Physics 126 Winter 2009
Lecture #11

Electromagnetic Waves

Prof. Keith Riles
kriles@umich.edu
Where we have gotten to...

- In static cases, no apparent connection between electricity and magnetism:
  - Static charges produce electric fields
  - Steady currents produce magnetic fields

- When fields change we see a connection: Changing magnetic field produces electric fields

Very important principle: responsible for production of nearly all our electricity
James Clerk Maxwell

- Scottish physicist: 1831-1879
- Building on Faraday, Ampere, etc.
- Realized a fourth rule must apply:
  Changing electric fields produce magnetic fields!
Unity of E & M

- “A Treatise on Electricity and Magnetism” by James Clerk Maxwell in 1873
- All E & M phenomena in 4 equations!
- Strong example of unity of physical phenomena
- Physicists still seek a grander unification of all forces in a simple set of laws like this....
Maxwell’s Equations

\[ \nabla \cdot \mathbf{E} = \frac{\rho}{\varepsilon_0} \]
\[ \nabla \times \mathbf{B} = \mu_0 (\mathbf{j} + \varepsilon_0 \frac{\partial \mathbf{E}}{\partial t}) \]
\[ \nabla \cdot \mathbf{B} = 0 \]
\[ \nabla \times \mathbf{E} = -\frac{\partial \mathbf{B}}{\partial t} \]

Gauss's Law

(no monopoles)

Ampère’s Law

Faraday’s Law
Production of Electromagnetic Waves

A transmission antenna

The current used to generate the electric wave creates a magnetic field

\[ T_2 > T_1 \]
Electromagnetic Waves

Far from the antenna we refer to the fields as the radiation fields. The electric and magnetic field lines both form loops and continue to move outward → EM waves

Maxwell: speed of an EM wave in a vacuum is:

\[ c = 3.00 \times 10^8 \text{ m/s} = \frac{1}{\sqrt{\mu_0 \varepsilon_0}} \]
Concept Test #1

Which of the following will NOT generate electromagnetic waves or pulses?

1) a steady direct current
2) an accelerating electron
3) a proton in simple harmonic motion
4) an alternating current
5) charged particles traveling in a circular path in a mass spectrometer
Properties of EM Waves

- At any point, the magnitudes of E and B depend only upon x and t, and not on y or z. A collection of such waves is called a **plane wave**.
- The electric and magnetic fields are perpendicular to each other at any point.
- The electric and magnetic fields are perpendicular to the direction of propagation.
- Both fields alternate in direction.
- The fields are in phase.
- The magnitudes of $E$ and $B$ in empty space are related by $E/B = c$.
- Not mechanical waves; EM waves can propagate in free space.
- Transverse waves

\[ c = f\lambda \]
Concept Test #2

A cellular telephone transmits electromagnetic waves at a frequency of 935 MHz. What is the wavelength of these waves?

1) 0.0106 m
2) 0.642 m
3) 2.40 m
4) 0.321 m
5) 1.22 m

\[
\lambda = \frac{c}{f} = \frac{3 \times 10^8 \text{ m/s}}{935 \times 10^6 \text{ Hz}} = 0.321 \text{ m}
\]
Describing EM Waves

\[
E = E_y = E_{\text{max}} \sin(kx - \omega t)
\]
\[
B = B_z = B_{\text{max}} \sin(kx - \omega t)
\]

where \( k = \frac{2\pi}{\lambda} \), \( \omega = 2\pi f \), and \( f \lambda = \frac{\omega}{k} = c \)

RMS values of the fields:

\[
E_{\text{rms}} = \frac{E_0}{\sqrt{2}}
\]
\[
B_{\text{rms}} = \frac{B_0}{\sqrt{2}}
\]
Concept Test #3

The electric field $\mathbf{E}$ of an electromagnetic wave traveling in the positive $x$ direction is illustrated in the figure. This is the wave of the radiation field of an antenna. What are the direction and the phase relative to the electric field of the magnetic field at a point where the electric field is in the negative $y$ direction?

**Note:** The wave is shown in a region of space that is a large distance from its source.

1) $+$y direction, in phase
2) $-$z direction, 90° out of phase
3) $+$z direction, 90° out of phase
4) $-$z direction, in phase
5) $+$z direction, in phase
Radio and Television Reception

- Broadcasted waves interact with receiving antenna wires and either the electric field or the magnetic field of the wave can be used.
- **Straight antennas are used to detect the electric field**, which oscillate electrons in the wire back and forth when the antenna is placed parallel to the E field. This produces an ac current, which is then amplified in the internal circuits. Receiver is tuned to pick up signals at the desired frequency, $f_0$.

$$f_0 = \frac{1}{2\pi\sqrt{LC}}$$
Loop antenna

- Loop antennas are used to detect the magnetic field when placed perpendicular to the magnetic field.
- Changing magnetic flux induces voltage and current in the loop in accord with Faraday’s Law. Receiver is tuned to detect signals at the desired frequency, $f_0$.

$$f_0 = \frac{1}{2\pi\sqrt{LC}}$$
The Electromagnetic Spectrum

- Like all waves, electromagnetic waves have a wavelength and frequency, related by: \( c = f \lambda \)

Light is an electromagnetic wave!
Concept Test #4

Which one of the following colors of visible light has the longest wavelength?

1) yellow
2) green
3) violet
4) red
5) blue
The Finite Speed of Light

- EM waves travel at a finite speed: \( c = 3 \times 10^8 \text{ m/s} \)
  (around the world in 0.13 s)
- This means you ‘see’ things in the past
- History of the cosmos is laid out before us.....
- A **light-year** or **lightyear** (symbol **ly**) is a unit of **length**: a light-year is the distance light travels in vacuum in one Julian year

\[
1 \text{ ly} = (3 \times 10^8 \text{ m/s})(60 \text{ s/min})(60 \text{ min/hr})(24 \text{ hr/day})(365 \text{ days/year})
\]

\[
1 \text{ ly} = 9.46 \times 10^{15} \text{ m}
\]
Looking Back in Time

- Sun: 8.3 minutes
- Nearest star: 4.3 years
- Across Milky way: 60,000 years
- Nearest Galaxy: 2.2 million years
- Most distant quasar: ~12 billion years
- Cosmic Microwave Background Radiation: 13.7 billion years
- Age of universe: 13.7 billion years

Andromeda galaxy (M31)
Study the Universe

- EM waves can travel through empty space
- Atmosphere transmits only optical and radio
- To see the rest of the universe in other wavelengths, we go to space
Search for Aliens

- SETI (Search for Extraterrestrial Intelligence) Institute

Hello! Go Blue! x thousand years later

x thousand years later

Huhh?

Hello!