Lab
9

Magnetic Interactions

What You Need To Know:

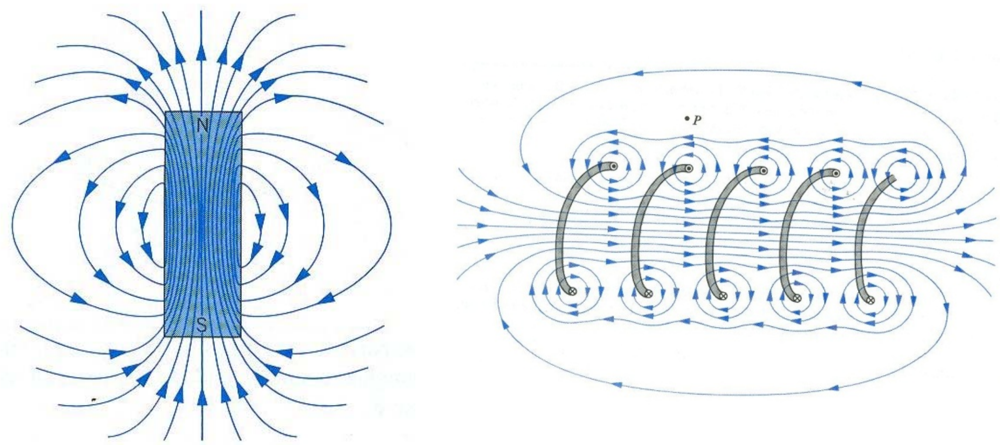
The Physics Electricity and magnetism are intrinsically linked and not separate phenomena. Most of the electrical devices you will encounter require both electric and magnetic fields. For example, Motors, generators, meters, solenoids, metal detectors, acoustic speakers and car ignition systems etc.

After some simple investigations you will be constructing a simple magnetometer which you will use to detect the strength of the Earth's magnetic field.

Bar Magnets and Electromagnets

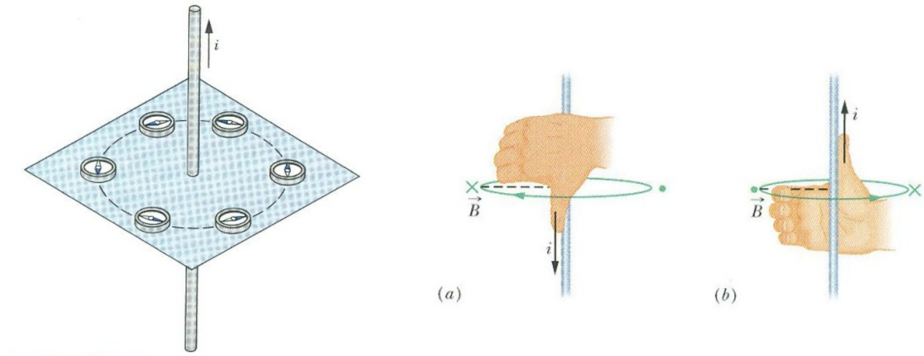
Magnetic fields are caused by current loops, electrons circulating in atoms mostly. A bar magnet has a north (N) and a south (S) pole. Like poles repel, unlike poles attract. You can construct an electromagnet

By wrapping a wire around an iron core (a nail) and then passing a current through it. This small solenoid would then be able to pick up paper clips and it acts like a small bar magnet. One end of the coil acts like a N pole of a bar magnet the other end acts like a S pole. Look at the magnetic field lines of the bar magnet and the coil below (the iron core would strengthen the magnetic field of the coil but it is not essential). The field lines are practically identical.



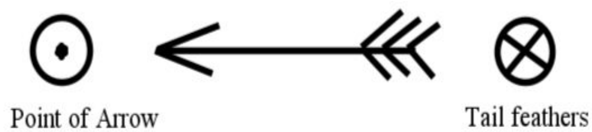
Ref: Halliday and Resnick "Fundamentals of Physics", 9th Extended Ed. , (Wiley & Sons , 2003)

You probably know a wire carry a current generates a magnetic field around the wire. You can detect the magnetic field by using a small compass and see how the N pole of the compass follows the field lines created by the wire. See figure below. The direction of the B field circulation can be found using the right hand rule (RHR). Put you right thumb in the direction of the + current I, then your fingers curl in the direction of the B field.

