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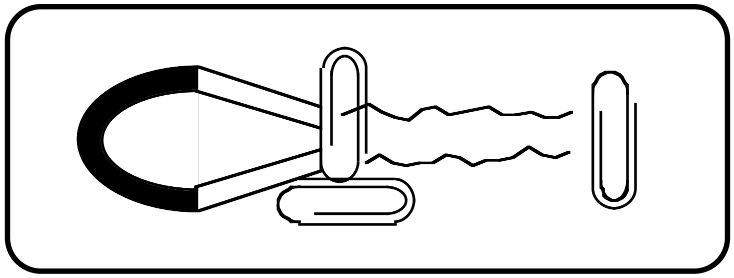
UNIT 25: MAGNETIC FIELDS



To you alone . . . who seek knowledge, not from books only, but also from things themselves, do I address these magnetic principles and this new sort of philosophy. If any disagree with my opinion, let them at least take note of the experiments. . . and employ them to better use if they are able.

Gilbert, 1600

OBJECTIVES

1. To learn about the properties of permanent magnets and the forces they exert on each other.

2. To understand how magnetic field is defined in terms of the force experienced by a moving charge.

3. To understand the principle of operation of the galvanometer – an instrument used to measure very small currents.

4. To be able to use a galvanometer to construct an ammeter and a voltmeter by adding appropriate resistors to the circuit.

OVERVIEW

As children, all of us played with small magnets and used compasses. Magnets exert forces on each other. The small magnet that comprises a compass needle is attracted by the earth's magnetism. Magnets are used in electrical devices such as meters, motors, and loudspeakers. Magnetic materials are used in magnetic tapes and computer disks. Large electromagnets consisting of current-carrying wires wrapped around pieces of iron are used to pick up whole automobiles in junkyards.

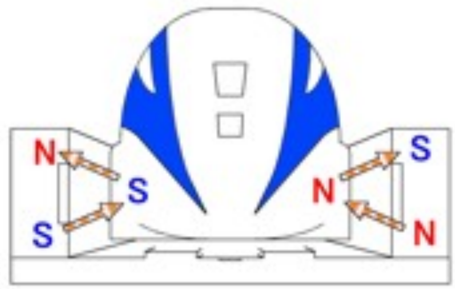


Diagram of a Maglev train electrodynamic suspension. (Wikimedia Commons)

From a theoretical perspective, the fascinating characteristic of magnetism is that it is really an aspect of electricity rather than something separate. In the next two units you will explore the relationship between magnetic forces and electrical phenomena. Permanent magnets can exert forces on current-carrying wires and vice versa. Electrical currents can produce magnetic fields and changing magnetic fields can, in turn, produce electrical fields. In contrast to our earlier study of electrostatics, which focused on the forces between resting charges, the study of magnetism is at heart the study of the forces acting between moving charges.

Maglev train coming out of Pudong international airport. (Wikimedia Commons)

SESSION ONE: MAGNETIC FORCES AND FIELDS

Permanent Magnets

The attraction of iron to a magnet is so familiar that we seldom realize that most of us know little more than the ancients about how the attraction occurs. Let us begin our exploration of magnetism by playing carefully and critically with some permanent magnets and observing what happens. For the activities involving permanent magnets you will need:

- 2 rod shaped permanent magnets w/ coloured ends
- 5 tiny compasses
- 2 40-cm lengths of string
- Scotch tape
- 2 rod stands
- 2 aluminum rods
- 2 right angle clamps

Interactions Involving Permanent Magnets

Permanent magnets can interact with each other as well as with other objects. Let's explore the forces exerted by one magnet on another.

✍ **Activity 25-1: Permanent Magnets and Forces**

(a) Do you expect the "like" ends of a magnet to attract or repel each other? What do you predict will happen if you bring "unlike" ends together?

(b) Fiddle with the two permanent magnets. Do the like ends attract or repel each other? How do the rules of attraction and repulsion compare to those for electrical charges of like sign? Are the rules the same or different? (One of the ends of a bar or cylindrical magnet is usually called the north pole and the other the south pole. You will explore why shortly.)

(c) Each pole represents a different type of magnetic charge. Can you find a magnet with just a north pole or just a south pole? (Such an object would be called a magnetic *monopole.*) Can you find unlike electrical charges separately? Discuss the differences between electrical and magnetic charges.

