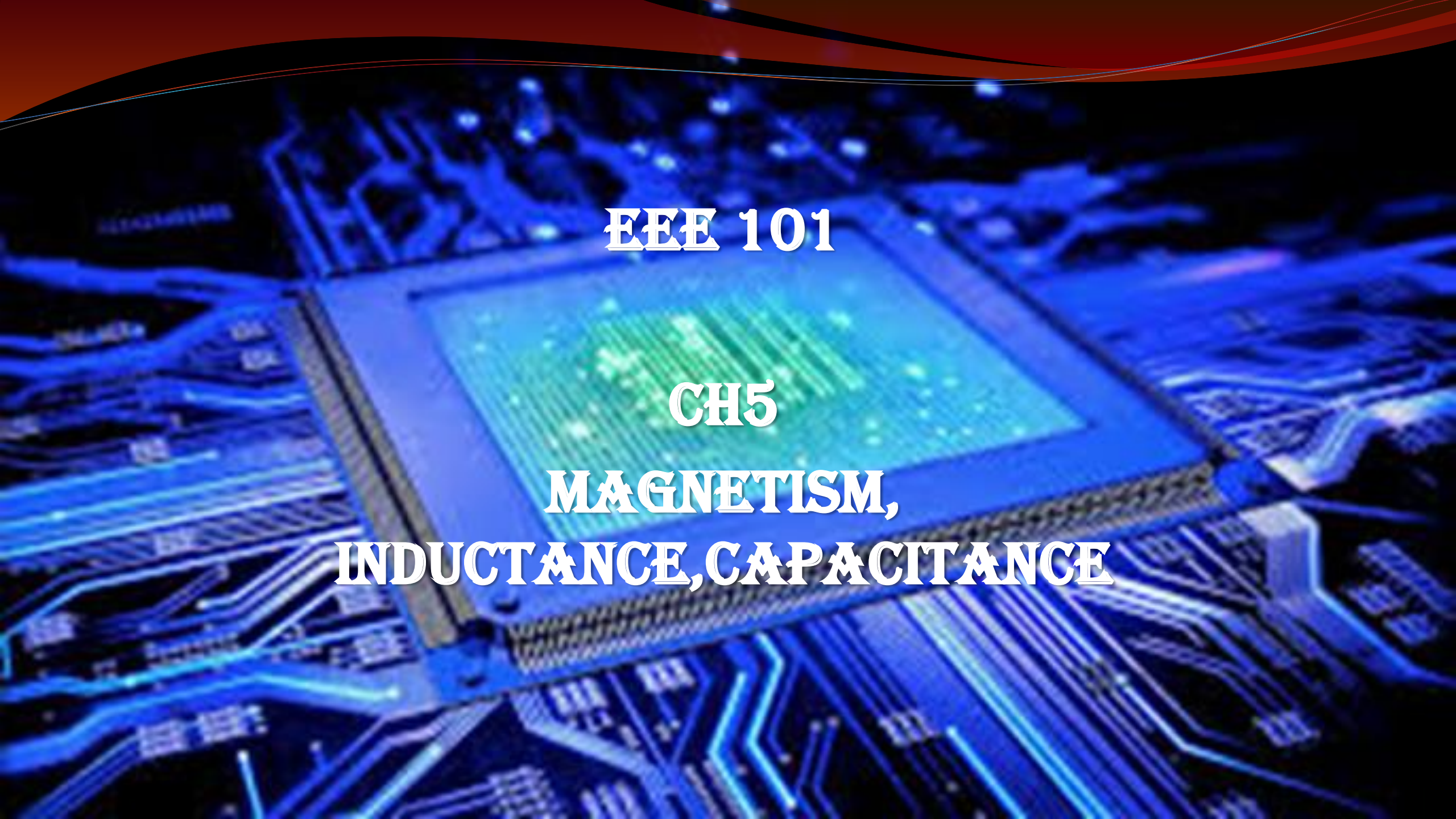

EEE 101
CH5
MAGNETISM,
INDUCTANCE,CAPACITANCE

Magnetism

- Electricity and magnetism are inseparable.
- Electric current always produces some form of magnetism, and magnetism is the most common method for generating electricity.
- In addition, electricity behaves in specific ways under the influence of magnetism.
- This chapter looks at magnetism, electromagnetism, and the relationship between magnetism and electricity.

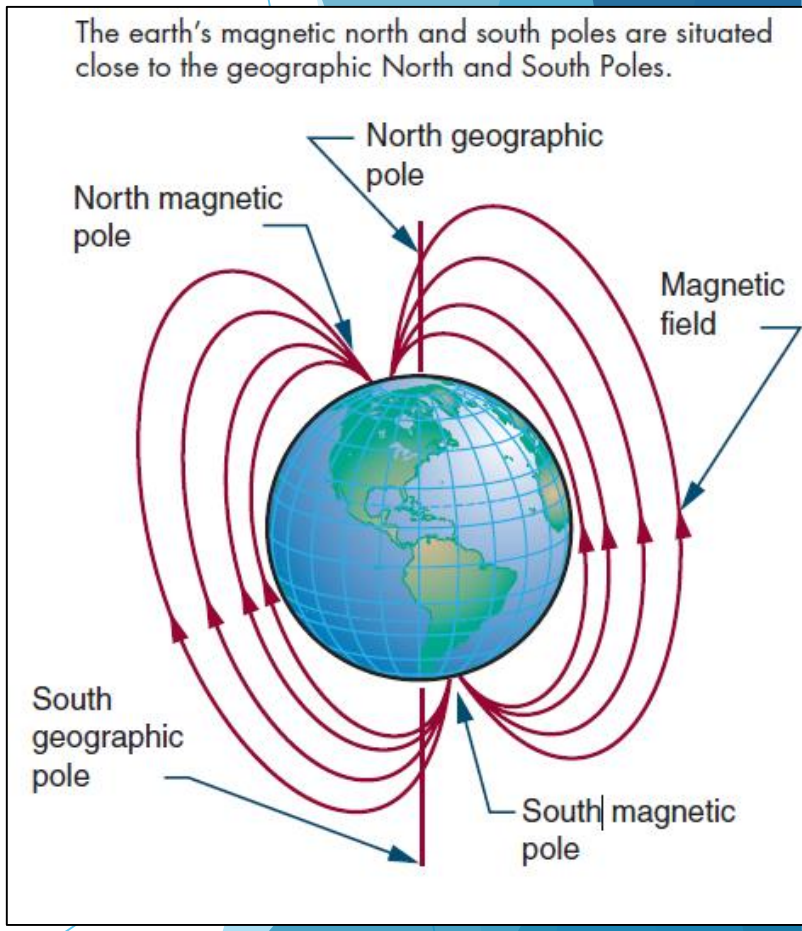
Magnetic Fields

- The word **magnet** is derived from magnetite, the name of a mineral found in Magnesia, a part of Asia Minor. This mineral is a natural magnet.
- Another type of magnet is the **artificial magnet**. This magnet is created by rubbing a piece of soft iron with a piece of magnetite.
- A third type of magnet is the **electromagnet** created by current flowing through a coil of wire.
- Magnets come in various shapes (Figure). Among the more common shapes are the horseshoe, the bar or rectangle, and the ring.
- Magnets that retain their magnetic properties are called **permanent magnets**. Magnets that retain only a small portion of their magnetic properties are called **temporary magnets**.



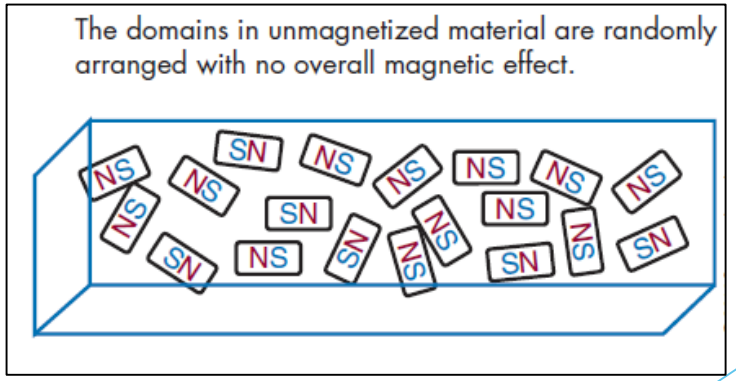
Magnetic Fields

- Magnets are made of metallic or ceramic materials. Alnico (*al*uminum, *ni*ckel, and *co*balt) and Cunife (copper [*Cu*], *ni*ckel, and Iron [*Fe*]) are two metallic alloys used for magnets.
- The earth itself is a huge magnet (Figure). The earth's magnetic north and south poles are situated close to the geographic North and South Poles.
- If a bar magnet is suspended, the magnet aligns in a north–south direction, with one end pointing toward the North Pole of the earth and the other toward the South Pole. This is the principle behind the compass.
- It is also the reason the two ends of the magnet are called the north pole and the south pole. Magnets align in a north–south direction because of laws similar to those of positive and negative charges: Unlike magnetic poles attract each other and like magnetic poles repel each other.
- The color code for a magnet is red for the north pole and blue for the south pole.



