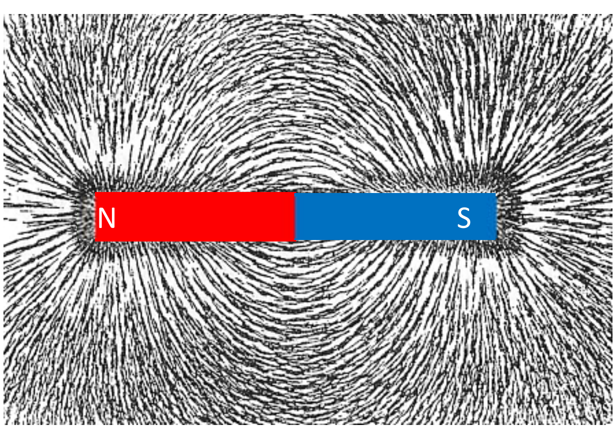
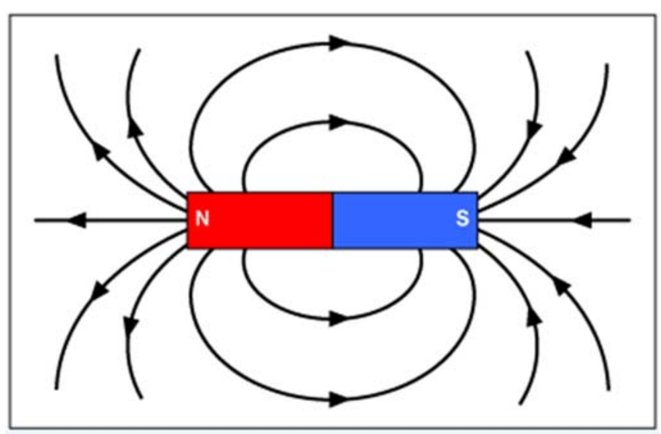
PHYS:1200 LECTURE 27 — ELECTRICITY AND MAGNETISM (5)

Everyone has played with magnets and knows that they stick to some materials and not to others. This lecture explores the physical principles behind magnetism, and some of the applications of magnetism. Magnetic effects are generally stronger than electric effects, so they are more easily visualized. As we learned in the previous lectures, charges produce electric fields. Magnetic fields are also associated with electric charges in motion, i.e., currents. For the permanent magnets that hold photos on the doors of refrigerators, the currents are embedded in the atoms of the magnet – they are atomic level currents that we cannot see. However, a current in a wire also produces a magnetic field, so we refer to this phenomena as electromagnetism. At the fundamental level, however, the magnetic fields of permanent magnets and electromagnets are due to currents.

Since the Earth is a big magnet, so we will spend some time discussing the Earth's magnetic field, how a compass works, and the interactions between the Earth's field and the particles that stream to the Earth from the Sun. Also, we will explain the phenomenon of the Van Allen radiation belts, discovered by the man for whom the physics building is named.

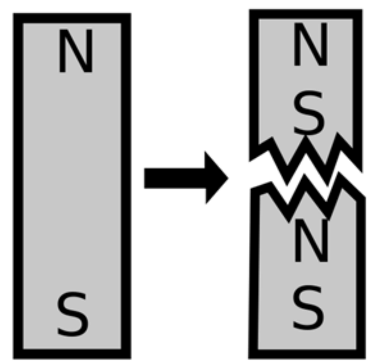
27-1. Permanent Magnets.—Since about 2500 years ago, the ancient Greeks and Chinese knew that certain materials would attract little bits of iron. Magnetite, Fe_3O_4, or loadstone, is a naturally magnetic material. A magnetic material influences the space around it by creating a





