Today’s Topics

- Electromagnetic Waves (EM Waves)
- The Hertz Experiment
- Review of the Laws of Electro-Magnetism
- Maxwell’s equation
- Speed of EM Waves
- EM Wave Spectrum, Wavelength and Frequency
- Antenna
- How to make a “HDTV” Antenna?
Review: General Waves (Ch. 16)

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

- Wave function for a running wave: \( y(x,t) = f(x-\nu t) \)

- Linear Wave equation and harmonic wave

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

Wave speed

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

A: Amplitude
\( \lambda \): wavelength
\( v = \nu f \)
\( k = \frac{2\pi}{\lambda} \)
\( \omega = 2\pi f \)

- Wavelength frequency relationship:
  \[ v = \nu f \]
Review: Gauss’s Law / Coulomb’s Law

- The relation between the electric flux through a closed surface and the net charge \( q \) enclosed within that surface is given by the Gauss’s Law

\[
\oint \mathbf{E} \cdot d\mathbf{A} = \frac{Q_{\text{enclosed}}}{\varepsilon_0}
\]

\( \varepsilon_0 \): permittivity of free space (a constant)
Gauss’ s Law for Magnetism

- The Gauss’ s Law for the electric flux is a reflection of the existence of electric charge. In nature we have not found the equivalent, a magnetic charge, or monopole
- We can express this result differently: if any closed surface as many lines enter the enclosed volume as they leave it

\[ \oint \mathbf{B} \cdot d\mathbf{A} = 0 \]
Review: Faraday’s Law

- The emf induced in a “circuit” is proportional to the time rate of change of magnetic flux through the “circuit” or closed path.

\[ \mathcal{E} = -\frac{d\Phi_B}{dt} \]

- Since \[ \mathcal{E} = \oint \vec{E} \cdot d\vec{l} \]

- Then \[ \oint \vec{E} \cdot d\vec{l} = -\frac{d\Phi_B}{dt} \]

nominal direction of \( \mathcal{E} \)

\( \Phi_B = \int \vec{B} \cdot d\vec{A} \)
Review: Ampere’s Law

- A magnetic field is produced by an electric current is given by the Ampere’s Law

\[ \oint \mathbf{B} \cdot d\mathbf{l} = \mu_0 I \]

- A changing electric field will also produce a magnetic field

Finally,

\[ \oint \mathbf{B} \cdot d\mathbf{l} = \mu_0 I + \varepsilon_0 \mu_0 \frac{d\Phi_E}{dt} \]

- \( \Phi_E = \int \mathbf{E} \cdot d\mathbf{A} \)

\( \varepsilon_0 \): permittivity of free space (a constant)

\( \mu_0 \): permeability of free space (also a constant)
Maxwell Equations

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

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

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

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

Also, Lotenz force Law \( \rightarrow \mathbf{F} = q\mathbf{E} + q\mathbf{v} \times \mathbf{B} \)

These are the foundations of the electromagnetism
Sources of \( \mathbf{E} \) and \( \mathbf{B} \) Fields

- Sources for the electric field:
  - Electric charges (Coulomb's Law, static)
    - subjects of past several weeks
  - Change of \( \mathbf{B} \) field (Faraday's Law, varying in time)

- Sources for the magnetic field:
  - Electric current (Biot-Savart Law/Ampere’s Law, static)
  - Change of \( \mathbf{E} \) field (Ampere-Maxwell Law, varying)

⇒ All these features are summarized in Maxwell Equations.

Thinking machine:
A varying \( \mathbf{E} \) can produce a (varying) \( \mathbf{B} \), a varying \( \mathbf{B} \) can produce a varying \( \mathbf{E} \)...... (looks like no charge is necessary)
EM Fields in Space

- Maxwell equations when there is no charge and current:

\[ \oint \mathbf{E} \cdot d\mathbf{A} = 0 \]
\[ \oint \mathbf{B} \cdot d\mathbf{A} = 0 \]

\[ \oint \mathbf{E} \cdot d\mathbf{l} = -\frac{d\Phi_B}{dt} \]
\[ \oint \mathbf{B} \cdot d\mathbf{l} = \varepsilon_0 \mu_0 \frac{d\Phi_E}{dt} \]

- Differential forms:

\( \frac{\partial E_y}{\partial x} = -\frac{\partial B_z}{\partial t} \)
\( \frac{\partial B_z}{\partial x} = -\mu_0 \varepsilon_0 \frac{\partial E_y}{\partial t} \)

\( \frac{\partial^2 E_y}{\partial x^2} = \mu_0 \varepsilon_0 \frac{\partial^2 E_y}{\partial t^2} \)
\( \frac{\partial^2 B_z}{\partial x^2} = \mu_0 \varepsilon_0 \frac{\partial^2 B_z}{\partial t^2} \)
Plane Electromagnetic Waves

- **EM wave equations:**
  \[
  \frac{\partial^2 E_y}{\partial x^2} = \mu_0 \varepsilon_0 \frac{\partial^2 E_y}{\partial t^2} \quad \frac{\partial^2 B_z}{\partial x^2} = \mu_0 \varepsilon_0 \frac{\partial^2 B_z}{\partial t^2}
  \]

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

- **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 transmit in vacuum!**
Demo: Hertz Experiment

In 1887, Heinrich Hertz first demonstrated that EM fields can transmit over space.

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The EM Wave

Two polarizations possible (showing one)
Spectrum of EM Waves

- **GHz**: 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

\[ \lambda f = c \]
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: \( \lambda = 1\text{-}10 \text{ m} \), UHF: \( \lambda = 0.1\text{-}1 \text{ m} \)
- Over-The-Air (OTA) DTV channels:  
  90% of them in UHF band \( \Rightarrow \lambda \sim 0.4 \text{ - } 0.6 \text{ m} \)
Receiving HDTV Signals

- Functional flow of a HDTV (or in general a digital TV)

- Antennas: Specially shaped/configured conductors for receiving radio frequency (RF) EM waves (via induction).

- Keywords for antennas: gain, impedance, bandwidth, orientation, polarization, impedance matching, velocity factor, ....
Half-Wave Antenna

A special configuration
¼-wave antenna

Standing Wave Condition (ch. 18)
Various RF Antennas

- Beverages
- Rhombic
- Vantenna
- Yagi
- Helical
- Loop
- Mocristrip
- Log-periodic