Electromagnetism and EM Waves

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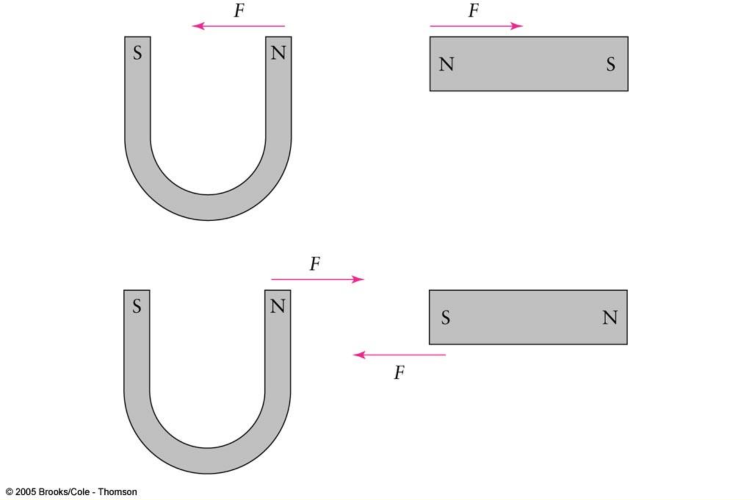
Magnetism

- Magnets always have at least two poles.
  - A **north pole** and a **south pole**.
- We have never observed a magnetic monopole — a magnet with only one pole.
- As for electric charges, opposites attract:
  - North pole is attracted to south pole.



Magnetism, cont'd

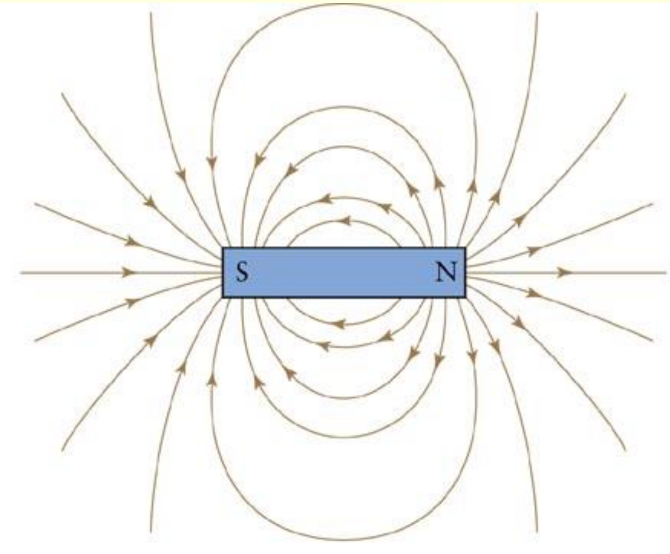
- There are different types of magnetic materials.
- The most common is:
  - *Ferromagnets* are materials in which a magnetic field is induced when it is near a magnet.
    - *If a piece of iron is brought near the south pole of a magnet, the part of the iron nearest the magnet has a north pole induced in it.*
    - *Once removed from the magnet, the iron loses essentially all of its magnetic field.*

Magnetism, cont'd

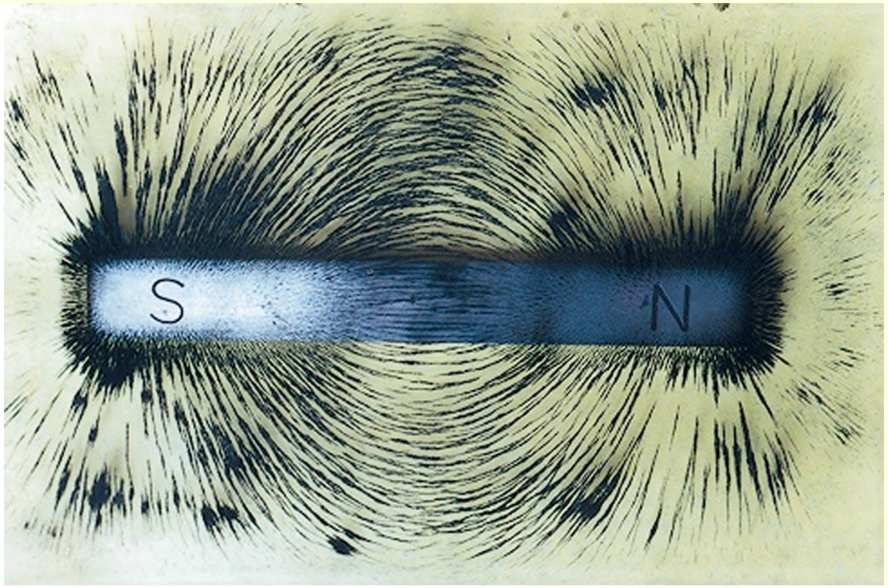
- Materials that maintain a magnetic field induced in them are called *permanent magnets*.
- As with gravitation and electrostatics, it is useful to employ the concept of a magnetic field.
- A *magnetic field* is produced by a magnet and acts as the agent of the magnetic force.
  - *Outside the magnet, the field points from north pole to south pole.*

Magnetism, cont'd

- Here is an example of a magnetic field.

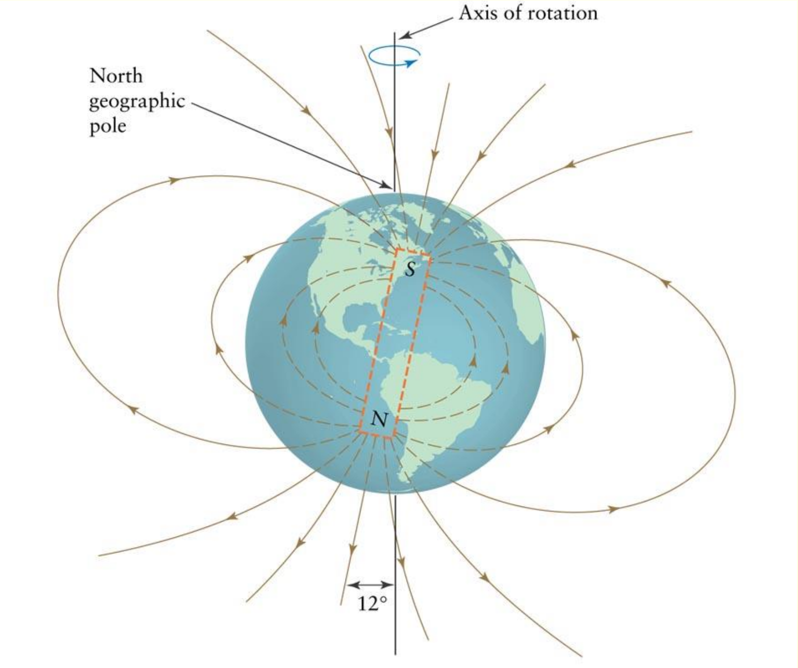


(a)



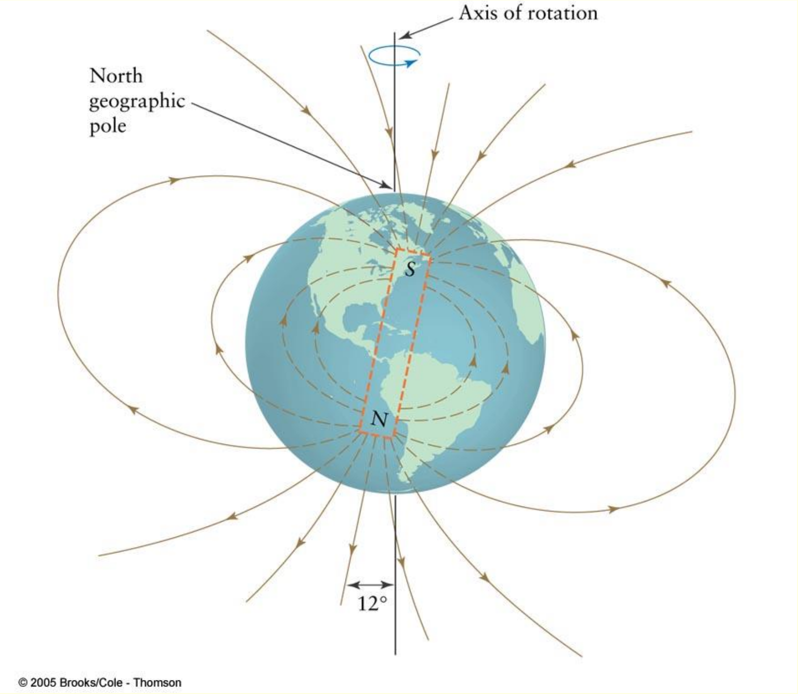
Magnetism, cont'd

- The Earth's geographic north and south pole correspond to magnetic poles.
- But the Earth does not rotate about the north-south pole axis.
  - *The magnetic axis is tilted about 12º from the Earth's axis of rotation.*



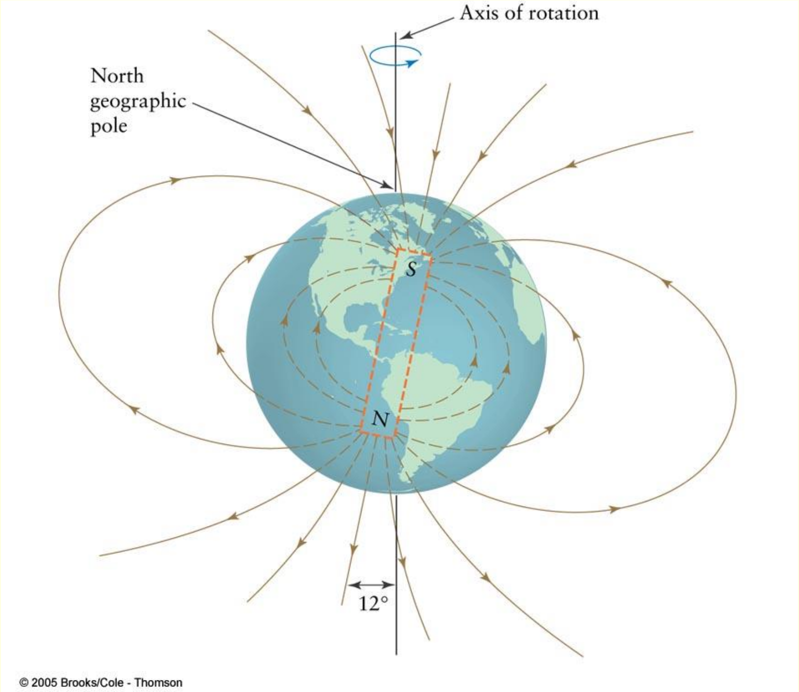
Magnetism, cont'd

- The geographic north pole corresponds to the magnetic south pole, and *vice versa*.
- So the north pole of a compass points to the geographic north pole because it is the magnetic south pole.