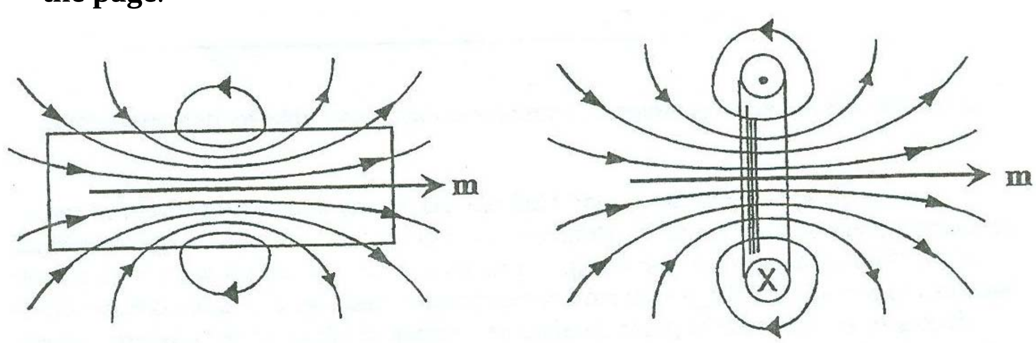


Ref: Halliday and Resnick "Fundamentals of Physics", 9th Extended Ed. , (Wiley & Sons , 2003)

We will follow standard book notation for directions into and out of the board. See the arrow below.



- When you see the circle with a **dot** in the center, the arrow is coming straight towards you and the direction is **out of the page**.
- When you see the circle with the **cross** in it, those represent the tail feathers of the arrow, it is moving directly away, so the direction is **into the page**.



Above is a picture of a bar magnet (dipole moment = m) the direction of the dipole points out from the N pole. Next to the bar magnet is a coil, the current is out of the page at the top and going into the page at the bottom… if you let the fingers of your right hand curl in that direction you will have your thumb pointing towards the right, which is the direction of the N pole and m.

Magnetic dipoles are usually thought of as small current loops. The magnitude of the magnetic dipole moment is;

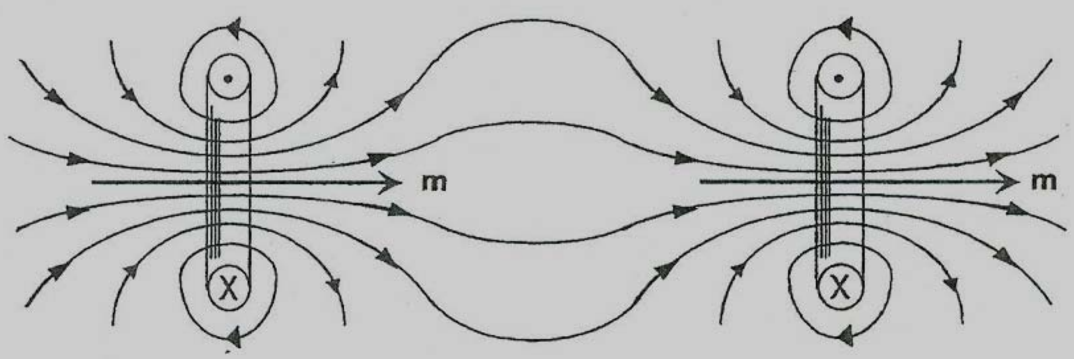
$$\vec{m} = I\,A\,\hat{n}$$

where I is the current in one loop, and A is the cross sectional area of the loop. If there are N turns on a coil you multiply by N, since the same current flows in each loop.

