Chapter 10 Magnetism

Learning Objective

- Proper interpretation magnetic field
- Magnetic moments in magnetic field
- Magnetic domains and Magnetization
- Electricity produces Magnetism
- Magnetism force on moving charges and the invention of motor
- Faraday's magnetic induction
- Generation of electromagnetic wave

Glossary

- Magnetic field
- Magnetic dipole
- Magnetic moment
- Magnetic domains
- Magnetization
- Compass
- Magnetic force
- Current loop
- Magnetic induction
- Faraday's Law
- EMF
- Antenna
- Electromagnetic wave

I. Introduction

Magnetism is a fundamental force of nature where certain materials, known as magnets, exhibit the ability to attract or repel other materials due to their inherent magnetic properties. This force is a result of the alignment of microscopic magnetic domains within the material. Historically the ancient Chinese and Greeks documented the properties of naturally occurring magnetic rocks called lodestones. However, it wasn't until William Gilbert's work in the 16th century that systematic investigations into magnetism began. Today we know that magnetism not just original from permanent magnets but also from electricity. Understand magnetism is essential for us to appreciate a wide range of applications such as compasses that utilizes the Earth's magnetic field for navigation, electric motors for doing mechanical works, generators for generating electricity, magnetic materials for storing digital data, superconducting magnets for medical imaging, and inductors for electronics.

II. Magnetic Field and Magnetic Force of Permanent Magnets

Permanent magnets are materials that inherently maintain their magnetic properties without the need for an external influence. Materials such as steel or iron can be magnetized when exposed to an external magnetic field.
Every permanent magnet has a north pole and a south pole, constituting a magnetic dipole. If a permanent magnet is divided into two, each part becomes a separate magnet with its own north and south poles. Further division results in even smaller magnets, but each will always possess both poles. Hence, a magnet is inherently dipolar, and a solitary north or south pole cannot exist on its own.

Just as with electric charges, opposite magnetic poles attract, while like poles repel each other. The force of attraction or repulsion increases as the poles get closer. The magnetic force between poles is analogous to electrical forces, though they may differ in magnitude. The magnetic field emitted by a bar magnet can be visualized in pattern as depicted in Fig. 1.

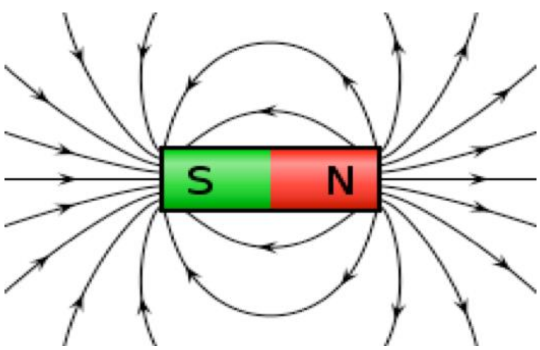


Fig. 1 Magnetic Field in Space Surrounding a Bar Magnet or a Magnetic Dipole.

The field pattern above looks similar to those generated by electric dipole illustrated in Fig. 3, with the magnetic field lines streaming away from the north pole but converging into the south pole. The north pole acts just like a (+) charge while the south pole likes a (-) charge. Should a mono magnetic pole exists, then magnetic field and a mono north pole interact just like what is described for electric fields and a (+) test charge. However, the simplest magnet comes in two opposite poles or dipole only. A standalone north or a south pole doesn't exist. So the magnetic field is best understood by its interact with a dipole magnet. Let's place a weak and tiny magnet, such as a compass, in a small region of space near a big and strong magnet as shown in Fig.1. A tiny and weak magnetic compass is used because we want both poles exposed to the same field for better understanding how the field work. The field interacts with compass needle, exerting two forces, one at each pole. The two forces have the same magnitude but in different directions. These two forces cause the compass rotate, until they become opposite and cancel each other out. (Initially this pair of forces causes the needle to oscillate but soon dies off due to friction.) The end result is the field aligns the compass needle a lone a magnetic field line, with the north pole oriented in the same direction as the arrow of a field line, while south pole points in the opposite direction. So, you can think of magnetic field lines does nothing but align a compass and renders its north pole oriented along the direction the arrows of the field line. (More technically in the direction tangential to the field line if the field line is a curve.)

In a nutshell, magnetic field aligns magnetic dipole, such as compass needles.

Such an alignment is illustrated by Fig.2A and 2B. The upper plane of the horizontal bar magnet is sprinkled with iron fillings while in the low half plane 5 compasses are place. Hence, both magnetic filings and interact with the magnetic field of the bar magnet. Note that each compass has its own orientation, no longer pointing to the geographic North Pole. If you draw a line (red in Fig.2B) connecting all five compasses, you will trace out an arc origination from the N pole of the bar magnet to the south pole, with each compass align exactly on the curve line. The uncolored end is the north pole of the compass needle, they point in the directions suggested by the arrows of the magnetic field line.

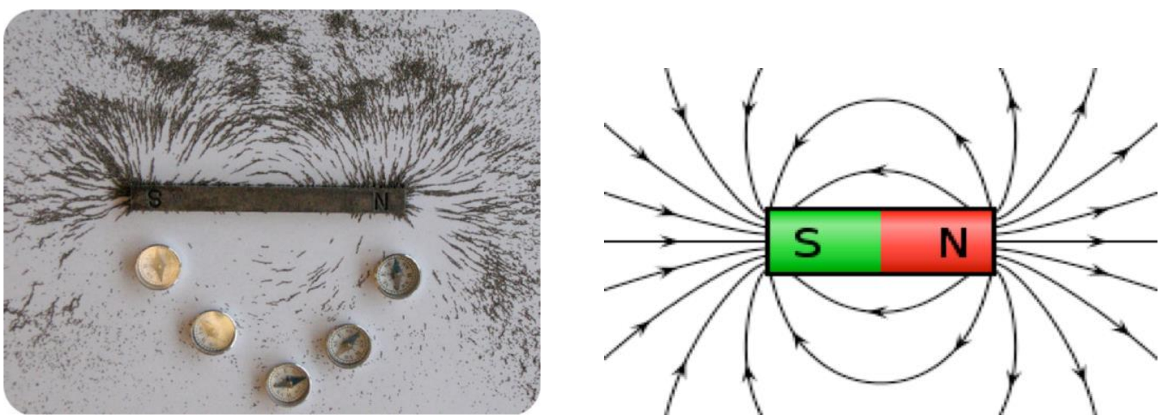


Fig. 2 A. Interaction between Magnetic Field and Magnetic Dipoles. Magnetic compasses are dipoles, i.e. north – south poles separated by a distance.

The magnetic fillings in the upper plane is much more revealing. The filling forms lines look exactly similarly the magnetic field lines illustrated on the right.