Magnetism, cont'd

- The Earth's magnetic poles are not stationary.
  - The south magnetic pole is not exactly where it was 20 years ago.
- Plus, the poles swap ends every few hundred thousand years.



Interactions between electricity and magnetism

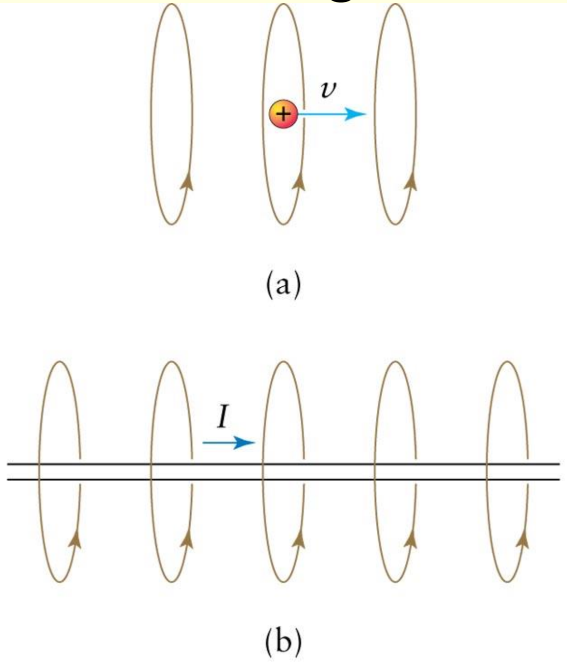
- Let’s summarize key aspects of electrostatics and magnetism.
  - Electric charges produce electric fields in the space around them.
  - An electric field causes a force on any charged object placed in it.
  - Magnets produce magnetic fields in the space around them.
  - A magnetic field causes a forces on the poles of any magnet placed in it.

Interactions between electricity and magnetism, cont'd

- The word *electromagnetic* is used when the interplay between electricity and magnetism is involved.
  - Numerous everyday items use electromagnetic properties:
    - electric motors, vacuum cleaners, computer disk drives, generators, microphones microwave ovens, and many more.

Interactions between electricity and magnetism, cont'd

- The first of the three observations is the basis of electromagnets:
  - **Observation 1**: A moving electric charge produces a magnetic field in the space around it.
    - An electric current produces a magnetic field around it.
- A single charged particle creates a magnetic field only when it is moving.

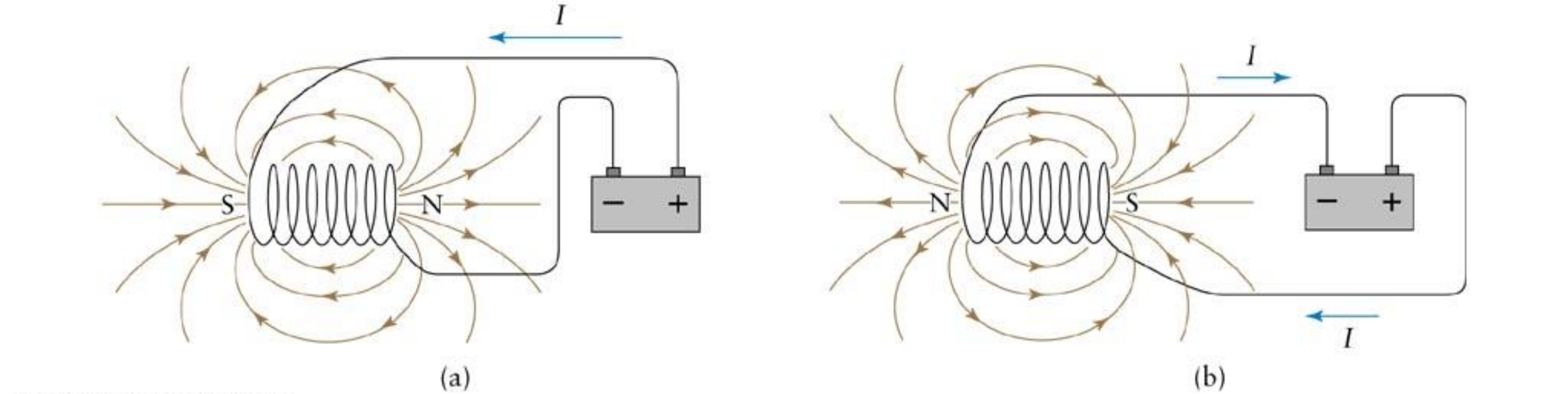


Interactions between electricity and magnetism, cont'd

- A DC current is a steady progression of electric charges.
- The magnetic field:
  - is constant,
  - has a strength proportional to the amount of current through the wire, and
  - has a strength that is inversely proportional to the distance from the wire.

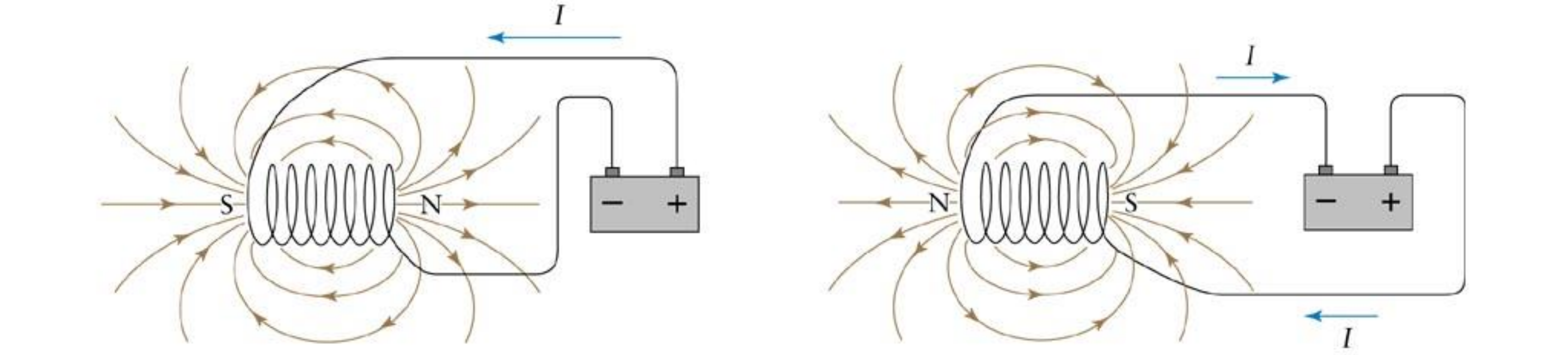
Interactions between electricity and magnetism, cont'd

- Most applications use a coil instead of a straight wire.
  - The coil is a length of wire wrapped in the shape of a cylinder (or a donut), usually around an iron core.
- The field has the shape of a bar magnet.



Interactions between electricity and magnetism, cont'd

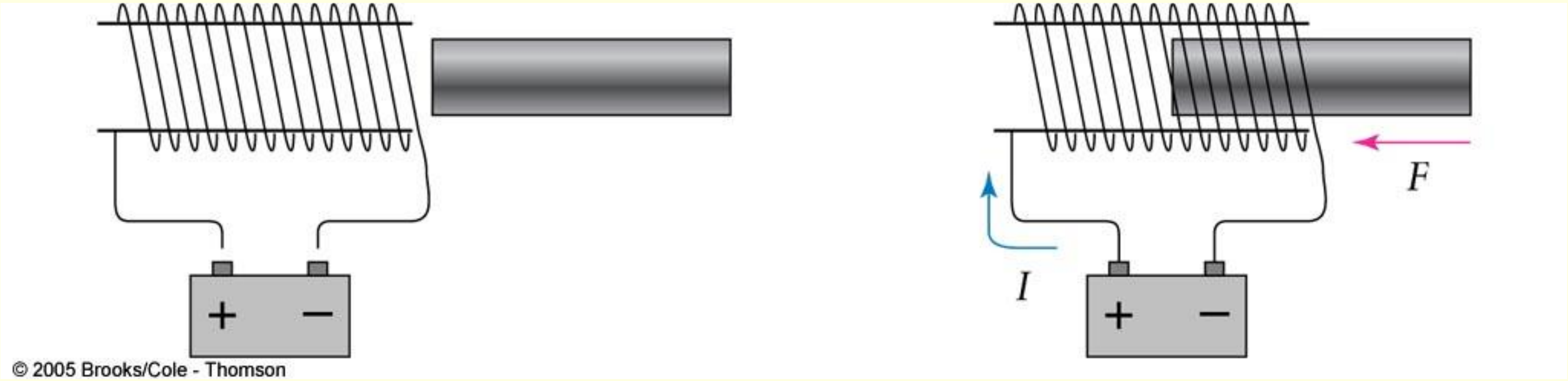
- This type of device is called an *electromagnet*.
  - It behaves like a permanent magnet. but only while the current is flowing.
  - Stop the current and the magnetic field vanishes.