Next, let's explore how magnets orient when they are placed close to each other and when they are placed far away from any visible object that might be attracted to them.

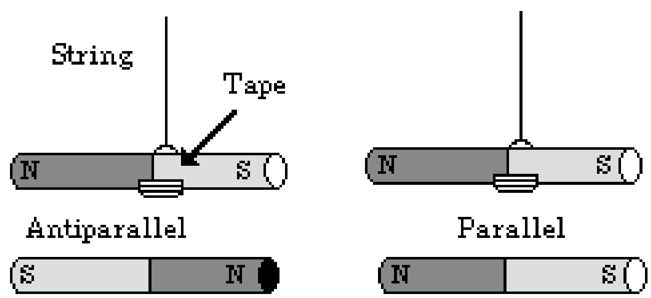


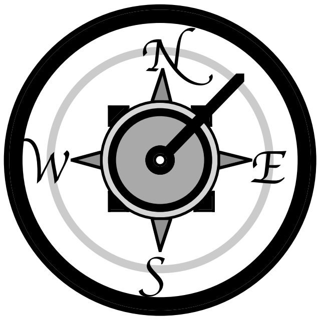
Figure 25-1: Possible Orientations for a Hanging Magnet

✍**Activity 25-2: Magnet Orientation**

(a) Tie a string tightly around the centre of one of the magnets and put a dab of scotch tape under the string as shown in Figure 25-1. Place the other magnet underneath the first as shown. Based on your previous observations, do you expect the suspended magnet to align itself parallel or anti-parallel to the stationary magnet? Why? **(Note:** If the rod stand is made of iron be sure it is far away from the magnet.)

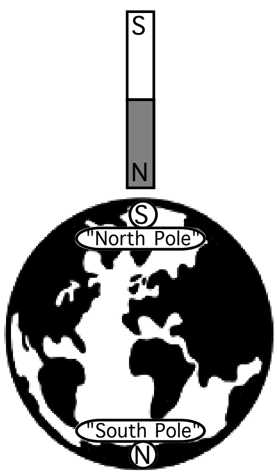
(b) Observe the magnets and circle the actual orientation in the diagram above. Cross off the orientation that you don't observe.

(c) Suspend both of the magnets at some distance away from each other. Do they appear to orient? Cite evidence for or against orientation. What is the direction of the orientation?



(d) If both magnets orient, what might be underneath the room? Would the orientation happen outdoors? What might be under the ground?

(e) Repeat observation (c) with two of the small compasses. (Just hold the compasses in your hands.) What does a compass needle probably consist of? Explain!



Want to know something crazy?! The north pole on the earth attracts the north pole on the magnet. So *magnetically, the earth's north pole is actually a south pole*. This is just as bad as the way Ben Franklin defined the signs of charges so that, once they were discovered, electrons turned out to be negative. Mixed up? Join the club.

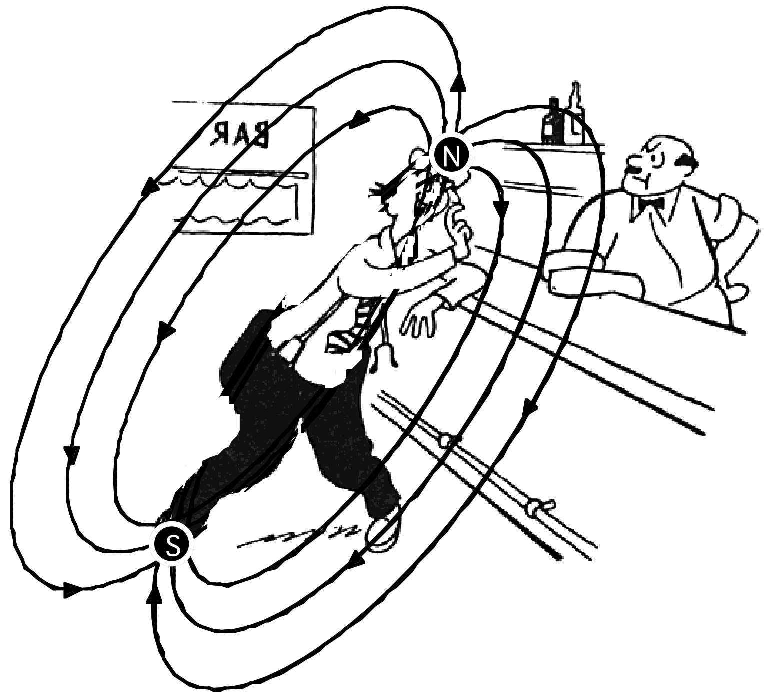
✍Activity 25-3: Determining Magnetic Poles

