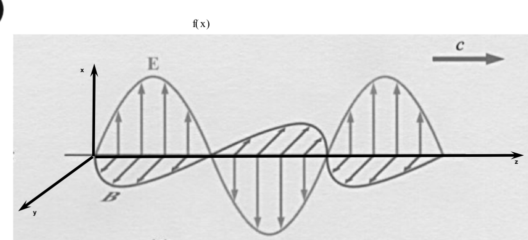
Lecture 15

Physics 1202: Lecture 15
Today's Agenda

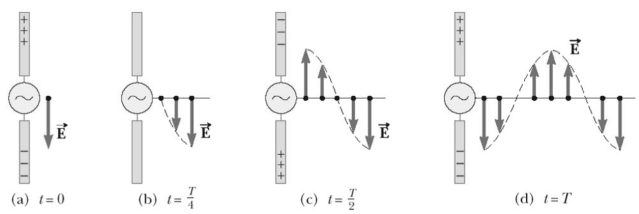
- Announcements: Team problems today
  - Team 7: Cailin Catarina, Matthew Canapetti, Kervin Vincent
  - Team 8: Natalie Kasir, Adam Antunes, Quincy Alexander
  - Team 9: Garrett Schlegel, Joyce Nieh, Matthew Lombardo
- **Homework #7: due Monday**
- **Midterm 1:**
  - **Average = 70%**
  - **Office hours if needed (M-2:30-3:30 or TH 3:00-4:00)**
- Chapter 25:
  - E&M waves: Production/properties
  - Spectra
  - Power & pressure
  - Polarization

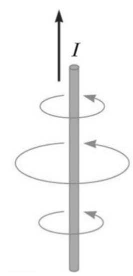
Chap. 25

Electromagnetic Waves



25-1: Generating E-M Waves





- **Two rods are connected to an ac source, charges oscillate between the rods (a)**
- **As oscillations continue, the rods become less charged, the field near the charges decreases and the field produced at t = 0 moves away from the rod (b)**
- **The charges and field reverse (c)**
- **The oscillations continue (d)**

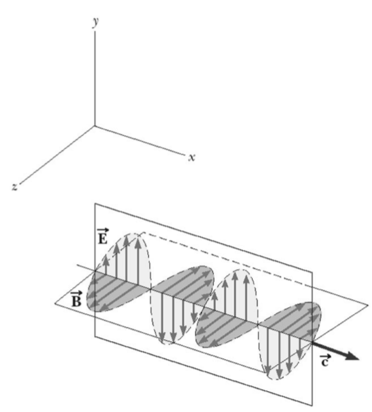
◦ Because the oscillating charges in the rod produce a current, there is also a magnetic field generated

◦ As the current changes, the magnetic field spreads out from the antenna

◦ The magnetic field is perpendicular to the electric field

Electromagnetic Waves are Transverse Waves

- **The E and B fields are perpendicular to each other**
- **Both fields are perpendicular to the direction of motion**
  - **Therefore, em waves are transverse waves**



◦ The ratio of the electric field to the magnetic field is equal to the speed of light

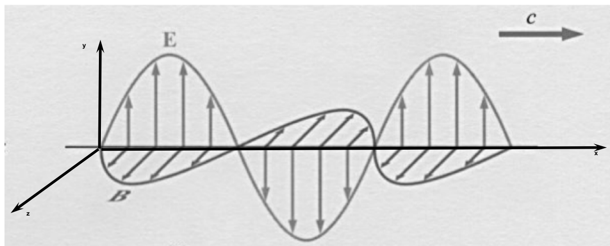
$$\boxed{c = \frac{E}{B}}$$

E & B in Electromagnetic Wave

- **Plane Harmonic Wave:**

$$E_y = E_0 \sin(kx - \omega t)$$
$$B_z = B_0 \sin(kx - \omega t)$$

where: $\omega = kc$, $E_0 = cB_0$



Note: the direction of propagation $\hat{s}$ is given by the cross product

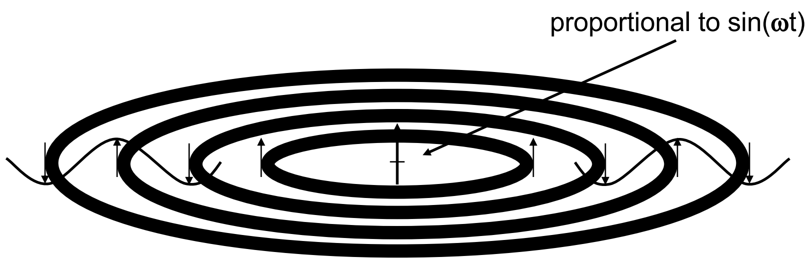
$$\boxed{\hat{s} = \hat{e} \times \hat{b}}$$

where $(\hat{e}, \hat{b})$ are the unit vectors in the (E,B) directions.

