Light and Waves:
A Conceptual Exploration of Physics

Exercises

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1. Theories of Light

Questions

1.1. What did Ibn Al-Haytham do?
(a) correctly explained how vision works
(b) promoted the particle explanation of light
(c) promoted the wave explanation of light
(d) developed the extramission theory
(e) explained particle-wave duality

1.2. What did Isaac Newton do?
(a) developed key ideas in calculus
(b) developed key ideas in physics
(c) performed experiments on light
(d) promoted the particle theory of light
(e) all of the above.

1.3. When do people's eyes emit light beams?
(a) when they are angry
(b) when they are feeling romantic
(c) whenever their eyes are open
(d) at night
(e) never

1.4. What is light?
(a) particles, not waves
(b) waves, not particles
(c) either waves or particles, but never both at once
(d) both waves and particles at the same time
(e) still unknown

1.5. What are electrons?
(a) particles, not waves
(b) waves, not particles
(c) either waves or particles, but never both at once
(d) both waves and particles at the same time
(e) still unknown

1.6. Matching. For each word on the left, give its definition from those on the right.

(a) diffraction	(1) waves bend when changing speed (e.g. light shining into water)
(b) interference	(2) waves combine, sometimes forming light and dark stripes
(c) refraction	(3) waves bounce off surfaces
(d) reflection	(4) waves bend when going past sharp edges

1.7. What were the dominant beliefs about light during the early Middle Ages (5th to 10th centuries CE)? Choose one for each part. (a) Extramission or intromission theories, (b) finite or infinite light speed, (c) particles or waves?

1.8. Would human hearing be best described as using extramission or intromission methods?

1.9. Give at least two reasons for how we know that the intromission theory is correct and the extramission theory is incorrect.

1.10. List two experimental results that support the wave explanation for light.

1.11. List two experimental results that support the modern particle explanation for light (photons).

Puzzles

1.12. Ostriches supposedly stick their heads in the sand because they think that they can't be seen then. Would this work if the extramission theory were true? Discuss. (This isn't actually true; ostriches don't actually stick their heads in the sand.)

2. Properties of Waves

Questions

2.1. If you increase the amplitude of a light wave, what changes?
(a) the color
(b) the brightness
(c) the wavelength
(d) the refractive index
(e) the speed

2.2. If you increase the wavelength of a light wave, what changes?
(a) the color
(b) the brightness
(c) the amplitude
(d) the refractive index
(e) the speed

2.3. Which light travels fastest?
(a) laser light
(b) sunlight
(c) ultraviolet light
(d) microwave light
(e) they are all the same

2.4. Will a brighter light wave travel faster than a dimmer light wave (in vacuum)?
(a) yes, if the brighter light has a shorter wavelength
(b) yes, if the brighter light as a longer wavelength
(c) yes, always
(d) no, the dimmer light goes faster
(e) no, they go the same speed

2.5. Which waves can be polarized (circle all that are appropriate):
(a) light

(b) sound
(c) string
(d) water
(e) radio

2.6. Consider a green laser beam that goes from water to air. Which happens?
(a) the light speed decreases
(b) the frequency increases
(c) the frequency decreases
(d) the wavelength increases
(e) the wavelength decreases

2.7. Suppose you're holding the end of a rope. What happens to the wavelength of waves on a rope if you move your hand up and down more quickly?
(a) they get longer
(b) they get shorter
(c) no change
(d) depends on the rope thickness
(e) depends on the rope length

2.8. John likes to sing to his pet fish, which is in a fish tank. Sound waves travel faster in water than in air. When John sings an 'A' note, which has a frequency of 440 Hz, what are the waves like at the fish?
(a) the frequency is 440 Hz, and the wavelength is longer
(b) the frequency is 440 Hz, and the wavelength is shorter
(c) the frequency is less than 440 Hz, and the wavelength is shorter
(d) the frequency is greater than 440 Hz, and the wavelength is unchanged
(e) the frequency is less than 440 Hz, and the wavelength is longer

2.9. Draw a picture of a wave. Label: a peak, a trough, the wavelength, the amplitude.

2.10. List the medium for each of the following types of waves, or write "no medium" if it doesn't have one: (a) water, (b) radio, (c) sound, (d) seismic.

2.11. List 2 examples for each: (a) transverse waves, (b) longitudinal waves.

2.12. Measure your heartbeat frequency and describe how you did it. Give your answer with the correct units.

Problems

2.13. This problem reviews the metric system, and helps develop a sense of scale for light waves. Use the following answers for the comparisons: "much larger" if it is more than 10x larger, "larger" if it is less than 10x larger, "similar" if the numbers are within about a factor of two, "smaller" if it is less than 10x smaller, and "much smaller" if it is more than 10x smaller. (a) What is the wavelength of green light in nm? How does it compare to the size of the following: (b) a bacterium, which is $\sim$2 µm long, (c) a water molecule, which is $\sim$0.2 nm in diameter, (d) a small protein, which is $\sim$2 nm in diameter, (e) a ribosome, which is a very large protein complex and $\sim$20 nm in diameter, (f) a cloud droplet, of which $\sim$20 µm is a typical size, (g) a raindrop, of which $\sim$2 mm is typical, (h) a soap bubble thickness, of which $\sim$500 nm is typical?

2.14. Lightning strikes the ground five kilometers away. (a) How long does it take the light to reach you? (b) How long does it take the sound (thunder) to reach you? (The speed of sound is about 340 m/s.)

2.15. In 1964, an earthquake near Anchorage, Alaska triggered a tsunami that traveled across the entire Pacific Ocean. It was detected in Peru, about 6500 miles away from Anchorage, 16 hours after the earthquake occurred. (a) What was the tsunami speed in miles per hour? (b) What percent of the speed of sound is this (the speed of sound is about 760 mph)?

2.16. In 1976, the world's fastest airplane, an SR-71 "Blackbird," flew 3462 miles from New York to London at an average speed of 1807 miles per hour. (a) How long did it take them? (b) How many times faster than the speed of sound did the airplane fly (the speed of sound is about 670 mph at airplane cruising altitudes)? (c) Why is it relevant to compare the airplane speed with the speed of sound?

2.17. The Parker Solar Probe is an unmanned spaceship that was launched in 2018 and will fly close to the sun in order to study it. It will reach a maximum speed of 192 km/s as it nears the sun in 2024, which will be the fastest that any human-built object has moved. (a) How many times faster than the speed of sound will the spaceship fly? (b) Is it useful to compare its speed with the speed of sound; why or why not? (c) At what percent of the speed of light will the spaceship fly?

2.18. A computer central processing unit chip (CPU) runs with a clock speed of 2.7 GHz. It executes one operation in each of these clock cycles. (a) How many seconds long is one clock cycle? (b) Electrical signals travel at the speed of light. How far can an electrical signal travel in one clock cycle? (c) Wires between the CPU's control unit and its cache memory (both on this chip), are about 2 cm long. How does this compare to how far an electrical signal can travel in one clock cycle (e.g. much shorter, shorter, similar, longer, much longer)?

2.19. It takes about 11.5 hours to fly from San Francisco to Beijing, which is about 5900 miles. (a) What is the average airplane speed in miles per hour? (b) What percent of the speed of sound is this (the speed of sound is about 670 mph at airplane cruising altitudes)? (c) What percent of the speed of light is this (the speed of light is $6.7 \cdot 10^8$ mph)?

2.20. (a) How far does light travel in 1 year (1 year $= 3.16 \cdot 10^7$ s; this distance is called a light-year)? (b) The closest star to Earth is Proxima Centauri, which is 4.24 light-years away. How far is this in kilometers? (c) The fastest any spacecraft has flown while far from the sun is Voyager 1, at 17 km/s. At this speed, how many years would it take a spacecraft to get to Proxima Centauri? (d) In one or two sentences, discuss the possibility of humans traveling to other stars, based on these numbers.

2.21. (a) What is the speed of light in water, where the refractive index is 1.33? (b) What is the speed of light in glass, where the refractive index is 1.52? (c) What is the speed of light in diamond, where the refractive index is 2.42?

2.22. Infrared light travels at $7.5 \cdot 10^7$ m/s in Germanium (a metal-like solid that is shiny in visible light but transparent to infrared light); what is the refractive index?

2.23. Bats use echolocation to find their prey, meaning that a bat emits a click and then waits for the sound to bounce off the prey and return to the bat. By timing the returned sound, the bat can figure out how far its prey is. (a) Suppose a moth is 2 m from the bat; how much time is there between when the bat clicks and then hears the echo? (b) A typical bat sound frequency is 50 kHz. What is the wavelength of a bat click, expressed in mm? (c) How does this compare to the size of a moth's body (e.g. much smaller, smaller, similar, larger, or much larger)?

2.24. For each of the following electromagnetic waves, list the type of radiation (e.g. visible, infrared, radio, etc.) and compute its frequency: (a) laser pointer: 635 nm, (b) dentist's office X-ray: 0.3 nm, (c) carbon dioxide vibration: 15 µm, (d) hydrogen atom emission: 122 nm, (e) AM station: 221 m.

2.25. For the following electromagnetic waves, list the type of radiation (e.g. visible, infrared, etc.) and compute its wavelength: (a) FM station: 94.9 MHz, (b) microwave oven: 2450 MHz, (c) bluetooth: 2.45 GHz, (d) TV remote control: $3.19 \cdot 10^{14}$ Hz.

2.26. People can hear sound waves between 20 Hz and 20 kHz. The speed of sound is 340 m/s. (a) What is the longest wavelength sound that people can hear? (b) What is the shortest wavelength sound that people can hear?

2.27. Most baleen whales (e.g. blue whales, humpback whales, and gray whales) make sounds at around 15 to 20 Hz, which can sometimes be detected across entire ocean basins. The speed of sound in seawater is about 1500 m/s. (a) What is the wavelength, in the water, for a 17 Hz whale sound? (b) How many hours would it take a whale vocalization to cross the Atlantic Ocean from the US to Europe, which is about 5500 km?

2.28. The first direct observation of gravitational waves was by the LIGO (Laser-Interferometer Gravitational-Wave Observatory) collaboration in 2016. These waves started with a frequency of 35 Hz and sped up to 250 Hz. Gravitational waves propagate at the speed of light. (a) What was the initial wavelength? (b) What was the final wavelength? (c) If these were electromagnetic waves, what band of radiation would they be in?

2.29. Determine the frequency of microwave light, for which $\lambda = 10$ cm.

2.30. A surfer finds that the waves are arriving with a 9.2 second period and are moving at 5.7 m/s. What is their wavelength?

2.31. Suppose you are in a bar 2 km from where the Seattle Seahawks are playing football, and you're watching the game on a TV. (a) The TV signal is transmitted with microwaves from the stadium, to a satellite that is 36,000 km above you, and then back down to the TV set. How long does this signal take to get to you? (b) You also hear cheering directly from the stadium when the Seahawks score a touchdown; how long does it take for the sound to reach you?

2.32. Consider a wave that has wavelength 7 mm and frequency 2 Hz. Could this be an electromagnetic wave in vacuum? Why or why not?

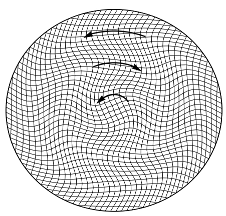
Puzzles

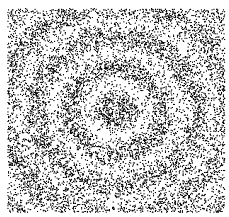
2.33. Several "musical roads" have been constructed in different countries. In each case, when a car drives over the road at a pre-specified speed, the tires vibrate on grooves that are cut into the pavement (like a rumble strip) and emit tones according to the vibration frequency. One of these, which was designed for a Honda advertisement and is in in Lancaster, California, plays part of the William Tell Overture (the Lone Ranger theme song) when driven over at

55 miles per hour. However, the engineers designed it wrong so that it is spectacularly out of tune. Given that the opening note of the song has a frequency of 349 Hz (an 'F' note), what pavement groove spacing should the engineers have used?

2.34. All of the planets in the solar system orbit the sun in a counter-clockwise direction, as seen when looking down at the Sun's (and Earth's) north pole. Most moons (including Io) also orbit counter-clockwise around their planets, and most planets (including Earth and Jupiter) rotate counter-clockwise on their axes. Would Rømer's results have been different if (a) Io orbited clockwise around Jupiter? (b) Jupiter orbited clockwise around the Sun? (c) the Earth rotated clockwise around its axis?

2.35. The following pictures show two-dimensional waves, of which the displacement is within the plane of the surface for the first two and out of it for the last one. (a) Is the wave in picture I transverse or longitudinal, and what is its polarization? (b) Same question for picture II. (c) Same question for picture III. (d) Which of these could represent water waves, if any? Explain. (d) For each picture, what type of seismic wave is it most similar to?


(I)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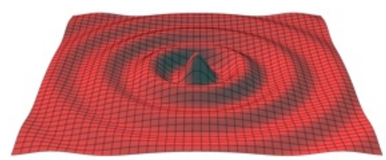

(III)

3. Superposition

Questions

3.1. What is the cause of Arago's spot, the bright light in the center of a shadow of a circular object?
(a) Interference around the object, and then diffraction at the center
(b) Light diffraction around the object, followed by destructive interference at the center
(c) Light diffraction around the object, followed by constructive interference at the center
(d) Destructive interference of different light wavelengths
(e) Light particles that collide off each other, with most collisions at the center

3.2. Which of the following is an example of Babinet's principle?
(a) Only standing waves of specific frequencies can exist in a string of fixed length
(b) The double slit experiment always produces a bright spot at the center
(c) Every point on a wave can be thought of as being a source that creates secondary waves
(d) The diffraction pattern for an object is identical to that for the same shape hole
(e) Interference between waves reflecting off two sides of a thin film produces bright colors

3.3. You're attending a party with loud music and are standing reasonably close to one of the two speakers. You find that the music is noticeably quieter if you move by just a few feet in some direction. What might make it quieter? (Choose all that are appropriate.)
(a) Constructive interference of sound from the two speakers
(b) Destructive interference of sound from the two speakers

(c) Constructive interference of sound from the speaker and its reflections off the walls
(d) Destructive interference of sound from the speaker and its reflections off the walls
(e) None of these; interference doesn't affect sound volume

3.4. What is the primary reason why microwave ovens have a turntable for spinning food?
(a) To let you see all sides of your food
(b) It stirs the food as it warms up
(c) Microwave ovens have hot and cold spots; the hot spots are at standing wave nodes
(d) Microwave ovens have hot and cold spots; the hot spots are at standing wave antinodes
(e) It keeps microwaves from leaking out of the oven

3.5. Which types of waves can form standing waves?
(a) only string waves
(b) string and light waves
(c) only mechanical waves
(d) only electromagnetic waves
(e) all types of waves

3.6. Many freeways have concrete walls next to them to reduce noise in adjacent communities. However, it is still possible to hear traffic noise when standing behind a wall. Why is that?
(a) sound waves diffract around the top of each wall
(b) sound waves go through cracks in the walls
(c) constructive interference of sound waves
(d) sound waves reflect off the walls
(e) sound waves travel faster in concrete than in air

3.7. A friend is looking at the interference fringes in the double-slit experiment that are created by a laser. She wants to change the experiment to yield a wider spacing between the fringes. Which of the following will help her? (Choose all that are appropriate.)
(a) make each slit wider
(b) make the slits farther apart
(c) make the slits closer together
(d) use a laser with a shorter wavelength
(e) place the viewing screen farther from the slits

3.8. You are trying to determine if a butterfly scale is colored due to structural coloration or colored pigments. Which tests would support structural coloration? (Choose all that are appropriate.)
(a) A microscope image shows a regular array of fibers
(b) The color goes away when bleach is added
(c) Placing the scale in water, where it swells, shifts the color to longer wavelengths
(d) Crushing the scale into a fine powder has no effect on the color
(e) The scale has different colors on different parts of it

3.9. Draw diagrams of waves that show (a) superposition, (b) constructive interference, and (c) destructive interference.

3.10. Noise-canceling headphones are headphones with a microphone on the outside of each earpiece that senses the incoming sound waves. Electronics in the headphones then emit the same sound through a speaker on the inside of the earpiece but with the polarity reversed. Explain how this reduces the amount of noise that you hear.

3.11. A thin film of oil on water strongly reflects blue light. (a) Draw a diagram that shows the cause of this. (b) Should the oil be made thicker or thinner to reflect green light?

3.12. If you watch the colors in a soap bubble that's in the sun, you will notice that it's colorful for a while, then it turns totally transparent, and then it pops. Explain why it turns transparent just before popping.

3.13. Suppose you're the only person on a small suspension bridge, and you want to jump up and down to create the first overtone standing wave in the bridge. (a) Where, along the bridge, would jumping be totally ineffective? (b) Where would jumping be most effective?

3.14. (a) Sketch a diagram showing the interference pattern that is observed for the double-slit experiment. (b) Sketch a similar diagram, but showing the result that one would expect to see if light were only a particle and not a wave, so the superposition principle did not apply.

Problems

3.15. Diffraction. (a) Draw a diagram that shows diffraction through a small hole. Now suppose you're in a room which has a 1 meter wide door, which is open, and music is playing outside. (b) What is the behavior of very low notes with $\sim$10 m wavelength (not go in the room, go in the room and travel in a straight line across it, or go in the room and fill the room)? (c) What is the behavior of medium notes with $\sim$1 m wavelength? (d) What is the behavior of very high notes ($\sim$10 cm wavelength)?

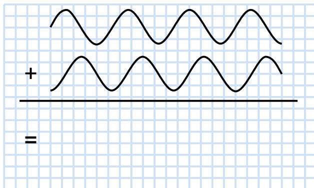
3.16. A violin E string is 32.8 cm long and has a fundamental frequency of 659 Hz. (a) What is the wave velocity on this string? (b) How many times faster than the speed of sound is this?

3.17. Consider an acoustic guitar with 65 cm long strings. The A string is tuned to produce a note with a fundamental frequency of 110 Hz. (a) What is the wavelength of the fundamental mode? (b) What is the wave velocity on the string? (c) What is the frequency of the first overtone? (d) The musician now shortens the vibrating part of the string by pressing it against a guitar fret (without changing the wave velocity) to make its fundamental frequency 123 Hz (a 'B' note); how long is the vibrating part of the string now?

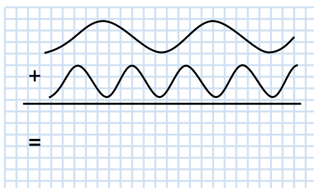
3.18. Ahmed wants to measure the thickness of one of his hairs using interference. He shines a laser with a 650 nm wavelength onto the hair and observes fringes on the wall, 3 meters away. He determines that the distance between the two brightness minima that are on either side of the central bright spot is 57 mm. How thick is the hair?

3.19. Consider a bathroom shower that is 1.5 m long and 1.5 m wide, and suppose you're singing in this shower. (a) What sound wavelength has the lowest resonant frequency, meaning that it's the fundamental frequency? (b) Using the fact that the speed of sound in air is 340 m/s, what is the frequency of this sound wave?

3.20. The waves in the following diagram are neither in phase nor out of phase, but are in between with what's called a phase shift. (a) Add them using the superposition principle. (b) Is the wavelength the same or different from the original waves? (c) Is the final amplitude the same as for constructive interference, or destructive interference, or in between?



3.21. The waves in the following diagram have exactly a factor of two difference in wavelengths. (a) Add them using the superposition principle. (b) Is the repeat interval in the final wave, meaning the distance where it exactly repeats itself, the same as that of the longer or shorter wavelength component wave? (c) Is the wave shape the same as that of the longer wavelength or shorter wavelength component wave, or neither?



Puzzles

3.22. Consider two radio antennas that are separated by exactly one wavelength. They broadcast waves with the same frequency and are in phase with each other. (a) Make a diagram (a top view, in which each antenna is a dot) that shows where the broadcasted radio waves interfere constructively and where they interfere destructively. Hint: use a drawing compass. (b) Now assume the towers are separated by two wavelengths and make a new diagram of where they interfere constructively and destructively.

3.23. A friend has a clever idea of building a flashdark, which is just like a flashlight except it shines darkness instead of light. His plan is that it will emit light that that is out of phase with the existing light, so the light waves will cancel out and produce darkness. Give some reasons for why this wouldn't actually work.

3.24. Suppose one guitar string oscillates at 196 Hz and another at 197 Hz. (a) If they are in phase at time 0, then how long, in seconds, will it take be for them to be in phase again? (b) What is the beating frequency of these strings? (c) What would the beating frequency be if the second string were changed to 198 Hz? (d) What if it were changed to 196.5 Hz? (e) Based on these results, what is the beating frequency when the frequency difference is Δf?

4. Wave Energy

Questions

4.1. Which types of waves transmit energy?
(a) waves don't transmit energy
(b) only electromagnetic waves
(c) only electromagnetic and water waves
(d) everything except sound waves
(e) all waves transmit energy

4.2. Chlorophyll is a molecule found in plants that is essential for their photosynthesis. It is a pigment that creates the green color of plants. Which of the following are true? List as many as are appropriate.
(a) chlorophyll primarily absorbs green light
(b) chlorophyll absorbs red and blue light, and transmits green light
(c) chlorophyll has no intrinsic color but is an example of structural coloration
(d) the electrons in chlorophyll resonate with green light waves
(e) chlorophyll absorbs energy from red and blue light

4.3. It is possible for a sustained high musical note to break a wine glass through resonance. (a) What two periodic processes are in resonance with each other? (b) Is this favored by strong or weak coupling? (c) Is this favored by strong or weak damping?

