C Team - Introduction to Magnetism

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June 5, 2015

1 Introduction

Magnetism is the physical phenomena that occurs in the presence of moving charges. Sources of magnetism can create magnetic fields, which in turn can create a magnetic forces that operates on other moving charges. Magnetism is an important part of physics, and it has a variety of real-world applications. Three main types of magnets - permanent magnets, current carrying wires, and moving charged particles - will be discussed in this lecture.

2 Permanent Magnets

Permanent magnets are some of the most well known examples of magnetism. In a permanent magnet, the magnetic field is a result of the magnetic dipole moment (a result of spin) of the unpaired electrons in the atoms that make up the magnet. In a permanent magnet, the electrons are the moving charges that create the field.

2.1 Formation of a Permanent Magnet

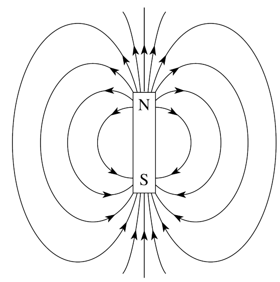
For an object to be a permanent magnet, it first must be made of the right material. Materials that are able to create permanent magnets are ferromagnetic. Examples of ferromagnetic materials are iron, nickel, and cobalt. In a ferromagnetic material, the spins of the unpaired electrons in the magnet align in the same direction in a particular region of an object. These regions are called domains, and when the domains of an object are aligned in the same direction, a permanent magnet is formed.

2.2 Magnetic Field of a Permanent Magnet

Permanent magnets have a north pole and a south pole. The magnetic field lines of a permanent magnet travel from the north pole to the south pole. Like an electric field, the strength of the magnetic field at a certain location is represented by the spacing between the field lines; small spacing corresponds with a strong magnetic field, and large spacing corresponds with a weak magnetic field. The magnetic field is represented by the letter "B", and is given units of Tesla (T).

$$1\text{T} = 1\frac{\text{N}}{\text{A}\cdot\text{m}}, \tag{1}$$

Bar Magnet:



2.3 Magnetic Fields in the z-direction

Sometimes, magnetic fields will be shown directed in the z-direction. Since paper can only fully represent 2D space, two symbols are used to represent magnetic fields in the z-direction. A magnetic field line pointing up out of the plane of the page is represented as a closed circle. A magnetic field line pointing into the plane of the page is represented as $\times$.

3 Current-Carrying Wires

A current-carrying wire is a long, electrically conductive cylinder that carries charge from one end to the other (from an area of high electric potential to the area of lower potential).

3.1 Magnetic Field of a Current-Carrying Wire

The magnetic field of a current carrying wire is made up of field lines that are concentric circles that surround the wire across the wire's length. The right-hand rule is used to find the direction of the magnetic field lines outside of a current-carrying wire. The magnetic field of a long, straight, wire, is given by the equation

$$B_{wire} = \frac{\mu_0}{2\pi}\frac{I}{r}, \tag{2}$$

where μ_0, known as the vacuum permeability, is equal to $4\pi \times 10^{-7}\text{T}\cdot\text{m/A}$. Similar to gravitational fields and electric fields, magnetic fields are also inversely related to distance, but here, r is not squared.

3.2 The Right-Hand Rule

To use the right-hand rule, point the thumb of your right hand in the direction of the current in the wire, and curl your hand keeping your thumb in the direction of the current. the curling of your fingers represents the direction of the magnetic field lines around the wire.

3.3 The Left-Hand Rule

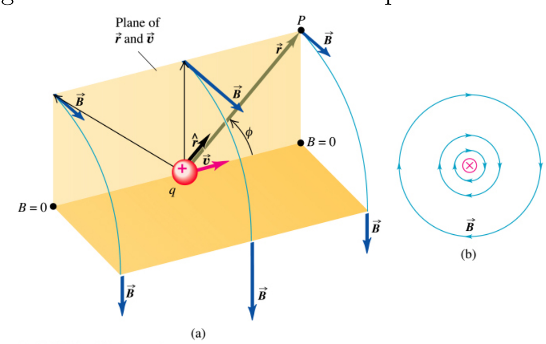
The left-hand rule is essentially the same as the right hand rule, except that the left hand is used to determine the cross-product. Thus, the vectors of cross-products using the right-hand rule and left-hand rule are opposites of each other.

4 Moving Charged Particles

The magnetic field for a moving charged particle can be described by the Biot-Savart Law:

$$\vec{B} = \frac{\mu_0}{2\pi} q \frac{\vec{v} \times \hat{r}}{r^2}, \tag{3}$$

where q is the charge of the particle, v is the velocity vector of the particle, $\hat{r}$ is the unit vector from the particle to the specified location of the magnetic field, and r is the magnitude of the distance from the particle to the location.



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5 The Magnetic Force

When a moving charge (or an object containing moving charges) is present in a magnetic field, it is acted upon by a magnetic force.