(a) Are the north poles on your small compasses red or white? How do you know? Warning: sometimes cheap little compasses get magnetized the "wrong" way. Check a group of little compasses. On the average, are the north poles on these magnets red or white? **Note:** Put away any compasses that point the wrong way.

Magnetic "Field" Lines Around a Bar Magnet

In preparation for defining a quantity called *magnetic field* which is analogous to, but not the same as, an electric field, you should explore the alignments of the small compass at various places near the larger cylindrical magnets. This will allow you to postulate the existence of magnetic flux and of a mathematical law for magnetic flux not unlike Gauss' law for electrical flux.

For now, let's accept an operational definition for the *direction* of the magnetic field: *Operationally, the magnetic field direction is defined as the direction in which the dark end or north pole of a compass needle is oriented in the presence of the field of interest.*



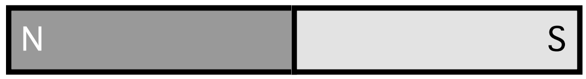
MAGNETIC FIELD LINES AROUND A BAR MAGNET

For the observations that follow you will need the following:

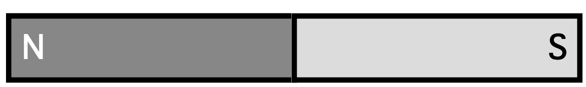
- 1 bar magnet
- 1 small compass
- Iron filings in a shaker
- 1 clear transparency sheet

✍**Activity 25-4: Field Directions Around a Bar Magnet**

(a) Use a small compass to map out the magnetic field in the space surrounding a large bar magnet ; denote the direction of the field with arrows. Don't forget to include the region just above (i.e. "in") the magnet between the north and south poles. Sketch lots and lots of arrows in the space on the next page.



(b) Take a look at a bar magnet with iron filings around it by placing a plastic transparency sheet on top of the magnet and then pouring iron filings on it. Draw a series of magnetic field lines "in" and around the magnet. Assume that the lines are continuous across the boundaries between the magnetic material and the surrounding air. Mark the lines with directional arrows pointing in the direction of the north pole of your compass.



(c) Pretend you are in a 2 dimensional world. (Flatland again!) Draw several closed loops in the space in part (b) above. Let one loop enclose no magnetic pole, another loop enclose one of the poles, and another enclose both of the poles. Assuming that each line coming into a loop is negative and each line coming out is positive, what is the net number of magnetic field lines coming in and out of a loop in each case?

(d) Now we come to a magnetic equivalent to Gauss's law describing the net magnetic flux, Φ_m, coming out of a closed three dimensional surface. Can you guess what Φ_m is equal to?

(e) Recall that Gauss' Law states that electric flux is proportional to the charge enclosed by a Gaussian surface. If the magnetic flux is equal to zero in all situations, is it possible to have a net magnetic charge? Explain your answer.

Does a Magnet Attract or Repel Electric Charges?

Maybe magnetic forces and electrical forces are the same thing, or perhaps they are related in some way. We now know that a magnet exerts a force on another magnet, but can it exert a force on electric charges? For the observations that follow you will need the following:

- A bar magnet
- Scotch tape
- A non-magnetic conducting bar or rod (the same size and shape as the magnet)

Magnetic Forces on Static Charges
Let's start by investigating the forces on static electrical charges. Remember that Scotch Brand Magic Tape gets charged when it is peeled suddenly off of a table top. You can check this by observing the repulsion between two tapes that have been peeled off a table top.

✍Activity 25-5: The Magnetic Force Exerted on Static Charges - Charged Scotch Magic Tape
(a) Test to see if there is any force on the electrically charged tape from either pole of your magnet. Do the same test with a non-magnetic conducting bar or rod. Summarize your findings.