(a) (b)

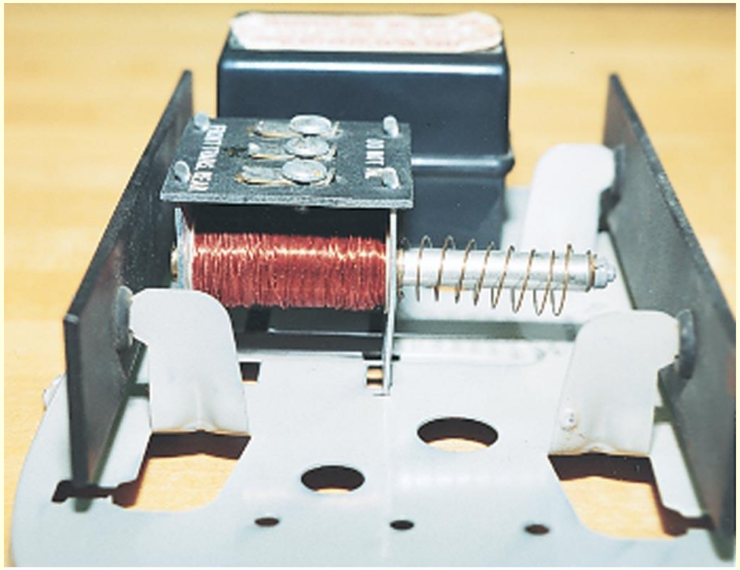
Interactions between electricity and magnetism, cont'd

- A coil with a length much larger than its diameter is called a *solenoid*.
- If an iron rod is partially inserted into a hollow core solenoid, the rod will be pulled into the solenoid when the current switches on.



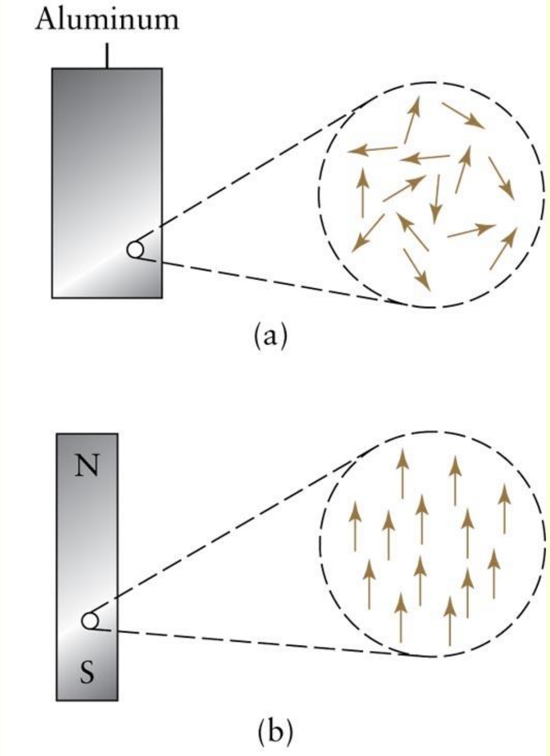
Interactions between electricity and magnetism, cont'd

- Examples of such a solenoid include:
  - non-digital doorbell chimes,
  - electric door locks, and
  - starter motors on car and truck engines.



Interactions between electricity and magnetism, cont'd

- This first observation helps explain why only certain materials can serve as permanent magnets.
  - In aluminum, the electron's fields are random.
  - In a ferromagnetic material, the fields can be forced to align by an external magnetic field.



Interactions between electricity and magnetism, cont'd

- The second observation is the basis of electric motors:
  - **Observation 2**: A magnetic field exerts a force on a moving electric charge.
    - A magnetic field exerts a force on a current-carrying wire.
- A stationary electric charge does not experience a force in a magnetic field.

Interactions between electricity and magnetism, cont'd

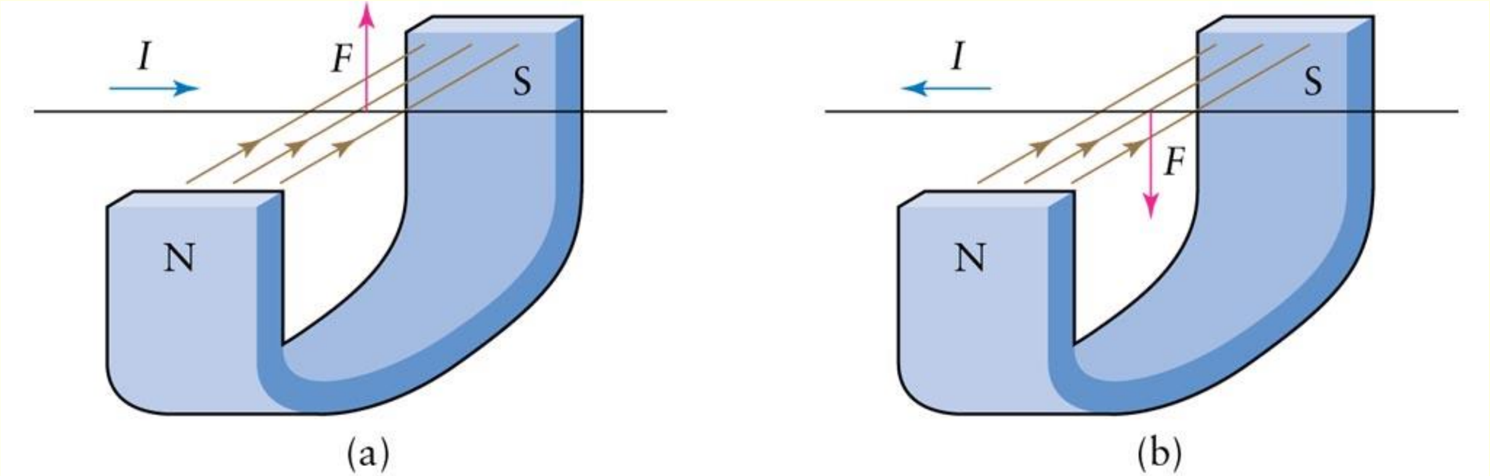
- This observation is in line with the first:
  - Anything that produces a magnetic field will itself be affected by other magnetic fields.
    - A moving charge creates a magnetic field.
    - So a moving charge experiences a force from other magnetic fields.

Interactions between electricity and magnetism, cont'd

- The force experienced by a moving electric charge in a magnetic field has an interesting property.
  - Note that the direction of the magnetic field producing by a current-carrying wire is perpendicular to the direction the current is flowing.

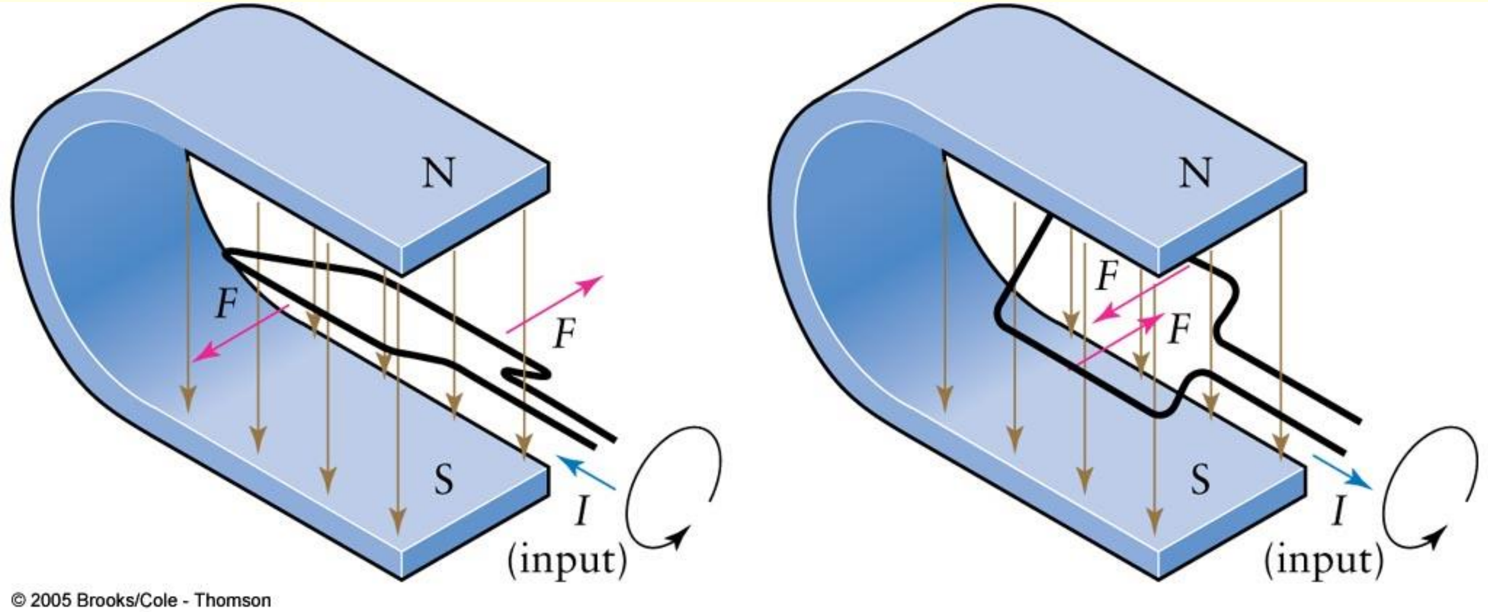
Interactions between electricity and magnetism, cont'd

- The force experienced by a moving electric charge is perpendicular to the direction of the field and the current.



