Phys132 - Fund. Physics 2 - Spring 2007 Chapters 21&22 - Magnetism

1 Introduction

Magnetism has to do with the movement of charges. Remember that moving charges can also be considered to be an electric current I, so magnetism also deals a lot with currents. Moving charges create magnetic fields and are affected by magnetic fields, similar to how any charges create and are affected by electric fields.

Applications include magnets, electromagnets, magnetic compasses, CRT's, transformers, motors, generators, mass spectrometers, audio speakers and microphones,

Magnets as we think of them are actually "magnetic dipoles". They have a north and a south pole, named that way because the north pole of a magnet is attracted to the north pole of the earth. This is because the earth creates a huge magnetic field. On the surface, it points north, which is the direction the magnet's north pole points.

Playing with two magnets, we find that opposite magnetic poles are attracted to each other and like magnetic poles repel. This means that outside of one magnet, the magnetic field points from north to south.

2 Magnetic Force on a Particle

Direction of the magnetic force — First Right-Hand Rule

The magnetic force is calculated as the result of a "cross product".

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

The first step is to evaluate the cross product $\vec{v} \otimes \vec{B}$. The direction can be calculated from the Right-Hand Rule. Point your forefinger in the direction of the first vector. Bend your middle finger in the direction of the second vector. Your thumb will then point in the direction of the cross product.

Magnitude of the magnetic force

The magnitude can be calculated in multiple ways.

$$F = qvB\sin\theta_{vB} = qv_{\perp}B = qvB_{\perp}$$

Either take the product of the magnitudes v and B and multiply it by the sine of the angle between the two vectors θ_{vB}, use the perpendicular component of $\vec{v}$, called $v_{\perp}$ times the magnetic field, or use the perpendicular component of $\vec{B}$.

Don't forget to multiply by the charge. Remember that electrons have negative charge and protons have positive charge. For negative charges, the actual force is in the opposite direction from $\vec{v} \otimes \vec{B}$.

3 Force on a current-carrying wire

Finding the magnetic force on a wire is similar to finding the magnetic force on a charge. Instead of qv, we use IL. The direction of the force is perpendicular to the wire.

$$\vec{F} = ILB\sin\theta_{IB}, \text{ (Dir by RHR)}$$

Application: Electric Motor

The simplest to analyze is a square coil, like in Section 21.6.

$$\tau = NIAB\sin\phi$$

4 Particle flying in a magnetic field.

With only a magnetic field, particles fly in a circular path. The magnetic force points toward the center of the circle.

$$r = \frac{mv}{qB}$$

Application: Velocity Selector

Cancel the magnetic force with an electric force. Only particles with the correct v get through.