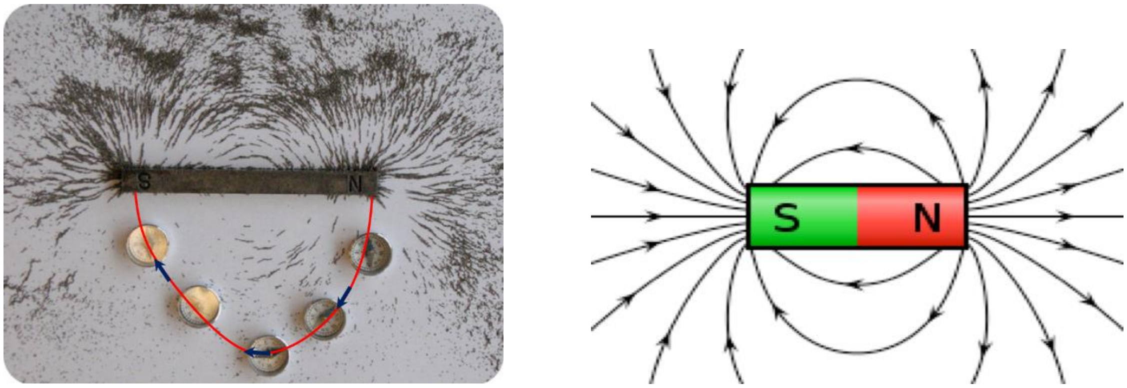


Fig. 2B. Evidence of Magnetic Field Lines emitted by a Bar Magnet.

Similar to the electric field, the density of magnetic field signify the strength (magnitude) of the magnetic field, the fields are more dense near the holes, thus magnetic attraction or repulsion near the pole than near the body of the bar magnet.

Bar magnet is a **magnetic dipole**. There are magnetics that have poles or more, but they are just a multiple of dipoles. Magnet dipole oscillate or process like a spinning top in magnetic field is also called a **magnetic moment**, to be elaborated later.

III. Magnetic Field Induced by Electric Current

Thus, magnetic field interacts with magnet poles. The strength of the interaction depends of the density of the field lines. Field lines near the poles are more dense, thus magnetic force is stronger experienced by a pole is stronger there. However, the force come in pair, one for the south pole one for the north in opposite direction, together they align the magnet in the magnetic field. The arrow of a field line indicates the direction orientation of the south pole of a compass placed there.

Not only permanently magnet can generate magnetic field, it is known that a conductor carrying electric current also generates magnetic field that is circularly warping around the conductor. Fig. 3A illustrates a set of compasses in circle around a vertical section of a wire coated in green, yet to be connected to a battery. Since the wires are disconnected from the battery, there is no electricity passing through it. The needles of all compasses align themselves in the same direction, with the red ends pointing to the North Pole of the earth. (The colored end of a compass needle, red in this case, if properly set is the north pole of the needle magnet, pointing toward the geographical North Pole of the earth.   The white end points toward the South Pole) At this moment the only thing influencing the magnetic compass's magnetic needle is the earth's magnetic field; thus all needles are orientated in the north-south direction.

Not only can permanent magnets also known as magnetic dipoles generate magnetic fields, but conductors carrying electric current can also produce magnetic fields that wrap circularly around the conductor. Fig. 3A shows a set of compasses arranged around a straight, vertical section of wire coils coated in green. The wire is not carrying any current because it is disconnected from the battery. In this state, all compass needles align in the same direction, with their red ends pointing towards Earth's North Pole. (Note: the red end of a properly set compass needle is its magnetic north pole, while the white end is the south pole. This implies that the Earth acts as a huge but weak magnet, with its magnetic south pole located at the geographic North Pole.) At this moment, Earth's magnetic field is the only entity influencing the orientation of the compass needles, aligning them all in the same north-south direction.

When the wire in Fig. 3A is connected to the battery, the orientation of the compass needles changes dramatically, aligning in a circular pattern as shown in Fig. 3B. This suggests that the electric current creates a magnetic field that is circular, as depicted in Fig. 4.

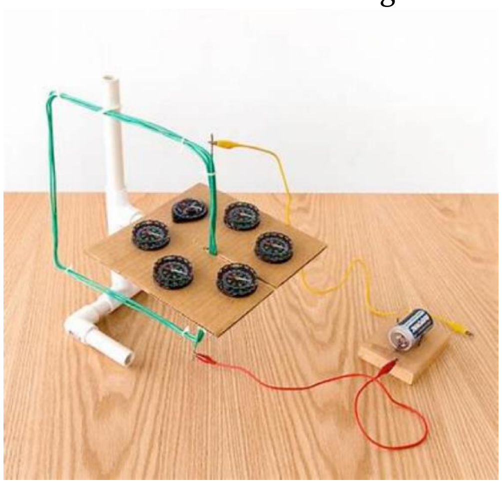


Fig. 3A. Open Circus No Current **Fig**. 3B. Closed Circuit, Current On.

(A.) Magnetic Compasses placed around a straight segment of wire wrapped in loops, not carrying electric current as it is not connected to the battery. Earth's magnetic field align all compasses in the geographic North-South direction.

(B.) When the electricity is turned on, the needles of the compasses oriented themselves, forming a circular pattern, an evidence that electric current is producing a circular magnetic field wrapping around the straight conductor.

Fig. 4 illustrates the magnetic field pattern generated by a wire carrying a *conventional current* that travels from the bottom up. In reality, this is caused by a current of electrons traveling downward. The figure shows only a cross-section of the magnetic field, revealing the magnetic field lines are concentric rings. These rings are denser (more intense) near the wire and become sparser (weaker) farther away from it. The same pattern would be observed if the cross-sectional plane were shifted either up or down along the straight wire. The arrows on the concentric field circles indicate the direction of the north pole of a magnetic dipole would be if placed there. Similarly, the denser are the field rings, the stronger the magnetic field.

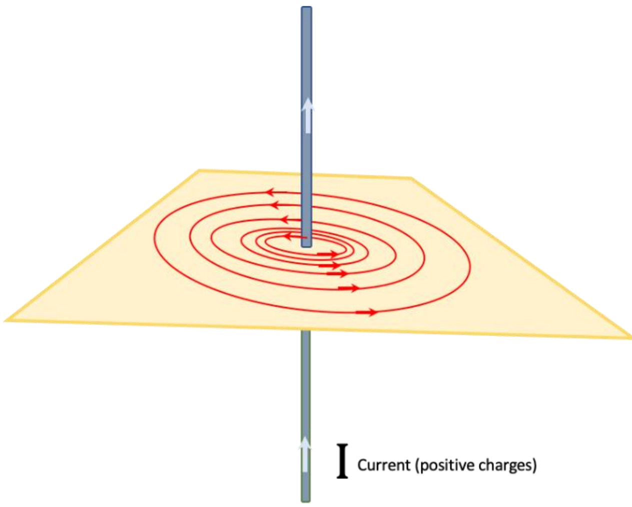


Fig. 4.Magnetic Field Generated by a Wire Carrying Electric Current

IV. Electromagnet

If an electric current generates a magnetic field, can it also be turned into a magnet, generating a magnetic field like a permanent magnet? Indeed it can! A commonly known trick is to wrap a wire around a pencil to form a coil, connect the wire's ends to a battery, and pass an electric current through it. The pencil then becomes a magnet capable of picking up paper clips. In doing so, a magnetic field is formed by passing electric current through a conducting coil, also known as a solenoid. Fig. 5 illustrates the magnetic field generated by a conventional current flowing through a wire wrapped into a coil. The conventional current enters in a clockwise direction, forming the S-pole, and exits at the other end, forming an N-pole. The magnetic field thus generated resembles that of a bar magnet, which is why it's called an electromagnet. In this way, a magnetic dipole is created by the current-carrying coil.

