A. Detecting Magnetic Fields

1. A "magnetic compass" is a small bar magnet balanced on a pivot. When it is in a magnetic field (such as the earth's) it can swing back and forth like a pendulum, but in a horizontal plane.
   a. When a *pendulum* stops swinging, its bob points in a direction parallel to the local *gravitational* field. The word "________" describes the direction of that *gravitational* field.
   b. When a *compass needle* stops swinging, it indicates the direction of the local _________ic field if it is not stuck. If it is stuck, you can free it by tapping it lightly. The local direction of the earth's *magnetic* field is indicated by a ________ needle, and is best described as "______ward".
   c. It seems that the local magnetic field pulls in opposite directions on the two ends of a compass needle, always trying to rotate it *except* when the needle is _____________ to the magnetic field.
   d. Draw force diagrams like the ones on on page 118 to illustrate the two cases described in 1c.
   e. Give the numerical value of the vector sum of the two magnetic forces acting on the ends of a compass needle in a uniform magnetic field. (Use 1d.) **TF = ___ ___**

2. A **"tangent galvanometer"** is a coil of wire in a vertical plane with a compass at its center.
   a. When there is no current in the wire, the compass is influenced only by the local magnetic field of the earth. In that case the compass needle points _______ if it isn't stuck. Does 1b agree? ___
   b. When you start an electric current in the coil the compass needle _______s . (moves, turns, spins)
   * c. Place the compass on the counter and lay one of the wires in your circuit on top of it, parallel to the needle. Write an *opening statement* about what happens when charge starts to flow in that wire.
   * d. Write a general conclusion about how artificial magnetic fields can be created. *Save it on RS XIV.*

3. Return the compass to the center of the coil. Find a way to orient your coil to make the coil's magnetic field point in the same direction as the earth's magnetic field, so that the compass needle is unaffected whenever the current is turned on or off, even if the current is more than half an amp.
   a. The compass shows that the coil's field is _____________ to the coil's axis, or ________________ to the plane of the coil. (parallel, perpendicular)
   b. The discovery described in 3a has been recorded in #___ on RS ___.
   * c. Reverse the coil current (it must be more than 0.5 A) and tap the compass gently, as in 1a. Describe what happens to the coil's magnetic field as a result of that reversal.
   d. If the magnetic field at the center of a coil points toward me, then the direction of electron flow in the coil must be _________wise. (clockwise, counterclockwise) -Does 3d contradict 3a? ___
   e. This discovery has been checked carefully and is recorded in # __ on RS __.

4. Place a pencil near the center of the platform to indicate the direction of the coil's magnetic field. *The pencil must be ____________ to the plane of the coil, as in 3a and 3c.* Then turn the coil and platform by hand to make the pencil point in a new direction without rolling off the platform. Must the pencil still indicate the direction of the *coil's* magnetic field?__ *If not, give evidence.*

5. When the coil current is roughly half an amp, see what happens to the compass needle when you rotate the coil (as in #4) with the compass at the center of the coil and with the pencil in place beside it. -Does the compass needle remain parallel to the pencil? ___ -Which of the directions listed below seems to be indicated by the compass? ___ (Recorded in #__ on RS ____.)
   A. The direction of the earth's magnetic field (See 2a & 2b.)
   B. The direction of the coil's magnetic field
   C. --of the vector sum of the two magnetic fields *Please illustrate your choice.*
   D. --of the vector difference between the two magnetic fields
   E. --of the vector sum of the forces acting on the needle (See 1e)

6. We use the letter "B" to represent magnetic fields, perhaps to honor an early investigator named Jean Biot. We shall use "B_C" to represent the coil's field, and "B_E" to represent the earth's magnetic field.
   a. *ACCORDING TO #5,* we expect the compass needle in a tangent galvanometer to indicate the direction of the __________ ______ of ___ and ___. (Please use the symbols defined above.)
   b. Choose a NEW symbol to represent the vector indicated by the compass needle: ____
   c. Suppose "B_C" points westward, "B_E" points northward and that those two fields have equal strengths: In what direction will the compass needle point? _______ *Correct 1d & 5 if necessary.*
   d. Carefully draw a vector diagram showing how that answer was obtained. Label each vector with the symbols defined above. Copies of these definitions have been saved on RS __.