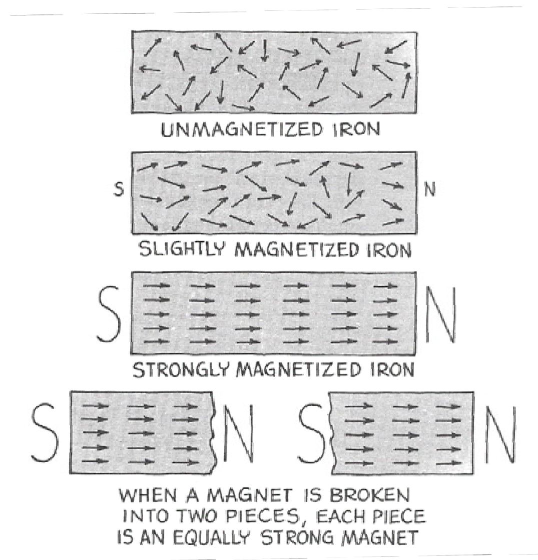
magnetic field which permeates space in a manner similar to the gravitational field that surrounds the Earth. The magnetic field of a bar magnet can be visualized by sprinkling iron filings around it as shown above on the left side. The ion filings settle into a two-dimensional pattern that reveals the magnetic field lines- the black lines in the diagram above on the right side

Unlike charges which exist individually as positive or negative, **magnets always have a north and a south pole that cannot be separated**. Like poles of two magnets repel each other and unlike poles attract. The magnetic field pattern for a bar magnet is shown as the diagram on the right above. The lines of magnetic field (we say “lines” even though they can be curved) always begin on a north pole and end on a south pole. In fact, a basic rule of nature is that magnetic field lines always form closed loops. This is related to the fact that the north and south poles can never be separated. If a bar magnet is broken in two pieces, the remaining pieces both have a north and a south pole. Although there have been many attempts to look for an isolated north or south pole (referred to as a monopole) none has ever been found.



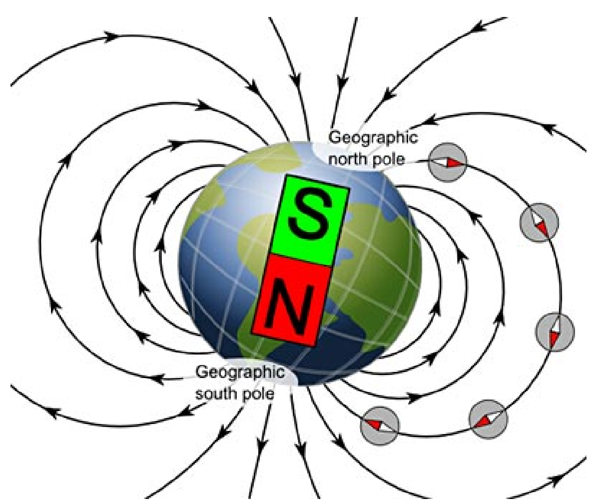
Magnetic properties of materials.—The magnetic properties of materials are due to the **motion of the electrons within the atoms**. Electrons exhibit two types of motion: an or**bital motion about the atomic nucleus, and a spinning motion** about their own axis like a top. These motions of the electrons are microscopic currents that create magnetic fields. The magnetic fields associated with the spinning motion of the electrons is most predominant. So we can think of each **spinning electron as a little electromagnet**. A pair of electrons spinning in opposite directions is not magnetic since the magnetic fields of each cancel one another. In most materials the various magnetic fields cancel each other and these substances are non-magnetic. Copper, aluminum, and the non-conductors are non-magnetic, and magnets will not stick to them. In materials like iron, nickel, and cobalt, the fields do not cancel each other entirely. In iron atoms, for example, there are 4 outer electrons whose spin magnetism is un-cancelled. Each iron atom, then, is a tiny magnet. The same is true to a lesser degree for the atoms of nickel and cobalt.

