CONCEPTUAL QUESTIONS

1. REASONING AND SOLUTION  A monochromatic light source emits photons of a single frequency. According to Equation 29.2, the energy, \( E \), of a single photon is related to its frequency, \( f \), by the relation \( E = hf \), where \( h \) is Planck's constant.

The photons emitted by a source of light do not all have the same energy. Since the photons do not all have the same energy, then, from Equation 29.2, we can conclude that the photons do not all have the same frequency. Therefore, the source is not monochromatic.

2. REASONING AND SOLUTION  According to the data given in Example 1, Chapter 24, the frequency of visible light ranges from \( 4.0 \times 10^{14} \text{ Hz} \) (red light) to \( 7.9 \times 10^{14} \text{ Hz} \) (violet light). According to Equation 29.2, the energy, \( E \), of a photon is related to its frequency, \( f \), by the relation \( E = hf \), where \( h \) is Planck's constant. According to Equation 29.2, the energy of a photon is directly proportional to its frequency.

   a. The red-colored light bulb emits photons with the lowest frequency compared to light bulbs of other colors (orange, yellow, green, or blue); therefore, the red-colored light bulb emits photons with the lowest energy.

   b. The color blue appears next to violet in the continuous visible spectrum; therefore, the frequency of blue light is slightly smaller than that of violet, but greater than the frequency of other colors of the visible spectrum. Thus, the blue-colored light bulb emits photons with the highest frequency compared to the other light bulbs; therefore, the blue-colored light bulb emits photons with the greatest energy.

3. REASONING AND SOLUTION  A photon emitted by a higher-wattage red light bulb does not have more energy than a photon emitted by a lower-wattage red bulb. The wattage of a bulb describes the power output of a bulb. Since average power is defined as energy per unit time, the power output of a light bulb tells us the rate at which the light bulb produces energy. According to Equation 29.2, the energy, \( E \), of a photon is related to its frequency, \( f \), by the relation \( E = hf \), where \( h \) is Planck's constant. Thus, the energy of a photon depends only on the frequency of the associated light wave. The frequency of red light is the same, regardless of the rate of energy production; therefore, all photons of red light have the same energy, regardless of the nature of their source.

   Remark: Since the higher-wattage bulb provides more energy per unit time than the lower-wattage bulb, we can conclude that the higher-wattage bulb produces more photons per unit time. All of the "red photons," however, have the same energy.

4. REASONING AND SOLUTION  When a sufficient number of visible light photons strike a piece of photographic film, the film becomes exposed. An X-ray photon is more energetic than a visible light
photon. Yet, most photographic films are not exposed by the X-ray machines used at airport security checkpoints. Since a single X-ray photon is more energetic than a single photon of visible light, we can conclude that the number of X-ray photons per unit time emitted by airport security machines is much smaller than the number of visible light photons per unit time produced by normal lighting fixtures.

5. **REASONING AND SOLUTION** When radiation strikes a metallic surface, a photon of the radiation can give up its energy to an electron in the metal. If the photon has enough energy to perform the minimum amount of work required to remove the electron from the metal, the electron can be emitted from the metal. The minimum amount of work required to remove an electron from a metal is called its work function. If the photon does not have enough energy to remove an electron, the energy of the photon is absorbed by the electron; the increase in energy is manifested as thermal motion.

Radiation of a given wavelength causes electrons to be emitted from the surface of one metal (metal 1) but not from the surface of another metal (metal 2). We can conclude that the individual photons of the radiation have sufficient energy to do the work required to remove the electrons from the surface of metal 1, but not enough energy to remove the electrons from the surface of metal 2. Therefore, the work function of metal 1 must be less than the work function of metal 2.

6. **REASONING AND SOLUTION** In a photoelectric effect experiment, the intensity of the light is increased while the frequency is kept constant. The frequency is greater than the minimum frequency $f_0$, so that photoelectrons are emitted from the negatively charged metal plate (see Figure 29.4).

Light intensity is the energy per second per unit area that crosses a transverse surface. According to Einstein's photon hypothesis (see Equation 29.2), a beam of light is composed of individual photons, each having an energy $E = hf$, where $h$ is Planck's constant and $f$ is the frequency of the light. From this viewpoint, the intensity of the light is equal to the energy of each photon multiplied by the number of photons per second per unit area crossing a transverse surface. An increase in the intensity of the light beam, therefore, corresponds to an increase in the number of photons per second that strikes the negatively charged metal plate. This will result in the emission of an increased number of photoelectrons per second at the negative plate.

a. As the number of photoelectrons emitted per second from the negative plate increases, the number of photoelectrons collected per second at the positive plate increases. Since the current in the phototube is proportional to the number of photoelectrons per second collected at the positive plate, increasing the light intensity will cause the current in the phototube to increase.

b. As discussed above, an increase in intensity will cause the number of photoelectrons emitted per second from the metal surface to increase.

c. According to Equation 29.3, the maximum kinetic energy that a photoelectron could have is given by $KE_{max} = hf - W_0$, where $W_0$ is the work function of the metal. Since the frequency is kept constant, and $W_0$ is a property of the metal that is independent of the intensity, an increase in intensity will have no effect on $KE_{max}$. The maximum kinetic energy that an electron could have remains the same.
d. The kinetic energy of an object of mass $m$ moving non-relativistically with speed $v$ can be expressed in terms of its momentum $p$ as follows:

$$KE = \frac{1}{2} mv^2 = \frac{(mv)^2}{2m} = \frac{p^2}{2m}$$

Therefore, treating the electron classically, the maximum momentum that a photoelectron could have is $p_{\text{max}} = \sqrt{2m(KE_{\text{max}})}$. Since the maximum kinetic energy that an electron could have remains the same as the intensity is increased at constant frequency, the maximum momentum that an electron could have remains the same as well.

e. According to Equation 29.8, the minimum de Broglie wavelength of an object of maximum momentum $p_{\text{max}}$ is given by

$$\lambda_{\text{min}} = \frac{h}{p_{\text{max}}}$$

Since the maximum momentum that a photoelectron could have remains the same as the intensity is increased at constant frequency, we can conclude that the minimum de Broglie wavelength that an electron could have also remains the same.