1. Imagine a round clock face with a wire coil around its circumference. One observer describes the electron flow in the coil as “clockwise”. This current generates an artificial magnetic field called "B_C" at the center of the clock. Use #5 on RS XIV to answer the following:
   a. How would you describe the direction of Bc? ____________ *Words like "north" and "east" are useless in this example because we have not been told which way the clock is facing. Instead, you must use a phrase like "toward the 7", or "away from the observer", or something similar.*
   b. A second observer stands *behind* the clock. How must that person describe the direction of *ELECTRON FLOW* in the coil? _____________
   c. If we wanted the artificial magnetic field at the center of the clock to point ***westward,*** the clock and coil would have to face ______ward. Does this contradict 1a or 1b? ___
   d. To increase B_C we must ___crease the coil current.

2. Suppose B_C points eastward and is 0.75 times as strong as the earth's magnetic field:
   a. Draw and label an accurate vector diagram showing how the *total* magnetic field at the center of the coil is determined from B_E and B_C. Use a protractor and ruler, as you did on pages 34 & 34R.
   b. The direction of that total field can best be described as __ degrees _____ from north.
   c. According to #6 on RS XIV, the compass needle in that region must indicate the direction of the _____ magnetic field, represented by the symbol ____.
   d. Suppose we increase the coil's magnetic field to twice its former strength: Draw a new triangle showing how the three B's are now related. The new deflection angle must be ___^{o} from north.
   e. Have you checked 2b & 2d by using trig? ___ If you don't know how, have you asked? ___
   f. Those diagrams show that the deflection angle can never be greater than __ deg.

3. Let's investigate the relationship between $\mathbf{B_C}$ and the **coil current:** *Without* plugging it in, arrange your coil so that B_C will point directly *EASTWARD* when the current is turned on. (Use 1c.)
   a. When the coil is plugged in, the angle between $\mathbf{B_C}$ and $\mathbf{B_E}$ will then be ___ deg. as it was in #2 & 1c.
   b. Place the compass at the coil's center, *with its zero-degree mark pointing directly north.* Make the settings in 3a and 3b as precisely as you can and estimate their uncertainties in degrees.
   c. Make a data table *and a graph* of **Needle Deflection vs Current.** *Use the degree markings on the compass. Don't go beyond 60 degrees. Do everything you can to make the uncertainties* ***small****.*
   d. Record the ranges or uncertainties of all measurements and save a copy of your data table.
   e. Hand in your team's graph before leaving the lab. *As usual, each member of the team must sign it.*

* 4. What was the name of the vector indicated by the compass needle? (See 2c above, or #6 on RS XIV.)
   a. How can its magnitude and direction be determined from B_C and B_E? (Name the operation.)
   b. Sketch a vector diagram to illustrate that relation. Label each vector as in #2.
   c. Which two vectors in the diagram form the needle's "deflection angle"? (Use 2d.)
   d. In your diagram please label the deflection angle ***and*** the angle mentioned in 3a. (Use 4c.)
   e. Use simple trigonometry to show how the ratio B_C/B_E is calculated from the deflection angle.
   f. How can the GLV and SLV of that ratio be calculated from the GLV and SLV of the angle?

5. Make a new column on your data table and a new graph to show how the B_C/B_E ratio depends on the coil current. Please express all of the ratios in *RANGE FORM.* (Use 4f.) *Put error bars on your graph to indicate those ranges.* Also make a straight or curved line showing the pattern that you see.

6. Write a conclusion about the relation between B_C and I_C. Write it on the graph, using the word "proportional". Omit the constant. (Proportionality constants are needed only in *equations.*) This conclusion has been saved in #__ on RS __.

7. Imagine a tangent galvanometer set up with B_C pointing eastward. B_E still points ______ward, but the compass needle points 53 degrees east from north. Use 4e to explain the following:
   a. In terms of B_E, how strong is the coil's magnetic field at its center? $\mathbf{B_C = (\_\_\_) B_E}$
   b. Exactly how is B_C affected if the current is doubled? (Use #6.) **B_C is _______ed.**
   c. Calculate the new deflection angle that will result if the coil current is doubled. (Use 2d & 4c.)

