Class 10
Magnetic Forces

Physics 106

Winter 2019

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Learning Outcomes

Las time we learned about:

- Examples of Series-Parallel Reduction
- Series RC Circuits and Time Constants
- Using Kirchhoff’s Rules
- The Origin of Magnetic Fields
- The Lorentz Force
Learning Outcomes

Today we will discuss:

- Examples of the Lorentz force.
- Magnetic forces on a wire.
- Motion of a charge in a magnetic field.
- Torques and forces on current loops.
- Electric Motors
Examples of the Lorentz Force
The Magnetic Force

- Call the angle between the vectors $\theta$
- The magnitude of the force is

$$F = qvB \sin \theta$$
The Magnetic Force

The force is perpendicular to $\mathbf{v}$ and to $\mathbf{B}$ and is given by the "right-hand rule."
Right Hand Rule #1

- Place your fingers in the direction of $\vec{v}$.
- Curl your fingers into the direction of the magnetic field, $\vec{B}$.
- Your thumb points in the direction of the force, $\vec{F}$, on a positive charge.
- If the charge is negative, the force is opposite that determined by the right hand rule.
Velocity Selector

Positive ions travel undeflected through a region containing both electric and magnetic fields. If $E = 1000$ V/m and $B = 0.100$ T, how fast are the ions moving?

\[ \frac{F}{E} = \frac{q}{vB} \sin \theta \]

\[ 90^\circ = \frac{F}{B} \]

\[ v = \frac{E}{B} = \frac{1000}{0.100} = 10000 \text{ m/s} \]
Velocity Selector

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F_E = F_B
\]

\[
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$$v = \frac{E}{B} = \frac{1000}{0.100} \text{ m/s} = 10000 \text{ m/s}$$
Magnetic Forces on a Wire
Magnetic Force on a Current-Carrying Wire

- A force is exerted on a current-carrying wire placed in a magnetic field.
- The current is a collection of many charged particles in motion.
- The direction of the force is given by right hand rule #1.
The magnetic force is exerted on each moving charge in the wire.

The total force is the sum of all the magnetic forces on all the individual charges producing the current.

\[ F = BIl \sin \theta \]

- \( \theta \) is the angle between \( \vec{B} \) and the direction of \( I \).
- The direction is found by right hand rule #1, placing your fingers in the direction of \( I \) instead of \( \vec{v} \).
Force on a Wire

- The blue $\times$ indicate the magnetic field is directed into the page.
- The $\times$ represents the tail of an arrow.
Force on a Wire

- The blue $\times$ indicate the magnetic field is directed into the page.
- The $\times$ represents the tail of an arrow.
- Blue dots $\circ$ would be used to represent a field directed out of the page.
- The $\circ$ represents the head of an arrow.

In this case, there is no current, so there is no force.
Force on a Wire

- The blue $\times$ indicate the magnetic field is directed into the page.
- The $\times$ represents the tail of an arrow.
- Blue dots $\circ$ would be used to represent a field directed out of the page.
- The $\circ$ represents the head of an arrow.
- In this case, there is no current, so there is no force.
Force on a Wire

- $\vec{B}$ is into the page
- The current is up
Force on a Wire

- $\vec{B}$ is into the page
- The current is up
- The force is to the left
Force on a Wire

- $\vec{B}$ is into the page
- The current is down
Force on a Wire

- $\vec{B}$ is into the page
- The current is down
- The force is to the right
Motion of a Charged Particle in a Magnetic Field
Force on a Charged Particle in a Magnetic Field

- A particle moves in a B field that is perpendicular to its velocity.
- The force is directed toward the center of a circular path, much like the tension of a ball on a string.
Force on a Charged Particle in a Magnetic Field

- The magnetic force changes the direction of the velocity of the particle
- The magnetic force does **not** change the speed of the particle
**Force on a Charged Particle**

- Equating the magnetic and centripetal forces:

\[ F = qvB = \frac{mv^2}{r} \]

- Solving for \( r \):

\[ r = \frac{mv}{qB} \]

- \( r \) is proportional to the momentum of the particle \((mv)\) and inversely proportional to the magnetic field.
- \( r \) is called the *cyclotron radius*.
Particle Moving in an External Magnetic Field

If the particle’s velocity is not perpendicular to the field, the path followed by the particle is a spiral (or helix).
The Magnetic Field of a Wire
Hans Christian Oersted

- 1777 – 1851
- Observed that a compass needle deflects when placed near a wire carrying a current
- First evidence of a connection between electric and magnetic phenomena
Magnetic Fields of a Long, Straight Wire

- A current-carrying wire produces a magnetic field
- The compass needle deflects in directions tangent to the circle
- The compass needle points in the direction of the magnetic field produced by the current

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Direction of the Field of a Long Straight Wire

Right Hand Rule #2

▶ Grasp the wire in your right hand
▶ Point your thumb in the direction of the current
▶ Your fingers will curl in the direction of the field
The Force Between Two Wires
The Force between Two Wires