(b) If the charged tape is attracted to both the magnetic *and* the non-magnetic bar or rod in the same way, can you conclude that there is any special interaction or force between either of the magnetic poles and the tape?

(c) Are magnetic attractions the same as electrostatic attractions? Explain using the results of your experiments.

Let's try something unusual. Let's see if a magnet can exert forces on electrical charges that are *moving*. In the front of the room there is cathode ray tube (CRT) where one can observe a beam of electrons. Your instructor will do this activity with you when you are ready. For this demonstration we will use:

- A bar magnet
- A cathode ray tube

✍Activity 25-6: The Magnetic Force Exerted on Moving Charges—an Electron Beam

(a) Place the north pole of your magnet perpendicular to the electron beam in two different orientations. What is the direction of the displacement (and hence the force on the beam) in each case? Sketch vectors showing the direction of the magnetic field, the direction of motion of the original electron beam before it was deflected, and the direction of the resultant force on the beam.

(b) You should have found that when the bar magnet is perpendicular to the beam of moving charge, the magnetic force $\vec{F}$ is perpendicular to both the direction of the magnetic flux line and the velocity of the moving charge, $\vec{v}$. What type of vector product can give a vector that is perpendicular to two other vectors? **Hint:** The only two products of vectors we have seen so far are the dot product and the cross product.

(c) Suppose we define magnetic field $\vec{B}$ as a vector quantity that points along the axis of the magnet away from the north pole and toward the south pole. Show that the vector cross product $\vec{F} = q\vec{v} \times \vec{B}$ properly describes your observations (at least qualitatively) in terms of the relative directions of the three vectors. **Hint**: Don't forget that q is negative in the case of an electron beam.

The force that results from the movement of charge in a magnetic field is known as the Lorentz force. This leads to a rather backwards mathematical definition of magnetic field. The magnetic field, $\vec{B}$, is defined as that vector which, when crossed into the product of charge and its velocity, leads to a force, $\vec{F}$, given by the cross product: .

$$\vec{F} = q\vec{v} \times \vec{B}$$

Review of the Vector Cross Product
Once again we have this weird mathematical entity called the *vector cross product*. You have probably utterly forgotten what the symbols mean. Let's review the cross product. The force on a moving charge in a magnetic field can be described mathematically as the "vector cross product" which has:

(1) *Magnitude*: The magnitude of the cross product is given by $|q|vB\, sin\theta$ where θ is the angle between the velocity vector and the magnetic field vector.
(2) *Direction:* The cross product, $q\vec{v} \times \vec{B}$, is a vector that lies in a direction ⊥ to both $\vec{v}$ and $\vec{B}$ and is "up" (for positive q) when the fingers of the right hand curl from $\vec{v}$ to $\vec{B}$ with the thumb up. The cross product is "down" (for positive q) when the fingers of the right hand curl from $\vec{v}$ to $\vec{B}$ with the thumb down. These properties of the cross product are pictured below.

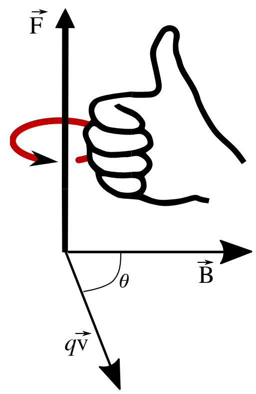


Figure 25-2: Use of the Right Hand Rule to Find the Direction of a Magnetic Force Exerted on a Moving Charge

The spatial relationships between $\vec{F}$, $\vec{v}$, and $\vec{B}$ are very difficult to visualize. In the next activity you can practise using the cross product.

✍Activity 25-7: Using the Lorentz Force in Calculations

Consider a charged particle travelling at $\theta = 27°$ with respect to a magnetic field of strength 5.6×10^{-3} T as shown in Figure 25-2 above. It has a speed of 4.5×10^{6} m/s.

(a) If the particle is a proton, what is the magnitude and direction of the force exerted on the particle by the magnetic field?

(b) If the particle is an electron, what is the magnitude and direction of the force exerted on the particle by the magnetic field?

