

PRINCIPLES OF PHYSICS

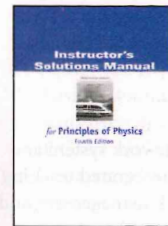
A CALCULUS-BASED TEXT FOURTH EDITION

SERWAY & JEWETT



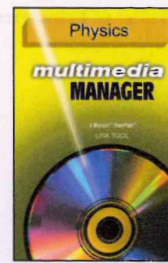
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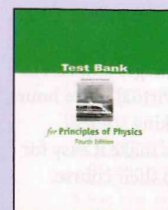
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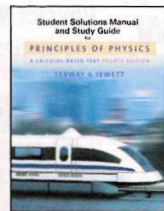


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PRINCIPLES OF PHYSICS

A CALCULUS-BASED TEXT **FOURTH EDITION**

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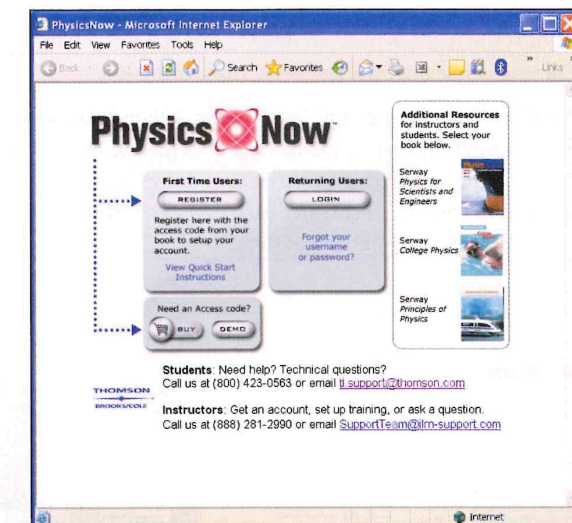
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$P_{\text{avg}} = S_{\text{avg}}/c$. Then the surface emits the beam, resulting in additional pressure $P_{\text{avg}} = S_{\text{avg}}/c$. If the surface emits only a fraction f of the beam (so that f is the amount of the incident beam reflected), the pressure due to the emitted beam is $P_{\text{avg}} = fS_{\text{avg}}/c$. Therefore, the total pressure on the surface due to absorption and re-emission (reflection) is

$$P_{\text{avg}} = \frac{S_{\text{avg}}}{c} + f \frac{S_{\text{avg}}}{c} = (1 + f) \frac{S_{\text{avg}}}{c}$$

For a beam that is 70% reflected, the pressure is

$$P = (1 + 0.70) \frac{9.6 \times 10^2 \text{ W/m}^2}{3.0 \times 10^8 \text{ m/s}} = 5.4 \times 10^{-6} \text{ N/m}^2$$

To finalize the problem, consider first the magnitude of the Poynting vector. It is about the same as the intensity of sunlight at the Earth's surface. (Therefore, it is not safe to shine the beam of a laser pointer into a person's eyes; that may be more dangerous than looking directly at the Sun.) To finalize further, note that the pressure has an extremely small value, as expected. (Recall from Section 15.1 that atmospheric pressure is approximately 10^5 N/m^2 .)

PhysicsNow™ Log into PhysicsNow at www.pop4e.com and go to Interactive Example 24.4 to investigate the pressure on the screen for various laser and screen parameters.

Space Sailing

When imagining a trip to another planet, we normally think of traditional rocket engines that convert chemical energy in fuel carried on the spacecraft to kinetic energy of the spacecraft. An interesting alternative to this approach is that of **space sailing**. A space-sailing craft includes a very large sail that reflects light. The motion of the spacecraft depends on pressure from light, that is, the force exerted on the sail by the reflection of light from the Sun. Calculations performed (before U.S. government budget cutbacks shelved early space-sailing projects) showed that sailing craft could travel to and from the planets in times similar to those for traditional rockets, but for less cost.