---

7. **REASONING AND SOLUTION** As the result of a Compton scattering experiment, an electron is accelerated straight ahead in the same direction as that of the incident X-ray photon. Momentum conservation requires that the total initial momentum be equal to the total final momentum. The total initial momentum consists only of the forward momentum of the incoming photon, which we assume to be traveling in the +x direction. The electron is initially at rest. Therefore, the direction of the final total momentum of the recoiling electron and the scattered photon must also point in the +x direction. There can be no component of the final total momentum along the +y or –y direction. We know that the recoiling electron has momentum only in the +x direction. Thus, in order for the y component of the total final momentum to be absent, the scattered photon must move either in the +x or –x direction. To distinguish between these two choices, it is necessary to refer to energy conservation, as well as momentum conservation.

---

8. **REASONING AND SOLUTION** A photon can undergo Compton scattering from a molecule such as nitrogen, just as it does from an electron. However, the change in photon wavelength is much less than when an electron is scattered. To see why, let us examine Equation 29.7 which gives the difference between the wavelength $\lambda'$ of the scattered photon and the wavelength $\lambda$ of the incident photon in terms of the scattering angle $\theta$: $\lambda' - \lambda = \frac{h}{mc} (1 - \cos \theta)$, where $h$ is Planck's constant, $m$ is the mass of the target particle, and $c$ is the speed of light in a vacuum. The mass of a nitrogen molecule is much greater than the mass of an electron. Therefore, the factor $\frac{h}{mc}$ will be much smaller if the target particle is a nitrogen molecule. Consequently, the change in the photon wavelength, $\lambda' - \lambda$, is much less than it is when the target particle is an electron.
9. **REASONING AND SOLUTION** When the speed of a particle with mass doubles, its momentum doubles, and its kinetic energy becomes four times greater. A photon, however, does not behave the same as a particle with mass. The momentum of a photon is $p = E/c$ (see the derivation of Equation 29.6); therefore, the energy of the photon can be written as $E = pc$. Clearly, when the momentum of a photon doubles, its energy also doubles. It does not become four times greater.

10. **REASONING AND SOLUTION** When bright light is incident on the radiometer, photons strike both the black and the shiny surfaces. The photons are absorbed by the black surfaces and are reflected by the shiny surfaces. Linear momentum is transferred to the panels because of the photon collisions. Since the orientation of the light is arbitrary, photons will strike the panels at arbitrary angles of incidence. Only the component of the photon's momentum that is perpendicular to the face of the panel contributes to its motion. As discussed in Conceptual Example 3, the momentum transfer to the panels is a maximum for the shiny surfaces and is twice as large in magnitude than it is for the black surfaces. Following the reasoning of Conceptual Example 3, we can use the impulse-momentum theorem and Newton's third law to deduce that the force on the shiny side is greater than the force on the black side. Therefore, in bright light, the arrangement would spin in the direction from the shiny side toward the black side. The observed spinning is in the opposite direction. Thus, photon collisions with the panels cannot be the cause of the spinning.

11. **REASONING AND SOLUTION** The linear momentum of an object of mass $m$ traveling with velocity $v$ is $p = mv$. The de Broglie wavelength of an object moving with momentum $p$ is given by Equation 29.8: $\lambda = h/p$, where $h$ is Planck's constant.

A stone is dropped from the top of a building. As the stone falls, it is uniformly accelerated, and its velocity increases uniformly in the downward direction. Consequently, the linear momentum of the stone also increases uniformly in the downward direction. According to Equation 29.8, the de Broglie wavelength of an object or particle is inversely proportional to the magnitude of its linear momentum. Therefore, as the stone falls, the de Broglie wavelength of the stone must decrease.

12. **REASONING AND SOLUTION** An electron and a neutron have different masses. According to Equation 29.8, $\lambda = h/p$, the de Broglie wavelength of a particle is inversely proportional to the magnitude of its linear momentum. Therefore, if the electron and the neutron have different speeds such that the magnitudes of their respective momenta are the same, they will have the same de Broglie wavelength.

13. **REASONING AND SOLUTION** Suppose that in Figure 29.1, the electrons are replaced with protons that have the same speed. The speed of the protons is the same as that of the electrons; however, the mass of a proton is greater than the mass of an electron. Therefore, the magnitude of the linear momentum of a proton is greater than the linear momentum of an electron traveling at the same speed. According to Equation 29.8, $\lambda = h/p$, the de Broglie wavelength of the "proton beam" will be smaller than that of the "electron beam." Equation 27.1 gives the condition that must be satisfied by the angle $\theta$ that locates the interference maxima in a Young's double-slit experiment: $\sin \theta = m\lambda/d$, where $m$ takes on integer values. According to Equation 27.1, the sine of the angle $\theta$
is directly proportional to the wavelength of the incident beam. Since the proton beam has a smaller wavelength than the electron beam, the values of \( \sin \theta \) that correspond to maxima will be smaller. Consequently, the difference in the corresponding values of \( \theta \) will be smaller, and the angular separation between the bright fringes will decrease when the electrons are replaced by protons.