Chapter 9: Potential, Magnetism and Electromagnetism

9.1 Introduction

There is an inherent difficulty in trying to break the topics of electromagnetism into chapters. The difficulty is that all the topics are related and rely on one another, so you either end up with one really long chapter, or you have unnatural chapter breaks, or you have many short chapters. In this treatment, we decided to go with the middle route. In many ways, this chapter is really a continuation of Chapter 8, so think of it as 8½.

The last chapter introduced us to the ideas of the electric force and the electric field. We first learned about the force, which requires two charged particles, and then we introduced and new idea which was the electricity around one object called the electric field. The electric field was based on the idea of an electric force and the two ideas are completely and totally linked. As you get into more and more advanced physics, it turns out that the more important idea is the electric field. If you were to open up an advanced physics Electromagnetism textbook, for example, you would find lots of questions like, "What is the electric field in this situation?" but very, very, few questions like, "What is the electric force on this particle?" The reason was stated before, but we repeat it here: It is assumed that if you can find the field, you can then find the force because the are simply related by $F = qE$. Thus, most of the focus in on finding the field. We are about to do that same thing again with another idea - electric energy. We are going to take an idea you are familiar with (energy) and then expand it into another idea (potential) which is linked by a simple equation. Once again, the important idea will be the second one, but the relationship between the two ideas is a very simple one.

9.2 - Electrical Potential Energy

Now that we understand the basics about electric forces and fields, it is time to tie all of these topics back into the rest of physics by discussing the relationship between electric fields and energy. This will allow us to use these concepts in conjunction with all of our other knowledge. Once again, we see that energy is the one concept that allows us to connect all of the other, different topics together. Notice how important this idea is - energy is what allows us to relate all of our ideas together. In order to use electricity in the rest of physics, we need to be able to calculate the energy involved in electrical situations.

Electric fields accelerate charges, thus causing a charge to increase (or decrease) its kinetic energy. Therefore, we say that a particle placed in an electric field has potential energy simply because of its position in the field. The change in electric potential energy of a particle in an external field is equal to the work done by the field on the charge (by the definition of energy from a previous chapter). Remember that we have said over and over again that energy and work are (nearly) interchangeable. If a particle moves from point A to point B in some electric field, it will undergo a potential change given by:

$$\Delta U_{AB} = -W_{AB}.$$

Where the negative comes from the fact that the field is working on the particle. We have become familiar with the idea of potential energy in regards to gravitation, and in fact you should remember that we have two different formulae for gravitational potential energy:

mgh - for the case of a uniform gravitational field

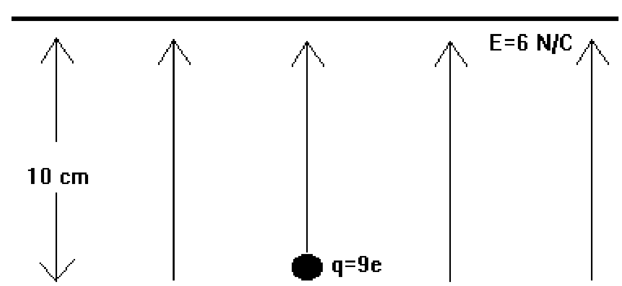
Gm_1m_2/r^2 - for the case of a spherical field

Our goal is now to develop equations like these two, but for electrical situations. We must also remember that unlike gravity, we have many different kinds of electric fields, not just uniform and spherical.

Remembering the idea that work and energy are interchangeable, let us consider the following example:

Example 9.2.1

Consider a uniform electric field between two plates. If a particle moves from one plate to the other, how much work did the field do on the particle? What is its change in potential energy?



What we see from this is very simple. In a uniform electric field, the work done is simply force times (parallel) distance.

$$W = Fd_{\parallel}$$

and the force is always $F = qE$

$W = qEd_{\parallel}$

or, recalling that work is a scalar dot product of two vectors:

$W = q(E \bullet d) = qEd\cos\theta$

Now we need to throw on a negative sign to change the work to a potential energy:

$\Delta U_{AB} = -qEd\cos\theta$

Which will work for any **UNIFORM** electric field. Remember that this is a potential energy and thus can be interchanged with any other forms of energy.

> Example 9.2.2
>
> A 2 C, 100 g charge is placed in a uniform electric field with a value of 3 N/C. After it has moved 15 cm, what is the final kinetic energy of the particle and what is its speed?

> Example 9.2.3
>
> A 120 mg, 0.3 C particle is fired into a 3.2 N/C uniform electric field that is 1 m deep with a kinetic energy of 5.2 J. What is it's speed when it exits the field if the force of the field is directly opposite to the motion of the particle?

Before we move on to the next type of field, here are some notes regarding the idea of electric potential energy.

Notes Regarding Electric Potential Energy

1.) The concept is exactly parallel to the idea of gravitational potential energy and can be used in the conservation of energy to find final velocities, etc.

2.) Only changes in electric potential energy can be discussed (we will discuss that in more detail later).

3.) The electric force is a conservative force, thus the potential energy is path independent.

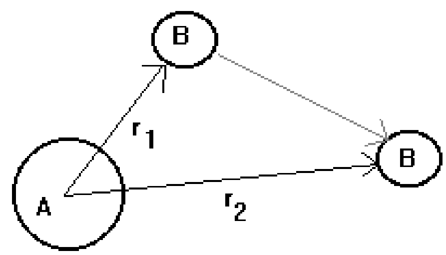
4.) The change in potential energy is easy to calculate, provided the electric field is constant (uniform) over the area in question. If the field is not constant, the calculation becomes more difficult. This is very similar to the fact that mgh only worked for ΔU of gravity when near the surface of the earth (where the field can be approximated as constant). If the field is uniform, the electric potential energy is given by:

$$\Delta U_{ele} = -qEd_{\parallel}$$

Where q is the charge moving in the external field E and $d_{\parallel}$ is the distance parallel to the field that the charge moved.

As always, when we try to apply this idea to spherical electric fields, things get a little trickier. However, we will find that they are still workable.

Consider the situation below.



If A and B are charged particles, and B is moved from r_1 to r_2 along the gray line, some work (either positive or negative) is done and thus there is some energy change. However, qEd is not applicable, since the field is not uniform. In order to solve this problem, a new concept is introduced in exactly the same manner as it was when we hit the same brick wall discussing gravity. The electric potential energy of a particle <u>at a point</u> is given by the following equation:

$$U = - \frac{1}{4\pi\varepsilon_o} \frac{q_1 q_2}{r}$$

Notice how there is no delta in front, as we otherwise might expect. The above formula is <u>the potential energy of a point charge q_1 (q_2) immersed in the field created by another point charge q_2 (q_1) at a distance r.</u> The charges are interchanged in the parenthesis because the equation can work either way (with either charge creating the field and the other being affected by that field).

The equation above is actually a change in energy, but it is the change in energy going from infinity to the point r. Just as we did with gravity, we do not have one equation that can give the energy as a particle moves from one point to another in a spherical field. On the example above, we would need to do the problem in two steps, and we would need to remember that going from r_1 to r_2 is the same as going from r_1 to infinity and then from infinity to r_2. The equation above give the energy change going from r to infinity and if we dropped the negative sign, it would be from infinity to r. Thus in the example with A and B, we would find the work done from infinity to r_1 and subtract the energy from infinity to r_2 leaving us the energy difference between r_1 and r_2 (recall that work is path independent, thus we can go to r_2 via r_1 and then subtract off the work done going to r_1).

Example 9.2.4

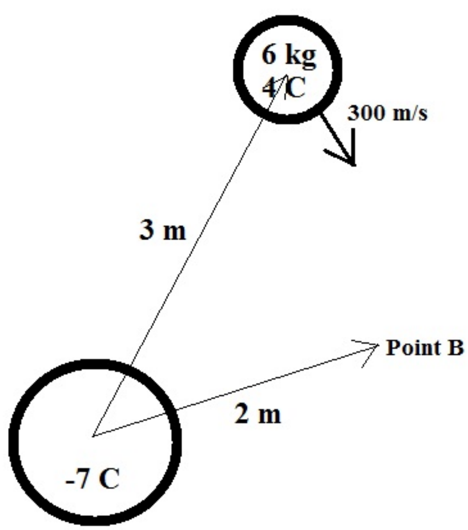
A 5 C charge is fixed at the center of a coordinate grid and a 150 g, 2 C charge is placed at (0, 1 m). The 2 C charge is released and it accelerates to (0, 4 m). What is it's final speed when it reaches the 4 m mark?

Example 9.2.5

In an identical situation to the one described in the previous example, a spring (k = 22 N/m) is placed at (0, 3.5 m) and it catches the charge. How far does the spring compress?

Example 9.2.6

Two charges are arranged as shown below, with the -7 C charge being fixed in place. The 4 C charge is traveling at 300 m/s when it passes the point in the diagram shown and then it continues on to point B. What is its final speed at point B?