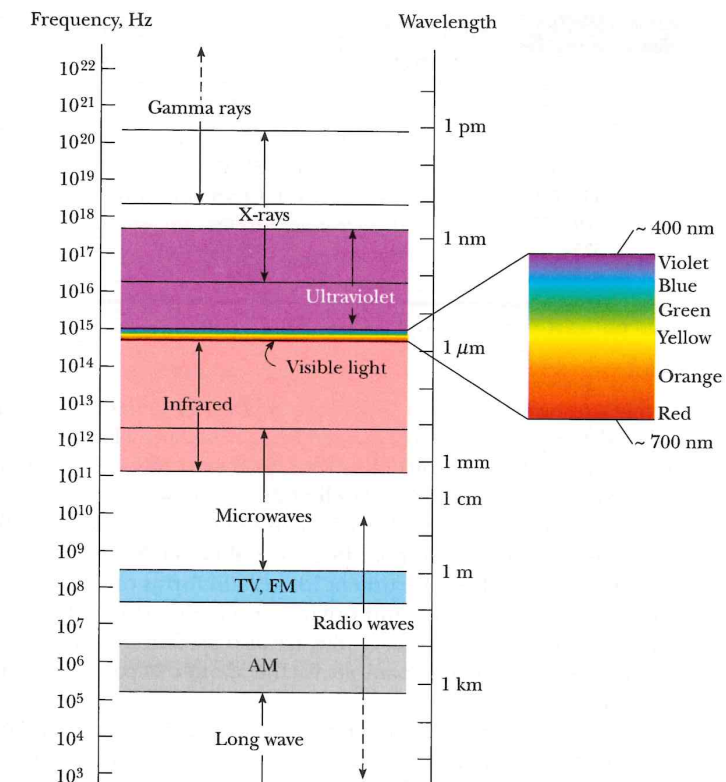
Calculations show that the radiation force from the Sun on a practical sailcraft with large sails could be equal to or slightly larger than the gravitational force on the sailcraft. If these two forces are equal, the sailcraft can be modeled as a particle in equilibrium because the inward gravitational force of the Sun balances the outward force exerted by the light from the Sun. If the sailcraft has an initial velocity in some direction away from the Sun, it would move in a straight line under the action of these two forces, with no necessity for fuel. A traditional spacecraft with its rocket engines turned off, on the other hand, would slow down as a result of the gravitational force on it due to the Sun. Both the force on the sail and the gravitational force from the Sun fall off as the inverse square of the Sun–sailcraft separation. Therefore, in theory, the straight-line motion of the sailcraft would continue forever with no fuel requirement.

By using just the motion imparted to a sailcraft by the Sun, the craft could reach Alpha Centauri in about 10 000 years. This time interval can be reduced to 30 to 100 years using a *beamed power system*. In this concept, light from the Sun is gathered by a transformation device in orbit around the Earth and is converted to a laser beam or microwave beam aimed at the sailcraft. The force from this intense beam of radiation increases the acceleration of the craft, and the transit time is significantly reduced. Calculations indicate that the sailcraft could achieve design speeds of up to 20% of the speed of light using this technique.

24.7 THE SPECTRUM OF ELECTROMAGNETIC WAVES

Electromagnetic waves travel through vacuum with speed c , frequency f , and wavelength λ . The various types of electromagnetic waves, all produced by accelerating charges, are shown in Figure 24.12. Note the wide range of frequencies and wavelengths. Let us briefly describe the wave types shown in Figure 24.12.

Radio waves are the result of charges accelerating, for example, through conducting wires in a radio antenna. They are generated by such electronic devices as LC oscillators and are used in radio and television communication systems.



Microwaves (short-wavelength radio waves) have wavelengths ranging between about 1 mm and 30 cm and are also generated by electronic devices. Because of their short wavelengths, they are well suited for radar systems used in aircraft navigation and for studying the atomic and molecular properties of matter. Microwave ovens are a domestic application of these waves.

Infrared waves have wavelengths ranging from about 1 mm to the longest wavelength of visible light, $7 \times 10^{-7} \text{ m}$. These waves, produced by objects at room temperature and by molecules, are readily absorbed by most materials. Infrared radiation has many practical and scientific applications, including physical therapy, infrared photography, and vibrational spectroscopy. Your remote control for your TV, VCR, or DVD player likely uses an infrared beam to communicate with the video device.

Visible light, the most familiar form of electromagnetic waves, is that part of the spectrum the human eye can detect. Light is produced by hot objects like lightbulb filaments and by the rearrangement of electrons in atoms and molecules. The wavelengths of visible light are classified by color, ranging from violet ($\lambda \approx 4 \times 10^{-7} \text{ m}$) to red ($\lambda \approx 7 \times 10^{-7} \text{ m}$). The eye's sensitivity is a function of wavelength and is a maximum at a wavelength of about $5.5 \times 10^{-7} \text{ m}$ (yellow–green). Table 24.1 provides approximate correspondences between the wavelength of visible light and the color assigned to it by humans. Light is the basis of the science of optics and optical instruments, to be discussed in Chapters 25 through 27.