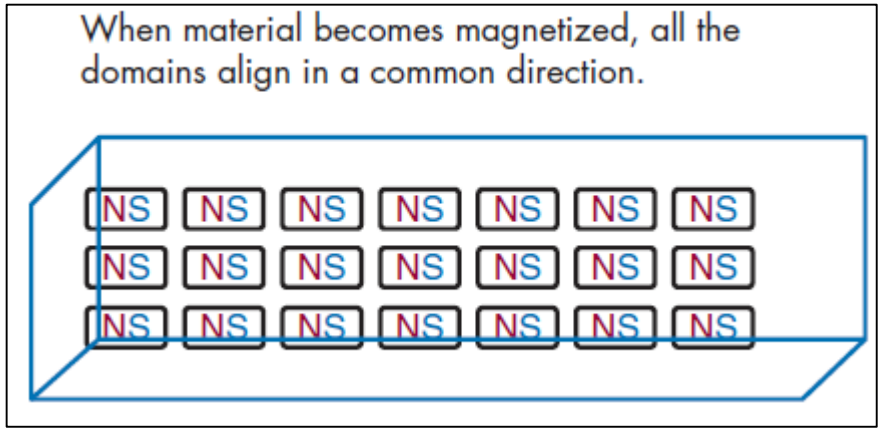
Magnetic Fields

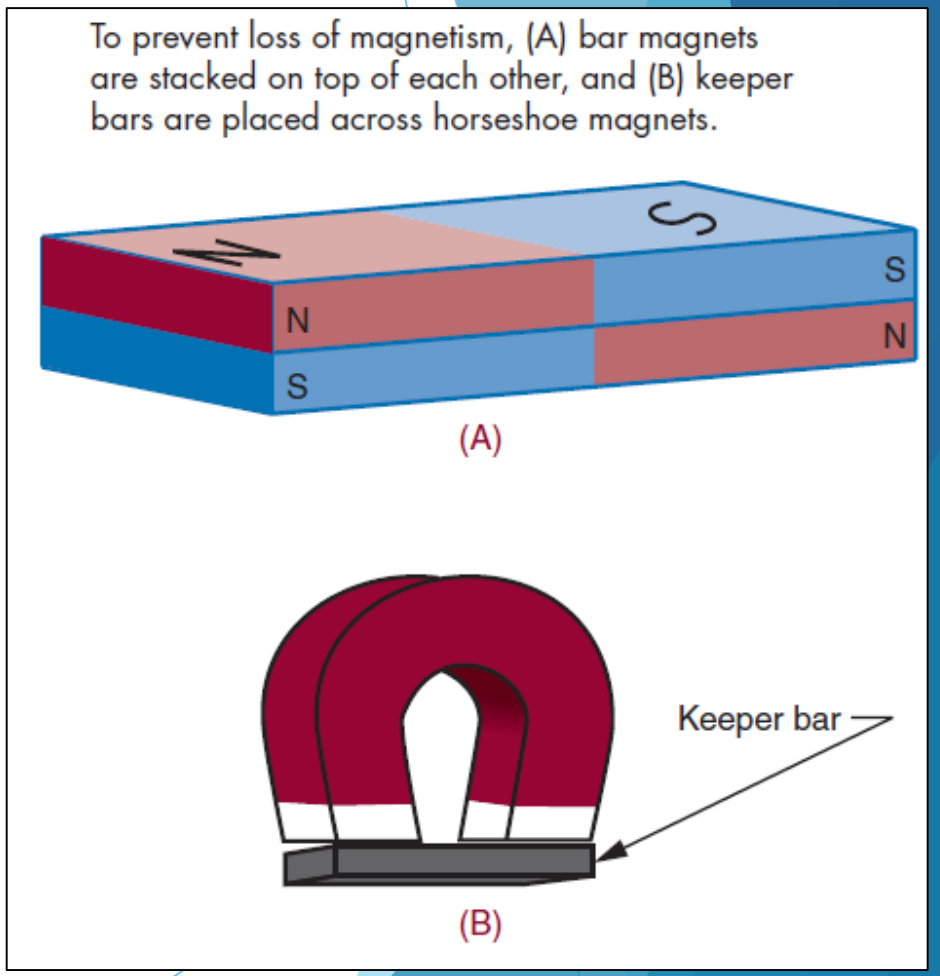
- **Magnetism**, the property of the magnet, can be traced to the atom. As electrons orbit around the nucleus of the atom, they spin on their axis, like the earth as it orbits the sun. This moving electrostatic charge produces a magnetic field.
- The direction of the magnetic field depends on the electron's direction of spin.
- Iron, nickel, and cobalt are the only naturally magnetic elements. Each of these materials has two valence electrons that spin in the same direction.
- Electrons in other materials tend to spin in opposite directions and this cancels their magnetic characteristics.
- **Ferromagnetic materials** are materials that respond to magnetic fields. In ferromagnetic materials, the atoms combine into **domains**, or groups of atoms arranged in the form of magnets. In an unmagnetized material, the magnetic domains are randomly arranged, and the net magnetic effect is zero (Figure).



Magnetic Fields

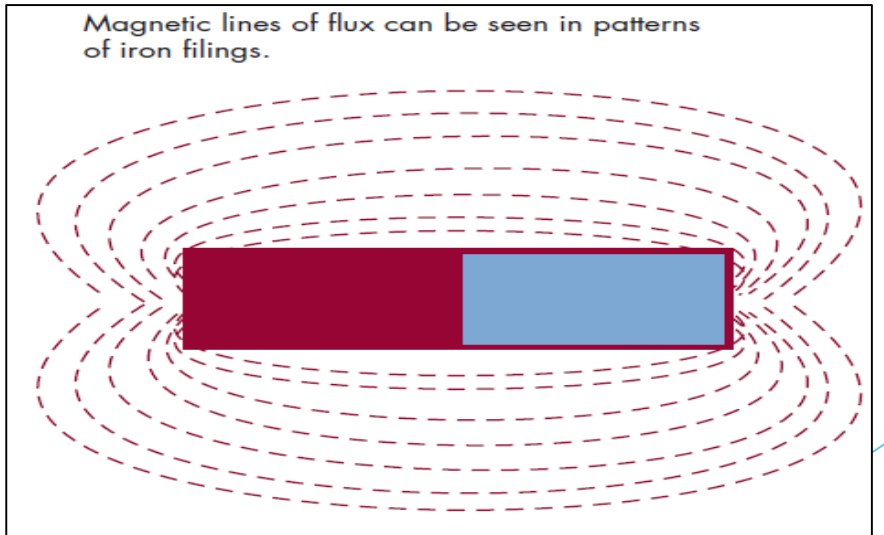
- When the material becomes magnetized, the domains align in a common direction and the material becomes a magnet (Figure 1).
- If the magnetized Material is divided into smaller pieces, each piece becomes a magnet with its own poles. Evidence of this "domain theory" is that if a magnet is heated or hit repeatedly with a hammer, it loses its magnetism (the domains are jarred back into a random arrangement). Also, if an artificial magnet is left by itself, it slowly loses its magnetism. To prevent this loss, bar magnets should be stacked on top of each other with opposite poles together; keeper bars should be placed across horseshoe magnets (Figure 2). Both methods maintain the magnetic field.





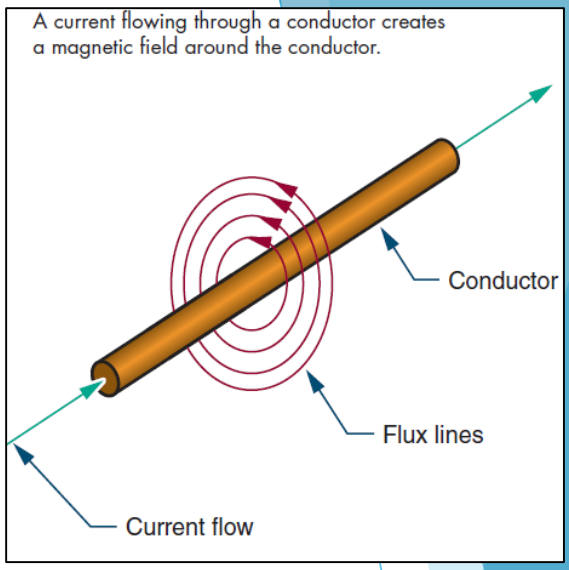
Magnetic Fields

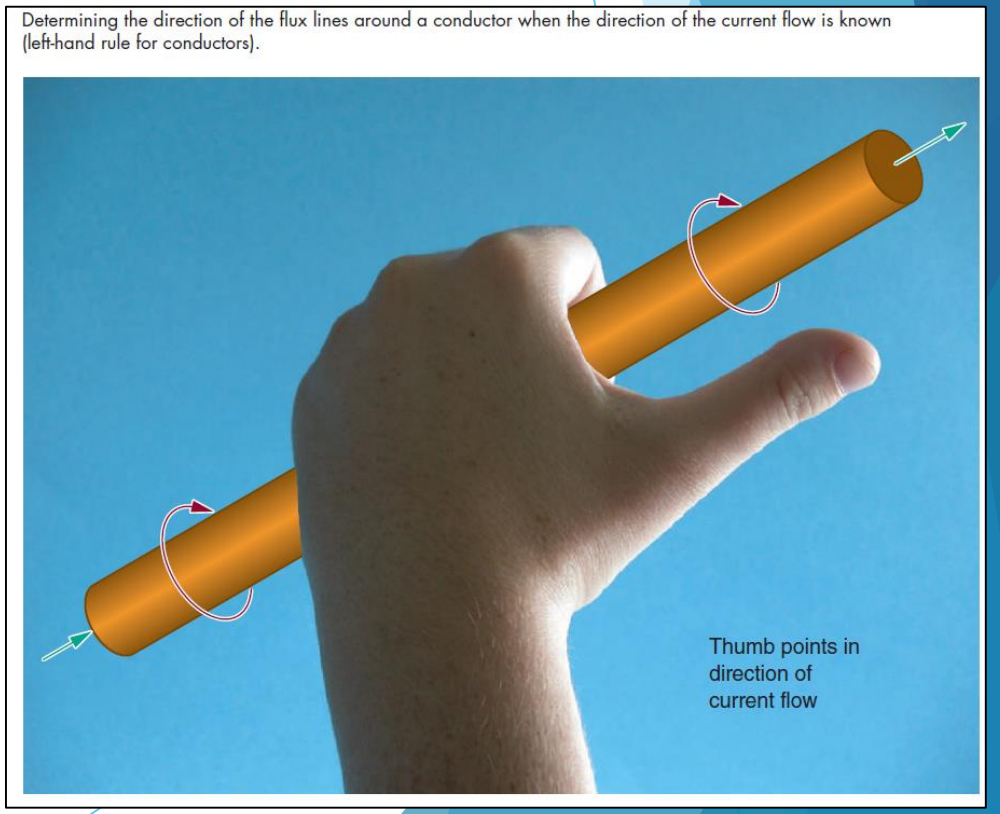
- A **magnetic field** consists of invisible lines of force that surround a magnet. These lines of force are called **flux lines**. They can be "seen" by placing a sheet of paper over a magnet and sprinkling iron filings on the paper. When the paper is lightly tapped, the iron filings arrange themselves into a definite pattern that reflects the forces attracting them (Figure).
- Flux lines have several important characteristics: They have polarity from north to south. They always form a complete loop. They do not cross each other because like polarities repel. They tend to form the smallest loop possible, because unlike poles attract and tend to pull together.
- The characteristic that determines whether a substance is ferromagnetic is called **permeability**. Permeability is the ability of a material to accept magnetic lines of force. A material with great permeability offers less resistance to flux lines than air.