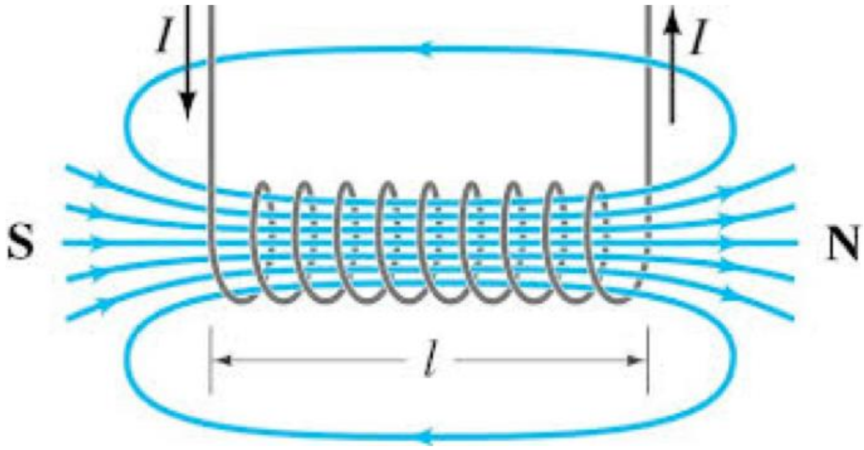


Fig. 5. Electromagnet. Magnetic field generated a conventional current passing current to a wire wound as a coil (solenoid). The field resembles that of a bar magnet.

V. Magnetic Moments and Magnetization

A magnetic dipole, such as a bar magnet, has a north and a south pole and tends to align with the magnetic field to which it is exposed. When a bar magnet is placed in a uniform magnetic field, it experiences two forces of equal magnitude but opposite directions at each pole, as illustrated in Fig. 6A. The direction of the force at the north pole aligns with that of the field arrows, while the force at the south pole is in the opposite direction. Fig. 6A shows the dipole rotating under the influence of these two equal and opposite forces. This pair of forces causes the magnetic dipole to rotate until it reaches the state depicted in Fig. 6B, where the forces exactly cancel each other out. This is also when the dipole is perfectly aligned with the magnetic field, similar to how a compass aligns itself in a magnetic field. (In reality, the dipole will oscillate initially before settling into this position due to the friction of the support suspending or pivoting the dipole.)

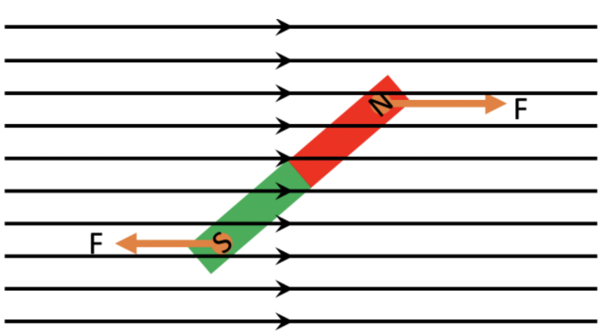


Fig. 6A. The arrow of the field indicates the direction of the force acting on the north pole. The force on the south pole is consequently in the opposite direction. These two forces are equal and opposite, causing the rotation of the magnet.

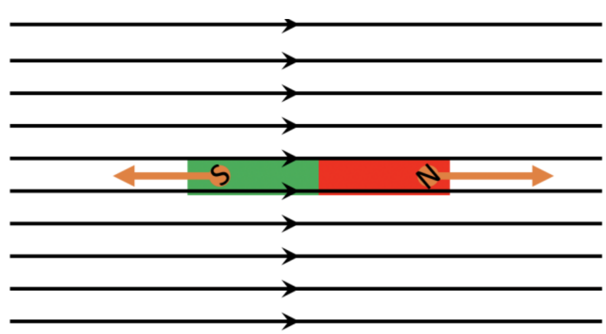


Fig. 6B. Alignment of Magnetic Dipole with the Magnetic Field. The pair of forces causes the magnet to rotate and align with the magnetic field, orienting the north pole of the magnet in the same direction as the field arrow."

VI. Magnet Moments

In Section 5, we mentioned that a current loop can behave much like a magnet. Specifically, a current loop also acts like a magnetic dipole when exposed to an external magnetic field. While it mimics the behavior of a magnetic dipole, a current loop doesn't have a pair of physical poles like a bar magnet. This type of dipole is referred to as a magnetic moment.

In fact, many entities possess magnetic moments. For instance, an electron orbiting the nucleus in an atom effectively functions as an atomic-scale current loop, acting like an extremely tiny magnet. This is also considered a magnetic moment. Moreover, subatomic particles like electrons, protons, and neutrons have an intrinsic magnetic moment, often referred to as spin or quantum spin.

Collectively, these various forms—be they dipolar magnets, current loops, orbital electrons, or particle spins—are all categorized under the term "magnetic moment." For this reason, the term "magnetic dipole" is often used interchangeably with "magnetic dipole moment."

All magnetic moments behave similarly when exposed to an external magnetic field: they will rotate—hence the term "moment"—until they align with the magnetic field as previously described, or they process in the magnetic field, much like a spinning top in gravity.

For convenience, an arrow is often used to represent a magnetic moment, with the arrowhead indicating the north pole. The magnetic dipole illustrated in Fig. 6 can thus be redrawn in Fig. 7 as a single large arrow. This single arrow serves as a universal symbol for various forms of magnetic moments, whether it's a bar magnet, a compass, an electron spin, or a current loop/coil.

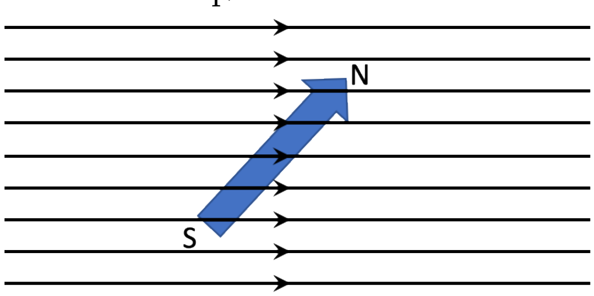


Fig. 7A. A Magnetic Moment in External Magnetic Field. The head starts rotating toward the field lines.

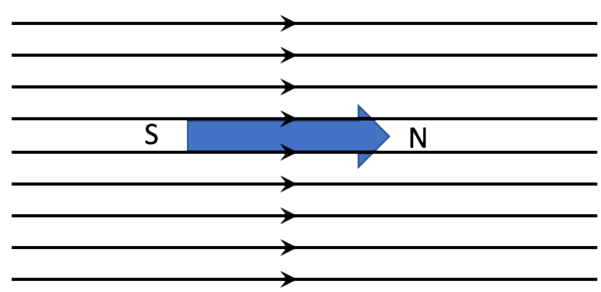


Fig. 7B. Magnetic Moment Aligned with External Magnetic Field.