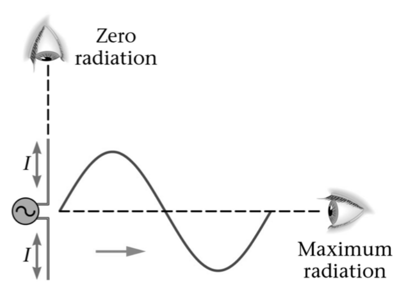
Nothing special about (E_y,B_z); eg could have (E_y,-B_x)

Note cyclical relation: $\hat{e} \times \hat{b} = \hat{s} \Rightarrow \hat{b} \times \hat{s} = \hat{e} \Rightarrow \hat{s} \times \hat{e} = \hat{b}$

Dipole radiation pattern

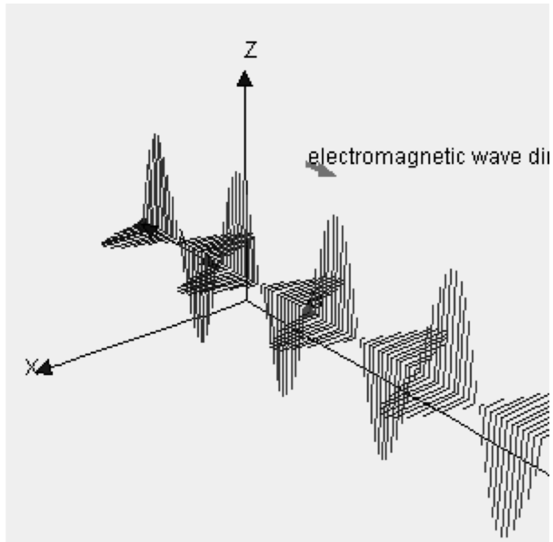


- **oscillating electric dipole generates e-m radiation that is polarized in the direction of the dipole**
- **radiation pattern is doughnut shaped & outward traveling**
  - **zero amplitude directly above and below dipole**
  - **maximum amplitude in-plane**

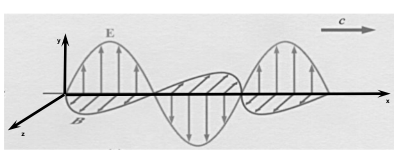


E & B Fields in EM wave

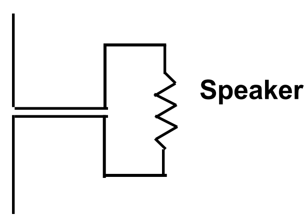
- **How it looks like …**



Receiving E-M Radiation



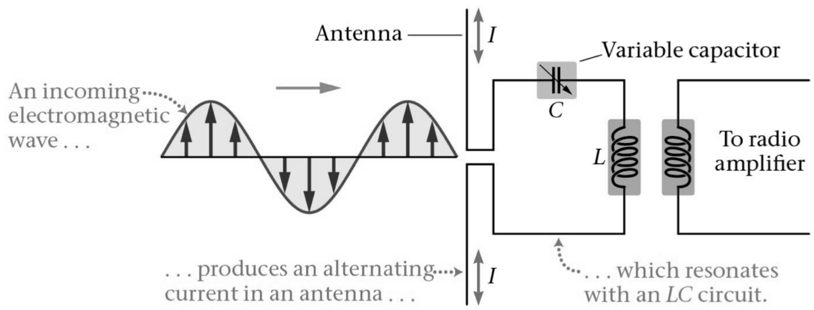
receiving antenna



One way to receive an EM signal is to use the same sort of antenna.

- Receiving antenna has charges which are accelerated by the **E** field of the EM wave.
- The acceleration of charges is the same thing as an EMF. Thus a voltage signal is created.

Receiving E-M Radiation



- **Using LRC circuit**
  - **Tune w for a specific "station"**
  - **For that w, current is maximum: resonance**

Loop Antennas
Magnetic Dipole Antennas

- The electric dipole antenna makes use of the basic electric force on a charged particle
- Note that you can calculate the related magnetic field using Ampere's Law.
- We can also make an antenna that produces magnetic fields that look like a magnetic dipole, i.e. a loop of wire.
- This loop can receive signals by exploiting Faraday's Law.

$$\boxed{\varepsilon = -\frac{\Delta \Phi_B}{\Delta t}}$$

$$\boxed{\varepsilon = -A\frac{\Delta B}{\Delta t}}$$

For a changing B field through a fixed loop of area A: $\Phi_B = A\,B$

Review of Waves from 1201

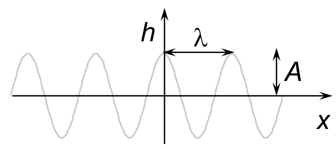
- **The one-dimensional wave equation:** $\frac{\partial^2 h}{\partial x^2} = \frac{1}{v^2}\frac{\partial^2 h}{\partial t^2}$

  has a general solution of the form:

  $$h(x,t) = h_1(x - vt) + h_2(x + vt)$$

  where h_1 represents a wave traveling in the +x direction and h_2 represents a wave traveling in the -x direction.

