# 3–20 Magnetic Fields

**Magnetism**: Magnetism is the result of spinning or moving charges. Each electron and proton acts like a tiny magnet. In most substances the protons and electrons balance each other in a manner that cancels the atoms overall magnetism. But in some substances like iron there is an imbalance that is not cancelled. In these substances the atoms act like tiny magnets. If a group of these atoms line up with all their north poles in the same orientation the group or domain acts like a larger magnet. If the smaller domains all line up in a bar of iron, for example, then the entire bar behaves as a magnet, with a north pole and a south pole. It is similar to electricity, where unlike poles attract, and like poles repel. It is different from electricity since, separate poles cannot exist by themselves. Magnetism and Electricity are interconnected. Electric fields can influence magnets, and magnetic fields can influence moving charged particles and current carrying wires.

**Magnetic Field Direction In Relation to Fixed Magnets:** The magnetic field $B$ comes out of a north pole (like $E$ comes out of + charges) and goes into a south pole (like $E$ goes into – charges). It must leave and enter the poles perpendicular to the surface of the magnet. The magnetic field direction is defined as the direction a north needle of a compass points. The north needle points away from north and towards south. So the Earth's magnetic south pole is located near the Earth's geographic north pole. $B$ is a measure of magnetic field strength, and is analogous to $E$ for electric fields, and $g$ for gravitational fields.

## The Magnetic Field Around a Current Carrying Wire (Right Hand Rule, Case 1)

A current carrying wire generates a magnetic field around it. The direction of the field is the direction the fingers curl around the wire if the thumb points in the direction of the positive current. The strength of the field is represented as follows: $\boxed{B = \frac{\mu_o}{2\pi}\frac{I}{r}}$ This measures the field of a wire carrying a current $I$ at a point in space a distance $r$ from the wire. This formula involves $r$. Remember that $r$ is used when a field radiates outward from a central source. In electricity radial field are generated by spherical point charges. In gravity radial field are generated by spherical point masses, such as planets. This field radiates out from the wire as shown above right. If you calculate $B$ at point P using the formula above you have also calculated $B$ at any point on the equipotential circle that P lines on. In fact you have calculated $B$ any point on a cylinder surrounding the wire at a radius $r$.

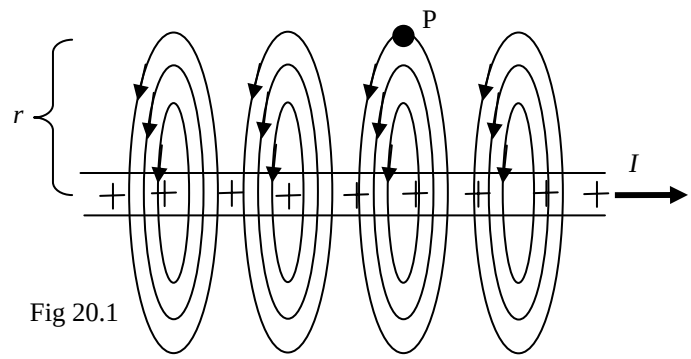

Fig 20.1

**What about direction?** This is a three dimensional problem, that is diagrammed on paper. You can only diagram what is happening in the plan of the page above and below the wire. We are working in a third dimension and must select a convention for depicting the magnetic field along the $z$-axis. Since $B$ is a vector we will use an arrow (traditional vector symbol), Fig 19.2. When this arrow is coming at you, you will see the point. So positive $z$ is depicted as dot or circled dot. When this arrow is going away from you, you will see the feathers. So negative $z$ is depicted as an $\times$ or a circled $\times$.

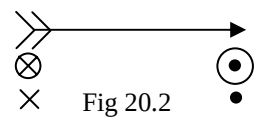
Fig 20.2

Using this convention the field around a carrying wire (Case 1) would look like Fig 19.3.

