Chapter 12

Magnetism

Chapter 12 is mostly finished, but is not in camera-ready format. This file doesn't have any of the many diagrams, but it does have selected excerpts from the text, with omissions indicated by .....

Together, Sections 12.1-12.3 show you logical ways to think about two characteristics of charge that is moving; it produces magnetism and it is affected by magnetism. Then 12.4 applies these principles to explain how generators make electricity and how motors use it.

12.1 Moving Charge produces Magnetism (curled right-hand rule)

Electric charge always produces an *electric field* "E", as described in Section 10.1. When electric charge **moves**, it also produces a *magnetic field* "B". Like E, B has magnitude and direction. In this section, we'll look at magnetic field direction.

Put this book flat on a table, look at the first picture and imagine that O is the point of a real arrow (the kind you shoot with a bow) coming straight toward you. O represents *electric current* moving up toward the ceiling; this current could be produced by + charge moving upward, or – charge moving downward. Now look at the third picture and imagine that O is the tail feathers of an arrow moving away from you. This represents current moving down toward the floor.

In the first picture, notice O (a wire that carries current upward), the □-location, the ····· line from O to □, and ↑ that shows the B-field produced by charges moving through O. There are three "perpendiculars": ↑ is ⊥ to ····· , and O is ⊥ to the plane (the book page) that contains ↑ and ····· . It will help your "spatial knowledge it you take 3 pens and point them in the directions of O, ····· and ↑, so you can "see" their 3-dimensional relationship. Notice that each pen is perpendicular to the other two pens.

In the first picture, 8 arrows show the B-field direction at 8 locations. Each arrow is ⊥ to its own ····· line. Do you see the circular pattern formed by the B-field arrows? This pattern shows the B-field direction, not "motion" or "flow". { B-field patterns are analogous to E-field patterns that, as emphasized in Section 10.3, also show direction but not motion. } .....[snip].....

[obviously, Section 12.1 is "not the same" without the pictures, so most of it is omitted here]

The second picture shows the first-picture situation from a different perspective. ..... This is called the *curled right-hand rule.*

The third and fourth pictures show .....

USING REAL 3-D MODELS: Can you look at this object [crude drawing of car] and know what it looks like from the front, the back, or in a diagonal view? Yes. Why? Because I've drawn such a good picture? Of course not. But if my inept drawing is enough to make you think "car", you can recall the detailed visual car-memories you've stored by looking at real 3-D cars. To master the spatial relationships of magnetism, you must store visual "magnetism memories". One good way to do this is by using 3-D models. When I describe objects (like pens, cans, tables,...), get real pens, cans or tables, study them to store visual memories, then "link" these memories to 2-D diagrams so the 2-D diagram will inspire the 3-D visual-thinking you need for solving problems.

The magnitude of the magnetic field "B" at a particular location is: .....

Magnetic Field caused by Horizontal Current

The picture below shows current ⇐ move sideways on a horizontal table surface and pass through the center of an imaginary sideways can. .....

The curled right-hand rule predicts the B direction on each side of the wire. As shown, point your thumb in the current direction, let your hand relax so the fingers naturally curl a little, and notice which way your fingers point.

Magnetic Field caused by Current Loops

The pictures below show a current loop. To use the curled right-hand rule, ...

The first picture below shows the B field produced by a *solenoid* (a cylindrical many-loop coil of wire). .....

The second picture shows the field of a *bar magnet.* .....

An oversimplified but useful model is that .....

The third picture shows the earth's magnetic field. .....

12.2 Moving Charge is affected by Magnetism (straight right-hand rule)

Section 12.1 explained that moving charge produces its own magnetic field.

The first picture shows what happens when moving charge (current) interacts with a magnetic field that is "external" (not the B-field that is being produced by the moving charge). The moving charges feel an upward force, ○. .....

The 3-dimensional spatial relationship between I, B_{ext} and F is imitated by the *straight right-hand rule,* shown in the second picture. The right hand is held so the fingers are straight (not curled) and the thumb is ⊥ to the fingers. The hand is flat; fingers, thumb and palm are in the same plane. Your thumb points in the direction of I, fingers point in the direction of B_{ext}, and palm faces in the direction of F (in the direction you normally "push" something with your hand).

Your textbook may give another version of the right-hand rule (that will produce the same answer as this one) but I suggest that you use the rule described above because 1) its hand-use is consistent with the "curled" right hand rule; for both rules, the thumb is I and fingers are B. 2) Your hand always remains in the same configuration; as explained in Problem 12-B, this lets you "use the rule as if it was an equation with 3 variables." ..... [snip] .....

The magnitude of "magnetic force" can be given in two equivalent ways:

$$\mathbf{F = q\ v\ B\ sin\theta} \qquad\qquad \mathbf{F = I\ l\ B\ sin\theta}$$

where **F** is the force acting on a charge **q** freely moving with speed **v**, affected by external field **B** (this is B_{ext} but the subscript is usually dropped), and **θ** is the angle between v and B. For the second equation, **F** is the force acting on a length **l** of wire carrying current **I**, and **θ** is the angle between I and B. .....

{ Optional: Some textbooks also give the vector-equations **F** = q **v x B** and **F** = I **l x B** . Each of these equations gives magnitude <u>and</u> direction, by using the *vector cross-product,* instead of using "F = qvB sinθ" or "F = IℓB sinθ" to get magnitude, and the straight right-hand rule to get direction. Each method, by using the right-hand rule or vector cross-product, gives the same results. }

PROBLEM 12-A

You'll learn more from this problem if you do its four parts in order: answer Part 1 and read its solution, answer Part 2 and read its solution, ...[snip].....