- **A specific solution for harmonic waves traveling in the +x direction is:**



$$h(x,t) = A\cos(kx - \omega t)$$

$$k = \frac{2\pi}{\lambda} \qquad \omega = 2\pi f = \frac{2\pi}{T}$$

$$v = \lambda f = \frac{\omega}{k}$$

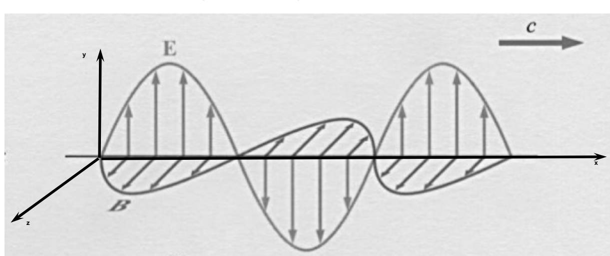
A = amplitude
λ = wavelength
f = frequency
v = speed
k = wave number

E & B in Electromagnetic Wave

- **Plane Harmonic Wave:**

$$E_y = E_0 \sin(kx - \omega t)$$
$$B_z = B_0 \sin(kx - \omega t)$$

where: $\omega = kc$, $E_0 = cB_0$



- **From general properties of waves :**

$$k = \frac{2\pi}{\lambda} \qquad \omega = 2\pi f = \frac{2\pi}{T} \qquad \Rightarrow \qquad c = \lambda f$$

$$v = \lambda f = \frac{\omega}{k}$$

25-2 The Propagation of EM Waves

- All electromagnetic waves propagate through a vacuum at the same rate:

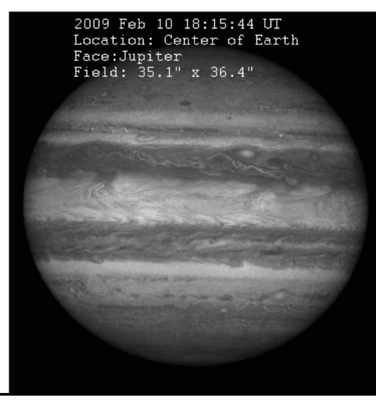
Speed of Light in a Vacuum

$$c = 3.00 \times 10^8 \text{ m/s} \qquad \text{25-1}$$

- In materials, such as air and water, light slows down, but at most to about half the above speed
- Using "tricks" of quantum mechanics
  - Can "stop" light in matter
  - More when we talk about modern physics !
- How can you determine c ???

Determining c

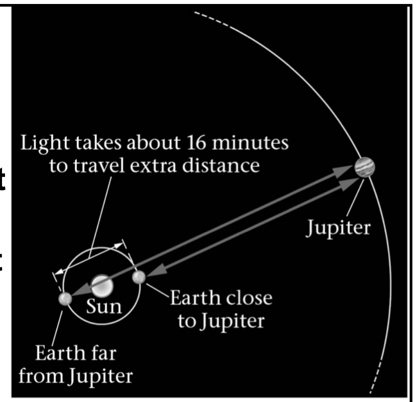
- c is so large: very hard to measure
  - first measurements in the late 1676
  - Danish astronomer Ole Rømer (1644 – 1710) while working at the Royal Observatory in Paris
  - timing the eclipses of the Jupiter moon Io



- Looking at when Io goes through Jupiter's shadow

Determining c

- By timing the eclipses of the Jupiter moon Io
- Io takes 42.5 hours to orbit Jupiter
- Rømer estimated that light would take about 16 minutes to travel a distance equal to the diameter of Earth's orbit around the Sun

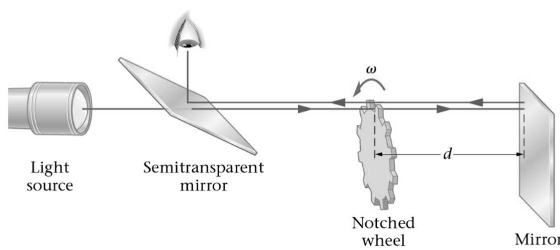


- This would give light a velocity ~ 225,000 km/s
- Approximate: need to account for motion of Jupiter as well … but 1st determination of finite speed for light !

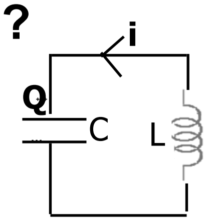
Hippolyte Fizeau experiment

23 September 1819
18 September 1896

- First laboratory measurement of c
- In 1849, using a ray of light passing (or not) through a wheel with 720 notches (turning up to 100 rev/sec.)
- Light reflected from mirror (8 km away)
- Found c ~ 3.13 X 10^6 m/s (5% too large)



c ?



