

M-3. Magnetic Fields

Teaching Notes

THE MAIN POINT

1. Use right-hand rules as a guide for sketching magnetic fields.
2. Apply the principle of superposition to magnetic fields.
3. Calculate B-fields created by several line currents.

SAMPLE LESSON PLAN

Discussion Question 1	10 minutes in groups.
Discussion Question 2	10 minutes in groups.
Problem 3	15 minutes in groups, 10 minutes GSI-led discussion & boardwork.
Problem 2	15 minutes in groups, 10 minutes GSI-led discussion & boardwork.
Problem 1	15 minutes in groups, 5 minutes GSI-led discussion & boardwork.
Problem 4	15 minutes in groups, 5 minutes GSI-led discussion & boardwork.

GENERAL TEACHING SUGGESTIONS

Field sketching. Most students find it difficult to sketch magnetic fields. This is partly because, unlike electric fields, magnetic fields have no simple “push or pull” test that tells you their direction. Instead, the main tool for B-field sketching is the field of a line current. This is the first field your students must memorize (along with the right-hand rule for the orientation of the field lines). This “elementary” line current field then helps in sketching the fields of more complicated current distributions. (We think of them as a sequence of tiny line currents.)

The strong emphasis on field sketching in this worksheet is an attempt to lay the groundwork for Ampère’s Law. As was the case with Gauss’s Law, a student cannot hope to use Ampère’s Law correctly unless he already knows what the field in question looks like. But when we get to actual Ampère’s Law problems, there is no time to practice sketching fields. This is why we are focusing so much on field sketching now.

Fields vs. field lines. I find that with B-fields, even more than with E-fields, there is a tendency to think about the field lines themselves as *constituting* the field. What I mean by this is that some students fail to understand that there is a B-field vector attached to each point in space, thinking instead that a B-field is a bunch of swirling lines. You may be able to head off this misunderstanding if, when you draw B-fields, you throw in a few actual **B** vectors once in a while, in addition to the field lines.

Be on the lookout for this confusion as the students work through Discussion Question 2 and Problem 3. (See the Sample Lesson Plan above.) Recall that Discussion Question 1 of Worksheet M-

2 *Magnetic fields* touches on a similar point---see the last paragraph under the Remarks on that question.

Biot-Savart. This worksheet provides almost no opportunity to cover the Biot-Savart Law. One reason for this is that the Biot-Savart Law, although fundamentally important to magnetostatics, is nevertheless prohibitively complicated to use in all but the simplest of situations. So if we wish to center the students' learning around *problem-solving*, then there are few realistic opportunities to bring in Biot-Savart. Incidentally, perhaps in recognition of this fact, Biot-Savart rarely appears on 7B exams.

If your lecturer is emphasizing Biot-Savart, then you may recommend that your students study section 35-2 of their text, and then try Question 40-3 of Elby's *The Portable TA*, Volume 2. Recommend that they bring their questions on this material to your office hours. Also, you may use the Biot-Savart Law to *derive* the magnetic fields for the infinite straight wire and the loop of wire. Challenge Problem M3 deals with finding the field of a Magnetic Dipole using the Biot-Savart Law.

It is relevant here to point out that Discussion Question 4 and Problem 1 are similar in spirit, but they differ slightly with regard to the Biot-Savart Law. Students who know what the fields of wires and loops look like can probably answer Problem 1 without Biot-Savart, just using symmetry principles and their intuitions. Discussion Question 4, on the other hand, requires Biot-Savart in a more crucial way (because of the "head-on" currents.) So if you are choosing between these two problems, you might consider making the choice based on the degree to which your lecturer is emphasizing Biot-Savart.

SAMPLE MINI-LECTURE AND BOARD SUMMARY

It should not be necessary to lecture much at the start of section. Remind the students that in Worksheet M-1 *Introduction to magnetism*, they learned the basic right-hand rule for the B-field of a line current: point your thumb in the direction of the current, and then your fingers curl around in the direction of the field lines. This should be enough to get them started on part (a) of Discussion Question 1 (see Sample Lesson Plan above), and then you can move amongst the groups helping people figure out part (b).