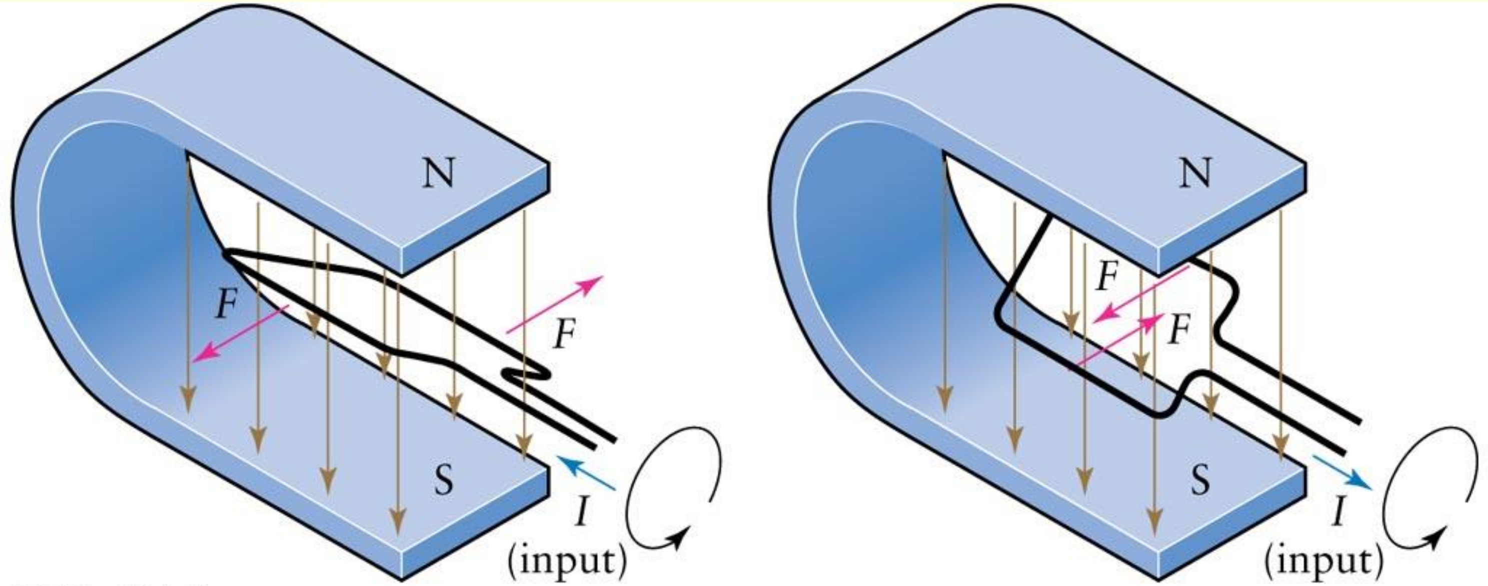
Interactions between electricity and magnetism, cont'd

- Electric motors exploit this electromagnetic interaction.
  - Rather than a straight wire, a motor uses a coil.



Interactions between electricity and magnetism, cont'd

- Each time the loop becomes horizontal, the direction of the current is reversed.
- This allows the magnetic force to continue rotating the coil.

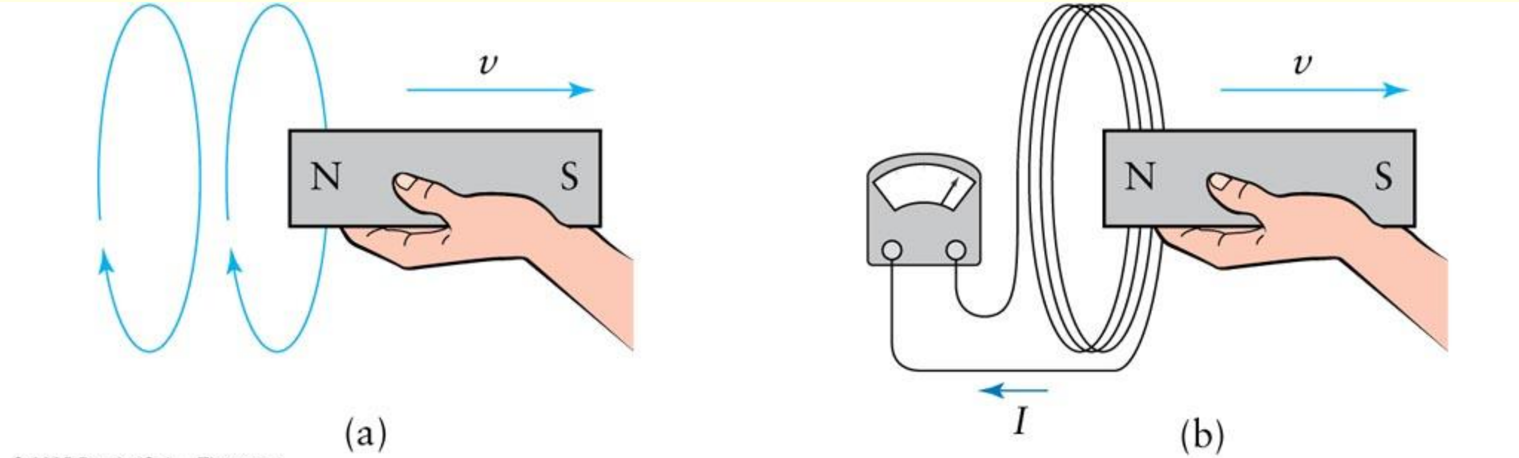


Interactions between electricity and magnetism, cont'd

- The third observation is the basis of electric generators:
  - **Observation 3**: A moving magnet produces an electric field in the space around it.
    - A coil of wire in motion relative to a magnet has a current induced in it.
- This process is known as **electromagnetic induction**.

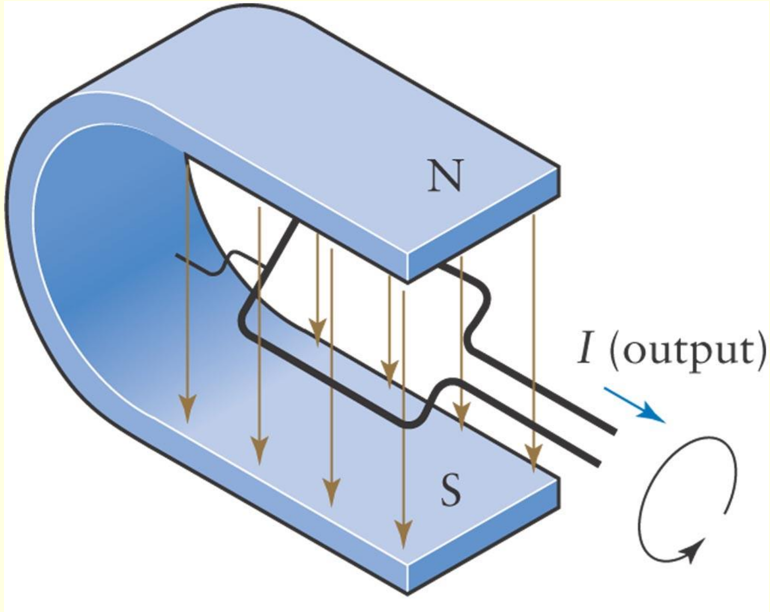
Interactions between electricity and magnetism, cont'd

- The electric field produced by a moving magnet if circular (left).
- Moving the magnet through a coil establishes a current in the coil.



Interactions between electricity and magnetism, cont'd

- Here is a simplified sketch of a generator.
  - As the coil rotates in the magnetic field, a current is established through the coil.



Principles of Electromagnetism

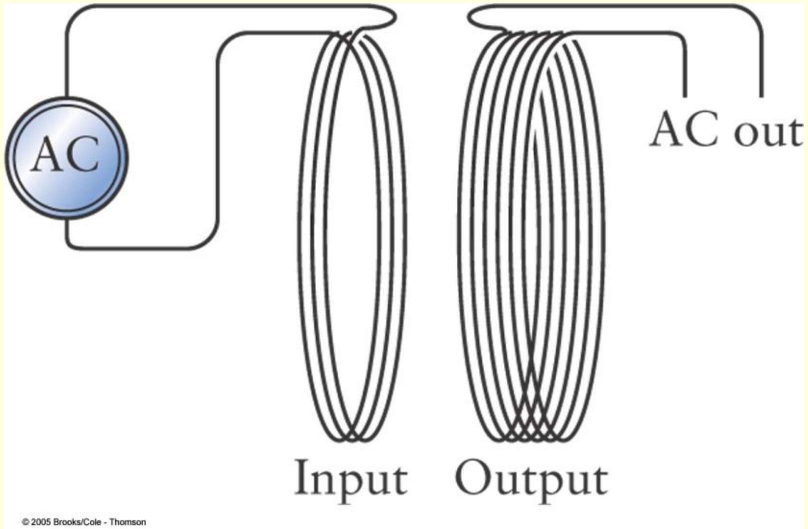
- We can make two general statements about electromagnetism.
- The text calls these the **Principles of Electromagnetism:**
  - An electric current of a changing electric field induces an electric field.
  - A changing magnetic field induces an electric field.

Principles of Electromagnetism, cont'd

- We mentioned earlier about a transformer as a device to transform AC voltage and current.
- Recall that AC current is a time-varying current.
- So by the principles of electromagnetism, it creates a changing magnetic field.
    - Remember than a steady current produces a steady magnetic field.

