EM III: Magnetism and Lorentz Force

FIZIKA SJPO Training

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Contents

1 Magnetism

1.1 Magnetic Fields

In the previous topics, when we studied electricity, we used the idea of an electric field. That is, something sets up an electric field, and a something else (a charge) interacts with the field. For magnetism, this idea also holds to an extent. Looking at how our compasses interact with the Earth's magnetic field, we can say that the Earth sets up the magnetic field, while the compass interacts with it to point North.

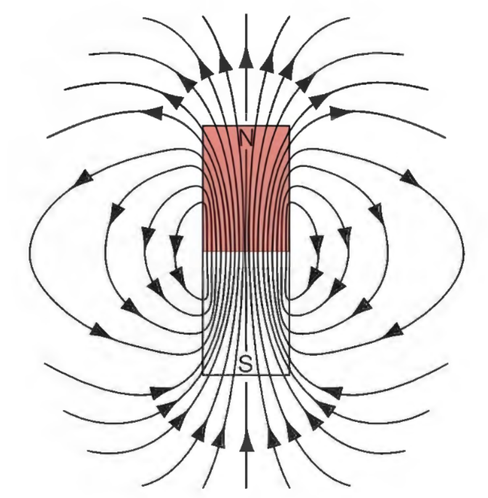
However, compared to the electric field, the magnetic field has several important differences. Here are some of them.

1. Charges feel an electric force in an electric field, but only feels a magnetic force when it is **moving perpendicularly** to a magnetic field. **Stationary** charges thus **do not** feel a magnetic force.

2. Similarly, while static charges can create an electric field, only moving charges (currents) can create an magnetic field.

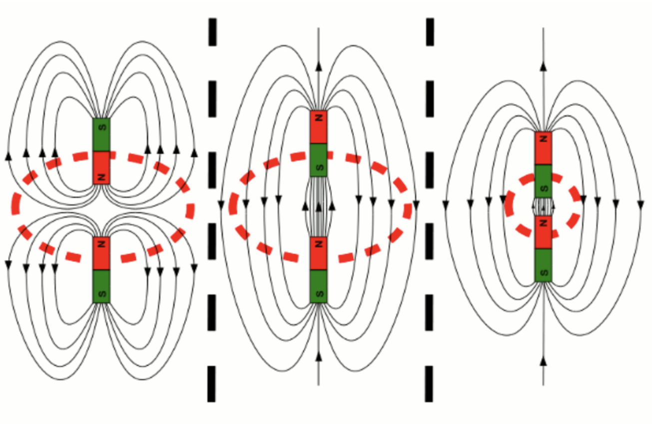
3. Electric fields can start and terminate from a source, but magnetic fields cannot start or end. Instead, it forms loops. This means that there is no magnetic monopoles (and thus no magnetic analogue to electric charges).

Let us look at how a magnetic field from a typical magnet looks like.



By convention, outside the magnet, the end where the magnetic field lines exits the magnet is the North pole, while the end where the magnetic field lines enters the magnet is the South pole. Since magnetic field lines have to form a continous loop with no start or end, inside the magnet, the magnetic field is from south to north.

Like poles repel, and unlike poles attract. This makes sense when you look at the following diagram. Like electric fields, magnetic field lines repel each other as well as try to minimise their length.

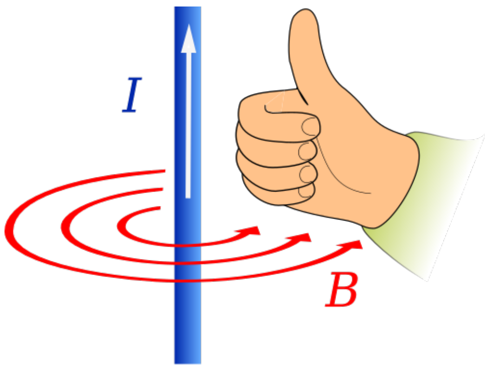


A magnetic field cannot really be visualise by putting some "magnetic" test charge in the field like electric fields. This is because magnetic test charges do not really exist. Instead, we can visualise magnetic fields with small test compasses, which would align to the magnetic field.

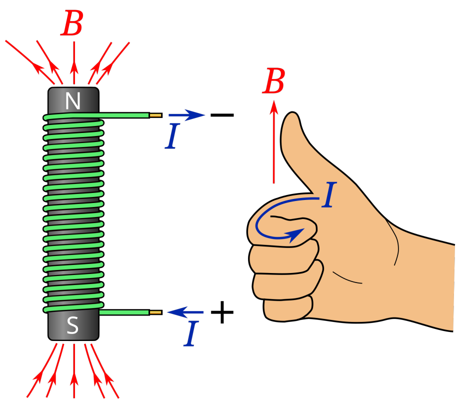
Going back to our example of compasses, the North pole of a compass points to the North. However, since unlike poles attract, and South poles attract North poles, the geographic North pole of the Earth is then the magnetic South pole of the Earth. (Yes this is a little confusing)

We usually call the magnetic field the **B** field. However, some people call the **B** field the magnetic flux density. In this set of notes we will just call the **B** field the magnetic field.

Another common magnetic field you will see is the magnetic field generated from a current carrying straight wire. A straight wire generates a circular magnetic field that is perpendicular to the current at all times. You can memorise the direction by aligning your thumb to the direction of the current, and the way your fingers curl is the direction of the magnetic field.