When you are ready to start Problem 3 (see Sample Lesson Plan above), you may need to provide the formula for the **B-field of an infinite line current**. Be sure to **draw a diagram** illustrating all the terms in the equation.

REMARKS ON THE DISCUSSION QUESTIONS AND PROBLEMS

Discussion Question 1

Draw your students' attention to the salient features of the line current field in part (a):

The B-field vectors are always tangential to an imaginary circle centered on the wire.

Equivalently, the B-field vectors are always perpendicular to an imaginary radius emanating from the wire.

The field gets weaker with distance from the wire as $1/r$.

For a truly infinite wire, the B-field is uniform in the lateral direction.

For part (b), have the students imagine that the loop is made up of lots of wire-like segments. This should help them to deduce some crude features of the field. However, recognize that probably no one will be able to sketch a really good picture of this field from “first principles.” In any case, when you’ve drawn some nice pictures of the field on the board (both perspective and end-view), tell the students that they will have to reproduce this picture themselves many times as the course goes on.

See also the comments in the General Teaching Suggestions above, under *Fields vs. field lines*.

Discussion Question 2

This question may look like a plug-in, but don’t treat it that way. If approached carefully in section, it can tell you how well your students are understanding the magnetic field concept, and it can also allow you to see how well the Lorentz force law ideas of Worksheet M-2 are sinking in.

If the students don’t know how to get started (or, what’s worse, if they are looking through the book for formulas on the force per unit length between two wires), have them draw an edge-on view of the two wires (with the two currents coming out of the paper, say). Then you can run them through a dialogue something like this:

- YOU: The way we’re going to think about this problem is, *Wire 1 creates a magnetic field, and the moving charges in Wire 2 feel it*. So: What does the field created by Wire 1 look like?
- STUDENT: (Draws concentric circles around Wire 1. Adds arrows based on right-hand rule at your prodding.)
- YOU: Good. So at the location of Wire 2, what is the direction of the B-field?
- STUDENT: I already drew it.
- YOU: Sorry, let me rephrase that: At the location of Wire 2, what is the direction of the B-field *vector*?
- STUDENT: Oh, like this. (Draws upwards arrow.)
- YOU: Good. So, if there is a moving charge right there, what force does it feel?
- STUDENT: I dunno.
- YOU: If a point charge is moving in an external magnetic field, how do we calculate the force it feels?
- STUDENT: Oh yeah, $\mathbf{F}_{\text{on } q} = q\mathbf{v} \times \mathbf{B}_{\text{ext}}$.
- YOU: So what is that in this case?
- STUDENT: Uh, is q positive or negative?
- YOU: Good question! Well, since the current is out of the paper, that’s like positive charges moving towards us.
- STUDENT: So the force is, um, to the left.
- YOU: OK, good. Draw that force on there. Now let’s have a new picture, below this one. *Now the way we’re going to think about the problem is, Wire 2 creates a magnetic field, and the moving charges in Wire 1 feel it*. So: What does the field created by Wire 2 look like?
- STUDENT: (Draws field correctly.)
- YOU: Good. So at the location of Wire 1, what is the direction of the B-field?
- STUDENT: (Draws downwards arrow.)

YOU: Good. So, if there is a moving charge there, what force does it feel?
STUDENT: Positive charge again?
YOU: Yeah.
STUDENT: To the right.
YOU: Good, draw the force on there. Now, looking at your two pictures, do the wires attract each other or repel each other?
STUDENT: Attract.
YOU: What about if the currents flow in opposite directions?
STUDENT: They repel.
YOU: Right, see if you can work through the argument again in that case.

One thing to notice about this dialogue is how *little* the GSI takes for granted when she works with a student or a group of students. Notice also the appearance, early in the dialogue, of the “fields vs. field lines” confusion (discussed in the General Teaching Suggestions above, under the heading *Fields vs. field lines*).