Recall LC Circuits

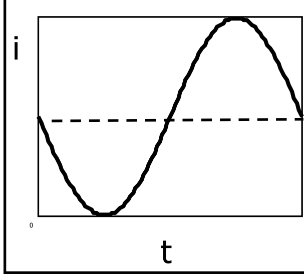
The energy is conserved

$$U_{\text{tot}} = U_C(t) + U_L(t)$$

$$U_L(t) = \frac{LI^2(t)}{2} \qquad U_C(t) = \frac{Q^2(t)}{2C}$$

LC:

current oscillates



When the capacitor is fully charged:

$$U_{\text{tot}} = U_C + U_L = \frac{Q_0^2}{2C} + 0$$

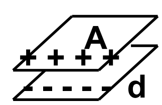
When the current is at maximum (I_o):

$$U_{\text{tot}} = U_C + U_L = 0 + \frac{LI_0^2}{2}$$

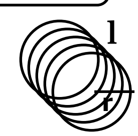
The maximum energy stored in the capacitor and in the inductor are the same:

$$\frac{Q_0^2}{2C} = \frac{LI_0^2}{2}$$

Energy is Stored in fields



- **The energy density for a parallel plate capacitor:** $W = \frac{1}{2}\frac{Q^2}{C} = \frac{1}{2}\frac{Q^2}{(A\varepsilon_0/d)}$
- **The Electric field is given by:** $E = \frac{\sigma}{\varepsilon_0} = \frac{Q}{\varepsilon_0 A} \quad \Rightarrow \quad W = \frac{1}{2}E^2\varepsilon_0 Ad$
- **The energy density u in the field is given by:** $\boxed{u = \frac{W}{\text{volum}} = \frac{W}{Ad} = \frac{1}{2}\varepsilon_0 E^2}$
- **The energy density for a long solenoid:** $B = \mu_0 \frac{N}{\ell} I$
- **The inductance L is:** $L = \mu_0 \frac{N^2}{\ell}\pi r^2$
- **Energy U:** $U = \frac{1}{2}LI^2 = \frac{1}{2}\left(\mu_0 \frac{N^2}{\ell}\pi r^2\right) I^2 = \frac{1}{2}\pi r^2 \ell \frac{B^2}{\mu_0}$
- **The energy density** $\boxed{u = \frac{U}{\pi r^2 \ell} = \frac{1}{2}\frac{B^2}{\mu_0}}$



N turns

Links between E & B

- In LC, maximum energy in C and L are equal $\frac{Q_0^2}{2C} = \frac{LI_0^2}{2}$
- If C and L have the same volume: $u_E = u_B$

$$\boxed{u_E = \frac{1}{2}\varepsilon_0 E_{\max}^2} \quad \boxed{u_B = \frac{1}{2}\frac{B_{\max}^2}{\mu_0}}$$

- E & B are related : $\boxed{E_{\max} = \frac{1}{\sqrt{\varepsilon_0 \mu_0}} B_{\max}}$

- **Units:**
  $\varepsilon_0 = 8.885 \times 10^{-12}\ C^2/Nm^2$
  $\mu_0 = 12.566 \times 10^{-7}\ N/A^2$

More about c

- **Units: $\varepsilon_0 = 8.885 \times 10^{-12}\ C^2/Nm^2$**
  $\mu_0 = 12.566 \times 10^{-7}\ N/A^2$
- **$[\varepsilon_0 \mu_0] = (C^2/Nm^2)\ (N/A^2) = (C^2/m^2)\ (s^2/C^2) = s^2/m^2$**
- **So $[\varepsilon_0 \mu_0] = [1/v^2]$**
- **We have** $\boxed{c = \frac{1}{\sqrt{\varepsilon_0 \mu_0}}}$
- **Using values above: c=299,276,596 m/s ~ $3X10^8$ m/s and**

$$\boxed{E = cB} \quad \textbf{or} \quad \boxed{c = \frac{E}{B}}$$

Lecture 15

Velocity of Electromagnetic Waves

- The wave equation for E_x: (derived from Maxwell's Eqn)

$$\frac{\partial^2 E_x}{\partial z^2} = \frac{1}{c^2}\frac{\partial^2 E_x}{\partial t^2}$$

- Therefore, we now know the velocity of electromagnetic waves in free space:

$$v = \frac{1}{\sqrt{\mu_0 \varepsilon_0}}$$

- Putting in the measured values for μ_0 & ε_0, we get:

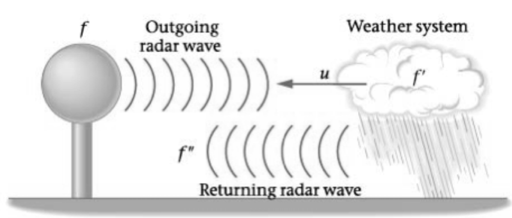
$$v = 3.00 \times 10^8 \mathrm{m/s} \equiv c$$

- This value is identical to the measured speed of light!
  - We identify light as an electromagnetic wave.

Doppler effect

- Like for any other wave
- Applies to electromagnetic waves
- The speed of the waves in vacuum does not change
  - but as the observer and source move with respect to one another, the frequency does change.

