Physics 116

Lecture 12
Electromagnetic waves
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Exam 1 scores will be posted on WebAssign today
- Will also appear on Catalyst Gradebook tomorrow

Each item was worth 6 points, 15*6=90, so I added 10 to make 100 max possible
So, everyone who took the exam got 10 pts just for showing up!

Exam statistics:
70.6 avg
12.8 std dev
70 median
94 max
46 min
# Lecture Schedule

(up to exam 2)

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Today: Focus on Electromagnetic Waves (25.1 – 25.2)
1) An air-track cart is attached to a spring and completes one oscillation every 5.67 s. At \( t = 0 \) s the cart is released at a distance of 0.250 m from its equilibrium position. What is the position of the cart when \( t = 29.6 \) s?

A) \( x = 0.0460 \) m  
B) \( x = 0.210 \) m  
C) \( x = 0.218 \) m  
D) \( x = 0.342 \) m  
E) \( x = -0.218 \) m

\[
A = 0.25m, \quad \omega t = 2\pi \left[ \frac{29.6s}{5.67s} \right] = 32.8\text{rad}
\]

\[
x(t) = A\cos(\omega t) = \left(0.25m\right)\cos(32.8\text{rad}) = 0.046
\]

2) A mass is oscillating on a spring with a period of 4.60 s. At \( t = 0 \) s the mass has zero speed and is at \( x = 8.30 \) cm. What is its acceleration at \( t = 2.50 \) s?

\[
x(0) = A = 8.3cm, \quad a(t) = -A\omega^2 \cos(\omega t)
\]

\[
\omega = \left(\frac{2\pi}{T}\right)
\]

\[
a(2.5\text{sec}) = -8.3cm \left(\frac{6.28}{4.6\text{s}}\right)^2 \cos \left(2\pi \left(\frac{2.5\text{s}}{4.6\text{s}}\right)\right)
\]

\[
= (-8.3cm)1.864 \left(rad / s\right)^2 (-0.963)
\]

\[
= 14.90cm
\]

3) A mass oscillates on the end of a spring, first on Earth, and then on the Moon. Where is the period the greatest?

A) Earth  
B) the Moon  
C) the same on both Earth and the Moon  
D) Cannot be determined from the information given.

\[
T = 2\pi \sqrt{\frac{m}{k}} : \text{no dependence on } g!
\]
4) A 92-kg man climbs onto a car with worn out shock absorbers and this causes the car to drop down 4.5 cm. As he drives along, he hits a bump, and this starts the car oscillating at an angular frequency of 4.52 rad/s. What is the mass of the car? \( g = 9.8 \, \text{m/s}^2 \).

A) 890 kg
B) 760 kg
C) 920 kg
D) 990 kg
E) 1900 kg

\[ k = -F / x = \frac{92 \, \text{kg} \left(9.8 \, \text{m/s}^2\right)}{0.045 \, \text{m}} = 20036 \, \text{N/m} \]

\[ \omega = \sqrt{\frac{k}{(M + 92 \, \text{kg})}} \rightarrow M = \left(\frac{k}{\omega^2}\right) - 92 \, \text{kg} = \frac{20036 \, \text{N/m}}{(4.52 \, \text{rad/s})^2} - 92 \, \text{kg} = 890 \, \text{kg} \]

5) A mass of 1.53 kg is attached to a spring and the system is undergoing simple harmonic oscillations with a frequency of 1.95 Hz and amplitude of 7.50 cm. What is the total mechanical energy of the system?

A) 0.844 J
B) 0.646 J
C) 0.633 J
D) 0.955 J
E) 0 J

\[ k = \omega^2 m = \left[2\pi \left(1.95 \, \text{Hz}\right)\right]^2 1.53 \, \text{kg} = 230 \, \text{N/m} \]

\[ E = \frac{1}{2} k A^2 = \frac{1}{2} \left(230 \, \text{N/m}\right) \left(0.075\right)^2 = 0.65 \, \text{J} \]

6) Doubling only the spring constant of a vibrating mass-and-spring system produces what effect on the system's mechanical energy?

A) increases the energy by a factor of square root of two
B) increases the energy by a factor of two
C) increases the energy by a factor of three
D) increases he energy by a factor of four
E) produces no change
7) When the mass of a simple pendulum is tripled, the time required for one complete vibration

A) increases by a factor of 2.
B) increases by a factor of 3.
C) **does not change.**
D) decreases to one-third of its original value.
E) decreases to $1/\sqrt{3}$ of its original value.

$$T = 2\pi \sqrt{\frac{L}{g}} : \text{ no dependence on } m$$

8) A spar buoy is a cylindrical object that floats in the ocean with its axis in the vertical direction. When it is disturbed a distance $h$ from its equilibrium position, the magnitude of the restoring force is equal to $(\rho g S) h$, where $\rho$ is the density of the water and $S$ is the cross-sectional area of the cylinder.