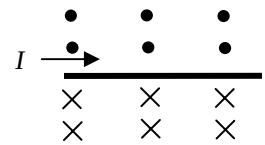

Fig 20.3

### Example 6-1: Superposition of Magnetic Field due to Current Carrying Wires

**Calculate the magnetic field caused by two crossed current carrying wires at point P in Fig 19.4.**

$$B = \frac{\mu_o}{2\pi}\frac{I}{r} = \left(2\times10^{-7}\right)\frac{(2)}{(0.1)} = 4\times10^{-6}T\ ,\ +z$$

$$B = \frac{\mu_o}{2\pi}\frac{I}{r} = \left(2\times10^{-7}\right)\frac{(3)}{(0.05)} = 1.2\times10^{-5}T\ ,\ -z$$

Add vectors: $\left(+4\times10^{-6}\right)+\left(-1.2\times10^{-5}\right) = -8.0\times10^{-6}T$

so it is $\boxed{8.0\times10^{-6}T,\ -z\ direction}$

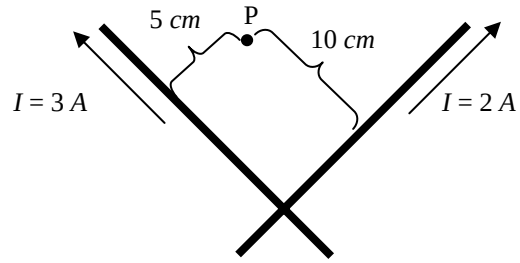

Fig 20.4

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## The Force of Magnetism on Charged Particle (Right Hand Rule, Case 2)

Charged particles are spinning and generate their own magnetic field and behave like tiny magnets. If you fire them between two large fixed magnets they will be interact with the larger magnetic field. When fields interact there is force. The force is equal and opposite, as always. The fixed magnets attract the particles, just as the particles are attracted to the fixed magnets.

$\boxed{F_B = qvB\sin\theta}$ Force on a charged particle (small $q$, point charge) traveling (velocity, $v$) in a magnetic field ($B$). You can drop $\sin\theta$ if you know the angle is 90°. ***This force is only felt on the component of velocity perpendicular to the field***. The angle $\theta$ is the angle between the particles velocity and the magnetic field that it travels in. In the example to the right the magnetic field is represented by arrows pointing in the $-y$ direction. Particles A and B experience no force since they have a $\theta$ equal to 0° and 180°. Particle C experiences the most force (if all particles entered the field at the same speed) since $\theta = 90°$. Particle D will have a force equal to the component of its velocity that is perpendicular to the field. Make sure thatthe problem gives you the correct angle, between the particle velocity and the magnetic field. Problems often try to give the wrong angle to see if you are awake.

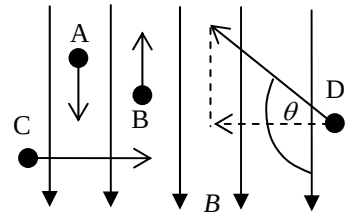

Fig 20.5

$\mathbf{F}_B = q\mathbf{v}\times\mathbf{B}$ is a cross product of vectors. In a cross product the greatest value is obtained when the vectors are perpendicular, allowing $\sin\theta$ to reach its largest value of 1.

**Take another look at the problem on the previous page**: The field $B$ is going into the page (-$z$) at point P. If a positive charge $+q$ is at this point and has an instantaneous velocity of $5\text{x}10^4$ *m/s*, what is the magnitude and direction of force on the particle?

$$F_B = qvB = \left(1.6\times10^{-19}\right)\left(5\times10^{4}\right)\left(8.0\times10^{-6}\right) = \boxed{6.4\times10^{-20}\,N,\ +y\ direction}$$

**Direction the Particle Will Deflect:** Use the right hand rule for positive charge and the left hand for negative charge. The charged particle will follow the right hand rule: The thumb is the charged particles velocity, the extended fingers represent the magnetic field, and the palm slapping represents the force that causes the charged particle to change direction. Remember if a force hits you from behind and parallel to your motion, you speed up. If a force hits you from in front and parallel to your motion you slow down. If a force hits at a right angle to your motion, you change direction (either projectile motion, or circular motion depending on the field). A positive charge is fired into a field in Fig 19.6. The field $B$ extends into the page, -$z$. Use the right hand rule tracing the path of the particle with the thumb, and keeping the fingers into the board. It traces a semicircle with the palm $F_B$ pointing to the center of the circle.