4.4. After a rock is dropped in a calm pool, the resulting water waves spread out in circles and get smaller. List two reasons why they get smaller (both were topics of this chapter).

4.5. We saw that the energy density of water waves decreases as the waves spread out in proportion to r^{-1}, where r is the distance travelled, and the energy density of light waves decreases in proportion to r^{-2}. How does the energy density of string waves depend on the distance that they travelled, given again as a power of r?

4.6. Lycopene is a plant pigment that is similar to β-carotene, except that the molecule is slightly longer. (a) Would you expect it to absorb higher frequency or lower frequency light? (b) What color would lycopene appear to be? (c) Lycopene is the major color pigment of either tomatoes or bananas; which one is it, based on your color prediction?

4.7. Anechoic chambers are rooms in which the walls are covered with surfaces that absorb all sound waves. Would you expect this absorption to work through resonance or damping?

4.8. Suppose an engineer designed a perfect light damper, which efficiently damped all light waves that hit it. What color would it appear to be?

4.9. Sketch the intensity spectrum for a green laser pointer.

4.10. In some Western movies, a person puts his ear on a train track to listen for an approaching train, because it's easier to hear a train through the rails than through the air. Why might this be?

Problems

4.11. On average, each person in the United States uses about 12,000 kWh (kilowatt-hours) of electricity per year. (a) What type of unit is kWh (e.g. energy, power, etc.)? (b) Convert this energy use rate to joules per year. (c) Convert this value to watts.

4.12. Ocean wave energy has long been recognized as an abundant source of renewable energy, so some devices have been developed for generating electrical power from wave power. One such device (an RM3 floating-point absorber wave-energy converter[1]) produced an average of 350 kW of power when the wave height, measured trough to peak, was 4.25 m and the wave speed was 16.7 m/s (water wave speeds depend on the wavelength, discussed in Section 6.5). How many times more power would this device have produced if (a) the waves had been only 1 meter high? (b) the waves were 6 m high? (c) the waves were moving at 20 m/s?

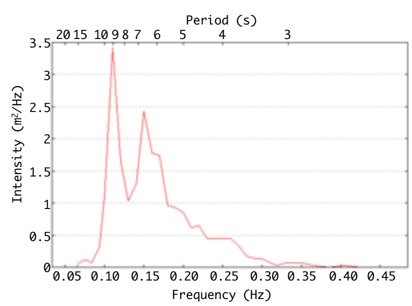
[1] Muljadi, Eduard and Yi-Hsiang Yu (2015) "Review of marine hydrokinetic power generation and power plant" *Electric Power Components and Systems* 43:1422.

4.13. Saturn is about 10 times farther from the sun than the Earth is. How many times weaker is the sunlight on Saturn? (Measured, for example, in watts of power per square meter at the planet's surface.)

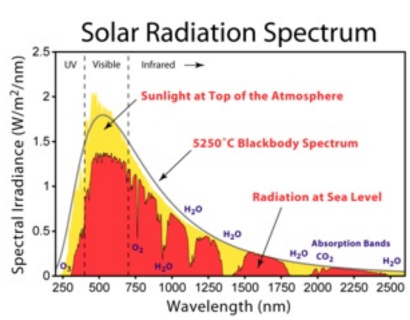
4.14. The Shanghai Superintense Ultrafast Laser Facility (SULF) built a laser that produced light pulses with 10.3 petawatts of power (peta $= 10^{15}$). Each pulse lasted for about 23 fs (femto $= 10^{-15}$). (a) Worldwide electricity consumption is about 2.4 TW on average (tera $= 10^{12}$). How many times more power was in the laser pulse? (b) How much energy was in the laser pulse? (c) How many times more energy is in a single packet of sugar (11 food calories)?

4.15. A 15 W LED light bulb is 2 m from a wall. (a) What is the power density of the light on the closest part of the wall? (b) A 2 mW red laser pointer is also 2 m from that wall, producing a red dot on the wall that has a radius of 2 mm. What is its power density? (c) Which is brighter at that spot, the light bulb or the laser pointer?

4.16. Shown below is a water wave spectrum, measured by an oceanographic buoy near Oahu, Hawaii. It shows the energy at different wave frequencies. (a) What are the peak frequencies of the two swells? (b) What are these two wave periods? (c) Which swell has a higher peak energy? (d) Which swell has a higher total energy?



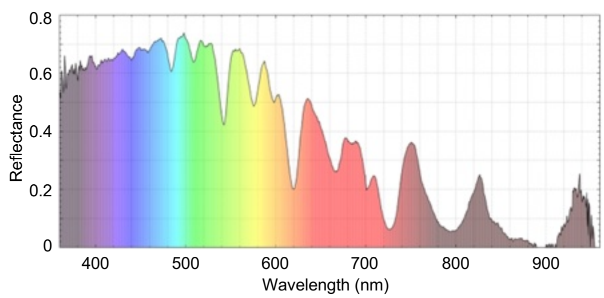
4.17. Shown below is the solar radiation spectrum. The yellow curve is the sunlight measured in space, above the atmosphere, and the red curve is the sunlight measured at sea level. Ignore the black curve. (a) At what color is the sun brightest both above the atmosphere and at sea level? (b) Sunlight is usually described as white; can you explain why? (c) Estimate the atmospheric transmission coefficient (in percent) at 300 nm, 500 nm, 1400 nm, and 1600 nm.



Puzzles

4.18. Linus plays a note on his piano, holding the piano key down so the note plays for a long time. (a) Would the sound exhibit a line or continuous spectrum? (b) What are some causes of attenuation? (c) If his piano were underwater instead of being in air, would the attenuation be stronger or weaker? (d) Would the widths of the peaks in the sound spectrum be wider or narrower when the piano is underwater? (Hints: consider how damping affects spectra, and whether more or fewer frequencies need to be added to produce the new waveform.)

4.19. Shown below is the Uranus reflectance spectrum (similar to transmission, but for reflected light instead). (a) Using this spectrum, what color would Uranus appear to be? (b) What are the dominant colors of the light that the atmosphere is absorbing? (c) Estimate the visible albedo of Uranus, meaning fraction of visible light energy (380 to 740 nm) that is reflected.



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5. Doppler Effects, Redshifts, and Blueshifts

Questions

5.1. A woman paddles her kayak on a lake on a windy day. When do the waves hit the boat with the highest frequency?
(a) When she's in the middle of the lake.
(b) When she's near the shore.
(c) When she kayaks downwind, going in the same direction as the waves.
(d) When she kayaks upwind, going into the waves.
(e) They always hit at the same frequency.

5.2. Many stars appear to have different colors. For example, Betelgeuse is red and Sirius is blue (both are in or near the Orion constellation). What is the primary cause of these color difference?
(a) They emit different color light, due to different surface temperatures
(b) The Doppler effect
(c) Red and blue shifts from star motion
(d) Gravitational redshift
(e) Cosmological redshift

5.3. Marvin the Martian has a green helmet. If the helmet appears violet, what is Marvin doing?
(a) Traveling very fast away from Earth
(b) Traveling very fast toward Earth
(c) Traveling very fast past the Earth

(d) Trying to blow up the Earth
(e) Not moving, but he's a long way from the Earth

5.4. In 2004, the Cassini spacecraft was orbiting Saturn when it released a lander called Huygens, which flew down to Saturn's moon Titan. The mission almost failed because the engineers didn't design the equipment to account for the Doppler shift between the fast-moving Cassini and the stationary Huygens. They fixed this by making sure that Cassini's velocity was perpendicular to the direction from Cassini to Huygens. Why did this work?

Problems

5.5. A stationary bat emits an ultrasonic sound with a frequency of 40.0 kHz. This "click" reflects off a moth that is flying toward the bat at 6.0 m/s. (a) What sound frequency does the moth hear? (b) What sound frequency does the bat hear in the echo off the moth?

5.6. You are on a train, traveling at 15 m/s, that is about to drive into a tunnel that is at the base of a large cliff. The train blows its whistle, which has a frequency of 600 Hz. (a) What frequency do you hear from the whistle directly? (b) What frequency does a stationary person who is ahead of the train hear? (c) What frequency does a stationary person who is behind the train hear? (d) What frequency do you hear in the echo off the cliff?

5.7. A galaxy called NGC 1357 has been observed to have a redshift: light that it emits at 656.2 nm is observed at 660.8 nm. In this problem, compute numbers to 4 significant figures. (a) What color is this light? (b) What are the two frequencies? (c) How fast is the galaxy moving away from us?

5.8. Low pressure sodium lamps are a common type of street light; these are inexpensive, yellow, and sometimes make a buzzing sound. The light comes from excited sodium atoms that emit light primarily at 589.0 nm. They are very hot, with a temperature of about 4000 Kelvin (3700°C or 6700°F). Because they are so hot, the atoms move very fast, with typical speeds of about 2000 m/s. In this problem, use 6 significant figures. Compute: (a) the wavelength of light that you detect from an atom moving toward you at 2000 m/s, (b) the wavelength of light that you detect from an atom moving away from you at 2000 m/s, (c) the difference between these two wavelengths, which is called the Doppler broadening of the spectral line width.

5.9. Tzipor is attending an air show. An airplane, which is emitting noise at about 120 Hz, flies past her at 415 m/s. (a) What frequency does she hear, if any, as the airplane approaches? (b) What frequency does she hear, if any, as the airplane departs?

5.10. The Helios-2 spacecraft was launched by the United States in 1976 to study the sun. In flying reasonably close to the sun (inside Mercury's orbit), it set a speed record of about 253,000 km/hr. Its communications radio broadcast at 2295.37 MHz. Assuming it was flying directly away from the Earth at the time of its speed record and that the Earth was effectively stationary (both of which are reasonably accurate) what was its radio frequency received at Earth?

5.11. A gravitational wave was detected in 2015 that had a frequency that sped up over time, ending at about 250 Hz. It arose from black holes that were about 1.3 billion light-years away and that were moving away from the Earth at about 28,000 km/s due to the expansion of the universe. What was the ending frequency that the black holes actually emitted (the gravitational redshift is small enough that it can be ignored)?

5.12. US-708 is one of the fastest known stars, traveling at about 1200 km/s relative to the Earth. Part of this speed is across the sky, which does not produce a Doppler effect, and part is away from the Earth, which does produce a Doppler effect. The latter "radial" speed is 708 km/s away from the Earth. What is the observed wavelength of 550 nm light that is emitted from the star?

5.13. When a car drives past Sergeant Murphy, he hears the pitch shift from 520 Hz to 345 Hz. (a) What pitch did the car emit? (b) How fast was the car going?

Puzzles

5.14. Bats use echolocation to find their prey, which are primarily moths. (a) How might Doppler effects interfere with their echolocation abilities? (b) How might bats use Doppler effects to their advantage? (c) How might moths use Doppler effects to evade bats?[1]

5.15. Alex and Sal are standing still on top of Mt. Washington, NH, where the wind is blowing at 231 miles per hour (103 m/s). Alex is directly upwind of Sal. (a) When Alex sings a note at 220 Hz, what frequency does Sal hear? (b) When Sal sings at 220 Hz, what frequency does Alex hear? (c) If Sal were to measure the wavelength of Alex's singing, what would he measure? (d) If Alex were to measure the wavelength from Sal, what would he measure? (e) What would be different if the wind speed were 350 m/s?

5.16. This is a continuation of the same problem, but with the additional information that Alex and Sal are standing 2 meters apart. (a) If Alex speaks with 1 W of sound power, what power density does Sal receive, in W/m^2? (b) If Sal speaks with 1 W of sound power, what power density does Alex receive?

5.17. Angular Doppler effect. Consider a jumprope that is tied at one end to a tree branch and held by a person at the other end, who is swinging it around in a circle in the normal sort of way. In more technical language, this is a circularly polarized string wave. To find the rotational frequency, you mount a camera beyond the tree branch and take a video of the rope as it goes around; later, you analyze the video to determine that the rope's period is 0.8 s. (a) What is the rope's rotational frequency? (b) Suppose the camera mount spins the camera in the same direction as the string (i.e. around the same axis as the string rotation) at 1 Hz. Now what rope frequency would you measure from the video? (c) What would the measured frequency be if the camera mount spun the camera in the opposite direction at 1 Hz? (d) More generally, if the string frequency is f_s and the camera rotates at f_c in the string's direction, what is the observed frequency f_o? (e) What does a negative observed frequency mean?

6. Mechanical Waves

Questions

6.1. Which of these changes would lead to the fastest waves on a string?
(a) less tension, lighter string

[1] Here are some references for those who want to learn more about this topic: Wikipedia "Doppler shift compensation"; Jones, "Echolocation" *Current Biology* 15:R484 (2005); Yin and Müller, "Fast-moving bat ears create informative Doppler shifts" *Proc. Natl. Acad. Sci. USA* 116:12270 (2019).

(b) less tension, heavier string
(c) more tension, lighter string
(d) more tension, heavier string
(e) just more tension, mass doesn't matter

6.2. What is the speed of sound on the moon?
(a) The same as on Earth, 340 m/s
(b) Faster than 340 m/s
(c) Slower than 340 m/s
(d) It depends on the temperature
(e) There is no sound on the moon

6.3. What factors are essential for mechanical waves to propagate? (Choose all that apply.)
(a) Things in motion keep on moving, even without external forces.
(b) Things in motion always come to a stop.
(c) There need to be forces that promote displacements in the medium.
(d) There need to be forces that reduce displacements in the medium.

6.4. Swiftlets are tropical birds that live in caves and navigate with echolocation using clicks. The caves are sufficiently crowded that hundreds of birds fly in the same space, all echolocating at once. Which properties of a bird's click could it vary, in order to distinguish its own echo from all of the other noises? (Choose all the apply.)
(a) Pitch
(b) Dispersion
(c) Timbre
(d) Inertia
(e) Loudness

6.5. Which of the following waves are dispersive? (Choose all that apply.)
(a) String
(b) Sound
(c) Capillary water waves
(d) Gravity water waves in deep water
(e) Gravity water waves in shallow water
(f) Seismic P-waves

6.6. Suppose that sound waves were dispersive, with long waves traveling faster than short waves. (a) Describe how this would affect conversations and music. (b) What would a plucked guitar string sound like?

6.7. For standing waves on strings, it was shown that the second harmonic is one octave above the fundamental frequency. (a) Are all string wave harmonics an integer number of octaves above the fundamental frequency? (b) Which harmonic is two octaves above the fundamental frequency?

6.8. The speed of waves on a membrane, such as the head of a drum, was not given here. From your knowledge of other wave speed equations, make some predictions about wave speeds on membranes: (a) does the wave speed increase or decrease with greater membrane tension? (b) does the wave speed increase or decrease with a heavier membrane?

6.9. A sand grain falls in a puddle and makes ripples that spread outward. (a) Are the long wavelength ripples on the inside or outside of the expanding circle? (b) A boulder falls into a lake and makes waves that spread outward. Are the long wavelength waves on the inside or outside of the expanding circle?

6.10. A tennis ball is floating in a lake and is just beyond reach. Can you retrieve it by throwing rocks in the water just beyond it, and letting the waves push it toward you? Explain.

Problems

6.11. Suppose a friend builds her own electric guitar and she decides to put the pickups exactly in the middle of the string. (a) Which harmonics will the pickups detect and amplify? (b) What are the frequency ratios of these harmonics relative to the fundamental frequency (e.g. 2:1). (c) Would these harmonics be consonant or dissonant?

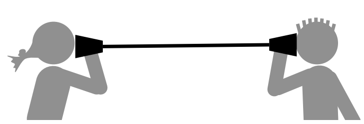
6.12. A person sings the A440 note. Then, he breathes in helium from a party balloon tries to sing the same note, but it comes out one octave higher. (a) Treating his vocal system as an open ended pipe, how many times faster was the speed of sound after he breathed in helium? (b) Using the speed of sound equation, how many times faster is the speed of sound in helium than in air? Use: $\gamma_{h.c.}$ is 1.4 for air and 1.67 for helium, and m_{air} is $4.8 \cdot 10^{-26}$ kg for air and $6.6 \cdot 10^{-27}$ kg for helium. (c) Why are these values different?

6.13. The "hull speed" of a boat is the speed of a water wave that has the same wavelength as the boat length. Boats generally have a hard time traveling faster than their hull speed. (a) What is the hull speed for a 5 meter canoe in deep water? (b) What about for a 100 meter long ship in deep water? (c) What about for a 10 cm long duck in deep water? (d) What about for a 5 meter canoe in 10 cm deep water?

6.14. Many American boat designers know the equation that the boat's hull speed is $v = 1.34\sqrt{L_{WL}}$ where v is the speed in knots and L_{WL} is the boat length in feet, measured at the waterline. Is this the same equation as the deep water wave speed for wavelength $\lambda = L_{WL}$? Use the conversions 1 knot = 0.514 m/s and 1 foot = 0.3048 meters.

6.15. The 2011 Japan tsunami was triggered by an earthquake 70 km offshore. (a) How long after the earthquake happened was the earthquake's P-wave felt in Japan, which traveled at 6 km/s? (b) The frequency of this sound wave is about 1 Hz, what was the wavelength? (c) Suppose the tsunami wavelength was 100 km, and the ocean is about 100 m deep in that region. What was the tsunami wave speed? (d) How long did it take the tsunami to reach Japan?

6.16. Two people are talking on a string telephone that is 14 m long. A string telephone has a cup at each end and a string that connects them, which carries the sound as string waves, shown below. The people pull on the string with about 2 pounds of force (9 N), so the string tension is 9 N. The string has a mass density of 1.2 g/m. How long does it take sound to go from one person to the other through the telephone?



6.17. A pipe organ is an aerophone with open ended tubes, with essentially the same physics as the flute. (a) For normal room temperature, where the speed of sound is about 340 m/s, how long is the pipe for the A440 note? (b) Suppose someone wanted to install an outdoor pipe organ at the South Pole that would be in tune when the temperature is -80°C (193 K). How long would the pipe be for the A440 note for that organ?

6.18. A whirly tube is a musical toy. It is a corrugated plastic tube that is open at both ends, 0.74 m long, and makes noise when swung in a circle. Faster swinging excites higher overtones and thus produces higher pitches. (a) What is the whirly tube's fundamental frequency? (b) What is the frequency of the second harmonic? (c) What is the frequency of the third harmonic? (d) What note is fundamental frequency, using scientific pitch notation? (e) What note is the second harmonic?

6.19. At the surface of the sun, the temperature is 5778 K, the average atomic mass is about $1.90 \cdot 10^{-27}$ kg (mostly atomic hydrogen and some helium), and the heat capacity ratio is $\gamma_{h.c.} = \frac{5}{3}$. The pressure varies from about 80 Pa to about 12 kPa. (a) What is the speed of sound? (b) How many times faster is this than the speed of sound on Earth?

6.20. This problem investigates seiche periods. (a) What is the fundamental frequency of a standing wave in a lake, for wave speed v and lake length L? (b) Assuming that a seiche is a shallow water wave, compute the wave period for lake length L, lake depth d, and gravitational acceleration g. This result is known as Merian's formula, originally derived by J.R. Merian in 1828. (c) Use this period to compute the seiche period for Lake Erie, which is about 288 km long and 19 m deep. (d) Compare your result to the actual value of 14.1 hours (is your prediction reasonably close? what are the major approximations that led to differences?).

6.21. People determine the directions where sounds come from with two methods. We hear an intensity difference between our ears for short waves and a phase difference between our ears for long waves. (a) Why is the intensity difference more useful for short waves? (b) Supposing an adult's ears are 20 cm apart and the sound comes directly from one side, how many wavelengths is this separation for a 100 Hz sound wave? (c) How many wavelengths is this for an 5000 Hz sound wave? (d) Why can we localize low notes but not high notes using a phase difference?

6.22. A whitewater river flows between two boulders, creating a series of stationary waves. These waves don't move relative to the land, but propagate upriver at the same speed as the water flows downriver (they are often called "standing waves", but are completely different from the standing waves that occur in a cavity, discussed in this book). If the wavelength is 3 m and the water is 4 m deep, what is the river flow speed?

Puzzles

6.23. The world's largest earthquake occurred on May 22, 1960 in Chile, with a magnitude of 9.5. How many times more energy was released here than Los Angeles's 1994 Northridge earthquake, which had a magnitude of 6.7?

6.24. Imagine you are holding a rope up by one end. At any point in the rope, the tension at that point arises from the weight of the rope that is below that point. This implies that the tension is high at the top and decreases to zero at the bottom. Suppose you put a pulse in the rope at the top, which then propagates downward. Would the pulse take infinite time to reach the bottom? Discuss.

6.25. A pipe of length L is closed at both ends. What are the natural frequencies for sound waves in this pipe as functions of L and the speed of sound?

6.26. The chromatic musical scale has 12 semitones in each octave. Assuming they are equally spaced (called equal temperament tuning), meaning that the frequency ratio between one note and the next one is a constant, what is the value of this constant?

7. Shadows and Pinhole Cameras

Questions

7.1. Which shapes are possible for the orthographic shadow of a cube on a flat surface? (Choose all that apply.)
(a) Triangle
(b) Square
(c) Rectangle
(d) Pentagon
(e) Hexagon

7.2. Lunar eclipses following the 1982 eruption of the Mexican volcano El Chichón were notably darker than normal. What could have caused this?

7.3. Suppose you observe a lunar eclipse that happens to occur exactly at sunset, so you can see the Sun in one direction and the Moon in the opposite direction. If you wave, and watch with a very good telescope, will you be able to see your shadow on the Moon? Why or why not?