In a sample of iron, the interactions between adjacent iron atoms is so strong that large clusters of atoms line up and produce microscopic regions called domains that are fully magnetized. However, not all the domains in the material are aligned, so that every piece of iron is not a magnet. In an ordinary nail, the domains in the nail are randomly oriented. They can be forced into alignment if a magnet is brought by the nail. This magnetic effect is only temporary and dissipates when the magnet is removed. The process of magnetization is illustrated in the diagram on the right. The arrows represent the magnetic fields in individual domains. Permanent magnets are made by placing pieces of iron in strong magnetic fields. In some metals, samarium-cobalt, and neodymium, the domains once aligned, tend to stay aligned and produce very strong magnetic fields.



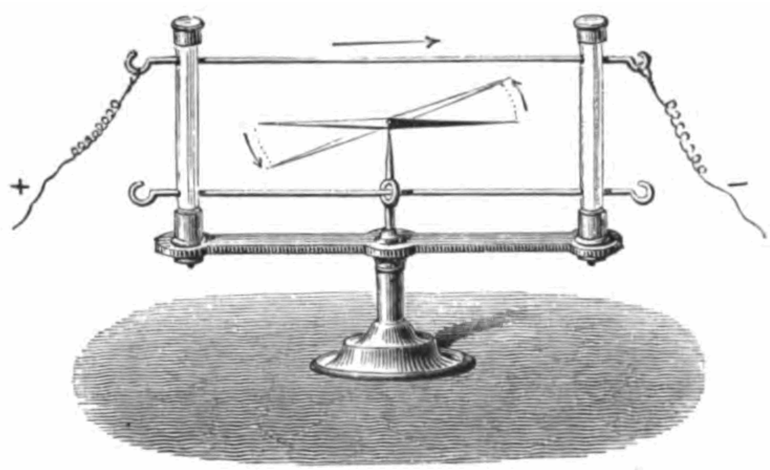
27-2. The Magnetic Field of the Earth.—The Earth and planets (with the exception of Venus and Mars) have an **intrinsic magnetic field**. The origin and nature of the Earth's magnetic field is not entirely understood, but is thought to be due to currents flowing in its molten core. The currents seem to be associated with the rotation of the planets. Jupiter, which has the highest rotation rate of all the planets (one revolution every ten hours) has the largest magnetic field.

A **compass needle (a north pole)** aligns with the magnetic field of the Earth. The magnetic poles of the Earth's field do not coincide with the geographical poles which coincide with the Earth's spin axis. In fact, the magnetic and geographic poles are roughly 1100 miles apart. The Earth's magnetic pole in the northern hemisphere is a south magnetic pole since it attracts the north pole of a compass. The north pole (magnetic) of a



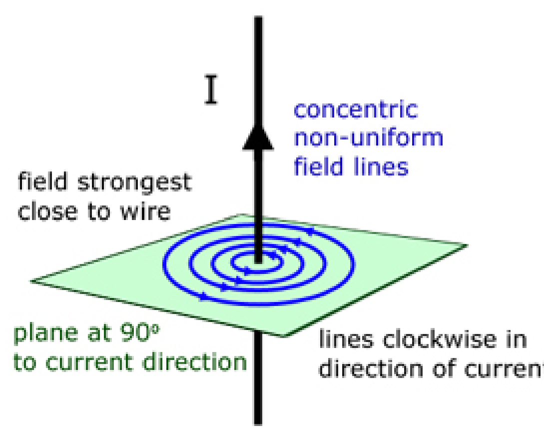
compass points north (geographic) because the north geographic pole is near the south magnetic pole. The magnetic field of the earth resembles the field that would be created by a **huge bar magnet that is tilted by about 12 degrees** from its spin axis. The discrepancy between the orientation of a compass and true north is called **magnetic declination,** and must be taken into account in navigation.