$$E = vB$$

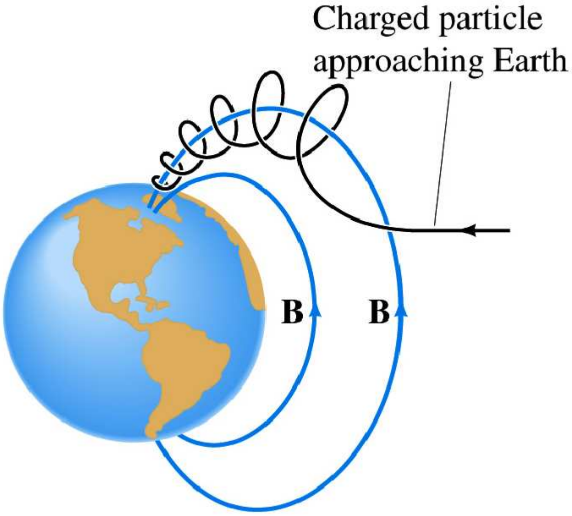
Application: Mass Spectrometer

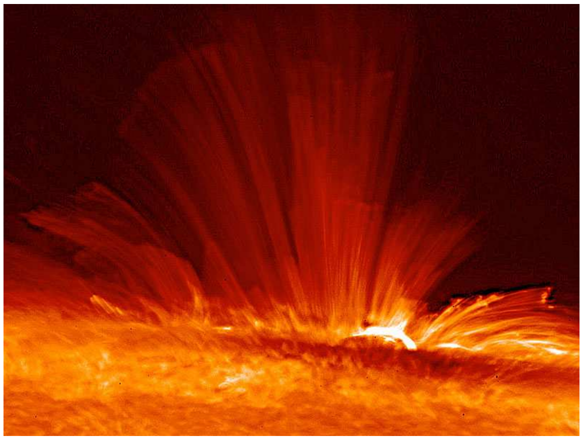
Vaporize and ionize atoms or molecules ($q = +e$), send them through an electric potential V, and then through a magnetic field B. Those that pick up just the right speed bend at the right radius and hit a detector. The electric potential gives each charge an energy of qV, and this energy becomes kinetic energy, so $qV = \frac{1}{2}mv^2$. Combine this with the radius of the path and solve for m to get:

$$m = \left(\frac{er^2}{2V}\right)B^2$$

Particles that are too heavy will go too far, and those that are too light will turn more easily. Only those with the desired v (chosen by setting V) will get through and be detected.

Application: Earth's Magnetic Field and Solar Wind

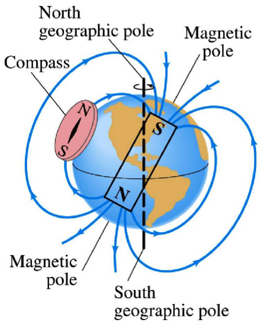




5 Sources of the Magnetic Field

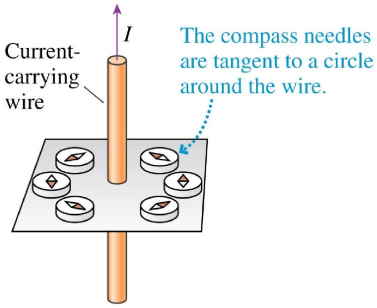
We started by saying that the magnetic field is all about moving charges and/or currents. So far, we have concentrated on the effects of the magnetic field: what it does. Magnetic fields exert forces on moving charges and on currents. Now we'll look at how to create a magnetic field.

The Earth is a Magnet

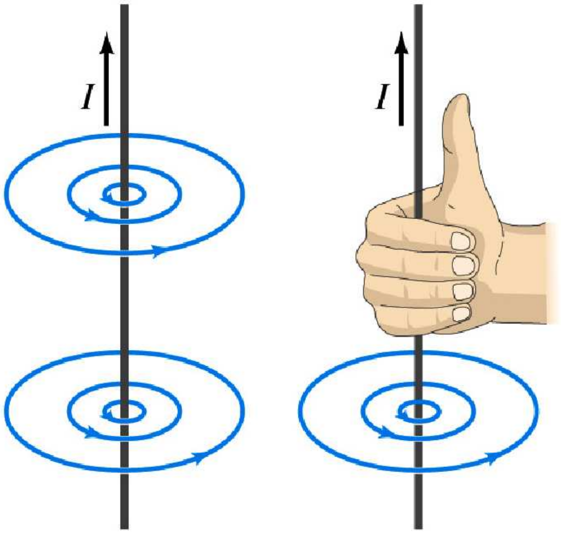


We can "see" the magnetic field of the earth by carrying a compass around. The needle always points in the direction of the field. If we place a compass needle near a wire that carries a current, we find the needle points *around the wire.*

Current I Creates $\mathbf{B}$



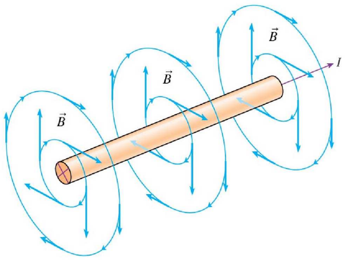
Connect the arrows and we can imagine the magnetic field lines circling the wire. The direction follows our second right-hand rule.



Second Right-Hand Rule for Straight Currents

For the field "near" a current, (1) point your thumb in the direction of the current and (2) your fingers curl in the direction of the field.

