Class 14: Outline

Hour 1:
Magnetic Fields
Expt. 5: Magnetic Fields

Hour 2:
Charges moving in B Fields
Exam Review
A New Topic: Magnetic Fields
Gravitational – Electric Fields

Mass $m$  
Create:  $\vec{g} = -G \frac{m}{r^2} \hat{r}$  
Feel:  $\vec{F}_g = m\vec{g}$

Charge $q$ ($\pm$)  
Create:  $\vec{E} = k_e \frac{q}{r^2} \hat{r}$  
Feel:  $\vec{F}_E = q\vec{E}$

Also saw… Dipole $\vec{p}$  
Create:  
Feel:  $\vec{\tau} = \vec{p} \times \vec{E}$
Magnetism – Bar Magnet

Like poles repel, opposite poles attract
Demonstration: Magnetic Field Lines from Bar Magnet
Demonstration: Compass (bar magnet) in Magnetic Field Lines from Bar Magnet
Magnetic Field of Bar Magnet

(1) A magnet has two poles, North (N) and South (S)
(2) Magnetic field lines leave from N, end at S
Bar Magnets Are Dipoles!

- Create Dipole Field
- Rotate to orient with Field

Is there magnetic “mass” or magnetic “charge?”

NO! Magnetic monopoles do not exist in isolation
Bar Magnets Are Dipoles!

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Magnetic Monopoles?

Electric Dipole
\[ \vec{p} \]
-\(q\) \quad q
When cut: 2 monopoles (charges)

Magnetic Dipole
\[ \vec{\mu} \]
S \quad N
S \quad N \quad S \quad N
When cut: 2 dipoles

Magnetic monopoles do not exist in isolation
Another Maxwell’s Equation! (2 of 4)

\[ \oint_S \vec{E} \cdot d\vec{A} = \frac{q_{in}}{\varepsilon_0} \]
Gauss’s Law

\[ \oint_S \vec{B} \cdot d\vec{A} = 0 \]
Magnetic Gauss’s Law
# Fields: Grav., Electric, Magnetic

<table>
<thead>
<tr>
<th>Mass $m$</th>
<th>Charge $q \ (\pm)$</th>
<th>No Magnetic Monopoles!</th>
</tr>
</thead>
<tbody>
<tr>
<td>Create: $\vec{g} = -G \frac{m}{r^2} \hat{r}$</td>
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Also saw…

<table>
<thead>
<tr>
<th>Dipole $\vec{p}$</th>
<th>Dipole $\mu$</th>
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<tr>
<td>Create: $\vec{E} \rightarrow \vec{B}$</td>
<td>$\vec{B} \leftarrow \vec{E}$</td>
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<td>Feel: $\vec{\tau} = \vec{p} \times \vec{E}$</td>
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</table>
What else is magnetic?
Magnetic Field of the Earth

North magnetic pole located in southern hemisphere

Also a magnetic dipole!
Earth’s Field at MIT

We will measure these components
Experiment 5: Bar Magnet & Earth’s Magnetic Field
Visualization: Bar Magnet & Earth’s Magnetic Field

Magnetic Field B Thus Far…

Bar Magnets (Magnetic Dipoles)…

- **Create:** Dipole Field
  - **Feel:** Orient with Field

Does anything else create or feel a magnetic field?
Demonstration: TV in Field
Moving Charges Feel Magnetic Force

Magnetic force perpendicular both to:
Velocity \( \mathbf{v} \) of charge and magnetic field \( \mathbf{B} \)

\[
\mathbf{F}_B = q \mathbf{v} \times \mathbf{B}
\]
Magnetic Field $\mathbf{B}$: Units

Since $\mathbf{F}_B = q \mathbf{v} \times \mathbf{B}$

B Units = \frac{\text{newton}}{(\text{coulomb})(\text{meter/second})} = 1 \frac{\text{N}}{\text{C} \cdot \text{m/s}} = 1 \frac{\text{N}}{\text{A} \cdot \text{m}}

This is called 1 Tesla (T)

$1 \ T = 10^4 \ Gauss \ (G)$
Recall: Cross Product
Notation Demonstration

OUT of page
“Arrow Head”

INTO page
“Arrow Tail”
Cross Product: Magnitude

Computing magnitude of cross product $\mathbf{A} \times \mathbf{B}$:

$$\mathbf{C} = \mathbf{A} \times \mathbf{B} \quad \left| \mathbf{C} \right| = \left| \mathbf{A} \right| \left| \mathbf{B} \right| \sin \theta$$

$|\mathbf{C}|$: area of parallelogram
Cross Product: Direction

Right Hand Rule #1: \( \vec{C} = \vec{A} \times \vec{B} \)

1) Curl fingers of right hand in the direction that moves \( \vec{A} \) (green vector) to \( \vec{B} \) (red vector) through the smallest angle

2) Thumb of right hand will point in direction of the cross product \( \vec{C} \) (orange vector)

### Cross Product: Signs

<table>
<thead>
<tr>
<th>i × j = k</th>
<th>j × i = −k</th>
</tr>
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<td>j × k = i</td>
<td>k × j = −i</td>
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</table>

Cross Product is Cyclic (left column)
Reversing **A** & **B** changes sign (right column)
PRS Questions: Right Hand Rule
Putting it Together: Lorentz Force

Charges Feel…

\[
\vec{F}_E = q \vec{E} \quad \quad \quad \quad \quad \quad \vec{F}_B = q \vec{v} \times \vec{B}
\]

Electric Fields  \quad  Magnetic Fields

\[
\vec{F} = q \left( \vec{E} + \vec{v} \times \vec{B} \right)
\]

This is the final word on the force on a charge
Application: Velocity Selector

What happens here?
Particle moves in a straight line when

\[
\vec{F}_{net} = q(\vec{E} + \vec{v} \times \vec{B}) = 0 \implies \vec{v} = \frac{E}{B}
\]
PRS Question: Hall Effect
Exam Review