Lecture 22

- Electricity and Magnetism
  - Electromagnetic waves
  - Properties
  - Spectrum

http://www.physics.wayne.edu/~apetrov/PHY2140/

Chapter 21
Lightning Review

Last lecture:

1. AC circuits
   ✓ Resistors, capacitors, inductors in ac circuits
   ✓ Power in an AC circuit
   ✓ Resonance in a RLC circuit

\[ X_C = \frac{1}{2\pi fC}, \quad X_L = 2\pi fL \]
\[ Z = \sqrt{R^2 + (X_L - X_C)^2} \]
\[ \tan \phi = \frac{X_L - X_C}{R} \]
\[ f_0 = \frac{1}{2\pi \sqrt{LC}} \]

**Review Problem:** The light bulb has a resistance \( R \), and the emf drives the circuit with a frequency \( \omega \). The light bulb glows most brightly at

1. very low frequencies.
2. very high frequencies.
3. the frequency \( \omega = 1/\sqrt{LC} \)
Reminder (for those who don’t read syllabus)

**Reading Quizzes (bonus 5%)**:

It is important for you to come to class prepared, i.e. be familiar with the material to be presented. To test your preparedness, a simple five-minute quiz, testing your qualitative familiarity with the material to be discussed in class, will be given at the beginning of some of the classes. No make-up reading quizzes will be given.

There could be one today…

… but then again…
Electricity and magnetism were originally thought to be unrelated.

In 1865, James Clerk Maxwell provided a mathematical theory that showed a close relationship between all electric and magnetic phenomena.
Maxwell’s predictions

- Electric field lines originate on positive charges and terminate on negative charges
  - Electric field is produced by charges
- Magnetic field lines always form closed loops – they do not begin or end anywhere
  - Magnetic field is produced by currents (moving charges)
- A varying magnetic field induces an emf and hence an electric field (Faraday’s Law)
  - Electric field is also produced by changing magnetic field

**Question:** is there a symmetry between electric and magnetic fields, i.e. can magnetic field be produced by changing electric field???

Maxwell: YES!!!

- Magnetic field is also produced by changing electric field.
Maxwell’s Predictions

If magnetic field can create electric field and vice versa, there is a very interesting phenomenon to be observed:

- Changing electric field produces magnetic field…
- … which in turn produces changing electric one (but: energy conservation)
- … which in turn produces changing magnetic field…

Maxwell concluded that visible light and all other electromagnetic waves consist of fluctuating electric and magnetic fields, with each varying field inducing the other.

Maxwell calculated the speed of light to be $3 \times 10^8$ m/s.
Note: Charges and Fields

- **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

These fields are *in phase*
- At any point, both fields reach their maximum value at the same time
Electromagnetic Waves

EM waves can be produced by an antenna, which is just some kind of wire that is connected to an ac source. The ac source produces oscillating + and - charges which set up electric field (due to the separation of charge) and a magnetic field (due to the current in the wire).

Note that the electric and magnetic fields are perpendicular to each other. This field begins to move away from the antenna and in a little while the ac source has caused the situation to reverse.
Electromagnetic Waves are Transverse Waves

The \textbf{E} and \textbf{B} fields are perpendicular to each other. Both fields are perpendicular to the direction of motion. Therefore, em waves are transverse waves.
An *RLC* circuit is used to tune a radio to an FM station broadcasting at 88.9 MHz. The resistance in the circuit is 12.0 Ω and the capacitance is 1.40 pF. What inductance should be present in the circuit?
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**Given:**
- RLC circuit
- \( f_0 = 88.9 \text{ Hz} \)
- \( R = 12.0 \Omega \)
- \( C = 1.40 \text{ pF} \)

**Find:**
- \( L = ? \)

The resonance frequency of the circuit should be chosen to match that of the radio station

\[
    f_0 = \frac{1}{2\pi\sqrt{LC}} \quad \text{or} \quad L = \frac{1}{4\pi^2 f_0^2 C}
\]

This is sufficient to know for a solution, as we know all of the quantities on the right hand side

\[
    L = \frac{1}{4\pi^2 \left( 88.9 \times 10^3 \text{ Hz} \right)^2 \left( 1.40 \times 10^{-12} \text{ F} \right)} = 2.29 \times 10^{-6} \text{ H}
\]
Properties of EM Waves

- Electromagnetic waves are transverse waves
- Electromagnetic waves travel at the speed of light

Because em waves travel at a speed that is precisely the speed of light, 
*light is an electromagnetic wave*
The sun is about $1.5 \times 10^{11}$ m from the earth. How long does it take light to get here?

$$t = \frac{\text{distance}}{\text{time}} = \frac{1.5 \times 10^{11} \text{ m}}{3 \times 10^8 \text{ m/s}} = 500 \text{ sec} = 8.3 \text{ min}$$
Properties of EM Waves, 2

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

\[ \frac{E}{B} = \text{speed of light} \]

- Electromagnetic waves carry energy as they travel through space, and this energy can be transferred to objects placed in their path
Properties of EM Waves, 3

Energy carried by em waves is shared equally by the electric and magnetic fields

Average power per unit area =

\[
\frac{E_{\text{max}} B_{\text{max}}}{2\mu_0} = \frac{E_{\text{max}}^2}{2\mu_0 c} = \frac{c B_{\text{max}}^2}{2\mu_0}
\]
Properties of EM Waves, final

Electromagnetic waves transport linear momentum as well as energy

- For complete absorption of energy $U$,
  $$p = \frac{U}{c}$$
- For complete reflection of energy $U$,
  $$p = \frac{2U}{c}$$

Radiation pressures can be determined experimentally
Determining Radiation Pressure

- This is an apparatus for measuring radiation pressure.
- In practice, the system is contained in a vacuum.
- The pressure is determined by the angle at which equilibrium occurs.
The Spectrum of EM Waves

- Forms of electromagnetic 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
The EM Spectrum

- Note the overlap between types of waves
- Visible light is a small portion of the spectrum
- Types are distinguished by frequency or wavelength

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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
Example: talking to a submarine

The U.S. Navy has long proposed the construction of extremely low-frequency (ELF) communications systems; such waves could penetrate the oceans to reach distant submarines. Calculate the length of a quarter-wavelength antenna for a transmitter generating ELF waves of frequency 75 Hz. How practical is this?
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**Given:**
- $\frac{1}{4}$ wavelength antenna
- $f_0 = 75$ Hz

**Find:**
- $L = ?$

First determine the wavelength, a forth of which will give us the length of an antenna

$$\lambda = \frac{v}{f} = \frac{3.00 \times 10^8 \ m/s}{75 \ Hz} = 4.00 \times 10^6 \ m = 4000 \ km$$

The required length of antenna is then a quarter of this

$$L = \frac{\lambda}{4} = \frac{4000 \ km}{4} = 1000 \ km$$