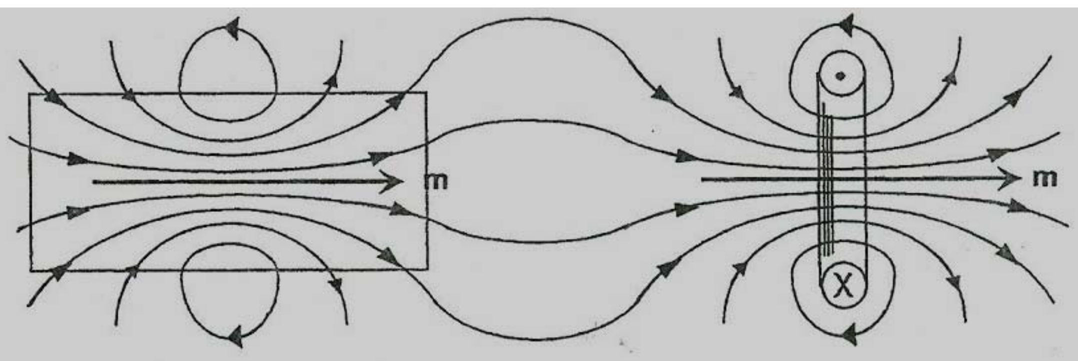
The unit vector $\hat{n}$ tells you the direction of $\vec{m}$, or which way up the N pole is, or which way the field lines emerge. Bar magnets and coils can be thought of as simple magnetic dipoles, this is an approximation however.

I think by now you can see that bar magnets and coils have the same field lines and can be used interchangeably. We can approximate their properties by simple magnetic dipoles. For further confirmation we show field lines of interacting bar magnets and coils.

Attractive Force Between Bars and Coils



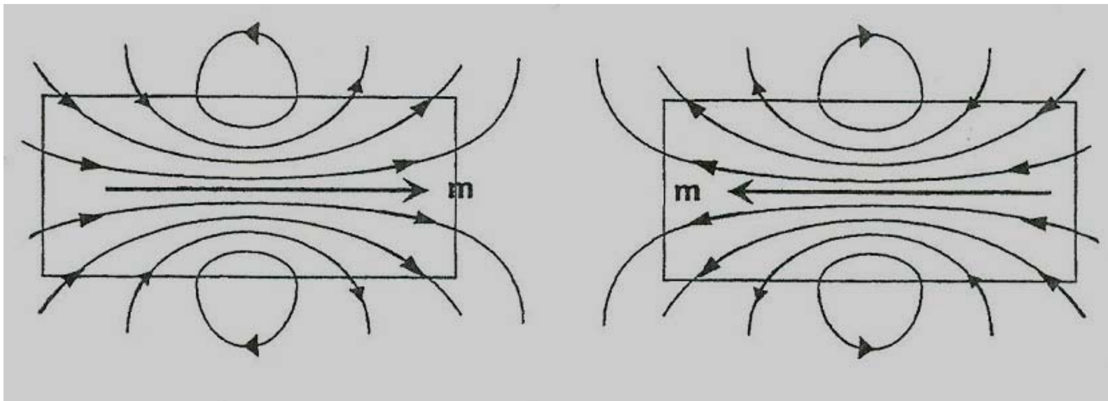
Magnetic lines of force for two current carrying coils with m having the same direction. The force is attractive.



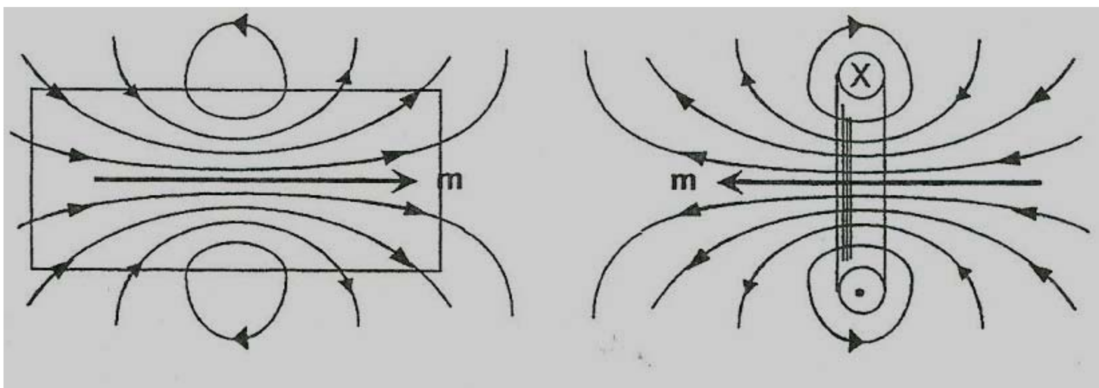
Magnetic lines of force for a permanent magnet and current carrying coil with m having the same direction. The force is attractive.

