Physics 202, Lecture 21

Today’s Topics

- Electromagnetic waves (overview)
- Maxwell’s equations
- Examples of EM waves
- Wave Motion (Review ch. 16)
General Waves (Review of Ch. 16)

- Wave: Propagation of a physical quantity in space over time
  \[ q = q(x, t) \]

- Examples of waves:
  Water wave, wave on string, sound wave, earthquake wave, electromagnetic wave, “light”, quantum wave....

- Waves can be transverse or longitudinal.
Seismic Waves

Longitudinal

Transverse

Transverse

Transverse

Direction of Propagation
Wave On A Stretched Rope

- It is a transverse wave

- The wave speed is determined by the tension and the linear density of the rope:

$$v = \sqrt{\frac{T}{\mu}} \quad ; \quad \mu \equiv \frac{\Delta m}{\Delta l}$$

conceptual understanding only
Wave Function

Waves are described by wave functions in the form:

\[ y(x,t) = f(x-\nu t) \]

- **y**: A certain physical quantity, e.g., displacement in the y direction.
- **f**: Can be any form.
- **x**: Space position. Coefficient arranged to be 1.
- **t**: Time. Its coefficient \( \nu \) is the wave speed.
  - \( \nu > 0 \) moving right
  - \( \nu < 0 \) moving left
Practical Technique: Identify Wave Speed in A Wave Function

- A wave function is in the form:
  \[ y(x,t) = \frac{2}{(x - 3.0t)^2 + 1} \]

- What is the wave speed:
  - Answer: 3.0 m/s to the right

- Illustrate wave form at t = 0s, 1s, 2s

![Wave form illustrations](Images)
Example of waves: Tsunami

http://science.howstuffworks.com/nature/natural-disasters/tsunami2.htm
Sinusoidal Wave

- A wave describe a function $y = A \sin(\omega t + \phi)$ is called sinusoidal wave. (Harmonic wave)
- Wave speed $v = \omega / k = \lambda f$
- At each fixed position $x$, the element is undergoing a harmonic oscillation.
  - The amplitude, frequency and phase constant of this oscillation are: $|A|, \omega, -kx - \phi$
- If we fix $t$ and take a snapshot, the wave form is periodic over space ($x$). The spacing period $\lambda$ is called wavelength and $\lambda = 2\pi / k$ (see next page)
Parameters For A Sinusoidal Wave

- Snapshot with fixed t:
  - wave length $\lambda = \frac{2\pi}{k}$
- Snapshot with fixed x:
  - angular frequency $\omega$
  - frequency $f = \frac{\omega}{2\pi}$
  - Period $T = \frac{1}{f}$
  - Amplitude $A$
- Wave Speed $v = \frac{\omega}{k}$
  - $v = \lambda f$, or
  - $v = \lambda / T$
- Phase angle difference between two positions
  - $\Delta \phi = -k \Delta x$
Sound waves: flute

- Speed of sound is 340 m/s. Length of a flute is ~0.6m. What is the lowest note flutes can make?
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\[ f = \frac{c}{2L} \]

\[
= \frac{(340 \text{ m/s})}{(1.2 \text{ m})} \\
= 280 \text{ Hz} \quad ("B", \text{ one note below "middle C"})
\]

Listen.
Tacoma Narrows Bridge
Linear Wave Equation

- Linear wave equation
  - Certain physical quantity
  - Wave speed

\[
\frac{\partial^2 y}{\partial x^2} = \frac{1}{v^2} \frac{\partial^2 y}{\partial t^2}
\]

- Sinusoidal wave
  - \( f \): frequency
  - \( \phi \): Phase
  - \( A \): Amplitude
  - \( \lambda \): Wavelength
  - \( v = \lambda f \)
  - \( k = \frac{2\pi}{\lambda} \)
  - \( \omega = 2\pi f \)

\[
y = A \sin\left(\frac{2\pi}{\lambda} x - 2\pi f t + \phi\right)
\]

