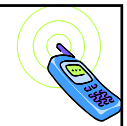
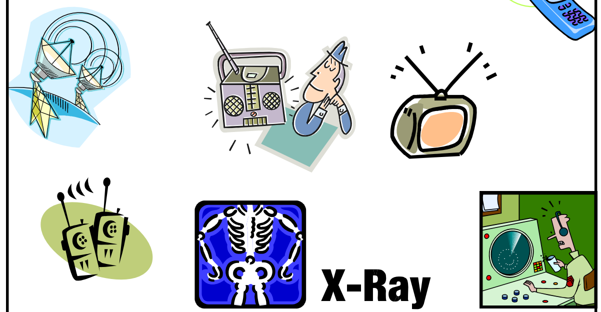
Electromagnetic Waves

Chapter 23

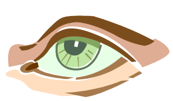
EM Waves around

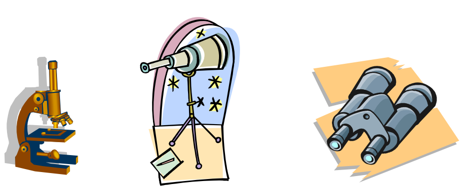




Energy from the Sun – EM waves

Light – EM waves





Galaxy M104 (see http://hubblesite.org/)

Galaxies/NGC 4038-4039

History - Maxwell's Theory

In 1865, James Clerk Maxwell developed a theory about electricity and magnetism.

His starting points were:

1. Electric field lines originate on + charges and terminate on – charges.
2. Magnetic field lines form closed loops.
3. A time varying magnetic field induces an electric field
4. A magnetic field is created by a current.

Charges and Fields, Summary

Stationary charges produce only electric fields

Charges in uniform motion (constant velocity) produce electric and magnetic fields

Charges that are accelerated produce electric and magnetic fields and electromagnetic waves

Maxwell's theory is a mathematical formulation that relates electric and magnetic phenomena.

His theory, among other things, predicted that electric and magnetic fields can travel through space as waves and he was able to predict the speed of travel.

The uniting of electricity and magnetism resulted in the **Theory of Electromagnetism**.

Electromagnetic Waves, Summary

A changing magnetic field produces an electric field

A changing electric field produces a magnetic field

These fields are in phase

At any point, both fields reach their maximum value at the same time

Maxwell's Predictions

A **time dependent** electric field produces a magnetic field and visa versa.

Accelerating charges will **radiate** electromagnetic waves.

Electromagnetic waves travel at the speed of light **c**:

$$c = 2.99792458 \times 10^8 m/s$$

The electric and magnetic fields in the wave are fluctuating in both **space and time**.

EM Waves and Hertz

In 1887, Heinrich Hertz generated and detected electromagnetic waves in his lab.

The waves radiated from a transmitter circuit and were detected in a receiver circuit.

Hertz used the fact that electrical circuits have resonant frequencies just like mechanical systems do.

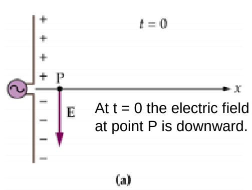
Producing EM Waves

Electromagnetic waves will be produced when a **charge undergoes acceleration**.

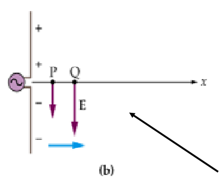
If an ac voltage is applied to an antenna, the charges will be accelerated up and down and radiate EM waves.

The radiated waves are made up of electric and magnetic fields.

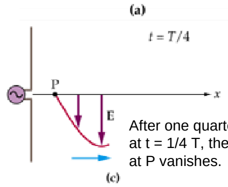
A traveling electromagnetic wave produced by an ac generator attached to an antenna.



At t = 0 the electric field at point P is downward.

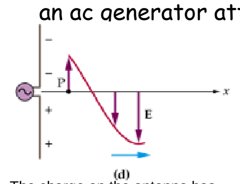


A short time later the electric field at P is still downward, but now with a reduced magnitude. Note that the field created at t = 0 has moved to point Q. The decreasing electric field at point P creates a magnetic field at point Q pointing into the viewgraph

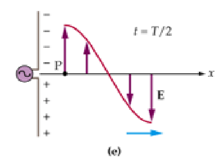


After one quarter of a cycle, at t = 1/4 T, the electric field at P vanishes.