SESSION TWO: MAGNETIC FORCES AND ELECTRIC CURRENTS

Magnetic Force on a Current Loop
The galvanometer, which is made up of a current loop and a permanent magnet, lies at the heart of many electrical measuring devices. In order to understand its operation, let's consider what happens when a rectangular loop carries current in the presence of a magnetic field.

Assume there is a current *I* flowing around the rectangular loop shown below. Since current consists, by definition, of moving electrical charges, any magnetic field at right angles to the current should exert a Lorentz force on the wire. Assume that the current loop is in the plane of the paper. A magnetic field, parallel to the plane of the paper, is present. The loop can pivot about the line CD.

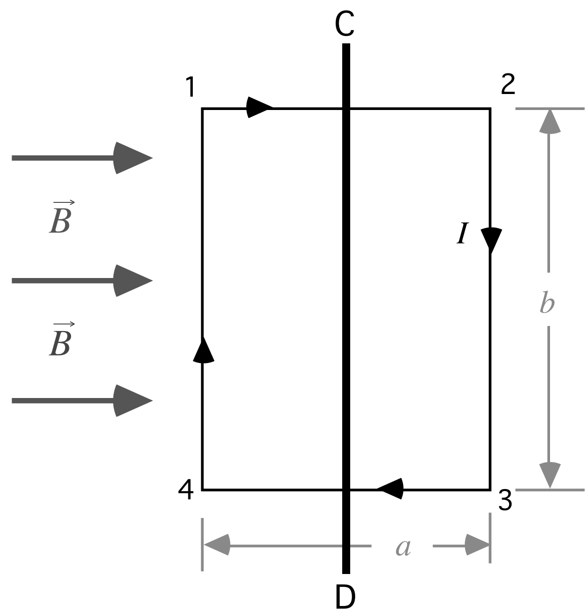


Figure 25-3: A Loop of wire of dimensions *a*,*b* in a magnetic field of magnitude *B*.

You can answer the questions below with a combination of direct observations and mathematical reasoning. For your observations you will need:

- 1 loop of wire, R <2 Ω, on a stand with one turn or multiple turns
- 4 D-cell batteries and battery holder
- 3 Alligator clip wires
- 1 strong horseshoe magnet
- 1 small compass
- 1 SPST switch

For the required mathematical reasoning assume that a positive current *I* is made up of a series of positive charges, *q*, each moving with an average speed *v* in the direction of *I*.

✍Activity 25-8: Predicted Forces on a Current Loop

(a) Use the Lorentz force equation to show mathematically that an electron with charge $q_e = -e = -1.6 \times 10^{-19}$ C moving at a velocity $\vec{v}$ will experience the same force in a magnetic field $\vec{B}$ as a positive charge with charge $q_e = e$ would experience moving at a velocity $-\vec{v}$. Be sure to use the vector signs in writing your symbols.

(b) Use the Lorentz force law and the right hand rule to determine the theoretically predicted direction of the magnetic force on each segment of the wire (e.g. 1-2, 2-3, 3-4, & 4-1). For simplicity, assume that the current *I* consists of *positive* charges, *q*, moving at an average speed, *v*, in the *same direction* as *I*. Assume that the loop lies in the plane of the paper as shown in the diagram. You can describe the directions of these forces in such terms as "right-to-left", "left-to-right", "into the paper", and "out of the paper".

(c) What motion of the loop do you predict will result from these forces?

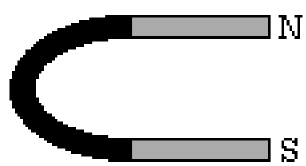
(d) What is the predicted direction of the forces on each segment of the loop of wire when the loop is rotated 90^0 about the axis through points C and D so that the plane of the loop is *perpendicular* to the plane of the paper?

(e) What should happen to the force on each segment of wire when the current in the loop increases? Should it increase, decrease or stay the same? Why?

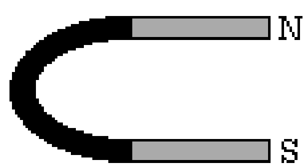
In order to observe the forces on a current loop we will need to put the loop into a magnetic field that has a definite direction and pass an electric current through it. We will use the space between the poles of a horseshoe magnet for the magnetic field. Can you guess why?