7.4. The Moon is not completely black during a total *solar* eclipse, but is dimly illuminated (likewise, it's often possible to see the dark side of a new moon). Where is this light coming from?

7.5. Three celestial objects, such the Sun, Moon, and Earth, are said to be in ***syzygy*** when they are lined up in a perfect line. Are the Sun, Moon, and Earth always, sometimes, or never in syzygy during eclipses?

7.6. When Venus crosses between the Earth and Sun, called a ***Venus transit***, it appears as a small black dot on the face of the Sun. During this time, is the Earth in Venus's umbra or penumbra?

7.7. Suppose an astronaut is on the Moon during a total lunar eclipse. What would this astronaut observe when facing the Earth?

7.8. Do the planets (e.g. Venus, Mars, and Jupiter) have phases, like the Moon? Explain.

Problems

7.9. It's a sunny day, you have a meter stick, and you want to measure the height of a flagpole that is casting a shadow on level ground. (a) When the meter stick is vertical, its shadow is 85 cm long. What is the sun's angle? (b) The flagpole's shadow is 7.4 meters long. How tall is the flagpole?

7.10. Suppose the sun is 45° above the horizon and is casting a shadow of a 50 foot tall flagpole. (a) How long is the orthographic projection of this shadow? (b) How long is the oblique projection on level ground?

7.11. Suppose the sun is shining onto a spherical ball, which is casting a shadow. Treat the sun as a small light source. (a) What is the shape of the orthographic projection? (b) What is the shape of the oblique projection? (c) Which has larger area?

7.12. Consider a light that is casting a shadow of a ball on a wall. (a) Under what conditions, if any, would the shadow have no umbra? (b) Under what conditions, if any, would it have no penumbra?

7.13. You are casting an orthographic shadow of a ball onto a wall. (a) How can you make the umbra larger than the ball (or is it impossible)? (b) How can you make the umbra smaller than the ball (or is it impossible)? (c) How can you make the radius of the penumbra larger than the ball's radius (or is it impossible)? (d) How can you make the radius of the penumbra smaller than the ball radius (or is it impossible)?

7.14. Suppose you have a pinhole camera which is 5 cm long between the hole and the film. You photograph a 1 cm long bug that is 10 cm in front of the pinhole. (a) Draw a diagram of this. b) What is the length of the bug's image on the film? (c) Is the image rightside up or upside down?

7.15. Miss Wimpole is sitting in her camera obscura and admiring the image of her parent's folly (a fake medieval ruin). While wondering how tall it is, she notices that a sheep is grazing at its base. She estimates that the sheep is three feet tall and she measures its image as 0.25 inches. Her camera obscura is 5 feet across, from hole to screen. (a) How far away is the folly? (b) The folly's image is 4 inches tall. How tall is the folly?

7.16. Suppose you take a picture of a candle with a pinhole camera that has 0.2 mm diameter hole. The candle is 1 meter from the camera and emits about 18 mW of visible light (12 lumens of light with about 683 lm/W). (a) What is the light power per square meter, at 1 meter away from the candle? (b) How much light power goes through the pinhole? (c) You take a 1 second exposure. How much energy goes through the pinhole?

Puzzles

7.17. A friend makes a pinhole camera with a 0.2 mm pinhole, but he doesn't make the pinhole perfectly round. Instead, it's closer to a square shape. Will this affect the image and if so, how?

7.18. If you look down on the solar system, looking at the Earth's north pole, you will see that the Earth's orbit around the sun, its rotation on its axis, and the Moon's orbit around the Earth are all counter-clockwise. (a) If the Moon is waxing, meaning that a larger fraction appears to be lit by the sun each night, then does the left or right appear to be bright for an observer in the Northern Hemisphere? (b) What about for an observer in the Southern Hemisphere? (c) Is a waxing moon high in the sky in the morning or evening for a Northern Hemisphere observer? (d) How about for a Southern Hemisphere observer?

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8. Reflection

Questions

8.1. As a candle is moved away from a plane mirror on a wall, what happens to its image?
(a) gets smaller
(b) gets larger
(c) gets either smaller or larger, depending on the observer's location
(d) the magnification is negative and increases toward zero
(e) the size does not change

8.2. For a flashlight that produces a beam of light, where is the light bulb compared to the reflector mirror?
(a) at the center of curvature
(b) at the mirror's focus
(c) halfway between the focus and the center of curvature
(d) halfway between the mirror and the focus
(e) up against the mirror

8.3. The focal length of a concave mirror has a magnitude of 20 cm. What is its radius of curvature?
(a) 10 cm
(b) 40 cm
(c) -40 cm
(d) 20 cm
(e) -20 cm

8.4. What types of images can mirrors produce? Select all that are appropriate.
(a) Magnified images
(b) Reduced images
(c) Upright images
(d) Inverted images

8.5. (a) Give one example of a surface that produces a diffuse reflection. (b) Give one example of a surface that produces a specular reflection.

8.6. For each of the following, can you use this to see your own reflection? Briefly explain why or why not. (a) A white wall, (b) A silver spoon, (c) A single silver atom, (d) The water's surface, (e) A white dinner plate.

8.7. What shapes of mirrors (flat, convex, or concave) may be used to (a) converge light rays, (b) diverge light rays (more than for no mirror at all), (c) neither converge nor diverge light rays, (d) form a real image, (e) form a virtual image, (f) produce an enlarged image, (g) produce a reduced image?

8.8. Several concrete "acoustic mirrors" were built in southeast England in the 1920s and 1930s that faced the English Channel. Explain how they could have been used to detect and locate incoming enemy aircraft.

8.9. A new skyscraper in London, called “20 Fenchurch Street” after its address, has a south-facing concave curved exterior. Before it was retrofitted with permanent awnings, it sometimes focused sunlight sufficiently well to melt parts of cars that were parked in the wrong places. The building’s facade is vertical at the ground and has a radius of curvature of about 540 m. (a) What is the focal length of this mirror? (b) Where is the sun’s image, relative to the base of the building, when the sun is to the south and on the horizon? (c) Is this a real image or a virtual image? (d) When the sun is 60°above the horizon (still due south), is the hottest spot on the ground closer to the building or farther away than when the sun was on the horizon?

8.10. Modern car headlights are complex optical instruments, designed to put the right amount of light in the right places. However, for the most part, they aim the light from a small bright halogen lamp filament to a collimated beam. Assume a simple design for this. (a) What shape is the reflector behind the light bulb (e.g. spherical, corner cube, parabolic, flat, convex)? (b) What is the name of the location where the light bulb filament is placed? (c) There is a separate filament for “high beam” output, which creates a beam of light that shines at a higher angle than the normal low beam. Is the high-beam filament above or below the low-beam filament (hint: draw a picture)? (d) The reflector usually extends out ahead of the light bulb. How much of the light emitted by the filament is directed into the collimated beam (choose from: 0%, <50%, 50%, >50%, or 100%)?

Problems

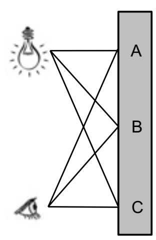
8.11. A “full-length mirror” is a flat mirror that is large enough so that you can see your entire body in it, from head to toe. Consider a woman who is 170 cm tall (5’6”) and whose eyes are 10 cm below the top of her head. (a) How high above the floor can the bottom of the mirror be, so she can still see her feet in the mirror? (b) How high above the floor does the top of the mirror need to be so she can still see the top of her head in the mirror? (c) From these answers, what is the minimum total length of the mirror? (d) Does you answer depend on how far she stands from the mirror?

8.12. Consider a 2-dimensional corner cube retroreflector in which two mirrors are perpendicular to each other (see Figure 8.5). For a ray that enters the reflector with incident angle θ, show that it will leave the reflector going toward the direction that it came from.

8.13. A concave mirror has focal length 10 cm and an object is 30 cm away from the mirror. (a) Draw a ray diagram for this system, showing the object, image, and any two rays. (b) Using the mirror equation, how far from the mirror is the image? (c) Using the magnification equation, what is the image magnification? (d) Do your diagram and quantitative results agree with each other?

8.14. A concave mirror has focal length 10 cm and an object is 3 cm away from the mirror. (a) Draw a ray diagram for this system, showing the object, image, and any two rays. (b) Using the mirror equation, how far from the mirror is the image? (c) Using the magnification equation, what is the image magnification? (d) Do your diagram and quantitative results agree with each other?

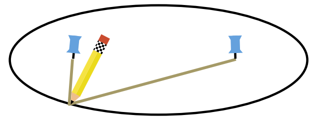
8.15. Suppose a room light is 2 m directly over your head and you are sitting 1 m away from a wall. Treating the wall as a diffuse reflector, calculate the time that the light takes to get to your eye, in ns, for its reflection off the wall at points (a) A, (b) B, and (c) C in the diagram. (d) Is there any point on the wall where the light takes less time than it does when it reflects at point B (use your intuition, guided by your prior results)? (e) Now suppose the wall is a specular reflector. For the light that reflects off the wall and goes to your eye, which point does it reflect off?



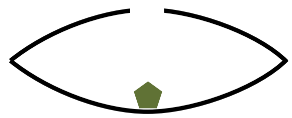
8.16. A simple periscope has two flat mirrors that are parallel to each other (see Figure 8.18). Consider looking through a periscope that is 1 m tall, at an object that is 5 m in front of the top periscope mirror. (a) When you look at that object through the periscope, where is the object's image relative to the lower mirror, including the image distance? (b) is this a real or virtual image? (c) Is the image right-side up or upside-down? (d) If there is text on the image, does it appear to be forward or backward? (e) Is the image larger, smaller, or the same size as the object?

8.17. A parabola is often defined with the math equation $y = x^2$. However, it can also be defined geometrically as the set of points that are equidistant between a straight line and a point. Using this geometric definition and Fermat's principle of least time, show that a parabola focuses light from a beam of parallel rays to its focus.

8.18. An ellipse can be drawn by attaching each end of a piece of string to two pins in a sheet of paper, pulling the middle of the string sideways as far as it goes with a pencil, and then drawing an arc with the pencil while keeping the string taught. The two pin locations are called the ellipse foci. (a) Using Fermat's theorem, show that waves that are emitted from one focus get reflected to the other focus. (b) The Mormon Tabernacle, a religious building in Salt Lake City, Utah, is famous for its acoustics. It is built as an ellipse with the speaker's pulpit at one focus. Where is the best place to sit to hear the speaker clearly?

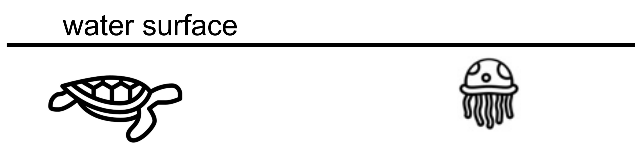


8.19. In a “magic mirror illusion”, two concave mirrors face each other like a clamshell, an object is placed on top of the lower mirror, and a person sees inside through a small hole in the upper mirror. Assume each mirror has a focal length of 10 cm, the middles of the mirror faces are 10 cm apart, and the object is 1 cm above the lower mirror. Where is its image and what is its magnification? (Hint: consider the upper mirror first.)



Puzzles

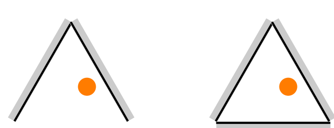
8.20. From underwater, the surface of the water can act as a mirror. Consider a sea turtle which is looking at a jellyfish that’s near the surface of the water. (a) Will the image that the turtle sees be a real image or virtual image? (b) Will the image of the jellyfish be left-right reversed, up-down reversed, both, or neither?



8.21. Consider the shadow of an object that is formed by direct sunlight. (a) Why is the edge of that shadow somewhat fuzzy, and not totally sharp? (b) Suppose sunlight reflects off a car windshield, which acts like a convex mirror. Will the virtual image of the sun appear larger or smaller than the actual sun? (c) After reflecting off the windshield, the sunlight forms a shadow of the same object. Will this shadow have a sharper or fuzzier edge? Why?

8.22. Consider looking into a corner cube retroreflector with one eye open. Where is the image of your eye?

8.23. Consider an object in a kaleidoscope that is made with 2 mirrors at a 60°angle to each other (left side of figure, below). (a) How many images will you see that arise from one reflection? (b) How many images from 2 reflections? (c) How many images from 3 reflections? (number of distinct images, not number of ways of getting them). Now consider an object in a kaleidoscope made with 3 mirrors (right side of figure). (d) How many total images will you see from this 3-mirror kaleidoscope?



8.24. The following figure shows two reflections of the Golden Gate Bridge in a soap bubble. Explain which surface of the bubble created each reflection.

8.25. When the sun is low in the sky, its reflection off water with ripples appears as a long stripe of "sun glitter", regardless of the wave direction. Explain.

8.26. If it is snowing extremely gently when it is quite cold, the snow crystals are sometimes tiny flat hexagonal plates that fall flat, with the plates nearly parallel to the Earth's surface. When this happens, people sometimes observe "light pillars" above bright lights, such as street lights. (a) Draw a diagram that explains this phenomenon, showing both a person and a street light. (b) How far from the person, relative to the distance to the street light, are the snow crystals that reflect the light to that person's eyes?

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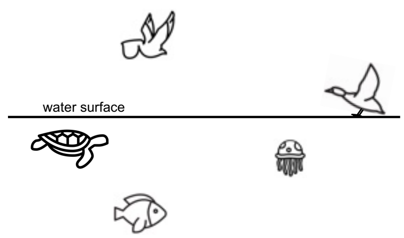
9. Refraction

Questions

9.1. Why does a straw in a glass of water appear to bend at the water's surface?
(a) straws become floppy when they get wet
(b) our eyes don't work correctly with light rays that come through water
(c) light rays from the straw bend when they leave the water, so the straw appears to be where it isn't
(d) light rays illuminating the underwater part of the straw bend as they enter the water
(e) light rays interact differently with wet and dry parts of the straw

9.2. Suppose you want to focus sunlight to start a fire, using a lens. (a) Do you want a concave or convex lens? (b) Will you be forming a real or virtual image? (c) Do you want a large diameter or small diameter lens?

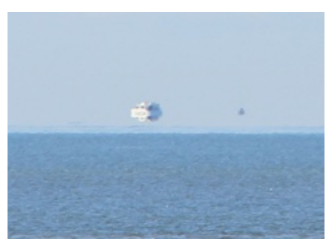
9.3. Consider the sea turtle that is underwater in the following figure. (a) Can it see everything that is in the air above the water (i.e. the birds shown in the picture)? (b) At what angle away from the vertical does the turtle look to see the feet of the duck that is about to land on the water? (c) Does the turtle see reflections of anything that is above the water? (d) Can the turtle see everything that is in the water (i.e. the fish and jellyfish)? (e) Does the turtle see strong reflections of things that are underwater; if so, which ones?



9.4. (a) Does light go faster in air or in water? (b) Does red light or blue light travel faster in water?

9.5. If you look at an object that's on the other side of a fire, candle, toaster, engine exhaust or some other heat source, it often appears to shimmer, which is called ***schlieren***. Explain how the regions of hot and cold air could cause this.

9.6. The following image shows a ***superior mirage*** (also called a Fata Morgana), in which light bends downward due to cold air near the Earth's surface. Draw a diagram that shows why the boat appears to floating in the air.



Problems

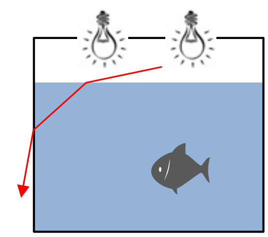
9.7. (a) Write down Snell's law. (b) Draw a picture that illustrates Snell's law, with the angles of incidence and transmission labeled.

9.8. Consider a laser, with a 640 nm wavelength, which is pointed straight down into water. The refractive index of water is 1.33. (a) What color is the laser? (b) What is the laser frequency in air? (c) What is the laser frequency in water? (d) What is the laser light speed in water? (e) What is the laser wavelength in water? (f) What color does the laser appear to be in the water?

9.9. A laser beam shines from air into a sheet of glass ($n = 1.52$) with an incident angle of 35°. (a) What is the angle of refraction? (b) Then, the same beam shines from this glass into water ($n = 1.33$), now with an angle of incidence equal to the previous angle of refraction. What is the new angle of refraction into the water? (c) A different laser beam shines directly from air to water, with an angle of incidence of 35°; compute the angle of refraction.

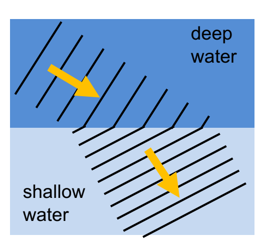
9.10. Dominic is an enologist (a wine maker) and he needs the sugar concentration of his grapes to be at least 20 brix (1 brix is 1 gram of sugar per 100 grams of juice). He lost his refractometer, so he shines yellow light into some grape juice and observes that the angle of incidence is 65.0°and the angle of refraction is 41.8°. (a) What is the refractive index of the grape juice? (b) Using the equation $B = 650(n - 1.333)$, where B is the sugar concentration in brix and n is the refractive index, what is the sugar concentration in brix? (c) Is the juice sweet enough for Dominic to use it for wine?

9.11. An aquarium has a vertical front and lights above it, as shown in the figure below. (a) Is it possible to look in the front of the tank and to see out the top (i.e. is the red ray that is shown actually possible or will it undergo total internal reflection)? (b) If the previous answer is yes, then what is the minimum angle of refraction for the light that shines in the top and leaves the aquarium through the front?



9.12. (a) Draw a diagram that illustrates total internal reflection. (b) Write down Snell's law for the case of total internal reflection (e.g. light going from glass toward air, where air is n_1 and glass is n_2). (c) What is the critical angle for light going from glass to air (the index of refraction for glass is 1.5)? (d) What is the critical angle for light going from cubic zirconia to air (this is fake diamond, index of refraction is 2.16)?

9.13. Consider water waves in 10 m deep water that have a 1 m wavelength. (a) What is the wave speed? (b) What is the wave frequency? These waves come to a region of water that is 5 cm deep, with a 60° angle of incidence (see the figure). (c) What is the wave speed in the shallow water? (d) Defining the refractive index as 1 in deep water, what is the refractive index for the shallow water region (i.e. what is the ratio of wave speeds)? (e) What is the wavelength in shallow water? (f) What is the angle of refraction into the shallow water?

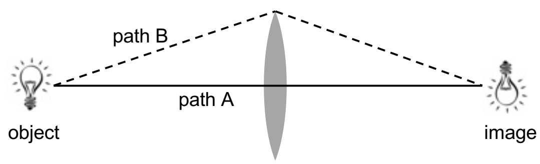


9.14. A converging lens has a focal length of 8 cm. A 3 cm tall flower is 20 cm from the lens. (a) Draw a ray diagram of this situation, showing the lens, optical axis, object, image, and at least two principal rays. (b) Compute the image location and height using math equations. (c) Do your two answers agree with each other? If not, go fix them.

9.15. A diverging lens has a focal length of 5 cm. A 4 cm tall object is 5 cm from the lens. (a) (a) Draw a ray diagram of this situation, showing the lens, optical axis, object, image, and at least two principal rays. (b) Compute the image location and height using math equations. (c) Do your two answers agree with each other? If not, go fix them.

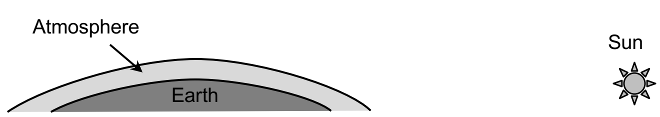
9.16. Two converging lenses are lined up sequentially. Each has a focal length of 10 cm, and they are 5 cm apart. An object is 20 cm from the first lens. (a) Compute the image location and magnification for the first lens. (b) Compute the final image location and total magnification for the pair of lenses.

9.17. Consider light going from an object through a convex lens and then to an image. The lens has a refractive index of 1.5, a radius of 5 cm, a maximum thickness of 1 cm, and a focal length of 26 cm. Suppose the object is 52 cm in front of the lens. In this problem, compute all times to 3 decimal places. (a) Where is the image of the object? (b) Is this a real or virtual image? (c) How long does it take light to go from object to image when it goes along the optical axis (path A in the figure)? (d) How long does it take light to go from object to image when it goes via the lens edge (path B)? (e) Which is faster, or are these the same?



Puzzles

9.18. The physical sunset time is the time when the top edge of the sun actually goes below the horizon. However, atmospheric refraction causes the sun to appear to set at a slightly different time. In other words, when we look at the setting sun, it appears to be in a slightly different place than where it really is. (a) By drawing rays on the figure shown below, does the setting sun appear to be higher or lower than it really is? (b) Is the apparent sunset time before or after the physical sunset time? (c) The atmosphere has normal dispersion, in which blue light has a higher refractive index than red light. Which image sets first, red or blue?



9.19. A trout that's swimming in a river sees a mayfly that is flying above the water, and it decides that it wants to eat the mayfly. To the fish, the mayfly appears to be 12 cm above the water. How high above the water is it really?