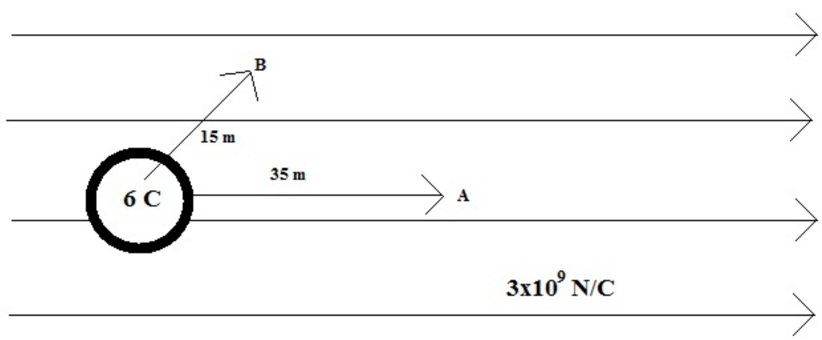
Now that we have examined uniform and spherical potential energy, it would make sense that we would move on to our two other types of fields, dipole and complex fields. However, there should be little that needs to be said, since energy is a scalar and can be added and subtracted algebraically. Let us try two simple examples:

Example 9.2.7

A dipole is created by two equal and opposite charges of 2 C. The dipole moment is 0.3 C.m and the dipole is placed so that it is orientated along the y-axis of s coordinate system with the center of the dipole at the origin. A 1.2 C charge is placed at (2 m, 2 m) and then moved to (3 m, 0). Find the amount of energy it took to move this particle.

Example 9.2.8

A 6 C charge is fixed in a uniform electric field as shown below. A 1 C charge is placed at point A and moved to point B - how much energy was required to move the 1 C charge?



The electric potential energy of a system has a number of various different meanings, all having to do with energy. It is a very important and useful idea and just to be sure we understand it, before we move on to the next idea, let us focus and elaborate on these meanings.

<u>The electric potential energy is the energy that is contained in the bonds of the system.</u> Way back in our energy chapter, we discussed the idea that every force has an energy associated with it. That energy was the energy that is either gained or released when the bonds are broken. Electric Potential Energy is the energy in the bonds between charged particles. Thus when we say things like: "It takes 13.6 eV to ionize hydrogen" we mean that the bond between the positive nucleus and the negative electron contains 13.6 eV of energy and we must supply that much to break the bond and remove the electron. Likewise, if we say something like: the chemical reaction gives off 5 J of energy, we mean that the electric potential energy between the atoms and molecules when the reaction is done contain 5 J less energy than the (different) bonds did before the reaction.

<u>The electric potential energy is the energy that would be available if the charges in the situation fly apart.</u> This is best

seen if the energy is positive, as in the case of two positive charges held a certain distance apart. For example: if we had two positive charges held a distance apart and we found the electric potential energy to be 3 J, then if we let the charges go and they flew apart, they would have a total of 3 J of kinetic energy. Naturally, that energy would not be automatically distributed 50%-50%, but the speeds would be based on the conservation of energy.

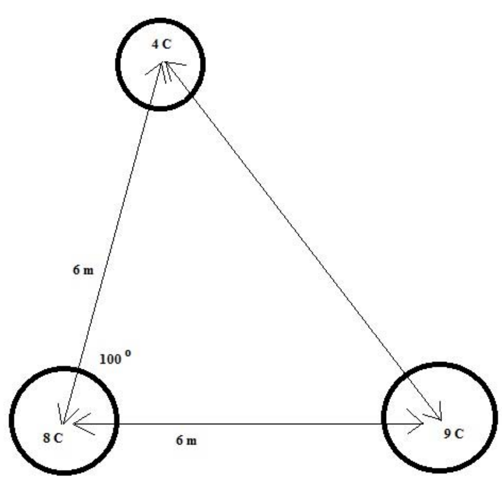
The electric potential energy is the energy that would be given up if the charges were allowed to form into the arrangement given. This is the reverse of the second statement above and only makes sense if the energy is negative. For example, if the problem states that a dipole is formed by a positive and negative charge coming together, and the potential energy is 3 J, then that means that as they formed together, they reached their positions with a total of 3 Joules of kinetic energy (which would have to have been removed in some manner if the charges are fixed in place at their locations).

The electric potential energy is the formation energy or energy required to assemble construct the situation. Again, this is just a restatement of the other statements, but it is a very, very common type of AP problem and one that is often also asked on tests in more advanced physics classes. The wording will often read something like this: "How much energy is required to construct the arrangement of charges shown below?" Or, "How much energy is required to bring a charge Q from infinity to the position shown below." The work done in assembling the charges (by an outside agent) is equal to the electric potential energy of the system.

Once again, all four of the statements above are really saying the same thing, but it is good to specifically spell them out so that students can understand what is being asked.

Example 9.2.9

How much energy is required to create the system shown below?



Example 9.2.10

Consider a coordinate system marked in meters. The following steps are taken (in the listed order).

1.) A 2 mC charge is moved to the origin.
2.) A -4mc charge is brought from far away and placed at (4,0)
3.) A 6 mC charge is brought from far away and placed at (0,3)

Find the energy required to carry out each step and the energy required to assemble this arrangement of charges.

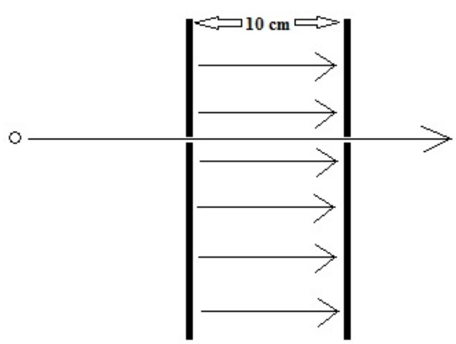
Practice Problems

Example 9.2.10

A 2 μC charge is placed in a uniform electric field with a value of 4 N/C. It moves 12 cm with the field. What is it's final kinetic energy?

Example 9.2.11

An electron traveling at 12,000 m/s passes through a small hole in two parallel plates, as shown below. The plates create a uniform electric field of value 5 N/C. When the electron exits the other side, what is its final speed?



Example 9.2.12

A small spring gun is constructed that fires a charged particle straight up in the air. The spring has a constant of 400 N/m, and is compressed 3 cm. The charged particle has a charge of 2 mC and a mass of 12 g. It is fired in a region of space with a downward facing uniform electric field of 2 N/C. Not neglecting gravity, how far does the particle rise before coming to a stop and falling back to the gun?

Example 9.2.13

A 200 g, 2 C charge is place 1.4 m away from a 3 C charge that is fixed in place. The 2 C charge is released and flies away. What is the speed of the charge when it is 2 m from the other charge?

Example 9.2.14

A 3 mC charge is fixed in place at the origin of a coordinate grid marked in centimeters. A 200 g, 4 mC is brought from very far away to (0,2) - how much energy is required for this operation? The charge is then “flicked” and ends up flying past the point (3,3) at 25 m/s. How much energy was imparted by the “flicking”?

Example 9.2.15

Four 130 mC charges are arranged in the shape of square with side of 3 cm each. Find the energy required to construct this arrangement.

Example 9.2.16

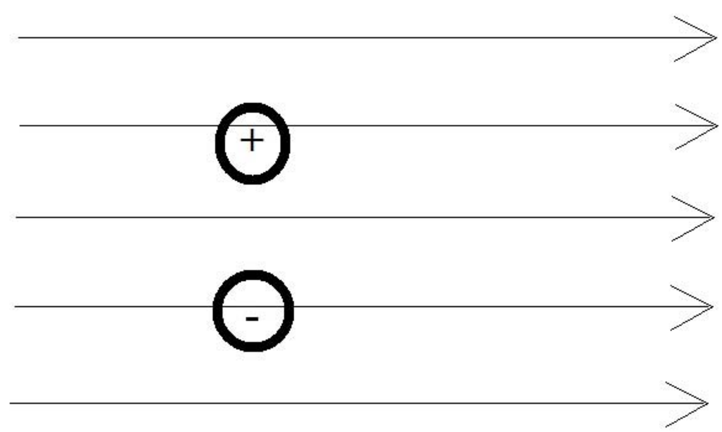
Consider a coordinate system marked in meters. The following steps are taken (in the listed order).

1.) A -12 C charge is moved to the origin.
2.) A -6 C charge is brought from far away and placed at (2,2)
3.) A 5 C charge is brought from far away and placed at (0,2)

Find the energy required to carry out each step and the energy required to assemble this arrangement of charges.

Example 9.2.17

A dipole made of two equal and opposite 0.5 C charges spaced 15 cm apart is placed in the uniform electric field (8 N/C) as shown below. How much energy is required to construct this arrangement, assuming that the uniform field has a distance of 125 cm?



9.3 - Electric Potential

Now that we understand Electric Potential Energy, it is time to move on to what is perhaps **the** single most confusing and misunderstood topic in all of physics (first year physics, at least): The topic of electric potential.

The first thing that is confusing about it is it's name: electric potential. Notice how close it is to electric potential energy. But they are not the same thing. To make this even more confusing, electric potential actually has at least six acceptable other names that mean exactly the same thing. Electric potential energy is only electric potential energy. It is very common for a single physics book (or the AP test, or a professor) to use all or some of the different names for electric potential interchangeably. The chart below shows what I am talking about.

Electric Potential Energy	Electric Potential
Other acceptable names: electrostatic potential energy	Other acceptable names: electric potential different potential difference potential voltage voltage difference electric voltage difference electrostatic potential electrostatic potential difference electrostatic voltage electrostatic voltage difference

Any and all of these names are acceptable to use at any time in a physics problem, and it is assumed that you know that these are all the same thing.