A certain spar buoy has a mass of 150 kg, cross-sectional area $S = 2.50 \text{ m}^2$, and is floating in seawater, $\rho = 1025 \text{ kg/m}^3$. Use $g = 9.8 \text{ m/s}^2$.

What is the frequency of oscillation if the buoy is pushed down and released?

A) 12.9 Hz
B) **2.06 Hz**
C) 7.19 Hz
D) 17.1 Hz
E) 2.72 Hz

Continue on next page...

\[ k = \rho g S = \left(1025 \text{ kg/m}^3\right) 9.8 \text{ m/s}^2 \left(2.5 \text{ m}^2\right) = 25112 \text{ N/m} \]

\[ f = \frac{1}{2\pi} \sqrt{\frac{k}{m}} = \frac{1}{6.28} \sqrt{\frac{25112 \text{ N/m}}{150 \text{ kg}}} = 2.06 \text{ Hz} \]
9) If the intensity level of one trombone is 70 dB, what is the intensity level of 76 trombones?

A) 146 dB
B) 89 dB
C) 70 dB
D) 76 dB
E) 82 dB

\[
70dB = 10 \log_{10} \left( \frac{I_1}{I_0} \right)
\]

\[
10 \log_{10} \left( \frac{76I_1}{I_0} \right) = 10 \log_{10} (76) + 10 \log_{10} \left( \frac{I_1}{I_0} \right)
\]

\[
= [10(1.88) + 70] = 89dB
\]

10) By what amount does the intensity level decrease when you triple your distance from a source of sound?

A) 9.5 dB
B) 4.8 dB
C) 6.0 dB
D) 12 dB
E) 3.0 dB

\[
R \rightarrow 3R \Rightarrow I \rightarrow \frac{I}{9}
\]

\[
dB = 10 \log_{10} \left( \frac{\frac{I}{9}}{I_0} \right) = 10(0.95) + 10 \log_{10} \left( \frac{I}{I_0} \right)
\]

11) A car approaches you at a constant speed, sounding its horn, and you hear a frequency of 76 Hz. After the car goes by, you hear a frequency of 65 Hz. What is the frequency of the sound emitted by the horn? The speed of sound in air is 343 m/s, and you are at rest.

A) 68 Hz
B) 69 Hz
C) 70 Hz
D) 71 Hz
E) 72 Hz

\[
76Hz = f \left( \frac{1}{1 - u_{SRC} / c} \right) \quad \text{(car approaching)}
\]

\[
65Hz = f \left( \frac{1}{1 + u_{SRC} / c} \right) \quad \text{(car moving away)}
\]

\[
f = 76Hz \left( 1 - \frac{u_{SRC}}{c} \right) = 65Hz \left( 1 + \frac{u_{SRC}}{c} \right)
\]

\[
76Hz - (76Hz) \left( \frac{u_{SRC}}{343m/s} \right) = 65Hz + (65Hz) \left( \frac{u_{SRC}}{343m/s} \right)
\]

\[
76Hz - 65Hz \left( \frac{343m/s}{76Hz + 65Hz} \right) = 26.8m/s
\]

\[
f = 76Hz \left( 1 - \frac{26.8m/s}{343m/s} \right) = 76Hz \left( 0.92 \right) = 70Hz
\]
12) Two wave pulses pass each other on a string. The one traveling toward the right has amplitude \(+A\), while the one traveling toward the left has an equal amplitude in the negative direction. At the point that they occupy the same region of space at the same time, the amplitude is

Cancellation
A) \(+2A\).
B) \(+A\).
C) 0.
D) \(-A\).
E) \(-2A\).

13) The lowest tone to resonate in an open pipe of length L is 200 Hz. Which one of the following frequencies will not resonate in the same pipe?

Must be integer multiple of 200 Hz
A) 200 Hz
B) 400 Hz
C) 600 Hz
D) 800 Hz
E) 900 Hz

14) Two pure tones are sounded together and a particular beat frequency is heard. What happens to the beat frequency if the frequency of the lower of the two frequencies is increased?

Difference in \( f \) gets smaller, beat frequency gets smaller
A) It increases.
B) It decreases.
C) It does not change.
D) It becomes zero.
E) It could either increase or decrease.
15) A bat emits a sound at a frequency of 39.0 kHz as it approaches a wall. The bat detects beats with a frequency of 827 Hz between the sound it emits and the echo bouncing from the wall. What is the speed of the bat? The speed of sound in air is 343 m/s.