10. Color

Questions

10.1. Tuan has a bucket of magenta paint. He wants it to be blue. Which pigment should he add?
(a) cyan
(b) green
(c) yellow
(d) black
(e) it's impossible

10.2. Suppose you're sitting in a red tent, where all of the light is red, and you're searching for your green socks. What color will they appear to be once you find them?
(a) red
(b) yellow
(c) green
(d) blue
(e) black

10.3. If a parrot, which has four types of cone cells including ultraviolet sensitivity, were to observe a standard television, what would it perceive?
(a) it wouldn't see a picture at all because it's shown with the wrong colors
(b) the image would appear in black, white, and shades of gray
(c) all of the colors would be completely scrambled
(d) the image would look roughly correct, but missing some colors
(e) the image would be much more vibrant than it is used to seeing

10.4. At night time, if you look directly at the flashing light of a distant airplane, it's often quite dim. However, if you see the same flashing light with your peripheral vision, it's usually much brighter. What causes this effect?

10.5. Fire engines used to be bright red because people thought they would be easy to see. However, many cities have replaced them with bright yellow fire engines because those are easier to see at night. Why is yellow easier to see at night?

10.6. Deer hunters often wear bright orange clothing with camouflage patterns. The clothing is obvious to people but not to deer. Deer, like dogs, have only two types of cones. Why can't deer see the orange clothing?

10.7. List at least two traffic safety signals that a person with red-green color blindness would have difficulty seeing.

10.8. What do the letters stand for in the following abbreviations: (a) ROYGBIV, (b) RGB, (c) CMYK, (d) HSV?

10.9. Describe the colors of the following objects when illuminated with red light: (a) a yellow tennis ball, (b) a red shirt, (c) a green leaf, (d) a white sheet of paper.

Problems

10.10. Complete the following color "equations." (a) red light + blue light = ___ light, (b) yellow light + blue light = ___ light, (c) blue light + ___ light = cyan light.

10.11. Complete the following color "equations," assuming illumination by white light in each case. (a) cyan paint + magenta paint = ___ paint, (b) cyan paint + red paint = ___ paint, (c) magenta paint + ___ paint = black paint.

10.12. Using the color subtraction scheme presented here, (a) what color results when white light is passed through a cyan filter (e.g. a cyan sheet of plastic)? (b) what color results when white light is passed through 4 cyan filters in a row? (c) In reality, would the transmitted light in these two cases be exactly the same or would it appear somewhat different? Explain.

10.13. Explain why the sun is white when overhead and red during sunrise and sunset, using the fact that air acts like a filter that removes cyan light.

10.14. Using the color picker in a computer drawing program, such as Microsoft Powerpoint, choose olive green. What are its values in (a) RGB, (b) CMYK, (c) HSB?

Puzzles

10.15. In 3D movies, viewers typically wear glasses with one red lens and one blue lens, with which they then view red and blue movie images separately. Could this work equally well if the colors were red and yellow, instead? Explain.

10.16. Sketch the color space for a dog's vision in which the x-axis is the excitation level for the yellow cones and the y-axis is the excitation level for the blue cones. Label the regions of the space that correspond to light of different wavelengths, including rough wavelength numbers. Indicate what regions of the space are inside and outside the gamut of dog color perception.

11. Electromagnetic Waves

Questions

11.1. An airport security officer discovers that someone's suitcase is emitting substantial amounts of gamma radiation. What might be inside?
(a) a chemical explosive
(b) a computer that's overheating
(c) something that's radioactive
(d) a live animal
(e) a two-way radio that's turned on

11.2. What would you be able to see if you had *soft* X-ray vision (Assume there's enough X-ray light to see)
(a) just the air
(b) pretty much the same as with visible light
(c) you could see through walls, but people would still appear fully dressed
(d) everyone would appear to be naked
(e) all you'd see of people would be their bones

11.3. What would you be able to see if you had *hard* X-ray vision? (Assume there's enough X-ray light to see)
(a) just the air
(b) pretty much the same as with visible light
(c) you could see through walls, but people would still appear fully dressed
(d) everyone would appear to be naked
(e) all you'd see of people would be their bones

11.4. Many kitchen appliances have a "brushed metal" surface, in which the metal is first polished to make it shiny and then roughened to create grooves and ridges that are about 0.5 to 1.5 µm high. What type of light scattering occurs here?
(a) Rayleigh scattering
(b) Mie scattering
(c) Metal scattering
(d) Tyndall scattering
(c) No light is scattered

11.5. Old fashioned television sets had "rabbit ear" antennas that stuck up out of the top of the TV. Sometimes, the TV would receive its signal better if these antennas were tilted to new angles. Why did this help?
(a) It aligned the antennas with the wave polarization
(b) It reduced wave scattering
(c) It improved resonance between the antenna and the waves
(d) It decreased wave emission from the antennas
(e) All of the above

11.6. Which of the following waves are substantially polarized? Select all that apply.
(a) Sunlight
(b) Sunlight after passing through a polarizer
(c) Sunlight reflected off a mirror
(d) Sunlight reflected off a water surface
(e) The blue sky

11.7. Which of the following waves can be made polarized? Select all that apply.
(a) Red laser light
(b) White sunlight
(c) Long radio waves
(d) Infrared light from a hot stove
(e) A "black light" (ultraviolet light)

11.8. Aluminum foil has a shiny side and a dull side. The surface roughnesses[1] of the two sides are about 184 nm and 28 nm. (a) Which of these values corresponds to the shiny side? (b) Explain how you can tell.

11.9. Draw a diagram of an electromagnetic wave which shows: (a) electric field vectors, (b) magnetic field vectors, (c) an arrow that shows the direction of wave propagation, and (d) the wavelength.

11.10. Snow blindness is essentially a sunburned cornea, which is painful but recovers with time. Why would this be more likely to occur when wearing cheap sunglasses that reduce visible light but don't block UV light, rather than not wearing sunglasses at all?

11.11. Would it be safe to look directly at the sun while wearing a pair of sunglasses that blocked all UV light? Why or why not?

11.12. Why are you told to wear a lead apron when your dentist takes X-rays of your teeth?

[1]These values were measured parallel to the rolling direction, and are from C. Sinagra, F. Bravaccino, C. Velotti, "Aluminium foil: focus on the surfaces", packmedia.net webmagazine, 11/10/2016.

11.13. Give examples of (a) a scalar quantity, (b) a vector quantity, (c) a scalar field, (d) a vector field.

11.14. (a) Why is the sky blue? (b) Why are sunsets red? (c) Why are clouds white?

11.15. If the Earth's atmosphere were 50 times denser than it is, what color would the sun appear when it's overhead?

11.16. Suppose you travel to high altitude, such as to the top of a high mountain or flying in an airplane. Will the sky overhead appear lighter blue or darker blue than normal?

Problems

11.17. List the following electromagnetic bands in order of (a) increasing frequency, (b) increasing wavelength, (c) increasing photon energy: FM radio, microwave, shortwave, gamma ray, visible.

11.18. Which band is wider, measured as the ratio of the highest frequency to the lowest frequency: visible light (390 to 700 nm) or AM radio (530 to 1700 kHz)?

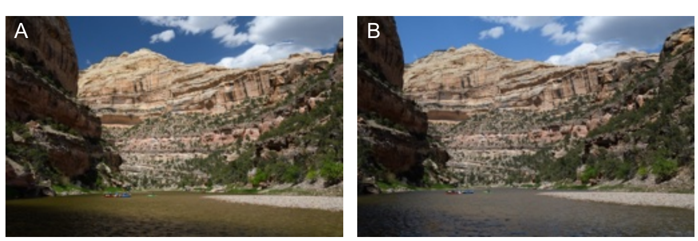
11.19. When light reflects off a horizontal water surface (e.g. a wet road), its electric field is mostly parallel to the water's surface. (a) To reduce glare, should your polarized sunglasses transmit light with a vertical or horizontal electric field? (b) Would wearing a second pair of polarized sunglasses at the same time reduce the glare even more, have essentially no further effect, or be completely opaque?

11.20. A store has a rack of sunglasses for sale, all of which it claims are polarized. Your friend doesn't believe that they are actually polarized. Describe one way in which you can test whether the sunglasses are polarized or not.

11.21. What percent of unpolarized light is transmitted through (a) two parallel polarizers? (b) two crossed polarizers? (c) Three polarizers, of which the second is rotated 45° from the first and the third is rotated another 45°(i.e. the first and third are crossed polarizers and the second is at a diagonal between them)?

Puzzles

11.22. The following two photographs (of Colorado's Yampa River) differ in that they were taken with filters that transmitted different light polarizations. (a) Which used a filter that transmitted horizontally polarized light, A or B? (b) Is the predominant polarization of the sky's Rayleigh scattering horizontal or vertical? (c) Approximately where is the sun (e.g. close to horizon behind the photographer, close to the horizon to the left, nearly overhead, etc.)?



11.23. Recalling that a standing wave in a cavity is the same thing as two traveling waves propagating in opposite directions, (a) draw at least 3 diagrams of the electric and magnetic fields of a standing electromagnetic wave, showing them at different times in the cycle. (b) Are the electric and magnetic fields in phase or out of phase? (c) Where is the energy when the electric field has its minimum values? (d) Where is the energy when the magnetic field has its minimum values?

11.24. Mars's atmosphere has very little air, but a lot of dust particles that range from 2 to 4 µm across. These dust particles are made of the same red minerals that form the surface of Mars. The mid-day sky is pink and the setting sun is blue, shown in the photograph below. The text says that these observations arise from Mie scattering, but could the same results arise from light absorption by the red colored dust particles instead? Explain.

11.25. Aristotle claimed that looking at the daytime sky from the bottom of a very deep well blocks out the blue scattered light, making stars visible just as they are at night time. Does this make sense or not? Explain.

12. Thermal Radiation

Questions

12.1. List the following in order from coldest to hottest, according to their actual temperature:
(a) the surface of a red giant star
(b) a bluish-white welder's arc
(c) the surface of the sun
(d) a blue light-emitting diode (LED)
(e) a black car sitting in the sun

12.2. List the following in order from coldest to hottest in terms of color temperature, not actual temperature:
(a) a "warm white" LED light bulb
(b) a "cool white" fluorescent light bulb
(c) a red traffic light
(d) the blue sky
(e) the surface of the sun

12.3. The Lockheed SR-71, named "Blackbird" for its black color, was the fastest airplane ever made, with typical speeds over Mach 3. Air friction at these speeds caused the plane's surface to reach temperatures over 500°C. What would have been some good reasons for painting the plane black? (Choose all that are appropriate.)

(a) To keep the pilot warm
(b) To keep the pilot cool
(c) For camouflage at night
(d) Black paint reflects radar
(e) It makes the plane quieter

12.4. By comparing the colors of burning wood in Figure 12.2 with the color temperature scale in Figure 12.4, estimate the temperature range for the burning embers.

12.5. (a) Which will get hotter when sitting in the sun: a black cat or a white cat? (b) Which will get colder when sitting outside on a clear night: a black cat or a white cat?

12.6. (a) What color roof will keep a house cooler on a hot summer day, black or white? (d) What color roof will lose less heat on a cold winter night, black or white?

12.7. The United States Department of Energy launched a "Cool roof initiative" in 2010 that required new and re-roofed Department buildings to use highly reflective roofing materials. Because of this policy, the United States National Nuclear Security Administration switched to cool roofs and then found that the switch reduced its heating and cooling costs by about 70%, enabling them to save about $500,000 per year[1]. Explain how using highly reflective roofing materials can reduce both heating and cooling costs.

12.8. New houses are often built with styrofoam insulation in the walls that's covered on one side with shiny aluminum foil. Explain why this foil is used, given that this insulation is on the inside of the wall, where it's never seen?

12.9. Two hikers get lost in the desert and have to spend the night. One wraps himself in a large black garbage bag (with a hole for his head) and the other wraps herself in a "space blanket," which is a large sheet of shiny mylar film. Who will stay warmer?

12.10. Europa is a rocky moon that orbits Jupiter. Would you expect it to be hotter or colder than our Moon? (Neither moon has any significant atmosphere.) Explain.

12.11. The military sometimes uses infrared cameras to locate enemy soldiers at night. Why is it hard to camouflage a person's infrared emission? Discuss some camouflage approaches that might work, at least partially.

12.12. You pour yourself a hot cup of coffee and are about the add some cream when the phone rings. Will the coffee be hotter after the phone call is over if you add the cream now, or if you wait until after the phone call to add it?

Problems

12.13. Consider a piece of pottery in a kiln that is at 1200°C. (a) What is the temperature of the pottery in Kelvin? (b) What is the wavelength for peak emission by the pottery? (c) What type of light is this (e.g. infrared, visible, or ultraviolet)? (d) Does the peak emission wavelength get shorter or longer as the kiln is made hotter?

12.14. Consider the same piece of pottery, still in a kiln at 1200°C, and assume that it has a surface area of 100 cm^2. (a) What is the temperature of the pottery in Kelvin? (b) How much total

[1] `https://energy.gov/articles/secretary-chu-announces-steps-implement-cool-roofs-doe-and-across-federal-government`

power does it radiate (units should be in W). (c) Does the emitted radiant power increase or decrease as the kiln is made hotter?

12.15. Consider a 100 W incandescent light bulb which has a temperature of 2700 K. What is the surface area of the filament in mm^2? (Hint: solve the Stefan-Boltzmann equation for the area.)

12.16. Sirius is a bluish-white star in the Canis Major constellation (close to Orion). The peak of its emission spectrum is at about 292 nm. What is the temperature of the surface of the star?

12.17. Consider 1 square meter of ground that is covered by snow, on a 0°C day. Assume the snow's visible emissivity is 0.05 and infrared emissivity is 0.95, and that the incident sun intensity (assumed to be all visible light) on this snow is about 100 W. (a) How much power does the snow absorb? (b) How much power does the snow emit? (c) Will these radiative influences warm or cool the snow overall?

12.18. Suppose a man, who is dressed in just a swimsuit, has a skin temperature of 91°F, a surface area of 2 m^2, an emissivity of 1, and is in a 68°F room. (a) How much power does he radiate? (b) How much radiant power does he absorb? (c) How much more radiation does he emit than absorb? (d) How many food calories does he burn in an hour, simply by radiating infrared light?

12.19. An ice-cold glass of lemonade, which is at 0°C and has a surface area of 170 cm^2, is sitting in a room that's 30°C. How much more radiation power does the lemonade absorb from the room than it emits?

12.20. Hypersonic weapons are unmanned military planes that fly at speeds over Mach 5. They are hard to detect by ground-based radar because they fly only tens of kilometers above the Earth's surface, in contrast to ballistic missiles, which fly hundreds of kilometers high. This question investigates whether hypersonic weapons can be detected by spy satellite. The nose cone of a hypersonic weapon, which we'll assume has a surface area of 1 m^2, gets heated to about 2000 K due to friction with air molecules. (a) What is the wavelength of peak emission? (b) How much power does the nose cone radiate? (c) Assuming that a spy satellite's resolution is around 100 m^2, meaning that each pixel in its photograph represents this much area on the Earth's surface, how much power does the Earth, at 300 K, radiate from 100 m^2? (d) How many times brighter or dimmer is the hypersonic weapon (assume the spy satellite detects all light wavelengths equally well)? (e) Would this suggest that a spy satellite could see the weapon or not? Explain.

12.21. Black holes are collapsed stars. Gravity is so strong around them that nothing can escape the edge of the black hole, called the "event horizon," including even light. However, whenever a pair of particles forms just outside of the event horizon, it's possible for one to fall in and the other to fly outward, with the net result that black holes actually radiate energy. This energy turns out to be identical to a blackbody of temperature $T = \frac{1.2 \cdot 10^{23}}{M}$, where M is the black hole mass in kg and T is the black hole temperature in kelvin. (a) Compute the temperature of a black hole that has one solar mass ($M_\odot = 1.99 \cdot 10^{30}$ kg), giving the answer in kelvin. (b) What is the wavelength of peak blackbody emission? (c) Calculate the radius of a 1 solar mass black hole's event horizon, using the relationship $R = 1.48 \cdot 10^{-27} M$, where R is in meters and M in kg. (d) How much total power does a 1 solar mass black hole radiate?

12.22. The universe began in the Big Bang about 14 billion years ago and immediately started expanding and cooling. About 378,000 years later, it had cooled to about 3000 K, at which point electrons and protons combined to form neutral atoms, and light could then travel long distances without constantly getting absorbed and re-emitted. This light, which had the spectrum of a 3000 K blackbody, still exists but has been redshifted dramatically due to continued universe expansion so that it now has the spectrum of a 2.73 K blackbody. It is called the cosmic microwave background, fills all space, and is seen uniformly in all directions. (a) What is the peak wavelength of this radiation? (b) Suppose a satellite has a surface area of 100 m^2; how much energy does it absorb from microwave radiation?

12.23. Procyon B is a white dwarf star in the Canis Minor constellation. Its mass is $1.20 \cdot 10^{30}$ kg, its temperature is 7740 K, and it emits $1.88 \cdot 10^{23}$ W of power. (a) What color is it? (b) What is its radius? (c) What is its density in kg/m^3? (d) What is the mass of 1 cm^3 of this star?

The Earth's energy budget

12.24. The solar constant. (a) The surface of the sun is about 5778 K and its radius is about 696,000 km. How much total power does the sun emit? (b) Imagine an entire sphere placed around the sun that has the radius of the Earth's orbit (149,500,000 km). What is the surface area of this sphere, in m^2? (c) How much of the sun's power goes through each square meter? This value is called the solar constant.

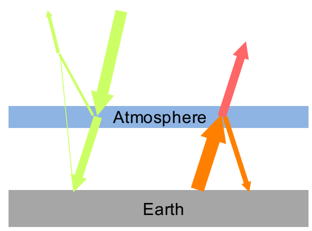
12.25. Projection effect. The total amount of sunlight that hits the Earth is the solar constant times the area of the Earth that is visible to the sun. However, we want to average this over the entire Earth, which is done here. (a) Defining the Earth's radius as R_E, give an equation for the area of the Earth that is visible to the sun, $A_{visible}$ (hint: it's just the area of a circle). (b) What is the surface area of the entire Earth, A_{total} as a function of R_E? (c) What is the ratio of $A_{visible}$ to A_{Earth}, simplifying as possible? This is the fraction of the solar constant that hits each square meter of the Earth's surface, on average. (d) Multiply this ratio by the solar constant from the last problem to get the average incoming sunlight on each square meter of the Earth.

12.26. Earth albedo. From the last problem, you should have found that average incoming sunlight is about 342 W/m^2. About 30% of this light reflects off clouds, the oceans, snow, and light colored sand without being absorbed, called Earth's albedo. (a) What is the power of the reflected light for each square meter? (b) What is the power of the absorbed light for each square meter?

12.27. Earth infrared emission. In the last problem, you should have found that the Earth absorbs about 239 W of sunlight per square meter. The Earth is extremely close to being at steady state, meaning that it is neither gaining nor losing energy. Thus, each square meter of the Earth's surface must also emit about 239 W of energy. (a) What is the temperature, in K, of a square meter that emits about 239 W? (b) What is this in Celsius? (c) What is wavelength of maximum emission for light from the Earth?

12.28. The greenhouse effect. In the last problem, you should have found that the Earth's temperature would be about -18°C if it didn't have a greenhouse effect. However, the actual average temperature is actually about 15°C. (a) How many degrees warmer is the Earth than what it would be if it didn't have an atmosphere? (b) How much power is radiated from 1 square meter of the Earth's surface, using the actual Earth surface temperature? (c) How much power does 1 square meter of the atmosphere send back to the Earth's surface? To calculate this, assume that the atmosphere isn't gaining or losing energy; if it's losing 239 W to space, from above, and it's gaining the amount of energy that you calculated in part b of this problem, then the difference must be the amount of energy that it sends back to Earth's surface. (d) What fraction of the energy emitted from the Earth's surface gets reflected back to Earth (i.e. the ratio of the two prior numbers)?

12.29. The following figure is a diagram of the numbers that you computed in the last several problems. (a) Copy it and write your numbers next to the arrows as appropriate. (b) Compare your results to Figure 12.7; which numbers there are essentially identical to the ones that you calculated? (c) What processes are included in Figure 12.7, which you ignored?



12.30. Global warming. You should have found above that about 39% of the radiation that the Earth emits is sent back to the Earth, meaning that about 61% of the energy escapes to space. Suppose the atmospheric reflectivity increased by 2%, so now 41% of the light returns to Earth and 59% goes to space. (a) Now, how much radiation goes from Earth to the atmosphere (the outgoing radiation is still 239 W from above, so divide this by 59%)? (b) What Earth temperature would produce this much outgoing radiation, in °C? (c) By how many degrees did this atmosphere change warm the Earth?

Puzzles

12.31. How much total radiation energy is in an empty teapot? Give the answer in terms of its temperature T, volume V, the Stefan-Boltzmann constant σ, and the speed of light c. The teapot's emissivity is 1. For convenience, assume it is a spherical cavity with radius r and assume that all light that is emitted from one side travels distance $2r$ before being absorbed again at the far side.

12.32. The Moon is about as far from the Sun as the Earth is, so the average temperature on the Moon should be about the same as the average temperature on the Earth but without the greenhouse effect. However, the Moon rotates very slowly, so there is a large difference between day and night sides. Calculate the temperature on the Moon on the equator at mid-day in °C. Assume that visible radiation comes in from the sun and infrared radiation gets emitted to a hemisphere of sky (ignore any radiation arriving from the sky). The Moon's albedo is about 12%, assume that it emits as a perfect blackbody, and use a solar constant value of 1362 W/m^2.