Lastly, a magnetic field similar to a permanent magnet can be generated by a solenoid, or a long coil of wire. To get the direction of the current in order to generate the magnetic field, you can use your right hand again. The direction of your thumb is the direction of the magnetic field while the direction your finger curls in is the direction of current.

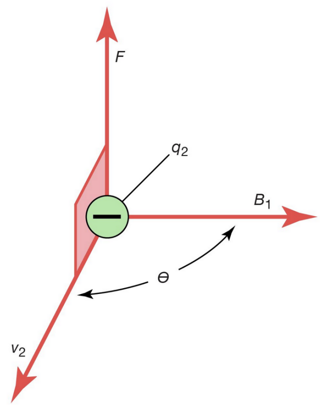


1.2 Lorentz Force

When a charge moves in an magnetic field, it experiences a magnetic force. If there is a also a electric field (and thus electric force) present, the net effect is known as a Lorentz force.

$$\mathbf{F} = q\left(\mathbf{E} + \mathbf{v} \times \mathbf{B}\right) \tag{1}$$

F is the magnitude of the Lorentz force, q is the amount of charge, v is the velocity of the charge, E and B are the strengths of the electric and magnetic field respectively. Note here that the cross product $\mathbf{v} \times \mathbf{B}$ means the magnetic force always acts perpendicular to the direction of motion, and to determine its magnitude we only care about the component of velocity perpendicular to the magnetic field.

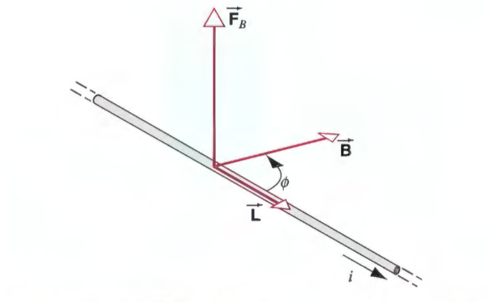


Suppose the B and the v are at an angle of θ with each other, the magnetic force is then $F = qvB\sin\theta$.

Similarly, we can look at a straight current-carrying wire in a magnetic field. Since current $I = q/t$ and the velocity of charges $v_\perp = l_\perp/t$, we have

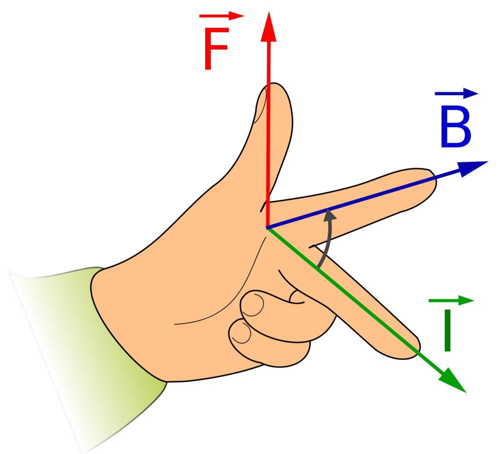
$$F_B = qv_\perp B = \frac{ql_\perp B}{t} = Il_\perp B \tag{2}$$

l is the length of the wire.

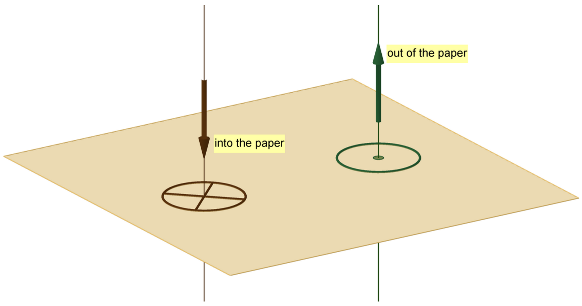


Here, the current I and B has to be perpendicular. If they are not, you have to take the component of I or B that is perpendicular to the other quantity.

These equations give us the magnitude of the Lorentz force, but not the direction. To obtain the direction, we can use the **left hand rule**. Orient your left hand to the configuration below, and your thumb will be the direction of the force, your index finger will be the direction of the magnetic field, and your middle finger is the direction of current. You can memorise the order using the mnemonic "FBI".

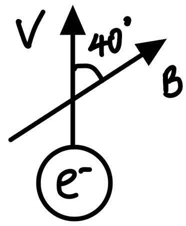


As you can see, magnetism is heavily 3-dimensional, with the force, current and field all pointing perpendicularly. As such, we need to develop a system to describe these directions on your paper. In the plane of the paper, each direction on your paper is described as "up", "down", "left" and "right". We then describe the other directions as "into the page" and "out of the page". Please keep to using these phrasing because saying something like "the magnetic field points to the top" is ambiguous because it could either mean up or out of the page.



Example 1.1. An electron with speed 1 ms^{-1} moves in an uniform magnetic field of strength 1 T. What is the magnitude of the force on the electron? What is the direction of the force? The

fundamental charge is 1.60×10^{-19}.



Solution. To obtain the magnitude, we use $F = qvB\sin\theta$. Plugging in the values, we get 1.03×10^{-19}.

To obtain the direction, we use the Left Hand Rule. The component of B points to the right, and the current points **downwards** as the charge is negative. So, the force is upwards.