Ultraviolet light covers wavelengths ranging from about $4 \times 10^{-7} \text{ m}$ (400 nm) down to $6 \times 10^{-10} \text{ m}$ (0.6 nm). The Sun is an important source of ultraviolet waves, which are the main cause of suntans and sunburns. Atoms in the stratosphere absorb most of the ultraviolet waves from the Sun (which is fortunate because ultraviolet waves in large quantities have harmful effects on humans). One important constituent of the stratosphere is ozone (O_3), which results from reactions of oxygen with ultraviolet radiation. This ozone shield converts lethal high-energy ultraviolet

FIGURE 24.12 The electromagnetic spectrum. Note the overlap between adjacent wave types. The expanded view to the right shows details of the visible spectrum.



Wearing sunglasses that do not block ultraviolet (UV) light is worse for your eyes than wearing no sunglasses. The lenses of any sunglasses absorb some visible light, thus causing the wearer's pupils to dilate. If the glasses do not also block UV light, more damage may be done to the eye's lens because of the dilated pupils. If you wear no sunglasses at all, your pupils are contracted, you squint, and much less UV light enters your eyes. High-quality sunglasses block nearly all the eye-damaging UV light. ■

PITFALL PREVENTION 24.3

HEAT RAYS Infrared rays are often called “heat rays.” This terminology is a misnomer. Although infrared radiation is used to raise or maintain temperature, as in the case of keeping food warm with “heat lamps” at a fast-food restaurant, all wavelengths of electromagnetic radiation carry energy that can cause the temperature of a system to increase. As an example, consider using your microwave oven to bake a potato, whose temperature increases because of microwaves.

TABLE 24.1 Approximate Correspondence Between Wavelengths of Visible Light and Color

Wavelength Range (nm)	Color Description
400–430	Violet
430–485	Blue
485–560	Green
560–575	Yellow
575–625	Orange
625–700	Red

Note: The wavelength ranges here are approximate. Different people will describe colors differently.

radiation to harmless infrared radiation. A great deal of concern has arisen concerning the depletion of the protective ozone layer by the use of a class of chemicals called chlorofluorocarbons (e.g., Freon) in aerosol spray cans and as refrigerants.

X-rays are electromagnetic waves with wavelengths in the range of about 10^{-8} m (10 nm) down to 10^{-13} m (10^{-4} nm). The most common source of x-rays is the acceleration of high-energy electrons bombarding a metal target. X-rays are used as a diagnostic tool in medicine and as a treatment for certain forms of cancer. Because x-rays damage or destroy living tissues and organisms, care must be taken to avoid unnecessary exposure and overexposure. X-rays are also used in the study of crystal structure; x-ray wavelengths are comparable to the atomic separation distances (≈ 0.1 nm) in solids.

Gamma rays are electromagnetic waves emitted by radioactive nuclei and during certain nuclear reactions. They have wavelengths ranging from about 10^{-10} m to less than 10^{-14} m. Gamma rays are highly penetrating and produce serious damage when absorbed by living tissues. Consequently, those working near such dangerous radiation must be protected with heavily absorbing materials, such as layers of lead.

QUICK QUIZ 24.5 In many kitchens, a microwave oven is used to cook food. The frequency of the microwaves is on the order of 10^{10} Hz. The wavelengths of these microwaves are on the order of (a) kilometers, (b) meters, (c) centimeters, or (d) micrometers.

QUICK QUIZ 24.6 A radio wave of frequency on the order of 10^5 Hz is used to carry a sound wave with a frequency on the order of 10^3 Hz. The wavelength of this radio wave is on the order of (a) kilometers, (b) meters, (c) centimeters, or (d) micrometers.

Thinking Physics 24.3

The center of sensitivity of our eyes is close to the same frequency as the center of the wavelength distribution of light from the Sun. Is that an amazing coincidence?

Reasoning It is not a coincidence; rather, it is the result of biological evolution. Humans have evolved so as to be most visually sensitive to the wavelengths that are strongest from the Sun. It is an interesting conjecture to imagine aliens from another planet, with a Sun with a different temperature, arriving at Earth. Their eyes would have the center of sensitivity at different wavelengths than ours. How would their vision of the Earth compare with ours?