B of very long Wire



$$B = \frac{\mu_0 I}{2\pi R}$$

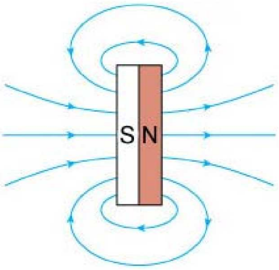
CPS Question: Consider two parallel DC currents. What direction is the magnetic force they exert on each other?

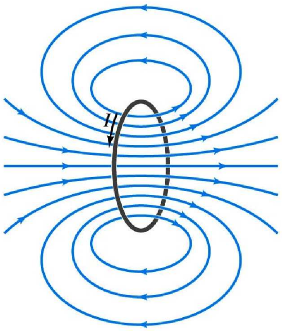
Second Right-Hand Rule for Current Loops

For a current flowing in a loop (coil or solenoid), (1) wrap your fingers in the direction of the loop and (2) your thumb points in the direction of the field inside the loop.

Coils

A coil is formed by a wire that is looped on top of itself several times. The individual loops are right on top of each other, forming a ring.





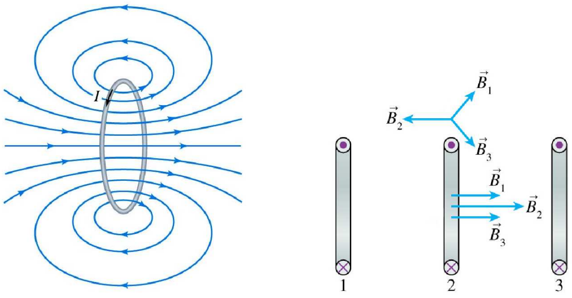
Inside the coil, the direction of the field is found by the RHR. The magnitude of the field at the center of the loop (where the field is the strongest) is

$$B = \frac{\mu_0 N I}{2R}$$

Solenoid

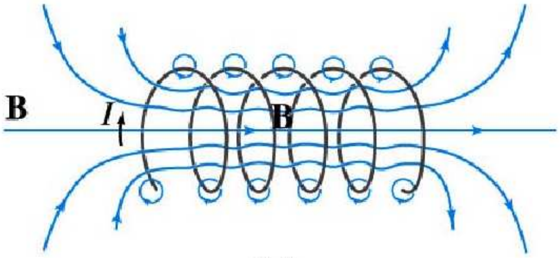
A solenoid is like a coil, but the individual loops are next to each other instead of on top of each other. The wires form a long tube, with the current going around the tube.

Field of one and three loops:

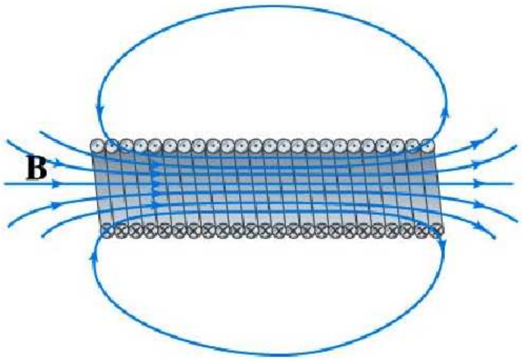


Outside the solenoid, the magnetic field is approximately zero. Inside the solenoid, the magnetic field is the same everywhere. The direction is found by the RHR. The magnitude is

$$B = \mu_0 n I$$



(a)



(b)

6 Ampere's Law

Remember Gauss's Law for electric fields (or remember that it exists)? There's a similar relationship for Magnetic fields. In this case, a ring-shaped path (not necessarily round) is drawn around a region. Calculate the average magnetic field along the ring and multiply it by the length of the ring. This value is equal to μ_0 times the total current passing through the ring.

$$B_{||}\ell = \mu_0 I_{\text{enc}}$$

Where $B_{||}$ is the **average** magnetic field along the path, ℓ is the length of the path, μ_0 is a constant, and I_{enc} is the electric current encircled by the path. One interesting result if this is from far away, a bunch of electric currents "look like" a single current that is the sum total of the individual currents. It is also used to find the magnetic field in a transformer, because the field is almost completely confined to the iron core with a constant value. (Figure 22.30)

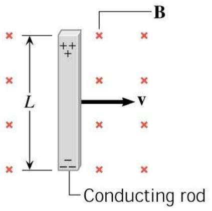
Ampere's Law tells us that magnetic field is always proportional to the current causing it. It doesn't say which parts of a path have the strongest field, though.

