and the larger the number of conductors, the higher will be the induced voltage.

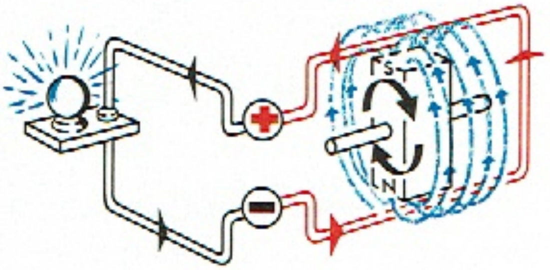
There are three general ways in which a voltage can be induced by the principle of electromagnetic induction. These three ways will be discussed under the headings of Generated Voltage, Self-Induction, and Mutual Induction.

generated voltage

A d.c. generator operates on the principle of moving conductors across a stationary magnetic field to produce voltage and current. To illustrate this principle of generated voltage consider the most basic type of d.c. generator where a single loop of wire is rotating between the N and S poles of a magnetic field. By applying the Right Hand Rule for an Induced Voltage to both sides of the wire loop, current is seen to flow in the direction indicated, and the voltages induced in the wire loop give a coil voltage that appears at the two commutator segments attached to the wire ends. The current then flows through brushes riding on the commutator to the external circuit, with the voltage polarities as shown.



Another application of the principle of generated voltage is to be found in an alternating current generator, where the magnetic field is made to cut across stationary conductors in order to produce voltage and current. The most basic type of alternating current generator is illustrated, with a rotating magnetic field cutting across stationary conductors that are mounted on the generator frame. By applying the Right Hand Rule, with the rotating field position as shown, current will flow through the conductor in the direction indicated with the voltage polarities as shown.



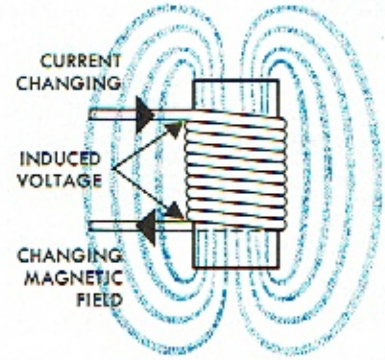
The voltage induced in a conductor by physically moving the conductor or the field is referred to as generated voltage. This principle as we have seen is used in d.c. generators and a.c. generators, both of which are covered in complete detail in Delco-Remy Training Chart Manuals DR-5133E and DR-5133K, respectively.

self-induction

The property of self-induction is a particular form of electromagnetic induction. Self-induction is defined as the inducing of a voltage in a current-carrying wire when the current in the wire itself is changing. In our previous discussions, a separate magnetic field provided by a horseshoe magnet was used to generate voltage in a conductor. In self-induction no separate field is used; instead the magnetic field created by a changing current through the wire itself is seen to induce a voltage in the wire. Hence, the voltage is self-induced.

The reason that a voltage is induced in a wire carrying a changing current can be explained as follows. Since the current creates a magnetic field in the form of concentric circles around the wire which expand and contract as the current increases and decreases, these magnetic circles cut across the conductor and thereby induce a voltage in the conductor. Since there is relative motion between the field and conductor, the condition necessary for inducing a voltage has been met.

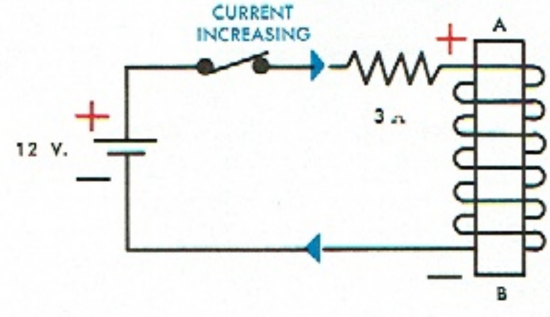
Consider a coil of wire with the turns wound tightly together over an iron core. When the current increases in one loop the expanding magnetic field will cut across some or all of the neighboring loops of wire; thus inducing a voltage in these loops. The coil of wire wound over an iron core is often called an **inductor**, and possesses the property of **inductance** which causes a voltage to be induced in the coil when the current is changing.