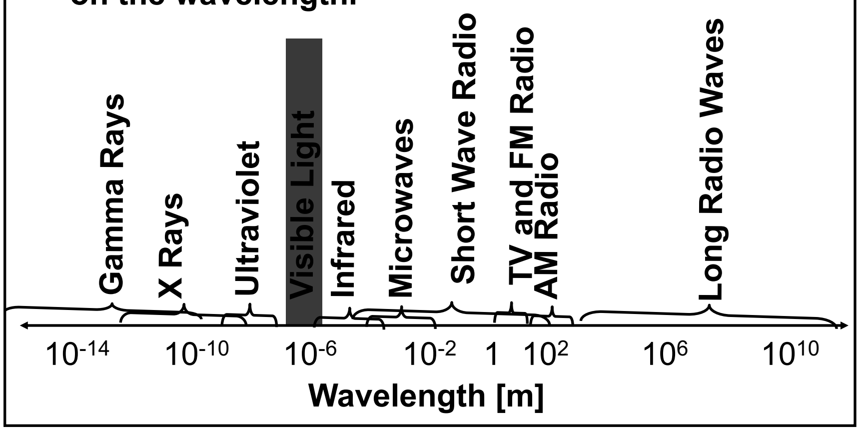
$$f' = f\left(1 \pm \frac{u}{c}\right)$$



Lecture 15

25-3: The EM Spectrum

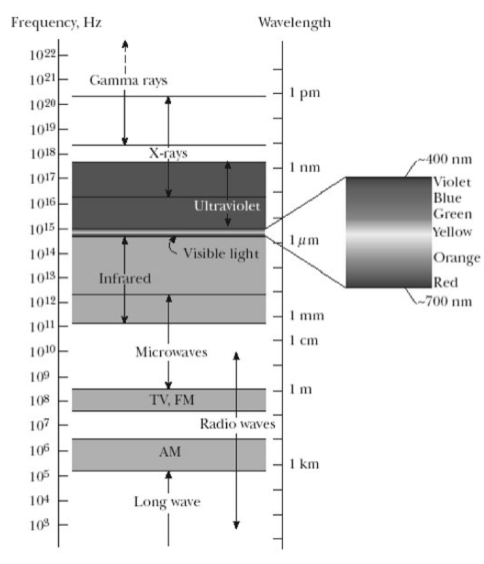
- These EM waves can take on any wavelength from angstroms to miles (and beyond).
- We give these waves different names depending on the wavelength.



The EM Spectrum

- Forms of EM waves exist that are distinguished by their frequencies and wavelengths

  $c = f\lambda$
- Wavelengths for visible light range from 400 nm to 700 nm
- There is no sharp division between one kind of em wave and the next



Lecture 15

Visible Spectrum

33-1 Electromagnetic Waves

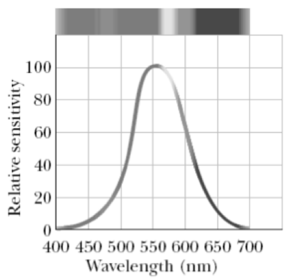
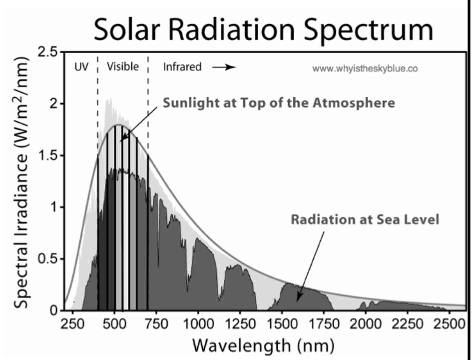


Fig. 33-2 The relative sensitivity of the average human eye to electromagnetic waves at different wavelengths. This portion of the electromagnetic spectrum to which the eye is sensitive is called *visible light.*



Notes on The EM Spectrum

- **Radio Waves**
  - **Used in radio and television communication systems**
  - **Generated by charges accelerating in conducting wires**
- **Microwaves**
  - **Wavelengths from about 1 mm to 30 cm**
  - **Generated by electronic devices**
  - **Well suited for radar systems**
  - **Microwave ovens are an application**
- **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)**
  - **Produced by rearrangement of electrons in atoms and molecules**

More on the EM Spectrum

- **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**
- 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

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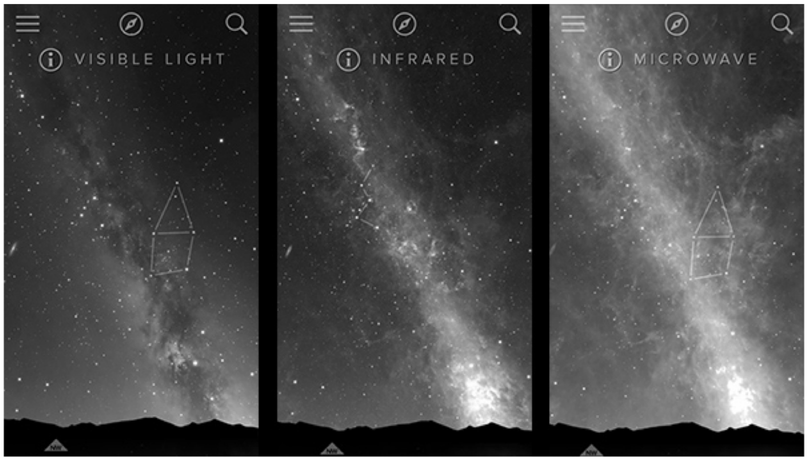
Lecture 15, ACT 1