12.33. Model the Venusian atmosphere as some number of layers, where each layer absorbs all of the IR light from below and then emits half of the energy upward and half of the energy downward. Consider 1 square meter of the surface. (a) Define the emission of the top layer to space as P_1, where this is layer number 1; how much power does one layer below it, layer 2, emit upward as a function of P_1? (b) How much power does the third layer emit upward? (c) Write an equation for P_n. (d) The surface is at 462 °C, so how much power does it emit upward? (e) Combine these last two results to solve for n, which is the number of layers; use the fact that $P_1 = 791$ W.

13. Photons

Questions

13.1. Which one of the following is true?
(a) X-ray photons are faster than infrared photons
(b) radio wave photons have more energy than infrared photons
(c) red photons have higher frequencies than blue photons
(d) X-ray photons have more momentum than radio photons
(e) none of the above; all photons are the same

13.2. Which properties do photons have (choose all that are appropriate)?
(a) rest mass
(b) energy
(c) momentum
(d) speed
(e) wavelength

13.3. Which has the most energy?
(a) one blue photon
(b) one red photon
(c) two blue photons
(d) two red photons
(e) they are all the same

13.4. Which has the most momentum?
(a) one blue photon
(b) one red photon
(c) two blue photons
(d) two red photons
(e) they are all the same

13.5. A beam of white light reflects off a mirror that's attached to a wall. Which way does the light push on the mirror?
(a) away from the wall
(b) into the wall
(c) parallel to the wall
(d) there is no force on the mirror
(e) it depends on the light wavelength

Problems

13.6. Considering a red photon and a blue photon, which has the greater value for each of the following properties (for each part, answer "red", "blue", or "same"): (a) wavelength, (b) frequency, (c) speed, (d) energy, (e) momentum, (f) rest mass.

13.7. Consider green light with a wavelength of 550 nm. (a) What is the light frequency? (b) What is the energy of a single photon? (c) Does a red photon have a higher or lower frequency? (d) Does a red photon have a higher or lower energy?

13.8. A red laser pointer emits 2 mW of 650 nm laser light. (a) What is the energy of each photon? (b) How many photons per second is this?

13.9. (a) What is the photoelectric effect? (b) How did its explanation change the understanding of the physics of light? (c) Give an example of how the photoelectric effect is used in modern technology.

13.10. Hydrogen and chlorine gases are combined in a balloon. Both are dimeric, meaning that each hydrogen molecule is two hydrogen atoms and each chlorine molecule is two chlorine atoms. The hydrogen bond strength is 432 kJ/mole and the chlorine bond strength is 240 kJ/mole. One mole of molecules is $6.02 \cdot 10^{23}$ individual molecules. (a) What is the bond strength of a single hydrogen molecule, measured in J? (b) What is the bond strength of a single chlorine molecule, measured in J? (c) What is the maximum wavelength photon that has enough energy to break one of these two bonds, which will then start a chemical reaction?

13.11. “Breakthrough starshot” is a research program that has the goal of sending tiny spacecraft to nearby stars. In their plan, these spacecraft will have shiny light sails and will be accelerated to about 20% the speed of light by shining a ground-based laser at them for about 10 minutes each. Supposing each spacecraft weighs 2 g and the laser wavelength is 10.6 μm (a CO_2 laser), how much laser power will be required?

13.12. Suppose an electron is not moving and it gets hit with one green photon with 500 nm wavelength, and assume the electron absorbs the photon. An electron’s mass is $9.11 \cdot 10^{-31}$ kg. (a) Use the conservation of momentum to compute the electron’s final speed. (b) Use the conservation of energy to compute the electron’s final speed (the kinetic energy of the electron is $\frac{1}{2}mv^2$, where m is the electron’s mass and v is its velocity). (c) Based on these results, is it possible for a lone electron to absorb a photon?

13.13. Consider a sidewalk section that has an area of 1 m^2 and assume the sun is directly overhead. Also, assume the sun is emitting primarily green light, which has a wavelength of 500 nm. (a) What is the energy of one sunlight photon? (b) Using the fact that the power of the sunlight on this square meter is about 1367 W, how many photons hit the sidewalk section in one second? (c) What is the momentum of one sunlight photon? (d) What is the momentum of all photons that hit this sidewalk section in one second? (e) Now suppose an ant falls on the sidewalk. A typical ant weighs $4 \cdot 10^{-6}$ kg and falls at 1.8 m/s. What is the ant’s momentum? (f) Which exerts a greater momentum, the ant or 1 second of sunlight? (g) Which would exert a greater momentum if the sidewalk were silvered, like a mirror?

13.14. When an excited hydrogen atom relaxes from its lowest energy excited state to its ground state, it releases a photon with an energy of $1.64 \cdot 10^{-18}$ J. (a) What is the photon wavelength? (b) What is the photon momentum? (c) What is the recoil speed of the hydrogen atom? (A hydrogen atom mass is $1.67 \cdot 10^{-27}$ kg; the total momentum is zero, so the atom momentum’s is equal and opposite the photon’s momentum.)

13.15. A hydrogen atom takes an average of $1.6 \cdot 10^{-9}$ s to relax from its first excited state to its ground state, releasing a photon with energy $1.64 \cdot 10^{-18}$ J. (a) What is the photon frequency?

(b) What is the spectral width of the photon in nm? (c) What is the spectral width as a percent of the photon frequency?

13.16. Suppose an atom takes 10^{-8} seconds to relax from an excited state to its ground state, emitting a photon in the process. (a) Taking this as the wave packet duration, how long is the wave packet in meters? (b) Discuss whether this is a reasonable measure of the photon's length.

13.17. The Very Long Baseline Array is a system of 10 radio telescopes, which are up to 8,611 km away from each other, that measure high frequency radio waves (in the microwave region) from distant stars. Every telescope measures the same radio wave peaks and troughs, which are then combined through a method called digital interferometry. (a) Do these radio waves have a large or small coherence length, compared to their wavelengths? (b) Would it be reasonable to say that a single radio wave photon is at least 8,611 km across? Explain why or why not.

13.18. The Voyager 1 spacecraft is at the edge of the solar system, about 11 billion km away. (a) How long does a radio signal from Voyager 1 take to get to the Earth? (b) Its radio works at 8 GHz. What is the wavelength? (c) What type of light is this? (d) What is the energy of 1 photon? (e) It has a 23 watt radio wave transmitter. How many photons per second is this? (f) This radio wave is aimed toward the Earth by a dish; by the time the signal gets to the Earth, the area of the radio beam is $4 \cdot 10^{15}$ km^2. What is the photon flux density, in photons per second per square km? (g) How about in photons per second per square meter?

Puzzles

13.19. Consider an empty cubical black cardboard box that has side length L and is at temperature T (most answers will be equations). (a) How much total power do the sides of the box radiate into the box through blackbody radiation? (b) Using the fact that an average photon travels distance $2L/3$ between when it is emitted and absorbed, what is an average photon's lifespan? (c) How much total radiation energy is inside the box? (d) What is the energy of one of these photons, assuming that all photons have the wavelength that corresponds to the peak of the blackbody distribution spectrum? (e) What is the density of photons in the box? (f) Evaluate the photon density for $T = 300$ K. (g) How many times more air molecules are there than photons, using the fact that the air molecule density at 1 atm pressure and 300 K is $2.45 \cdot 10^{25}$ molecules/m^3. (h) How far apart are the photons, on average, at 300 K (the cube root of the volume per photon)?

13.20. Consider a spherical teapot of temperature T and radius r. The inside of the teapot is painted black and radiates blackbody radiation. (a) How much pressure does this radiation exert against the sides of the teapot, as an equation? Note that pressure is force per unit area, $P = F/A$, and force is change of momentum per time unit, $F = \Delta p/\Delta t$. Assume that all emitted light is at the peak of the blackbody distribution spectrum and that photon emission and absorption occur with photons moving perpendicular to the surface. (b) Evaluate this pressure in atmospheres for $T = 2000$ K, using the facts that the SI unit for pressure is Pa and 1 atm $= 101,325$ Pa.

13.21. Zoro is flying toward the star Betelgeuse so fast that the red starlight appears blue to Zoro due to the Doppler shift. When she measures the energy of one of these starlight photons, will it have the energy of a red photon or a blue photon? Explain.

14. Matter Waves

Questions

14.1. All hydrocarbons, which are molecules that are made of hydrogen and carbon (e.g. methane, propane, butane, and gasoline) burn in the presence of oxygen with a blue flame that has a temperature of about 1950°C. Which one of the following could explain this blue flame?
(a) There are additives in fuels that make the flame blue for safety
(b) Blackbody radiation from the burning gases
(c) All hot gases are blue
(d) Excited carbon dioxide emits blue light
(e) Rayleigh scattering

14.2. When hydrocarbons burn without sufficient oxygen, they create a flame that is white, yellow, or orange, depending on the temperature. Which one of the following could explain this flame color?
(a) Emission from sodium atoms in the fuel
(b) Emission from hydrogen atoms in the fuel
(c) Emission from hot air molecules (primarily nitrogen, oxygen, and argon)
(d) Fluorescence from carbon dioxide
(e) Blackbody radiation from particles of unburned fuel

14.3. Which one is true about Heisenberg's uncertainty principle?
(a) It reflects an underlying limit to the physical world
(b) It reflects the limitations of current technology
(c) It only applies to electrons
(d) It is the central assumption of quantum mechanics
(e) It was an interesting hypothesis but later disproven

14.4. Compare the de Broglie wavelengths of a charging elephant and a sleeping mosquito. Which one is true?
(a) The elephant's wavelength is longer
(b) The mosquito's wavelength is longer
(c) They have the same wavelength
(d) De Broglie wavelengths don't apply to animals
(e) Which wavelength is longer depends on the animals' temperatures

14.5. Many animals can see ultraviolet light, so some hunters are concerned that wearing clothing with fabric brighteners in them, which are essentially fluorescent dyes, will make their clothes glow in the ultraviolet and thus be visible to animals. Is this a valid concern? Why or why not?

14.6. (a) Draw an energy level diagram for fluorescence, with arrows for excitation, non-radiative relaxation, and emission. (b) In which state are most of the atoms? (c) Is fluorescent emission at a longer, shorter, or the same wavelength than the excitation?

14.7. (a) Draw an energy level diagram for a simple laser showing pumping (excitation), non-radiative relaxation, and stimulated emission. (b) In which state are most of the atoms? (c) Is laser emission at a longer, shorter, or the same wavelength than the excitation?

14.8. Match the scientist on the left with the discovery on the right.

(a) Werner Heisenberg	(1) Only one electron can be in any quantum state
(b) Louis de Broglie	(2) Cold atoms can overlap each other
(c) Wolfgang Pauli	(3) Matter waves are complex wave functions
(d) Erwin Schrödinger	(4) Position and momentum can't be known simultaneously
(e) Satyendra Bose	(5) Particles have wavelengths and frequencies

Problems

14.9. Electrons in a piece of metal move at a range of speeds, of which the fastest move at the so-called Fermi velocity, which is about 1570 km/s for copper. (a) What is the de Broglie wavelength of these electrons? (b) How does this compare to the separation between copper atoms, which is about 0.26 nm? (c) Would it be more accurate to say that each electron is bound to an individual atom, or is spread out over several atoms?

14.10. Consider two electrons in an atom, one in the 1s orbital and the other in the 2s orbital. (a) Which electron has the longer de Broglie wavelength, or are they the same? (b) Which electron has the higher de Broglie frequency, or are they the same?

14.11. Consider vibrations of a HCl molecule that are represented by a quantum harmonic oscillator. Suppose the molecule is in a superposition of the two lowest energy states, $n = 0$ and $n = 1$. (a) Sketch the wave function at time 0, by adding the two component wave functions (the appropriate solid blue lines in Figure 14.13). (b) At time $\tau/2$, where τ is the harmonic oscillator period and is equal to $1/f$, it's reasonable to consider the $n = 0$ wave function as unchanged, but the $n = 1$ wave function as having rotated around through half of its period, shown with the dashed lines in Figure 14.13. Sketch the wave function at time $\tau/2$. (c) At time τ, the $n = 0$ wave function is still unchanged, but the $n = 1$ wave function has now completed one full rotation. Sketch the wave function again. (d) Describe the motion that these wave functions are showing.

14.12. Arrange the following molecules in order from weakest bond (or no bond at all) to strongest bond. Use an "=" symbol if two molecules have the same bond strength. Each molecule is composed of one helium atom and one hydrogen atom. HeH^{3+}, HeH^{2+}, HeH^{+}, HeH, HeH^{-}.

14.13. Use the Rydberg formula for hydrogen atom emission. (a) Compute the wavelength for the case where $n_1 = 2$ and $n_2 = 3$. (b) What color is this? (c) Compute the wavelength for the case where $n_1 = 1$ and $n_2 = 2$. (d) Compute the wavelength for the case where $n_1 = 1$ and $n_2 = \infty$. (e) What color is this? (f) Are there any n_1 and n_2 combinations that can give a shorter wavelength? (g) What is the energy of one photon of this wavelength (i.e. the ionization energy)?

14.14. Electron microscopes achieve higher resolution than light microscopes because electrons can have much shorter wavelengths. (a) For an electron traveling at $1.9 \cdot 10^7$ m/s, what is its wavelength? (b) How many times shorter is this than the 350 nm wavelength of a violet photon?

14.15. Consider a sample of hydrogen atoms that are in their ground states (hard to achieve on Earth, but common in interstellar space). (a) Draw an energy level diagram of a hydrogen atom, with the energy levels labeled. (b) Suppose light of 103 nm shines on the hydrogen atoms; what energy level will the hydrogen get excited to (hint: just guess and then compute the wavelength with the Rydberg formula to see if you're correct)? (c) What three wavelengths will the hydrogen atoms emit as they relax back to the ground state?

14.16. When table salt is put in a candle flame, it burns bright yellow because of emission from the sodium atoms. This emission is at 590 nm. How much energy does the atom lose during this transition?

14.17. Consider a particle in a box. Its average velocity is clearly 0 because it's staying in the box, but its instantaneous velocity varies over time, which we'll estimate here. (a) Using the de Broglie wavelength equation, what is the approximate velocity of this particle as an equation? (It should be a function of m, n, L, and h.) (b) Compute the velocity of an electron in the $n = 1$ state of carotene ($L = 2.4$ nm). (c) Compute the velocity of an electron in the $n = 11$ state of carotene.

14.18. The energy levels for a particle in a 3-dimensional cubical box are $E_{n_x,n_y,n_z} = \frac{h^2}{8mL^2}(n_x^2 + n_y^2 + n_z^2)$, where m is the particle mass, L is the side length, and each of the n values is a non-negative integer (i.e. 1, 2, 3, ...). (a) What is the zero-point energy for a particle in this box? (b) What is the energy of the first excited state? (c) How many different quantum states (i.e. different sets of n_x, n_y, and n_z values) correspond to this energy? (d) What is the next energy level? (e) How many different quantum states correspond to this energy?

14.19. Carbon monoxide (CO) vibrations are represented well as a quantum harmonic oscillator with a vibrational frequency of $6.4 \cdot 10^{13}$ Hz. Suppose it is excited to its 3rd excited state ($n = 3$). (a) What wavelengths of light can it emit? (b) Vibrational transitions that only change the quantum number by 1 tend to couple more strongly to light than others, yielding stronger absorption and brighter emission; what is the wavelength for this transition?

14.20. Butadiene is a molecule with a conjugated π system, much like carotene. It has four electrons that are free to move and has a length of 0.553 nm. (a) Use the particle in a box model to compute the wavelength of its lowest energy absorption. (b) How close is this to the experimental result of 217 nm, given as a percent error?

14.21. Zoe's pet rat got loose, but she knows that it's somewhere in her bedroom, which is about 4 meters across. (a) Taking 2 m as the uncertainty in the rat's location, what is the uncertainty in its velocity from the Heisenberg uncertainty principle (it weighs exactly 0.4 kg)? (b) Could its velocity be much higher than this value? (c) Zoe hears gentle snoring, so she believes that her rat is asleep, and is moving slower than this value; is this possible? (d) If Zoe had a machine that could measure the rat's velocity extremely precisely, could this measurement result be lower than this value? Explain.

14.22. It was shown above that the quantum excitation frequency for a harmonic oscillator is the same as the classical resonance frequency. Let's see if this is true for a particle in a box as well. (a) Find an equation for the classical frequency for a particle in a box, as a function of E, m, and L (hint: start by solving for the period, τ as a function of the velocity, v). (b) Show that a photon that excites a particle in a box from level n to level $n + 1$ has frequency $\frac{h}{8mL^2}(2n + 1)$. (c) Approximate this photon frequency for large n, in which $2n + 1 \approx 2n$. Then, express the photon frequency as a function of E, m, and L (hint: solve for E_n in terms of n and substitute). (d) Are the classical resonance and quantum transition frequencies essentially the same? Discuss.

Puzzles

14.23. Researchers have created a “living laser” by expressing GFP in laboratory grown cells and then turning a population of the cells (uniformly dispersed in water) into a laser[1]. Discuss what the researchers would have needed to assemble to create this laser, and things that they would have needed to consider.

14.24. In the Schrödinger’s cat experiment, suppose you open the box and find the cat is dead. Could you then measure its temperature (or do some other medical forensics) to find out when it died, and this would answer whether it had been in a superposition state or not?

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15. Gravitational Waves

Questions

15.1. Does gravity bend light?
(a) Never
(b) Yes, but only if the gravity is strong enough
(c) Yes, but only certain light wavelengths
(d) Yes for photons, but not for light waves
(e) Always

15.2. Suppose you’re standing on a bathroom scale, and it shows your weight suddenly increase and then decrease. List the following potential causes in order from most likely to least likely:
(a) It was caused by a passing gravitational wave
(b) The Earth suddenly changed mass
(c) You suddenly changed mass
(d) You moved a little bit
(e) The scale is unreliable

15.3. You are looking at a binary star edge-on, with its axis of rotation pointed up and down. What gravitational wave polarization will you observe?
(a) Up-down
(b) Left-right
(c) +
(d) x
(e) circular

15.4. What are gravitational waves? Select all appropriate answers.
(a) A form of electromagnetic radiation
(b) Waves in the gravitational field
(c) Part of the strangeness of quantum mechanics
(d) The dominant cause of the Earth’s tides
(e) Waves that distort space itself

15.5. Which properties do gravitational waves possess? Select all appropriate answers.
(a) Two linear polarizations

[1] Malte Gather and Seok Hyun Yun, “Single-cell biological lasers” *Nature Photonics* 5:406, 2011.

(b) Longitudinal waves
(c) Transport energy and momentum
(d) Wavelengths and frequencies
(e) Propagate at the speed of light

Problems

15.6. For the gravitational waves emitted by the Moon orbiting the Earth ($T = 27$ days), what are (a) the wave frequency in Hz and (b) the wavelength? (c) Express this wavelength in light-days.

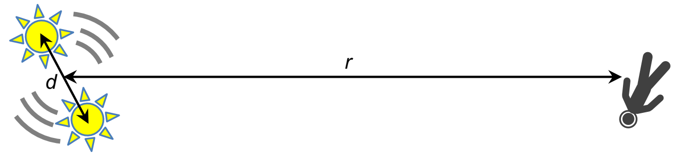
15.7. Calculate how much gravitational wave power the Earth emits as it orbits the sun.

15.8. Using the gravitational field equation (eq. 15.2), calculate the gravitational field exerted by the Moon, to 4 significant figures, at (a) the center of the Earth, (b) the surface of the Earth closest to the Moon, and (c) the surface of the Earth farthest from the Moon. (d) Calculate the difference between parts b and c.

15.9. Using the gravitational field equation (eq. 15.2), calculate the gravitational field, to 5 significant figures, exerted by the Sun at (a) the center of the Earth, (b) the surface of the Earth closest to the Sun, and (c) the surface of the Earth farthest from the Sun. (d) Calculate the difference between parts b and c. (e) If you did the previous problem too, then compare the answers to explain why the Moon has a greater effect on Earth's tides than the Sun.

15.10. Two stars, each of mass m, are orbiting each other in a binary star with orbital frequency f. The binary star has radius, r, which is half of the distance between the two stars. (a) What is the speed of each star, v, as a function of the other variables? (b) The fact that each star moves in a circle implies that it is accelerating toward the circle's center at rate $a = \frac{v^2}{r}$ (called the centripetal acceleration); equate this to the gravitational acceleration and solve for r in terms of G, m, and f. (c) Compute the distance between the black holes that were observed in the GW150914 event when their gravitational waves had a frequency of 250 Hz, assuming each black hole had 30 times the sun's mass. (d) Compute the power emitted by these black holes at the same point of their inspiral.

15.11. Consider a binary star, of which each star has mass M and they are separated by distance d. An observer is distance r away from the center of this system, along an axis that is perpendicular to the star's axis of rotation, and is measuring the gravitational field from the stars. (a) What field does this observer measure when the stars appear lined up, with one behind the other? (b) What field does this observer measure when the stars appear stacked up, with one above the other? (c) Compute the difference between the two prior answers, and approximate using the assumption that $d \ll r$ so that r only appears once in the final equation (hint: $\frac{1}{(x+a)^2} \approx \frac{1}{x^2}(1 - \frac{2a}{x} + \frac{3a^2}{x^2})$ when $a \ll x$). (d) Does this field fall off faster or slower with distance than that of gravitational waves, which is proportional to r^{-1}?



Puzzles

15.12. Suppose the sun blinked into and out of existence with a 1 second period (ignore the fact that this violates conservation of mass). (a) Would this produce gravitational waves, and if so, (b) would they be longitudinal or transverse, (c) what sort of polarization would they have, and (d) what would their frequency be?