VII. Magnetic Materials

Non-magnetic materials

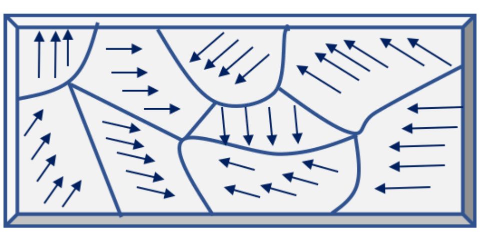
You might be curious about why some materials are magnetic while others are not. The magnetism in a material primarily arises from the alignment of the intrinsic magnetic moments of electrons within its atoms. In materials where atoms have fully filled electron shells or paired electron spins, there is typically little to no net magnetic moment. As a result, these materials exhibit weak or no magnetic properties. Non-magnetic materials such as plastic, wood, and ceramics fall into this category; they show little to no response to magnetic fields.

On the other hand, some materials naturally behave as strong magnets, while others are weak magnets. There are also materials that do not exhibit magnetic properties until exposed to an external magnetic field. Once magnetized, these materials transform themselves into magnets.

Ferromagnetism, Magnetic Domains, and Magnetization.

Because of the way of magnetic moments are arranged inside the material, magnetic materials can be classified into 5 different kinds from ferromagnetism to diamagnetism. Ferromagnetic materials such as iron, nickel, cobalt and their alloys, are strong permanent magnet and reacts strongly to external magnetic field. Yet we know that iron is not always magnetic. A nail only become magnetic and it get magnetized in another magnet's magnetic field.

A ferromagnetic material is distinguished by strong interactions between adjacent magnetic moments, which lead to the formation of distinct magnetic domains. Within each domain, these magnetic moments are aligned, creating a strong overall magnetization, as shown in Fig. 8A. In this figure, the arrows within a domain represent aligned magnetic moments, and groups of these aligned moments make up individual domains. You can think of each domain as a small magnet, and the entire material consists of these small magnets oriented in various directions. In Fig. 8A, you'll notice that these domains are not aligned with each other, effectively cancelling out each other's magnetism.



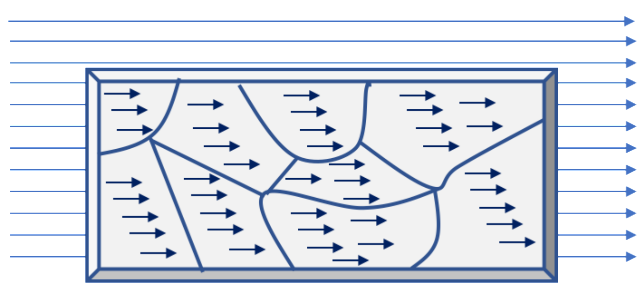


Fig. 8A. Magnetic Domains   Fig. 8B Domains Alignment When in random orientations.   Exposed to an Eternal Magnetic Field.

This is why a seemingly non-magnetic piece of iron can be magnetized; it contains these magnetic domains. In contrast, metals like copper that lack magnetic domains cannot be magnetized. When an external magnetic field is applied to a ferromagnetic material, its magnetic domains align, increasing its magnetization. Once the external field is removed, the domains gradually return to their randomized states, causing the material to demagnetize over time. This demagnetization process can be accelerated by applying heat or a mechanical shock, i.e., by hammering it.

In a nutshell, a material can be magnetized if it contains magnetic domains that are initially misaligned but can be aligned through exposure to an external magnetic field.

VIII. Magnetic Force and the Motor

Magnetic field interacts not only with a magnetic moment, e.g. a compass, it also interacts with a moving charge provided that it is moving perpendicular the direction of the field. If the charge is stationary or a moving in the direction parallel or antiparallel to the magnetic field, it experiences no force acting on it. Fig. 9 depicts such a situation. A stationary positive charge inside a region of magnetic field, and a negative charge moving westward at a constant speed antiparallel to the magnetic field in another region of magnetic field. They both experience no force at all, plus or minus.

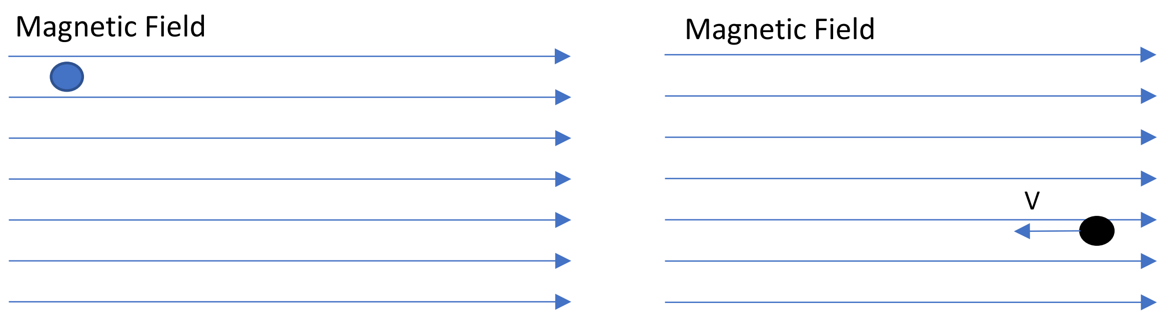


Fig. 9 A Charge at Rest or a Charge in and Moving Antiparallel to the Magnetic Field.

However, if a charge moves in a direction perpendicular to the magnetic field, it experiences a force that is also perpendicular to both its direction of motion and the magnetic field. While this may sound counterintuitive, it is a fundamental aspect of how nature operates. Fig. 10 illustrates this interaction. Imagine a positive charge situated at the back of a room filled with a uniform magnetic field, oriented such that the north is at the back and the south is at the front. The magnetic field lines run from the west wall to the east wall. For simplicity, only one plane of the magnetic field is shown, although it actually fills the entire room.

In the absence of any external forces, the positive charge would travel in a straight line from the north to the south of the room. This hypothetical straight-line path is indicated by the dashed line in Fig. 10. However, what actually happens is that the charge, moving with velocity V, deviates from this straight path and curves upward, as indicated by the red dashed curve. This suggests that a force, perpendicular to both V and the magnetic field H, acts on the moving charge as it crosses the magnetic field lines. The relationship between this force (F), the velocity (V), and the magnetic field (H) is displayed in the upper right corner of the diagram. The directions of F, V, and H are said to be mutually perpendicular: F is directed upward, V is directed toward the south, and H is directed toward the east. Notice that V and H initially lie in a plane, while F is perpendicular to that plane.

In a nutshell, the mere action of the charge cutting across the magnetic field lines generates this perpendicular force, known as the magnetic force, a fascinating aspect of electromagnetic phenomena.