Principles of Electromagnetism, cont'd

- A transformer consists of two coils in close proximity.
- If an AC current is applied to the left coil, the changing current through the coil creates a changing magnetic field.
- So the right coil is in a changing magnetic field.

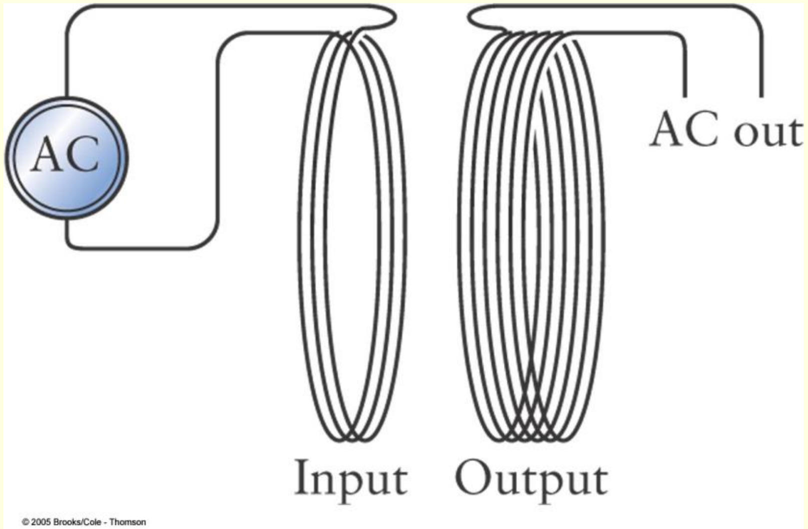


Principles of Electromagnetism, cont'd

- Since a changing magnetic field induces an electric field, there is a current in the right coil.
- The limiting principle of the transformer is that the power input (on the left) must ideally equal the power output (on the right).

$$P_{\text{in}} = P_{\text{out}}$$

$$I_{\text{in}}V_{\text{in}} = I_{\text{out}}V_{\text{out}}$$



Principles of Electromagnetism, cont'd

- Note that each loop of the coil has the same voltage induced in it.
- The voltage of the entire coil is the sum of the voltages in each loop.
  - Each loop is in series with the others.
  - Voltages in series add.

Principles of Electromagnetism, cont'd

- The result is:

$$\frac{\text{voltage output}}{\text{voltage input}} = \frac{\text{number of turns in output coil}}{\text{number of turns in input coil}}$$

- We can write this as:

$$\frac{V_o}{V_i} = \frac{N_o}{N_i}$$

  - V_i & V_o represent the input and output voltages.
  - N_i & N_o represent the number of coils on the input and output coils.

Principles of Electromagnetism, cont’d

- Recall that a step-up transformer increases the output voltage.
  - So the output coil has more turns than the input coil.
- A step-down transformer decreases the output voltage.
  - So the output coil has fewer turns than the input coil.

Example
Example 8.1

A transformer is being designed to have a 600-volt output with a 120-volt input. If there are to be 800 turns of wire in the input coil, how many turns must there be in the output coil?

Example
Example 8.1

ANSWER:

The problem gives us:

$$V_o = 600 \text{ V}$$

$$V_i = 120 \text{ V}$$

$$N_i = 800$$

The number of turns in the output coil is

$$\frac{V_o}{V_i} = \frac{N_o}{N_i} \rightarrow N_o = N_i \times \frac{V_o}{V_i}$$

Example

Example 8.1

ANSWER:

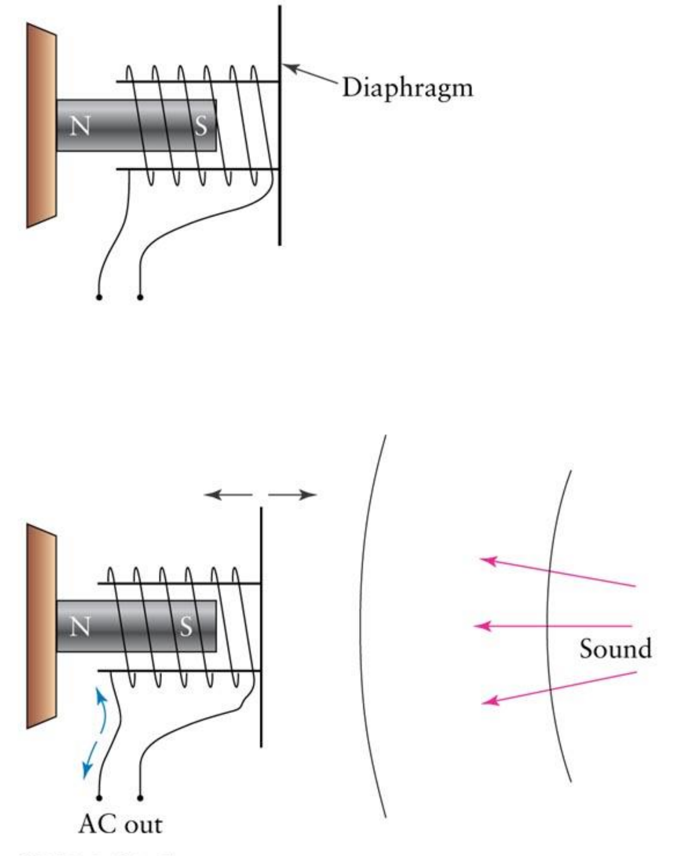
Inserting the given values:

$$N_o = 800 \times \frac{600}{120} = 800 \times 5$$

$$= 4,000 \text{ turns.}$$

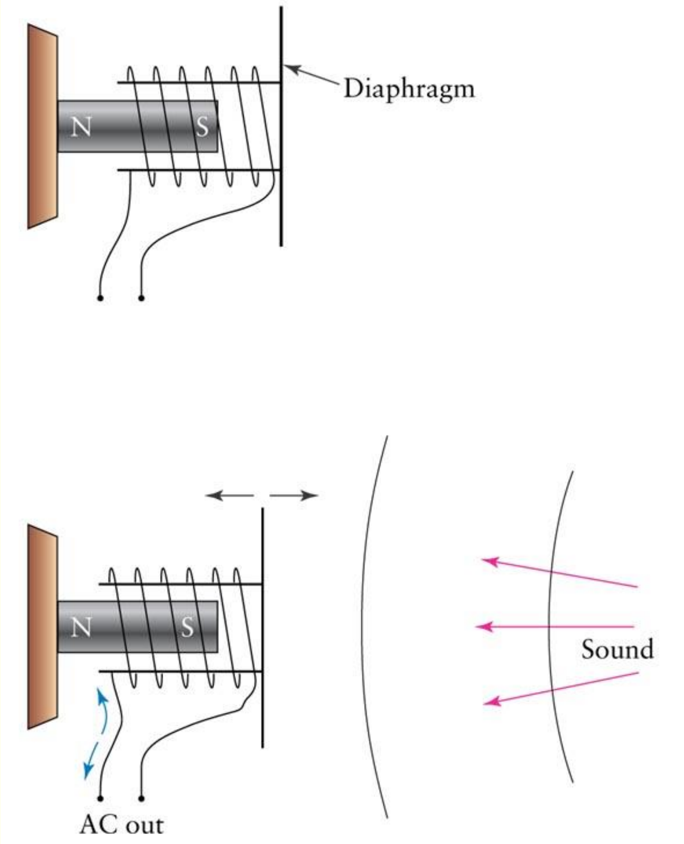
Applications to sound reproduction

- Some microphones use the principles of electromagnetism.
  - A dynamic microphone consists of a rigid magnet, surrounded by a moveable coil attached to a diaphragm.



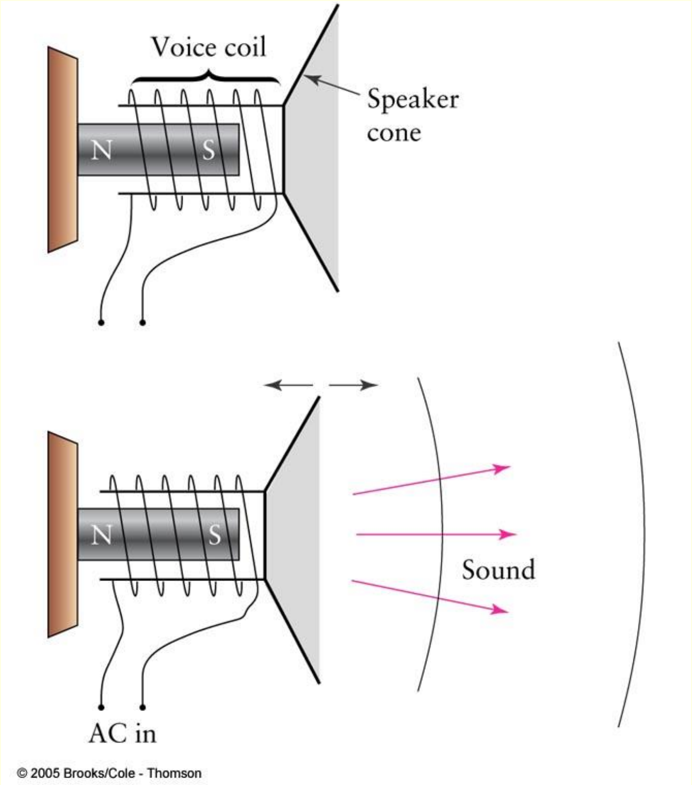
Applications to sound reproduction, cont'd

- As a sound wave strikes the diaphragm, it forces the coil to move.
- Because of the fixed magnet, the coil "sees" a changing magnetic field.
- This induces a current in the coil.
- This current mirrors the waveform that struck the diaphragm.