You get the same effect with 2 bar magnets.

Repulsive Force Between Bars and Coils



Magnetic lines of force for two permanent magnets with opposing **m** vectors. The force is repulsive.



Magnetic lines of force for a current carrying coil and a permanent magnet with opposing **m** vectors. The force is repulsive.

You get the same effect with 2 coils.

How a Dipole Interacts With a Magnetic Field

A magnetic dipole will tend to twist so that the orientation aligns with the external magnetic field. The torque $\vec{\tau}$ (twisting force) on the dipole (bar magnet or coil) is given by,

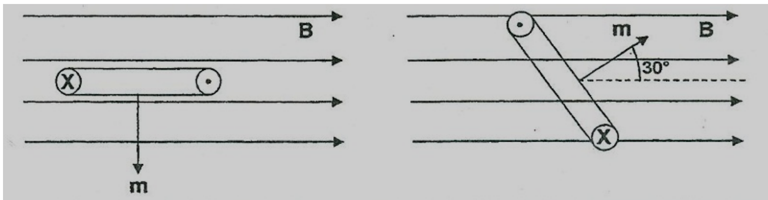
$$\vec{\tau} = \vec{m} \times \vec{B} = mB\sin\theta\,\hat{n}$$

where all symbols with arrows are vectors and $\hat{n}$ is a unit vector in the direction of $\vec{\tau}$.

The energy U of the dipole in the magnetic field is given by $U = -m \cdot B$

Work through the following two example problems and make sure you understand what's going on:

Example 1 Consider a circular coil of wire of radius r = 2 cm which has 200 turns of wire and carries a current of 0.2 A. The B-field strength is 1.2 T. (Answers are highlighted.)



Coil with B field parallel to it's diameter   Coil with B field at 30° to the normal of it's plane

a) What is the magnitude of the magnetic dipole of the coil?

|m| = N I πr2 = 5.03 x 10-2 Am2 { or units can be Joules/Tesla}.

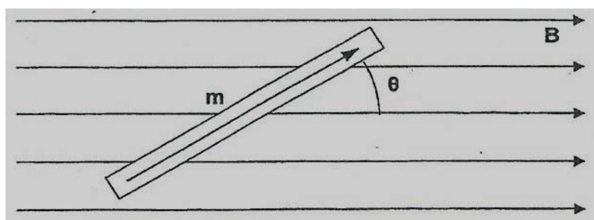
b) If the B-field is parallel to the diameter of the coil, as in the fig. on the left, what is the magnitude and direction of the torque acting on the coil.

Torque out of page, coil rotates CCW, |τ| = |m| B sin (90)= 0.06 N (Newtons).

c) If the dipole m is at 30 degrees to the B-field as shown in the right fig., what is the magnitude and direction of the torque acting on the coil?

Torque into page, coil rotates CW, |τ| = |m| B sin (30)= 0.03 N.

Example 2 <u>This will be important later, make sure you follow it!</u> Consider a bar magnet of mass m_b , length L, and magnetic moment m, which is in a magnetic field B. The dipole is initially at rest and makes an angle θ with the magnetic field.



When released, the dipole undergoes simple harmonic motion. The torque is given by, $\tau = I\ddot{\theta}$ where I is the moment of inertia and dots above θ represent time derivatives. (This is similar to F = ma for linear motion). Using the small angle approximation, small angle approximation sin θ ~ θ, the equation of motion can be written as;

$$\frac{d^2\theta}{dt^2} = -\frac{mB\theta}{I} = -\omega^2\theta$$

where the moment of inertia given by $I = \frac{m_b L^2}{12}$ and $\omega^2 = \frac{mB}{I}$ is the square of the angular frequency of the motion. The magnet oscillates with a period T = 2 s, m_b = 20 grams, L = 10 cm and B = 0.5 x10^{-4} T. What is the magnetic dipole moment of the bar magnet? (Answer on next page.)