Electricity and Magnetism

- When current flows through a wire, it generates a magnetic field around the wire (Figure 1). This can be shown by placing a compass next to a wire that has no current flowing through it. The compass aligns itself with the earth's magnetic field. When current passes through the wire, however, the compass needle is deflected and aligns itself with the magnetic field generated by the current. The north pole of the compass indicates the direction of the flux lines.
- The direction of the flux lines can also be determined if the direction of the current flow is known, using the **left-hand rule for conductors**. If the wire is grasped with the left hand, with the thumb pointing in the direction of current flow, the fingers point in the direction of the flux lines (Figure 2).

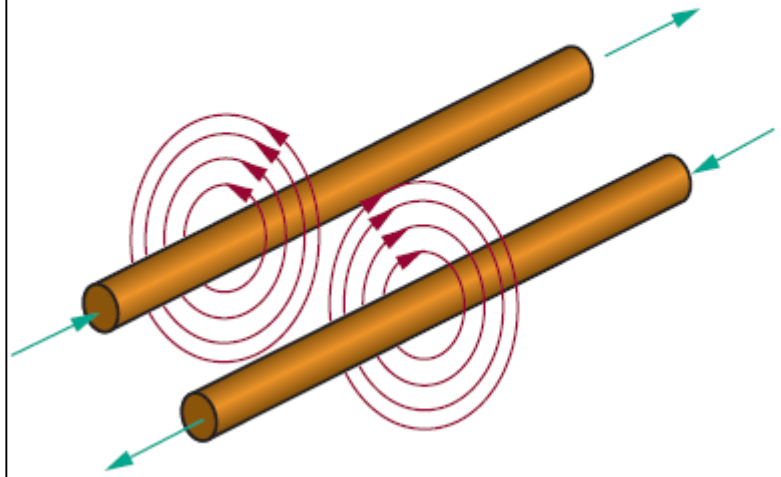




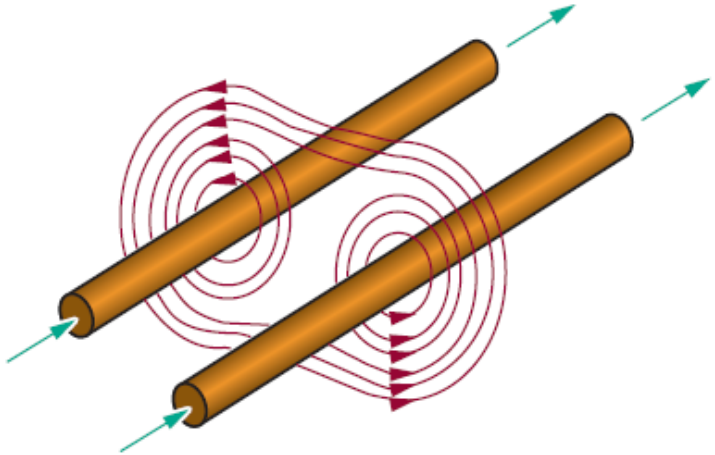
Electricity and Magnetism

- When the polarity of the voltage source is reversed, the flux lines are also reversed.
- If two wires are placed next to each other with current flowing in opposite directions, they create opposing magnetic fields that repel each other (Figure 1).
- If the two wires carry current flowing in the same direction, the fields combine (Figure 2).

When current flows in opposite directions through two conductors placed next to each other, the resulting magnetic fields repel each other.



When current flows in the same direction through two conductors placed next to each other, the magnetic fields combine.



Electricity and Magnetism

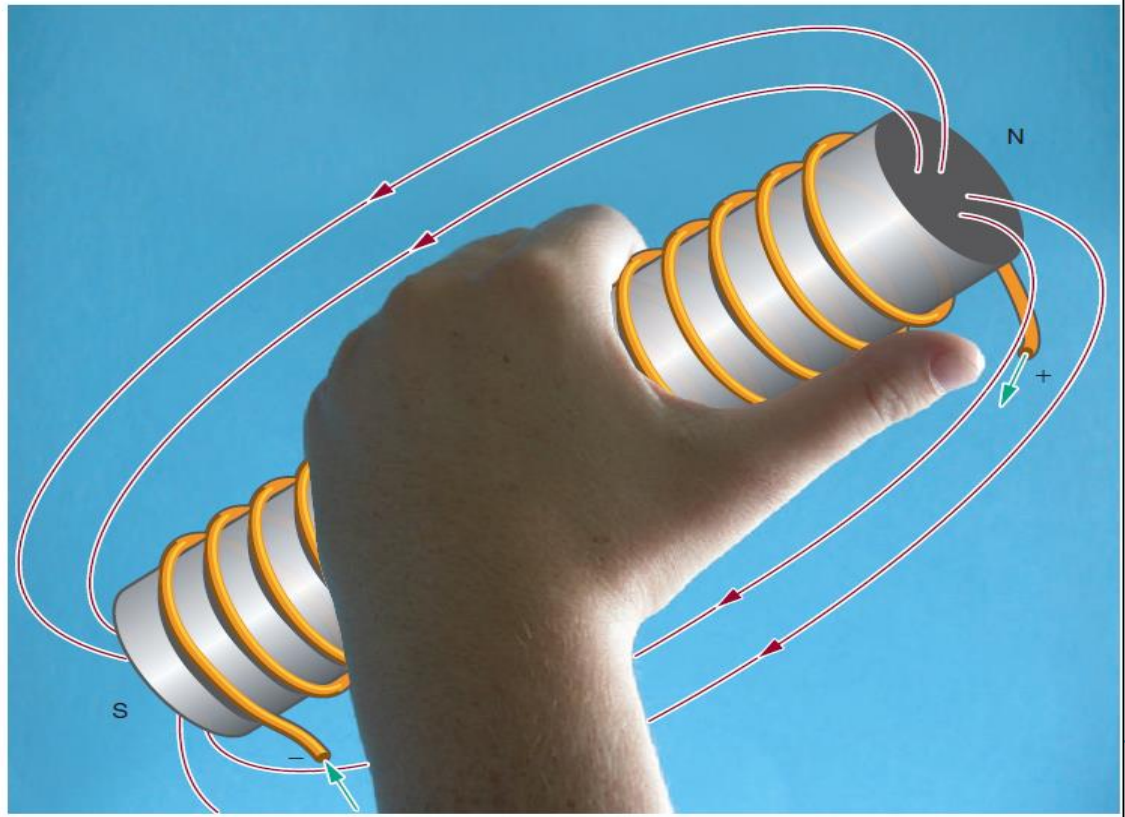
- A single piece of wire produces a magnetic field with no north or south pole and little strength or practical value. If the wire is twisted into a loop, three things occur:
  - (1) The flux lines are brought together.
  - (2) The flux lines are concentrated at the center of the loop.
  - (3) North and south poles are established.

  This is the principle of the electromagnet.
- An electromagnet is composed of many turns of wire close together. This allows the flux lines to add together when a current flows through the wire. The more turns of wire, the more flux lines are added together. Also, the greater the current, the greater the number of flux lines generated. The strength of the magnetic field, then, is directly proportional to the number of turns in the coil and the amount of current flowing through it.
- A third method of increasing the strength of the magnetic field is to insert a ferromagnetic core into the center of the coil. An iron core is typically used because it has a higher permeability (can support more flux lines) than air.

Electricity and Magnetism

- Use the **left-hand rule for coils** to determine the polarity of the electromagnet; grasp the coil with the left hand, with the fingers pointing in the direction of the current flow. The thumb then points in the direction of the north pole (Figure).

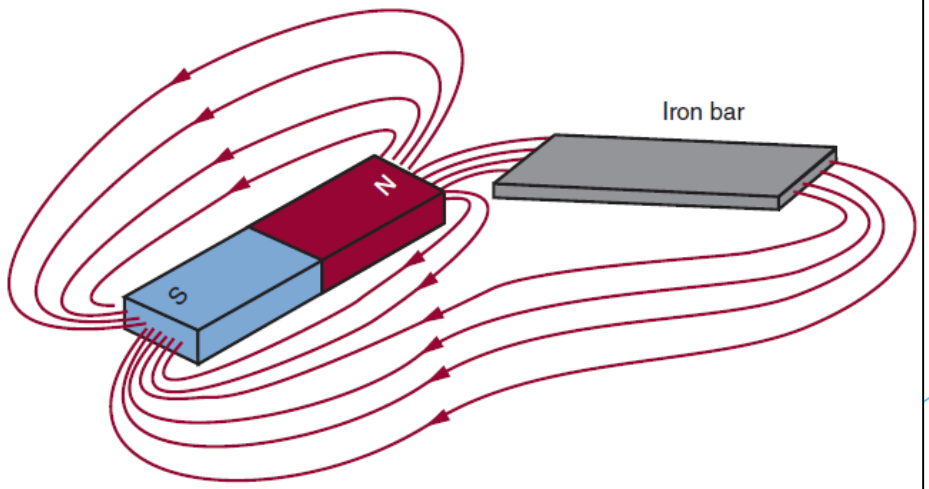
Determining the polarity of an electromagnet (left-hand rule for coils).



Magnetic Induction

- **Magnetic induction** is the effect a magnet has on an object without physical contact. For example, a magnet may induce a magnetic field in an iron bar (Figure).
- In passing through the iron bar, the magnetic lines of force cause the domains in the iron bar to align in one direction. The iron bar is now a magnet.
- The domains in the iron bar align themselves with their south pole toward the north pole of the magnet, because opposite poles attract. For the same reason, the iron bar is drawn toward the magnet. The flux lines now leave from the end of the iron bar; the iron bar is an extension of the magnet. This is an effective way to increase the length or change the shape of a magnet without physically altering it.

Placing an iron bar in a magnetic field extends the magnetic field and magnetizes the iron bar.



Magnetic Induction

- When the magnet and iron bar are separated, the domains in the iron bar return to their random pattern, although a few domains remain in north–South alignment, giving the iron bar a weak magnetic field. This remaining magnetic field is called **residual magnetism**.
- The ability of a material to retain its magnetic field after the magnetizing force is removed is called **retentivity**. Soft iron has low retentivity. Alnico, an alloy made of aluminum, nickel, and cobalt, has high retentivity.
- Inserting a low reluctance material in front of the magnetic field can bend flux lines. Low-reluctance materials are called **magnetic shields**. An example is the material called Mu-metal. The magnetic shield is placed around the item to be protected. Electronic equipment, especially oscilloscopes, requires shielding from magnetic flux lines.