15.13. Consider a rapidly rotating binary star with a 1 second period. Now, suppose one of the stars stopped existing but the other kept moving along its exact same orbit as if nothing had happened (ignore the fact that this violates conservation of momentum). (a) Would this single star produce gravitational waves, and if so, would they be (b) longitudinal or transverse, (c) what sort of polarization would they have, and (d) what would its frequency be?

15.14. List some challenges and possible solutions in building a gravitational wave laser.

A. Numbers

Questions

A.1. Which one of following values is *not* equal to 0.000042?
(a) $4.2 \cdot 10^{-5}$
(b) $42 \cdot 10^{-6}$
(c) $0.042 \cdot 10^{-3}$
(d) $4.2 \cdot 10^{5}$
(e) 0.000042

A.2. Without using a calculator, what is $9.1 \div 10000$?
(a) $9.1 \cdot 10^{-4}$
(b) $9.1 \cdot 10^{4}$
(c) 0.000091
(d) 1100
(e) 9.1

A.3. How many significant figures are in the number 0.0003810?
(a) 3
(b) 4
(c) 5
(d) 7
(e) 8

A.4. What is $89.3 \div 0.71$?
(a) 100
(b) 130
(c) 126
(d) 125.8
(e) 125.774647887

A.5. What is $6.2 \cdot 10^{-8} + 110.3$?
(a) 116.5
(b) $1.165 \cdot 10^{-8}$
(c) 110.300000062

(d) 110.3
(e) $6.2 \cdot 10^{-8}$

Problems

A.6. Write the following numbers using scientific notation. (a) 13400, (b) 0.0000082, (c) 4.7.

A.7. Arrange the following numbers in sequence, from smallest to largest: 5, $500 \cdot 10^{-3}$, $0.5 \cdot 10^{2}$, $5 \cdot 10^{-2}$.

A.8. Compute the following without using a calculator: (a) $(3 \cdot 10^{8})^2$, (b) $\frac{1}{2 \cdot 10^{14}}$, (c) $\frac{(6 \cdot 10^{-34})(3 \cdot 10^{8})}{900 \cdot 10^{-9}}$.

A.9. Using a calculator, compute (a) $(3.00 \cdot 10^{8})(3.15 \cdot 10^{7})$, (b) $\frac{2.0 \cdot 10^{8}}{5.6 \cdot 10^{14}}$.

A.10. Compute (a) $0.056 + 0.00734$, (b) $1200.0 - 5$, (c) $5.001 + 3.2 \times 0.20000$.

A.11. Assuming uncertainties represent outer limits, compute (a) $(11 \pm 3) + (5 \pm 2)$, (b) $(11 \pm 3) - (5 \pm 2)$.

A.12. Assuming uncertainties represent outer limits, compute (a) $(11 \pm 3) \times (5 \pm 2)$, (b) $(11 \pm 3) \div (5 \pm 2)$.

A.13. Assuming uncertainties represent standard deviations, compute (a) $(11 \pm 3) + (5 \pm 2)$, (b) $(11 \pm 3) - (5 \pm 2)$.

Puzzles

A.14. Suppose you have 100 bricks that are each 20 ± 1 cm long and you lay them down in a row with each brick touching the one next to it. (a) Taking the uncertainty as the outer limit, what is the length of the row of bricks, including its uncertainty? (b) Taking the uncertainty as the standard deviation, what is the length of the row of bricks, including its uncertainty? (c) Explain why the resulting uncertainty values are so different.

B. Units

Problems

B.1. For each part, use the unit conversion method presented here and show your work. (a) How many km is 4000 miles? (b) How many nm is 17 µm (the width of a human hair)? (c) How many cycles per day is 97 MHz?

B.2. For each part, use the unit conversion method presented here and show your work. (a) How many gallons are in 0.25 acre-feet (the annual water use of a typical family)? (b) How many km/liter are equal to 40 miles per gallon? (c) How many US$/gallon is equal to 1.28 euros/liter (the price of gasoline in France), assuming that 1 euro equals $1.14?

B.3. Following are several equations. For each, simply calculate what the units are for the result, if possible; if it's not possible, write "invalid equation." Don't worry about the numerical values.
(a) $E = hf$ (photon energy). h is in J s, f is in Hz.
(b) $f = \left(\frac{1}{d_o} + \frac{1}{d_i}\right)^{-1}$ (curved mirror equation). d_o and d_i are in m.
(c) $\lambda = \frac{g}{2\pi f^2}$ (deep water wavelength). g is in m/s^2, f is in Hz.

B.4. Following are several equations. For each, simply calculate what the units are for the result, if possible; if it's not possible, write "invalid equation." Don't worry about the numerical values.
(a) $P = A\sigma T^4$ (Stefan-Boltzmann law). A is in m^2, σ is in $\mathrm{W\,m^{-2}K^{-4}}$, T is in K.
(b) $\tau = \frac{L}{v(1-R)}$ (laser cavity decay time). L and R are in m, v is in m/s.
(c) $h_r = \frac{h_a}{\lambda}$ (relative water depth). h_a and λ are in m.

B.5. What is the mass of the Pacific Ocean? The density of seawater is 1029 $\mathrm{kg/m^3}$, the volume of the Pacific Ocean is $7.1 \cdot 10^{17}$ m^3, and the answer should be in kg.

B.6. Suppose x is in J/photon and y is in J/s. How can x and y be combined to produce an answer in photons/s (e.g. xy, x/y, y/x, etc.)?

B.7. Suppose x is in waves/m and you want to convert this to m/wave. How would you calculate the answer from x?

B.8. Suppose σ is in $\mathrm{W\,m^{-2}K^{-4}}$ and T is in K. How can σ and T be combined to produce an answer in $\mathrm{W\,m^{-2}}$?

B.9. Suppose x is in apples/pie, y is in slices/pie, and z is in slices/person. How can x, y, and z be combined to produce an answer in apples/person?

B.10. Electricity is normally sold in units of kilowatt-hours (KWh). Simplify this to (a) a metric derived unit, (b) metric base units (ignore prefixes and other scaling, just focus on the type of unit).

C. Algebra

Questions

C.1. Which of the following statements are incorrect? Choose all that are appropriate.
(a) $5x^2 - 3x = x(5x - 3)$
(b) $\frac{9x}{x^2+5} = \frac{9x}{x^2} + \frac{9x}{5}$
(c) $\frac{x^2+5}{9x} = \frac{x^2}{9x} + \frac{5}{9x}$
(d) $\frac{1/x}{x/3} = \frac{3}{x}$
(e) $5 + xy = yx - 3 + 8$

Problems

C.2. Simplify to remove fractions of fractions: (a) $\frac{1}{1/x}$, (b) $\frac{1/x}{x}$, (c) $\frac{x/y^2}{y/x^2}$.

C.3. Solve for y: (a) $x = y - 43$, (b) $x = 1/y$, (c) $5x = \frac{2y}{x}$.

C.4. Solve for r: $V = \frac{4}{3}\pi r^3$

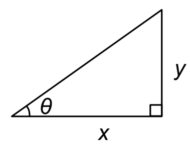
C.5. Solve for λ: $E = \frac{hc}{\lambda}$

C.6. Solve for x: $x^2 - 16 = 0$

D. Geometry

Questions

D.1. Consider a right triangle with base x, height y, and interior angle θ as shown in the following figure. Which of the following are *incorrect*? Choose all that are appropriate.

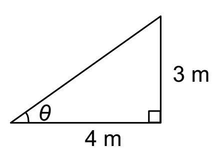


(a) $\sin\theta = \frac{x}{y}$
(b) $\tan\theta = \frac{y}{x}$
(c) $\cos\theta = \frac{x}{\sqrt{x^2+y^2}}$
(d) $\frac{1}{\cos\theta} = \frac{\sqrt{x^2+y^2}}{y}$
(e) $\frac{\sin\theta}{\cos\theta} = \frac{y}{x}$

Problems

D.2. Consider a brick that has side lengths a, b, and c. What is the length of a diagonal line that goes from one corner to the corner that's farthest away from it.

D.3. The right triangle shown below has sides of length 3 m and 4 m. (a) What is the triangle's perimeter? (b) What is the angle shown as θ in the figure?



Puzzles

D.4. Is the Pythagorean theorem true for a triangle that's not flat, but drawn on the surface of a sphere? (Hint: try to come up some simple triangle on a sphere where it's clearly wrong.)

E. Answers to odd-numbered problems

Chapter 1

1.1 a. **1.3** e. **1.5** d. **1.7** (a) extramission; (b) infinite speed; (c) particles. **1.9** There is no evidence of rays emitted by eyes; Light is known to travel at a finite speed and stars are very far away, so the extramission theory cannot explain how we can see stars; Light is known to enter people's eyes, of which one piece of evidence is that our eyes feel pain when looking at a very bright light such as the sun; Our eyes are not depleted of any substance when we look far out into space. **1.11** Atomic emission shows distinct colors; photoelectric effect (ultraviolet photons eject electrons from metal surfaces); some chemical reactions can only be started by ultraviolet light; sunburns only happen in ultraviolet light; blackbody radiation can only be explained when assuming particle nature of light.

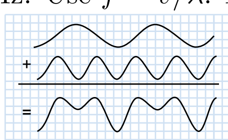
Chapter 2

2.1 b. **2.3** e. **2.5** a,c,e. **2.7** b. **2.9** See figure 2.3. **2.11** (a) String, drum head, all electromagnetic (light, radio, UV, IR, etc.), gravitational, seismic S-waves; (b) Slinky (when pushing on end), sound, seismic P-wave. **2.13** (a) Any value between 500 and 570 nm, of which 540 is close to the middle of the range; (b) smaller; (c) much larger; (d) much larger; (e) much larger; (f) much smaller; (g) much smaller; (h) similar. **2.15** (a) 406 miles per hour. Use $v = d/t$, where $d = 6500$ miles and $t = 16$ hours. This is similar to the speed of a commercial airliner. (b) 53%. Compute with (460mph)/(760mph)$\cdot$100%. **2.17** (a) 565 times faster. Divide $192 \cdot 10^3$ m/s by 340 m/s. This is very fast. (b) No, it's not relevant because there's no sound in space. (c) 0.064%. Divide $192 \cdot 10^3$ m/s by $3 \cdot 10^8$ m/s and multiply by 100%. Despite being very fast, it's still vastly slower than the speed of light. **2.19** (a) 513 miles/hour. Use $v = d/t$ with $d = 5900$ miles and $t = 11.5$ hours. (b) 76%. Divide 513 mph by 670 mph and multiply by 100%. Commercial aircraft speeds are substantially limited by the speed of sound. (c) $7.7 \cdot 10^{-5}$ %. Divide 513 mph by $6.7 \cdot 10^8$ mph and multiply by 100%. Airplanes are vastly slower than light. **2.21** (a) $2.26 \cdot 10^8$ m/s. Use $v = c/n$, where $c = 3 \cdot 10^8$ m/s and $n = 1.33$. (b) $2 \cdot 10^8$ m/s. Use $v = c/n$, where $c = 3 \cdot 10^8$ m/s and $n = 1.33$. (c) $1.24 \cdot 10^8$ m/s. Use $v = c/n$, where $c = 3 \cdot 10^8$ m/s and $n = 2.42$. **2.23** (a) 0.012 s. Rearrange $v = d/t$ to $t = d/v$. The sound travels to the moth and back, which is $d = 4$ m, and $v = 340$ m/s. (b) 0.0068 m, which is 0.68 cm. Rearrange $v = \lambda f$ to $\lambda = v/f$ with $v = 340$ m/s and $f = 50 \cdot 10^3$ Hz. (c) Similar to the size of a typical moth body. **2.25** For all parts, rearrange $v = \lambda f$ to $\lambda = v/f$ and use $v = 3 \cdot 10^8$ m/s and the given frequency. (a) Radio, 3.16 m, from $\lambda = (3 \cdot 10^8 \text{ m/s})/(94.9 \cdot 10^6 \text{ Hz})$. (b) Microwave, 0.12 m or 12 cm, from $\lambda = (3 \cdot 10^8 \text{ m/s})/(2450 \cdot 10^6 \text{ Hz})$. (c) Microwave, 0.12 m or 12 cm, from $\lambda = (3 \cdot 10^8 \text{ m/s})/(2.45 \cdot 10^9 \text{ Hz})$. It's the same as a microwave oven. (d) Infrared, $9.40 \cdot 10^{-7}$ m or 940 nm, from $\lambda = (3 \cdot 10^8 \text{ m/s})/(3.19 \cdot 10^{14} \text{ Hz})$. **2.27** (a) 88 m. Rearrange $v = \lambda f$ to $\lambda = v/f$ and use $v = 1500$ m/s and $f = 17$ Hz. (b) 1.0 hours. Rearrange $v = d/t$ to $t = d/v$ and use $d = 5500 \cdot 10^3$ m and $v = 1500$ m/s to get $t = 3667$ s. Divide by 60 to get minutes and another 60 to get hours. **2.29** $3.0 \cdot 10^9$ Hz. Rearrange $v = \lambda f$ to $f = v/\lambda$ and use $v = 3 \cdot 10^8$ m/s and $\lambda = 10 \cdot 10^{-2}$ m. **2.31** 0.24 s. Rearrange $v = d/t$ to $t = d/v$ and use $v = 3 \cdot 10^8$ m/s and $d = 72000 \cdot 10^3$ m; this distance is doubled because the signal has to go to the satellite and back. (b) 5.9 s. Use the same $t = d/v$ equation but now v is the speed of sound, 340 m/s, and $d = 2 \cdot 10^3$ m. **2.33** This is identical to the car analogy that was introduced in the chapter but now with actual cars, so the same equation applies. Rearrange $v = \lambda f$ to $\lambda = v/f$ and use $v = 55$ mph **2.35**

(a) Transverse, horizontal or in-plane. (b) Longitudinal, no polarization. (c) Transverse, vertical or out-of-plane. (d) None, water waves combine transverse (vertically polarized) and longitudinal motions, meaning a combination of pictures II and III. (e) S-wave for I, P-wave for II, and S-wave for III.

Chapter 3

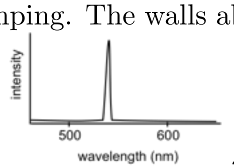
3.1 c. **3.3** b, d. **3.5** e. **3.7** c, e. **3.9** (a) See Figure 3.3. (b) and (c) See figure 3.6. **3.11** (a) See Figure 3.14. (b) Thicker. **3.13** (a) At any of the nodes, which are the bridge ends and the center of the bridge. (b) At either antinode, which are 1/4 and 3/4 of the way along the bridge. **3.15** (a) See 3.19. (b) Not go in the room. These low notes have waves that are much larger than the doorway, so they don't go through the doorway appreciably. (c) Go in the room and fill it. These medium notes have wavelengths that are similar to the door width, so they diffract strongly. (d) Go in the room and travel straight across it. The high notes have much shorter wavelengths than the door width, so they go through the door but do not diffract strongly. **3.17** (a) 130 cm, which is 1.30 m. This is twice the length of the guitar string. (b) 143 m/s. Use $v = \lambda f$, where $\lambda = 1.30$ m and $f = 110$ Hz. (c) 220 Hz. Use $f = v/\lambda$, where v is unchanged and λ is half of its prior value. (d) 58 cm. Use $\lambda = v/f$, where v is unchanged and $f = 123$ Hz. Then divide by 2 because the string length is half of the wavelength from the equation $\lambda = 2L/n$. **3.19** (a) 3.0 m. The fundamental mode wavelength is twice as long as the cavity, from $\lambda = 2L/n$ with $n = 1$. (b) 113 Hz. Use $f = v/\lambda$. Plug in $v = 340$ m/s and $\lambda = 3.0$ m.

3.21 

3.23 (1) It would shine light rays in a different direction than the incoming light waves, so their destructive interference would only be at a very few points at best. Those points could conceivably be at some object's surface but that doesn't help. It needs to be at both of your eyes (and everyone else's eyes) all at once for an object to appear dark. (2) It has no way to detect the incoming light waves. (3) Even if it could detect the incoming light waves, it couldn't measure the incoming light wavelength, phase, and polarization accurately enough.

Chapter 4

4.1 e. **4.3** (a) Sound waves in air drive oscillations in wine glass vibrations. (b) Strong coupling (increased primarily by better positioning of speaker and glass). (c) Weak damping (sound waves cannot break cheap wine glasses because they have too much damping). **4.5** It does not change. String waves are 1-dimensional so they don't spread out, so the energy density stays the same. **4.7** Damping. The walls absorb sound over a broad frequency range, which only occurs with damping.

4.9 

4.11 (a) Energy. (b) $4.3 \cdot 10^{10}$ J, using 1 kW = 1000 J, 1 hr = 3600 s, and 1 W s = 1 J. (c) 1400 W, by dividing the annual energy by $3.15 \cdot 10^7$ s per year. **4.13** 100 times weaker. The sun's power spreads out as it moves away from the sun. The area that this power goes through increases as the square of the distance from the sun (e.g. the surface area of a sphere is $4\pi r^2$), so increasing the distance by a factor of 10 increases the area by a factor of 10^2. **4.15** (a) 0.30 W/m^2. Divide the power by the sphere surface area, $\rho_{3D} = \frac{15\text{ W}}{4\pi(2\text{ m})^2} = 0.30$ W/m^2. (b) 159 W/m^2. Divide the power by the illuminated area, $\rho = \frac{2\cdot 10^{-3}\text{ W}}{\pi(2\cdot 10^{-3}\text{ m})^2} = 159$ W/m^2. (c) The laser pointer. **4.17** (a) Green or blue-green. The spectrum peak is at slightly less than 500 nm. (b) Radiation is similar at all visible wavelengths, so sunlight looks white. (c) About: 0% at 300 nm, 70% at 500 nm, 0% at 1400 nm, and 100% at 1600 nm. The transmission coefficient is the ratio of the light at the Earth's surface to the light above the atmosphere. **4.19** (a) Blue. The green, blue, and violet colors are reflected strongly, while the red, orange, and yellows are not, producing an overall blue color. (b) Red, orange, and yellow. This absorption turns out to arise from methane in Uranus's atmosphere. (c) 50%. Draw vertical lines at 380 and 740 nm to delineate the visible region, then a horizontal line at the height where there is as much area (corresponding to reflected visible light energy) in the visible portion above the line as below it; this height is at about 50%.

Chapter 5

5.1 d. **5.3** b. **5.5** (a) 40,706 Hz. Use eq. 5.1 or 5.2 using $v_o = 6.0$ m/s and $c = 340$ m/s. (b) 41,412 Hz. The Doppler effect gets doubled due to the echo. **5.7** (a) Red. (b) Emits at $f_s = 4.572 \cdot 10^{14}$ Hz and observed at $f_o = 4.540 \cdot 10^{14}$ Hz. Convert from wavelength to frequency with $f = \frac{c}{\lambda}$, where $c = 3 \cdot 10^8$ m/s. (c) $2.1 \cdot 10^6$ m/s. Use eq. 5.2 and solve for Δv to get $\Delta v = c\frac{\Delta f}{f_s}$. Here, $\Delta f = 4.572 \cdot 10^{14}$ Hz $- 4.540 \cdot 10^{14}$ Hz $= 0.032 \cdot 10^{14}$ Hz. Note the significant figures. Both frequencies were computed to four significant figures but the numbers were close enough to each other that only the last two of them were left after the subtraction. As a result, the answer is most correctly given with just two significant figures. This problem can also be solved with eq. 5.3. **5.9** (a) No sound. The plane is supersonic and she is ahead of the shock wave. (b) 54 Hz. Use eq. 5.3 with $f_s = 120$ Hz, $c = 340$ m/s and $v_s = 415$ m/s. **5.11** 275 Hz. The 28,000 km/s receding speed is $2.8 \cdot 10^7$ m/s, which is 9.33% the speed of light. This is large enough to use the relativistic Doppler shift equation, eq. 5.7. Here, $\beta = -0.0933$ and $f_s = 250$ Hz. **5.13** (a) 415 Hz. Rearrange eq. 5.3 to $\frac{f_s}{f_o} = 1 \mp \frac{v_s}{c}$. Defining $f_a = 520$ Hz and $f_r = 345$ Hz as approaching and receding speeds, their sum is $\frac{f_s}{f_a} + \frac{f_s}{f_r} = 2$, from which $f_s = 415$ Hz. (b) 68.6 m/s. Rearrange eq. 5.3 some more to get $v_s = c(1 - \frac{f_s}{f_a}) = 68.6$ m/s. **5.15** (a) 220 Hz. They are not moving relative to each other. (b) 220 Hz. Again, they are not moving relative to each other. (c) 2.01 m. This is a moving source problem (Figure 5.4 and eq. 5.3), where Alex is moving in the medium in the direction that is away from Sal at $v_s = 103$ m/s and $c = 340$ m/s. An observer who is stationary in the medium would hear Alex at 169 Hz, which is $\lambda = 2.01$ m; Sal is moving but measures the same wavelength. (d) 1.08 m. This is the same as part c but with the opposite sign. (e) Alex would not hear Sal at all because the wind speed is faster than the speed of sound, so no waves would propagate to Alex. **5.17** (a) 1.25 Hz. Use $f = \frac{1}{T}$. (b) 0.25 Hz. Subtract the camera frequency from the rope frequency. (c) 2.25 Hz. Add the camera and rope frequencies. (d) $f_o = f_s - f_c$. (e) The camera is rotating faster than the string, making the video of the string appear to rotate backward.