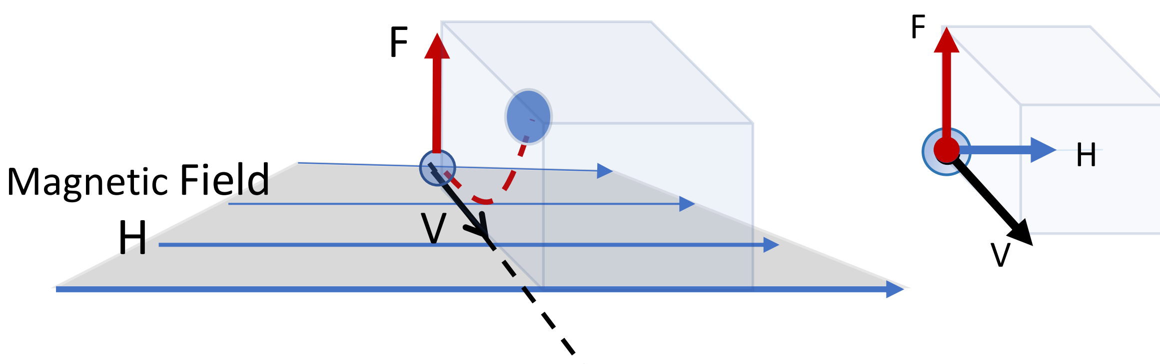


Fig. 10 Magnetic Force Acting on a Moving Charge Crossing Magnetic flux.

As the positive charge is elevated by the magnetic force as it is moving forward, its velocity changes. According to the principle that the magnetic force must be perpendicular to both the eastward magnetic field and the new direction of velocity, the force's direction must adapt accordingly. In essence, the magnetic force modifies the trajectory of the positive charge so that it remains perpendicular to the magnetic field. In doing so, the charge traces out a circular path within the magnetic field, assuming the field is uniform. Such a force that leads to circular motion is widely known as centripetal force. Indeed, the magnetic centripetal force tugs the positive charge to move in a counterclockwise circle when exposed to a uniform magnetic field.

If it is the negative charge that moves toward the front, it would experience a force opposite to that of the positive charge. Indeed, the magnetic force will push downward, causing it to curve downward in a clockwise circle, just as expected. Hence, if an electron moves toward the front, its motion would mirror that of a positive charge, moving in a clockwise circle below the floor. Conversely, if it enters from the south wall, it would experience an upward force and travel in a clockwise circle.

The ability to manipulate electrons using both electric and magnetic fields was the principle behind CRT (Cathode-Ray Tube) TVs, which predate modern OLED (Organic Light Emitting Diode) TV. In a CRT TV, electric field is used to shoot a beam of electrons in a vacuum tube, while a magnetic field perpendicular to the motion of the beam deflects the electrons. These electrons then strike a phosphor-coated screen to emit light line by line, rapidly creating images that give the illusion of motion. Similarly, electron microscopes utilize both electric and magnetic fields to achieve highly magnified images. These instruments can reveal details as small as viruses or even individual atoms, capabilities far beyond what an optical microscope can offer.

However, one of the most widely used applications of this principle that we are all familiar with is an electric motor. Now that we understand that charges are pushed when moving perpendicular to a magnetic field, we can see how this can be applied to create mechanical work. If we run an electric current through a conducting rod that is exposed to a magnetic field perpendicular to the current, the rod will experience a force. Imagine it is a conductor that lies in the North-South direction in the magnetic field as depicted in Fig.10. Then, pass an electric current through it, following the convention that electrons flow from the front to the back, while the (imaginary) positive charges move from the back to the front. The magnetic force will act on the flowing charges all at once, effectively lifting the entire conductor upward, as illustrated in Fig. 11.

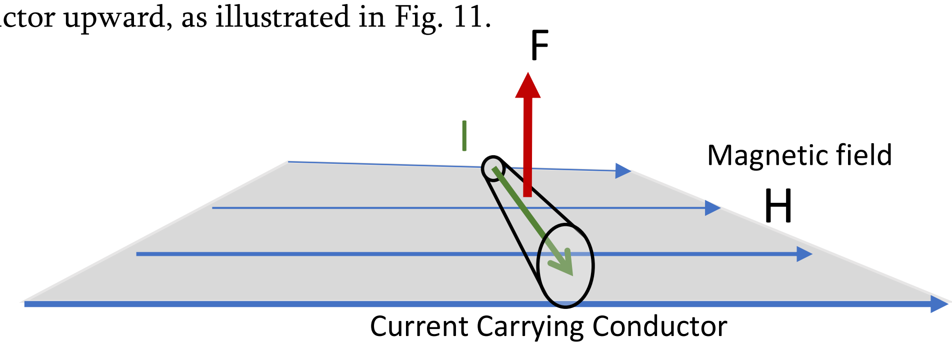


Fig.11 A Current Carrying Conductor in Magnetic Field.

The magnetic force can lift the charges the current that is running perpendicular to the magnetic field, effectively lifting or pushing the current carrying conductor. A motor operates on this principle but adds a clever twist, as illustrated in Fig. 12. By introducing a rectangular coil, two long segments of the coil are arranged to be perpendicular to the magnetic field that fills a cavity between two set of permanent magnets. In this setup, the electrons, powered by a battery, flow in opposite directions through these segments depicted in green. This generates a pair of antiparallel forces acting (red) on the coil, causing it to spin.

A typical motor features a coil wound hundreds or thousands of times, along with a commutator that allows the current to flow in one direction in one segment of the loop and in the opposite direction in another segment. This design enables the motor to spin continuously when electricity is supplied. The spinning motor can then drive a gearbox to perform various tasks, such as turning the wheels of a car.

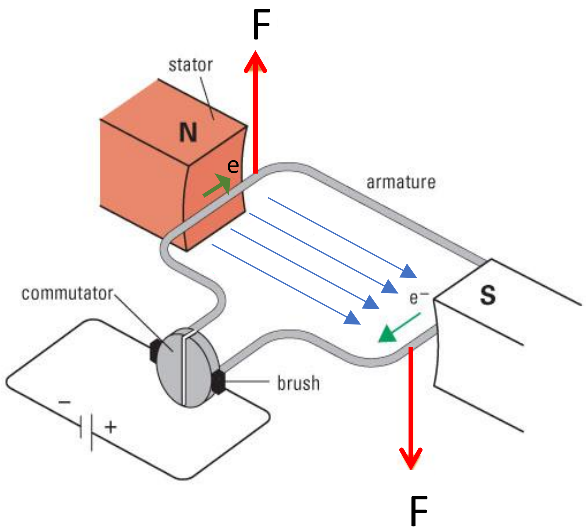


Fig. 12. A Simple DC motor. Source: SWCPHYSICS30/WordPRess.com [Link]

Fig. 13 provides a link to an animation demonstrating how the motor work. In reality, the design of a motor can be more complicated. The most common types of DC motor rely on magnetic forces produced by currents in the coils.