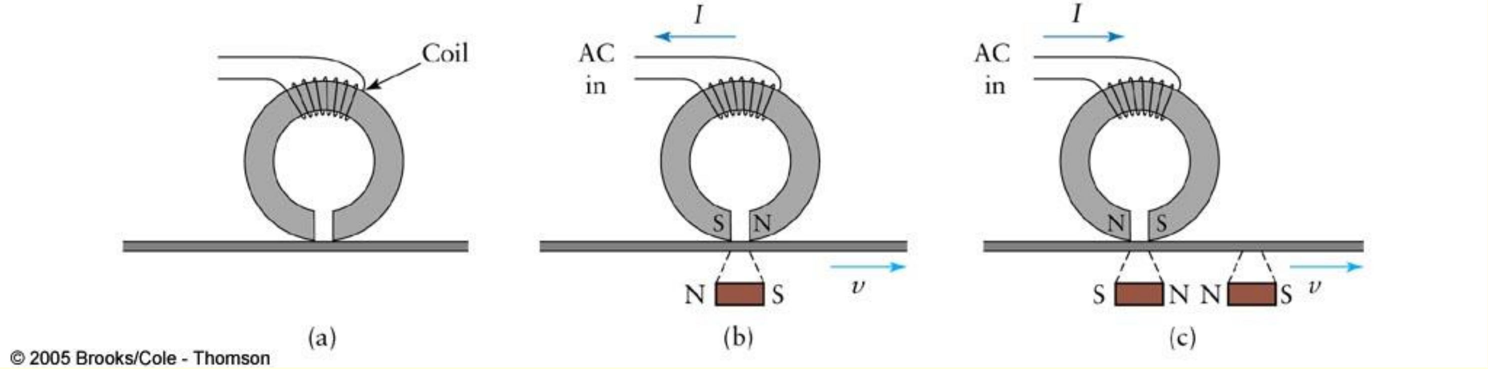
Applications to sound reproduction, cont'd

- A basic speaker uses the same approach, only in reverse.
  - As an AC current is passed into the coil, a magnetic field is created by the coil.
  - This electromagnetic field interacts with the field of the fixed, permanent magnet.



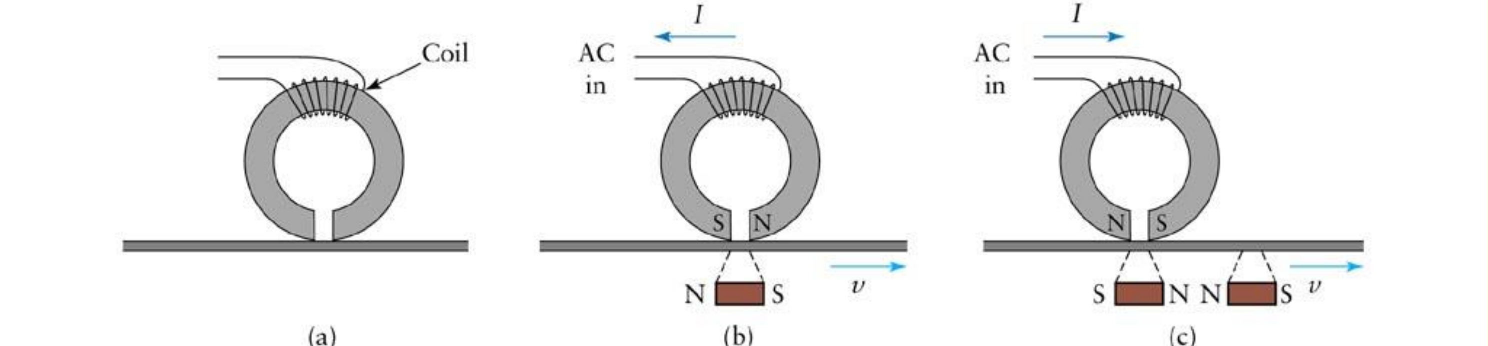
Applications to sound reproduction, cont'd

- Magnetic storage also uses the electromagnetic principles.
- The magnetic media in a material covered with a magnetic substance.
- The read/write head is essentially just a ring shaped-electromagnet.



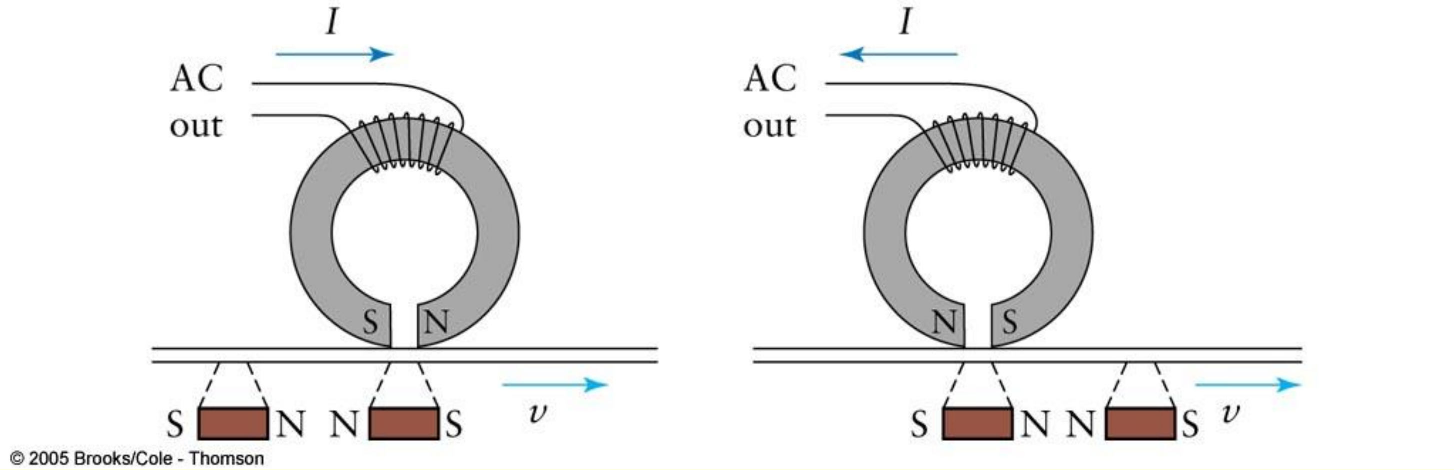
Applications to sound reproduction, cont'd

- During recording, the medium moves by the head while an alternating current is passed through the coil.
- This generates an alternating magnetic field in the electromagnet's gap.
- This field orients the magnetic particles on the medium.



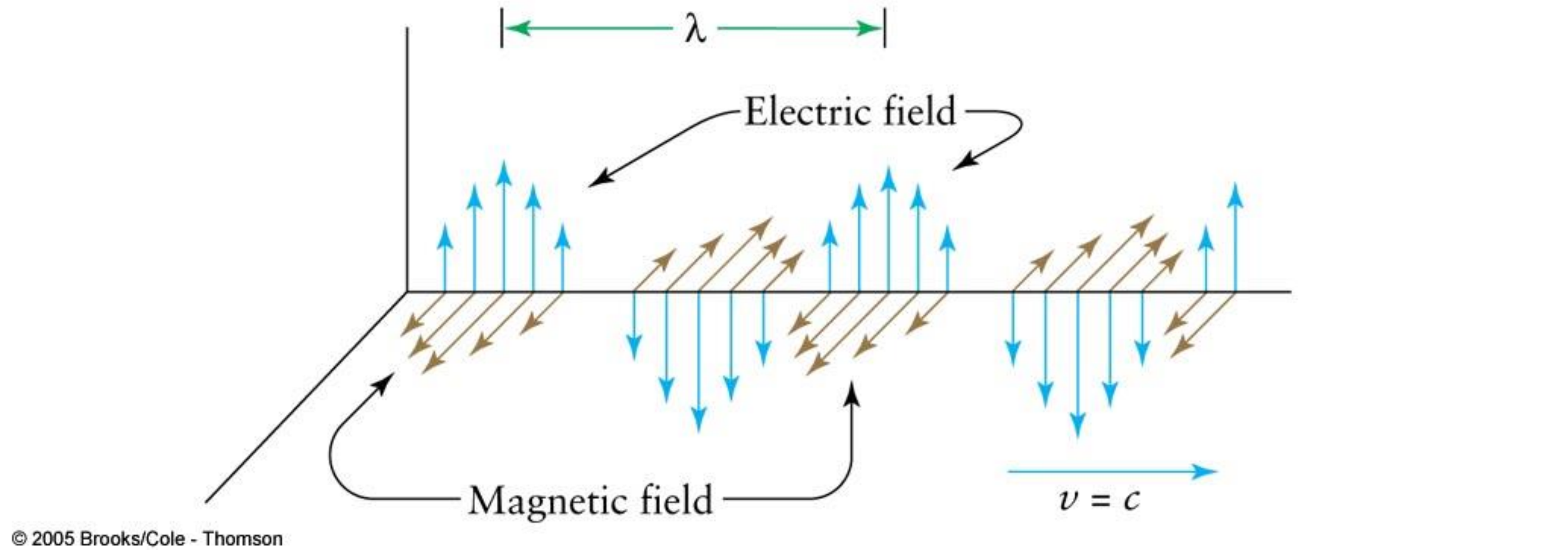
Applications to sound reproduction, cont'd

- During playback, the gap of the electromagnet “sees” a varying magnetic field as the medium moves past the gap.
- The changing magnetic field produces a current in the coil which can then be measured for whatever purpose.



Electromagnetic waves

- **Electromagnetic waves** are transverse waves consisting of a combination of oscillating electric and magnetic fields.