7 Induction

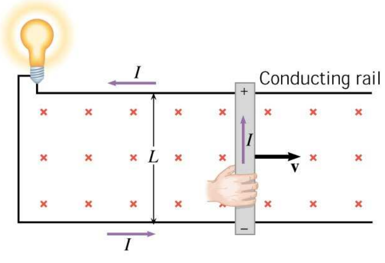
If we move a coil in a magnetic field, an EMF (electromotive force, aka voltage) is generated in the coil. This idea is used in many places. Generators/alternators consist of a rotatable coil in a magnet. It also works if the coil is held stationary and the magnet moves.

DEMO: Coil and magnet.

The easiest case to understand is a rectangular coil moving into a magnetic field. (Figure 22.4, below). The EMF in this case is $\mathcal{E} = vBL$.



(*a*)



(*b*)

When something is connected across the wires to allow current to flow ($I = \mathcal{E}/R$), energy is required. Magnetic fields can't actually do any work (because the force is perpendicular to the motion of the charges). The energy comes from the force pushing the conductor through the magnetic field. This force is $F = ILB$ as we discussed before.

EMF can be generated in other cases, such as when the magnetic field is moving or changing, or when a loop of wire is rotating. To understand these cases, we need to use the concept of magnetic flux.

8 Magnetic Flux and Faraday's Law

The total magnetic field passing through an area surrounded by a loop of wire is called the magnetic flux.

$$\Phi = BA\cos\phi$$

Here, B is the magnetic field, A is the area of overlap between the field and the loop, and ϕ is the angle between the field and the normal vector. If any of these three things changes, then the flux changes. Any change in flux causes an EMF. Faraday's Law gives the average EMF caused by a change in magnetic flux:

$$\mathcal{E} = -N\frac{\Delta\Phi}{\Delta t}$$

Example: In the case above, we said the EMF was $\mathcal{E} = vBL$. We can analyze that case by Faraday's Law. In a time of Δt, the bar moves a distance of $v\Delta t$. This changes the area of the loop by $\Delta A = Lv\Delta t$. The magnetic field is constant and the angle is fixed at 0 ($\cos\phi = 1$), so the change in flux is $\Delta\Phi = B(\Delta A) = BLv\Delta t$. In Faraday's Law, we only have one loop ($N = 1$), so $\mathcal{E} = BLv$.

9 Lenz's Law

Faraday's Law is good at giving us the magnitude of the voltage generated in a loop, but it is hard to use it to get the direction. One would have to keep careful track of vectors and signs, then interpret the sign of the answer. Lenz's Law makes things easier. Lens's Law states that when a changing flux causes an EMF in a loop, the direction of the EMF is such that if it could cause a current (and it often does), the current creates a magnetic field to oppose the original **change** in flux. In other words, magnetic systems like the steady state and oppose change. To use Lenz's Law, use the following steps:

1. Which direction is the original magnetic field?
2. Is the flux increasing or decreasing?
3. If the flux is increasing, the new magnetic field must be opposite the original field.
   If the flux is decreasing, the new magnetic field must be in the same direction as the original field.
4. Use the second RHR to find out what direction the induced current must go to create this new magnetic field.