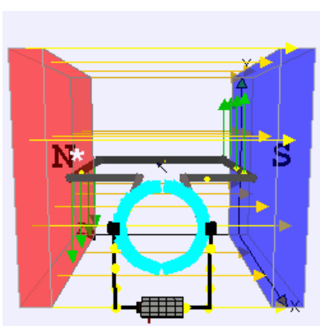


Fig. 13 Animation of a Simple DC motor. Visit [here] to view the animation. https://en.wikipedia.org/wiki/File:Ejs_Open_Source_Direct_Current_Electrical_Motor_Model_Java_Applet_(_DC_Motor_)_80_degree_split_ring.gif

IX. Magnetic Induction and the Generator

We have learned so far that electric current can generate a magnetic field and a conductor carrying a current running across magnetic field lines (flux) can experience magnetic force acting on it. Somehow magnetism must be related electricity. It naturally raises the question: can a magnetic field induce charges to move? In other words, could we use a magnetic field to generate an electric current in a conductor without requiring a battery or a capacitor? The answer is yes.

Imagine placing a stationary charge in a magnetic field. If the field suddenly changes in intensity or direction—say, because a magnetic pole is approaching, retreating, or rotating—the charge will respond by moving to counteract the change. This is an attempt to minimize the variation in the magnetic field. Remember, a moving charge itself creates a magnetic field. The magnetic field induced by the moving charge will be oriented in the opposite direction to the original, externally applied magnetic field, thereby mitigating the change.

This concept is easier to understand when demonstrated using a wire loop. When the magnetic field through the loop changes, an electromotive force is induced in the loop, causing charges to move and generating an electric current. This phenomenon is known as electromagnetic induction governed by Faraday's Law. Faraday's Law succinctly states that if the magnetic field around a wire or coil changes, a voltage or electric field will be induced, thereby driving an electric current within the wire or coil.

Since electrons in a wire loop move in random directions. In this state, the loop produces no electric current by itself. When this loop is placed in a static magnetic field, still no current is generated. However, the situation changes if the magnetic field varies. For instance, let's consider a scenario where the north pole of a magnet on the left of Fig. 14 approaches the wire loop. As the magnet nears, the density of magnetic field lines (flux) increases around the loop because the flux is more intense closer to the pole. As the magnetic flux intensifies, an electric current is induced in a clockwise direction, meaning electrons are compelled to move in a specific path. A current

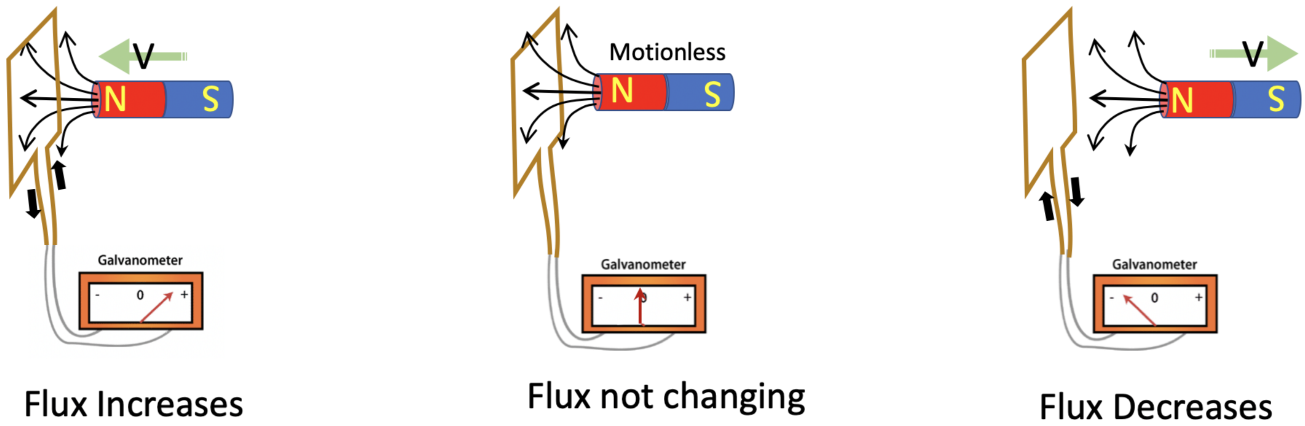


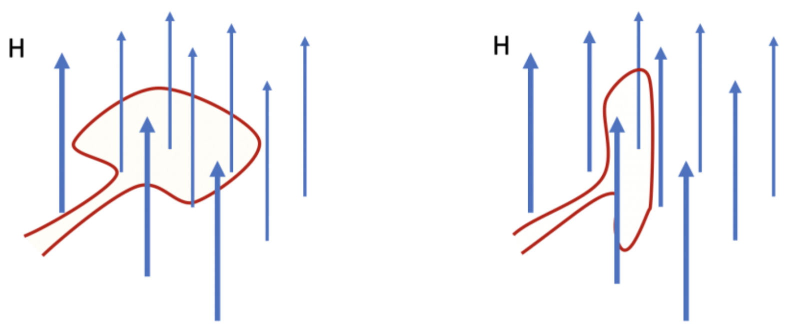
Fig. 14 Magnetic Induction.

detector, the Galvanometer, moves its needle to the right in response to the presence of the current. Pay attention to the needle of the Galvanometer in the illustration. Since a current can only move is there is a voltage. It means the change in flux creates a voltage. Middle of Fig. 14, the magnet motion is halted, thus no change in flux is felted by the loop. The detector register no current at all. Right of Fig. 14: flux decreases when the pole moves away, the detector senses a current going in the opposite direction, meaning the voltage induced has reversed its polarity.

This induced current running in the loop itself generates its own magnetic field, which opposes the incoming magnetic field, effectively reducing its strength of the field imposed on the loop. Again electrons are only driven by electric fields or a potential difference. Thus, the varying magnetic field induces an electric field within the wire loop, creating a potential difference, or voltage, from one end of the loop to the other end to drive the current. In effect, the changing magnetic field acts as a source of voltage for the conductor. Instead of calling it the battery voltage, this induced voltage is also referred to as Electromotive Force (EMF). In battery, the voltage is created by chemical reactions. In magnetic induction, the voltage is created electromagnetic interaction. Thus the term EMF. This phenomenon is known as Faraday's Law.

Another way for a wire loop to experience a change in magnetic flux is through rotation. When the plane of the wire loop faces the magnetic field directly, it intercepts the maximum amount of flux. However, when the loop's plane is not aligned with the magnetic field, it captures less flux. As the loop completes a 360-degree spin, it intercepts the most flux at the starting point (0 degrees) and at half a turn (180 degrees). At a quarter turn (90 degrees) and three-quarters turn (270 degrees), it intercepts the least amount of flux. The larger the intercepted flux, the greater the induced electromotive force (EMF), allowing it to drive a more robust current. This concept is the basis of electricity generation through a rotating loop in a magnetic field.

Fig. 15 illustrates that when the coil itself is rotated using mechanical force, the loop will capture the maximum magnetic flux when it lies perpendicular to the magnetic field lines and will capture progressively less as it becomes parallel to the field. During each complete rotation, the flux interception initially increases then decreases in the first half-turn when the loop face the flux, then it increase and decreases again turning it back on the flux in the second half-turn, restarting the cycle. This produces a positive current in the first half of the cycle and a negative current in the second half, resulting in alternating current (AC). This is precisely how an electrical generator functions.



The wire wire intercepts maximum flux

The intercepts no flux after rotated 90° left or right.