Be on the lookout for students who believe that Wire 1’s magnetic field exerts a force on Wire 1 itself. There are subtle issues lurking here, but let’s not raise them. Just lay down the law: *An object’s own field never exerts a net force on itself.*

Discussion Question 3

This question draws the students’ attention to the fact that electric and magnetic fields can both exist at the same time, and that electric and magnetic fields can both be created by the same object. Occasionally there is some confusion on these points.

Your students may ask why an ordinary current-carrying wire does not produce an electric field. By drawing a picture showing negative electrons passing through a lattice made of positive protons, you should be able to convince them that there is no net charge in an ordinary current-carrying wire, and hence no field at macroscopic distances.

So in this sense, hooking a battery up to a piece of copper is a lot different from throwing a positively-charged piece of plastic.

Make sure you emphasize how you can approximate the moving charges as a current! Dimensional analysis helps here. We have a charge per unit length and a speed. Multiplying them together gives charge per time, or a current. You should emphasize the meaning of this current: it is the amount of charge passing through a single point [or plate] per unit time.

Discussion Question 4

Notice that Discussion Question 4 and Problem 1 are similar in spirit, but they differ slightly with regard to the Biot-Savart Law. Students who know what the fields of wires and loops look like can probably answer Problem 1 without Biot-Savart, just using symmetry principles and their intuitions. Discussion Question 4, on the other hand, requires Biot-Savart in a more crucial way (because of the “head-on” currents.) So if you are choosing between these two problems, you might consider making the choice based on the degree to which your lecturer is emphasizing Biot-Savart.

Problem 1

This is the trickiest problem on the worksheet, so I would not do it first. (See the Sample Lesson Plan above.)

Notice that Discussion Question 4 and Problem 1 are similar in spirit, but they differ slightly with regard to the Biot-Savart Law. Students who know what the fields of wires and loops look like can probably answer Problem 1 without Biot-Savart, just using symmetry principles and their intuitions. Discussion Question 4, on the other hand, requires Biot-Savart in a more crucial way (because of the “head-on” currents.) So if you are choosing between these two problems, you might consider making the choice based on the degree to which your lecturer is emphasizing Biot-Savart.

When you discuss this problem at the board, stay organized. Begin with a statement that frames the problem as a whole, such as

$$\mathbf{B}_{\text{hairpin, at P}} = \mathbf{B}_{\text{semicircle, at P}} + \mathbf{B}_{\text{top half-wire, at P}} + \mathbf{B}_{\text{bottom half-wire, at P}},$$

or the cuter version

$$2\mathbf{B}_{\text{hairpin, at P}} = \mathbf{B}_{\text{loop, at P}} + \mathbf{B}_{\text{top full wire, at P}} + \mathbf{B}_{\text{bottom full wire, at P}}.$$

(For the latter we imagine superposing a second hairpin over the given one.) Then carefully discuss with the students how to deal with each term. A good way to start is by taking each contribution in turn and asking which direction it points in. This requires intuitive use of the right-hand rule.

Problem 2

Field sketching is probably not a habit with your students yet. As people are getting started with part (a), prompt them by asking what the field of the large loop *looks like*.

If necessary, refer them back to their diagrams from of Discussion Question 1. Don't let up until they can apply the right-hand rule properly.

When the students have found the answer, you might ask them if it makes sense that the current should be less than i_0 .

Problem 3

This is a good problem to start with. (See the Sample Lesson Plan above.)

A careful diagram is essential for doing the vector addition properly. A good way to get the picture right is to remember that the B-field vectors of a wire are perpendicular to an imaginary radius emanating from the wire.

One goal of this problem is to create a distinction in the students' minds between field *lines* and field *vectors*. (See the General Teaching Suggestions above, under *Fields vs. field lines*. See also the sample student-teacher dialogue appearing in the remarks under Discussion Question 2.)

If you want to ask a follow-up question, you might ask for the force on a point charge at *rest* at point P.

Problem 4

Try to save at least a little time for this problem. (See the Sample Lesson Plan above.) The students will re-visit the uniform current sheet in Problem 4 of Worksheet M-4 *Ampère's Law*.