But what is electric potential? Remember the idea of a field - we introduced the idea of a field because we wanted a way to discuss the electric force of one object. Notice how we have the same issue again here: Electric potential energy involves two objects and the energy does not exist around one single object. However, it would be nice if we could discuss the electric energy that is around one object (even though it does not exist). When we encountered this problem with electric force, we used a test object to find the force and then got rid of the quantity related to the test object by dividing the force by the charge. We do the exact same thing here. We use a test object to find the energy and then divide by the charge of the test object. This leaves us with a quantity related to, but not the same as, energy. The new quantity is called electric potential, or voltage. Mathematically,

$$\Delta V_1 = \Delta U_{12}/q_2$$

Notice how this gives us units of Joules per Coulomb (J/C) which is defined as a Volt (V).

Voltage is an essential quantity in the study of electricity, yet it is often one of the least understood quantities in first year physics classes. Because it is so important, I will list here a number of important ideas about voltage. Some of these are repetitive, but the ideas are so important that I want to present them in as many different ways as possible just in case you can comprehend one way better than another.

- Voltage is a measure of the energy that would be there if a charge was placed at that location.
- Voltage is measured in Joules per Coulomb, thus if something is

10 Volts, that means there would be 10 Joules of energy if 1 Coulomb of charge was placed at that location.

- Voltage involves only one charge, energy involves two charges.
- A charge creates voltage around itself, but it is affected only by voltages created by other charges (charges do not affect themselves).
- Voltage and energy are related by charge - $\Delta U = q\Delta V$ in all situations.
- Voltage is related to work, since work is related to energy. If you know the voltage, you can find the work done.
- Just like Electric Potential Energy, voltage is actually a difference - voltage makes no sense if only one point is considered.
- If the voltage being discussed appears to refer to only one point, it is understood that the voltage is between that point and infinity. For example: If a problem says the voltage at point P is 20 V, that means the voltage between P and infinity is 20 V.
- Voltage is what could happen, energy is what is happening.

You may also remember that in the past we have used a unit of energy called an electron-volt. You can now see how that unit was created and exactly what the unit means. One electron-volt (eV) is the energy one electron gets after passing through one Volt of potential. Notice, however, that it is a mixed-up unit. Volts are standard SI units of measure, but the unit of charge should be a Coulomb. By using the elementary charge it designates the electron volt as a mixed up set of units. Notice also that the conversion factors are the same between Coulomb and elementary charge as they are between Joule and electron-volt.

$$1 \text{ eV} = 1.6\times10^{-19} \text{ J}$$

Potentials in Uniform Fields

Once again, uniform fields are the easiest to work with. We know how to calculate the potential energy of a uniform field:

$$\Delta U = -qEd\cos\theta$$

and since we find potential we are simply dividing by the test charge:

$$\Delta V = -Ed\cos\theta = -E \bullet d$$

remember that the above equation is a vector dot product, just like potential energy in the previous section. Also, remember that potential is always a difference, so when discussing uniform fields, you will never hear the term “the potential at point P is 4 V,” because that phrase is meaningless. It will always be phrased as “the potential between points A and B is 4 V,” or “the potential across a 10 cm range is 4V.”

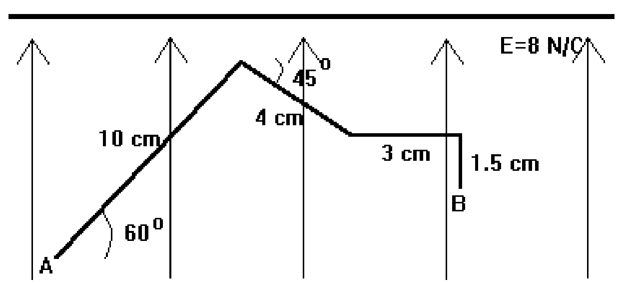
The formula above is so simple, that the easiest way to become familiar with it is simply to do some examples.

Example 9.3.1

A particle of charge 3e is moved 25 cm directly against a uniform electric field of strength 10 N/C. What is its change in potential energy? What is its change in potential?

Example 9.3.2

What is the change in potential if a charge of 4 C is moved along the path indicated (from A to B) in the field below?



Example 9.3.3

An electron is dropped into an external electric field and travels across an area of 9 V. What is the speed of the particle at the end of that area?

Potentials in Spherical Fields

Spherical fields, our next consideration when discussing potentials, are also simple because they can be described by one simple equation. As we do this, however, please remember to keep in mind that all of our equations are constructed with one of our points being infinity. Potential, like potential energy, only exists as a change between two points. So if we say things like, the potential at point P is 4 V, we really mean the potential difference between P and infinity is 4 V.

Once again, we start with potential energy:

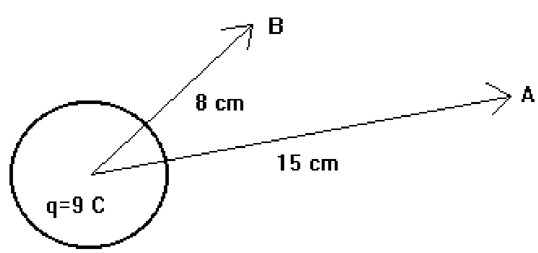
$U = (1/4\pi\varepsilon_o)q_1q_2/r$

then we divide out the test charge,

$V = (1/4\pi\varepsilon_o)q_1/r = Cq/r$

Example 9.3.4

What is the potential at point A in the diagram below? What is the potential difference between points A and B?



Potentials in Complex Fields

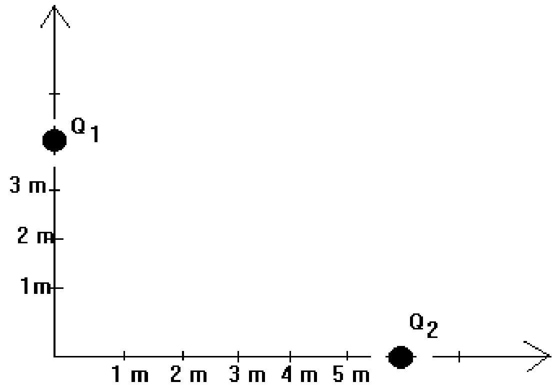
Potential, just like potential energy, is a scalar, making it very easy to work with in complicated situations. Since we don't have to worry about directions, we can just add potentials calculated from different fields. Two simple examples will demonstrate this easily.

Example 9.3.5

A 4 C charge is placed at the origin and a 6 C charge is placed at (0,1 m). What is the potential at (0, 3 m)?

Example 9.3.6

If Q_1 has a charge of 3 C and Q_2 has a charge of 4 C, what is the potential at the origin?



Equipotential Surfaces and Final Comments on Potential

Before we leave the concept of potential, it is worth mentioning the concept of equipotential surfaces. Equipotential surfaces are surfaces drawn to help visualize the field (much like Faraday's Lines of Force), but they are specifically related to the potential of the field. They are drawn exactly as their name suggests. We go into the field and draw a line connecting all the points at the same potential. This results in a diagram that is the electrical corollary to a topographical map. A topographical map shows lines of positions at the same level, an equipotential plot shows places at the same potential.

Some notes on equipotentials are made below, and the student should take some time to understand each statement and be able to explain or defend each statement made.

Notes on Equipotential Surfaces

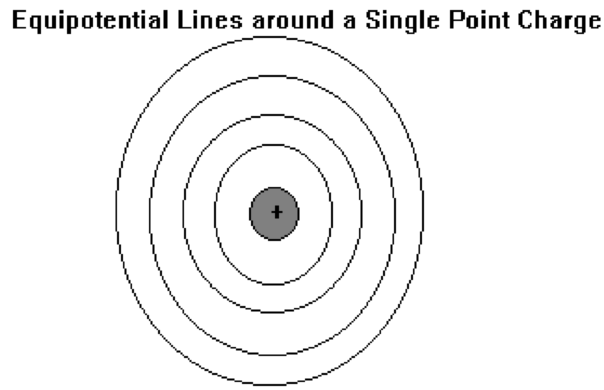
1.) Since the lines are equipotential, moving a charge along a line requires no change in potential, thus no change in energy. Also, moving a charge from one point on the line and then bringing it back to the line (regardless of the path) requires no energy.

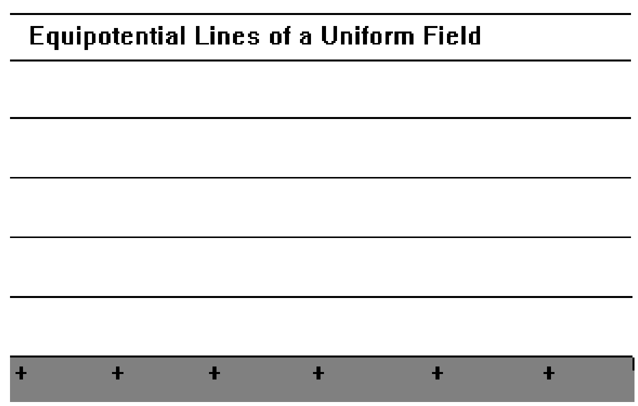
2.) Moving a charge from one line to another requires the same amount of energy, regardless of the path or starting point or ending point along the line.

3.) Equipotential lines will always be at right angles to field lines (this makes drawing the lines easier if the field lines are drawn first).

4.) Equipotential lines near the surface of conductors are parallel to the conductor.

Most equipotential plots are very complicated, thus I will only draw two of the most simple plots below.





Summary of Electrostatic Principles and Formulas

In our discussion of the electric force, field, potential energy, and potential, we have had many formulas and it might be handy to draw up a table that summarizes this info. The table is a bit complicated, but it may help you organize your thoughts.