Example 1.2. The magnetic field created by a straight wire is given by

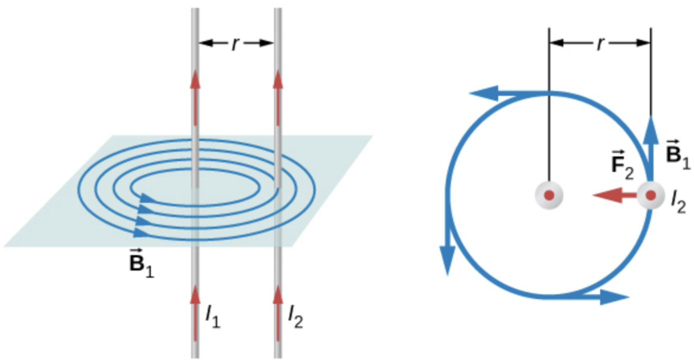
$$B = \frac{\mu_0 I}{2\pi r} \tag{3}$$

We will derive this equation later.

What is the force between 2 straight wires of 1 m carrying 1 A of current upwards, seperated by a distance of 1 cm? Is this force repulsive or attractive? Permeability of vacuum is 1.26×10^{-6}.

Solution. In the plane of the paper where the wires exist, the direction of the magnetic field is either into or out of the page. Hence, it is always perpendicular to the direction of the current in the other wire, so the magnetic force is simply $F = BIL$, where B follows the equation given in the question. Combining both equations, we get

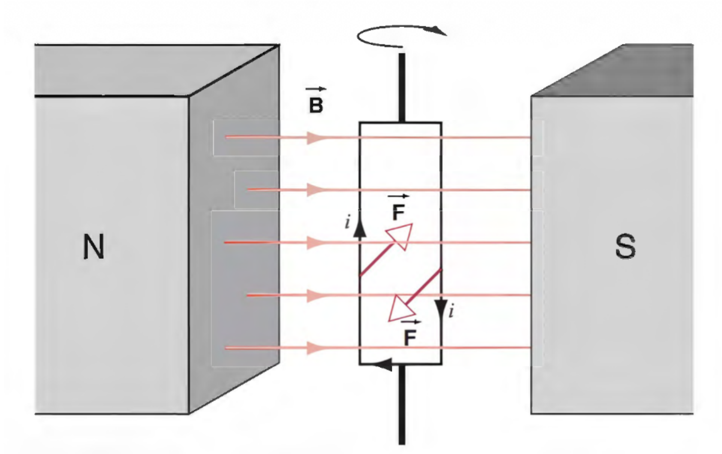
$$F = \frac{\mu_0 I^2 L}{2\pi r} = \frac{\mu_0 I^2 L}{2\pi r} = \frac{1.26 \times 10^{-6}(1)^2(1)}{2\pi(1 \times 10^{-2})} = 1.26 \times 10^{4} \tag{4}$$



Now we deal with the direction of the force. Let's observe the force on the right wire, which is caused by the magnetic field generated by the left wire. At the right wire, the direction of the magnetic field is into the page. Thus, by the Left Hand Rule, the force on the right wire is to the left. You can do the same and look at the force on the left hand side, and realise that the force points to the right. So this force is attractive.

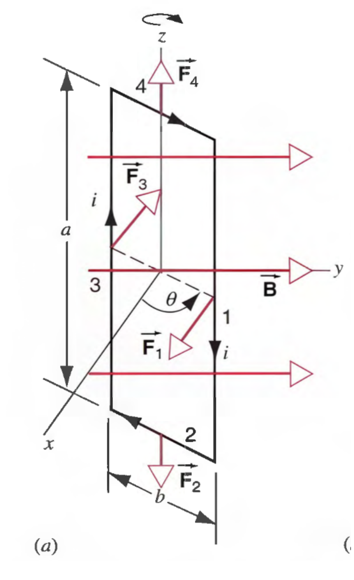
If I reverse the direction of one of the wires, the 2 wires would then repel instead of attract.

Example 1.3. An electric motor works by running current through a rectangular loop of wire, and placing the rectangular loop of wire in an external, uniform magnetic field B. Suppose the current in the loop is I, the length of the loop is a and the breadth is b, and the angle at which the rectangular loop is at with respect to the B field is θ. What is the torque on the motor as a function of θ?.



Solution. The current running through the breadth of the wire is useless because no matter how you rotate the loop, it is always parallel to the magnetic field, thus it experiences no force. So, only the current running through the length matters. This current is always perpendicular to the magnetic field, so the force on this part of the loop is $F = BIa$. What is more important though, is the direction of this force. Looking at the diagram, for the left part of the wire, the force points into the page, and for the right part of the wire, the force is out of the page.

However, to calculate the torque, the force vector has to be perpendicular to the moment arm. Here, it is not always parallel. Imagine if the wire loop is rotated such that it is perpendicular to the magnetic field. The force vector and the moment arm (breadth of the wire loop) would be parallel! So there is no torque generated.



Thus, to account for the changes in the moment arm when θ changes, the torque from both parts of the wire is

$$\tau = (2)\left(\frac{1}{2}\right) bBIa\sin\theta = BIab\sin\theta = BIA\sin\theta \tag{5}$$

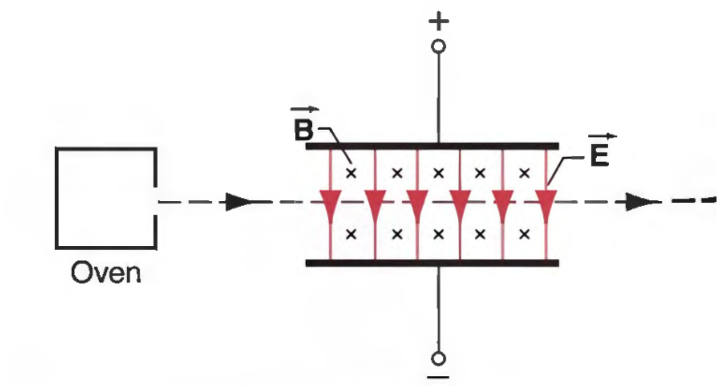
We defined $A = ab$ as the area of the loop.