24.8 POLARIZATION

As we learned in Section 24.3, the electric and magnetic vectors associated with an electromagnetic wave are perpendicular to each other and also to the direction of wave propagation as shown in Active Figure 24.3. The phenomenon of polarization

described in this section is a property that specifies the directions of the electric and magnetic fields associated with an electromagnetic wave.

An ordinary beam of light consists of a large number of waves emitted by the atoms of the light source. Each atom produces a wave with its own orientation of the electric field $\vec{E}$, corresponding to the direction of vibration in the atom. The direction of polarization of the electromagnetic wave is defined to be the direction in which $\vec{E}$ is vibrating. Because all directions of vibration are possible in a group of atoms emitting a beam of light, however, the resultant beam is a superposition of waves produced by the individual atomic sources. The result is an **unpolarized** light wave, represented schematically in Figure 24.13a. The direction of wave propagation in this figure is perpendicular to the page. The figure suggests that *all* directions of the electric field vector lying in a plane perpendicular to the direction of propagation are equally probable.

A wave is said to be **linearly polarized** if the orientation of $\vec{E}$ is the same for all individual waves *at all times* at a particular point as suggested in Figure 24.13b. (Sometimes such a wave is described as **plane polarized**.) The wave described in Active Figure 24.3 is an example of a wave linearly polarized along the y axis. As the field propagates in the x direction, $\vec{E}$ is always along the y axis. The plane formed by $\vec{E}$ and the direction of propagation is called the **plane of polarization** of the wave. In Active Figure 24.3, the plane of polarization is the xy plane. It is possible to obtain a linearly polarized wave from an unpolarized wave by removing from the unpolarized wave all components of electric field vectors except those that lie in a single plane.

The most common technique for polarizing light is to send it through a material that passes only components of electric field vectors that are parallel to a characteristic direction of the material called the **polarizing direction**. In 1938, E. H. Land discovered such a material, which he called **Polaroid**, that polarizes light through selective absorption by oriented molecules. This material is fabricated in thin sheets of long-chain hydrocarbons, which are stretched during manufacture so that the molecules align. After a sheet is dipped into a solution containing iodine, the molecules become good electric conductors. The conduction, however, takes place primarily along the hydrocarbon chains because the valence electrons of the molecules can move easily only along the chains (valence electrons are “free” electrons that can readily move through the conductor). As a result, the molecules readily *absorb* light whose electric field vector is parallel to their length and *transmit* light whose electric field vector is perpendicular to their length. It is common to refer to the direction perpendicular to the molecular chains as the **transmission axis**. An ideal polarizer passes the components of electric vectors that are parallel to the transmission axis. Components perpendicular to the transmission axis are absorbed. If light passes through several polarizers, whatever is transmitted has the plane of polarization parallel to the polarizing direction of the last polarizer through which it passed.

Let us now obtain an expression for the intensity of light that passes through a polarizing material. In Active Figure 24.14, an unpolarized light beam is incident

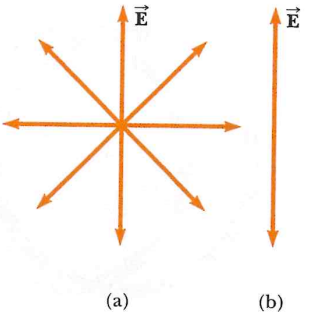
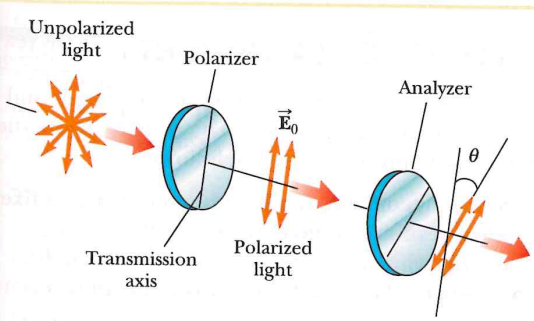


FIGURE 24.13 (a) An unpolarized light beam viewed along the direction of propagation (perpendicular to the page). The time-varying electric field vector can be in any direction in the plane of the page with equal probability. (b) A linearly polarized light beam with the time-varying electric field vector in the vertical direction.



ACTIVE FIGURE 24.14

Two polarizing sheets whose transmission axes make an angle θ with each other. Only a fraction of the polarized light incident on the analyzer is transmitted through it.

PhysicsNow Log into PhysicsNow at www.pop4e.com and go to Active Figure 24.14 to rotate the analyzer and see the effect on the transmitted light.

Center of eyesight sensitivity