27-3. Electromagnets.—Hans Christian **Oersted** observed in 1820 that a compass needle would rotate in response to a current in a nearby wire. This showed the relationship between

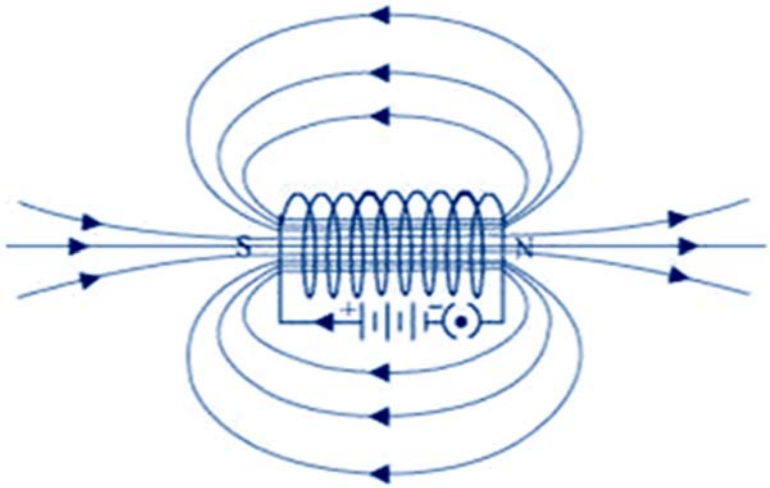


Oersted's apparatus showing that a current in a wire caused a nearby compass needle to rotate. This established the principle of electromagnets.

currents and magnetic fields --- **currents are the source of magnetic field.** A mathematical formula that relates the current to the magnetic field was obtained experimentally by **Ampere** at about the same time. This is known as **Ampere's Law**. A long straight wire carrying a current produces a magnetic field pattern that is in the form of concentric circles surrounding the wire. As described earlier in this lecture, the magnetic field lines form closed loops. The field is strongest close to the wire and gets weaker with distance from the wire. The fields of electromagnets can also be mapped out using small bits of iron.

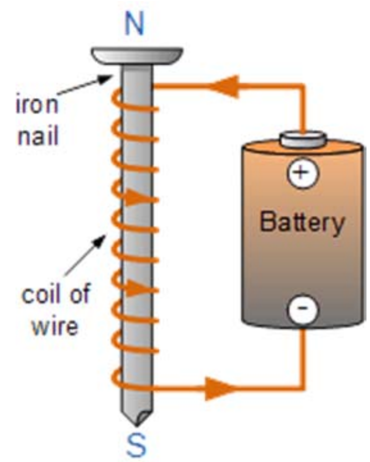


Another common electromagnet configuration is the **solenoid** which is a set of circular coils wound on a cylindrical form. Notice that the field of a solenoid closely resembles the field of a bar magnet and has a north and south pole. The field lines loop around from the north pole to the south pole and always close on themselves. The magnetic field is strongest inside the coil.



Magnetic field of a solenoid.

A **simple electromagnet** can be made using a nail with wire wrapped around it and a battery to drive current in the wires. When current is applied to the coil surrounding the nail, the nail becomes magnetized and a stronger magnetic field is produced than the field of the coil alone. The magnetization of the nail is not permanent and will diminish quickly after the current in the coil is turned off.