Now that we have looked at the basics of magnetic fields, we can look at several applications of magnetic fields.

1.3 Electric Fields and Magnetic Fields

A charge can experience an electric force and a magnetic force at the same time. Gravitational forces are not included because it is negligible due to the small mass of charges. These forces are added up with normal vector additions. One interesting application of these 2 forces is a velocity selector.

Example 1.4. An experiment is set up as follows.



Protons of varying velocity passes through the regions of constant electric and magnetic fields. Find the expression for the velocity of the proton when the proton is not deflected.

Solution. Using the left hand rule, the direction of the magnetic force is upwards. The direction of the electric force is downwards. The electric force is constant, since it only depends on the charge and the electric field, and both are constants. The magnetic force however, depends on the velocity of the charged particle. Thus, if the proton is very slow, the electric force is higher than the magnetic force, and the proton is deflected downwards. If the proton is very fast, the magnetic force is higher than the electric force, thus the proton is deflected upwards.

To find the speed where the proton is not deflected, we equate the magnetic and electric forces.

$$qvB = qE \tag{6}$$
$$vB = E \tag{7}$$
$$v = \frac{E}{B} \tag{8}$$

1.4 Magnetic Fields and Circular Motion

The Lorentz force always points perpendicularly to the velocity of the charge. This is very convenient for circular motion, because for a particle to undergo circular motion, the particle must also experience a centripetal force that is perpendicular to its velocity. As such, the Lorentz force is a great candidate for the centripetal force.

Example 1.5. A proton undergoes circular motion in a magnetic field of strength 0.1 T, with speed 0.0002 ms^{-1}. What is the radius of this circular motion? The fundamental charge is 1.60×10^{-19}, and the mass of a proton is 1.67×10^{-27}

Solution. Equating the centripetal force to the magnetic force.

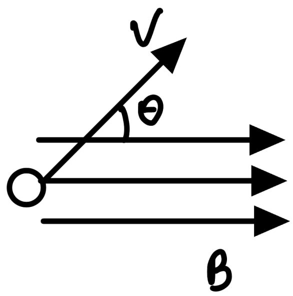
$$\frac{mv^2}{r} = qvB. \tag{9}$$

Dividing both sides by v and solving for r, we get

$$r = \frac{mv}{qB} = \frac{(1.60 \times 10^{-19})(0.002)}{(1.67 \times 10^{-27})(0.1)} = 1.9 \times 10^6 \tag{10}$$

However, what if there is a component of velocity in the direction of the magnetic field? Since the force points perpendicularly to the velocity and field, the direction of the force is unchanged. Thus, this is exactly the same motion as a circular motion except you have a component of velocity in the direction of the field! Let's illustrate this idea with an example.

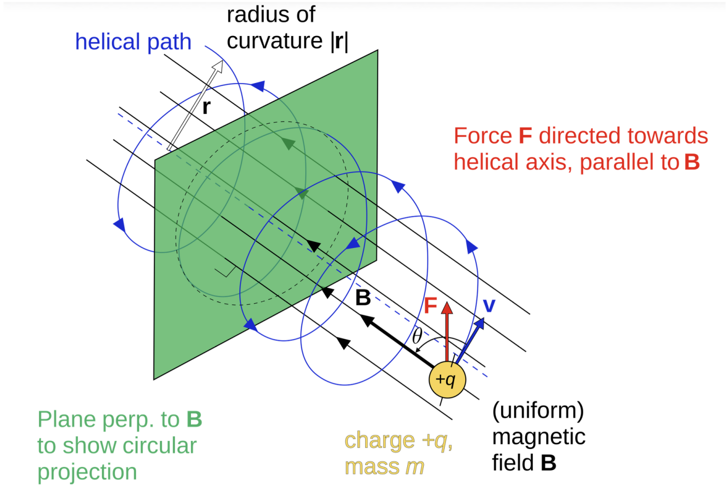
Example 1.6. A point charge with charge q is released with initial velocity v, in a direction that is θ degrees from the magnetic field of strength B. (a) Describe the motion of the point charge. (b) Find the radius r, period T, and pitch p of the motion.



Solution. (a) Since the velocity and magnetic field is not parallel, there is a magnetic force. By the left hand rule, this force points into the page (if the charge is positive). Let us focus on the component of velocity perpendicular to the magnetic field, which points upwards. With the velocity upwards and the force into the page, the charge undegoes circular motion.

Looking at the velocity parallel to the field, since there is no magnetic force, the charge continues moving parallel to the field with constant speed.

Adding up the effects of both the parallel and perpendicular components of velocity, we can see that the overall motion of the charge is a helix.