Fig. 15 Flux Interception Changes As the Wire Loop Rotates. Maximum when loop plane is facing flux in the same or opposite direction, zero when faces the flux 90°.

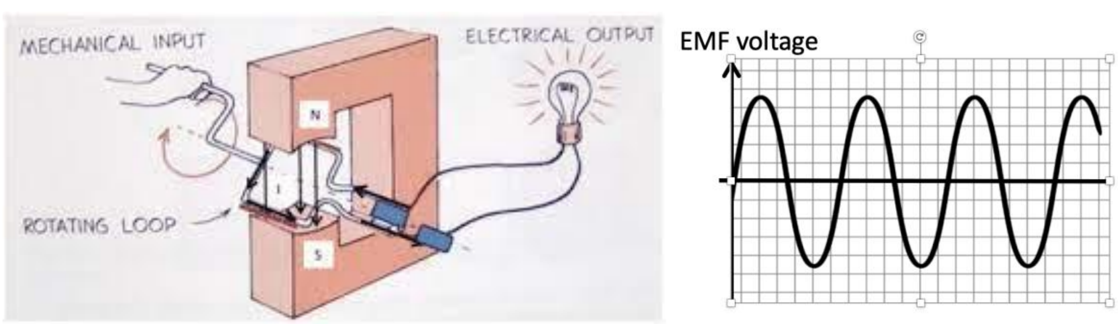


Fig. 16 Generator. As the wire loop is mechanically rotated in magnetic field, the flux interception creates an EMF that drives the electric current. In the first half of turn, the EMF is positive, second half negative. Source: CK-12.Com

This is essentially how the electricity we enjoy is generated on an industrial scale. The wire loops consist of numerous turns and can be wound around in gigantic scale. The coils are not manually cranked but are instead driven by the power generated from sources such as hydropower from dams or steam power from nuclear power plants. Fig.17 shows what a steam turbine generator looks like.

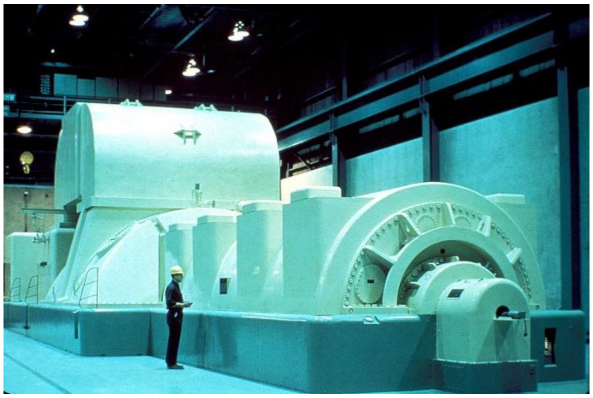


Fig. 17 Electric Generator in Industrial Scale. It is powered by a steam turbine.

X. Electromagnetism

If a varying magnetic field can generate an electric field, the natural question to ask is whether a varying electric field can also generate a magnetic field. This question was explored by James Clerk Maxwell before being empirically verified as true. If a charge is stationary or moving at a constant speed, the magnetic field it emits remains constant, displaying no changes or ripples. However, if the charge is accelerated or oscillated back and forth, the electric field itself changes, creating ripples. These ripples represent variations in the field strength across space and, in turn, induce a magnetic field. Fig. 18 below depicts the electric of a stationary charge along with an oscillating charge in up and down direction. On the left is a stationary charge that has a radiating static field with no ripples, while on the right is a charge oscillating up and won creating ripples in the field. It is the varying electric field (ripples) generates magnetic field.

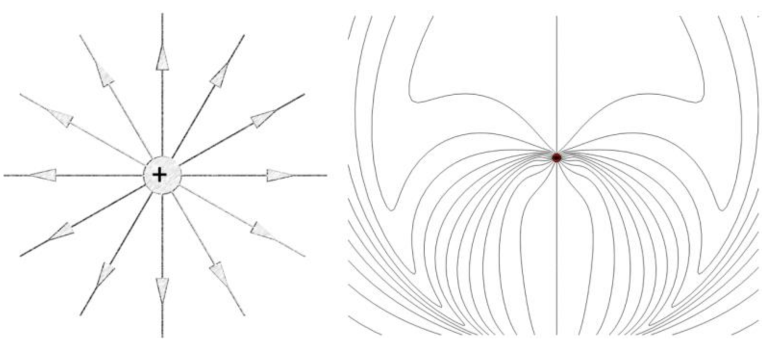


Fig. 18 : Static Electric Field (left) Vs Left: Electric Field Ripples (right). The former is generated by a stationary charge while later by an charge oscillating up and down.   To see the ripples effect visit: https://www.compadre.org/osp/EJSS/4126/154.htm

Maxwell's theory posited that if a varying electric field generates a varying magnetic field, which in turn generates another varying magnetic field, the result would be a self-perpetuating electromagnetic wave or radiation. These electromagnetic waves travel through a vacuum at the speed of light. Depends on rate of oscillation, waves generated cover a wide spectrum of frequencies, from low-frequency radio waves to high frequency X-rays and gamma rays. See Fig. 19 below. Light is just a small portion of the electromagnetic spectrum that humans can perceive as colors.

"While visible light, ranging from red to violet, is essential for our survival, radio waves provide us with global communication technology. Thanks to radio waves, we can communicate with people on the other side of the Earth within a fraction of a second. Smartphones are equipped with antennas that transmit radio waves carrying encoded voice or text messages to nearby cell towers. These towers further relay the information to the Internet. Incoming messages are broadcast in a similar manner using radio waves. Smartphones also contain antennas that act as receivers. The oscillating electric fields of the electromagnetic waves induce currents in the receiving antenna, which are then decoded and displayed as messages on our screens.

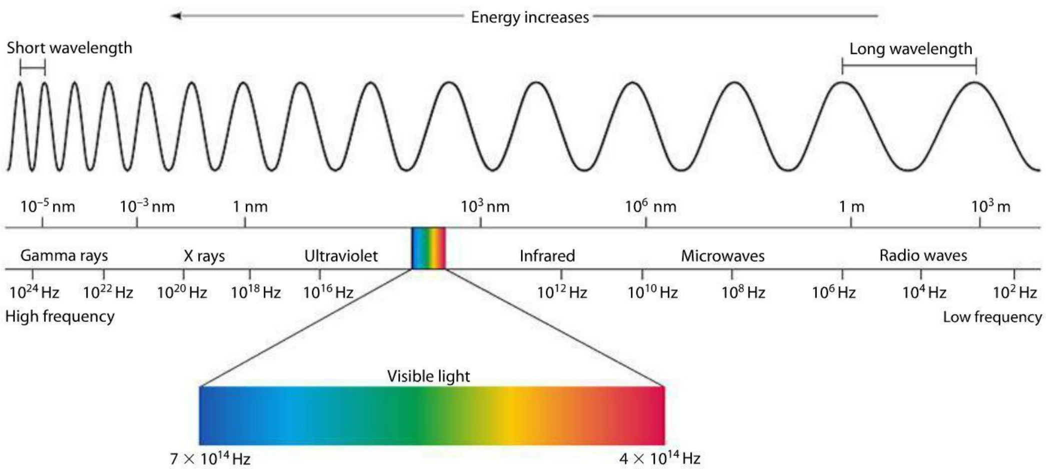


Fig. 19 Electromagnetic Radiations. Only part of it – the visible light -- is visible to us.