	Particles Create		Particles Experience	
	single particle	group of particles	from a single particle	from a uniform field
Force	NA	NA	F=qE or $F=Cq_1q_2/r^2$	F=qE
Field	$E=Cq_1/r^2$	use vectors	E=F/q	E=F/q

Potential at a Point	V=Cq/r	add pot. from each charge	V=Cq/r (from other particles)	N/A
Change in Potential	use above and subtract	add pot. from each charge	$\Delta V = V_f - V_i$	$\Delta V=Ed$
Work (Potential Energy)	NA	NA	$W=q\Delta V$	W=Fd or $W=q\Delta V$ or W=qEd

As we leave this section, I would like to stress the importance of the concept of potential. Of all the electrical concepts, potential is the most often used. It is essential that the student become comfortable with exactly what potential means.

Practice Problems

Example 9.3.7

A region between two plates is filled with an electric field of 4000 N/C and the plates are separated by a distance of 12 cm. What is the voltage between the plates?

Example 9.3.8

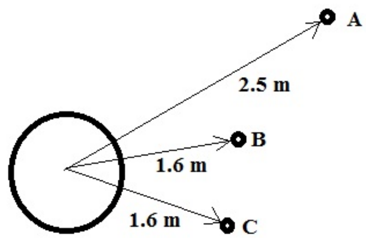
If an electron traverses a difference of 10,000 V, what is the speed of the electron as it leaves the other side?

Example 9.3.9

What is the potential 3 m from a point charge of 6 μC?

Example 9.3.10

What is the potential difference between points A and B in the diagram below? What is the potential difference between points A and C?



Example 9.3.11

A 0.3 C charge is placed at the origin and a 0.6 C charge is placed at (10 cm, 0). What is the voltage at (0, 5 cm)?

Example 9.3.12

A charge is placed at the origin and the voltage from (0, 1 m) to (0, 2 m) is found to be 3 V. What is the charge at the origin?

9.4 - Magnetism

The concept of magnetism and the magnetic field are both trickier than the idea of electricity and the electric field. For that reason, there is not usually a large emphasis on magnetism in first year physics classes. The most often covered topics in magnetism are: a conceptual understanding of magnetism and magnetic materials, an introduction to Lorentz’s Law, and deeper, more sophisticated applications of the Lorentz Law. In this treatment, we will address the first two topics in this section, but the last has been rolled in to the next section (Electromagnetism).

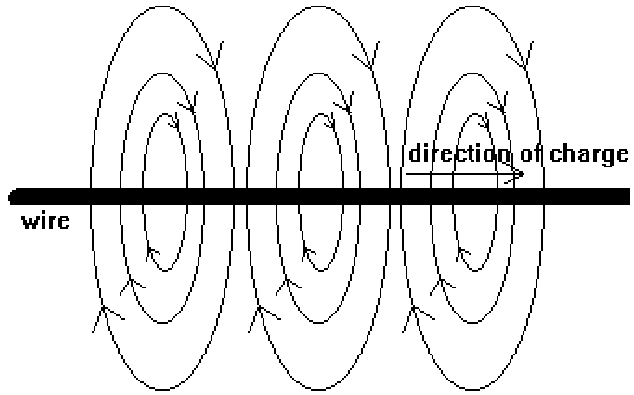
Introduction to Magnetism and Magnetic Materials

We have discussed the concept of the electric field (and its corresponding topics: force, potential energy, and potential) in some depth and now it is time to begin discussing the magnetic field. Recall, from our discussion of forces, that both the electric and magnetic field are aspects of the same fundamental force; electromagnetism. Both fields are simply different aspects of this one, underlying force. The magnetic field, however, is quite a bit more complicated and harder to understand. Because of this, magnetism is often treated in basic physics textbooks simply on a conceptual level. Even in more advanced books, the qualitative aspects of magnetism are only covered in a very simple way and often approximations are used. Although this seems like a cop-out, it should be said that magnetic fields affect things differently than electric fields and thus need to be examined differently. Most of the important magnetic effects do not require the same type of calculations as electric effects and many of the important aspects of magnetism fall under the category of material science.

One of the main reasons for magnetism's complexity is the important fact that there are no magnetic charges. Unlike gravity (which is a field due to a mass) or the electric field (due to a charge), there is not a characteristic of a particle that directly produces a magnetic field. Magnetic fields are created by charges in motion. If an electric charge stands still, it creates an electric field. If an electric charge moves, it creates both an electric field (which is distorted due to the charges motion) and a magnetic field. Thus magnetism never arises without electric charges and electric fields accompanying it. Often, the magnetic field can be very strong while the electric field is weak, thus it can seem that the magnetic field is standing on its own. This brings us back to the fact that there appears to be no magnetic charges. Because there is no "magnetic particle" (the correct terminology is magnetic monopole), the fields are strikingly different than those created by the electric monopole (a single point charge) or a gravitational monopole (a single point mass). Magnetism is created by moving electric charges, thus in some ways, magnetism can be understood as an electric field viewed from a moving frame of reference.

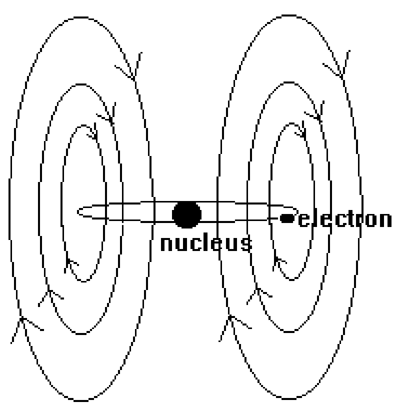
There are three ways an electric charge can move to produce a magnetic field: linearly, circularly or rotationally. The linear motion of an electric charge results in a magnetic field that surrounds the line of motion like concentric circles (or more precisely, concentric cylinders). One excellent example of this would be charge moving through an electric wire. Every electric wire carrying a flow of electricity (a current) creates a magnetic field around it. In fact, this was the first discovery that convinced people that electricity and magnetism were somehow connected. Hans Orstead, a physics teacher, one day happened to be teaching magnetism immediately after finishing a lecture on electricity. On his table he had his demonstrations set up, and he had a compass very close to his electrical wires. He noticed that when he connected the battery to the wires, the compass needle turned away from magnetic north. It was this seminal discovery that led the way to unifying the two effects under the same force.

The field line of the magnetic field around a current carrying wire are shown in the diagram below.

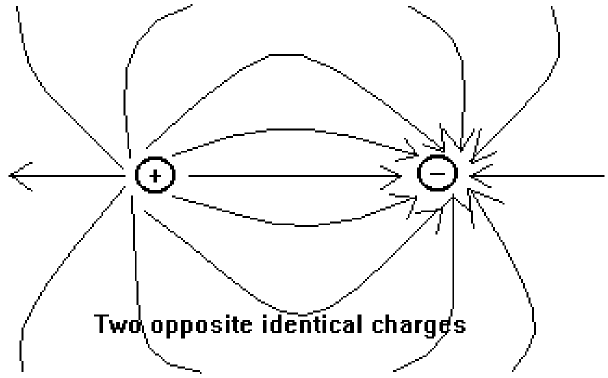


While it is true that these fields exist around all wires carrying current, they are not generally noticeable in your household wiring for two reasons. First, a large amount of charges must be flowing by for the field to be "noticeable" and secondly, since the electricity in your home is AC or alternating current, the resulting magnetic field switches direction 60 times a second.

The second type of motion that can cause a magnetic field is orbital or circular motion. The best example of this would be an electron in orbit around the nucleus of an atom. We should recall that electrons actually exist in clouds, and not as single, orbiting particles, but the approximation can be used to best understand the phenomena. The field created by an orbiting electron looks like this:

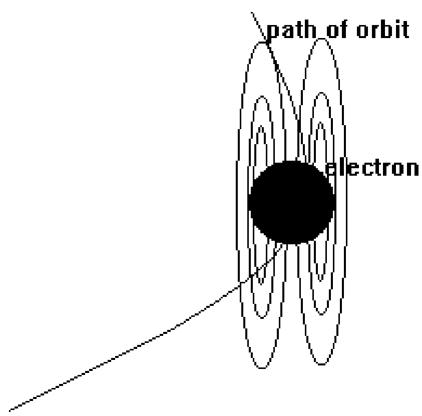


The field in this instance looks like concentric, misshapen "donuts". This shape is very, very important. The field produced in this way is called a dipole field. Notice the resemblance to an electric field created by a positive and negative charge separated by a short distance. That particular field looked this:



If we imagine such a field, and then move the positive and negative charges infinitely close together, we have a magnetic dipole field. Since there are no such things as magnetic charges, a dipole field is considered the simplest possible magnetic field. It occurs often and it essential that the student understand the characteristics and shape of the field.

The third method of motion that was mentioned was rotational motion. We know that electrons "spin" in their orbit much like the earth rotates as is orbits the sun. In actuality, the characteristic of spin for an electron is really not describing the electrons rotation, but it is helpful to view it in that manner. Such a motion results in the magnetic field as shown below:



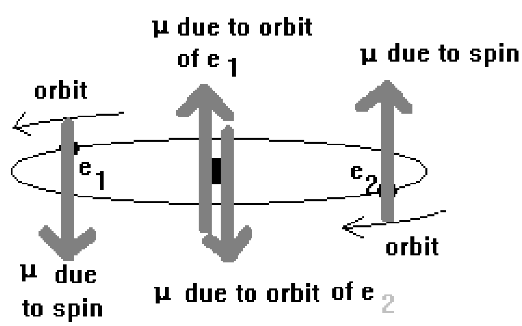
We see that in this case, the magnetic field is once again a dipole field, this time centered on the charge itself. In a piece of material, the rotational magnetic fields tend to be much much greater than those caused by the orbital motion of the electron.