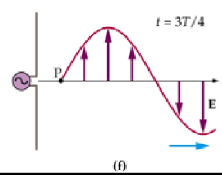
A traveling electromagnetic wave produced by an ac generator attached to an antenna.



The charge on the antenna has reversed polarity now, and the electric field at P points upward.

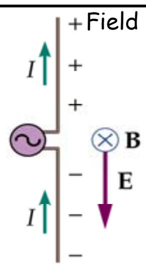


When the oscillator has completed half a cycle, t = 1/2 T, the field at point P is upward and of maximum magnitude.

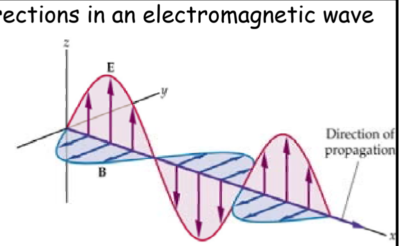


At t = 3/4 T the field at P vanishes again. The fields produced at earlier times continue to move away from the antenna.

Field directions in an electromagnetic wave

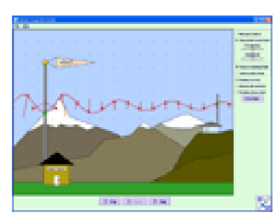


At a time when the electric field produced by the antenna points downward, the magnetic field points into the page. In general, the electric and magnetic fields in an electromagnetic wave are always at right angles to each other.



An electromagnetic wave propagating in the positive x direction. Note that E and B are perpendicular to each other and in phase. The direction of propagation is given by the thumb of the right hand, after pointing the fingers in the direction of E and curling them toward B (palm towards B).

Computer Simulation



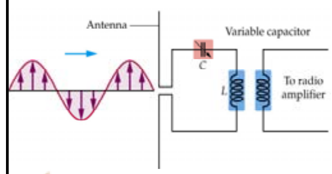
http://www.colorado.edu/physics/phet/web-pages/index.html

Properties of EM Waves

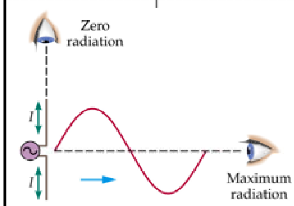
The radiated EM waves have certain properties:

- EM waves all travel at the speed of light c.
  $c^2 = 1/(e_0\mu_0)$
- the E and B fields are perpendicular to each other
- the E and B fields are in phase (both reach a maximum and minimum at the same time)
  for EM waves in vacuum E=cB
- The E and B fields are perpendicular to the direction of travel (transverse waves)

Receiving radio waves



Basic elements of a tuning circuit used to receive radio waves. First, an incoming wave sets up an alternating current in the antenna. Next, the resonance frequency of the LC circuit is adjusted to match the frequency of the radio wave, resulting in a relatively large current in the circuit. This current is then fed into an amplifier to further increase the signal.



Electromagnetic radiation is greatest when charges accelerate at right angles to the line of sight. Zero radiation is observed when the charges accelerate along the line of sight. These observations apply to electromagnetic waves of all frequencies.

Plane Waves

EM waves in free space are plane waves. That means that the E and B fields are confined to a plane and uniform within the plane at all time.

As we said, EM waves travel at the speed of light. Light speed can be derived from two other quantities we have already used:

$$c = \frac{1}{\sqrt{\mu_0 \varepsilon_0}} = 3\times10^{8}\ \text{m/s}$$

Light from Sun – about 8 minutes

Light from stars – years!

Light

Light is an electromagnetic wave

$$c = f\lambda = 3\times10^{8}\ \text{m/s}$$

λ wavelength

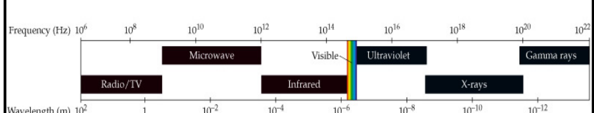
f frequency

As light waves travel through space they:

transport energy

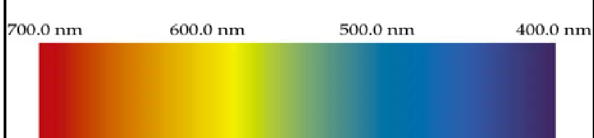
transport momentum

EM waves can be generated in different frequency bands: radio, microwave, infrared, visible, ultraviolet, x-rays, gamma rays



Note that the visible portion of the spectrum is relatively narrow.