8. The compass at the center of another tangent galvanometer points 45 degrees east from north when B_C points east. Without changing the current, we rotate the coil until B_C points 30^o south from west.
   a. Draw the vector sum of B_c and B_e for both arrangements, i.e. before and after.
   b. Using page 34R, describe the direction of the new total magnetic field at the coil’s center.

1. In #1 on page 120 we decided that a magnetic field is a condition in space which causes a pair of ___________ic forces to act on the two _____s of a ___________ ___________.
   a. Did you record that definition on a review sheet? ___ --Which one? ___ --Did you copy similar definitions for electric and gravitational fields from page 116 or 117? ____ --Where? ___
   b. How must a coil's field strength depend on the number of turns in the coil?
   c. What other variables must B_c depend upon? (Explain your reasoning.)

2. Let "R" represent the radius of circular coil with several turns. A compass placed at the center of the coil can easily detect the magnetic field generated by the current in the coil, just as in the tangent galvanometer experiment. Now a second circular coil is set up around the first one, in the same plane and centered at the same point. Current in the second coil also creates a magnetic field at the center, as the compass can easily verify. The radius of the second coil is twice the radius of the first coil.
   a. To ensure that the two coils to carry currents which are exactly equal in magnitude, we can connect them in _________. To make the two artificial magnetic fields at the center point in opposite directions, we must make one current ______wise and the other ________wise.
   * b. How can we use the compass to decide which field is the stronger one? (Use #5 on RS XIV.)
   * c. What do we expect the compass to do if the two fields in 2b have equal strengths?
   * d. What *DOES* the compass do when we turn on the current in this arrangement?
   e. Using 2c, 2d, & 2e, sketch a graph describing the relation between Bc and coil radius.

* 3. Repeat the previous experiment with a new pair of coils. Let one coil have *twice as many turns* as the other one, as well as having twice the radius. Describe exactly what you do and what you see. Then make a conclusion about the strengths of fields generated by this new pair of coils.

4. Think of the wire in one of those circular coils as a lot of identical segments. Each segment is so short that it looks more like a dot than a piece of wire.
   a. Does each segment's current contribute to the magnetic field at the center? ___
   b. Is there any reason to believe that some segments contribute more than others? ___ *If so, explain.*

5. The circumference of the outer coil in #3 was ____ times the circumference of the inner coil, and the outer coil had __times as many turns as the inner coil. Therefore it had ___ times as many identical segments as the inner coil. Suppose we change the outer coil to make it have the *same* number of segments as the inner coil: That reduces the length of the outer coil wire by a factor of __.
   a. According to #1b, its number of turns and the strength of its field are both multiplied by ____.
   b. Let "B_i" represent the field generated by the inner coil and let "B_o" represent the field generated by the modified outer coil. How must they compare when the currents are equal? $\mathbf{B_o/B_i}$ **= ___**

6. Let "d**B**" represent the strength of the artificial magnetic field at the center produced by one segment of current. How must d**B** depend upon the distance "r" between the segment and the center? According to 5c, d**B** must be proportional to ______ *Insert a symbol with a numerical exponent. Then use 17d on RS II with the data in 5c to check your answer.*

7. Let "d**B**" represent the magnetic field produced at the observer's location by one segment of current. Let "___" represent the length of that segment. Doubling that length is like placing two identical segments end-to end. That change causes "d**B**" to be multiplied by __. Use "proportional" language:
   a. How must d**B** depend on the length of the segment? (Use the symbols above.) ____ _______
   b. Let "___" represent the current in a segment: How must d**B** depend on that current? ____ ____
   c. Let "___" represent the distance between the segment and the observer: How must d**B** depend on that distance? ____ ____ -Does 7c contradict #6? __ -Does #6 contradict #5? ___
   d. Is there any *other* variable that the segment-field might depend on? __ -If so, figure out how the field strength must depend on it or describe an experiment that you might do to find out.

8. Combine those relations (7a-7d) into a single formula predicting the magnetic field at any point in space produced by the current in any segment of wire at any other point in space. Define a new symbol to represent the proportionality constant in this new formula. **dB = _______**

* 9. Is it possible to predict the magnitude and direction of the magnetic field at *any* location, produced by *any* arrangement of current-carrying wires by using #8 along with the hand rule? If so, please *explain how*. If not, please explain *why not*. (I am *not* asking if the prediction will be easy.)