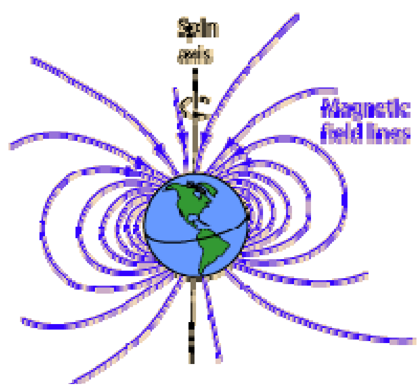
Answer …

$$m = \frac{\omega^2 I}{B} = \frac{\left(\frac{2\pi}{T}\right)^2 \left(\frac{m_b L^2}{12}\right)}{B} = \frac{\left(\frac{2\pi}{2}\right)^2 \left(\frac{(20\,x10^{-3})(10\,x10^{-2})^2}{12}\right)}{0.5x10^{-4}}$$

$$m = 3.29\ J/T$$

Magnetic Field Lines of the Earth

The Earth's magnetic field lines are oriented at about 11 degrees from the vertical. The N magnetic pole is down and the S pole is up. That is why the N pole end of a compass needle (which is a small magnet) is attracted towards the geographic "north" pole region. It is as if there was a large bar magnet inside the earth with the N pole facing down towards Australia and the S pole facing up towards Greenland. This effect comes from the spinning iron core. At any spot on Earth, there will be horizontal and vertical components to the B-field lines. We will be looking more closely at this later.



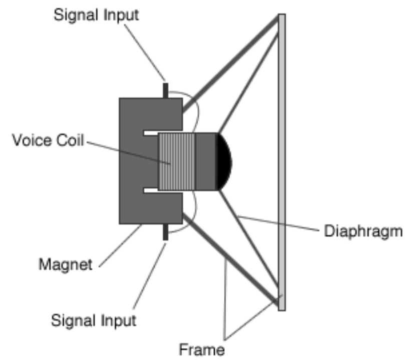
http://hyperphysics.phy-astr.gsu.edu/hbase/magnetic/magearth.html

What You Need To Do:

There will be two short exercises and then you will build a magnetometer to measure the Earth's magnetic field.

Part 1 This is a fun experiment, you may have done this as a kid, if not no worries you get to play now! You're going to make an electromagnet and pick up some paper clips. You put a coil of wire around an iron core… turn on the current in the coil and bingo you have an electromagnet!

Note that you use electromagnets every day, a very common use is for audio speakers. The varying ac current/ signal goes to a coil which is wrapped around a magnet. See the simple diagram below. The coil moves in and out with the diaphragm which causes longitudinal wave or sound waves.



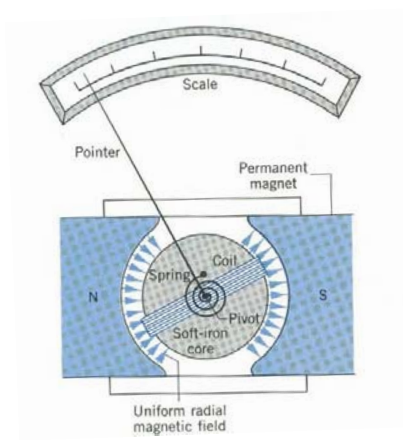
SETUP: You should have a rubber coated iron rod which is not magnetized. Each iron atom within the rod is a small magnetic dipole. Within the rod there are groups of atoms which are in alignment called domains. In un-magnetized iron these domains can be oriented in any direction. The domains can be brought into alignment by placing the rod in a magnetic field. If a number of domains are aligned with each other the rod becomes magnetized. The overall field can be much greater than the original causing the rod to become a magnet!

You have 3 coils each with a different number of turns. You are to place one coil at a time on the iron rod. As the number of turns N on the coils increases so should the magnetic field. You can test this by picking up paper clips. The coils will be connected to the +18 Volt terminal and the ground terminal of the power supply, adjust the current to about 0.06A.

Make a table in your notebook, simply write down the number of turns N vs., the number of paper clips you picked up with your electromagnet. That's it. Have fun!

Number of turns N in Coil	Number of Paper clips
400	
2000	

Part 2 We are going to make a simple ammeter of the type shown below, only a bit more basic.



SETUP: You have been given a fine circular coil, magnet, magnet holder/point, card for a scale, plastic base, dc power supply and digital multi-meter. The magnet is of a type with the poles on the <u>sides</u> rather than at the ends. Using the protractor, in your kit, draw an arc on the card to be used as a scale. Assemble the parts to make a meter. Place the fine coil horizontally on the blue base.