- **Consider your favorite radio station. I will assume that it is at 100 on your FM dial. That means that it transmits radio waves with a frequency f=100 MHz.**
- **What is the wavelength of the signal ?**

A) 3 cm B) 3 m C) ~0.5 m D) ~500 m

The EM Spectrum

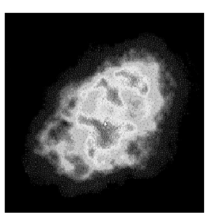
- Each wavelength shows different details



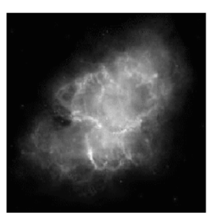
The EM Spectrum

- Each wavelength shows different details

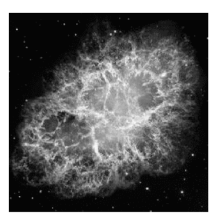
Crab Nebula: Remnant of an Exploded Star (Supernova)



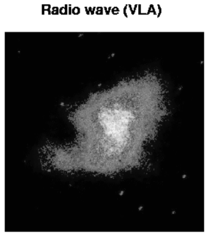
Radio wave (VLA)



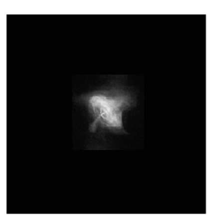
Infrared radiation (Spitzer)



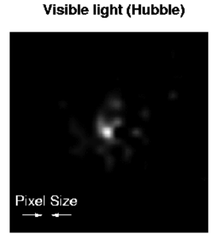
Visible light (Hubble)



Ultraviolet radiation (Astro−1)



Low−energy X−ray (Chandra)



High−energy X−ray (HEFT)
*** 15 min exposure ***

Lecture 15

Energy in EM Waves / review

- **Electromagnetic waves contain energy which is stored in E and B fields:**

$$u_E = \frac{1}{2}\varepsilon_0 E^2 \quad = \quad u_B = \frac{1}{2}\frac{B^2}{\mu_0} \qquad E_0 = cB_0 \qquad c = \frac{1}{\sqrt{\varepsilon_0\mu_0}}$$

- **Therefore, the total energy density in an e-m wave = u, where**

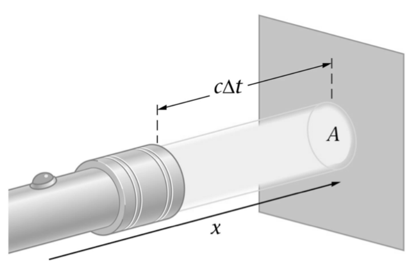
$$u = u_E + u_B = \varepsilon_0 E^2$$

- **The Intensity of a wave is defined as the average power transmitted per unit area = average energy density times wave velocity:**

$$I = vu = c\varepsilon_0\langle E^2\rangle = \frac{\langle E^2\rangle}{\mu_0 c} = \frac{1}{2}\frac{E_{\max}^2}{\mu_0 c} = \frac{P_{\text{avg}}}{A}$$

25-4 Energy and Momentum in Electromagnetic Waves

- **The energy a wave delivers to a unit area in a unit time is called the intensity.**



$$I = \frac{\Delta U}{A\Delta t} = \frac{u(Ac\Delta t)}{A\Delta t} = uc$$

25-4 Energy and Momentum in Electromagnetic Waves

- **Substituting for the energy density:**

$$\boxed{I = uc = \frac{1}{2}c\epsilon_0 E^2 + \frac{1}{2\mu_0}cB^2 = c\epsilon_0 E^2 = \frac{c}{\mu_0}B^2}$$

- **An electromagnetic wave also carries momentum:**

$$p = \frac{U}{c}$$

Momentum in EM Waves

- Electromagnetic waves contain momentum: $p = \frac{U}{c}$
- The momentum transferred to a surface depends on the area of the surface. Thus Pressure is a more useful quantity.
- If a surface completely absorbs the incident light, the **momentum** gained by the surface p
- We use the above expression plus Newton's Second Law in the form F=Δp/Δt to derive the following expression for the **Pressure**,

$$P_{\text{abs}} \equiv \frac{F}{A} = \frac{1}{A}\frac{\Delta p}{\Delta t} = \frac{1}{c}\left(\frac{1}{A}\frac{\Delta U}{\Delta t}\right) \quad \left.\begin{aligned} P_{\text{avg}} &= \frac{\Delta U}{\Delta t} \\ I &= \frac{P_{\text{avg}}}{A} \end{aligned}\right\} \frac{1}{A}\frac{\Delta U}{\Delta t} = I$$

$$\Rightarrow \boxed{P_{\text{abs}} = \frac{I}{c}}$$

$$P_{\text{ref}} = \frac{2I}{c}$$

- If the surface completely reflects the light, conservation of momentum indicates the light pressure will be double that for the surface that absorbs.