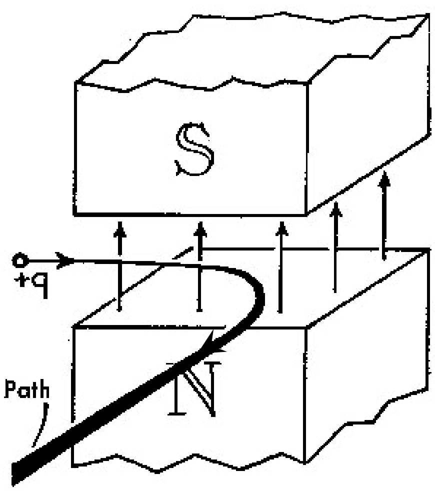
27-4. Magnetic Forces

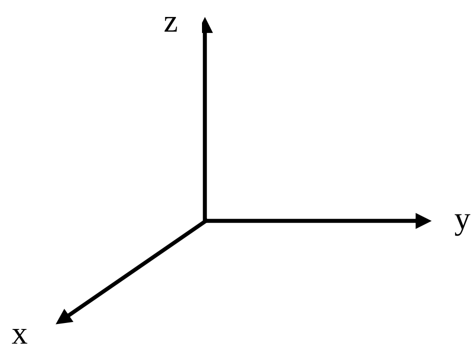
a. Magnetic forces on charged particles.—Magnetic fields exert magnetic forces on charged particles. Two charges simply attract or repel each other along the line on which they lie, however, magnetic forces are more complicated than electric forces. **The rules for magnetic forces on charged particles are**:

- A charged particle in a magnetic field experiences a magnetic force only if the charged particle is moving (There is no magnetic force on a stationary charged particle.).
- There is no magnetic force on a charged particle if it moves parallel to a magnetic field.
- A moving charged particle experiences a magnetic force if its velocity has a component perpendicular to the magnetic field.