- Two wires each have a current traveling upward.
- $\vec{B}$ from the first wire on the second wire is out of the screen.
- The direction of the force is toward the first wire.
Forces and Torques on Current Loops
The Current Loop

- Consider a square loop of length $a$ on a side.
- A uniform $B$ field points to the right.
Force on the Current Loop

- The forces on the top and bottom segments are shown.
- A force on the front segment comes out of the screen.
- A force on the back segment goes into screen.
Force on the Current Loop

The net force on the loop is zero, as long as the field is uniform.
Torque on a Current Loop

- There is a net torque that causes the loop to rotate clockwise.
- The torque on the side loops is zero.
- The torque on the top loop is Force $\times$ moment arm.

\[ \tau = \left( I a B \right) \left( \frac{a}{2} \sin \theta \right) \]

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Torque on a Current Loop

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\[ \tau = \left( I a B \right) \left( a^2 \sin \theta \right) \]
Torque on a Current Loop

- There is a net torque that causes the loop to rotate clockwise.
- The torque on the side loops is zero.
- The torque on the top loop is \( \text{Force} \times \text{moment arm} \)

\[
\tau = (IaB) \left( \frac{a}{2} \sin \theta \right)
\]
The total torque is twice this.

\[ \tau = 2(laB)\left(\frac{a}{2} \sin \theta\right) \]

\[ = la^2B \sin \theta \]

\[ = IAB \sin \theta \]
Torque on a Current Loop

▶ We can increase the torque by making a winding of $N$ loops of wire.
▶ Each loop then contributes an equal torque.
Torque on a Current Loop

\[ \tau = NBI \sin \theta \]

- Applies to any shape loop
- N is the number of turns in the coil
- Maximum when the loop is vertical
- Zero when the loop is horizontal
Magnetic Moment

- It is convenient to describe the "magnetic strength" of a coil or a permanent magnet by a quantity called the "magnetic dipole moment".
- For a current loop, the magnitude of the dipole moment is $\mu = IAN$.
- The direction of the dipole moment for a current loop is the same as the direction of the magnetic field in the loop.
- The direction of the dipole moment for a permanent magnet is in the direction of the magnetic field inside the magnet, from south toward north.

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The torque on a current loop is always in the direction that rotates $\vec{\mu}$ into $\vec{B}$. 
Motors
Electric Motor

- An electric motor converts electrical energy to mechanical energy
- An electric motor consists of a rigid current-carrying loop that rotates when placed in a magnetic field
Motors

A simple motor consists of a current-carrying coil in a uniform magnetic field.
Motors

A torque on the coil tends to align the magnetic dipole moment of the loop with the external field.
Motors

Let’s think of a battery as providing the current in the coil. (This is done by using commutators.)
Motors

But there's one problem...
Motors

But there’s one problem… As the dipole moment rotates past the magnetic field, the direction of the torque reverses!
Motors

We’ve created a vibrator instead of a motor.
Motors

But, we could keep the loop (armature) turning in the same direction if we could reverse the magnetic dipole moment at just the right time. This could be done by changing the direction of the battery.
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But, we could keep the loop (armature) turning in the same direction if we could reverse the magnetic dipole moment at just the right time. This could be done by changing the direction of the battery.
Motors

It’s a little hard to keep moving the leads on the battery back and forth by hand. So we need a better way of doing that.
Commutators and Brushes
Commutators and Brushes

Electrical contact is made to the rotating loop by means of commutators and brushes.
Commutators and Brushes

Electrical connections are made by pressing conductors together.
Commutators

With *double commutators*. Each end of the loop is connected to a separate commutator.
AC Current

The easiest way to change the direction of the current in the loop is to use AC current instead of a battery. The direction of the current through the loop automatically changes sign periodically.
AC Current

Note that the speed of such a motor is closely tied to the frequency of the AC power supply.
The Split Commutator

Another clever solution is to use a "split commutator." A split commutator automatically changes the end of the loop connected to the positive terminal of the battery every half cycle.
DC Motors

Thus, split commutators allow motors to be operated by DC power sources. The speed of a DC motor can be adjusted by changing the current through the coil.
A New Idea
Connections between Electricity and Magnetism

- Moving electric charges such as currents produce magnetic fields
- Magnetic fields cause forces on moving charges
- ... but steady magnetic fields can never change a charge’s speed or start a charge moving
Is Something Missing?

- Is there some way that we can make electric current with a magnetic field?
- If we put a magnet in a coil of wire, does the magnet affect the electrons in the wire?
- Why isn’t there any current in the wire?
- What could we do to change the symmetry?
How Does This Work?

- Describe the magnetic field of the magnet.
- Field lines are looping though the wires in the coil.
- If you are sitting the magnet, what do you see?
- Free electrons in the wire are moving in a magnetic field, so they feel a force.
- Would you see the same thing in a uniform magnetic field?
- No, the field would not push electrons around the loop, just to one side the coil.
Making a Theory That Works

- A theory must be good if the observer is sitting on the coil or if she is sitting on the magnet.
- We understand what happens when the magnet is at rest and the coil is moving — "Motional EMF".
- How can we explain this when the coil is at rest?