✍**Activity 25-9: The field insides a U-shaped Magnet**

(a) If a horseshoe magnet is just a bar magnet bent into the shape of a horse shoe, what do you predict is the direction of the magnetic field between its poles? Sketch the lines. **Hint:** Take a look at the field lines from your straight magnet.



(b) Place a small compass between the poles of a horseshoe magnet and sketch the actual field lines in the diagram below.



Next let's check out your predictions for the force on a loop placed at various angles between the poles of a horseshoe magnet. For the required observations you should start by wiring 4 D-cell batteries, the rectangular loop on the stand and the switch in series. Only close the switch for a very short time to observe the result.

✍Activity 25-10: Observed Forces on a Current Loop

(a) Place the loop of wire so its plane is parallel to the magnetic field between the poles of the magnet. Pass current through the loop. What happens? How does this compare with your prediction?

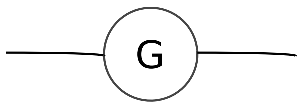
(b) What happens when you add another battery to the circuit so that the current increases? What happens if you reverse the polarity of the batteries so the current travels through the loop in the opposite direction?

(c) Explain how you might use this setup to measure current.

(d) Place the loop of wire so its plane is perpendicular to the magnetic field between the poles of the magnet. Pass current through the loop. What happens? How does this compare with your prediction?

The Galvanometer

A measuring instrument called the galvanometer consists of a series of wire loops placed in a magnetic field while current passes through them. Although digital electronic meters use different methods to measure voltage and current, the galvanometer lies at the heart of many high precision analogue voltmeters and ammeters. A diagram of a typical galvanometer is shown below.



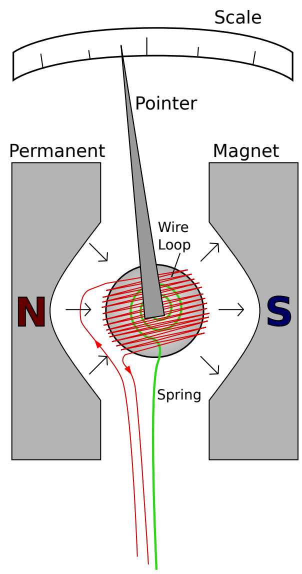


Figure 25-4: The Guts of a Typical Galvanometer (Wikimedia Commons)

The ability of the new digital multimeters to make accurate current measurements for small currents is lousy. Let's construct a more accurate ammeter using a galvanometer. For this activity you will need the following items:

- 1 galvanometer
- 4 alligator clip leads, approx. 30 cm
- 1 D-cell battery with holder
- 1 ammeter
- 1 SPST switch
- An assortment of resistors
- 1 digital multimeter

Your galvanometer is just an ammeter capable of measuring very small currents. The internal resistance of a galvanometer can be represented by the symbol R_g where the value of R_g is usually listed on the meter. Most galvanometers also list the full scale deflection current, i.e. the maximum current on the scale. Some galvanometers list the amount of current that will cause one division of deflection; the full scale deflection current, I_{fs}, can easily be determined from this information.

✍Activity 25-11: Using a Galvanometer to Make an Ammeter

(a) Let's summarize the characteristics of your galvanometer in preparation for measuring a current that is up to 5 times the full scale deflection current of your galvanometer.

Internal Resistance: R_g = _________
(Measure with ohmmeter.)

Full Scale Deflection Current (max. I on the scale): I_{fs} = _______

5 Times the Full Scale Deflection Current: I_{max} = ________

(b) We will design an ammeter that reads a maximum current, I_{max}, which is 5 times the full deflection scale current, I_{fs}. To accomplish this we must put a small resistor in parallel with the galvanometer to "shunt" off most of the current. Examine the circuit diagram below, and then show mathematically that the value of the shunt resistance, R_s, must be given by the equation

$$R_s = \frac{I_{fs}\ R_g}{(I_{max} - I_{fs})}$$

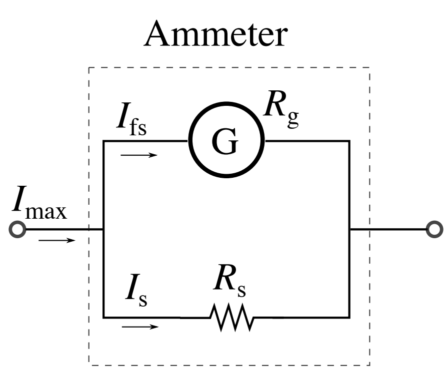


Figure 25-5: Wiring an ammeter unit using a galvanometer and shunt resistor.