- For a charged particle moving perpendicular to a magnetic field, the magnetic force on it is perpendicular to the magnetic field and the velocity.

The path of a positively charged particle moving into a region between the poles of a magnet is shown in the diagram below. The magnetic field is in the +z direction, the velocity of the particle





is in the +y direction, and the magnetic force is in the +x direction. If the particle had a negative charge, the magnetic force would be in the – x direction.

Magnetic fields have the effect of **confining charged particles along the field**. The charged particles execute a **helical motion** around the magnetic field line while moving along the field. The trajectory of an electron in a magnetic field is illustrated in the diagram below.

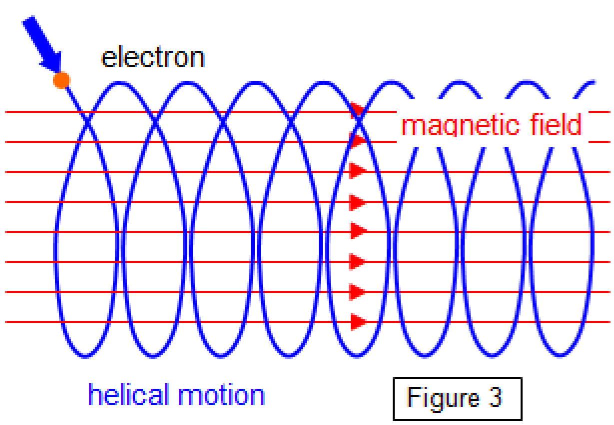
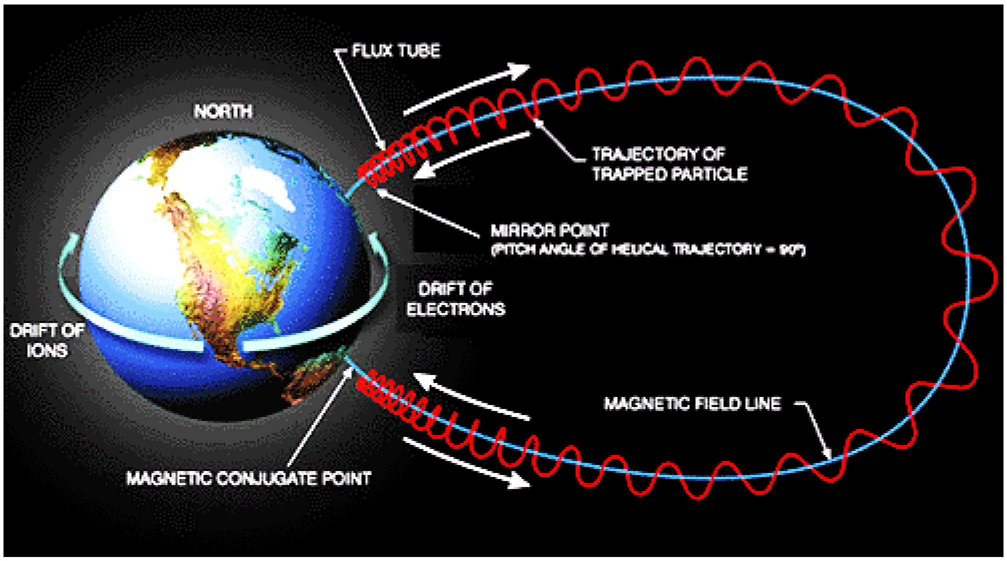
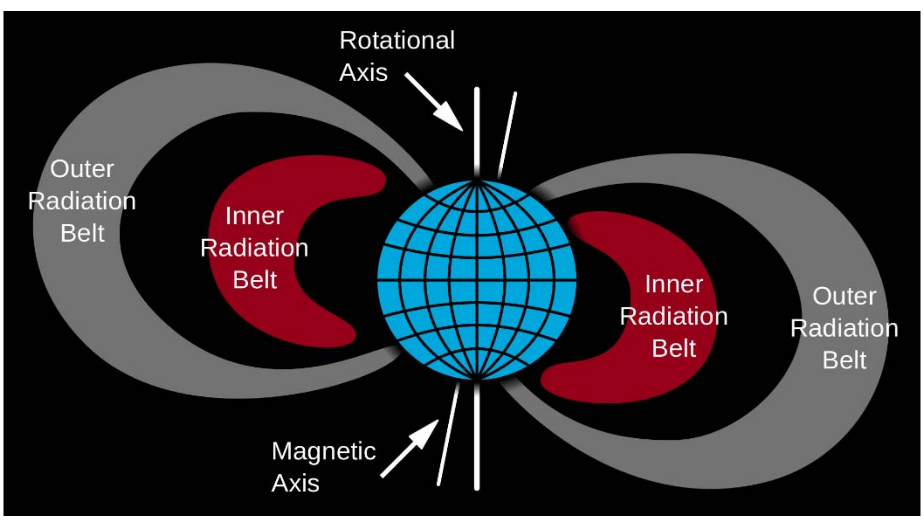