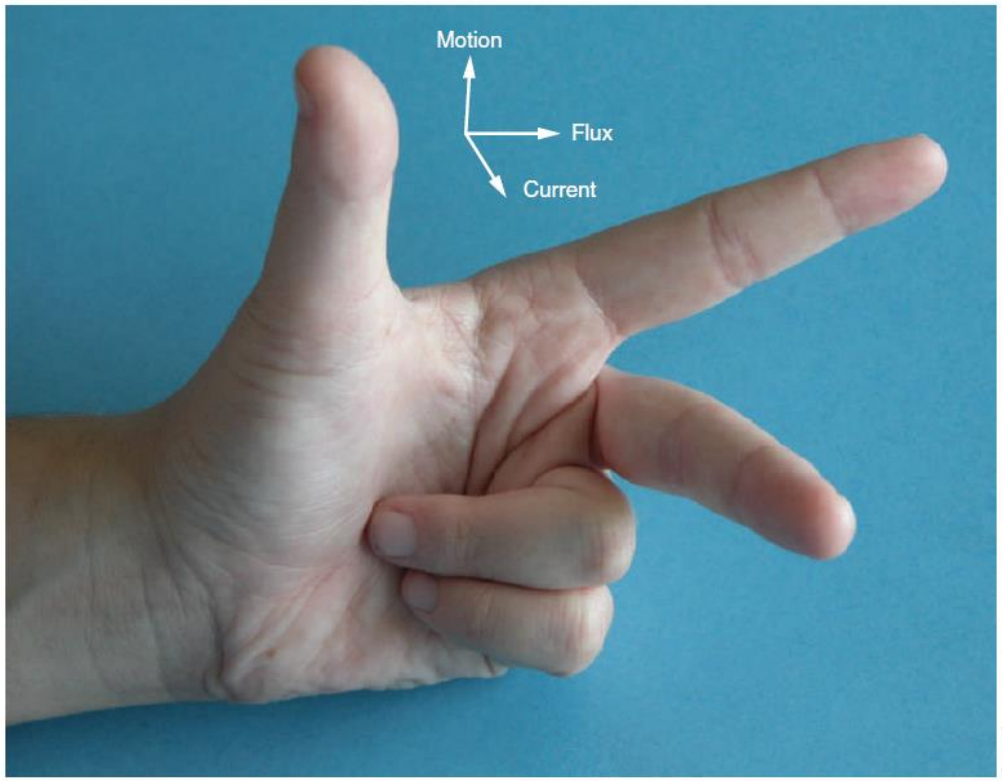
Magnetic Induction

- **Electromagnetic induction** is the principle behind the generation of electricity: When a conductor passes or is passed by a magnetic field, a current is produced (induced) in the conductor. As the conductor passes through the magnetic field, free electrons are forced to one end of the conductor, leaving a deficiency of electrons at the other end. This results in a difference of potential between the ends of the conductor. This difference of potential exists only when the conductor is passing through a magnetic field.
- When the conductor is removed from the magnetic field, the free electrons return to their parent atoms. For electromagnetic induction to occur, either the conductor must move or the magnetic field must move. The voltage produced in the conductor is called *induced voltage*.
- The strength of the magnetic field, the speed with which the conductor moves through the magnetic field, the angle at which the conductor cuts the magnetic field, and the length of the conductor determine the amount of induced voltage.
- The stronger the magnetic field, the greater the induced voltage. The faster the conductor moves through the field, the greater the induced voltage.
- Moving the conductor, the magnetic field, or both can produce motion between the conductor and the magnetic field. The maximum voltage is induced when the conductor moves at right angles to the field. Angles less than 90° induce less voltage. If a conductor is moved parallel to the flux lines, no voltage is induced. The longer the conductor is moving through the magnetic field, the greater the induced voltage.

Magnetic Induction

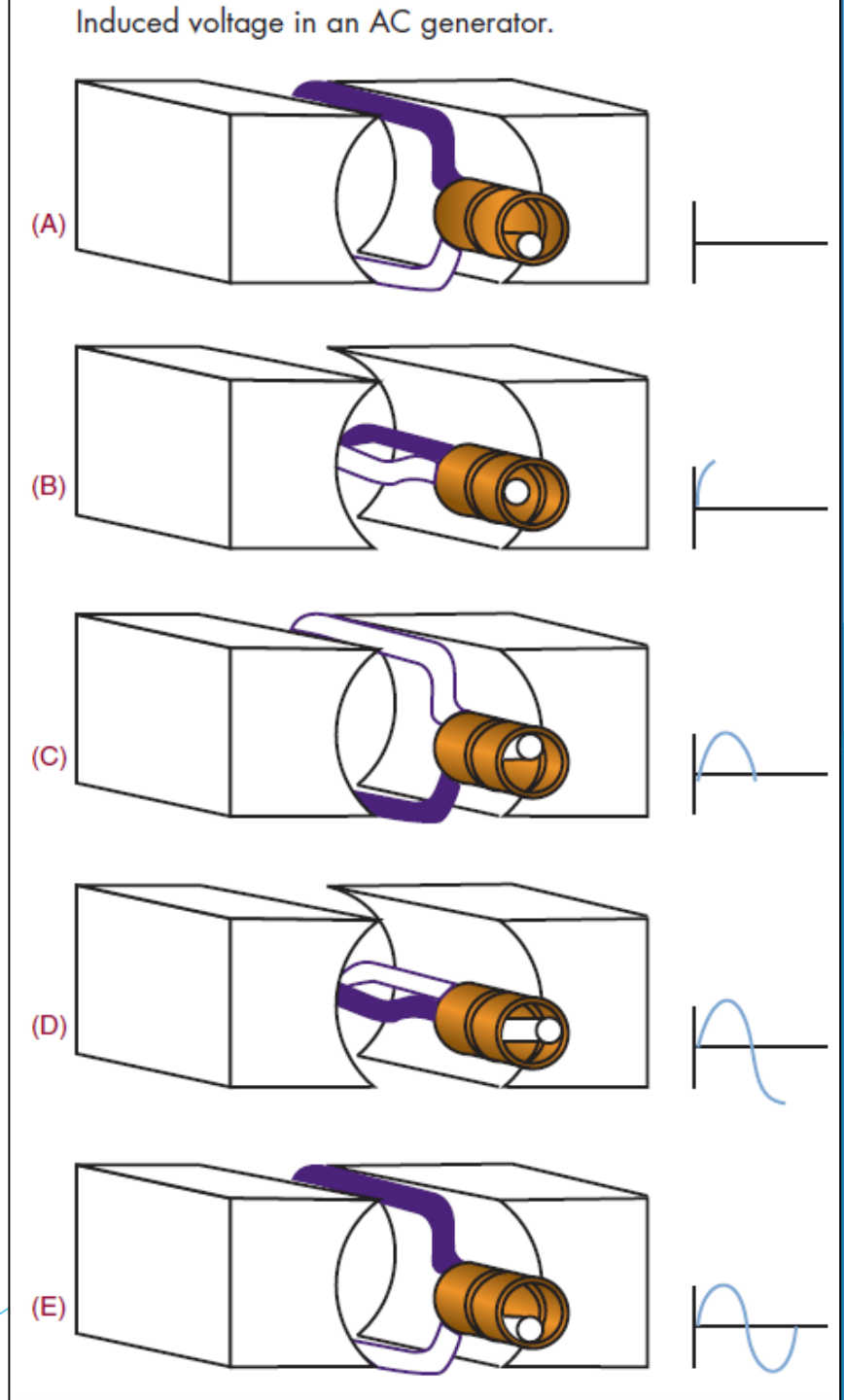
- **Faraday's law**, the basic law of electromagnetism, states: The induced voltage in a conductor is directly proportional to the rate at which the conductor cuts the magnetic lines of force.
- The polarity of an induced voltage can be determined by the following **left-hand rule for generators**: The thumb, index finger, and middle finger are held at right angles to each other (Figure). The thumb points in the same direction as the motion of the conductor, the index finger points in the direction of the flux lines (North to south), and the middle finger points toward the negative end of the conductor, the direction of the current flow.

The left-hand rule for generators can be used to determine the direction of the induced current flow in a generator.



Magnetic and Electromagnetic Applications

- An alternating current (AC) generator converts mechanical energy to electrical energy by utilizing the principle of electromagnetic induction. The mechanical energy is needed to produce motion between the magnetic field and the conductor. Figure shows a loop of wire (conductor) being rotated (moved) in a magnetic field. The loop has a light and dark side for ease of explanation. At the point shown in part A, the dark half is parallel to the lines of force, as is the light half. No voltage is induced.
- As the loop is rotated toward the position shown in part B,the lines of force are cut and a voltage is induced. The induced voltage is at this position, when the motion is at right angles to the magnetic field.