Now, let's make a statement that determines the voltage polarity of the self-induced voltage in a conductor or coil of wire, and then explain this statement more fully in the following paragraph.

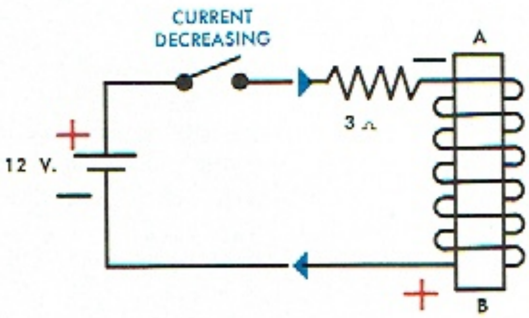
The polarity of an induced voltage is such as to oppose the change in current that produced it.

By change in current is meant whether the current is increasing or decreasing in value.



Consider first a circuit containing a coil of wire (inductor), with the current increasing immediately after the switch is closed from zero to its maximum value, say from zero to four amperes. During this time a voltage will be induced in the inductor in such a direction as to oppose the increasing current; **the inductor itself becomes a source of voltage that attempts to prevent the current from increasing in the circuit.** In order to oppose the increasing current, the inductor will have to generate a voltage in a direction opposite to the battery current; hence the polarity at A is positive (+) and at B is negative (−). The induced voltage opposes the change in current; that is, the induced voltage tries to maintain the "status quo" and keep the battery current at zero when the switch is closed. The induced voltage polarities at the coil are therefore as shown.

The battery current, however, in time overcomes the inductive effect of the coil, and reaches its final steady value of, say, four amperes. When the switch is opened, the current decreases from four amperes to zero



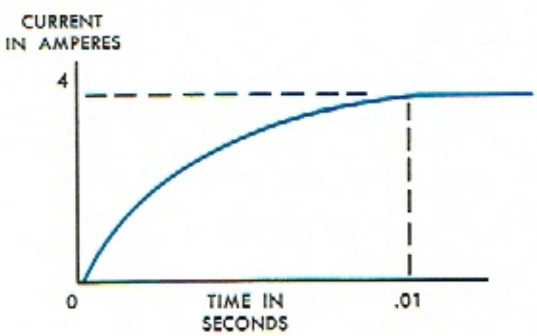
amperes. This changing current induces a voltage in the coil that tries to maintain the "status quo"; it attempts to keep the current flow at the four-ampere value. The polarity of the induced coil voltage therefore must be as shown, because the coil attempts to supply current in the same direction originally supplied by the battery. It attempts to keep the current flow at the four-ampere value, and this effect can be observed in an arc that may appear across the switch when it is opened.

It should be noted that the induced voltage polarity for any direction of current flow is determined by whether the current is increasing or decreasing.

	Induced Voltage A	Induced Voltage B
Current Increasing	+	−
Current Decreasing	−	+

Although the inductive voltage tries to prevent any change in current value, the effects of the battery voltage and the closed or open switch in time cause the current to reach a constant value. The induced voltage, however, does have its effect upon the circuit in causing a time delay for the current to reach its final value after the switch is closed or opened.

Consider first the case when the switch is closed. Due to the inductive effect of the coil the current slowly rises to its maximum value of four amperes. When the final current of four amperes is reached, there is no changing magnetic field, no induced voltage, and the resistor alone acts to establish the final current value. Ohm's Law applied to this circuit gives the final current value of four amperes; or $4 \text{ amperes} = \frac{12 \text{ volts}}{3 \text{ ohms}}$.



There is a certain amount of energy stored in an inductive coil when current is flowing through it. This energy is directly related to the amount of current (I) and the inductance of the coil, whose symbol is (L). The inductance of any coil is determined primarily by the number of turns of wire, their spacing, and the type of material used in the core of the coil. The amount of energy stored in a coil is given by the following equation:

$$\text{Energy} = \frac{\text{Inductance} \times \text{current} \times \text{current}}{2} = \frac{L \times I \times I}{2}.$$

From this equation it is seen that the higher the inductance and the higher the current, the greater will be the energy stored in the coil.