An astute student may have noticed that in all the magnetic fields shown, the field lines are forming loops. This is an important aspect of the magnetic field. If we recall that our field lines must always begin or end on a charge or at infinity, and we recall that there are no magnetic charges, we can see that magnetic field lines should form closed loops.

Since so many magnetic fields turn out to be dipole fields, it is only logical that we should talk about a magnetic dipole moment for magnetism. The symbol for such a moment is usually given as μ and it is a characteristic of the source of the magnetic field. Since there are no magnetic charges, μ is as close as we can get to describing the source of magnetism. It is helpful and informative to consider the parallels between gravity, electricity and magnetism. In this case, μ is the source of a magnetic field, just as m is the source of a gravitational field and q is the source of an electric field. When you ask what is causing a magnetic field, your answer would be the dipole moment μ. Dipole moments can also react to magnetic fields, just as masses and charges can react to gravity and electricity, respectively. However, since the simplest field is a dipole field, and the simplest characteristic is a dipole moment, the simplest interaction is that of a dipole in a dipole field, not always an easy thing to analyze or calculate.

Magnetic Materials

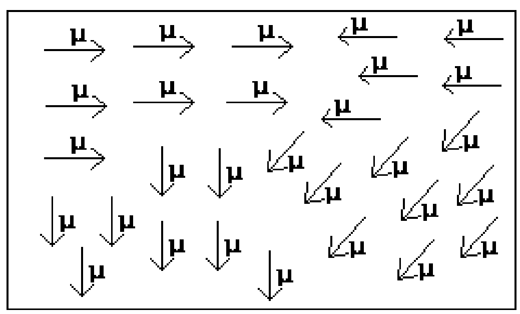
We know from experience that some materials are magnetic, and some can be made magnetic by bringing them in contact with a magnet. Thus we should take a few minutes and discuss what makes a material magnetic. If we think about our previous discussion of the motion of the electrons in an atom, we can see that each electron contributes two dipole moments (one from its orbit and one from its spin) to the overall atom. In most materials, these moments (and thus the fields) contributed by all the different electrons in an atom tend to cancel each other out. The diagram below illustrates this for an imaginary atom.



On this particular atom, all the moments cancel out and there is no overall moment for the atom.

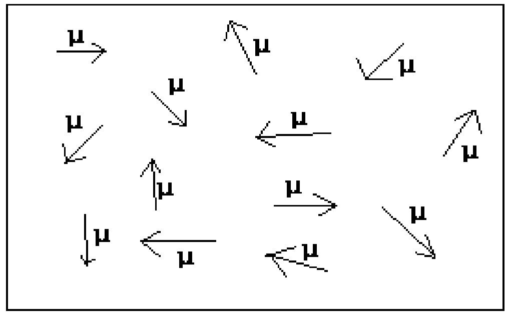
However, often there is some tiny residual moment left over for the entire atom (consider the case for the atom above if one electron were removed). In certain atoms, this moment can be very large due to the position and spin of its particular combination of electrons. This in and of itself is still not significant, since atoms in most materials tend to be randomly oriented and even if each individual atom has a magnetic moment, the overall material might not (again due to cancellations of all the individual moments adding together to equal zero). There are three particular types of magnetic materials where these contributions become significant.

The first and most familiar type of magnetism is called ferromagnetism. This is the strongest form of magnetism present in materials and is what is commonly considered when magnetic materials are discussed. We have already stated that the rotation of electrons contributes most strongly to the magnetism of a material and you may have learned in chemistry that electrons tend to "pair up" with opposing spins. This pairing effect tends to negate the overall magnetic moment of the atom. However, some material contain unpaired electrons (such as iron) due to either an odd number of electrons, or more importantly, a break in the usual pattern of subshell filling in the atom. These atoms tend to have strong magnetic moments and near-by atoms align themselves by a process known as exchange coupling. This process is a complicated (quantum) effect that cannot be explained by ordinary physical means. This causes the atoms in certain regions to become aligned all in the same direction, giving that region an overall magnetic moment. The diagram below illustrates this principle.

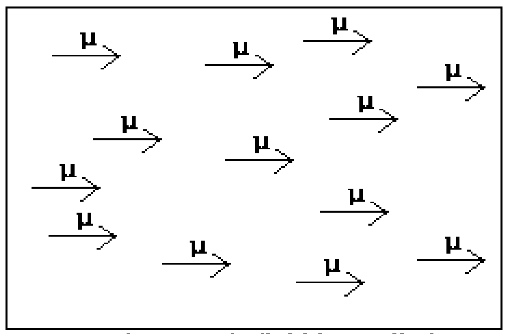


The regions where all the dipole moments are aligned are called domains. Each domain acts like a little magnet with a moment created by the reenforcement of all the little moments in the atoms. In general, these domains will tend to cancel each other out, instead of each atom canceling each other atom. These domains often consist of billion and billions of atoms and the exchange coupling is strong enough that normal collisions of atoms have no effect on the domain.

When a ferromagnetic material is placed in an external magnetic field, all of these domains line up in the same direction and the material becomes highly magnetic. This is the reason that a piece of iron, when in contact with a magnet, acts like a magnet itself. The pictures below illustrate how this occurs, but each arrow represents a domain, not a single atom.

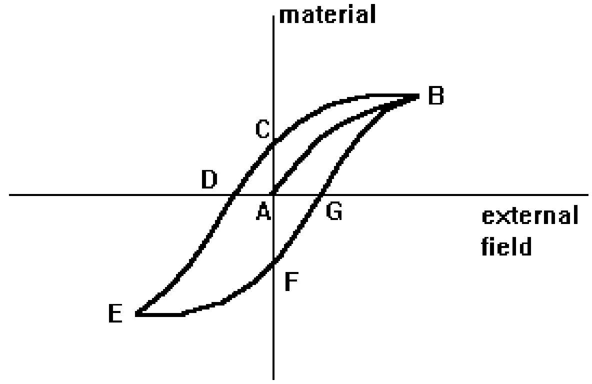


Before external field is applied



After external magnetic field is applied

As long as this field is applied, the domains remain aligned. When the external field is removed, the natural jostling from the motion of atoms causes most of these domains to return to the random states they occupied before the external field was switched on. However, some of these domains remain aligned, thus leaving the material with a residual amount of magnetism (consider the experiment often done in middle school science classes of rubbing a piece of steel in one direction with a magnet - the steel remains magnetized for some time after. This is because the repeated rubbing causes more and more domains to remain aligned.) The phenomena of residual magnetism left over in a ferromagnetic material after an external field is removed is called hysteresis. Each and every material behaves differently under these conditions and a material's behavior is usually represented by what is called a hysteresis curve. On such a graph, the independent variable (x-axis) is the external field being applied to the material and the dependent variable (y-axis) is the magnetic field of the material (how magnetic the material has become). Consider the diagram below:



In this diagram, we begin a point A where there is no external field, and no magnetism in the material. The segments from there represent:

A-B: The external field is turned on and slowly increased, causing the material to become more and more magnetic.

B-C: The external field is reduced to zero, leaving a residual amount of magnetism in the material.

C-D: The external field is once again increased, but this time it is reversed, causing the material to become less and less magnetic, eventually returning it to zero.

D-E: The external field continues increasing negatively, causing the material to once again gain a field.

E-B: The reverse process of B-E.

It is this type of process that is used to store information magnetically (such as on a cassette or video tape or a computer disk). In those cases a magnetic material (the tape) is exposed to a magnetic field (created by the recorder or disk drive) and the material gets a residual magnetic field in a certain spot (or in a certain pattern) that can be reread later.

Although this explains how something can become magnetic, it does not necessarily explain how something loses its magnetism. If we consider the concept of domains, we can see that losing magnetism equates with the disordering of domains. Any process that causes the domains to become unaligned will reduce magnetism. For example, dropping a magnet will reduce its magnetism, as will heating a magnet. Every ferromagnetic material has what is called a Curie Temperature (named after its discoverer, Pierre Curie) where the thermal effects exactly cancel out the exchange coupling which keeps the atoms aligned. When the Curie temperature is reached, the material no longer exhibits magnetic effects.

The second category of materials are called Paramagnetic materials. If a material that does have some magnetic moment left over in its atoms (recall that often the pairing of electrons result in the overall moment being zero) is exposed to an external magnetic material, all of the atoms will line up with their moments in the same direction (recall our treatment of an electric dipole in an external field). Notice that here we are talking about atoms, not domains as in ferromagnetism. The overall moments of paramagnetic materials are not strong enough to engage exchange coupling, which creates domains. Instead, we deal with atoms individually and have much less of an effect. When all the moments are aligned, the material itself becomes one large magnet and has its own magnetic moment. Although the external field aligns all the moments, they do not often stay aligned due to the collisions of particles in the material. If the external field is shut off, all the moments tend to scramble back to their original positions. Thus the paramagnetic effect is very weak and very temporary. This is not the effect that is normally though of when one considers magnetism (such as steel, etc).

The third type of magnetic material, or effect, is diamagnetism. This is a very, very weak effect that is present in all materials, but rarely noticed. If a material is brought into a magnetic field, the field will actually attempt to force the electrons into an orbit that aligns their magnetic field with the external one. If the electron is not already spinning that way, it will resist the attempt and a slight repulsive force will be produced. Diamagnetism actually causes materials to be repelled by the magnet causing the external field. As was mentioned, all materials are slightly diamagnetic, but the effect is too slight to notice.