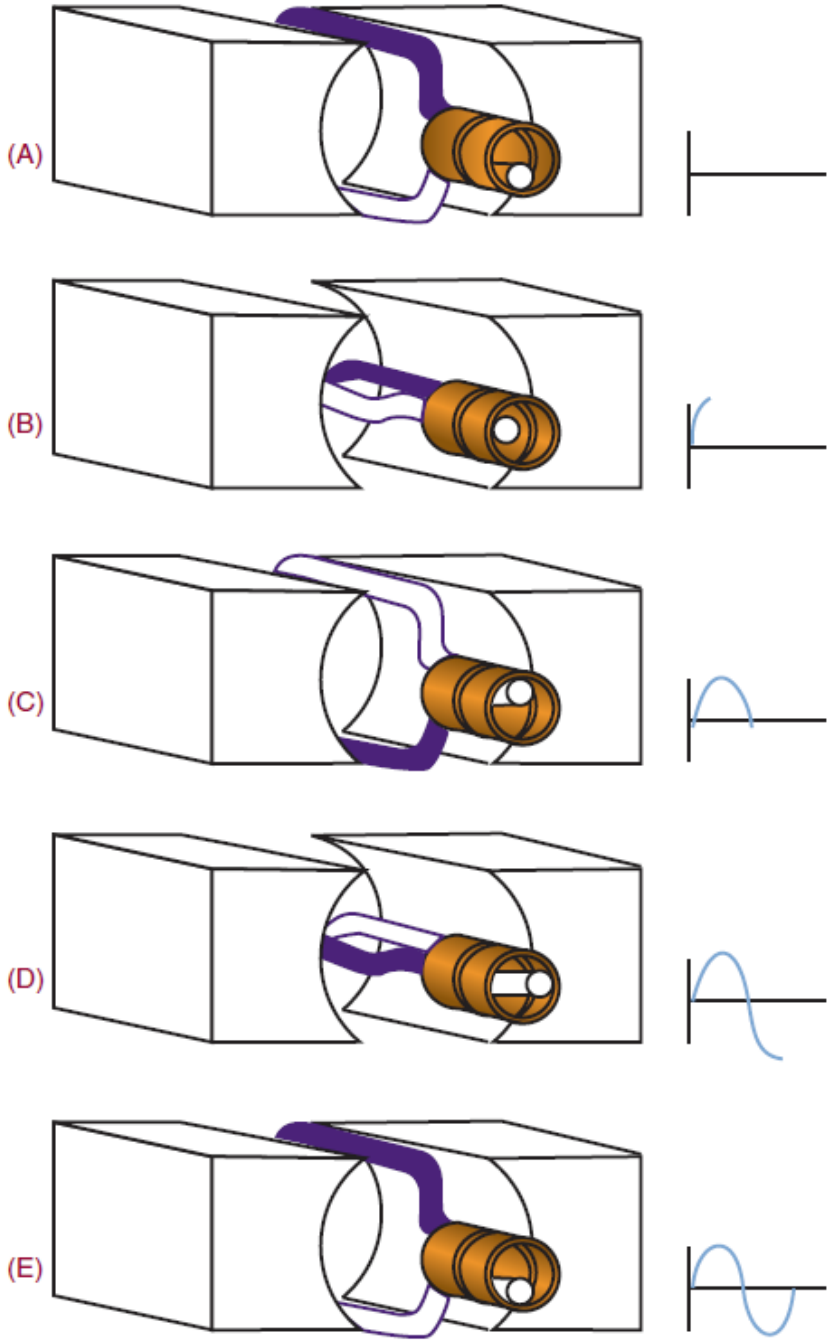


Induced voltage in an AC generator.

Magnetic and Electromagnetic Applications

- As the loop is rotated to position C, fewer lines of force are cut and the induced voltage decreases from the maximum value to zero volts. At this point, the loop has rotated 180°, or half a circle. The direction of current flow can be determined by applying the left-hand rule for generators. The arrow shows the direction of current flow at position B.
- When the loop is rotated to position D, the action reverses. As the dark half moves up through the magnetic lines of force and the light half moves down, applying the left-hand rule for generators shows that the induced voltage changes polarities. The voltage reaches a peak at position D and decreases until the loop reaches the original position. The induced voltage has completed one cycle of two alternations.

Induced voltage in an AC generator.



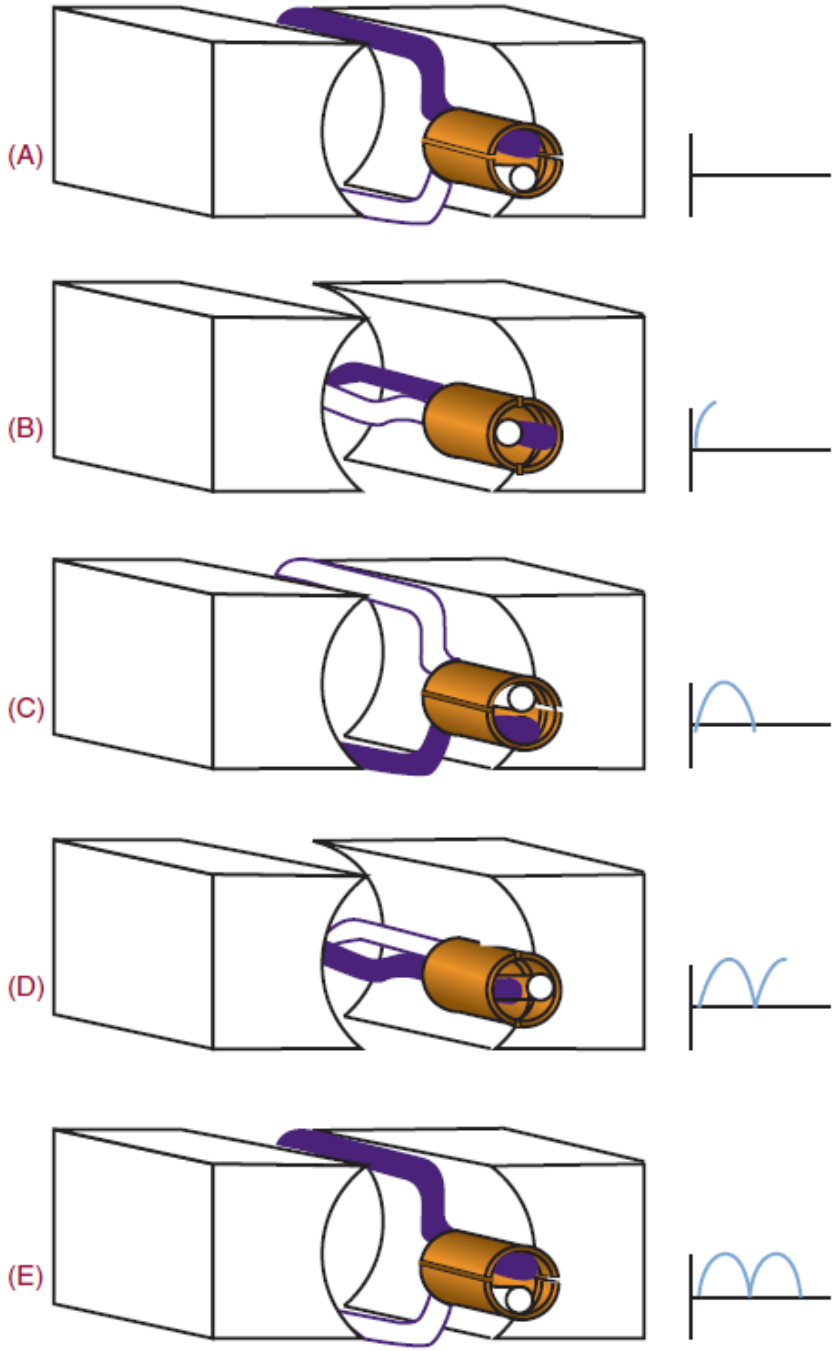
Magnetic and Electromagnetic Applications

- The rotating loop is called an **armature**, and the source of the electromagnetic field is called the **field**. The armature can have any number of loops.
- The term *armature* refers to the part that rotates in the magnetic field, regardless of whether it consists of one loop or multiple loops.
- The **frequency** of the alternating current or voltage is the number of complete cycles completed per second. The speed of rotation determines the frequency.
- An **AC generator** is often called an **alternator** because it produces alternating current.

Magnetic and Electromagnetic Applications

- A DC (direct current) generator also converts mechanical energy into electrical energy. It functions like an AC generator with the exception that it converts the AC voltage to DC voltage. It does this with a device called a **commutator**, as shown in Figure.
- The output is taken from the commutator, a split ring. When the loop is rotated from position A to position B, a voltage is induced. The induced voltage is greatest as the motion is at right angles to the magnetic field.
- As the loop is rotated to position C, the induced voltage decreases from the maximum value to zero.
- As the loop continues to rotate to position D, a voltage is induced, but the commutator reverses the output polarity so that it remains the same as before.
- The loop then returns to the original position, E. The voltage generated from the commutator pulsates, but in one direction only, varying twice during each revolution between zero and maximum.

Induced voltage in a DC generator.



Magnetic and Electromagnetic Applications

- A relay is an electromechanical switch that opens and closes with an electromagnetic coil (Figure).
- As a current flows through the coil, it generates a magnetic field that attracts the plunger, pulling it down. As the plunger is pulled down, it closes the switch contacts.
- When the current through the coil stops, a spring pulls the armature back to its original position and opens the switch.
- A relay is used where it is desirable to have one circuit control another circuit. It electrically isolates the two circuits. A small voltage or current can control a large voltage or current. A relay can also be used to control several circuits some distance away.
- A doorbell is an application of the relay. The striker to ring the bell is attached to the plunger. As the doorbell is pressed, the relay coil is energized, pulling down the plunger and striking the bell. As the plunger moves down, it opens the circuit, de-energizing the relay. The plunger is pulled back by the spring closing the switch contacts, energizing the circuit again, and the cycle repeats until the button is released.

Examples of various types of relays.



Magnetic and Electromagnetic Applications

- A solenoid is similar to a relay (Figure). A coil, when energized, pulls a plunger that does some mechanical work. This is used on some door chimes where the plunger strikes a metal bar. It is also used on automotive starters. The plunger pulls the starter gear in to engage the flywheel to start the engine.
- Phonograph pickups use the electromagnetic principle. A magnetic field is produced by a permanent magnet that is attached to a stylus (needle). The permanent magnet is placed inside a small coil. As the stylus is tracked through the groove of a record, it moves up and down and from side to side in response to the audio signal recorded. The movement of the magnet in the coil induces a small voltage that varies at the audio signal response. The induced voltage is then amplified and used to drive a loudspeaker, reproducing the audio signal.

Examples of types of solenoids.