A) 2.7 m/s  
B) 3.0 m/s  
**C) 3.6 m/s**  
D) 5.4 m/s  
E) 9.0 m/s

\[ f_0 = 39\text{kHz}, \quad f' = f_0 + f_{\text{beat}} = 39\text{.827kHz} \]

\[ f_{\text{reflected}} = f_0 \left( \frac{1}{1 - \frac{v}{c}} \right) \quad \text{(moving source)} \]

\[ f' = f_{\text{reflected}} \left( 1 + \frac{v}{c} \right) \quad \text{(moving observer)} \]

\[ 39.827\text{kHz} = f_0 \left( \frac{1 + \frac{v}{c}}{1 - \frac{v}{c}} \right) = 39\text{kHz} \left( \frac{343\text{m/s} + v}{343\text{m/s} - v} \right) \]

\[ 39.827\text{kHz} \left( \frac{343\text{m/s}}{s - v} \right) = 39\text{kHz} \left( \frac{343\text{m/s}}{s + v} \right) \]

\[ v = \frac{39.827\text{kHz} - 39\text{kHz}}{39\text{kHz} + 39.827\text{kHz}} \cdot \frac{343\text{m/s}}{s} = 3.6 \text{ m/s} \]
Electromagnetic waves

- Discoveries about electric and magnetic fields:
  - H. Ørsted (1820) found electric currents deflected compasses
  - Electric current makes magnetic field: \( E \) and \( B \) fields are related
  - M. Faraday (1840) found \textit{changing} \( B \) fields create \textit{currents}
    - Electric generator! Legislator: “What use is this toy, sir?”, Faraday: “Why, sir, you will soon find a reason to put a tax upon it!”
  - J. Maxwell (1865): unified electricity and magnetism (Maxwell’s eqns)
    - Included \textit{assumption} that changing \( E \) field also makes a \( B \) field
  - H. Hertz (1888): first observed E-M waves (radio waves!)
    - Spark in loop of wire produced spark across the room in another
    - G. Marconi (c1900): radiotelegraphy (“spark transmitters”)
- If you make a time-varying \( E \) field, it automatically makes its own time-varying \( B \) field (and vice-versa)
  ...as described by Maxwell’s equations
Recall PHYS 115

- You learned some background material for this topic last term:
  - Faraday’s Law: induced emf around a coil is proportional to rate of change of magnetic flux
    \[ \text{flux } \Phi = B \cdot A \]
    \[ B = \text{magnetic field (tesla), } A = \text{area of coil, } m^2 \]
    \[ E \text{ (volts)} = -\frac{\Delta \Phi}{\Delta t} \]
    (the minus sign is Lenz's contribution)
    - Flow of charge (current induced by emf) implies an E field is created by changing B
  - Lenz’s Law: the induced emf creates a current that produces a new B field opposing the change in magnetic flux
    - Rather confusing without Maxwell’s equations
      - Which every physics student should at least see once!
Maxwell’s equations: connecting \( \mathbf{B} \) and \( \mathbf{E} \)

- Electric current \( \mathbf{I} \) makes a magnetic field \( \mathbf{B} \), with field lines around the wire
  - If charges move back and forth (oscillating current), we get time-varying magnetic fields
  - Magnetic fields are perpendicular to the electric current direction (field lines are rings around the current)
- Time varying \( \mathbf{B} \) fields produce time-varying \( \mathbf{E} \) fields...
- Maxwell’s equations (1865) tell us how they are related:

**“Cultural supplement”:**

These symbols represent operations in calculus (“partial derivatives”) which find the rate of change of fields with respect to position and time. (They mean: only \( \mathbf{B} \) changes)

\[
\begin{align*}
(1) \quad & \nabla \cdot \mathbf{E} = \frac{\rho}{\varepsilon_0} \\
(2) \quad & \nabla \times \mathbf{E} = -\frac{\partial \mathbf{B}}{\partial t} \\
(3) \quad & \nabla \cdot \mathbf{B} = 0 \\
(4) \quad & \frac{1}{\mu_0 \varepsilon_0} \nabla \times \mathbf{B} = \frac{\mathbf{I}}{\varepsilon_0} + \frac{\partial \mathbf{E}}{\partial t} \quad \left( c^2 = \frac{1}{\mu_0 \varepsilon_0} \right)
\end{align*}
\]

\( \varepsilon_0 \) and \( m_0 \) can be determined by measuring electric and magnetic forces. Maxwell found they were related to \( c \), the speed of light!
Facts we already know about EM waves