Electromagnetic waves, cont'd

- These waves travel at the "speed of light."
  - We use the symbol c to represent the speed of light.

$$c = 299,792,468 \text{ m/s}$$

$$= 3 \times 10^8 \text{ m/s}$$

$$= 186,000 \text{ miles/sec}$$

  - The formula $v = f\lambda$ holds for EM waves.

Example

Example 8.2

An FM radio station broadcasts an EM wave with a frequency of 100 megahertz. What is the wavelength of the wave?

Example
Example 8.2

ANSWER:

The problem gives us: $f = 100\ \text{MHz}$

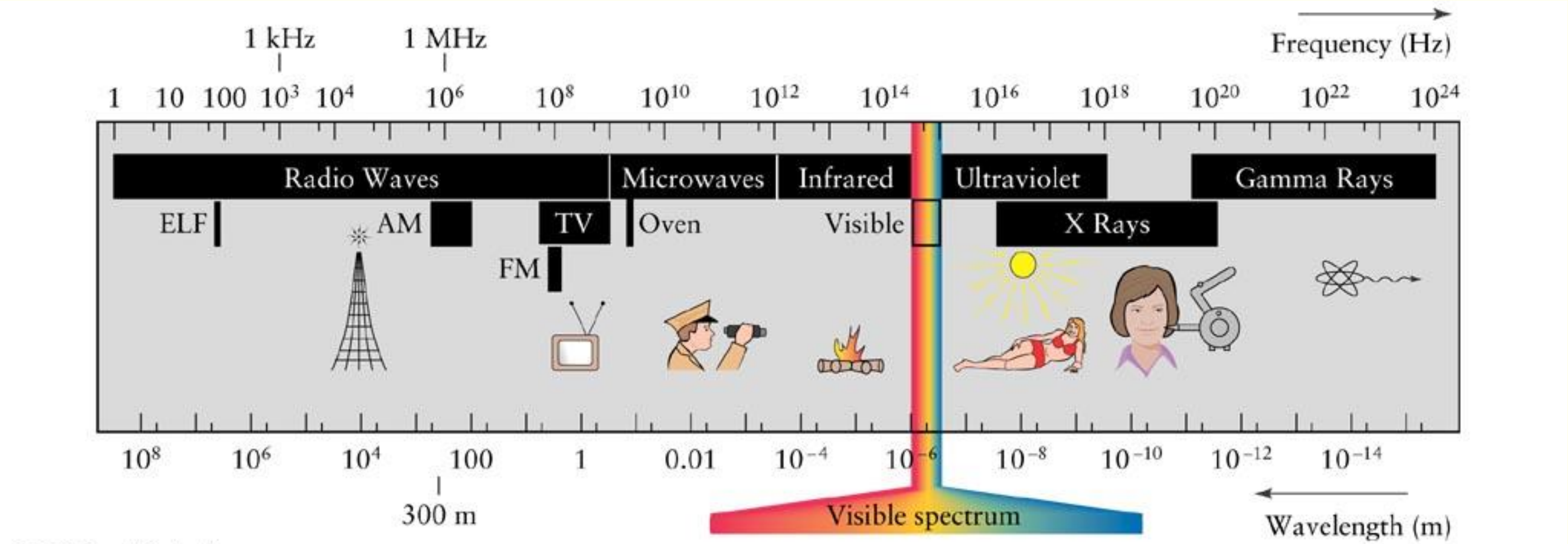
The wavelength is

$$c = f\lambda \rightarrow \lambda = \frac{c}{f} = \frac{3\times10^{8}\ \text{m/s}}{100\times10^{6}\ \text{1/s}}$$

$$= 3\ \text{m.}$$

Electromagnetic waves, cont'd

- EM waves are named according to their wavelength and frequency.



Electromagnetic waves, cont'd

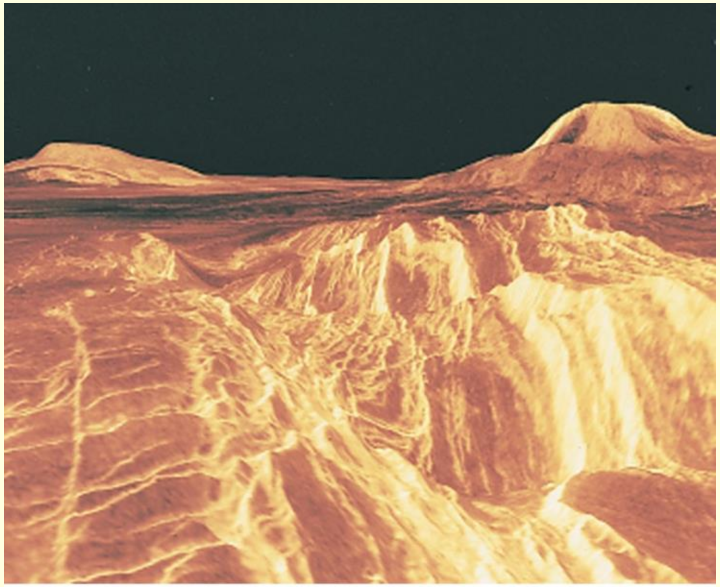
- *Radio waves* are the lowest frequency EM waves.
  - Their frequency range is from 100 to about 10^9 Hz.
  - They are sub-divided into several groups:
    - ELF – extremely low frequency.
    - VHF – very high frequency.
    - UHF – ultra high frequency.

Electromagnetic waves, cont'd

- They are easily created with AC current.
- Radio wave pass easily through the atmosphere so they are good for communications.
  - Low frequency waves are reflected by the upper atmosphere.
  - High frequency waves are used to space communications.

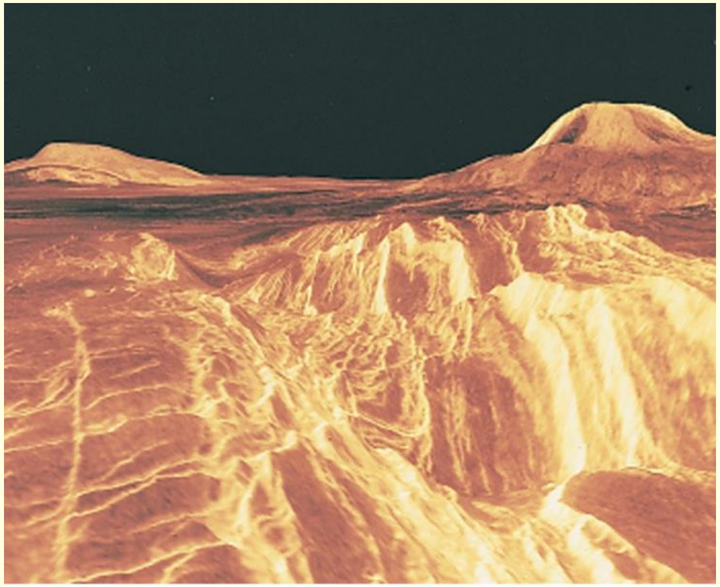
Electromagnetic waves, cont'd

- *Microwaves* are the next highest frequency waves.
  - They range from 10^9 to 10^{12} Hz.
  - They are used for communications and radar.
    - Doppler radar uses microwaves and the Doppler effect to measure the speed of an object.



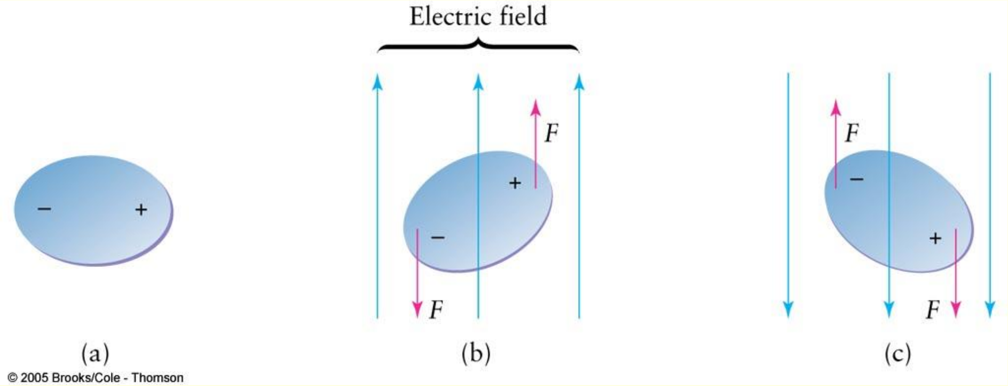
Electromagnetic waves, cont'd

- Their frequency allows them to penetrate clouds and smoke more effectively than some other types of EM wave.
  - This image shows the surface of Venus.
  - Microwaves were used to penetrate the thick cloud cover.



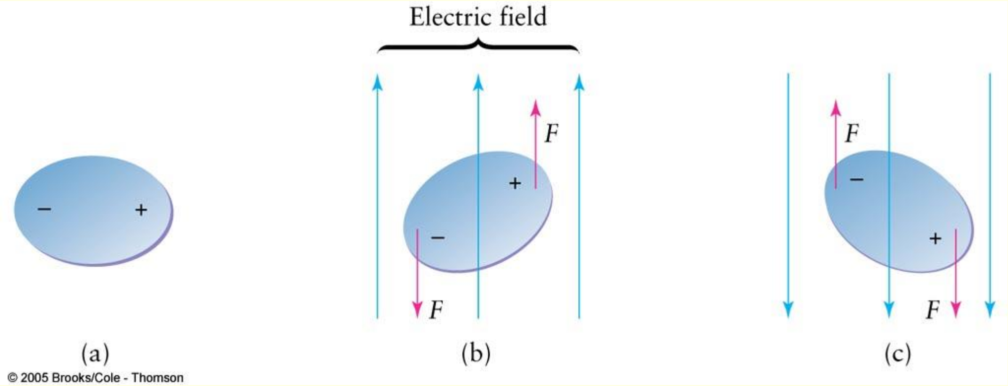
Electromagnetic waves, cont'd

- Microwaves are also useful at heating certain substances, e.g., water.
  - Water is a polar molecule.
    - The negative charge of the hydrogen is displaced from the positive charge of the oxygen.
  - When exposed to microwaves, the water molecules rotate because of the varying electric field.