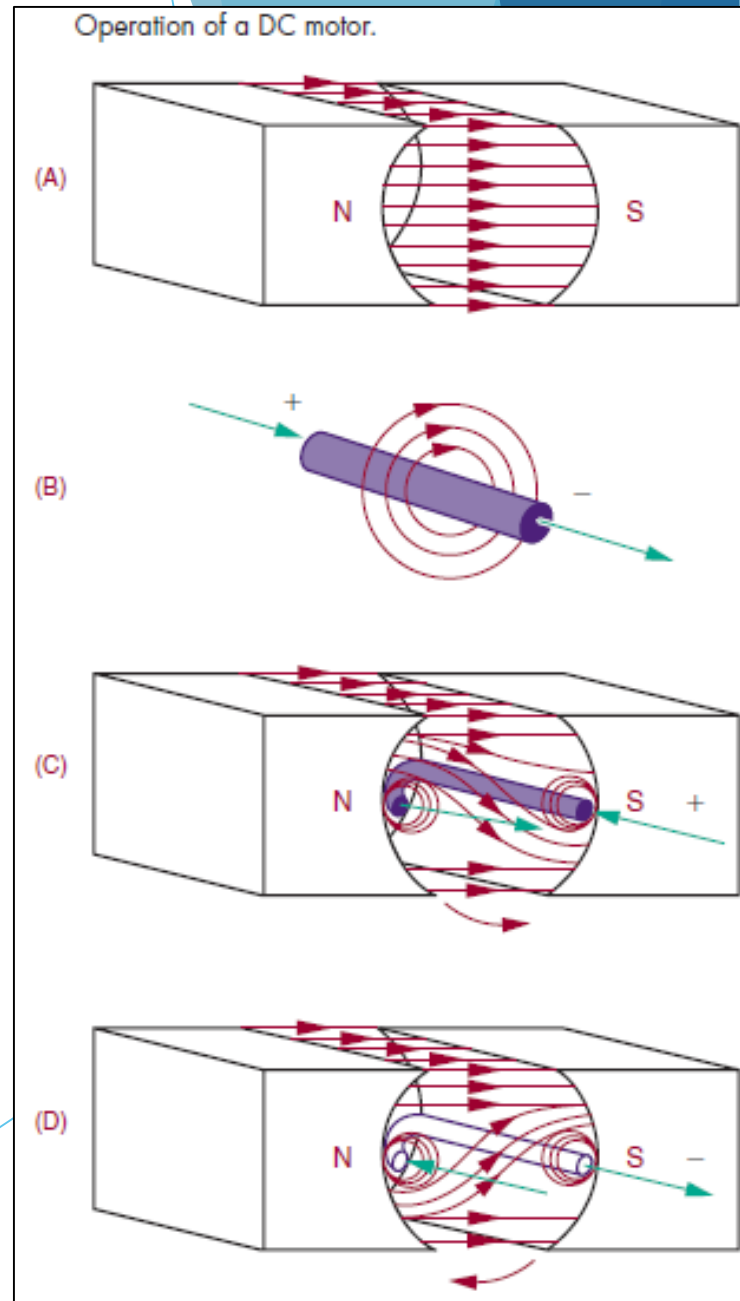


Magnetic and Electromagnetic Applications

- **Loudspeakers** are used for all types of audio amplification. Most speakers today are constructed of a moving coil around a permanent magnet. The magnet produces a stationary magnetic field. As current is passed through the coil, it produces a magnetic field that varies at the rate of the audio signal. The varying magnetic field of the coil is attracted and repelled by the magnetic field of the permanent magnet. The coil is attached to a cone that moves back and forth in response to the audio signal. The cone moving back and forth moves the air, reproducing the audio sound.
- Magnetic recording is used for cassette recorders, video recorders, reel-to-reel recorders, floppy disk drives, and hard disk drives. All these devices use the same electromagnetic principle to store information. A signal is stored on the tape or disk with a record head, to be read back later with a playback head.
- In some equipment, the record and playback head are combined in one package or they may be the same head. The record and playback head are a coil of wire with a ferromagnetic core. In a tiny gap between the ends of the core is a magnetic field. As the storage medium, a piece of material covered with iron oxide, is pulled across the record head, the magnetic field penetrates the tape, magnetizing it. The information is written on it in a magnetic pattern that corresponds to the original information. To play back or read the information, the medium is moved past the gap in the playback head. The changing magnetic field induces a small voltage into the coil winding. When this voltage is amplified, the original information is reproduced.

Magnetic and Electromagnetic Applications

- The operation of a DC motor (Figure) depends on the principle that a current-carrying conductor, placed in and at right angles to a magnetic field, tends to move at right angles to the direction of the field.
- Figure A shows a magnetic field extending between a north pole and a south pole.
- Figure B shows the magnetic field that exists around a current carrying conductor. The plus sign implies that the current flows inward. The direction of the flux lines can be determined using the left-hand rule.
- Figure C shows the conductor placed in the magnetic field. Note that both fields become distorted. Above the wire, the field is weakened, and the conductor tries to move upward. The amount of force exerted upward depends on the strength of the field between the poles and the amount of current flowing through the conductor.
- If the current through the conductor is reversed (Figure D), the direction of the magnetic flux around the conductor is reversed. If this occurs, the field below the conductor is weakened and the conductor tends to move downward.



Magnetic and Electromagnetic Applications

- A method of determining the direction of a current-carrying conductor in a magnetic field uses the **right-hand motor rule**: When the thumb, index finger, and middle finger of the right hand are extended at right angles to each other, the middle finger points in the direction of current flow in the conductor; the index finger indicates the magnetic field from the north pole to the south pole; the thumb points in the direction of the motion of the conductor.
- The force acting on a current-carrying conductor in a magnetic field depends on the strength of the magnetic field, the length of the conductor, and the amount of current flowing in the conductor.
- If a loop of wire, free to rotate horizontally, is placed between the two poles of a magnet, the loop spins as the poles repel each other. The current flows in one direction on one side of the loop and in the other direction on the other side of the loop. One side of the loop moves down and the other side of the loop moves upward. The loop rotates in a counterclockwise direction around its axis. A commutator reverses the direction of current flow in the loop every time it reaches the top or zero torque position. This is how a DC motor rotates. The loop or armatüre rotates in a magnetic field. Permanent magnets or electromagnets may produce this field. The commutator reverses the direction of current through the armature. Note the resemblance between a DC motor and a **DC generator**.

Magnetic and Electromagnetic Applications

- The basic meter movement uses the principle of the DC motor. It consists of a stationary permanent magnet and a moveable coil. When the current flows through the coil, the resulting magnetic field reacts with the field of the permanent magnet and causes the coil to rotate. The greater the current flow through the coil, the stronger the magnetic field produced. The stronger the magnetic field produced, the greater the rotation of the coil. To determine the amount of current flow, a pointer is attached to the rotating coil. As the coil turns, the pointer also turns. The pointer moves across a graduated scale and indicates the amount of current flow. This type of meter movement is used for analog meters such as voltmeters, ammeters, and ohmmeters.
- A conductor carrying a current can be deflected (moved) by a magnetic field. It is not the conductor that is deflected, but the electrons traveling in the conductor. The electrons are restricted to the conductor, so the conductor also moves. Electrons can travel through other media. In the case of television picture tubes, electrons travel through a vacuum to strike a phosphor screen where they emit light. The electrons are produced by an electron gun. By varying the electron beam over the surface of the Picture screen, a picture can be created. To move the beam back and forth across the screen, two magnetic fields deflect the beam. One magnetic field moves the beam up and down the screen, and the other magnetic field moves the beam from side to side. This method is used in television, radar, oscilloscopes, computer terminals, and other applications where a picture is desired on a screen.

Inductance

- When a current flows through a conductor, a magnetic field builds up around the conductor.
- This field contains energy and is the foundation for inductance.
- **Inductance** is the characteristic of an electrical conductor that opposes a change in current flow.
- The symbol for inductance is **l**.
- An **inductor** is a device that stores energy in a magnetic field.

Principles of Inductance

- Inductance exhibits the same effect on current in an electric circuit as inertia does on velocity of a mechanical object. It takes more work to start a load moving than it does to keep it moving because the load possesses the property of inertia.
- Inertia is the characteristic of mass that opposes a change in velocity. Once current is moving through a conductor, inductance helps to keep it moving. The effects of inductance are sometimes desirable and other times undesirable.
- As noted in Chapter of Magnetism, the basic principle behind inductance states, *when a current flows through a conductor, it generates a magnetic field around the conductor.*
- As the magnetic flux lines build up, they create an opposition to the flow of current.

Principles of Inductance

- When the current changes direction or stops, or the magnetic field changes, an electromotive force (emf) is induced back into the conductor through the collapsing of the magnetic field. The opposition to the changes in current flow is identified as a counter electromotive force (counter emf). **Lenz's law** summarizes this effect—an induced emf in any circuit is always in a direction to oppose the effect that produced it. The amount of counter emf is in proportion to the rate of change: The faster the rate of change, the greater the counter emf.
- All conductors have some inductance. The amount of inductance depends on the conductor and the shape of it. Straight wire has small amounts of inductance, whereas coils of wire have much more inductance.
- The unit by which inductance is measured is the **henry (H)**, named for Joseph Henry (1797–1878), an American physicist. A henry is the amount of inductance required to induce an emf of 1 volt when the current in a conductor changes at the rate of 1 ampere per second. The henry is a large unit; the millihenry (mH) and microhenry (mH) are more commonly used.

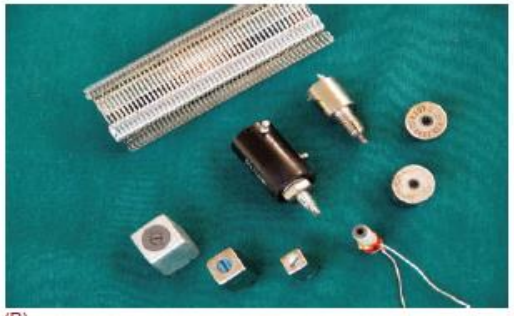
Inductors

- Inductors are devices designed to have a specific inductance.
- They consist of a conductor coiled around a core and are classified by the type of core material—magnetic or nonmagnetic.
- Figure 1 shows the symbol used for inductors.
- Inductors can also be **fixed** or variable. Figure 2 shows the symbol for a variable inductor. **Variable inductors** are created with adjustable core material.
- Figure 3 shows several types of inductors used for adjusting the core material. Maximum inductance occurs when the core material is in line with the coil of the wire.
- **Air-core inductors**, or inductors without core material, are used for up to 5 millihenries of inductance. They are wrapped on a ceramic or phenolic core (Figure 4).

Various types of fixed inductors (A), variable inductors (B).



(A)



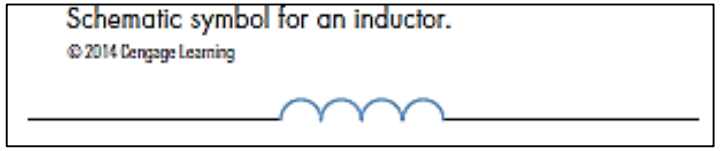
(B)

Air-core inductors.



Schematic symbol for an inductor.

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Schematic symbol for a variable inductor.