Radiation pressure

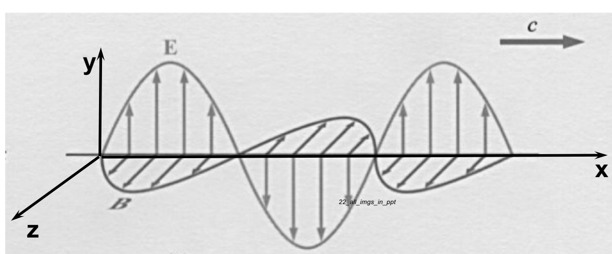
- Therefore, it exerts pressure, called the radiation pressure:

$$\text{pressure}_{\text{av}} = \frac{I_{\text{av}}}{c}$$

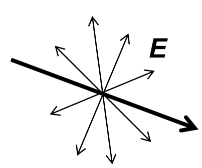
- Radiation pressure is responsible for the curvature of this comet's dust tail.

25-5: Polarization of light

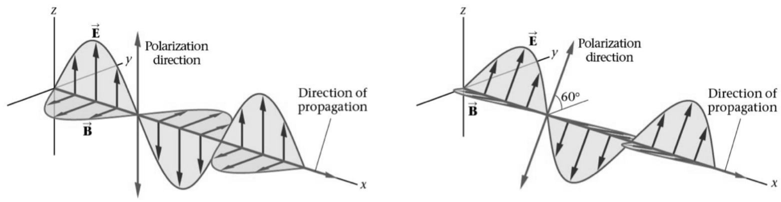
- Recall E&M wave



- *This is an example of linearly polarized light*
  – Electric field along a fixed axis (here y)
- Most light source are nonpolarized
  – Electric field along random axis

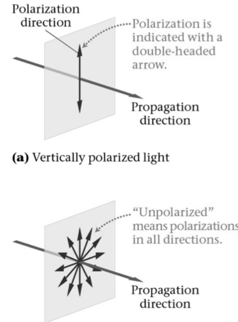


25-5 Polarization



(a) Polarization in z direction (b) Polarization 60° to y direction

- The polarization of an EM wave refers to the direction of its electric field
- Polarized light has its electric fields all in the same direction.
- Unpolarized light has its electric fields in random directions.

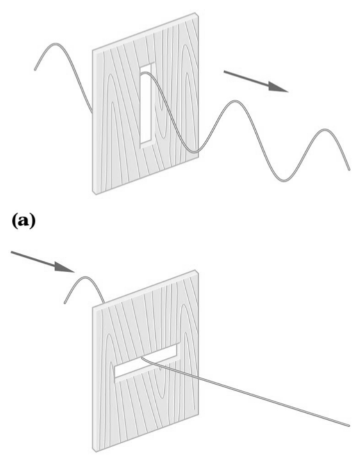


(a) Vertically polarized light

(b) Unpolarized light

25-5 Polarization

- A beam of unpolarized light can be polarized by passing it through a polarizer
- It allows only a particular component of the electric field to pass through
- Here is a mechanical analog:



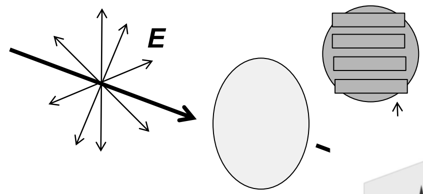
(a)

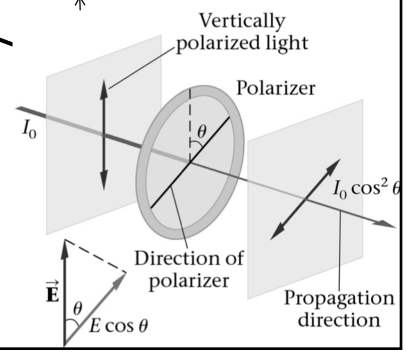
(b)

Polarizers

E. H. Land (1909 – 1991): Polaroid

- **Made of long molecules (polymers)**
  - **Block electric field along their length**
  - **Electric field perpendicular passes through**





- **So E_{after}=E cosθ**
- **Recall that I ~ E^2**

$$I = I_0 \cos^2\theta$$

25-5 Law of Malus

- **Étienne-Louis Malus**
  - **23 July 1775 – 24 February 1812**
  - **French officer in Napoleon'army**
  - **Napoleon Egypt expedition: 1798 to 1801**
- **Since the intensity of light is proportional to the square of the field, the intensity of the transmitted beam is given by the Law of Malus:**

Law of Malus

$$I = I_0 \cos^2 \theta$$

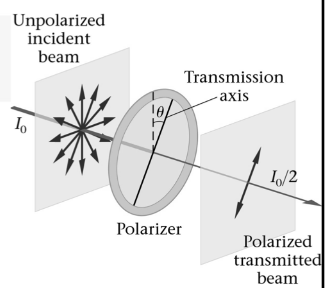
- **The light exiting from a polarizer is polarized in the direction of the polarizer.**