The Lorentz Force and Some Practical Applications

We have learned that a stationary electric charge creates a stationary electric field and that a moving electric charge creates both a magnetic and electric field. If we then consider a moving charge to be a "magnet" we would expect that when an electric charge moves in an external magnetic field, it will be affected by the field. That is indeed the case. When an electric charge moves in an external magnetic field, it experiences a force from that field. This force is called the Lorentz Force and is given by the vector equation of:

$$\underline{F} = q(\underline{v}\times\underline{B})$$

Where F is the force, q is the charge on the particle, v is the velocity of the particle (as a vector) and B is the external magnetic field (B is the normal variable assigned to magnetic fields). Since this is a cross product, a few notes can be made. First, the magnitude of the force is given by

$$F=qvB\sin\theta$$

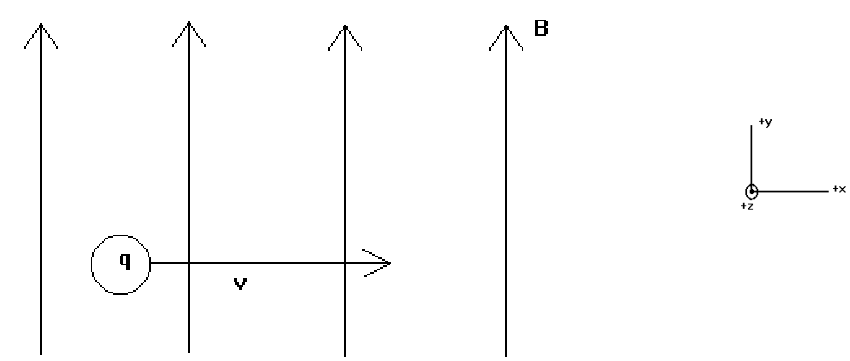
Where θ is the angle between the field lines and the velocity of the charged particle. Secondly, since it is a cross product, the force will always be perpendicular to the plane containing the velocity and the field. As the particle moves, it will be pushed at right angles to both its velocity and the field. In order to illustrate this on two dimensional pages, we should introduce some new conventions.

X = an arrow going into the page
• or ⊙ = an arrow coming out of the page

These can be remembered easily by thinking of an arrow being shot from a bow, the point coming at you is out of the page and the feathers vanishing into the page represents a vector going away from you. Besides this notation, the student should also be able to identify directions from a given coordinate system. For example, it is often the practice (on the AP test) for a given problem to come with a given coordinate system. In these cases, the answer is expected to be given by referencing the given system (on the AP test, if a student gets the problem correct, but does not answer according to the coordinates given, they are counted wrong, e.g. answering to the right instead of +x direction). With this in mind, let us do some simple examples of calculating the Lorentz force on a particle.

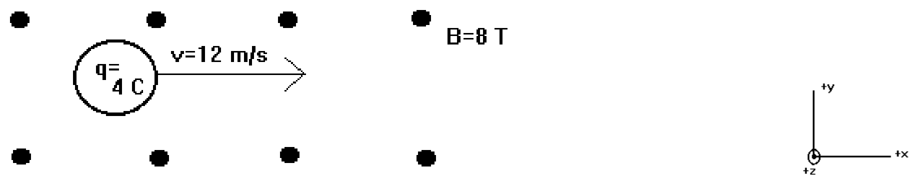
Example 9.4.1

Explain the forces acting on the particle in the magnetic field below and give your answer according to the given coordinate system.



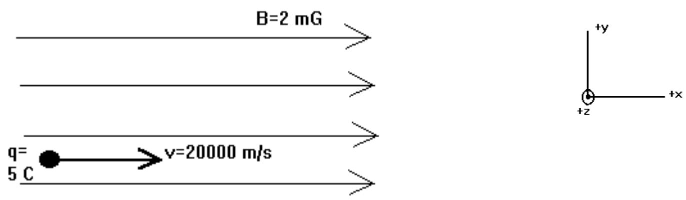
Example 9.4.2

What is the force on the particle below? (The magnetic field is out of the page.) Answer according to the given coordinate system.



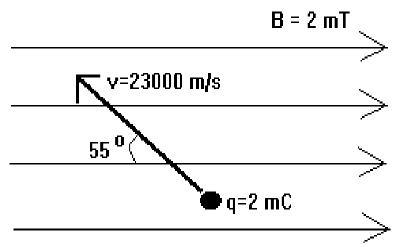
Example 9.4.3

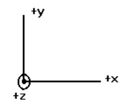
Find the force on the particle shown below, answer according to the coordinate system given.



Example 9.4.4

Repeat the above instructions.





Example 9.4.5

An electron is launched in the +x direction into a 0.3 T magnetic field at 30,000 m/s. The magnetic field points in the +y direction. An electric field is added to the region so that the electron travels in a straight line. Determine the direction and the magnitude of the electric field needed.

This last example is a very common type of problem, sometimes called a "cross field" problem. The AP test have something akin to this on it every year. These problems seem tricky, but once you understand them they are very simple. All you are doing is balancing out the Lorentz force with the electric force. The hardest part is to find the direction of the electric field by using the right hand rule and then taking the opposite, since you need to counteract it.

The first three examples were almost trivial, but they illustrate a previously discussed important result. The value of the cross product of $\underline{v} \times \underline{B}$ is directly dependent on how perpendicular $\underline{v}$ and $\underline{B}$ are in direction. It is a maximum when the two are perpendicular and zero when they are parallel (according to the sine function, which is in its definition). Some books explain this in the following illustrative explanation: The Lorentz force is dependent on how many field lines the velocity vector crosses. For the force to exist, the velocity must cross the field lines, the more it crosses, the greater the force. While not technically correct (can the astute student figure out why?) this explanation is a helpful way to visualize what is happening when a charged particle moves in a magnetic field.

Charged Particles in Magnetic Fields - Circular Motion

Consider the motion of a particle moving in a magnetic field so that its velocity is perpendicular to the field, as in example 9.4.2. We know that it will experience a force perpendicular to the velocity, and thus it will accelerate. However, since the force will <u>always</u> be perpendicular to its velocity, it will never speed up or slow down. If we think about this for a moment, we can see that the particle will move in a circle.

In fact, since the force is perpendicular to the velocity at all times, circular motion is the most common motion of a charged particle in magnetic field. Most of the time, if you inject a charge particle into a magnetic field, you will end up with circular motion.

> Example 9.4.6
>
> A charged particle of mass m, and charge q, is moving at velocity v along the x axis through a magnetic field B pointed in the +z direction. Derive an equation for the radius of the circular path and determine the plane of travel.

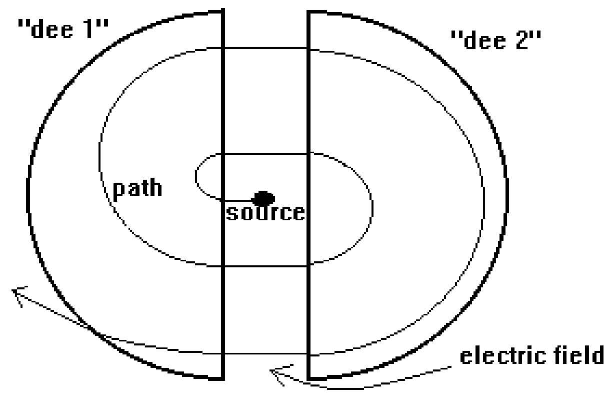
The equation derived above is a very important one, and we should take a minute to look at what factors affect the radius of the path. Notice how m and v are on top, thus more massive particles and faster moving particles will trace out larger circles (as one would expect) and particles with more charge or higher external fields will trace out smaller circles.

> Example 9.4.7
>
> An electron is fired from a device that uses a voltage to propel the electron into a 0.04 T magnetic field. It moves in a circular path with radius of 20 cm. What is the voltage in the device?

> Example 9.4.8
>
> A 0.8 mg, 0.3 mC charge is moving in a 10 cm radius circle in a magnetic field of 2 T. After 4 seconds, the radius has dropped to 4 cm due to collisions with other particles. What is the power loss in this situation?

Besides the basic problems discussed above, The Lorentz principle can be used to explain many different situations, especially in the area of particle physics. Particle physics deals with the behavior of very tiny particles, protons, neutrons, electrons and even the much smaller quarks. One common practice in particle physics is colliding particles (usually protons or electrons) and examining what arises out of the collision. Interestingly, when elementary particles collide, they often produce an array of exotic particles (kaons, muons, etc). in their debris. These exotic particles rarely last for more than a millisecond and then they decay into other particles.

In order to collide particles, it is necessary to bring them up to very high speeds and then either smash them into a target or another fast moving particle. One of the first devices used to accelerate particles up to high speeds was called the cyclotron. It consisted of two "dee" shaped areas that contained strong magnetic fields and a region in between that contained an electric field that could be switched in direction very quickly.

