From Last Time...

- Coulomb force between charged particles
  - Same form as gravitational force
- Electric field lines: path followed by charged particle
- Electric current: flow of charged particles
- Electrostatic potential:
  - Measured in volts.
  - Analogous to gravitational potential.
- Magnetic field:
  - Arises from electric currents (moving charges)
  - Also results in force on an electric current
- Faraday effect:
  - Changing magnetic field *induces* electric current
  - Magnetic field from induced currents opposes change in applied field
James Clerk Maxwell

- 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 Starting Points

- Electric field lines originate on positive charges and terminate on negative charges (Gauss’s law for E)
- Magnetic field lines always form closed loops - they do not begin or end anywhere (Gauss’s law for B)
- A varying magnetic field induces an emf and hence an electric field (Faraday’s Law)
- Magnetic fields are generated by moving charges or currents (Ampère’s Law)
Maxwell’s Predictions

• Maxwell used these starting points and a corresponding mathematical framework to prove that electric and magnetic fields play symmetric roles in nature
• He hypothesized that a changing electric field would produce a magnetic field
• Maxwell calculated the speed of light to be $3 \times 10^8$ m/s
• He concluded that visible light and all other electromagnetic waves consist of fluctuating electric and magnetic fields, with each varying field inducing the other
Hertz’s Confirmation of Maxwell’s Predictions

- Heinrich Hertz was the first to generate and detect electromagnetic waves in a laboratory setting
Hertz’s Experimental Apparatus

- An induction coil is connected to two large spheres forming a capacitor.
- Oscillations are initiated by short voltage pulses.
- The inductor and capacitor form the transmitter.
Hertz Transmitter

- Hertz's radio wave generator (transmitter). The free standing structure on the right was a two meter high reflector with a spark gap and short dipole antenna at its focal point. The apparatus on the table was an induction coil to generate a high voltage spark at the gap. Figure 1 diagrams adapted from "Electric Waves", by Heinrich Hertz, MacMillan & Co. (1900)

- http://www.newscotland1398.net/nfld1901/marconi-nfld.html
Magnified view of the spark gap and dipole transmitting ("feed") antenna at the focal point of the reflector. The high voltage spark jumped the gap between the spherical electrodes. The electrical impulse produced by the spark generated damped oscillations in the dipole antenna.

Magnified view of the spark gap and dipole receiving antenna at the focal point of a receiving reflector similar to the transmitting one. The width of the small spark gap on the right is controlled by the screw below it. The vertical dipole antenna at the left was about 40 centimeters long.
Hertz’s Conclusions

- Hertz hypothesized the energy transfer was in the form of waves
  - These are now known to be electromagnetic waves
- Hertz confirmed Maxwell’s theory by showing the waves existed and had all the properties of light waves
  - They had different frequencies and wavelengths
Hertz’s Measure of the Speed of the Waves

• Hertz measured the speed of the waves
  - He used the waves to form an interference pattern, and calculated the wavelength (will see this at end of lecture)
  - From $v = f \lambda$, $v$ was found
  - $v$ was very close to $3 \times 10^8$ m/s, the known speed of light
• Provided evidence in support of Maxwell’s theory
Marconi: applying Hertz’s discoveries

- Spark gap of a ship's wireless transmitter, circa 1900.
- Front panel has been swung down to reveal the device but would be closed in operation for protection against noise and ozone.
- The hemispheres were energized from an induction coil.

- 1912 Portable Aircraft Spark Transmitter.
Early ‘Coherer’ to detect waves

- Used as a sensitive detector of EM wave.
- The coherer uses a small glass tube with metal filings. With no signal the filings have a very high resistance. With the application of Radio Frequency EM wave the filings stick together or cohere and cause the D.C. resistance of the filings to drop to a very low value.
The entire receiver

- A small battery and a sensitive relay is connected to the coherer through RF chokes and this relay in turn operated a bell or buzzer.
- The relay also operated a tapping device which taps on the coherer to reset the filings.
- The code speed with such a receiver was low usually less than ten words per minute. It is a great receiver to pick up lighting storms.
- Marconi used a device in place of the bell called an Inker that printed dots and dashes on a strip of paper.
Marconi Transatlantic radio transmitter

- Induction coils
- Capacitor banks
- Spark gap
Marconi Transmitter at Poldhu, Cornwall

- The first transatlantic radio transmissions were made from Poldhu in 1901. This photographs conveys the size of the antenna installation, comprising twenty 200-foot masts and driven by a 25 kW alternator. Unfortunately, a gale blew the masts down just before the first test transmissions in December 1901, which were nevertheless successful using a hastily-rigged two-mast antenna.