With no current in the coil of wire only gravity acts on the coil and the pointer should be vertical. If it doesn't try moving the magnet around or putting paperclips on one side to balance it out. Make a mark on the card to indicate the zero position. If all is fine then the magnetic dipole of the magnet is horizontal. *(You don't have a spring, gravity will counter balance the torque due to the B field).*

Now we're going to apply a current to the coil. The coil will become a dipole (like a bar magnet) with the N pole either vertically up or down, depending on the direction of the current. The dipole/coil will want to align with the permanent magnetic field which is horizontal. There is a torque on the dipole/coil $\tau = m \times B$. As the pointer rotates, a gravitational torque is set up which balances the torque of the magnetic field. The system will come to a new equilibrium position. Increasing the current increases the magnetic torque and you get a bigger deflection. If you reverse the current the pointer will deflect in the opposite direction. (There was a torque calculation on page **9 - 4**.)

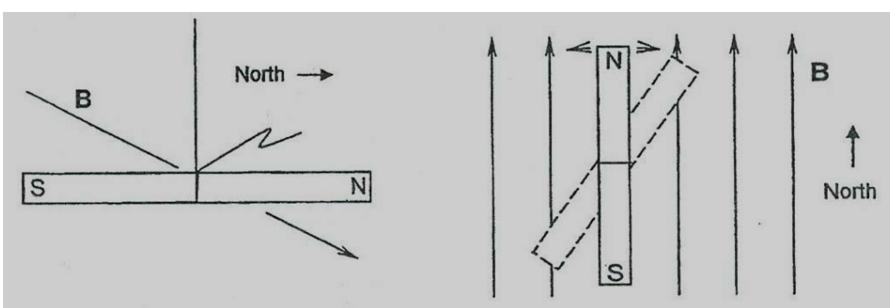
By adjusting the voltage of the dc power supply and measuring the current using the digital multi-meter, calibrate your ammeter. Get at least 5 results for the table.

Current (Amps)	Degrees of Deflection

Now you have a calibrated ammeter use it to find the current of a dry cell battery. (almost dead battery)

Current is I = _______________.

Part 3 Finally, we're going to measure the Earth's magnetic field! This will involve the horizontal component of the Earth's B-field and a calculation similar to that on page **9 - 5**. We will be hanging a bar magnet up horizontally by a thin thread and watching it rotate in the horizontal component of the Earth's B field.



Magnet suspended horizontally in the earth's magnetic field

Top view with the earth's magnetic field lines shown

The magnet will come to rest pointing north… just like a compass needle which is in fact a small bar magnet!

If the magnet is rotated form the northerly direction, 2 torques will come into play;

- A torque due to the twist in the fine thread
- A magnetic torque due to the interaction of the bar magnet (dipole) with the Earth's B-field. *The first torque is very small if we use a fine thread and we shall neglect it (too small to worry about).*

The second torque cannot be neglected. It has a component along the vertical direction which is given by $\tau = -mB_H \sin\theta$ where B_H is the horizontal component of the Earth's magnetic field. The rotational equation of motion is $\tau = I\ddot{\theta}$ where *I* is the moment of inertia of the bar magnet… which is just a rod of length *L*. The moment of inertia of the rod is $I = \frac{m_b L^2}{12}$ and the square of the angular frequency is $\omega^2 = \frac{mB}{I}$. Using the small angle approximation, $\sin\theta \sim \theta$, the equation of motion can be written as (see page **9 - 5**),

$$\frac{d^2\theta}{dt^2} = -\frac{mB_H\theta}{I} = -\omega^2\theta$$

The bar magnet will oscillate back and forth with angular frequency ω. Clearly we need to determine the angular frequency ω, the moment of inertia *I* and dipole moment *m*, of the magnet to find B_H.

So to find B_H we need the dipole moment *m* of the bar magnet, we need the moment of inertia *I* of the bar magnet and the angular frequency of the motion ω.

$$B_H = \frac{I\,\omega^2}{m}$$

So here's what you need to do…

(i) <u>To find the moment of inertia *I*</u>:

For this we need to measure the mass of the bar magnet and its length.