Chapter 6

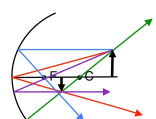
6.1 c. **6.3** a,d. **6.5** c,d. **6.7** (a) No. The harmonics are integer multiples of the fundamental frequency, not integer octaves. For example, the 3rd harmonic is between 1 and 2 octaves above the fundamental. (b) The 4th harmonic. **6.9** (a) Inside. These are capillary waves, in which long waves are slow and short waves are fast. (b) Outside. These are gravity waves, in which short waves are slow and long waves are fast. **6.11** (a) All the odd harmonics: 1, 3, 5, 7, etc. This is because all even harmonics have a node at the center, whereas all odd harmonics have an antinode at the center. (b) 3:1, 5:1, 7:1, etc. The frequencies increase linearly for standing waves on a string, so the n'th harmonic has frequency n times faster than the fundamental, which is a ratio of n:1. In this case, only the odd harmonics are amplified, so only those ratios are listed. (c) Reasonably consonant. The numbers in the ratios are reasonably small. **6.13** (a) 2.79 m/s. Use the deep water wave speed, $v = \sqrt{\frac{g\lambda}{2\pi}}$ with $g = 9.8$ m/s^2 and $\lambda = 5$ m. (b) 12.49 m/s, using the same equation. Big ships can go very fast. (c) 0.39 m/s, again with same equation. Length strongly affects duck swimming. Longer water birds (e.g. mergansers, cormorants, and geese) generally swim faster than short ducks (e.g. coots). When short ducks need to swim fast, they usually skim over the water, rather than swimming through the water (watch ducklings sometime). (d) 0.99 m/s. Use the shallow water wave speed, $v = \sqrt{gd}$. Boats can't go fast in shallow water. **6.15** (a) 12 s. From the definition of velocity, use $t = \frac{d}{v}$, where $d = 70$ km and $v = 6$ km/s. (b) 6 km. This is from $\lambda = \frac{v}{f}$, where $v = 6$ km/s and $f = 1$ Hz. (c) 32 m/s (64 mph). The tsunami wavelength is much longer than the water depth, so use the shallow water wave speed equation, $v = \sqrt{gd}$, where $g = 9.8$ m/s^2 and $d = 100$ m. (d) 2200 s, which is 36 minutes. Use $t = \frac{d}{v}$, where $d = 70$ km and $v = 32$ m/s. **6.17** (a) 0.386 m. The pipe has a node at each end, so $\lambda = 2L$ for the fundamental mode. Convert to frequency with $v_{sound} = \lambda f$ and rearrange to get $L = \frac{v_{sound}}{2f}$. Here, $f = 440$ Hz. (b) 0.317 m. The speed of sound equation is $v_{sound} = \sqrt{\frac{\gamma k_B T}{m}}$ where $\gamma = 1.4$, $k_B = 1.38 \cdot 10^{-23}$ m^{2}kg s^{-2}K^{-1}, $m = 4.8 \cdot 10^{-26}$ kg, and $T = 193$ K. From these, the speed of sound is 279 m/s. Plug this into the equation for the pipe length from part (a), $L = \frac{v_{sound}}{2f}$, using the same 440 Hz frequency as before. **6.19** (a) 8360 m/s. Use the speed of sound equation, $v = \sqrt{\frac{\gamma k_B T}{m_{air}}}$, plugging in $\gamma = \frac{5}{3}$, $k_B = 1.38 \cdot 10^{-23}$ m^{2}kg s^{-2}K^{-1}, $T = 5778$ K, and $m_{air} = 1.90 \cdot 10^{-27}$ kg. Ignore the pressure. (b) About 25 times faster. Divide 8360 m/s by 340 m/s. **6.21** (a) Short waves are attenuated more than long waves. Also, long waves tend to diffract more around a person's head. (b) 0.06 waves. Compute wavelength with $\lambda = \frac{v}{f} = 3.4$ m/wave, using $v = 340$ m/s and $f = 100$ Hz. Dividing 0.2 m by 3.1 m/wave gives 0.06 waves. (c) 2.9 waves. Use the same equation but with $f = 5000$ Hz. (d) When the phase difference is only part of a wave, it's easy to tell which ear is receiving it first. However, when the difference is multiple waves, it's hard to match up waves heard with one ear with those heard by the other ear. Also, faster waves take faster signal processing. **6.23** 15,800 times more energy. The magnitude difference here is 2.8 and a magnitude difference of 1 corresponds to $\sqrt{1000}$ times more energy, so a magnitude difference of 2.8 is $(\sqrt{1000})^{2.8} = 15,800$ times more energy. **6.25** $f = \frac{nv}{2L}$, exactly as for as open-ended pipe. The boundary conditions are different from an open ended pipe, but the fundamental mode still represents a half wave, and likewise for higher harmonics. Thus, the natural frequencies are the same.

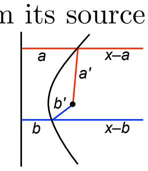
Chapter 7

7.1 b,c,e. **7.3** No. The sun is not a point light source, so your shadow spreads out and turns fuzzier at increasing distances. The Moon is so far away that your shadow is completely indistinguishable by that point. **7.5** Always in syzygy. They have to be lined up for an eclipse to happen. **7.7** The astronaut would view a new earth, meaning that the Earth is completely dark. Also, the Earth would block the astronaut's view of the Sun, essentially creating a solar eclipse. **7.9** (a) 49.6°. Rearrange the equation $\tan\theta = \frac{h}{s_{oblique}}$ to $\theta = \arctan\frac{h}{s_{oblique}} = \arctan\frac{1.00\text{ m}}{0.85\text{ m}} = 49.6°$. (b) 8.7 m. Rearrange the equation $\tan\theta = \frac{h}{s_{oblique}}$ to $h = s_{oblique}\tan\theta = (7.4\text{ m})\tan 49.6° = 8.7$ m. **7.11** (a) A circle. (b) An ellipse. (c) The oblique projection. It has the same width as the orthographic projection, but is longer. **7.13** (a) Make the light source smaller than the ball. (b) Make the light source larger than the ball. (c) The penumbra radius is always larger than the ball's radius. (d) Impossible; the penumbra cannot be smaller than the ball. **7.15** (a) 720 ft. Rearrange the equation $\frac{h_i}{d_i} = \frac{h_o}{d_o}$ to $d_o = \frac{h_o d_i}{h_i} = \frac{(3\text{ ft})(5\text{ ft})}{0.25/12\text{ ft}} = 720$ ft. (b) 48 feet. Rearrange the equation $\frac{h_i}{d_i} = \frac{h_o}{d_o}$

to $h_o = \frac{d_o h_i}{d_i} = \frac{(720 \text{ ft})(4/12 \text{ ft})}{5 \text{ ft}} = 48$ ft. **7.17** It will make the image slightly blurrier than normal because the light has more ways to get to any individual point on the film. Also, each point source of light, such as a star, will appear as a tiny square.

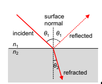
Chapter 8

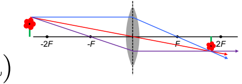
8.1 e. **8.3** b. **8.5** (a) Wall, paper, rock, table top, etc. (b) Mirror, water surface, glass surface, etc. **8.7** (a) Concave. (b) Convex; (c) Flat. (d) Concave. (e) Flat, concave, and convex. (f) Concave. (g) Concave and convex. **8.9** (a) 270 m. (b) On the ground, 270 m south of the base of the building. (c) Real image. (d) Closer to the building. To see this, draw a picture and notice that as the sun moves higher in the sky, the angle of incidence for each ray that hits the mirror increases; this means that the angle of reflection increases as well, causing the rays to hit the ground closer to the building. **8.11** (a) 80 cm. Her eyes are 160 cm above the floor; drawing a picture shows that the light that goes from her feet to her eyes must reflect off the mirror at a position that is half the height between her feet and eyes, which is 80 cm above the floor (formally, this result arises from the law of reflection, which asserts equal incident and reflected angles, and then use of similar triangles shows that the distances are equal below and above the reflection point). (b) 165 cm. This is halfway between her eyes the top of her head. (c) 85 cm. Note that this is exactly half of the woman's height. (d) No. We didn't use the distance to the mirror to find the answer, which implies that it doesn't affect the answer. **8.13** (a) 

(b) 15 cm. From the mirror equation, $\frac{1}{d_i} = \frac{1}{f} - \frac{1}{d_o}$. (c) $-\frac{1}{2}$. Use the magnification equation, $M = -\frac{d_i}{d_o}$. (d) Yes. **8.15** (a) 10.79 ns. The light travels distance 1 m to the wall and then $\sqrt{5}$ m to you, using the Pythagorean theorem, which is 3.23 m. Divide by the speed of light to get the time. (b) 9.43 ns. The light travels $2\sqrt{2}$ m which is 2.83 m; then divide by the speed of light. (c) 10.79 ns. This is the same as part a. (d) No. See Figure 8.23. (e) Point B. By symmetry, reflection at point B obeys the law of reflection, whereas reflection elsewhere does not. **8.17** The following diagram shows two parallel rays that start at distance x from a plane and reflect off a parabolic mirror and go to the focus. From the geometric definition of a parabola, length $a = a'$ and $b = b'$, so each ray has length x from its source to the focus. This is true for all parallel rays, so they all get redirected to the focus. 

. **8.19** For the upper mirror, $f = 10$ cm and $d_o = 10 \text{ cm} - 1 \text{ cm} = 9$ cm. From 8.6, $d_i = -90$ cm, so the image is 90 cm above the top of the upper mirror. From eq. 8.7, its magnification is $M = 10$. For the lower mirror, $f = 10$ cm, the object distance is $d_o = 10 \text{ cm} + 90 \text{ cm} = 100$ cm, where the 10 cm arose from the change of mirror location and the sign on 90 cm changed due to the different mirror orientation. From the equations, $d_i = 11.1$ cm and $M = 0.111$. The image is real and its position is 11.1 cm above the lower mirror, making it float in space just above the back of the upper mirror. Its total magnification is $M = 10 \times 0.111 = 1.1$, so it's just slightly larger than the original object. **8.21** (a) It is fuzzy because the sun isn't a point source but covers some area in the sky, so rays from different parts of the sun have shadow edges at different locations (see Chapter 7). (b) Smaller than the actual sun. Convex mirrors provide a wide field of view, so everything in the view has to appear smaller. This can also be shown using a diagram which shows that the sun's (virtual) image is at the mirror focus; it appears the same size as the actual sun when seen from the mirror surface, but appears smaller when seen from farther away. (c) Sharper edge than a direct shadow from the sun because the image of the sun is smaller. **8.23** (a) 2 images; one from the left mirror (L) and one from the right mirror (R). (b) 2 images; each hits both mirrors, but in the opposite order, so they are LR and RL. (c) 1 image; the light reflects three times as RLR or LRL, but both options put the image in the same location. (d) Infinite. Every image can reflect off another mirror to create yet more images. **8.25** If the water were perfectly smooth, the sun's reflection would appear as a dot, at the location that obeys the law of reflection between the sun's position and the angle to our eyes. Here, the water has small ripples which make it slightly not flat. A slight tilt of the water surface redirects light by twice that amount, by the law of reflection, causing the sun's reflection to spread out. This spread has an equal angle in all directions, because experience shows that it's independent of the wave direction, so one might expect it to appear as a circle. However, there is a lot more water surface in a given field of view when considering the water in the direction to the sun, rather than perpendicular to this direction, so the water on this axis has more chances to get the necessary tilt angles. As a result, the water in the direction to the sun appears brightest.

Chapter 9

9.1 c. **9.3** (a) Yes. (b) At the critical angle, which is about 48.8°. (c) No. (d) Yes. (e) Yes, but only the jellyfish has a strong reflection; it's angle is shallow enough for total internal reflection, whereas the fish's reflection on the surface is minimal. **9.5** Hot air has a lower refractive index than cold air. Patches of air with these different refractive indices causes light rays to shift around by small amounts, causing objects to appear to move, or to shimmer. **9.7** (a) $n_1 \sin\theta_1 = n_2 \sin\theta_2$. (b) 

. **9.9** (a) 22.2°. Rearrange Snell's law to solve for the angle of refraction, $\theta_2 = \arcsin(\frac{n_1}{n_2}\sin\theta_1)$, and plug in $n_1 = 1.00$, $n_2 = 1.52$, and $\theta_1 = 35°$. (b) 25.6°. Use the same equation, but now $n_1 = 1.52$, $n_2 = 1.33$, and $\theta_1 = 22.2°$. (c) 25.5°. Again, use the same equation, now with $n_1 = 1.00$, $n_2 = 1.33$, and $\theta_1 = 35°$. Note that the answers for the last two parts are the same. **9.11** (a) Yes. If you look in with a grazing ray going upward, your view will refract to the critical angle, which is 48.8°from the normal for the front face. This ray has an angle of 41.2°from the normal for the top of the water. That's less than the critical angle, so the view escapes through the top. (b) 61.2°. A grazing ray from the top enters the water with the critical angle of 48.8°, which is an incident angle 41.2°relative to the front face. Use Snell's law with $n_1 = 1.33$, $n_2 = 1.00$, and $\theta_1 = 41.2°$. **9.13** (a) 1.25 m/s. The depth is much more than the wavelength, so use the deep water wave speed equation, $v_{deep} \approx \sqrt{(1.56\text{ m/s}^2)\lambda}$ with $\lambda = 1$ m. (b) 1.25 Hz. Use $f = \frac{v}{\lambda} = (1.25\text{ m/s})/(1\text{ m})$. (c) 0.49 m/s. The water is much shallower than the wavelength, so use the shallow water equation, $v_{shallow} = gd = (9.8\text{ m/s})(0.05\text{ m})$. (d) 2.55. Divide 1.25 m/s by 0.49 m/s. (e) 0.39 m. Use $\lambda = \frac{v}{f} = (0.49\text{ m/s})/(1.25\text{ Hz})$. (f) 19.9°. Rearrange Snell's law, $n_1 \sin\theta_1 = n_2 \sin\theta_2$ to $\theta_2 = \arcsin(\frac{n_1}{n_2}\sin\theta_1) = \arcsin(\frac{1}{2.55}\sin 60°)$. **9.15** (a) 

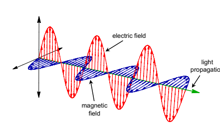
. (b) $x_i = -2.5$ cm and $h_i = 2$ cm. Use the thin lens equation, $\frac{1}{x_i} = \frac{1}{f} + \frac{1}{x_o}$, with $f = -5$ cm and $x_o = -5$ cm to get the location. Use the lens magnification equation, $M = \frac{x_i}{x_o}$ to get the magnification. The result is 0.5, which is multiplied by the 4 cm object height to get the image height. (c) Yes. **9.17** (a) 52 cm behind the lens. This can be solved with the thin lens equation, but it's easier to recognize that the object is at the $-2F$ point, so the image is at the $2F$ point. (b) Real. (c) 3.486 ns. Use $t = \frac{d}{v}$. Path A has two segments in air of 51.5 cm, on each side of the lens, and one segment in glass of 1 cm. Using $c = 2.998 \cdot 10^8$ m/s, the time spent in each air segment is 1.718 ns. The time in glass uses $v = (2.998 \cdot 10^8 \text{ m/s})/1.5 = 1.999 \cdot 10^8$ m/s and $d = 1$ cm to give $t = 0.0500$ ns. Add the segments to get 3.486 ns. (d) 3.485 ns. Path B is essentially fully in the air, and each segment has length $\sqrt{(52 \text{ cm})^2 + (5 \text{ cm})^2} = 52.240$ cm. The total length is 104.48 cm, and divide by the speed to light to get 3.485 ns. (e) They are the same, to within round-off error. Also, they should be the same due to Fermat's principle of least time. **9.19** 16.0 cm. The apparent depth equation, $\frac{d_1}{d_2} = \frac{n_1}{n_2}$ applies equally well to looking from water to air, but now the refractive indices need to be reversed. Thus, $\frac{d_1}{d_2} = \frac{1.33}{1} = 1.33$, so the mayfly is 1.33 times higher than it appears. It appears at 12 cm, so it's really at 16.0 cm.

Chapter 10

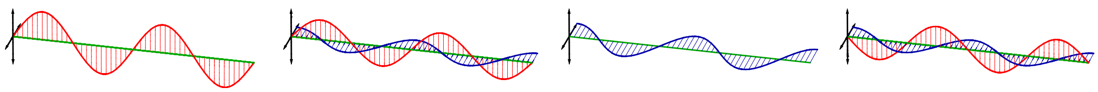
10.1 a. **10.3** d. **10.5** At night, people only see with their rod cells because these cells are generally more sensitive than cones. However, rod cells are insensitive to red light, so red things appear black at night. On the other hand, rods are sensitive to yellow light, so yellow fire engines show up well at night. **10.7** Any traffic signals with red in them, or, worse, red and green combined. Examples are traffic lights, stop signs, and red brake lights on a car. A single flashing light is particularly problematic because color-blind people can't tell if it's a flashing red or flashing yellow light. **10.9** (a) Red. (b) Red. (c) Black. (d) Red. **10.11** (a) Blue. (b) Black. (c) Green or black. **10.13** When the sun is overhead, there is relatively little air between us and it, so little light is blocked and the sun appears white. When the sun is close to the horizon, there is a lot of air between us and it, so much more cyan light is removed, leaving a red color. **10.15** Yes. It would work if the movie projector showed one image with red light the other with *actual* yellow light (e.g. 570 nm), as opposed to a mixture of red and green. Also, the 3D movie glasses would need relatively narrow band filters that transmitted only red for one eye and only yellow for the other eye. At this point, different images would be presented to the two eyes, so they would see the two images separately, without interference. The fact that both eyes use the same types of cones to see those images is unimportant.

Chapter 11

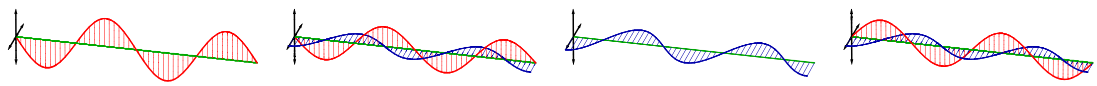
11.1 c. **11.3** e. **11.5** a. **11.7** a, b, c, d, e. **11.9** This is identical to Figure 11.7:



11.11 No. Looking directly at the sun is dangerous because it concentrates a great deal of energy on a small part of the eye's retina, which then gets burned. Blocking UV light reduces the energy some, but a lot of visible light energy remains, still burning the retina. **11.13** (a) Temperature, mass, height, number of objects, energy, etc. (b) Wind strength and direction, uphill steepness and direction, vehicle speed and direction, electric field at some location, etc. (c) temperature map, disease prevalence map, height of a string as a function of string position, height of water surface as function of position, etc. (d) water flow map, wind speed and direction map, hill steepness and direction map, electric field, magnetic field, etc. **11.15** Red. This is because even more of the bluer components would be scattered away than with our current atmosphere, leaving just the redder components. **11.17** (a) Shortwave, FM radio, microwave, visible, gamma ray. (b) Gamma ray, visible, microwave, FM radio, shortwave. (c) Shortwave, FM radio, microwave, visible, gamma ray. **11.19** (a) Vertical. They need to block the horizontally polarized light to reduce glare. (b) No further effect. After the first pair of sunglasses, all light is vertically polarized, and all of this is transmitted by the second pair of sunglasses. **11.21** (a) 50%. The first polarizer blocks half of the light, and all of the remaining light goes through the second one. (b) 0%. The first polarizer blocks half of the light, and the second blocks the remaining light. (c) 12.5%. The first polarizer blocks half of the light. For the second, use Malus's law with $\theta = 45°$ to give 50% transmission. The light emerges at 45° and then hits the third polarizer, which is rotated another 45°, so Malus's law again gives 50% transmission. Multiply all three 50% values to give a total transmission of 12.5%. **11.23** (a) The following images show the electric fields in red and magnetic fields in blue for an electromagnetic wave in a cavity, for 8 time points



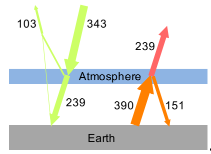
in a cycle.



(b) Out of phase. (c) In the magnetic field. (d) In the electric field. **11.25** No, this doesn't make sense (and also isn't true). If you look at a tiny spot of the sky during the daytime, the blue light rays that you see in that spot were scattered by air molecules that are in the column of air that extends from your eyes and through that spot. Standing in the bottom of a well doesn't change this, and doesn't block these blue light rays. Thus, the sky appears just the same when standing in the bottom of a well as when standing outside.