(c) Use the equation you just derived to calculate the value of the shunt resistance that you need to use to have I_{max} be 5 times the full deflection scale current, I_{fs}.

Shunt Resistance: R_s = _________

(d) You can test your new galvanometer-based ammeter by wiring it in series with a resistor and battery as shown in the circuit in Figure 25-6 below.

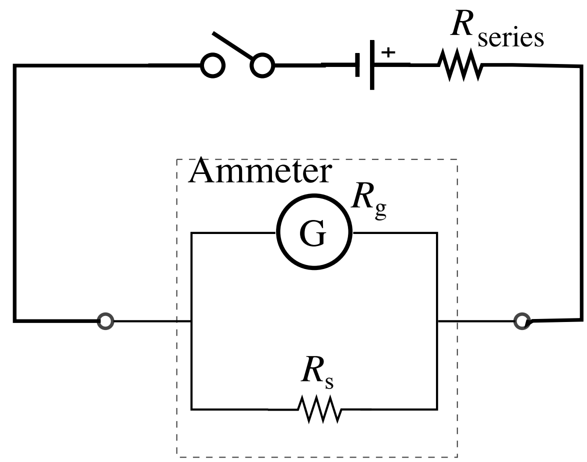


Figure 25-6: Ammeter in series with a resistor and battery.

Before you actually wire up the circuit to test your ammeter, choose a shunt resistor with a resistance as close as possible to the one you calculated in part (c). Measure its value with a multi-meter and also measure the actual potential difference across your battery.

Actual value of the shunt resistance: R_s = _________

Actual battery potential difference: $\mathcal{E}$ = __________

(e) Next, calculate the value of I_{max} corresponding to the value of your **actual shunt resistance**, R_s , (**Hint:** Rearrange the equation in part (b) to solve for I_{max} .) and then calculate the value of the resistor you will need in series with your battery to limit its current to no more than I_{max}.

Maximum current that can be measured: I_{max}= ______

Series resistance : R_{series} = _________

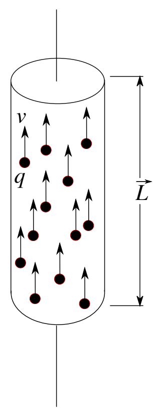
(g) Test your circuit using a resistor, $R > R_{series}$, in series with the batteries to reduce the circuit current to less than I_{max}. Record the value that your ammeter gives for the circuit current below. (Remember to use I_{max} from above as your full-scale value.) **Use another ammeter to verify your meter reading and record the value below.** How do the two values compare? How well did your ammeter work?

$I_{your\ ammeter}$ = ___________

$I_{other\ ammeter}$ = ___________

Magnetic Forces on a Current Carrying Conductor
Since current represents a collection of many charged particles in motion, a current-carrying wire experiences a force in the presence of a magnetic field unless the field is parallel to the wire. In order to use the Lorentz force law to calculate the force on a conductor of length L carrying a current, you need to relate the average or drift velocity of the charge flowing through the wire to the current in the wire and the length of the wire. Suppose a charge q travels through a straight wire of length L in a time Δt.

✍**Activity 25-12: Relating the Lorentz Force to Current**
(a) What is the equation for the average drift velocity $\langle\vec{v}\rangle$ of the charges in terms of the length vector $\vec{L}$, which has a magnitude equal to the length of a straight wire segment and the same direction as the current, and Δt?



(b) What is the equation for the current, I, in the wire in terms of q and Δt?

(c) Show that $q\langle\vec{v}\rangle = I\vec{L}$ so that the Lorentz force on a straight current-carrying wire of length L can be given by the expression below, assuming $|\langle\vec{v}\rangle| = v$:

$$\vec{F} = q\vec{v} \times \vec{B} = I\vec{L} \times \vec{B}$$

(d) Suppose a wire is not straight, then we would have to divide it up into small almost straight segments. Use the expression in part (c) above to express the force, $d\vec{F}$, on a small, almost straight, segment of length $d\vec{L}$ in the presence of a magnetic field $\vec{B}$.