- Light waves are a variety of EM wave
- Light waves propagate through a vacuum (beeper + light demo)
  - No material medium is required for light to propagate
- The speed of light is huge, in human terms: ~ 300,000,000 m/s
- EM waves are produced by changing E or B fields
- Changing E or B fields are created by accelerated charges (changing currents)
- We can use changing currents to make radio waves
  - Example: push charge into and out of a dipole antenna
  - This produces E fields parallel to the dipole and B fields perpendicular to it
E-M wave (from a charge oscillating at center)

- See this website for many interesting “movies” illustrating things we have talked about

http://www.phys.hawaii.edu/~teb/java/ntnujava/
Recall from last week: Doppler effect:

If sound source and observer are in relative motion, observed frequency will differ from source’s frequency

- Sound waves require a material medium to propagate
- Recall: **Galilean relativity**
  - If two coordinate systems differ only by a constant \( v \), not by an acceleration, we can simply add velocity vectors to get apparent \( v \) in either
  - Standard example: rowboat in a river that is flowing with speed \( v \)
    - rower has speed \( u \) relative to water,
    - water has speed \( v \) relative to earth,
    - so rower’s speed relative to earth is \( u + v \)
      - \( u \) is + if same direction as river (rowing downstream), negative if opposite (upstream)
  - **Coordinate system of medium (air, water, etc) is “special” for sound waves**
    - Sound waves have speed \( c \), and \( f \) and \( \lambda \) are related by \( c = \lambda f \)
    - For an observer moving relative to medium with speed \( u \), apparent propagation speed \( c' \) will be different: \( c' = c \pm u \) (sign depends on relative direction of \( u \))
      - Wavelength cannot change – it’s a constant length in the medium, and same length in moving coordinate system (motion does not change lengths)
      - Observed frequency has to change, to match apparent speed and fixed wavelength: \( f' = \frac{c'}{\lambda} \)
Doppler effect:

- So if observer is moving (speed $u$) relative to source at rest in medium, then apparent frequency $f'$ is:

$$f' = \frac{c'}{\lambda} = \frac{(c + u)}{(c / f)} = \left(\frac{c + u}{c}\right)f = f\left(1 + \frac{u}{c}\right)$$

  + sign if $u$ is toward source,  
  Minus sign if away from source

- However, if source is moving (speed $u$) relative to observer at rest in medium, then
  - Frequency remains constant (same time interval between wavefront emissions)
  - But source now chases its own waves (or runs away from them): wavelength in the medium is shorter or longer
    - Wave speed = $c$
    - Time between successive peaks = $T$
    - Distance between peaks = $cT - uT = \text{wavelength}$
    - Frequency of wave in medium (and for observer):

$$f' = \frac{c}{\lambda'} = \frac{c}{(c - u)T} = \left(\frac{c}{c - u}\right)f = f\left(\frac{1}{1 - u / c}\right)$$

  minus sign if toward observer,  
  + sign if away from observer.  
  Notice: different $f$ for observers on opposite sides of the source!

Notice the central role of the medium in both cases
Doppler effect for EM waves (light, radio, etc):

- For EM waves, there is **no material medium**
  - In the 1800s, people assumed there *had* to be some kind of medium for light -- so maybe it could be massless or otherwise undetectable
  - If the “luminiferous ether” exists, it plays the same role as air for sound waves: its rest frame is a special coordinate system for light waves
  - **Fact: no such thing** (more on this later this week)

- Speed of light is the **same** in all coordinate frames (!)
  - Does not depend on motion of source or observer
  - So we only need the Doppler formula for “source at rest”

\[ f' = f \left( 1 \pm \frac{u}{c} \right) \]  (+ for approaching, - for moving apart)

Now \( u = \text{relative speed between source and observer} \)
This formula is accurate only if \( u \ll c \)  (Einstein will tell us more…)

Example: car 1 moves N at 50 mph, car 2 (ahead of 1) moves N at 25 mph
Then they are **approaching** each other at **relative speed** 25 mph

We have no medium to define a specially significant coordinate frame
Any warm object makes E-M waves!

• Any object’s molecules are vibrating in place
  ...As long as its temperature is above “absolute zero” = 270° below zero Celsius!

• Molecules are made of charged particles
  – So they emit E-M radiation
  – Frequency of emission depends on molecular speed
  – Total radiation from any object covers a broad range of frequencies (wavelengths): random mix of molecular speeds

• Calculated *spectrum* (graph of intensity vs wavelength) from an ideal radiator is called “blackbody spectrum”
  – Ideal radiator = ideal radiation absorber
  – Color of an object = color of light it reflects (does not absorb)
    • So, what color would an ideal absorber appear to be?
Light travels through a vacuum while sound cannot. This is because…

A) Sound waves require a material medium, light does not

B) Light waves require a material medium, sound does not

C) Light moves in a mysterious hidden dimension unknown to Man

D) Huh? Sound CAN travel through a vacuum