Determine mass of bar magnet, m_b = ____________________ kg

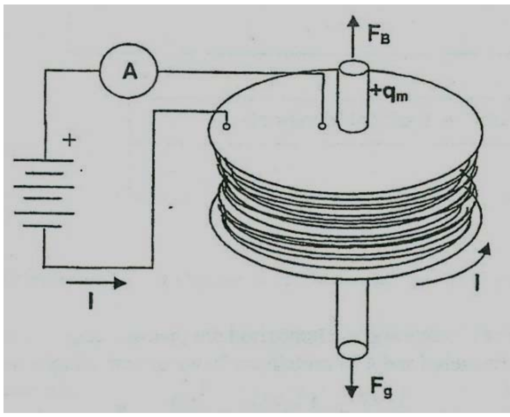
Length of bar magnet, L = ____________________ m

Moment of inertia of bar magnet, $I = \frac{m_b L^2}{12}$ = ______________________ kg · m^2

(ii) To find the moment of inertia of the bar magnet m:

This is tricky and we need to use a trick. We will assume the magnetic dipole can be treated like an electric dipole.. with "magnetic charge q_m". The dipole moment can then be expressed as $m = q_m L$, where L is the length of the bar magnet. We will place the bar magnet inside a coil and hold it vertically. We will balance the weight of the magnet with the upward magnetic force due to the coil's magnetic field. When we know the current through the coil which causes the bar magnet to be suspended, we find the magnetic field of the coil and hence we can find the magnetic moment of the bar magnet.

The B-field at the center of a coil is given by, $B = \frac{\mu_o N I_o}{2R} = k I_o$ here, $\mu_0 = 4\pi \times 10^{-7}$ Hm^{-1}, and I_o is the current through the coil that holds the magnet suspended and we find $k = 2.2 \times 10^{-2}$ T/A. See figure below.



The upward force, F_B due to the magnetic field of the coil is balancing the downward force, F_g due to gravity. Staring with that …

$$F_B = F_g$$
$$q_m B = m_b g$$
$$q_m I_o k = m_b g$$

we get … $$q_m = \frac{m_b g}{I_o k}$$

So we take this result and find $m = q_m L = \frac{m_b g L}{I_o k}$.

Use your measurements, taken previously, find magnetic moment of the bar magnet,

m = ______________ A/m^2 (or J/T).

(iii) <u>To find the horizontal component of the Earth's magnetic field</u>:

Now let's bring it all together. We have one more quantity to find and that is the angular frequency of the bars oscillation …

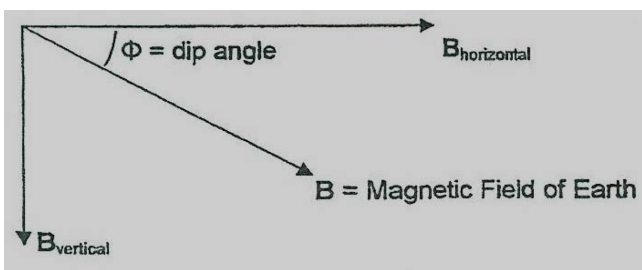
$$B_H = \frac{I\,\omega^2}{m} = \frac{I\left(\frac{2\pi}{T}\right)^2}{m} = \frac{4\pi^2 I}{mT^2}$$

where T is the oscillation period. Tie a thin thread around your bar magnet and hang it up. Displace it slightly from the equilibrium (from the N direction) so it swings back and forth. Using a stopwatch (provided) determine the period of the oscillation. Find the time for the bar to go through 6 to 10 swings then divide by the number of swings to get the period T. Do this at least 3 times to get an average.

Trial	Time, **t** (s)	# of oscillations, **N**	Period, **T = t/N**	Magnetic Field, $\mathbf{B_H}$
1				
2				
3				

Finally, the full strength of the Earth's magnetic field, which has a vertical as well as horizontal component, can be determined if the angle the field makes with the horizontal, the "dip" angle ϕ is known or can be measured. The full strength of the Earth's magnetic field is given by,

$$B_{Earth} = \frac{B_H}{\cos\phi} = B_H \sec\phi$$



Vector diagram showing the dip angle of the Earth's magnetic field

The dip angle $\phi = 60^o$ at Fullerton. (It has to do with longitude.)

Find the full magnitude of the Earth's magnetic field. B_{Earth} = ________________ T