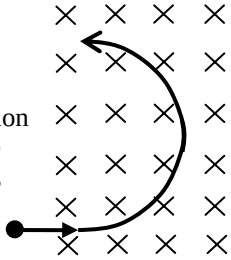
Fig 20.6

$F_C = F_B$ $\boxed{m\dfrac{v^2}{r} = qvB}$ we can drop $\sin\theta$ since all vectors are 90° apart

**A charged particle flying in a magnetic field will move in a *<u>circular path</u>*. All vectors are perpendicular to each other. The force on a charged particle in a magnetic field is always perpendicular, so *<u>no work is done</u>* in this case.**

## Charges Accelerated Through a Potential Difference that Subsequently Enter a Magnetic Field

$\boxed{qV = \frac{1}{2}mv^2\ \ (not\ given)}$ In the electric field a charge $q$ is accelerated through a potential difference. It then enters a magnetic field. In this case an electron is accelerated through the potential difference. So you use the left hand to find the direction of the charge once it enters the magnetic field. ***The direction is clockwise***. The force causing the electron into circular motion is $F_E$. $F_C = F_B$ which leads to $\boxed{m\dfrac{v^2}{r} = qvB\ \ (not\ given)}$. Also the electron has a tangential velocity of $\boxed{v = \dfrac{2\pi r}{T}\ \ not\ given}$ and a centripetal acceleration of $\boxed{a_c = \dfrac{v^2}{r}}$.

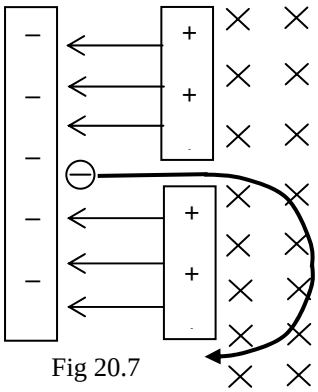
Fig 20.7

While work is done accelerating the electron (force through a distance) by the electric field, no work is done on the electron while it is in the magnetic field. Substituting 90° into the work equation $\boxed{W = F\cdot s\cos\theta}$ gives an answer of $\boxed{W = 0}$. At any instant the direction of motion (tangent) is perpendicular to the center seeking force $F_B$.

**What would a proton do?** The opposite. In the above scenario the proton would circle counter clockwise. The particle experiencing the motion can be switched, the plates & electric field can be switched. Also the magnetic field could

be draw out of the paper. Be prepared for anything. Use the right hand for positive charges and the left for negative charges. Analyze the situation carefully!

## The Force of Magnetism on Current Carrying Wire (Right Hand Rule, Case 3)

Note that this is different from case 1. In case 1 we dealt with the magnetic field created by and surrounding a current carrying wire. In this scenario we will put a wire into a magnetic field created by two large fixed magnets. Then we will turn the current on. The wire will then turn into a magnet as well. The magnetic field of the fixed magnets will then interact with the magnetic field of the current carrying wire. When fields interact there is a force. The force will be equal and opposite, but the larger magnetic field is created by fixed magnets. The smaller field will be in a wire which is free to move. So the larger fixed field will cause the wire to jump. This is the basis for the electric motor and for stereo speakers.

$\boxed{F_B = BI\ell\sin\theta}$ is the force of a large fixed magnetic field on a current carrying wire where a length $\ell$ of the wire is in the larger magnetic field. Use $\sin\theta$ as above.