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Inductors

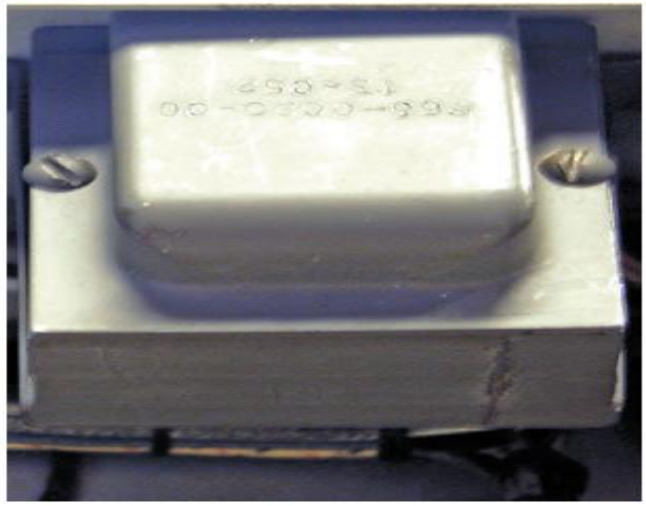
- **Ferrite-core inductors** and powdered iron cores inductors are used for up to 200 millihenries. The symbol used for an iron-core inductor is shown in Figure 1. An iron-core inductor is also referred to as a choke. Chokes are used in DC and low-frequency AC applications.
- **Toroid-core inductors** are donut-shaped and offer a high inductance for a small size (Figure 2). The magnetic field is contained within the core.
- **Shielded inductors** have a shield made of magnetic material to protect them from the influence of other magnetic fields (Figure 3).
- **Laminated iron-core inductors** are used for all large inductors (Figure 4). These inductors vary from 0.1 to 100 henries, the inductance depending on the amount of current flowing through the inductor. These inductors are sometimes referred to as chokes. They are used in the filtering circuits of power supplies to remove AC components from the DC output.

Schematic symbol for an iron-core inductor.

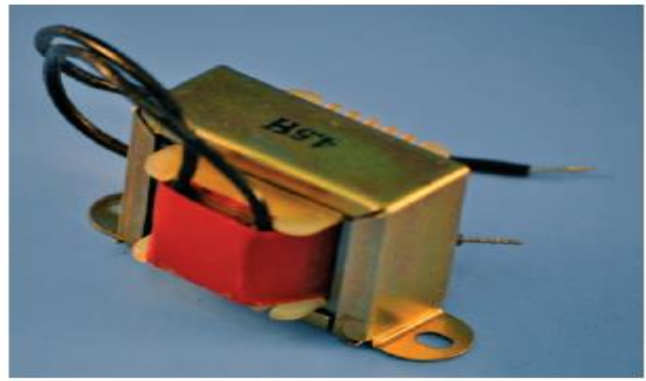
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Toroid-core inductor.



Shielded inductor.



Laminated iron-core inductor.

Inductors

- Inductors typically have tolerances of +-10%, but tolerances of less than 1% are available.
- Inductors, like resistors, can be connected in series, parallel, or seriesparallel combinations.
- The total inductance of several inductors connected in series (separated to prevent their magnetic fields from interacting) is equal to the sum of the individual inductances.

$$L_T = L_1 + L_2 + L_3 \ldots + L_n$$

- If two or more inductors are connected in parallel (with no interaction of their magnetic fields), the total inductance is found by using the formula:

$$\frac{1}{L_T} = \frac{1}{L_1} + \frac{1}{L_2} + \frac{1}{L_3} \ldots + \frac{1}{L_n}$$

L/R Time Constants

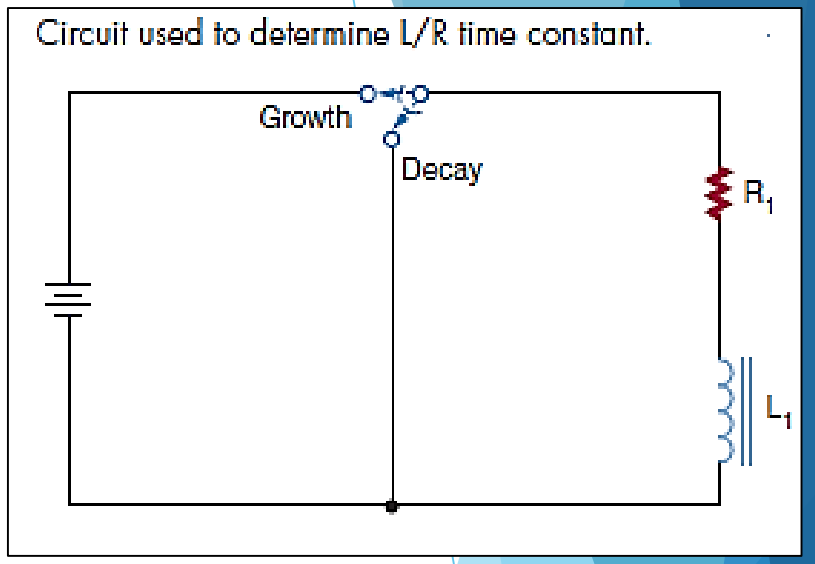
- An **L/R time constant** is the time required for current through a conductor to increase to 63.2% or decrease to 36.8% of the maximum current. An RL circuit is shown in Figure.
- L/R is the symbol used for the time constant of an RL circuit. This can be expressed as follows:

$$t = \frac{L}{R}$$

where t = time in seconds,

L = inductance in henries,

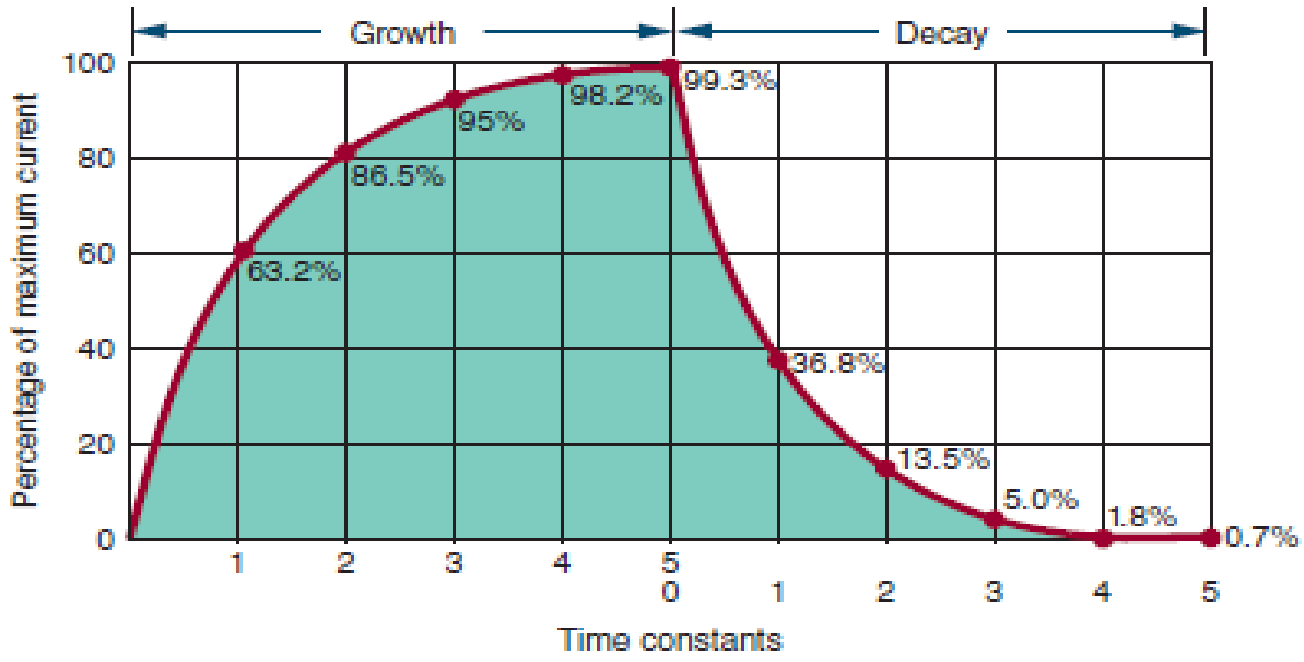
R = resistance in ohms



L/R Time Constants

- Figure charts the growth and decay (or increase and decrease) of a magnetic field, in terms of time constants.
- It takes five time constants to fully transfer all the energy into the magnetic field, or to build up the maximum magnetic field. It takes five full-time constants to completely collapse the magnetic field.

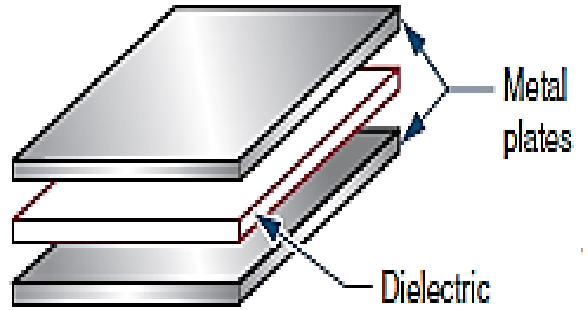
Time constants required to build up or collapse the magnetic field in an inductor.



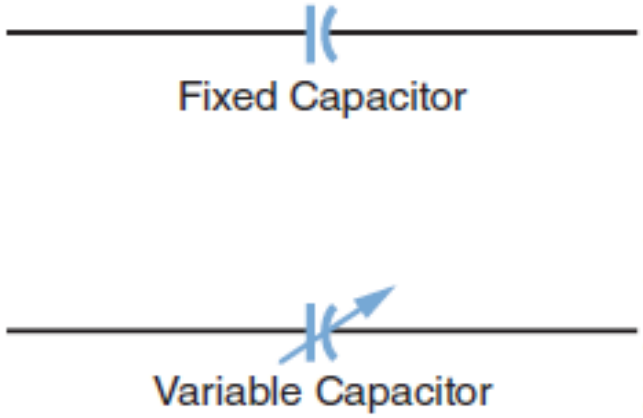
Capacitance

- Capacitance allows for the storage of energy in an electrostatic field.
- Capacitance is present whenever two conductors are separated by an insulator.
- **Capacitance** is the ability of a device to store electrical energy in an electrostatic field.
- The symbol for capacitance is **C**.
- A capacitor is a device that possesses a specific amount of capacitance.
- A **capacitor** is made of two conductors separated by an insulator (Figure 1). The conductors are called **plates** and the insulator is called a **dielectric**. Figure 2 shows the symbols for capacitors.

A capacitor consists of two plates (conductors) separated by a dielectric (insulator or nonconductor).



Schematic symbols for capacitors.



Capacitance

- When a DC voltage source is connected to a capacitor, a current flows until the capacitor is charged. The capacitor is charged with an excess of electrons on one plate (negative charge) and a deficiency of electrons on the other plate (positive charge). The dielectric prevents electrons from moving between the plates.
- Once the capacitor is charged, all current stops. The capacitor's voltage is equal to the voltage of the voltage source.
- A charged capacitor can be removed from the voltage source and used as an energy source. However, as energy is removed from the capacitor, the voltage diminishes rapidly.
- In a DC circuit, a capacitor acts as an open circuit after its initial charge. An open circuit is a circuit with an infinite resistance.