(b) To find the radius, we equate the magnetic force to the centripetal force.

$$\frac{m(v\sin\theta)^2}{r} = qvB\sin\theta \tag{11}$$

Rearranging,

$$r = \frac{mv\sin\theta}{qB} \tag{12}$$

To find the period T, we can find the time taking for the charge to complete 1 cycle.

$$T = \frac{2\pi r}{v\sin\theta} = \frac{2\pi m}{qB} \tag{13}$$

To find the pitch, we take the period, and find the distance the charge has travelled in the direction of the field.

$$p = vT\cos\theta = \frac{2\pi mv\cos\theta}{qB} \tag{14}$$

1.5 Ampere's Law

Ampere's law allows us to get equations for magnetic fields just like how Gauss's law allows us to get equations for electric fields. Similar to Gauss's law, Ampere's law can only be used in certain geometries.

Recall that in Gauss's law, we first draw an appropriate Gaussian volume around the object, and then calculate the electric flux through the surfaces. In Ampere's law, you draw an Amperian loop around the object, the calculate the line integral through the loop. "Line integral" in the context of Ampere's law simply means $B \times l$ where l is the length where the magnetic field is present.

Ampere's law is

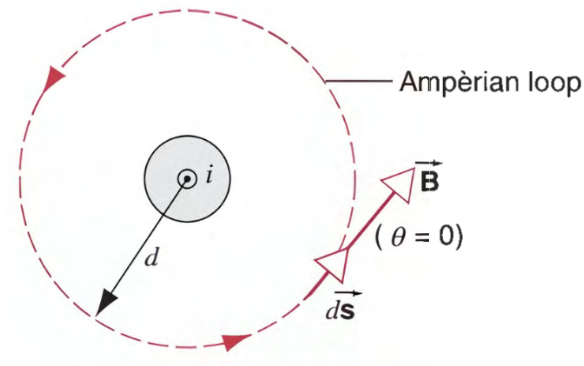
$$\oint \mathbf{B} \cdot d\mathbf{l} = Bl = \mu_0 I_{inc} \tag{15}$$

I_{inc} is the amount of current included in the loop. We only count the current passing perpendicularly through the loop.

This simplification can be made because we only use Ampere's law in situations with symmetry such that the magnitude of B along the loop is either a constant value or 0. Let us look at a few examples.

Example 1.7. Derive the magnetic field created from an infinite, straight, current carrying wire carrying current I.

Solution. We know that qualitatively, the magnetic field lines forms circles in the plane and is always perpendicular to the direction of the wire. To make sure the magnetic field is always constant across all part of our Amperian loop, we can choose a circle as our Amperian loop.



With this as our Amperian loop, the length where the B field is present is simply the circumference of the circle, which is $2\pi d$. Hence, the line integral is simply $Bl = B2\pi d$

Equating this expression to the right hand side of Ampere's law, we get

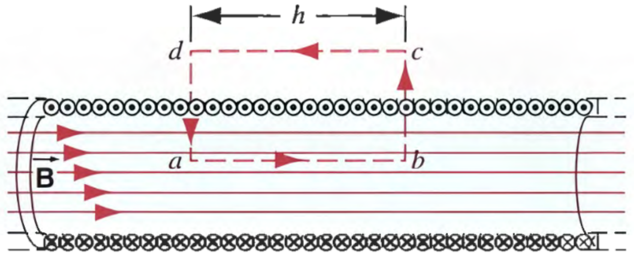
$$2\pi dB = \mu_0 I \tag{16}$$

The only current passing through our loop is the current in the wire, I. Rearranging, we obtain

$$B = \frac{\mu_0 I}{2\pi d} \tag{17}$$

Example 1.8. Derive the magnetic field inside a long, straight solenoid with current I, N turns and length l.

Solution. The magnetic field strength inside the solenoid is uniform, and pointing to the left, and the magnetic field outside the solenoid is 0. Since for the path integral, the direction of the magnetic field has to be the same direction as the direction of the loop, here we can use a rectangular loop.



On the 2 vertical edges, the magnetic field always points perpendicularly to these 2 edges, so the path integral is 0. Outside, the path integral is likewise 0 because there is no magnetic field. Hence, the only non-zero path integral is for the edge at the bottom. Hence, we can use Ampere's law

$$Bh = \mu_0 I_{inc} \tag{18}$$

Where h is the length of our rectangular loop. But what is I_{inc}? The current included is not necessarily the current in the wire, I. As shown in the diagram, there are many wires that passes through our rectangular loop. The number of wires that passes through our loop with length l is the $N\frac{h}{l}$, where N is the total number of turns in the solenoid (with distance l). Substituting this into our expression:

$$B = \frac{\mu_0 N I}{l} \tag{19}$$

If we define the current density i as the current per unit length, that is, $i = I/l$, then,

$$B = \mu_0 N i \tag{20}$$

2 Problems

Problem 2.1. If the magnetic field vector is directed toward the north and an electron is moving toward the east, what is the direction of the magnetic force on the electron?

(A) East

(B) West

(C) South

(D) Up

(E) Down

Problem 2.2. A proton moves in a circle with radius 1 mm within a region of uniform magnetic field 0.1 T. What is the magnitude of the proton's linear momentum and kinetic energy?

Problem 2.3. (SJPO 2013) An alpha particle (a He nucleus, containing two protons and two neutrons and having a mass of 6.64×10^{-27} kg) travelling horizontally at 35.6 km/s enters a uniform, vertical 1.10 T magnetic field. What is the diameter of the path followed by this alpha particle?