Figure 3

b. The Van Allen radiation belts.— Charged particles confined on the Earth's magnetic field lines is the origin of the Earth's radiation belts named in honor of Professor James A. Van Allen, for who the physics building is named. The Sun which appears as a relatively calm bright object in the sky is anything but calm. Its surface exhibits a tremendous amount of turbulent behavior and spews out a continuous stream of mostly electrons and protons referred to as the solar wind. Occasionally, huge eruptions occur on the Sun's surface releasing on the order of a trillion kg of mass in CMEs (**coronal mass ejections**). When these charged particles reach the Earth some of them get trapped on the Earth's magnetic field lines and move up and down from the northern hemisphere to the southern hemisphere as shown below. (see slide 17 also) The particles also



move longitudinally around the earth forming two layers or belts encircling the earth that are known as the Van Allen Radiation belts. These regions of trapped protons and electrons were discovered in 1958 by Professor Van Allen and his colleagues using instruments built at the University of Iowa (in a laboratory under the Pentecrest) and deployed onboard the Explorer I

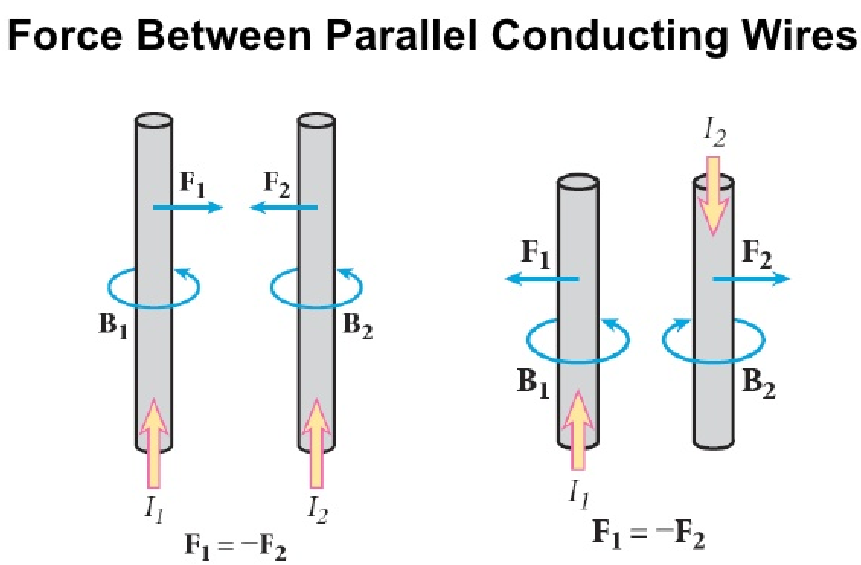


satellite. *Radiation* is the general term used to describe any effect that is detected using a Geiger counter. The radiation belts are actually regions of enhanced populations of highly energetic charged electrons and protons rather than electromagnetic radiation. The discovery of the radiation belts led one member of Van Allen's team to declare that "space is radioactive"!

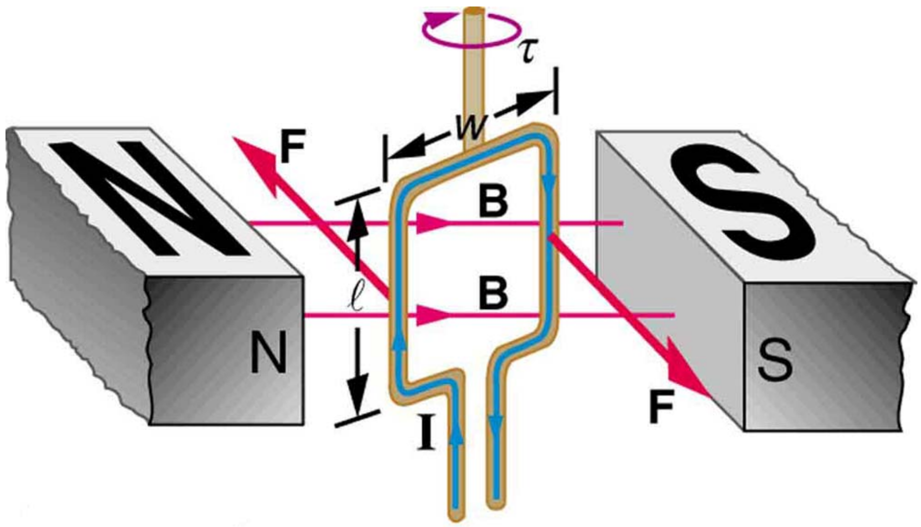
The charged particles trapped by the Earth's magnetic fields have a dramatic effect in the Earth's Polar Regions where the magnetic field lines concentrate at the poles. Electrons which are accelerated downward toward the north pole collide with oxygen and nitrogen molecules in the upper atmosphere, and the excited molecules emit visible light in spectacular patters known as the **aurora or Northern Lights** (Southern lights in the southern hemisphere). (see slide 14).

c. Magnetic forces on wires carrying currents.—The current in a wire is nothing more than a stream of moving electrons. I**f a current-carrying wire is placed in a magnetic field, the electrons experience a magnetic force which is seen as a force on the wire as a whole.** This is illustrated on slide 20.

Since currents produce magnetic fields, two nearby current-carrying wires will also experience a magnetic force. This is illustrated on slide 21 and in the diagram below.



d. The electric motor.—The magnetic force on a coil of wire in a magnetic field is the principle behind the **electric motor**. When a current-carrying loop of wire is placed between the poles of a magnet, the magnetic force on it produces a torque which causes it to rotate as illustrated on slide 22 and in the diagram below.



When this loop is attached to a shaft, the device is an **electric motor**, which converts electrical energy into mechanical energy. Some additional applications of magnetic forces are illustrated **on slides 19, 24, and 25.**