The boundaries between various bands of the spectrum are not sharp, but instead are somewhat arbitrary. (1 nm = 10^{-9}m)



Notes on The EM Spectrum

Radio Waves

Used in radio and television communication systems

Microwaves

Wavelengths from about 1 mm to 30 cm

Well suited for radar systems

Microwave ovens are an application

Notes on the EM Spectrum, 2

Infrared waves

- Incorrectly called "heat waves"
- Produced by hot objects and molecules
- Readily absorbed by most materials

Visible light

- Part of the spectrum detected by the human eye
- Most sensitive at about 560 nm (yellow-green)

Notes on the EM Spectrum, 3

Ultraviolet light

- Covers about 400 nm to 0.6 nm
- Sun is an important source of uv light
- Most uv light from the sun is absorbed in the stratosphere by ozone

X-rays

- Most common source is acceleration of high-energy electrons striking a metal target
- Used as a diagnostic tool in medicine

Notes on the EM Spectrum, final

Gamma rays

- Emitted by radioactive nuclei
- Highly penetrating and cause serious damage when absorbed by living tissue

Looking at objects in different portions of the spectrum can produce different information

Problem

Find the frequency of blue light with a wavelength of 470 nm.

$c = \lambda f$

$$\boxed{f = \frac{c}{\lambda} = \frac{3\times10^8}{470\times10^{-9}} = 6.4\times10^{14}\ \text{Hz}}$$

Problem

As you drive by an AM radio station, you notice a sign saying that its antenna is 142 m high. If this height represents one quarter-wavelength of its signal, what is the frequency of the station?

$$142\ \text{m} = \frac{\lambda}{4} \quad \text{therefore} \quad \lambda = 4\times142 = 568\ \text{m}$$

$$f = \frac{c}{\lambda} = \frac{3\times10^8}{568} = \boxed{528\ \text{kHz}}$$

Doppler Effect and EM Waves

- A Doppler Effect occurs for em waves, but differs from that of sound waves
- For sound waves, motion relative to a medium is most important
- For light waves, the medium plays no role since the light waves do not require a medium for propagation
- The speed of *sound* depends on its frame of reference
- The speed of *em waves* is the same in all coordinate systems that are at rest or moving with a constant velocity with respect to each other

Doppler Equation for EM Waves

The Doppler effect for em waves

$$f_0 \approx f_s\left(1 \pm \frac{u}{c}\right)$$

- f_o is the observed frequency
- f_s is the frequency emitted by the source
- u is the relative speed between the source and the observer
- The equation is valid only when u is much smaller than c

Doppler Equation, cont

The positive sign is used when the object and source are moving toward each other

The negative sign is used when the object and source are moving away from each other

Astronomers refer to a red shift when objects are moving away from the earth since the wavelengths are shifted toward the red end of the spectrum

examples:

Nexrad (The Doppler weather radar)

NAVSTAR Navigation system

Energy and Momentum in EM Waves

The EM waves carry energy

The energy density u (energy per unit volume) in a region of empty space where electric and magnetic fields are present is

$$u = \frac{1}{2}\varepsilon_0 E^2 + \frac{1}{2\mu_0}B^2 = \varepsilon_0 E^2 = \frac{1}{\mu_0}B^2$$

The average power per unit area in an EM wave is also called **intensity** of the wave (I = power/area: units W/m^2)

$$I = \frac{1}{2}\sqrt{\frac{\varepsilon_0}{\mu_0}}E_{\max}^2 = \frac{1}{2}\varepsilon_0 c E_{\max}^2$$

Radiation Pressure

The EM waves carry energy and momentum p

For an electromagnetic wave absorbed by an area A the average momentum transferred to the surface is

$$\Delta p = \frac{IA\Delta t}{c}$$

This momentum transfer is responsible for the phenomenon of radiation pressure.

When an EM wave is completely absorbed by a surface perpendicular to the direction of propagation of the wave, the rate of change of momentum equals the force on the surface (units Pa = 1N/m^2. pressure = force/area).

$$pressure = \frac{I}{c}$$

For a totally reflective surface →

$$pressure = \frac{2I}{c}$$

Question ?

If a light beam carries momentum, should a person holding a flashlight feel a recoil analogous to the recoil of a rifle when it is fired?

Question ?