(A) 0.67 mm

(B) 1.34 mm

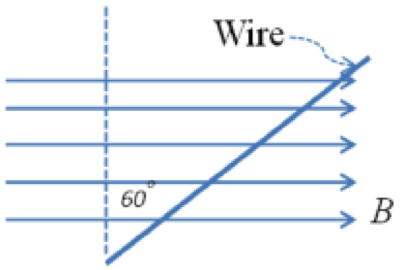
(C) 1.58 mm

(D) 2.15 mm

(E) 5.36 mm

Problem 2.4 (HRK)**.** A single-turn current loop, carrying a current of 4.00 A, is in the shape of a right triangle with sides 50 cm, 120 cm, and 130 cm. The loop is in a uniform magnetic field of magnitude 75.0 mT whose direction is parallel to the current in the 130 cm side of the loop. (a) Find the magnetic force on each of the three sides of the loop. (b) Show that the total magnetic force on the loop is zero.

Problem 2.5. (SJPO 2014) Calculate the force on a 20 cm length of wire carrying a current of 4.0 A at a direction as shown below. The magnetic field strength is 3.0 T.



(A) 2.4 N

(B) 1.2 N

(C) 240 N

(D) 120 N

(E) 2.1 N

Problem 2.6. An electron moves at constant speed in a uniform magnetic field. If the initial velocity of the electron is perpendicular to the magnetic field, the electron's path is a:

(A) straight line

(B) helix

(C) circle

(D) parabola

(E) hyperbola

Problem 2.7. (SJPO 2012) The figure shows a radioactive substance being held in a small lead box with a hole where α, β and γ rays emit from the hole. The rays trace out the paths indicated in the diagram. The rays finally impact on a screen at points A, B and C. It can be seen that $AB > AC$. Which of the following electric/magnetic fields can possibly have been applied in the space just above the hole and between the lead box and the screen?

Note: α particles are positively charged ($+2e$), β particles are negatively charged ($-e$), and γ rays are neutral (no charge).

I. Uniform Magnetic field pointing into the paper

II. Uniform Magnetic field pointing out of the paper

III. Uniform Electric field pointing to the right

IV. Uniform Electric field pointing to the left

(A) I or III

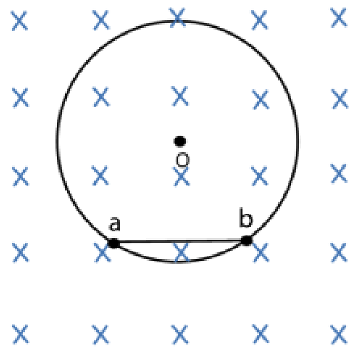
(B) I or IV

(C) II only

(D) II or III

(E) II or IV

Problem 2.8. (SJPO 2012) A charged particle moves in a circular path in a magnetic field of $B = 0.8$ T. As shown in the diagram below, the particle takes 2.0×10^{-4} s to travel from a to b and then continues to take another 1.0×10^{-3} s to go from b to a. The distance between a and b is 0.30 m and the charge on the particles is 3.0×10^{-8} C. The momentum of the particle is



(A) 7.2×10^{-9} kg m/s

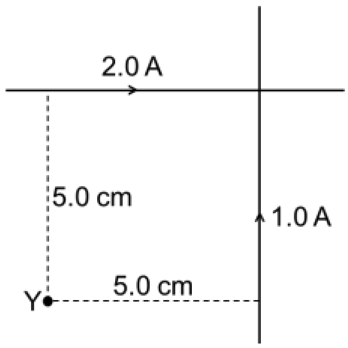
(B) 3.6×10^{-9} kg m/s

(C) 1.44×10^{-8} kg m/s

(D) 2.88×10^{-8} kg m/s

(E) 5.76×10^{-8} kg m/s

Problem 2.9. Two infinitely long wires lie perpendicular to each other and carry current in the directions shown in the diagram. The amount of current carried by each wire is also indicated. What is the direction and strength of the magnetic field at point Y, located 0.05 m from each wire?



(A) 4.0×10^{-6} T, into paper

(B) 4.0×10^{-6} T, out of paper

(C) 1.2×10^{-5} T, into paper

(D) 1.2×10^{-5} T, out of paper

(E) 0 T

Problem 2.10. (SJPO 2019) An electron is moving in a straight line in a region where there exists a magnetic field and an electric field perpendicular to each other. What will be the motion of the electron if the electric field is switched off?

(A) The electron will move with the same speed in a circular path.

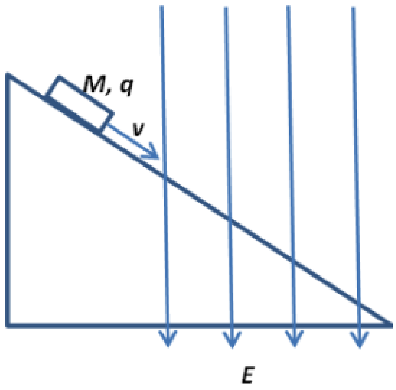
(B) The electron will move with the same speed in a parabolic path.

(C) The electron will move with the same speed in a straight line.

(D) The electron will move with a reduced speed in a circular path.

(E) The electron will move with a reduced speed in a straight line.

Problem 2.11. (SJPO 2014) As shown in the diagram below, a mass M with charge $+q$ is sliding down the slope at constant velocity v. When the mass enters the region with the uniform electric field E,



(A) the mass will continue to slide down at constant velocity v.