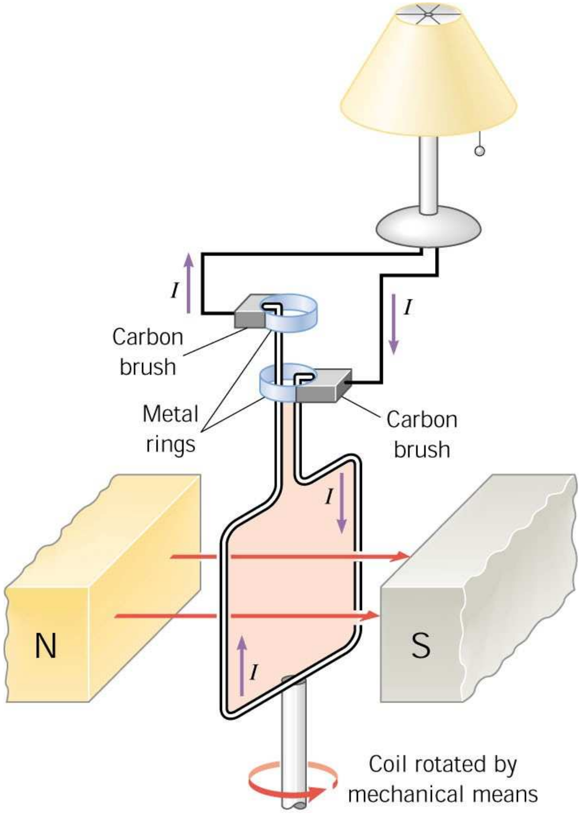
If the flux is increasing, we must oppose the original field to try to knock the flux back down. If the flux is decreasing, we must add to the original magnetic field to get the flux back up. Use the RHR to figure out which direction the current must flow to accomplish the task.

10 Electric Generator

A generator or alternator consists of a coil that is spun in a magnetic field. The EMF at any given time changes like a sine wave.

$$\mathcal{E} = \mathcal{E}_{\text{max}} \sin \omega t \qquad\qquad \mathcal{E}_{\text{max}} = NAB\omega$$

Here, ω is the spinning rate of the shaft, in rad/s, N is the number of loops of wire in the coil, A is the area, and B is the magnetic field.



DEMO: Generator

Any motor also works as a generator. The EMF of a motor is called “Back EMF” because it opposes the voltage driving the motor, reducing the current. This is good. When the motor is spinning fast, only a small current is required to keep it spinning. Slow a motor down, though, and the back EMF gets small, so the current can be quite large. In this way, a motor draws more current when the speed is slow. It then gets to push harder. The current is $I = \dfrac{V - \mathcal{E}}{R}$.

11 Inductors

Any coil of wire that exists just by itself is an inductor. Any electric current in the coil will create a magnetic field, and that magnetic field going through the ring of the coil constitutes a flux. The flux is

$$N\Phi = LI$$

Where N is the number of turns of wire in the coil, Φ is the flux ($\Phi = BA_{\text{coil}}$), L is called the inductance, and I is the current. A change in the total flux on the left-hand side causes an EMF. The only thing on the right-hand side that can change is the current I, so in an inductor, a change in current causes a voltage. Faraday’s Law becomes:

$$\mathcal{E} = -L\frac{\Delta I}{\Delta t}$$

It's negative because the inductor opposes any change in current.

With two coils near each other, the second coil can "feel" the magnetic flux created by the first. The formula is basically the same, except that we call it M for mutual inductance between the two coils. The first coil (the one we're putting a current through) is called the primary, and the second coil is called the secondary. $N_S\Phi_S = MI_P$

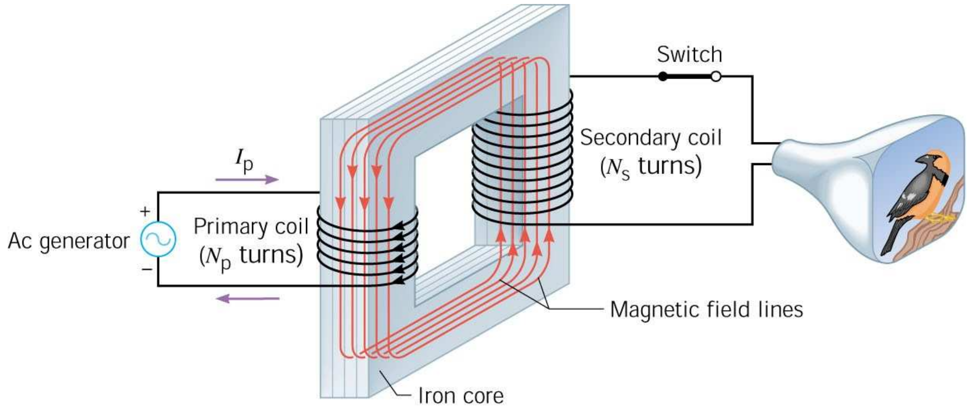
A magnetic material placed inside an inductor increases the magnetic flux (because the tiny magnets inside the material orient themselves with the coil's magnetic field). This has the effect of increasing the inductance. This effect is used in traffic sensors, which detect the change in inductance of a coil when a car is sitting on top of it. These sensors can be used to trip traffic lights, count cars, or even measure speeds.