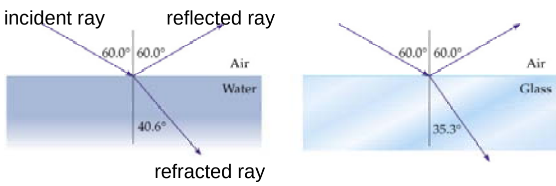
Why is the radiation pressure on a perfectly reflecting surface twice as great as on a perfectly absorbing surface?

The reflection of light

Reflection and Refraction

When a light ray travels from one medium to another, part of the incident light is reflected and part of the light is transmitted at the boundary between the two media.

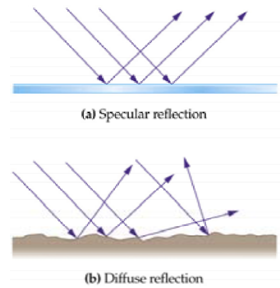
The transmitted part is said to be refracted in the second medium.



Types of Reflection

If the surface from which the light is reflected is smooth, then the light undergoes specular reflection (parallel rays will all be reflected in the same directions).

If, on the other hand, the surface is rough, then the light will undergo diffuse reflection (parallel rays will be reflected in a variety of directions)

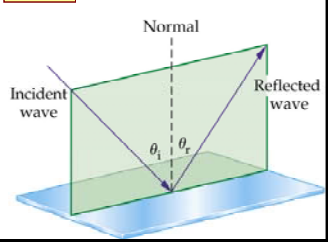


The Law of Reflection

For specular reflection the incident angle θ_i equals the reflected angle θ_r:

$$\theta_i = \theta_r$$

The angles are measured relative to the normal as shown.



The Refraction of Light

The Refraction of Light

The speed of light is different in different materials. We define the index of refraction, *n*, of a material to be the ratio of the speed of light in vacuum to the speed of light in the material:

$$n = \frac{c}{v}$$

When light travels from one medium to another its velocity and wavelength change, but its frequency remains constant.

For a vacuum, n = 1

For other media, n > 1

n is a unitless ratio

Snell's Law

In general, when light enters a new material its **direction** will change. The **angle of refraction** θ_2 is related to the **angle of incidence** θ_1 **by Snell's Law:**

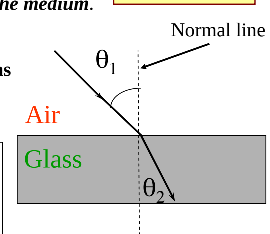
$$\frac{\sin\theta_1}{v_1} = \frac{\sin\theta_2}{v_2}$$

where ***v*** is the velocity of light ***in the medium***.

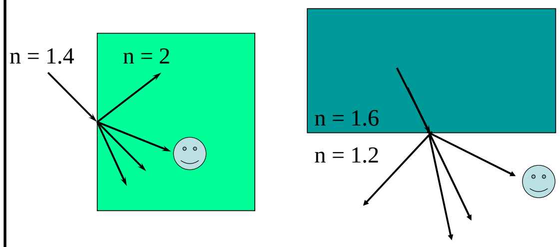
Snell's Law can also be written as

$$n_1 \sin\theta_1 = n_2 \sin\theta_2$$

The angles θ_1 and θ_2 are measured **relative to the line normal** to the surface between the two materials.



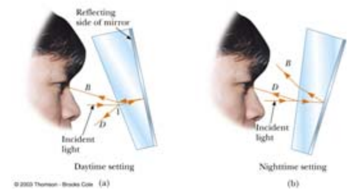
Example: Which way will the rays bend?



Which of these rays can be the refracted ray?

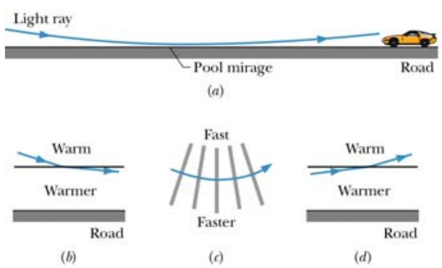
$$n_1 \sin\theta_1 = n_2 \sin\theta_2$$

Application – Day and Night Settings on Auto Mirrors



- With the daytime setting, the bright beam of reflected light is directed into the driver's eyes
- With the nighttime setting, the dim beam of reflected light is directed into the driver's eyes, while the bright beam goes elsewhere

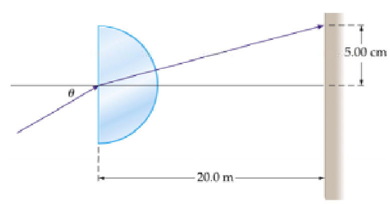
A Common Mirage



problem

Problem

You have a semicircular disk of glass with an index of refraction of $n = 1.52$. Find the incident angle θ for which the beam of light in the figure will hit the indicated point on the screen.