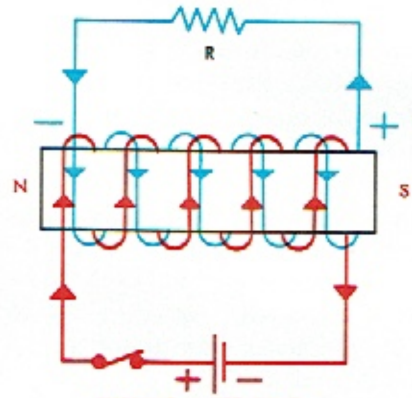
A standard ignition system operates on the principle of energy stored in the primary winding of an ignition coil. When the distributor contacts open, the current suddenly drops to zero, and from the energy equation the energy in the coil suddenly drops to zero. Some of this energy is transferred by **mutual induction** (see the next section) to the secondary winding of the ignition coil, and the energy is dissipated in the form of an arc across the spark plug.

In an ignition system the time delay in primary winding current build-up when the distributor contacts close is very important. If the contacts open before the final maximum value of current is reached, the energy stored in the coil (see the energy equation) is reduced, making less energy available to fire the plug. Although the inductance of the ignition coil may cause a time delay for current build-up of only a fraction of a second, this interval of time must be closely correlated with the time the distributor contacts are closed for proper operation.

mutual induction

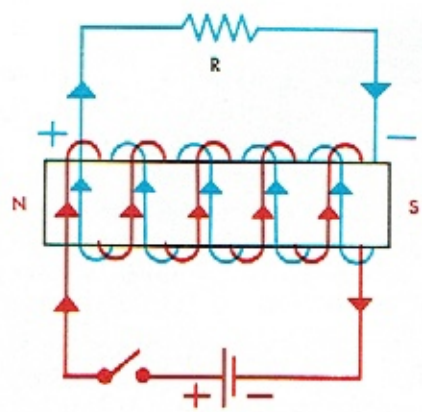
If a changing magnetic flux created by current flow in one coil links or cuts across the windings of a second coil, a voltage will be induced in the second coil. The property whereby a voltage is induced in one coil because of a changing current in another coil is called **mutual induction.**

In order to illustrate the principle of mutual induction, consider the illustrated circuit, where the blue winding, called the secondary, is wound over an iron core and the red winding, called the primary, is wound over the blue winding. When the switch is closed, current will increase in the primary, and the expanding lines of force will cut across the secondary, causing a voltage to be induced in the secondary. Similarly, when the switch is opened, the sudden decrease in current in the primary will induce a voltage in the secondary. The blue coil, or secondary winding, then becomes a source of voltage, and will supply current to resistor R.



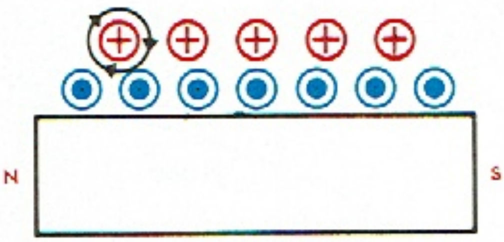
CURRENT INCREASING

The polarity of the induced voltage in the secondary can be determined in a number of different ways. One of the simplest methods is to observe the direction of current in the primary, and note that the current direction in the secondary must oppose any change in the primary current. Thus when the primary current is increasing, the secondary current must flow in the opposite direction around the core in order to oppose the increase, and the secondary voltage polarity is established as shown. However, if the primary current is decreasing, the secondary current must flow in the same direction around the core in order to oppose the change; that is, to attempt to keep the flux in the core from changing. The secondary polarity accordingly is as shown.