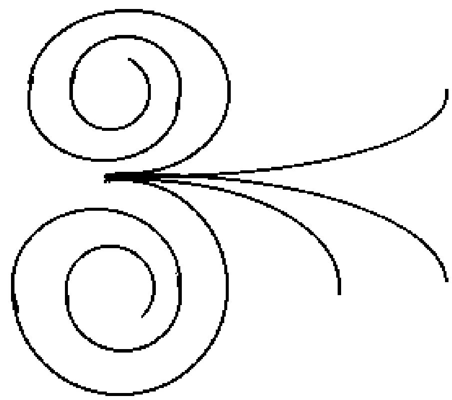


The source gives out a charged particle (proton, electron) and the electric field accelerates it into dee 1. Once in the dee, it is exposed to a magnetic field (out of the page for dee 1) that bends it back into the electric field. The direction of the electric field is switched and the particle accelerates again into dee 2 when a magnetic field (also out of the page) bends it back into the accelerating area. Notice how the particle is only gaining speed in the electric field. The dees are just there to make it pass through the region over and over again (actually many, many more times than have been drawn). Eventually its speed is so great that it leaves the dees altogether and can then collide with a target. There is one main problem with these devices. If the magnetic field is constant, the radius must be very, very large if high speeds (energies) are to be obtained. Creating and maintaining a magnetic field over a large half-circular area is simply impractical. The solution is called a Synchrotron. In such a device, the radius of the spiral is kept constant by varying the magnetic field. These devices are then circular tubes instead of full area circles. Today, many particle accelerators are in operation that use this principle. For example, Fermilab in Illinois has a circumference of 6.3 km.

The next example of how the Lorentz Principle is used in particle physics has to do with interpreting the results of a particle collision. Often the collisions are staged inside a magnetic field and the paths are traced by some sort of monitoring device (historically a chamber filled with gas that would condense behind the moving particles-called a bubble chamber, but these have been replaced by a more modern computerized version called a scintilization chamber). Knowing the magnetic field, certain properties of the particles themselves can be determined by their tracks.

Example 9.4.9

Discuss the motion and nature of the particles whose tracks through a magnetic field are represented below. The field points into the page.



Notice how only one aspect can be determined and the other two must be known (of the set m,v,q). In reality, q should either be +1 or -1 (unless you are dealing with quarks or large ions) and v can be determined by the measuring device. Besides the picture, scientists examining these collisions also use the conservation of mass/energy, the conservation of charge and the conservation of momentum to precisely determine the particles involved.

One final aspect of the Lorentz Force should be mentioned. All of our previous examples have dealt with particles that are moving in the plane of the magnetic field, or exactly at right angle to the field. If the particle is not, the path will not be circular. Consider a particle that is moving out of the page at a 45^0 angle and imagine a magnetic field that has field lines parallel to the page. In such a case the particle will spiral upwards contained in a cylinder of radius $(mv\sin 45^0)/qB$. (Why?) Exactly such a principle keeps the charged particles that enter the atmosphere from space locked in what is called the Van Allen Radiation Belt, an area of space full of spiraling charged particles.

Work in a Magnetic Field

If we consider a charged particle spiraling in a magnetic field, we might ask how much work the field is doing on the particle. This question leads us to an interesting conclusion. Since the force and the motion (whose direction is given by the direction of the velocity) are always perpendicular: the magnetic field is incapable of doing work on a charged particle. I encourage the student to remember this little fact and to think it over and be sure they understand why this is.

Practice Problems

Example 9.4.10

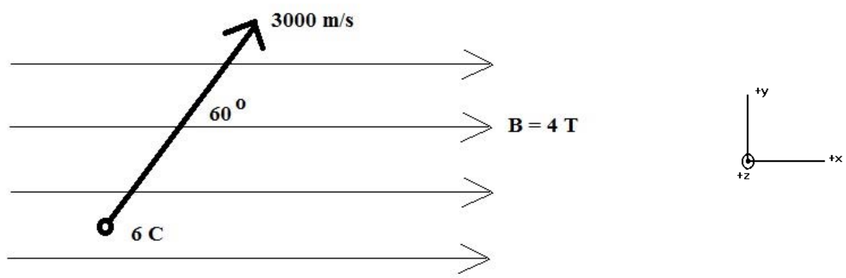
A magnetic field is pointed in the -x direction and a charged particle is launched in the -y direction. What is the direction of the Lorentz Force on the particle?

Example 9.4.11

A magnetic field is pointed in the +z direction and a charged particle is launched in the -x direction. What is the direction of the Lorentz Force on the particle?

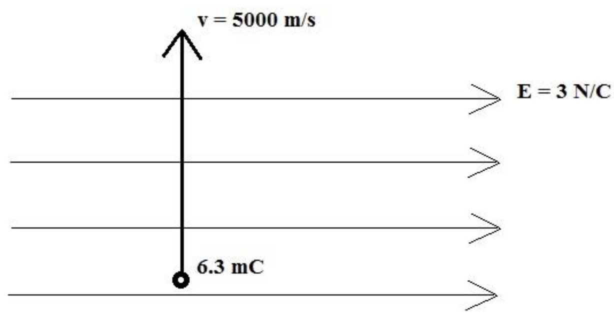
Example 9.4.12

What is the force (magnitude and direction) on the particle below? Give the direction according to the given coordinate system.



Example 9.4.13

A charged particle is traveling through a region with both a magnetic and electric field as shown below. If the particle travels in a straight line through the field, determine the magnetic field value and direction.



Example 9.4.14

An electron is fired into a 2 T magnetic field and begins orbiting with a radius of 25 cm. What is the kinetic energy of the electron in eV?

Example 9.4.13

An charged particle (mass = 75 mg, charge = 0.3 mC) is fired at 1,200 m/s into a 2 T magnetic field and begins its circular motion. If the power loss due to friction is 0.09 W, how long will it take for the particle's radius of orbit to decay to one half of its original value?

Homework Assignments

Assignment 9.2: Electric Potential Energy

1.) An electron is fired at 5,000 m/s into a uniform electric field of 1.6 N/C directed against its motion. How far does it go before coming to a stop?

2.) A 2.3 g particle charged to 0.5 mC enters a uniform electric field pointed in the same direction as it is moving. If the field lasts exactly 10 cm, what is the final kinetic energy of the electron when it leaves the field?

3.) A 2 C charge is fixed at the origin of a coordinate grid marked in meters. A second charge of 2 C is then brought from a great distance to (2,2). How much work was required to position this charge? The charge at (2,2) is then allowed to move freely to (3,3). How much has it's kinetic energy increased?

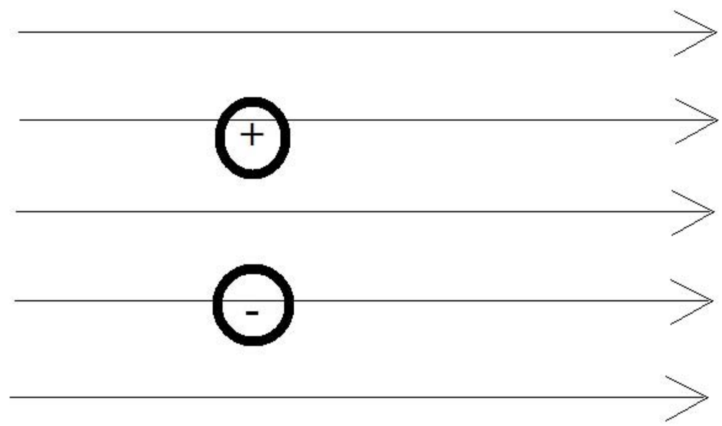
4.) Two negative charges are held together, 15 cm apart. The charge on the left has a charge of 3 C and a mass of 20 g, while the charge on the right is 2 C, 28 g. The charges are then released and fly apart. After a very great distance, what the speed of each particle?

5.) Consider a coordinate system marked in meters. The following steps are taken (in the listed order).

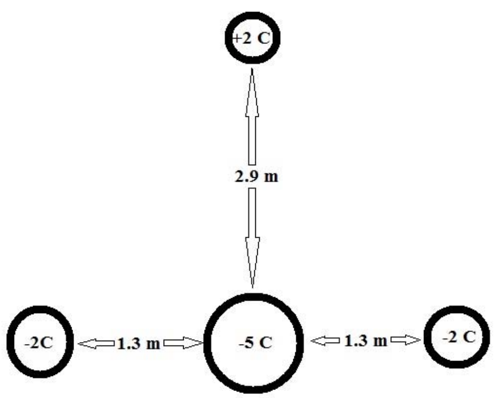
    1.) A 7 C charge is moved to the origin.
    2.) A -8 C charge is brought from far away and placed at (6,3)
    3.) A -9 C charge is brought from far away and placed at (0,4)

    Find the energy required to carry out each step and the energy required to assemble this arrangement of charges.

6.) A dipole made of two equal and opposite 1.3 C charges spaced 5 cm apart is placed in the uniform electric field (6 N/C) as shown below. How much energy is required to construct this arrangement, assuming that the uniform field has a distance of 125 cm?



7.) Find the energy required to construct the arrangement of charges below.



8.) Measuring atomic radii is a tricky business because of the way the electrons are spread in clouds around the nucleus. However, consider that an atom of copper has an approximate radius of 1.28×10^{-10} m. Ignoring the presence of the other electrons, how much energy would be required to remove the last electron from a copper atom? How does this compare to the ionization energy of copper (1.237×10^{-18} J). What is the percent error? Using the given value of the ionization energy, what is the effective value of the charge of the nucleus considering the shielding effect of the other electrons?

9.) Applying simple electrostatic principles to atoms rarely (if

ever) yields accurate results because of the quantum nature of electrons and the resulting difficulty in assigning them a meaningful location around the atom. Nevertheless, consider the following (crude) approximation technique for calculating ionization energy:
Assume that the ionization energy of an atom is equal to the electrostatic work required to remove an electron totally from orbit. Approximating the entire nucleus and the shielding electrons as a point charge with a positive charge of 0.75e located entirely at the center of the atom and calculating the work required to remove the last electron yields fair results for a number of elements.

a.) Why is the effective charge less than the charge on one proton, regardless of what atom you are considering?
b.) What would be the first ionization energy for silver using this method?
c.) What percent error does this yield?
d.) What would be the second ionization energy for silver using this method? What is the percent error?
e.) Which is a better approximation, the first or the second ionization energy? Why?
f.) Can you determine a better approximation for the second ionization energy?