Electromagnetic waves, cont'd

- The increased motion of the molecules means increased kinetic energy.
- Recall that temperature is essentially the average kinetic energy of the molecules.
- The frequency 2,450 MHz is used in most ovens.
  - This frequency is most effective at making the water molecules rotate.



Electromagnetic waves, cont'd

- *Infrared* radiation is next higher in frequency.
  - It ranges from 10^{12} to about 4×10^{14} Hz.
  - It is the predominant component in heat radiation.
  - IR is constantly emitted by molecules simply due to their thermal vibrations.
  - Remote controls use IR since it is cheap & effective at short range.

Electromagnetic waves, cont'd

- *Visible light* extends beyond IR in frequency.
  - It ranges from 4×10^{14} to 7.5×10^{14} Hz.

Table 8.1 Approximate Frequencies and Wavelengths of Different Colors

Color	Frequency Range ($\times10^{14}$ Hz)	Wavelength Range ($\times10^{-7}$ m)
Red	4.0–4.8	7.5–6.3
Orange	4.8–5.1	6.3–5.9
Yellow	5.1–5.4	5.9–5.6
Green	5.4–6.1	5.6–4.9
Blue	6.1–6.7	4.9–4.5
Violet	6.7–7.5	4.5–4.0

Electromagnetic waves, cont’d

- There is nothing special about visible light.
  - It is simply another band of EM radiation.
  - Our eyes are simply adapted to deciphering visible light as various colors.
- It is a surprisingly narrow band.
  - The highest frequency is barely double the lowest frequency.
    - The highest frequency we can hear is about 1,000 times higher than the lowest audible frequency.
- Like IR, it is emitted by hot objects.
  - Color can be a measure of an object’s temperature.

Electromagnetic waves, cont'd

- *Ultraviolet radiation* begins at frequencies beyond those of the visible color violet.
  - Its range is 7.5×10^{14} to 10^{18} Hz.
  - It is emitted by very hot objects as part of the heat radiation.
  - UV provides the energy for chemical reactions in the skin that cause tanning or "sunburns."

Electromagnetic waves, cont'd

- Fluorescent lights use the UV emitted by mercury atoms to cause a powder on the tube's inner surface to emit visible light.
  - This powder is said to be *fluorescent*, thus the name.

Electromagnetic waves, cont'd

- *X-rays* are the next higher frequency of EM waves.
  - They extend from 10^{16} to 10^{20} Hz
  - Their wavelengths are about 10^{-8} to 10^{-11} meters.
    - This corresponds to the size of atoms.
  - They are useful for examining the atomic structure of materials.

Electromagnetic waves, cont'd

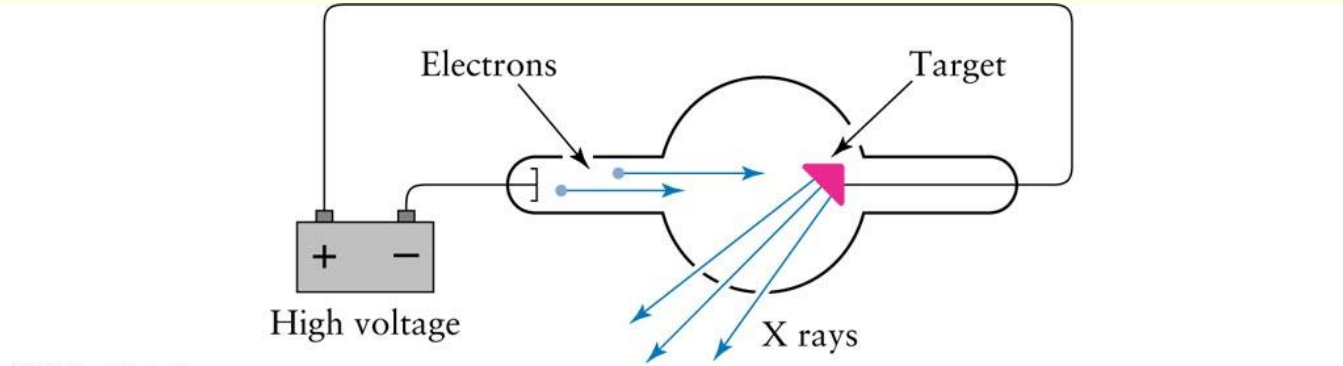
- They are used for medical imaging since materials containing relatively large atomic numbers absorb x-rays more than those with lower atomic number.
  - The calcium in bones implies that bones absorb x-rays.
  - The carbon and oxygen in the skin and muscles absorb less.

Electromagnetic waves, cont'd

- An x-ray image is really an image of the "shadow" cast by the object.
  - A normal photograph is an image of the light reflected off the object.

Electromagnetic waves, cont'd

- X-rays are easily produced by bombarding a metal with high-energy electrons.
- The electrons are rapidly decelerated as they strike the metal.
- The decelerating electrons emit x-rays.



Electromagnetic waves, cont'd

- *Gamma-rays* are the highest frequency EM waves.
  - Their frequency range is 3×10^{9} to beyond 10^{23} Hz.
  - Their wavelengths are on the same scale as nuclear diameters.
  - They are commonly emitted during nuclear reactions.

Blackbody radiation

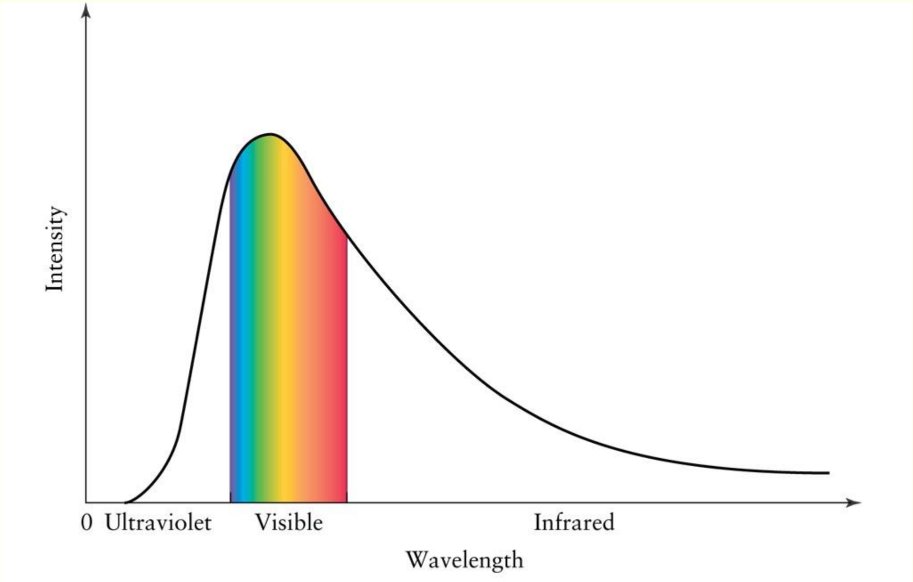
- Every object emits EM radiation due to the thermal motion of its atoms and molecules.
- If the atoms have greater thermal motion, the object must be at a higher temperature.
- An object that perfectly absorbs all EM radiation would appear black.
  - If it absorbs everything, then nothing reflects off of it.
    - We see objects because of their reflected light.

Blackbody radiation, cont'd

- Such an object is called a *blackbody*.
  - It emits radiant energy at a higher rate than any other object of the same size and temperature.
    - This is because most objects will reflect some of the incident radiation.
    - The blackbody absorbs more energy and therefore gets hotter.
- **Blackbody radiation** is the radiation emitted by a blackbody.

Blackbody radiation, cont'd

- The *blackbody radiation curve* shows the intensity at each wavelength of radiation emitted by a blackbody.
  - The size and shape of the graph depends on the object's temperature.



Blackbody radiation, cont'd

- Three aspects of heat radiation are affected by the object's temperature:
  - The amount of each type of radiation emitted increases with temperature.
  - The total amount of radiant energy emitted per unit area per unit time increases rapidly with any increase in temperature.
    - The total radiant energy emitted per second is proportional to the fourth-power of the absolute temperature:

$$P \propto T^4 \quad \left(T \text{ in kelvins}\right)$$

Blackbody radiation, cont'd

- At higher temperatures, more of the power is emitted at successively shorter wavelengths of EM radiation.
  - For a blackbody, the wavelength that is given the maximum power is inversely proportional to its temperature:

$$\lambda_{\max} = \frac{0.0029}{T}$$

    - T is in kelvins, and
    - $\lambda_{\max}$ is in meters.

Example

Example 8.3

Assuming that the Sun is a blackbody with a temperature of 6,000 K, at what wavelength does it radiate the most energy?

Example
Example 8.3

ANSWER:

The problem gives us: $T = 6,000\ \text{K}$

The wavelength is

$$\lambda_{\max} = \frac{0.0029}{T} = \frac{0.0029}{6,000}$$

$$= 4.8 \times 10^{-7}\ \text{m}$$

Blackbody radiation, cont'd

- This means we can determine the temperature of an object my measuring the EM radiation it emits.
  - A *thermogram* is a "picture" of the IR radiation emitted by an object.