**Direction the Wire Will Deflect**: Use the right hand rule for positive current and the left hand for negative current. Use the right hand rule in Fig 19.8. The thumb is the direction of charge movement, as before, except now it is charges $Q$ moving in the wire to create a current $I$. So the thumb is the direction of positive current $I$. The fingers are held straight and are the direction of the magnetic field as before. The direction the palm will slap is the direction of the force magnetic $F_B$. For negative current use the left hand.

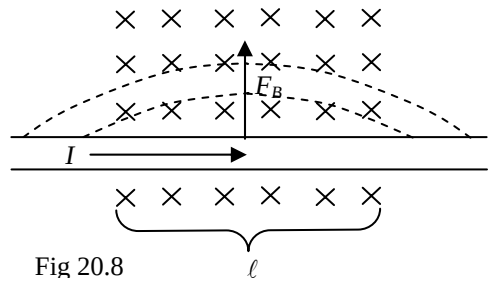

Fig 20.8

**Calculus:** $\mathbf{F} = \oint I d\ell \times \mathbf{B}$

## Electric and Magnetic Fields in the Same Location

In some problems a region of space will hold an electric and a magnetic field. Typically the electric plates that generate the electric field $E$ are drawn, while the magnets that create the magnetic field $B$ are located out of and into the page. In this orientation the magnetic field is either in the +z or – z direction, while the electric field is in either the +y or –y direction. But, you can expect other variations of this configuration. Lets follow a charge particle that enters this dual field.

A proton traveling through the charged plates as configured would normally experience projectile motion. The electric field extends downward from the positive plate to the negative plate (direction a positive test charge would move). But, in this problem the proton continues in a straight line. Since the force of the electric field is in the y direction, we should sum our forces in this direction.

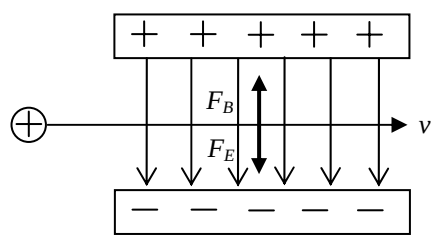

Fig 20.9

$\sum F_y = -F_E + F_B$ The other force that is countering force electric is force magnetic, since this problem deals with two overlapping, but different fields. It is not moving in the y direction so the sum of force must be zero.

$0 = -F_E + F_B$ $\quad \boxed{F_E = F_B}$ $\quad qE = qvB$ $\quad \boxed{E = vB}$

### Example 20-1: Combining Some of the Key Problems into One

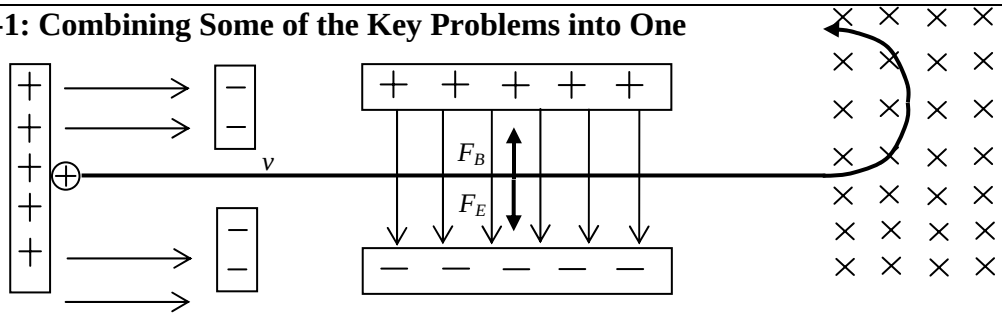

Fig 19.10

$qV = \frac{1}{2}mv^2$ $\qquad F_E = F_B$ $\qquad F_C = F_B$

$\boxed{v = \sqrt{\frac{2qV}{m}}}$ $\qquad qE = qvB$ $\qquad m\frac{v^2}{r} = qvB$

***v* is constant for the rest of the problem.** $\quad \boxed{E = vB}$ ***B* is in *-z*-direction** $\quad \boxed{B = \frac{mv}{qr}}$

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