Necessary information:
Atomic radii of silver: 1.44×10^{-10} m
Ionic radii of silver: 1.26×10^{-10} m
First ionization energy: 1.21×10^{-18} J
Second ionization energy: 3.44×10^{-18} J

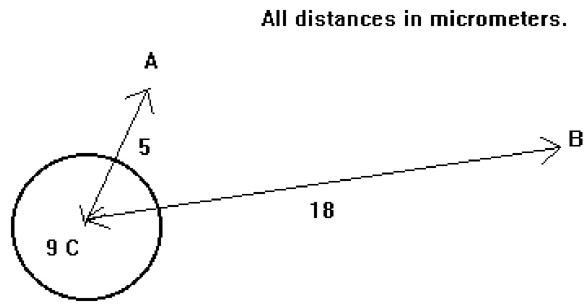
Homework 9.3 - Potential

1.) Find the average value of the electric field (E) between two points 0.5 cm apart that are at a potential difference of 6 V.

2.) If a charge of 34e moves across a potential difference of 9 V, how much energy does it gain ? (remember: Work = Energy) Give your answer in both units of energy.

3.) Imagine a Cartesian coordinate system with a charge of 7e located at the origin. Determine (a.) the potential at point (0.2 μm,0 μm), (b.) the potential at (0.3 μm,0.4 μm), and (c.) the potential difference between the two points.

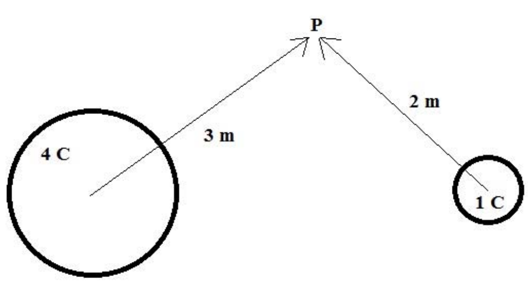
4.) What is the voltage difference (potential) between points A and B below ?



5.) Consider two charges placed on a coordinate grid, one at point (0,0) and the other at point (3 m,4 m). If the first has a charge of 3 mC and the second has a charge of 5 mC, what is:

a.) the force on the 5 mC charge?
b.) the force on the 3 mC charge?
c.) the electric field the 5 mC charge experiences?
d.) the electric field the 3 mC charge experiences?
e.) the electric field at point (2,2) due to the 3 mC charge?
f.) the electric field at point (2,2) due to the 5 mC charge?
g.) the complete electric field at point (2,2), including direction.
h.) the voltage at (3,4) if the 5 mC charge was not there?
i.) the work done in placing the 5 mC charge at point (3,4)?
j.) the work needed to move the 5 mC charge from (3,4) to (2,3)?

6.) What is the potential at the point labeled P below?



7.) Three charges, two with a charge of -0.4 mC, and one with a charge of +0.4 mC, are arranged in an equilateral triangle with sides of 12 cm. Find a.) the voltage at the center of the triangle, and b.) the energy required to construct the arrangement.

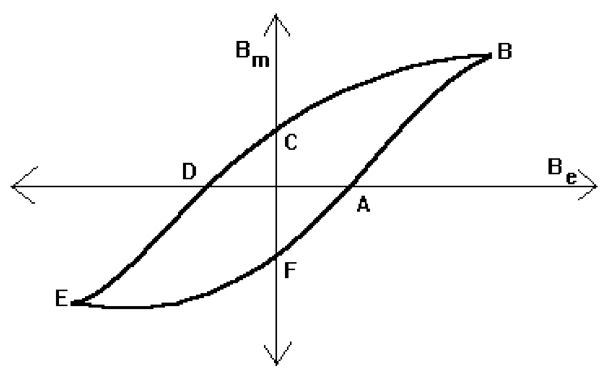
8.) Using logic and best guesses, draw the equipotential lines or surfaces around a.) a thin wire charged with a uniform linear charge density, and b.) a thin, flat, metal square that is charged negatively.

Homework 9.4 - Magnetism

1.) Two charged particles move in concentric circles in a B-field and have the same mass and velocity. If the radius of particle A's path is one half the radius of particle B's path, what relationship exists between their charges ? (B5)

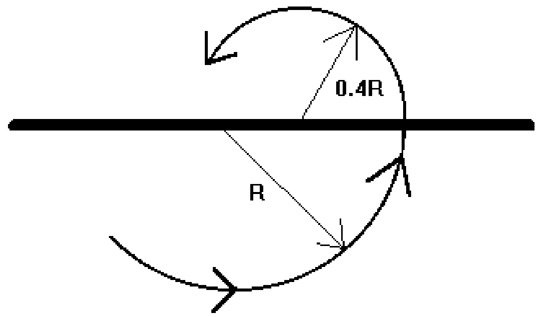
2.) If a charge of 18 C moves at a speed of 9 m/sec through a magnetic field of 6 T at an angle of 35 degrees, what force does it feel ? (B11)

3.) On the hysteresis curve below, which section, point or points represent:
   a.) The material producing no magnetic field?
   b.) The external field having no value, but the material producing a field?
   c.) The material going from producing a field pointing in the negative direction to producing a field in the positive direction?
   d.) The external field pointing in the negative direction while the material produces a field in the positive direction?



4.) Suppose a particle moves in a magnetic field as shown below. After the particle has completed half a circle, the field suddenly changes. It the new radius (R_2) equals $1.5R_1$, what is the new value of the field compared to the old value?

5.) A proton moves in a magnetic field as shown below. The dark section is a thin film (of negligible depth) that causes the proton to give up some of its energy. What percent of its energy was lost in the film?



6.) A proton in a magnetic field circles with a radius of 10 cm. If the proton has an energy of 150 MeV, what is the strength of the field?

7.) A proton moves in a straight line path through a region which contains both a magnetic and electric field. If the electric field points to the right, the velocity of the proton is 1.5×10^{7} m/sec upwards and the magnetic field has a magnitude of 2 T, what is (a.) the direction of the magnetic field, and (b.) the value of the electric field?

8.) An unknown particle circles in a magnetic field of 4 T with a radius of 35 cm. Determine an equation that must be satisfied regarding the particles mass, charge and energy. (i.e. an equation containing only numbers and the three allowed variables: m, q, E)

9.) Imagine that a proton is moving across a magnetic field of 3 T, making a circle of radius 10 cm at t=0. After 200 revolutions, the radius has dropped to 9 cm. What is the rate of energy loss the proton is undergoing? You may use 9.5 cm as an average radius to calculate the distance traveled and the average of the beginning and ending velocity to calculate the time.

10.) Decipher: "Exclusive dedication to necessitous chores without interlude of hedonistic diversion renders John a hebetudinous fellow." (DNCTHWG)

Activities and Labs

Activity 9.1 - Mapping Magnetic Fields

In this activity you will use a compass and bar magnets to map out the magnetic field around magnets. Since we have learned that a dipole will always align itself with a field, wherever we place the compass it will point along field lines.

Procedure:

1.) Place a blank sheet of paper on the table and place a single bar magnet in the center.
2.) Place the compass on the table near the magnet and put a dot at each end of the compass needle.
3.) Move the compass until the south tip of the compass points directly at the dot you made in step 2 for the north end of the compass.
4.) Dot both ends of the compass.
5.) Continue this procedure until the line you are making either goes off the page or back into the magnet.
6.) Connect all the dots with a smooth curve.
7.) Repeat this procedure about six times, or until the field pattern becomes obvious.
8.) Now repeat the entire activity with two more different combinations and positions of magnets.

Lab 9.1 - Strength of Magnetism

In this lab, you will measure the strength of repulsion between two magnets at different distances and attempt to determine the mathematical relationship between the magnetic force and distance.

Materials: two neodium magnets, clear plastic tube that just fits the magnets, lead weights, ruler.

This lab will be accomplished by securing the plastic tube to the table and putting one magnet at the bottom of the tube. The other magnet will then be placed in the tube so that it repels from the other magnet, being suspened. The distance between the two magnets will be measured, then weights will be added on top of the second magnet to achieve different distances between the two.

Procedure:

1.) Set up the tube securely, using ring stands and clamps and place the first magnet at the bottom.

2.) Using the most accurate and precise balance availiable, find the mass of the second magnet. Record the mass as the first trial.

3.) Place the second magnet in the tube so that it is suspended above the first.

4.) Measure and record the distance between the two magnets.

5.) Add weights on top of the second magnet, until the distance decreases. Record both the total mass and the distance.

6.) Repeat the above procedure until you have 10 data points. Try to make the interval between the distances even, not the differences between the masses.

Total Mass	Measured Distance	Force Between Mags

Hints on Conclusions: Your goal is to determine the relationship between the magnetic force and distance. What is that relationship? Is this what was expected? Did we study anything in a previous chapter that might have led you to believe the relationship should have been something specific? Does this relation hold for other magnets? What are the restrictions on this relationship holding for other situations? In what ways could this experiment be made more accurate? What were the factors that affected the overall accuracy of the experiment? Can you use this information to determine an equation of a kind similar to NULG or Coulomb's law? Why or why not? There is one constant that you know should be present in a magnetic equation, can you use it to determine an appropriate equation?