(B) the velocity of the mass will increase as it slides down the slope.

(C) the velocity of the mass will decrease as it slides down the slope.

(D) the mass will come to a stop immediately.

(E) the mass will reverse direction and accelerate up the slope.

Problem 2.12. In the question above, we consider the case of applying an additional magnetic field pointing into the paper in the region where the electric field exists. We would expect that in the region where the fields exist,

(A) the mass will continue to slide down at constant velocity v.

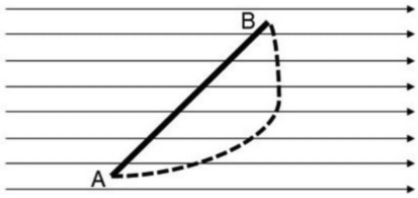
(B) the velocity of the mass will increase as it slides down the slope.

(C) the velocity of the mass will decrease as it slides down the slope.

(D) the mass will come to a stop immediately.

(E) the mass will reverse direction and accelerate up the slope.

Problem 2.13. The diagram shows two separate segments of wire (represented by solid and dotted lines) that are carrying a current I from point A to B in the presence of a uniform magnetic field indicated by the arrows. Which of the following statements about the force due to the external magnetic field on the wires is correct?



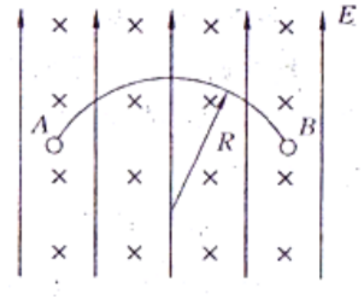
(A) The force acting on the solid line wire is bigger than that on the dotted line wire.

(B) The force acting on the dotted line wire is bigger than that on the solid line wire.

(C) The force acting on both wires are zero.

(D) The force acting on both wires are the same, but non-zero.

Problem 2.14. (SJPO 2011) An E-field and a B-field crosses each other as shown in the figure below, with the E-field pointing vertically upward. The E-field is tuned such that the force it exerts on each drop balances the drop's own weight. Oil Drops A and B both carry charges of the same magnitude and sign and are of the same mass. A is stationary and B moves in a circular path with radius R and speed v. If A and B are to collide and combine, the final charged drop will



(A) exhibit linear motion with half the speed that B used to have.

(B) exhibit uniform circular motion with radius, $R/2$.

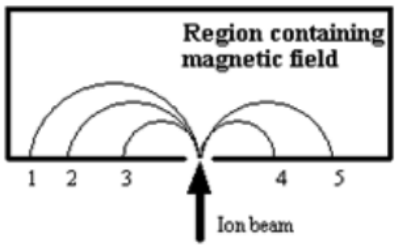
(C) exhibit uniform circular motion with radius R.

(D) exhibit uniform circular motion with half the period that B used to have.

(E) None of the above.

Problem 2.15. (SJPO 2015) A beam consisting of five types of ions labeled A, B, C, D, and E enters a region that contains a uniform magnetic field as shown in the figure. The field is perpendicular to the plane of the paper, but its precise direction is not given. All ions in the beam travel with the same speed. The table below gives the masses and charges of the ions.

Ion	Mass	Charge
A	$2u$	$+e$
B	$4u$	$+e$
C	$6u$	$+e$
D	$2u$	$-e$
E	$4u$	$-e$



Which ion falls at position 3?

(A) A

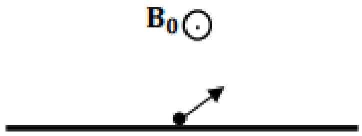
(B) B

(C) C

(D) D

(E) E

Problem 2.16. (SJPO 2018) An electron is emitted from the surface of a metal plate at an angle of 45 degrees from the surface. The electron's initial kinetic energy is 2.4×10^{-17} J. A uniform magnetic field $B_0 = 1$ T is applied in the direction as shown in the figure. How far is the electron when it is furthest from the plate from which it was emitted? Assume no other forces other than that due to the magnetic field.



(A) 0.012 mm

(B) 0.033 mm

(C) 0.041 mm

(D) 0.071 mm

(E) No limit. It just keeps going.

Problem 2.17. (SJPO 2011) A long, thin, vertical wire has a net positive charge λ per unit length. In addition, there is a current I in the wire. A charged particle moves with speed u in a straight-line trajectory, parallel to the wire and at a distance r from the wire. Suppose that the current in the wire is reduced to $I/2$. Which of the following changes, made simultaneously with the change in the current, is necessary if the same particle is to remain in the same trajectory at the same distance r from the wire?

(A) Doubling the charge per unit length on the wire only

(B) Doubling the charge on the particle only

(C) Doubling both the charge per unit length on the wire and the charge on the particle

(D) Doubling the speed of the particle

(E) Introducing an additional magnetic field parallel to the wire

Problem 2.18. Following on the question above, the particle is later observed to move in a straight-line trajectory, parallel to the wire but at a distance $2r$ from the wire. If the wire carries a current I and the charge per unit length is still λ, the speed of the particle is

(A) $4u$

(B) $2u$

(C) u

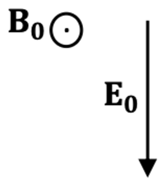
(D) $u/2$

(E) $u/4$

For the next 3 questions, we consider the case where the effect of the magnetic field is very strong. The motion of an electric charge in a magnetic field can be visualised as the superposition of a relatively fast circular motion ("gyrates") around a point called the guiding center and a relatively slow drift of this point.