General wave: superposition of sinusoidal waves
Maxwell Equations (preview)

\[ \oint \vec{E} \cdot d\vec{A} = \frac{q}{\varepsilon_0} \rightarrow \text{Gauss’s Law/ Coulomb’s Law} \]

\[ \oint \vec{B} \cdot d\vec{A} = 0 \rightarrow \text{Gauss’s Law of Magnetism, no magnetic charge} \]

\[ \oint \vec{E} \cdot d\vec{l} = -\frac{d\Phi_B}{dt} \rightarrow \text{Faraday’s Law} \]

\[ \oint \vec{B} \cdot d\vec{l} = \mu_0 I + \varepsilon_0 \mu_0 \frac{d\Phi_E}{dt} \rightarrow \text{Ampere Maxwell Law} \]

Also, Lotentz force Law \( \rightarrow \)

\[ \vec{F} = q\vec{E} + q\vec{v} \times \vec{B} \]

These are the foundations of the electromagnetism
Electromagnetic Waves

- EM wave equations (from last 2 of Maxwell’s eqns)
  \[ \frac{\partial^2 E_y}{\partial x^2} = \mu_0 \varepsilon_0 \frac{\partial^2 E_y}{\partial t^2} \]
  \[ \frac{\partial^2 B_z}{\partial x^2} = \mu_0 \varepsilon_0 \frac{\partial^2 B_z}{\partial t^2} \]

- Plane wave solutions:
  \[ E = E_{\text{max}} \cos(kx - \omega t + \phi) \]
  \[ B = B_{\text{max}} \cos(kx - \omega t + \phi) \]

- Speed of EM wave:
  \[ c = \frac{1}{\sqrt{\mu_0 \varepsilon_0}} = 2.9972 \times 10^8 \text{ m/s} \] (In vacuum)

- Wavelength and Frequency Relationship:
  \[ \lambda f = c = 3 \cdot 10^8 \text{ m/s} \]

- EM wave can be transmitted in vacuum!
The EM Wave

Two polarizations possible (showing one)
Spectrum of EM Waves

- VHF: 30-300 MHz
- UHF: 300 MHz - 3.0 GHz
- Cell phone: 800/900/1800/1900 MHz
- Wifi: 2.4/5 GHz
- Microwave Oven: 2.4 GHz
- Cordless phone: 0.9/2.4/5.8 GHz

\( \lambda f = c \)

MHz

GHz
Wavelength For TV Signals

- Wavelength and frequency relationship for EM wave

\[ \lambda f = c = 3 \cdot 10^8 \text{ m/s} \]

In vacuum

- Example: Determine the wavelength (in air) of an EM wave of frequency 687 MHZ (HDTV channel 3, CBS = UHF ch. 50)

\[ \lambda = \frac{c}{f} = \frac{3 \cdot 10^8 \text{ m/s}}{687 \text{ MHz}} = \frac{3 \cdot 10^8 \text{ m/s}}{6.87 \cdot 10^8 \text{ s}^{-1}} = 0.44 \text{ m} \]

- VHF: \( \lambda = 1-10 \text{ m} \), UHF: \( \lambda = 0.1-1 \text{ m} \)

- Over-The-Air (OTA) DTV channels:

90% of them in UHF band \( \rightarrow \lambda \sim 0.4 - 0.6 \text{ m} \)
Now you see it, now you don’t: x-ray vs visible light

unknown, 2011

Bertha Roentgen, 1895

me, 2005

visible

X-ray
Now you see it, now you don’t: x-ray vs visible light

Neutrinos from SN-1987A

- SN1987A confirmed our understanding of:
  - Luminosity
  - energies of neutrinos
  - duration of burst

are qualitatively correct.
Evidence of Dark Matter

Merger of Galactic Clusters

dark matter (blue)
ordinary, luminous matter (red)

clusters collide at millions of miles per hour. normal, baryonic matter in each interacts with the similar matter in the other and slowed down, emits X-rays

dark matter did not interact significantly and passed through without disruption. difference caused the dark matter to move ahead, leaving X-ray luminous, baryonic matter lagging behind
Now you see it, now you don’t:
Infrared vs visible light
Now you see it, now you don’t: Infrared vs visible light

Infrared (IR), false color added  visible
Strings on a Bass

http://vimeo.com/4041788