Magnetic Torque on a Current Loop

The first diagram below is a bird's eye view of the "current loop" in Part 2. The second diagram shows this loop as seen by an observer whose eyes are a little above the level of the loop. ..... The third picture shows the observer's view when the loop has rotated 90° so the original "south side" is on top; in this orientation, total force and total torque are both zero. .....[snip].....

12.3 Combining the Two Right-Hand Rules

[this section needs a brief introduction]

SIMILARITIES: For each rule, curled right-hand rule (in 12.1) and straight right-hand rule (in 12.1),
1) you must <u>always use your right hand</u>, and keep it in the correct orientation (curled or straight), and
2) your <u>thumb is current</u> and your <u>fingers are magnetic field</u>. (in versions of The Rules in this chapter)

DIFFERENCES

The curled right-hand rule answers this question: What is the direction of the B-field that is <u>being produced by</u> moving charge? { B magnitude is found using $B = \mu_o I / 2\pi r$. }

The straight right-hand rule answers this question: What is the direction of the force <u>acting on</u> moving charge (due to its interaction with an "external" B-field)? { F magnitude is found using F = I l B sin or F = q v B sinθ . }

In one case (12.1, curled) the focus is on what moving charge <u>does</u>. It is <u>active</u> and it <u>produces</u> B.

In the other case (12.2, straight) the focus is on what <u>is done to</u> the moving charge. It is <u>passive</u> and is <u>affected by</u> B that has been produced elsewhere.

PROBLEM 12-B

Two long horizontal wires are 40 cm apart; 50 C/s flows → in the top wire and 30 C/s flows → in the bottom wire. What force acts on a .50 m length of each wire?

SOLUTION 12-B

Use the **curled** right-hand rule to find the direction of B produced by the top wire and .....[snip].....

To find the direction of force on either wire, we use the **straight** right-hand rule. .....

{ What happens if parallel currents run in opposite directions, → and ← ? }

12.4 Induced Voltage and Current: Faraday's Law and Lenz's Law

This section continues the explorations in Sections 12.1-12.3, to study the relationships between moving charge and magnetism.

This picture shows the *normal vector* **n** pointing straight away (at a 90° angle) from a plane with surface area **A**. ..... [snip] .....

To decide the direction of $\mathcal{E}$ and I, imagine that you are Lenz's "defender of the status quo" who decides what should be done to "oppose the change in flux." { Use principles from Section 12.1 to determine the I-direction that will produce B in the needed direction. } .....

During the first change,
B is upward and increasing.
I must **FIGHT** this increase by
producing my own downward B,
so $I_{induced}$ should be clockwise.

[picture goes here]

$B_{induced}$ FIGHTS, to
minimize ○ increase.

During the second change,
B is upward and decreasing.
I must minimize this change by
HELPING with my own upward B;
$I_{induced}$ should be counter-clockwise.

[picture goes here]

$B_{induced}$ HELPS, to
minimize ○ decrease.

Use the curled right-hand rule to decide what direction $I_{induced}$ must flow in order to produce the desired $B_{induced}$ and $\Phi_{induced}$.

The second circuit is "open" so current doesn't flow, but it still has induced emf.

Notice that the magnitude & direction of induced current depend on B change (and thus Φ change), not on B itself. In the second situation, for example, $B_{induced}$ has the same magnitude whether the original B changes from 3 T to 1 T or from 13 T to 11 T, and the direction of $B_{induced}$ is ○ even though $B_{original}$ is also ○.

PROBLEM 12-D: emf induced by relative motion

As shown here, a metal bar is pushed rightward at constant speed v on horizontal, frictionless, zero-resistance rails. The original B is constant and ○.

1a) Use Faraday's & Lenz's laws to find the magnitude & direction of induced emf. { Hint: Draw i & f pictures separated by Δt. A = height x width, $\Delta x = v\,\Delta t$. }

1b) Use principles from earlier in Chapter 12 to find the magnitude & direction of induced emf. { Hint: Other useful formulas are $F = q\,E$ (from Section 10.1), $\Delta V = E\,d$ (from 10.7). }

2) What will happen due to interaction between $I_{induced}$ and original B? Find magnitude & direction.

3) Calculate power in two ways (to find them, use your memory or the summaries for Chapters 4 and 11) and show that $P_{produced} = P_{used}$.

SOLUTION 12-D

1a) ..... **3)** .....

Energy is conserved, so if no energy is lost (due to friction or in other ways) we expect that power produced by the person's push will be equal — no more, no less — to power used in the electrical circuit.

Generators and Motors

Problems 12-C & 12-D explore the effects of changing B & A, two flux-factors in "$\Phi \equiv B\,A \cos ø$". Now we'll look at what happens when the third factor, cos ø , is changed by the "rotation of a loop" while B and A remain constant. .....

The rest of this section will help you develop an intuitive understanding of the way electricity is produced in *generators* and is used in *motors*. .....

The first picture below shows ..... Now look at the first picture in Solution 12-D and imagine .....

The second picture is a bird's eye view of the same loop later, after a 90° rotation. .....

Notice that ..... [snip] .....

In a GENERATOR,
mechanical energy is used
to produce electrical energy.

In a MOTOR,
electrical energy is used
to produce nechanical energy.

The rest of this section is optional, but recommended. It takes you through a cycle of motion one step at a time, so you can see and understand the 3-dimensional logic of generators and motors. By comparing the top-row pictures (for a generator) with the bottom-row pictures (for a motor), it will be easy for you to see the similarities and differences between these two devices. ..... [snip] .....

The #1 pictures in the top & bottom rows are similar, but cause-effect is reversed. In a generator, an external agent makes the loop move and this causes induced current. In a motor, an external agent makes current flow and this causes motion.

12.5 Inductors and LR Circuits (this section has not been written yet)

Eventually, Chapter 12 will be "finished" in a camera-ready format.