To understand the motion, you should consider effects due to all forces present on the particle together carefully and follow the particle's motion through a few cycles. If you find the problems challenging, don't worry, they are meant to be!

Problem 2.19 (SJPO 2017)**.** An electron gyrates in a constant, uniform magnetic field B_0 outwards through paper and a constant, uniform electric field E_0 is downwards. Which of the following statements is true?



(a) The guiding center moves right.

(b) The guiding center moves left.

(c) The guiding center moves outwards.

(d) The guiding center moves downwards.

(e) The guiding center moves upwards.

Problem 2.20 (SJPO 2017)**.** An electron gyrates in the presence of a constant uniform electric field with magnitude E and magnetic field, with magnitude B. The electric and magnetic fields are perpendicular to each other. The magnitude of velocity of the guiding center after time t is:

(a) EB

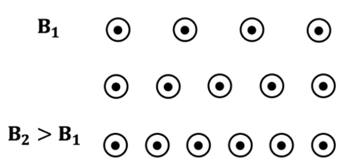
(b) E/B

(c) B/E

(d) eEt/m_e

(e) $EB(em_e/t)^2$

Problem 2.21 (SJPO 2017)**.** A proton gyrates and spirals in a region of non-uniform magnetic field only. Its guiding center has an initial velocity and moves naturally from the region of higher magnetic field to a region of lower magnetic field and in the direction of the magnetic field. Which of the following statements is true?



(A) The velocity of the guiding center does not change because there is no work done by the magnetic force which is perpendicular to the motion.

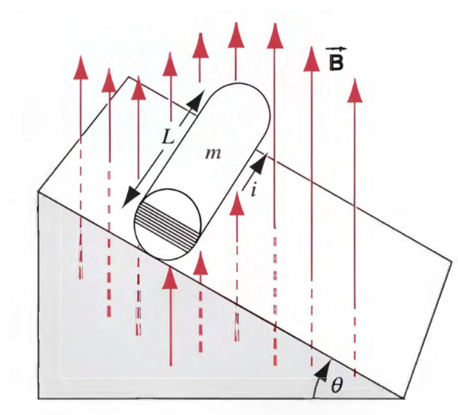
(B) The velocity of the guiding center does not change because as it moves to a region with lower magnetic field, only the radius of the gyration increase.

(C) The velocity of the guiding center decreases as the velocity of the proton decreases when it moves to a region with lower magnetic field.

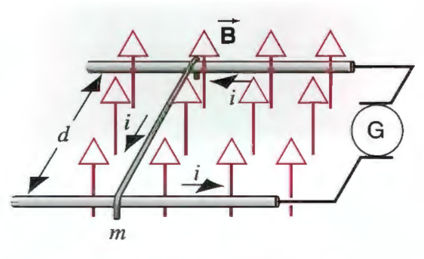
(D) The velocity of the guiding center increases as there is a magnetic force in the direction of the magnetic field.

(E) The velocity of the guiding center increases as there is a force acting on the proton with direction from high to low magnetic field.

Problem 2.22 (HRK)**.** Figure below shows a wooden cylinder with a mass m = 262 g and a length L = 12.7 cm, with N = 13 turns of wire wrapped around it longitudinally, so that the plane of the wire loop contains the axis of the cylinder. What is the least current through the loop that will prevent the cylinder from rolling down a plane inclined at an angle 0 to the horizontal, in the presence of a vertical, uniform magnetic field of 477 mT, if the plane of the windings is parallel to the inclined plane?

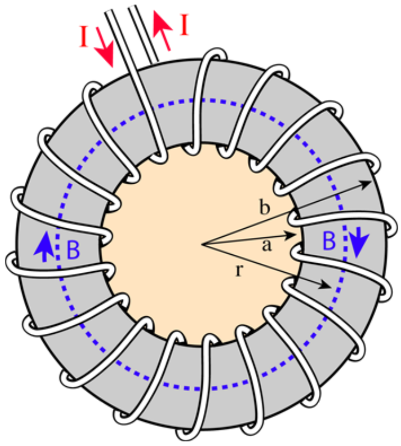


Problem 2.23 (HRK)**.** A metal wire of mass m slides without friction on two horizontal rails spaced a distance d apart, as in Fig. 32-36. The track lies in a vertical uniform magnetic field B. A constant current i flows from generator G along one rail, across the wire, and back down the other rail. Find the velocity (speed and direction) of the wire as a function of time, assuming it to be at rest at t = 0.

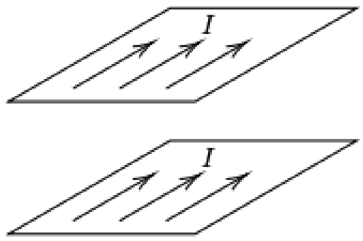


Problem 2.24. Find the magnetic field inside a long, thick cylindrical wire carrying current I with radius R.

Problem 2.25. Find the magnetic field B inside a toroid.



Problem 2.26. Two identical thin, wide and parallel square metal plates each carry a uniform current I in the same direction along their length. What is the force that one plate exerts on the other?



(A) 0

(B) $\mu_0 I^2$

(C) $\frac{1}{2}\mu_0 I^2$

(D) $\frac{1}{\pi}\mu_0 I^2$

(E) $\frac{1}{2\pi}\mu_0 I^2$