problem

$$n_1 \sin\theta_1 = n_2 \sin\theta_2$$

$$1 \times \sin\theta_1 = 1.52 \times \sin\theta_2 \qquad \tan\theta_2 = \frac{5}{20}$$

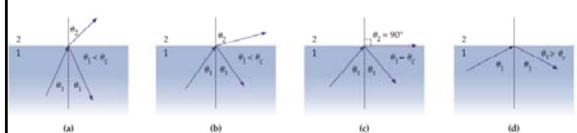
Therefore $\theta_2 = 14^\circ$

$$\sin\theta_1 = 1.52 \times \sin 14^\circ$$

Therefore $\theta_1 = 21.6^\circ$

Total Internal Reflection

When light travels from a medium with $\mathbf{n_1 > n_2}$, there is an angle, called the **critical angle θ_c**, at which all the light is reflected and none is transmitted. This process is known as **total internal reflection.**



The incident ray is both reflected and refracted.

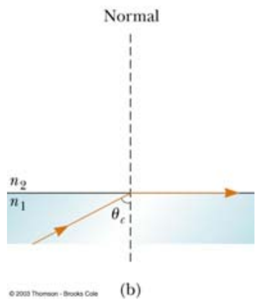
Total Internal Reflection

Critical Angle

A particular angle of incidence will result in an angle of refraction of 90°

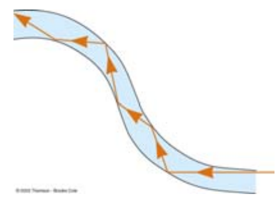
– This angle of incidence is called the *critical angle*

$$\sin\theta_c = \frac{n_2}{n_1} \quad for \quad n_1 > n_2$$



Fiber Optics

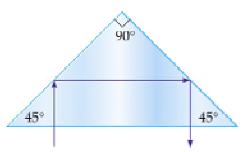
- An application of internal reflection
- Plastic or glass rods are used to "pipe" light from one place to another
- Applications include
  - medical use of fiber optic cables for diagnosis and correction of medical problems
  - Telecommunications



problem

Problem

A ray of light enters the long side of a 45°-90°-45° prism and undergoes two total internal reflections, as indicated in the figure. The result is a reversal in the ray's direction of propagation. Find the minimum value of the prism's index of refraction, *n*, for these internal reflections to be total.



problem

At the first reflection,

$$n_{med} \sin 45^\circ = 1$$

This is the same for the second reflection.

Therefore,

$$\sin 45^\circ \geq \frac{1}{n_{med}} \quad or$$

$$n_{med} \geq \frac{1}{\sin 45^\circ} = \sqrt{2}$$

$$\boxed{n_{med} = 1.414}$$

?

Question

Sometimes when looking at a window, one sees two reflected images, slightly displaced from each other.

What causes this effect?

?

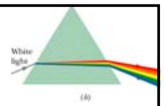
Question

A student claims that, because of atmospheric refraction, the sun can be seen after it has set and that the day is therefore longer than it would be if the earth had no atmosphere.

What does the student mean by saying the sun can be seen after it has set?

Does the same effect also occur at sunrise?

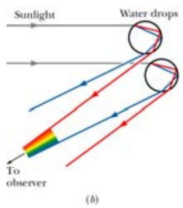
Dispersion



The index of refraction of a material depends on wavelength!

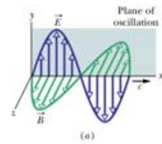
It is called dispersion.

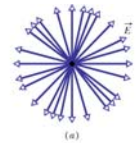
Example:

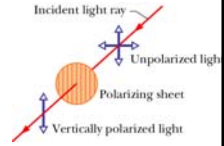


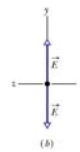
Polarization

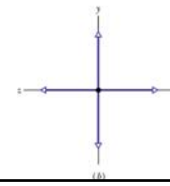
Polarized and unpolarized light





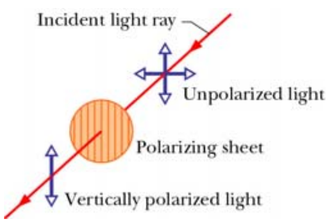






Polarization

by filters



by reflection