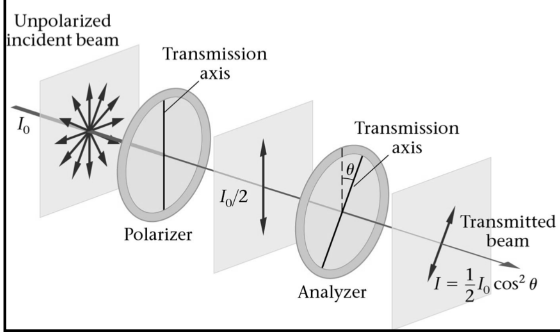
25-5 Polarization

- **For unpolarized light passing through a polarizer**
  - **the transmitted intensity is half the initial intensity**

Transmitted Intensity for an Unpolarized Beam

$I = \frac{1}{2} I_0$



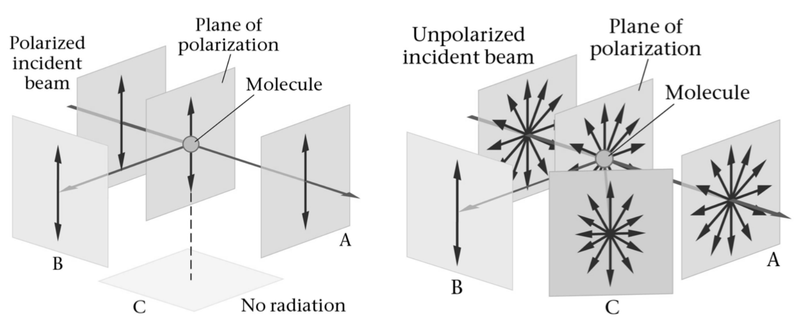


- **A polarizer and an analyzer can be combined**

$$I = \frac{1}{2} I_0 \cos^2 \theta$$

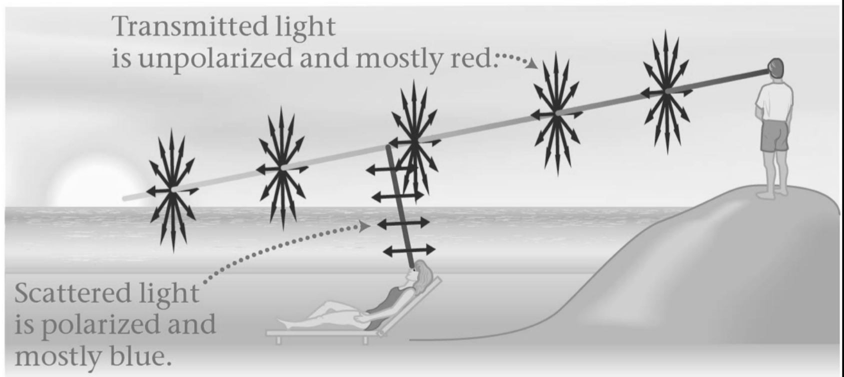
25-5 Polarization

- **Scattering of light by atoms/molecules**
  - **Unpolarized light can be partially or completely polarized**
  - **atoms/molecules which act as small antennas**
  - **If the light is already polarized, its transmission will depend on its polarization.**



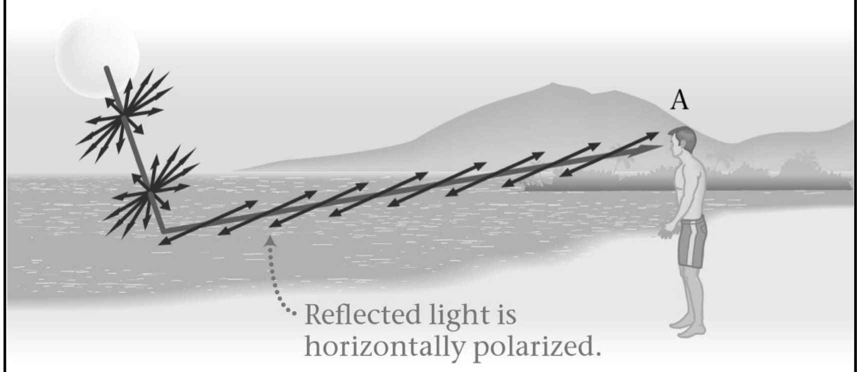
25-5 Polarization

- This means that sunlight will be polarized, depending on the angle our line of sight makes with the direction to the Sun.



25-5 Polarization

- Polarization can also occur when light reflects from a smooth surface:



Lecture 15

Recap of Today's Topic :

- Announcements: Team problems today
  - Team 7: Cailin Catarina, Matthew Canapetti, Kervin Vincent
  - Team 8: Natalie Kasir, Adam Antunes, Quincy Alexander
  - Team 9: Garrett Schlegel, Joyce Nieh, Matthew Lombardo
- **Homework #7: due Monday**
- **Midterm 1:**
  - **Average = 70%**
  - **Office hours if needed (M-2:30-3:30 or TH 3:00-4:00)**
- Chapter 25:
  - E&M waves: Production/properties
  - Spectra
  - Power & pressure
  - Polarization