5.1 Magnetic Force on a Moving Charge

The Lorentz force equation can be used to determine the magnetic force that acts upon a moving charged particle. This equation is:

$$\vec{F} = q[\vec{E} + (\vec{v} \times \vec{B})], \tag{4}$$

but with the absence of an electric field, the equation simplifies to

$$\vec{F} = q\vec{v} \times \vec{B}. \tag{5}$$

Expressing this equation using the magnitude of force, the equation becomes

$$|\vec{F}| = q|\vec{v} \times \vec{B}|, \tag{6}$$

$$F = qvBsin(\theta), \tag{7}$$

where θ is the angle between the direction of motion and the magnetic field.

5.2 Magnetic Force on a Current-Carrying Wire

Similar to the magnetic force on a moving charged particle, the magnetic force on a current-carrying wire is:

$$\vec{F} = I\vec{\ell} \times \vec{B}, \tag{8}$$

which simplifies to

$$F = ILBsin(\theta), \tag{9}$$

6 Work of Magnetic Fields

Since the magnetic force is always perpendicular to the direction of motion of the object being acted upon, magnetic fields do not do any (scalar) work on an object.

7 Electromagnetic Induction

Just as magnetism can be generated by moving charges, or more specifically, by an electric current, magnetic fields can generate electric potential differences and thus electric currents. This process is known as electromagnetic induction.

7.1 Magnetic Flux

In order to fully understand how electromagnetic induction works, we must understand the concept of magnetic flux. the magnetic flux is the amount of magnetic field that passes perpendicular through a given surface. The magnetic flux, in simplest terms, can be represented as:

$$\phi = BA, \tag{10}$$

where B is the magnetic field and A is the area that the surface that the magnetic field passes through. Note that this equation only works if the magnetic field is perpendicular to the surface. Otherwise, you would need to use the projection of BA onto the normal vector (the unit vector perpendicular to a given surface that extends outward from the surface) of the surface.

7.2 Changing Magnetic Flux

Under certain conditions, the magnetic flux through a system can change, either because of a change in the magnitude of area or magnetic field. A change in magnetic flux can be defined by:

$$\Delta\phi = \phi_f - \phi_i \tag{11}$$

$$\Delta\phi = (BA)_f - (BA)_i. \tag{12}$$

7.3 Induced Voltage

Using the concept of changing magnetic flux, induced voltage can be found in a system of changing magnetic flux. An induced voltage, or emf (ε), can be found using the Farady-Lenz Law. The Faraday-Lenz Law is:

$$\varepsilon = -\frac{\Delta\phi}{\Delta t} \tag{13}$$

Note that the emf produced is always negative of the change in magnetic flux in a system. The reason why there is a negative sign is because a system undergoing a change in magnetic flux attempts to resist any change to the system, resulting in a voltage which in turn produces an opposing magnetic field. The magnitude of the emf produced is:

$$\varepsilon = \frac{\Delta\phi}{\Delta t} \tag{14}$$

7.4 Motional Emf

Given a rectangular wire loop of area A that is entering a uniform magnetic field, the magnetic flux of the system increases since the area that the magnetic field is passing through is increasing. Let's suppose that the rectangular wire loop has its length ℓ in the x-direction and its height h in the y-direction. The loop of wire enters into the magnetic field from the left, so the change in length per unit time is:

$$v = frac\ell t \tag{15}$$

The magnitude of the emf produced here is:

$$\varepsilon = \frac{\Delta\phi}{t} = \frac{B\Delta A}{t} = \frac{Bh\Delta\ell}{t} = B\ell v. \tag{16}$$

This is known as the motional emf.

8 Induced Current

Using ohm's law:

$$V = \varepsilon = IR, \tag{17}$$

the induced current of a given wire loop can be found:

$$I = \frac{\varepsilon}{R}, \tag{18}$$

where R is the internal resistance of the wire.

9 Applications of magnetism

9.1 Electric Generators

Electric Generators use the concept behind the Faraday-Lenz Law. The current-carrying wires loops inside a generator experience changing magnetic flux, which produces an emf for practical use.

9.2 Electric Motors

Electric motors convert electrical energy into mechanical energy. An electric current runs through the solenoid (coil of wire) in the center attached to a central rod, creating an electromagnet, which interacts with permanent magnets just outside of the solenoid. This interaction causes the solenoid, and the rod, to spin, thus creating mechanical energy.

9.3 Mass Spectrometers

Mass spectrometers are used to determine the masses and amounts of different substances. The particles of the substance are ionized and sent into a magnetic field at a certain velocity (using a velocity selector). A magnetic field with a known magnitude in the mass spectrometer deflects charged particles in a certain way as to determine the masses and amounts of the particles that make up a substance.

9.4 Cyclotrons

Cyclotrons are used as particle accelerators. Cyclotrons use magnetic fields to accelerate charged particles to high speeds. As particles are accelerated in a cyclotron, they travel in a outward spiral.