A radio wave is a type of electromagnetic wave characterized by its low frequency (or long wavelength). The range of radio waves typically varies from hundreds of Hertz to millions of Hertz as displayed on the right hand side of Fig.19 above. AM (Amplitude Modulation) radio stations operate within the kilohertz (kHz) range, while FM (Frequency Modulation) radio operates in the megahertz (MHz) range. These radio waves, which are used for various applications including radios, TV, and cell phones, are commonly generated using dipole antennas, as depicted in Fig. 20 below.

The dipole antenna used for this purpose has two conducting rods equal in length stretching out horizontal forming a T-shape with the supporting body. When one rod carries positive charges, the other rod must carry negative charges. By rapidly alternating the polarity of the charges in each rod – switching between positive and negative – a current (a flow of charges) is effectively created that oscillates back and forth. This oscillating current generates a varying electric field, which, in turn, induces a varying magnetic field. This interplay results in the formation of electromagnetic waves, happened to be in the radio frequency range, that propagate away from the antenna at the speed of light.

Fig. 20 illustrates the process of generating an electromagnetic radio wave and the relationship between the electric and magnetic fields during propagation. The photograph on the left displays a real T-shaped UHF antenna that has a pair of stretching out arms. Imagine, at a given instant, positive charges are concentrated in the upper arm and negative charges in the lower arm. These plus-minus charges, separated by a distance, create dipoles. The electric field pattern of a single dipole aligns with the familiar pattern shown in Fig. 3 of the Electricity section. When multiple electric dipoles are distributed over two rods, a familiar dipolar pattern emerges, as demonstrated in part (a) of the figure.

In the subsequent moment, charges in the upper arm are switched to negative charges, causing the dipolar electric field's direction to reverse. This change is achieved by introducing an alternating current (A.C. current). As a consequence of the current, a circular magnetic field wraps around the antenna rods as depicted in part (b) of Fig.20. This magnetic field is inherently perpendicular to the electric field. This relationship is visually depicted in part (c). The electric field E is more intense near the center of the antenna and gradually tapers towards both ends. This E-field is rendered as a vertical blue wave on the right side of the antenna in part (c). The accompanying magnetic field is shown as a horizontal orange wave, perpendicular to the electric field.

As the antenna alternates its current back and forth between the two rods, the electric field continuously changes polarity, oscillating between positive and negative. This oscillation, in turn, induces a changing magnetic field. Consequently, a dynamic interplay arises where the changing electric field generates a magnetic field, and the changing magnetic field induces an electric field and so on... This remarkable process gives rise to an electromagnetic wave. Once born, this electromagnetic wave propagates outward from the antenna at the speed of light

The illustrated wave in part (c) depicts the electric field (E) in blue and the magnetic field (H) in orange. As the electromagnetic wave travels, the E and H fields are mutually perpendicular. The electric field alternates between positive and negative crests, and this variation is mirrored by the magnetic field. This synchronized fluctuation leads to the propagation of the radio wave.

(a (b (c

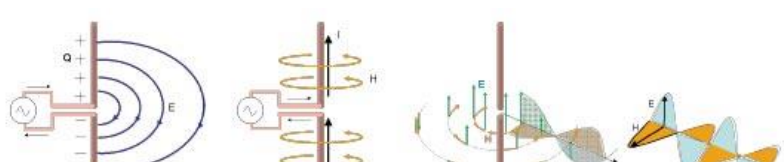


Fig. 20 UHF Dipole Antenna Generates Radio Waves

(a) Plus and mini charges on the separated rods a field analogous to a dipole field, the field flip the direction when the upper and low arms reverse their charges.
(b) The movement of alternate plus and minus charge is basically an A.C. current; the current induces magnetic field wrapping around the rod clockwisely when the positive charges are in the top rod; but reverses the direction when the top rod becomes negatively charged.
(c) The electric field(E) is the strongest at the center and tapers off to the ends of the two rods. E is represented by the blue vertical wave. The induced magnetic wave (H) is represented by the horizontal orange wave that is perpendicular to the E wave. The induced magnetic wave H in turns generate an electric wave. An electromagnetic wave is thus born, traveling at speed of light leaving the antenna behind. Source: https://interferencetechnology.com/wp-content/uploads/2007/05/Antenna-Fundamentals-Figure-3.jpg

The verbal description of the genesis of electromagnetic wave is cumbersome. It makes such better sense if visualized. Visit the animation at a site listed below. https://upload.wikimedia.org/wikipedia/commons/d/dd/Dipole_receiving_antenna_animation_6_800x394x150ms.gif

Recall electric fields have the capability to influence the motion of electrons. This characteristic enables a receiver antenna to collect electric fields from radio waves and convert it into electric currents, which can subsequently be detected as a signal. Thus, an antenna's role isn't limited to emission; it also excels at reception with some twists in the design. An antenna can receive an electromagnetic wave, converting it into a minute electric current. This currents, in turn, can be interpreted as signals. Once these signals are decoded, they manifest as TV images or smartphone messages etc.

Since electrons of atoms within our body are sensitive the electric fields of electromagnetic waves, it's prudent to exercise caution around strong or high-frequency radiations, which could potentially be harmful. Certain types of radiation, such as UV, X-rays, and Gamma-rays, possess the capacity to strip electrons from atoms in our bodies.

In a nutshell, the interplay between electricity and magnetism is a fascinating science: Electricity can give rise to magnetism, which, in turn, influences the movement of electric charges. This interaction not only facilitates mechanical work through electricity but also engenders electromagnetic waves. These waves, in the form of electricity and magnetism, underpin modern communication systems.

Electrons, nuclei, and atoms constitute intrinsic quantum systems that lie beyond the purview of this course. The understanding of quantum behaviors layered upon electricity and magnetism paves the way for even more advanced modern technologies, including microelectronics, supercomputers, and lasers. The knowledge of electricity and magnetism stands as a monumental achievement in our understanding of the natural world.

Exercises:

1) There are two poles for each magnet A) true b) false
2) Single pole could exist like an individual charge a) true b) false
3) Like poles repel and unlike poles attract A) true b) false
4) The earth can be viewed as a giant magnet with its north pole located at geographically south pole a) true b) false
5) The moving charges could produce a magnetic field surrounding them.

   a) True b) false

6) The moving charges would experience magnetic force if placed in a magnetic field

   a) True b) false

7) A wire carrying electric current produces a magnetic field. A) true b) false
8) A changing magnetic field would produce electric current inside a loop if the loop is placed in this changing field.

   a) True b) false

9) The idea for a generator is that a moving rod in a magnetic field produces electricity.

a) True b) false

10) The idea for a motor is that loops carrying electricity would experience magnetic force if placed in a magnetic field

a) True b) false