Capacitance

- The amount of energy stored in a capacitor is in proportion to the size of the capacitor.
- The capacitors used in classrooms are usually small and deliver only a small shock if discharged through the body. If a capacitor is large and charged with a high voltage, however, the shock can be fatal.
- Charged capacitors should be treated like any other voltage source. Use a commercial shorting stick or a screwdriver with an insulated handle and a lead attached to discharge capacitors.
- The basic unit of capacitance is the **Farad (F)**. A farad is the amount of capacitance that can store 1 coulomb (C) of charge when the capacitor is charged to 1 volt.
- The farad is too large a unit for ordinary use, so the **microfarad (mF)** and **picofarad (pF)** are used. The letter **C** stands for capacitance.

Capacitors

- Four factors affect the capacitance of a capacitor:
  1. Area of the plate
  2. Distance between the plates
  3. Type of dielectric material
  4. Temperature
- A capacitor is either fixed or variable. A **fixed capacitor** has a definite value that cannot be changed.
- A **variable capacitor** is one whose capacitance can be changed either by varying the space between plates (trimmer capacitor) or by varying the amount of meshing between two sets of plates (tuning capacitor).
- Capacitance is directly proportional to the area of the plate. For example, doubling the plate area doubles the capacitance if all other factors remain the same.
- Capacitance is inversely proportional to the distance between the plates. In other words, as the plates move apart, the strength of the electric field between the plates decreases.

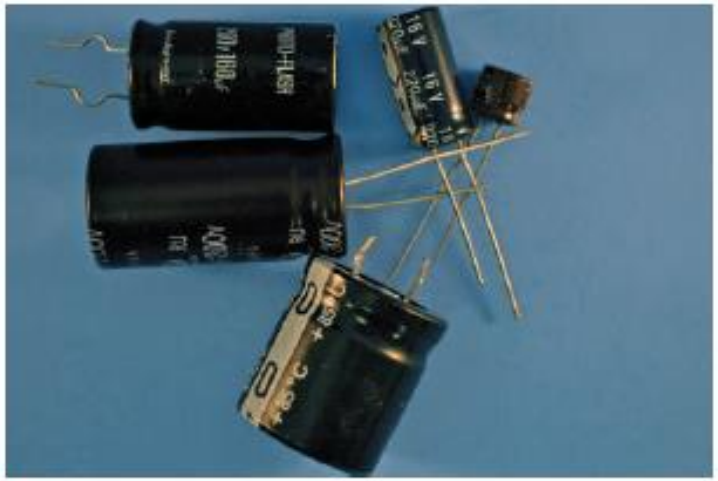
Capacitors

- The ability of a capacitor to store electrical energy depends on the electrostatic field between the plates and the distortion of the orbits of the electrons in the dielectric material.
- The degree of distortion depends on the nature of dielectric material and is indicated by its dielectric constant.
- A **dielectric constant** is a measure of the effectiveness of a material as an insulator. The constant compares the material's ability to distort and store energy in an electric field to the ability of air, which has a dielectric constant of 1. Paper has a dielectric constant of 2 to 3; mica has a dielectric constant of 5 to 6; and titanium has a dielectric constant of 90 to 170.

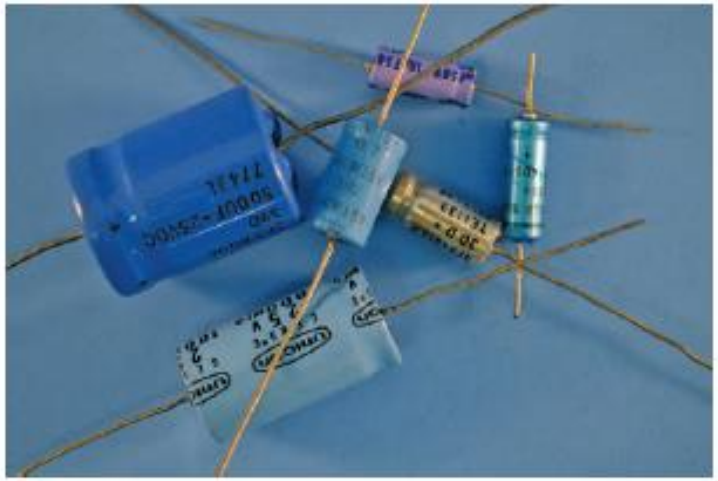
Capacitors

- The temperature of a capacitor is the least significant of the four factors. It need not be considered for most general-purpose applications.
- Capacitors come in many types and styles to meet the needs of the electronics industry.
- **Electrolytic capacitors** offer large capacitance for small size and weight (Figure). Electrolytic capacitors consist of two metal foils separated by fine gauze or other absorbent material that is saturated with a chemical paste called an electrolyte. The electrolyte is a good conductor and serves as part of the negative plate. The dielectric is formed by oxidation of the positive plate. The oxidized layer is thin and a good insulator. An electrolytic capacitor is polarized, having positive and negative leads. Polarity must be observed when connecting an electrolytic capacitor in a circuit.

Electrolytic capacitors. (A) Radial capacitor leads (B) Axial capacitor leads.



(A)

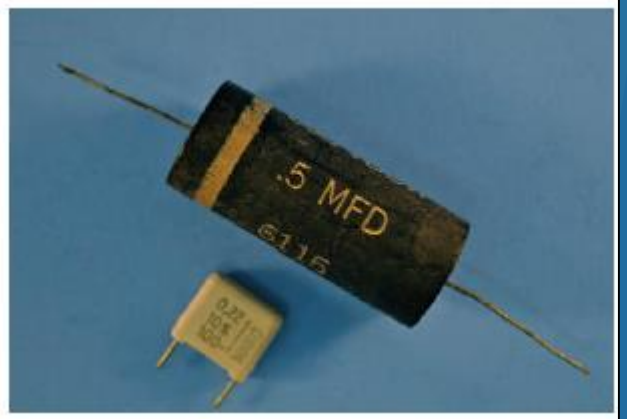


(B)

Capacitors

- **Paper capacitors** and plastic capacitors are constructed by a rolled foil technique (Figure 1). A paper dielectric has less resistance than a plastic film dielectric, and plastic film is now being used more as a result. The plastic film allows a metallized film to be deposited directly on it. This reduces the distance between plates and produces a smaller capacitor.
- The **ceramic disk capacitor** is popular because it is inexpensive to produce (Figure 2). It is used for capacitors of 0.1 microfarad and smaller. The ceramic material is the dielectric. This is a tough, reliable, general-purpose capacitor.
- Variable capacitors also come in all sizes and shapes (Figure 3). Types include padders, trimmers, and tuning capacitors. Padder and trimmer capacitors must be adjusted by a technician. The user can adjust tuning capacitors.

Paper and plastic capacitors.



Ceramic disk capacitors.



Variable capacitors.



Capacitors

- Like resistors and inductors, capacitors can be connected in series, parallel, and series-parallel combinations.
- Placing capacitors in series effectively increases the thickness of the dielectric. This decreases the total capacitance, because capacitance is inversely proportional to the distance between the plates. The total capacitance of capacitors in series is calculated like the total resistance of parallel resistors:

$$\frac{1}{C_T} = \frac{1}{C_1} + \frac{1}{C_2} + \frac{1}{C_3} \ldots + \frac{1}{C_n}$$

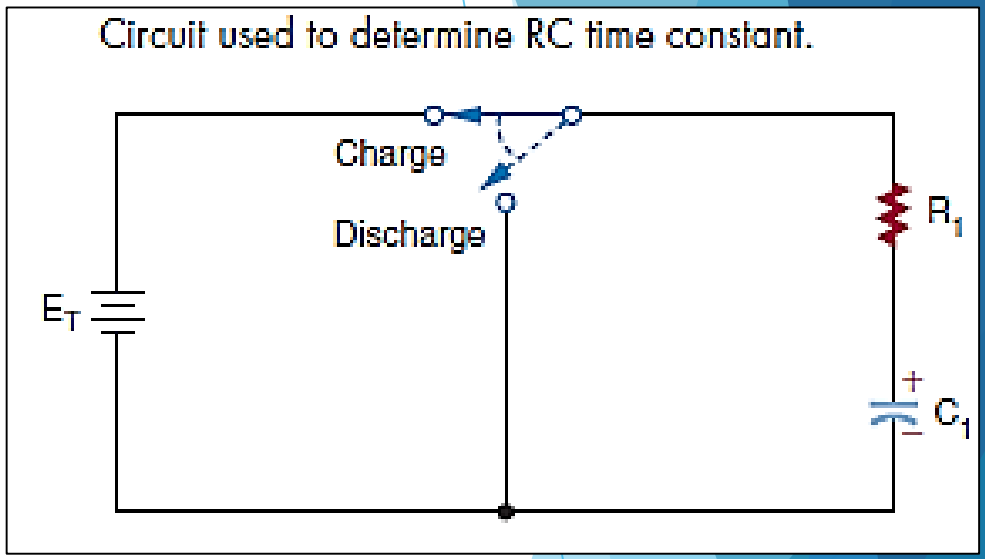
- When capacitors of different values are connected in series, the smaller capacitors charge up to the highest voltage. Placing capacitors in parallel effectively adds to the plate area. This makes the total capacitance equal to the sum of the individual capacitances:

$$C_T = C_1 + C_2 + C_3 \ldots + C_n$$

- Capacitors in parallel all charge to the same voltage.

RC Time Constants

- An **RC time constant** reflects the relationship among time, resistance, and capacitance.
- An RC circuit is shown in Figure. The time it takes a capacitor to charge and discharge is directly proportional to the amount of the resistance and capacitance.
- The time constant reflects the time required for a capacitor to charge up to 63.2% of the applied voltage or to discharge down to 36.8%. The time constant is expressed as follows:



Circuit used to determine RC time constant.

$$t = RC$$

where t = time in seconds

R = resistance in ohms

C = capacitance in farads

RC Time Constants

- The time constant is not the time required to charge or discharge a capacitor fully.
- Figure shows the time constants needed to charge and discharge a capacitor. Note that it takes approximately five time constants to fully charge or discharge a capacitor.

Chart of time constants required to charge and discharge a capacitor.