Chapter 12

12.1 d, e, a, c, b. **12.3** b,c. **12.5** (a) Black. (b) Black. **12.7** Highly reflective materials couple less strongly to radiation, so they absorb less sunlight during the day and emit less radiation at night. This reduces temperature fluctuations, so less heating is needed at night and less cooling during the day. **12.9** The person with the space blanket will stay warmer because it reflects her radiation back to her, whereas the person in the garbage bag will get colder because the bag will radiate his heat away from him. **12.11** A person's heat has to get out somehow if the person isn't going to overheat. This heat typically results in infrared emission. There are a few ways to mask this. One is to use a reflective sheet only on the side facing the enemy, so heat can escape in the other direction. Alternatively, a thermally conductive sheet will disperse the heat over a larger area, so it's not as hot and emits less radiation. Yet another approach is to scatter different warm objects around so that the enemy can't tell which one is the person. **12.13** (a) 1473 K. Add 273 to convert from °C to K. (b) 1.967 µm. Use Wien's displacement law. (c) Infrared. (d) Shorter, from T dependence of Wien's displacement law. **12.15** 33.2 mm^2. Solve the Stefan-Boltzmann law for A to get $A = \frac{P}{\sigma T^4}$ and substitute in $P = 100$ W and $T = 2700$ K, which gives $3.32 \cdot 10^{-5}$ m^2. Convert units using 10^6 mm^2 = 1 m^2. **12.17** (a) 5 W. Multiply 100 W of incident radiation by $\epsilon_{vis.} = 0.05$. (b) 299 W. Use the Stefan-Boltzmann law, with $T = 273$ K, and multiply the result by $\epsilon_{IR} = 0.95$. (c) Cools off. **12.19** 2.77 W. Use the Stefan-Boltzmann law with $A = 0.017$ m^2 and $T = 273$ K to get the emission of 5.35 W. Repeat but with $T = 303$ K to get the absorption of 8.12 W. Take the difference. **12.21** (a) $6.03 \cdot 10^{-8}$ K. Use the equation given, $T = \frac{1.2 \cdot 10^{23}}{M}$, with $M = M_\odot = 1.99 \cdot 10^{30}$ kg. (b) $4.8 \cdot 10^4$ m, which is 48 km. Use Wien's displacement law. (c) 2945 m. Use the radius equation given, $R = 1.48 \cdot 10^{-27} M$ and the solar mass. (d) $2.05 \cdot 10^{-29}$ W. Use the Stefan-Boltzmann law with the temperature from above and surface area of $\pi R^2 = 2.73 \cdot 10^7$ m^2. **12.23** (a) Bluish-white from the color temperature scale in Figure 12.4. (b) $8.57 \cdot 10^6$ m. Rearrange the Stefan-Boltzmann law to $A = \frac{P}{\sigma T^4}$ and insert numbers to get $A = 9.23 \cdot 10^{14}$m^2. The surface area is $A = 4\pi R^2$ and solve for R. (c) $4.54 \cdot 10^8$ kg/m^3. The white dwarf density is $\frac{M}{V}$, where V is the volume and is equal to $\frac{4}{3}\pi R^3 = 2.64 \cdot 10^{21}$ m^3. (d) 454 kg. Multiply the star density by

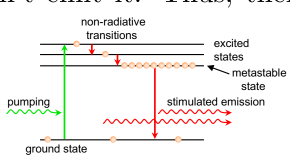
1 cm^3 = 10^{-6} m^3. **12.25** (a) $A_{visible} = \pi R_E^2$. (b) $A_{total} = 4\pi R_E^2$. (c) $\frac{A_{visible}}{A_{total}} = \frac{1}{4}$. (d) 342 W/m^2. **12.27** (a) 254 K. Rearrange the Stefan-Boltzmann law to $T = \sqrt[4]{P/A\sigma}$ and substitute in $P = 239$ W and $A = 1$ m^2. (b) -18°C. Subtract 273 to convert from K to °C. (c) 11.4 µm. Use Wien's displacement law with $T = 254$ K. **12.29** (a) 

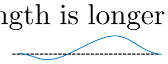
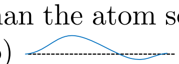
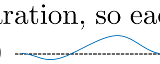
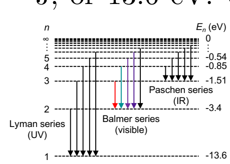
. (b) The numbers calculated here are close to Figure 12.7 values for "Incoming solar radiation", "Reflected solar radiation", "Outgoing longwave radiation", and "Surface radiation". Other numbers differ. (c) Figure 12.7 includes several heat transfers to the atmosphere: incoming solar radiation absorption by the atmosphere, thermals, and evapotranspiration, which we ignored. Because of this larger heat transfer to the atmosphere, they also calculated a larger "Downwelling radiation". **12.31** $6V\sigma T^4/c$. The inside surface of the teapot has area $4\pi r^2$. Substituting this into the Stefan-Boltzmann law, shows that the surface emits $4\pi r^2\sigma T^4$ power. The light that is emitted travels distance $2r$ at the speed of light, c, so it spends $\frac{2r}{c}$ time within the pot. Multiplying this time by the power gives the radiation energy within the pot, which is $8\pi r^3\sigma T^4/c$. To express this in terms of the volume, use $V = \frac{4}{3}\pi r^3$, leading to the result $6V\sigma T^4/c$. **12.33** (a) $P_2 = 2P_1$. The top layer emits P_1 upward, so it also emits P_1 downward. To stay at steady state, it must absorb $2P_1$ from below, meaning that the 2nd layer emits $2P_1$ upward. (b) $P_3 = 4P_1$. (c) $P_n = 2^{(n-1)}P_1$. (d) 16548 W. Use the Stefan-Boltzmann law with $T = 273 + 462 = 735$ K. (e) 5.4 layers. Rearrange the P_n equation to give $n - 1 = \log_2 \frac{P_n}{P_1}$ and substitute in numbers. The result is $n - 1 = 4.4$, so $n = 5.4$.

Chapter 13

13.1 d. **13.3** c. **13.5** b. **13.7** (a) $5.45 \cdot 10^{14}$ Hz. Use the frequency-wavelength relation, $c = \lambda f$. (b) $3.61 \cdot 10^{-19}$ J. Use the Planck-Einstein relation, $E = hf$. (c) Lower frequency. (d) Lower energy. **13.9** (a) The photoelectric effect is the emission of electrons from a material by light. (b) Einstein explained that electrons were ejected by individual photons, which was only possible if the photons had high enough energies, which supported the particle explanation for light. (c) Essentially all electronic light sensors are based on the photoelectric effect, including photomultiplier tubes, night-vision goggles, and digital cameras. **13.11** $3.00 \cdot 10^{10}$ W. The spacecraft speed needs to be $0.2 \times 3 \cdot 10^8$ m/s $= 6 \cdot 10^7$ m/s. At this speed, its momentum will be 120,000 kg m/s. Each photon has momentum $h/\lambda = 6.25 \cdot 10^{-29}$ kg m/s, but each one imparts twice this amount on the spacecraft because it bounces off and returns back toward Earth, so each photon imparts $1.25 \cdot 10^{-28}$ kg m/s momentum. Dividing the spacecraft momentum by the photon momentum gives $9.60 \cdot 10^{32}$ photons. Each photon has energy equal to $E = hc/\lambda = 1.87 \cdot 10^{-20}$ J, and multiplying by the number of photons gives total light energy of $1.80 \cdot 10^{13}$ J. Divide this by 10 minutes, which is 600 seconds, to get $3.00 \cdot 10^{10}$ W, which is the necessary laser power. **13.13** (a) $3.98 \cdot 10^{-19}$ J. Use $E = hc/\lambda$. (b) $3.44 \cdot 10^{21}$ photons. 1367 W is the same thing as 1367 J/s, meaning that 1367 J of energy is incident in 1 second. Divide total joules by joules per photon from before to get the number of photons, (1367 J)/($3.98 \cdot 10^{-19}$ J/photon) $= 3.44 \cdot 10^{21}$ photons. (c) $1.33 \cdot 10^{-27}$ kg m/s (these units are the same as J s/m). Use $p = h/\lambda$. (d) $4.56 \cdot 10^{-6}$ kg m/s. Multiply the number of photons by the momentum per photon. (e) $7.2 \cdot 10^{-6}$ kg m/s. Use $p = mv$ with m as the ant's mass and v as the ant's velocity. (f) The ant. (g) The sunlight. Silvering the sidewalk would cause the sunlight to exert twice as much momentum, from both the photon hitting and the photon rebounding. This would double the light momentum to $9.12 \cdot 10^{-6}$ kg m/s, which is more than the ant's momentum. **13.15** (a) $2.47 \cdot 10^{15}$ Hz. Rearrange the Planck-Einstein relation to $f = E/h$. (b) $5.0 \cdot 10^7$ Hz. Use the spectral width equation $\sigma_f = \frac{1}{4\pi\sigma_t}$, where σ_t is the lifetime. You can also use the energy-time uncertainty to give $\sigma_E = \frac{h}{4\pi\sigma_t} = 3.3 \cdot 10^{-26}$ J. Then, convert to frequency with the Planck-Einstein relation $f = E/h$. (c) $2 \cdot 10^{-6}$ %. Divide the spectral width by the frequency and then multiply by 100%. (d) **13.17** (a) Larger coherence length. The wavelength is in the microwave region, so $\lambda \sim 10$ cm, and the wave peaks are at least 8,611 km wide. (b) Yes, it is reasonable to say that each photon is 8,611 km across because the coherence length is a valid measure for photon size. **13.19** (a) $6L^2\sigma T^4$. Use the Stefan-Boltzmann equation, $P = A\sigma T^4$, where $A = 6L^2$. (b) $\frac{2L}{3c}$. Rearrange $v = \frac{d}{t}$ and replace v by c to get $t = \frac{d}{c}$. Substitute in $d = \frac{2L}{3}$. (c) $4L^3\sigma T^4$. Multiply the emission power with the photon lifetime. (d) $\frac{hcT}{b}$. Find the wavelength from Wien's displacement law, $\lambda = \frac{b}{T}$ and convert to energy with the Planck-Einstein relation, $E = \frac{hc}{\lambda} = \frac{hcT}{b}$. (e) $\frac{4\sigma T^3 b}{hc}$. Divide the energy in the box by the energy per photon to get $photons = \frac{4L^3\sigma T^4 b}{hcT} = \frac{4L^3\sigma T^3 b}{hc}$. Then divide by the box volume to get the density. (f) $8.93 \cdot 10^{22}$ photons/m^3. Plug in numbers. (g) 274 times more air molecules. Divide the air molecule density by the photon density. (h) 22.4 nm. Invert the photon density to get $1.12 \cdot 10^{-23}$ m^3/photon and take the cube root to get $2.24 \cdot 10^{-8}$ m. **13.21** It will have the energy of a blue photon. The Planck-Einstein equation, $E = hf$ refers to the frequency that is detected, not the frequency that the photon was emitted at. When someone bumps into normal objects, the bump is bigger when going faster because of the higher relative speed. For photons, the relative speed is always the speed of light, but the bump is still bigger when going faster, now due to the Doppler shift.

Chapter 14

14.1 d. **14.3** a. **14.5** No, it's not a valid concern. Fluorescent dyes only absorb ultraviolet light, and don't emit it. Thus, their clothes don't glow in the UV. **14.7** This is a duplicate of Figure 14.27: 

. (b) The metastable state. (c) Longer wavelength. **14.9** (a) 0.463 nm. The de Broglie wavelength is $\lambda = \frac{h}{p}$ and $p = mv$, so $\lambda = \frac{h}{mv}$. Plug in $h = 6.626 \cdot 10^{-34}$ J s, $m = 9.11 \cdot 10^{-31}$ kg, and $v = 1570 \cdot 10^3$ m/s. (b) The wavelength is about twice as large as the atom separation. (c) The wavelength is longer than the atom separation, so each electron is spread out over many atoms. **14.11** (a)  (b)  (c) . (d) The hydrogen atom is bouncing back and forth, as in a classical oscillator. **14.13** (a) 656.3 nm, by plugging numbers into the Rydberg formula. (b) Red. (c) 121.5 nm. (d) 91.16 nm. (e) Ultraviolet. (f) No. This is the smallest possible n_1 and the largest possible n_2, so the $\frac{1}{n_1^2} - \frac{1}{n_2^2}$ difference is as large as possible. (g) $2.179 \cdot 10^{-18}$ J, or 13.6 eV. Use the photon energy $E = \frac{hc}{\lambda}$. **14.15** (a) This is a duplicate of Figure 14.17: 

. The energy levels and n values are important for this problem but the transitions and energy values are not. (b) $n = 3$. From the Rydberg formula, if $n_1 = 1$ and $n_2 = 3$, then $\lambda = 103$ nm. (c) 656 nm, 121 nm, and 103 nm. Transitions from $n = 3$ are $3 \rightarrow 2$ and then $2 \rightarrow 1$, and $3 \rightarrow 1$, which give these wavelengths, from the Rydberg formula. **14.17** (a) $\frac{hn}{2Lm}$. The wavelengths for a particle in a box are $\lambda = \frac{2L}{n}$ and the momentum for a particle is $p = \frac{h}{\lambda}$. Also, momentum is $p = mv$. Combine these to get $v = \frac{h}{m\lambda} = \frac{hn}{2Lm}$. (b) $1.52 \cdot 10^5$ m/s. Plug numbers into the previous equation with $h = 6.626 \cdot 10^{-34}$ J s, $n = 1$, $L = 2.4 \cdot 10^{-9}$

m, and $m_e = 9.109 \cdot 10^{-31}$ kg. (c) $1.67 \cdot 10^6$ m/s. Plug in the same numbers but now $n = 11$. **14.19** (a) 4.69 µm, 2.34 µm, and 1.56 µm. Harmonic oscillator energies are $E_n = hf(n+\frac{1}{2})$, so $\Delta E = hf(n_1+\frac{1}{2}) - hf(n_2+\frac{1}{2}) = hf\Delta n$. The possible Δn values from $n = 3$ are 1, 2, and 3, for which the transition energies are 1, 2, and 3 times hf, and the transition frequencies are 1, 2, and 3 times f. Convert to wavelengths with $\lambda = \frac{c}{f}$. (b) 4.69 µm, from part (a). **14.21** (a) $6.6 \cdot 10^{-35}$ m/s. Rearrange the uncertainty principle, $\sigma_x\sigma_p \geq \frac{h}{4\pi}$, to $\sigma_p \geq \frac{h}{4\pi\sigma_x}$ and plug in numbers to get $\sigma_p \geq 2.63 \cdot 10^{-35}$ kg m/s. Divide by the mass to get the velocity. (b) Yes. The uncertainty principle is an inequality, so uncertainties can be arbitrarily larger than the Heisenberg limit. In practice, rats often move at several meters per second. (c) No. The uncertainty principle states that the rat's velocity is unknown to within $6.6 \cdot 10^{-35}$ m/s, so Zoe can't know that it's moving slower than that. (d) Yes. The uncertainty principle describes a lack of prior knowledge. However, any particular measurement is allowed to result in a precise value, including a value that's less than the velocity uncertainty (however, a velocity measurement that's this precise would cause the position uncertainty to be larger than the room size, thereby potentially catapulting the rat out of the room). **14.23** They needed to assemble a laser cavity by adding a reflecting mirror at one end and a partially reflecting mirror at the other. They also needed a strong pump light source that was tuned to the GFP absorption wavelength. Other considerations include: is GFP efficient at converting absorbed light into fluorescence or is too much absorbed light lost to non-radiative energy loss (this efficiency is called quantum yield); is the metastable state sufficiently long-lived to achieve population inversion; are the cells sufficiently transparent in the emitted light wavelengths that laser light can be amplified without excessive losses; and is GFP a sufficiently stable protein that it won't degrade excessively with repeated optical cycling.

Chapter 15

15.1 e. **15.3** c. **15.5** a, c, d, e. **15.7** 196.4 W. Use the gravitational wave power equation, $P = \frac{32G^4m_1^2m_2^2(m_1+m_2)}{5c^5r^5}$, plugging in $G = 6.674 \cdot 10^{-11}$ m^{3}kg^{-1}s^{-2}, $c = 2.998 \cdot 10^8$ m/s, $m_{Earth} = 5.792 \cdot 10^{24}$ kg, $m_{Sun} = 1.9891 \cdot 10^{31}$ kg, and $r = 1.496 \cdot 10^{11}$ m. **15.9** (a) $5.9316 \cdot 10^{-3}$ m s^{-2}. This is the same as the last problem, but use the sun's mass, $1.3275 \cdot 10^{20}$ kg, and the Earth-sun distance, $r = 1.496 \cdot 10^{11}$ m. (b) $5.9321 \cdot 10^{-3}$ m s^{-2}. Same approach but subtract the Earth's radius. (c) $5.9311 \cdot 10^{-3}$ m s^{-2}. Same approach but add the Earth's radius. (d) $5 \cdot 10^{-7}$ m s^{-2}. (e) The difference between the gravitational accelerations on the two sides of the Earth is about 4.4 times higher from the moon than from the sun. **15.11** (a) $a = \frac{GM}{(r+d/2)^2} + \frac{GM}{(r-d/2)^2}$. Add up the gravitational fields from the two stars, accounting for their different distances. (b) $a = 2\frac{GM}{r^2}$. Again, add up the two fields, this time using distance r to both stars. (c) $\Delta a = \frac{3GMd^2}{r^4}$. Approximate the first answer to $a = \frac{GM}{r^2}(1 - \frac{d}{r} + \frac{3d^2}{2r^2}) + \frac{GM}{r^2}(1 + \frac{d}{r} + \frac{3d^2}{2r^2})$, which simplifies to $a = \frac{GM}{r^2}(2 + \frac{3d^2}{r^2})$. Subtract the second answer to get $\Delta a = \frac{GM}{r^2} \cdot \frac{3d^2}{r^2}$ and simplify. (d) This near field falls off as r^{-4}, which is much faster than the r^{-1} dependence of gravitational waves. **15.13** (a) Yes, the gravitational field changes periodically, so it would create gravitational waves. (b) A mixture of longitudinal and transverse. It's fully transverse for an observer on the axis of rotation, who sees a circularly polarized wave. On the other hand, an observer in the plane of rotation, would see a longitudinal wave from the star moving closer and farther and a transverse wave from the star moving up and down. (c) See the previous answer. (d) 1 Hz. It's the same as the star rotation period because the gravitational field changes at this frequency. The frequency needed to be doubled for two stars because they are symmetric about their center of mass, but this single star isn't symmetric.

Appendix A

A.1 d. **A.3** b. **A.5** d. **A.7** $5 \cdot 10^{-2}$, $500 \cdot 10^{-3}$, 5, $0.5 \cdot 10^{2}$. **A.9** (a) $9.45 \cdot 10^{15}$. (b) $3.6 \cdot 10^{-7}$. **A.11** (a) 16 ± 5. (b) 6 ± 5. **A.13** (a) 16 ± 3.6. Add 11 and 5 to get 16. Compute the uncertainty as $\sqrt{3^2 + 2^2}$. (b) 6 ± 3.6. Subtract $11 - 5$ to get 6 and compute the uncertainty the same way as before.

Appendix B

B.1 (a) 6437.4 km. Work: ? km $= \frac{4000\ \cancel{\text{miles}}}{1} \cdot \frac{5280\ \cancel{\text{ft}}}{1\ \cancel{\text{mile}}} \cdot \frac{12\ \cancel{\text{inch}}}{1\ \cancel{\text{ft}}} \cdot \frac{2.54\ \cancel{\text{cm}}}{1\ \cancel{\text{in}}} \cdot \frac{1\ \cancel{\text{m}}}{100\ \cancel{\text{cm}}} \cdot \frac{1\ \text{km}}{1000\ \cancel{\text{m}}} = 6437.4$ km. (b) 17,000 nm. Work: ? nm $= \frac{17\ \cancel{\mu\text{m}}}{1} \cdot \frac{1\ \cancel{\text{m}}}{10^6\ \cancel{\mu\text{m}}} \cdot \frac{10^9\ \text{nm}}{1\ \cancel{\text{m}}} = 17,000$ nm. (c) $8.4 \cdot 10^{12}$ cycles/day. Work: ? cycles/day $= \frac{97\ \cancel{\text{MHz}}}{1} \cdot \frac{10^6\ \cancel{\text{s}^{-1}}}{1\ \cancel{\text{MHz}}} \cdot \frac{60\ \cancel{\text{s}}}{1\ \cancel{\text{min}}} \cdot \frac{60\ \cancel{\text{min}}}{1\ \cancel{\text{hr}}} \cdot \frac{24\ \cancel{\text{hr}}}{1\ \text{day}} = 8.4 \cdot 10^{12}\ \text{day}^{-1}$. **B.3** (a) J. Work: $E = hf = \text{J}\,\text{s}\,\text{Hz} = \text{J}\,\text{s}\,\text{s}^{-1} = \text{J}$. (b) m. Work: $f = (\frac{1}{d_o} + \frac{1}{d_i})^{-1} = (\text{m}^{-1} + \text{m}^{-1})^{-1} = (\text{m}^{-1})^{-1} = \text{m}$. (c) m. Work: $\lambda = \frac{g}{2\pi f^2} = \frac{\text{m}\,\text{s}^{-2}}{\text{s}^{-2}} = \text{m}$. **B.5** $7.3 \cdot 10^{20}$ kg. Use the same unit conversion method: ? kg $= \frac{1\ \cancel{\text{ocean}}}{1} \cdot \frac{7.1 \cdot 10^{17}\ \cancel{\text{m}^3}}{1\ \cancel{\text{ocean}}} \cdot \frac{1029\ \text{kg}}{1\ \cancel{\text{m}^3}} = 7.3 \cdot 10^{20}$ kg. **B.7** $1/x$. **B.9** xz/y.

Appendix C

C.1 b, d. **C.3** (a) $y = x + 43$. (b) $y = \frac{1}{x}$. (c) $y = \frac{5x^2}{2}$. **C.5** $\lambda = \frac{hc}{E}$.

Appendix D

D.1 a, d. **D.3** (a) 12 m. Use the Pythagorean theorem to find that the hypotenuse is $\sqrt{3^2 + 4^2} = 5$, meaning 5 m, and then add up the sides to get 12 m. (b) 36.9°. Use any inverse trig function with the appropriate pair of sides. Using the two legs, for example, $\theta = \arctan \frac{3\ \text{m}}{4\ \text{m}} = 36.9°$.