12 Transformers

A transformer is a pair of coils that share the same magnetic field and the same magnetic flux. Because the EMF depends on the change in flux, any change in flux causes an EMF in both coils. The ratio of the EMF's is equal to the ratio of the number of turns of wire in each coil. Because a transformer cannot create energy from nowhere, if the voltage is increased, the current must be decreased.

$$\frac{V_P}{V_S} = \frac{N_P}{N_S} = \frac{I_S}{I_P}$$

We used transformers to change AC voltages from one value to another. Power transmission wants high voltages to reduce the currents, but home safety wants low voltages and must deal with higher currents. A transformer is called step-up or step-down based on what it does to a voltage. Only AC voltages work in transformers, because it is the change in flux that causes the EMF in the secondary.



13 Concept List

Magnetic Poles and Field
Compass
Magnetic Force (moving charge and current)
Electric Motor
Circular Motion, Mass Spectrometer
Velocity Selector
Field of a wire, coil, and solenoid
Ampere's Law

Electromagnetic Induction
Flux, Faraday's Law
Lenz's Law
Generator
Back EMF of Motor
Inductor
Transformer
Right-Hand Rules

14 Review - Concepts to remember

- Magnetic fields come out of the **north** pole of a magnet and into the **south** pole. A compass needle in an external magnetic field will want to point in the direction of the external magnetic field. The Earth's field points North, toward the magnetic south pole.
- Magnetic fields create forces on moving charges and forces on currents. The force is perpendicular to both the magnetic field and the velocity or current. We use the RHR to get the direction and formulas to get the magnitude of the force.
- A coil experiences a **torque** in a magnetic field that tries to make it point in the direction of the field (just like the compass needle). This is the concept behind the **electric motor**.
- An **electric field** can be used to cancel the magnetic force. Since magnetic force depends on speed, this electric field only works at one velocity, a concept used in the **velocity selector**.
- Charges flying through a magnetic field move in **arcs, circles, or helices** with a calculatable radius. We use this concept for the **mass spectrometer**.
- Electric **currents create magnetic fields**. A straight current has the field wrap **around** it with a direction by the RHR and a magnitude that decreases with distance from the wire. A **loop or coil** has a field that looks like a bar magnet's field, with a dir by the RHR. A **solenoid** is a long coil that has a uniform field inside and almost no field outside.
- **Ampere's Law** is sometimes used to calculate the magnetic field due to a current. It tells us that magnetic field is always **proportional** to the current causing it.
- A wire moving in a magnetic field has an **EMF** (voltage) generated in it. This is true whether the wire or the magnet is moving!
- **Magnetic flux** is a way of measuring the total magnetic field passing through a ring. The units are magnetic field times area, and it decreases if the field is hitting the ring at an angle. **Change in magnetic flux** is what causes an EMF (Faraday's Law).
- **Lenz's law** tells which **direction** an induced EMF (and its current) are pointing. The current, if it exists, tries to counter the original change in flux that caused the EMF.
- A **generator** or alternator uses a spinning coil in a magnetic field to generate electricity. The EMF can be calculated from Faraday's Law. An electric motor also experiences an EMF, called "**Back EMF**", which effectively reduces the input voltage. At full speed, the Back EMF is almost the input voltage, and the current is small. At low speed, there's little Back EMF and the motor pushes harder.
- An **inductor** is basically any coil. The **total flux** is the product of the inductance and the current. In an inductor, a change in current causes a voltage.
- A **transformer** is a pair of coils that share their magnetic field (and flux). The "turns ratio" causes an AC voltage to be stepped-up or stepped-down. The current does the opposite.