Before gale

After gale
The jury-rigged antenna

- 24 September 1901: Temporary aerial used for Atlantic Leap following destruction of original circular aerial by 17th September gale.
- Poldhu communicated through its rebuilt antenna with a ship installation on the Philadelphia out to 700 miles in daylight and 1550–2100 miles at night.
Transatlantic receiver

Left to right: Kemp, Marconi, and Paget pose in front of a kite that was used to keep aloft the receiving aerial wire used in the transatlantic radio experiment.
What’s all this about antennae?

• When a charged particle undergoes an acceleration, it must radiate energy
  - If currents in an ac circuit change rapidly, some energy is lost in the form of em waves
  - EM waves are radiated by any circuit carrying alternating current

• An alternating voltage applied to the wires of an antenna forces the electric charge in the antenna to oscillate
Electromagnetic Waves
Electromagnetic Waves
Electromagnetic Waves
Electromagnetic Waves
Electromagnetic Waves
Electromagnetic Waves
EM Waves from an Antenna

- 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)
EM Waves by an Antenna

- 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.
- EM wave consists of both electric and magnetic fields.
EM Waves Question?

Which direction should I orient my antenna to receive a signal from a vertical transmission tower?

A) Vertical  B) Horizontal  C) 45 Degrees
Electromagnetic Waves

Current (up and down) creates B field into and out of the page.
Electromagnetic Waves

• A Transverse wave.
• Electric and magnetic fields are perpendicular to propagation direction
• Can travel in empty space

\[ f = \frac{v}{\lambda} \]
\[ v = c = 3 \times 10^8 \text{ m/s} \ (186,000 \text{ miles/second!}) \]
Detecting EM waves

**FM antenna**

**AM antenna**

Oriented vertically for radio waves
Measure of EM wave speed

- Around 1670, Danish astronomer Olaus Roemer discovered that eclipses of Jupiter's moons appear delayed by some twenty minutes when the Earth is furthest from Jupiter relative to when the Earth is closest to Jupiter. He interpreted the delay as light travel time and inferred the speed of light.
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
Electromagnetic spectrum

- Any frequency of motion of a source charge produces an EM wave.
- Radio waves have $f \sim \text{MHz}$, $\lambda \sim \text{km}$. For visible light waves, $\lambda \sim 50 \text{ nm}$
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
Wave effects in EM radiation

- Same effects as in sound waves.
- Doppler shift: change in light frequency due to motion of source or observer
- Interference: superposition of light waves can result in either increase or decrease in brightness.
EM version of Doppler shift: the red shift

• If a star is moving away from us, the light from that star will be shifted to lower frequencies - the Red Shift.

• All astronomical objects are found to be retreating from each other - the Universe is expanding.

• Extrapolating back in time, the Universe must have begun from a single point in space and time - the Big Bang.
Interference of light waves

- Can be constructive or destructive
- Depends on whether crests or troughs coincide.
- As in sound waves, crests and troughs become separated due to different distances.
- Very small wavelengths make these effects more subtle than in sound waves.
- Remember constructive & destructive interference?
Constructive Superposition

\[ t +1 \]
\[ t -1 \]
\[ t +2 \]
\[ t -2 \]
Destructive Superposition

Out of Phase
180 degrees
Interference: Key Idea

Two rays travel almost exactly the same distance.

Bottom ray travels a little further.

Key for interference is this small extra distance.
Interference Requirements

- Two (or more) waves
- Same Frequency
- Coherent (waves must have definite phase relation)
Interference of light waves

- Coherent beams from two slits

- *Constructive interference:* waves in phase at screen
Destructive interference

(c)

Fri. Oct 8
Phy107 Lecture 14
Interference: secondary maxima

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(b)
Resulting diffraction pattern
Hertz’s Measure of the Speed EM Waves

- Hertz measured the speed of the waves from the transmitter
  - He used the waves to form an interference pattern and calculated the wavelength
  - From $v = f \lambda$, $v$ was found
  - $v$ was very close to $3 \times 10^8$ m/s, the known speed of light
- This provided evidence in support of Maxwell’s theory