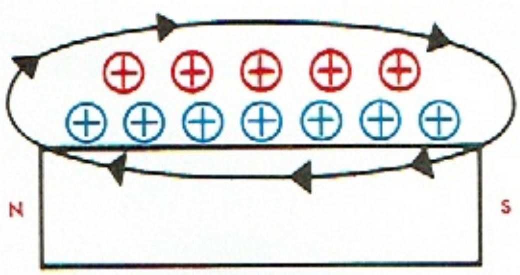
CURRENT DECREASING

An alternate method of ascertaining the secondary induced voltage polarity is to use the Right Hand Rule for an Induced Voltage. Taking a lengthwise cross-sectional view of the assembly, when current increases in the primary, the circular lines of force expand and strike the secondary on the top side. By



CURRENT INCREASING

using the Right Hand Rule for an Induced Voltage, the current flow direction is determined as shown. As stated in the previous paragraph, the two coils carry current in opposite directions around the core when the primary current is increasing. When the primary current decreases, the circular lines of force strike the secondary windings on the



CURRENT DECREASING

underneath side, and the current flows in both coils in the same direction around the core. The voltage polarity is determined accordingly, with current coming out of the secondary positive terminal and returning to the negative terminal.

The magnitude of the voltage induced in the secondary winding is determined primarily by the number of turns in the primary and in the secondary. If when the switch is opened a self-induced voltage of 250 volts occurs in the primary, and the secondary has 100 times as many turns as the primary, the secondary voltage will be $250 \times 100 = 25{,}000$ volts.

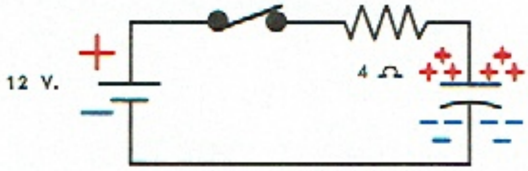
The typical example just discussed is applicable to the construction and operation of an ignition coil, and explains how the 12-volt battery voltage is raised by self-induction in the primary to 250 volts, which is then raised by mutual induction to 25,000 volts in the secondary winding for firing the spark plugs.

capacitors

Two conductors such as two metal plates spaced very close together and separated by a thin insulating material such as paper, mica, or air is called a **capacitor** (or condenser). When the two plates are connected to a source of voltage, the assembly exhibits the property of **capacitance.** The symbol for capacitance is C, and the unit of measure is the farad, or micro-farad. The greater the area of the plates, and the shorter the distance between them, the greater will be the capacitance.

CAPACITOR

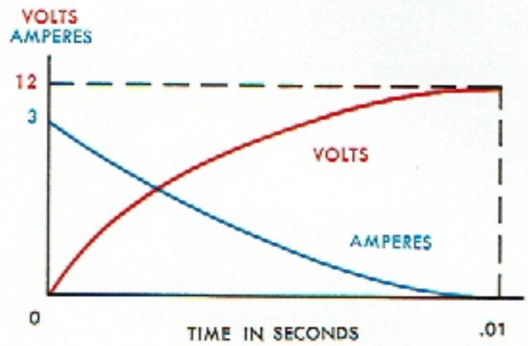
In order to explain the action of a capacitor, consider the circuit illustrated and remember that the metal plates in all capacitors are insulated from each other. Since the plates are insulated from each other, it would seem that no current will flow in this circuit. This is indeed the case, **except** at the instant of time when the switch is closed. When this is done, the voltage across the plates will suddenly change from zero to 12 volts. The study of capacitors involves the application of a changing voltage across the capacitor plates, and then observing what happens to the current and voltage in the circuit.



When the switch is closed, electrons will leave the battery and congregate on the capacitor negative plate as shown. This plate will have an excess of electrons. At the same time, electrons will leave the other plate and cause this plate to become positively charged. It is important to note that the electrons flow through the circuit but **not** through the insulating material separating the two plates.

As the two plates become negatively and positively charged, a voltage appears across the plates. Remember that a voltage between two points is the direct result of a difference in charge between the two points. As more and more electrons accumulate on the negative plate and leave the positive plate, the voltage across the plates approaches the battery voltage. When the capacitor voltage equals the battery voltage, the flow of electrons will stop. The equation giving the amount of charge on a capacitor is Charge = Capacitance × Voltage. Thus the higher the capacitance and applied voltage, the greater will be the charge on the capacitor.

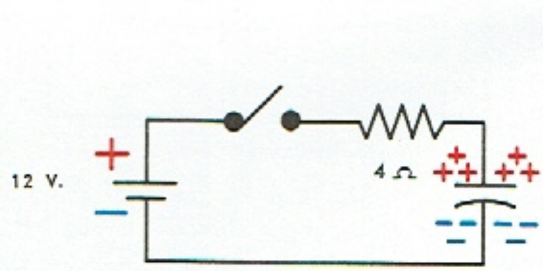
The curves showing the flow of current into, and the voltage across, the capacitor plates are shown. At the very instant the switch is closed, the initial current is determined by the resistor R in the circuit, or $I = \frac{E}{R} = \frac{12}{4}$ = 3 amperes. Initially the capacitor acts like a short circuit, since only the resistor R limits the initial current flow. As the charge on the plates increases, the capacitor voltage increases to oppose the battery voltage, and the current decreases with time. Finally the current flow stops completely when the capacitor voltage is equal and opposite to the battery voltage. The time needed for the current to reach a zero value may be only a fraction of a second. Although this time interval may seem very short, it can be of major importance in electrical systems where voltages are changing at extremely rapid rates.



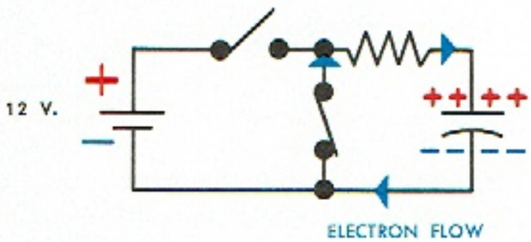
If the switch is suddenly opened, the charge and voltage on the capacitor will remain. The accumulated charge represents stored energy, and a capacitor has the ability to store electrical energy, or to store a charge. The amount of energy stored is expressed by the formula

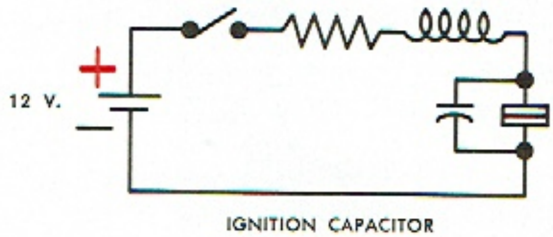
$$\text{Energy} = \frac{\text{Capacitance} \times \text{Voltage} \times \text{Voltage}}{2}.$$

Thus, the higher the capacitance and voltage the higher the energy stored in the capacitor. In time the charge will leak off the plates through the insulating material and surrounding air, reducing the charge and voltage to zero.



By adding another switch to the circuit, the energy stored in the capacitor may be used to send a current through the resistor. When the switch is closed, a momentary surge of current will flow through the resistor until the charge on the two plates is equal. The initial current will be $I = \frac{E}{R} = \frac{12}{4} = 3$ amperes, since the capacitor voltage is 12 volts. As the electron flow continues, the voltage across the plates decreases, until finally the current value is zero. Again, the time interval may be only a fraction of a second. The following important observations should be made from the foregoing discussion.





1. A capacitor as it builds up a charge develops a counter voltage across its plates.
2. The capacitor has the ability to store a charge, or to store energy.
3. Current flows only during the very short interval of time when the capacitor voltage and battery voltage are unequal.

Capacitors used in automotive-type electrical circuits usually consist of a roll of two layers of thin metal foil separated by a very thin sheet of insulating material. The assembly is then sealed in a metal can. Capacitors of this type are used primarily to perform either one of two functions in an electrical circuit, as follows.

The characteristic of a capacitor to act initially like a short circuit when a sudden difference in voltage is applied across its plates makes it ideally suited to "trap" or temporarily store electrical energy that otherwise could damage electrical components. To illustrate, consider an ignition circuit in which a capacitor is connected across the distributor contact points. When the contacts separate a high voltage is induced in the ignition coil primary winding because of self-inductance. This high voltage causes the capacitor plates to charge when the contacts first separate; the capacitor acts initially like a short circuit and current flows into the capacitor to minimize arcing at the contacts. High voltages originating when a circuit is opened may exist for a very short interval of time, such as 1/1,000,000 of a second, and are called **transient voltages.**

Another application where the capacitor is used to reduce the magnitude of changing voltages is in regulators, where a constantly changing voltage needs to be "smoothed-out" to a more constant voltage. A capacitor used in this way is connected across the changing voltage, and is called a filter capacitor.